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Rapid Natural Habitat Degradation and Consequences for Sockeye Salmon Production in the Chignik Lakes System, Alaska

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ABSTRACT

Degradation of salmon rearing habitat in Black Lake since the 1950s and its effects on sockeye salmon production in the Chignik watershed were evaluated in an effort to identify potential measures to restore habitat and salmon runs. During the late 1960s, channel migration of the West Fork River led to down-cutting of upper Black River, leading to the lowering of water elevation of Black Lake. Concurrently, sediment influx from Alec River raised the bottom of the lake, especially in deeper lake areas. These events led to a 23% to 44% reduction in water volume of Black Lake. Presently, water depth of Black Lake during low water periods averages approximately 1 m (3.28 ft). Recent observations indicate the lake elevation is likely continuing to decline. In response to the declining lake elevation, Alec River, where more than 400,000 sockeye spawn each year, has been shifting toward the outlet area of the lake which is separated from the main lake area by a large, newly formed sandspit.

In spite of these habitat changes, adult sockeye salmon runs and productivity (return per spawner) have not declined since the late 1960s because survival at sea and weather during freshwater residence have been highly favorable. Nevertheless, intensive investigations of sockeye salmon in the watershed indicate habitat degradation has significantly affected production of Chignik sockeye salmon. Many young-of-the-year sockeye salmon in Black Lake emigrate to Chignik Lake during spring and summer, apparently in response to the shallow depth. This emigration occurred before and after the recent decline in lake elevation. However, sampling during the 1990s revealed that essentially no sockeye salmon overwinter in Black Lake, whereas periodic sampling in the 1960s indicated many if not most sockeye salmon over-wintered in Black Lake during the 1950s and 1960s. Winter studies revealed that sockeye salmon tolerated low oxygen levels in Black Lake significantly less than juvenile coho salmon, which continue to over-winter in Black Lake. During the 1990s, adult sockeye salmon runs significantly declined when juveniles experience low dissolved oxygen levels in Black Lake. During years of favorable conditions, many Black Lake sockeye salmon successfully emigrated and over-wintered in Chignik Lake, and produced large adult returns. The shallow lake and unstable winter environment of Black Lake appears to have influenced the highly variable returns of adult salmon to Black Lake, which are considerably more variable than other Alaskan stocks.

Successful emigrations of numerous, relatively large juvenile Black Lake sockeye salmon to Chignik Lake led to reduced growth of yearling Chignik Lake sockeye salmon. Competition in Chignik Lake appears to have led to reduced adult returns to Chignik Lake, based on the inverse relationship between Black and Chignik sockeye runs and density-dependent growth in the lake. Although salmon harvests throughout Alaska increased substantially in response to the 1976/1977 ocean climate change, harvests of Chignik sockeye salmon increased considerably less than that of other major sockeye salmon stocks in Bristol Bay and central Alaska. Habitat degradation in Black Lake and increased competition in Chignik Lake during some years appears to have inhibited Chignik salmon population growth in response the ocean climate change relative to other stocks. Measures to restore habitat in Black Lake were identified, but the potential beneficial effects of restoration measures on adult sockeye production are difficult to quantify. No action to restore habitat will likely allow gradual degradation of habitat in Black Lake. In turn, habitat degradation would gradually lead to lower salmon production, but the

level of reduced salmon production may not be readily detectable without careful comparisons across watersheds in Alaska. A decline in salmon production in the Chignik system may be more apparent if climate conditions shifts back to that of the 1950s.

SUMMARY

The Chignik Regional Aquaculture Association (CRAA) is concerned that Black Lake is naturally degrading as a juvenile sockeye salmon nursery habitat. CRAA considers the changes in the Black Lake drainage, which have been especially dramatic over the last few decades, a major threat to Chignik sockeye salmon production. In accordance, CRAA believes that it along with state and federal governments should be proactive in protecting and, when possible, restoring Black Lake to benefit all Chignik users including commercial, subsistence, sport fishers and wildlife.

This report documents 1) the physical changes of the Black Lake system that have occurred since about the late 1950's, 2) the effects of these changes on Chignik sockeye salmon habitat, rearing, and production, and 3) addresses selected restoration and mitigation options including a flow control structure at the lake's outlet and the rerouting of Alec River, the lake's principal inlet stream. A key part of this analysis is the attached collection of photographs (Appendix) that visually document significant changes in habitat since the 1950s.

Habitat Changes

Salmon habitat in upper Chignik watershed has changed significantly since the 1950s, based on photographs and physical measurements of the lake. These changes are believed to have resulted from channel migration of the West Fork River (circa 1970), which is a large tributary to Black River that connects Black Lake to Chignik Lake. The West Fork River collects glacial runoff, rainfall, and groundwater from Mount Veniaminof, an active 8,400 ft volcano, and transports significant quantities of volcanic sand to Black River approximately 4.5 km below Black Lake. During the 1950s, the West Fork River created a large delta extending across Black River. This large delta constricted Black River and maintained water level in Black River and Black Lake at a high level during the 1950s and 1960s. During approximately 1970, the West Fork River shifted approximately 5 km downstream toward Chignik Lake. Soon after this channel shift, a 3.5 ft waterfall developed in the Black River within 1 km below the original West Fork confluence, apparently in response to changing flows, bank failure, and the lack of substantial volcanic sediment input from the West Fork River. The waterfall inhibited boat travel for approximately one year before eroding. Evidence suggests that the channel migration of the West Fork River gradually led to degradation of upper Black River, which in turn has led to lowering of the surface elevation of Black Lake.

During the 1980s, it became apparent to Chignik Lake Village residents and to FRI researchers that the shallow Black Lake was becoming shallower. In the early 1980s, an aerial photograph documented emergence of a sandspit extending across the outlet of Black Lake. During the 1960s, this sandspit was a shallow bar and, on occasion, FRI researchers towed a 6' deep net across it. In a low water period in 1990, the exposed sandspit crossed approximately 80% of the lake outlet, but no vegetation was present. The outlet sandspit, which separates the lake outlet area from the main lake rearing area, has become a substantial feature of Black Lake. Vegetation is now growing on the sandspit and along other areas of the lake shoreline and upper Black River, suggesting lake level may be continuing to decline. In several areas, the lake perimeter is now considerable distance (100s m) from the lake berm that contained the lake during the 1950s.

Black Lake has become shallower in response to lower lake elevation and significant transport of volcanic sand in the Alec River where approximately 400,000 sockeye salmon spawn each year. A 1949 lake elevation measurement and a USGS land elevation benchmark indicate average lake level declined approximately 0.67-1.1 m (2.2-3.6 ft). During 1960, average and maximum depths were 2.6 m (8.5 ft) and 6.4 m (21 ft), respectively. During 1989-1992, average and maximum depths decreased to 1.9 m (6.2 ft) and 4.0 m (13.1 ft), respectively. This change, on average, corresponds to approximately 27% and 38% reduction in average and maximum depth, or 23-44% less water volume based on the 1992 depth survey and the estimated decline in lake elevation. During 1992, Black Lake contained 54% less water volume during extreme low water periods compared with high water periods. Thus, seasonal shifts in water volume of Black Lake are significant.

Alec River provides the large majority of water flowing into Black Lake. Alec River splits into a north and south channel approximately 1.7 km from Black Lake. Previously, most water flowed through the north channel to Alec Bay and the main lake rearing area. Presently, during low water periods such as spring when fry are moving into Black Lake, approximately 70% of the water is carried by the south channel leading to the lake outlet, which is isolated from the main lake area by the outlet sandspit that extends across up to 85% of Black Lake (2002 estimate). Migration of the Alec River channel appears to be associated with the decline in lake elevation. Channel erosion and discharge measurements indicate the Alec River is continuing to shift toward the lake outlet. In 2003, the sandbar that deflects water into the south channel enlarged considerably. This change will likely lead to increased flow into the south channel and to the outlet area of the lake.

Consequences for Chignik Sockeye Salmon Production

Ruggerone and Rogers (1989) hypothesized during the late 1980s that the significant changes in Black Lake could lead to large fluctuations in adult salmon return to Black Lake because the shallow lake could experience winterkill in some years. Also, it was hypothesized that large emigrations of fry from Black Lake could adversely affect growth and survival of Chignik Lake sockeye salmon, which are relatively small at age.

<u>Adult Returns</u>

Chignik sockeye salmon runs exhibit long-term trends that are characteristic of salmon runs in western Alaska. Chignik salmon runs were large during the early 1900s, averaging 1.86 million salmon during 1922-1950. Abundance declined during the mid-1900s, averaging 1.1 million salmon during 1951-1975. During 1976-2002, sockeye salmon runs were relatively high, averaging 2.66 million salmon. On average, the Black Lake run represented 50% of the total Chignik run.

The patterns of sockeye salmon runs and productivity (return per spawner; R/S) by stock and for the total Chignik system do not show a decline that might be expected with significant changes in Black Lake habitat. However, all salmon runs in western and central Alaska have exhibited significant increases in run size and productivity since the mid-1970s. Greater salmon runs have been associated with a climate shift that occurred during 1976-1977, leading to significant changes in many species abundance and to greater growth of salmon at sea. The climate shift that enhanced salmon growth and survival throughout Alaska may have masked adverse changes in freshwater habitat. Thus, more detailed analysis within the Chignik Lakes were conducted to evaluate the effects of habitat changes in Black Lake on production and productivity of Chignik sockeye salmon.

Overwintering of Juvenile Sockeye Salmon in Black Lake

Intermittent studies conducted during the 1960s, 1970s, and 1990s documented large numbers age-0 sockeye salmon migrating from Black Lake to Chignik Lake during spring and summer. This migration was believed to be density-dependent: greater numbers of fry migrated in response to greater numbers of fry in Black Lake and in response to declining water levels that typically occur from spring through summer. However, daily sampling of Black River during 1992 and 1993 revealed that flooding of Black Lake could stimulate major out-migrations of fry and fry migrations did not appear to be related to lake level. Furthermore, fry captured in Black River (excluding the flood migration) contained less prey and were different size compared with fry remaining in Black Lake, indicating migrating fry were not a random subset of fish in Black Lake except for the flood event.

Sampling of Black Lake by townet during fall indicated most sockeye salmon fry remain in Black Lake, but no yearling sockeye salmon remain in the lake. Townet catch rates of sockeye salmon fry in Black Lake are exceptional, averaging approximately 12 times greater than those in Bristol Bay lakes. Feeding studies indicate prey availability (mostly chironomids, but *Bosmina* in late summer) is high and growth is relatively rapid. Water temperature is relatively warm and generally conducive to efficient growth, although high temperatures (20°C near surface) may occasionally impact adult sockeye salmon. New analyses presented here indicated growth of Black Lake sockeye fry was dependent on sockeye salmon abundance and spring temperature.

Periodic sampling of fry and smolts in Black River indicated many sockeye salmon overwintered in Black Lake during the 1960s. Catch rates of smolts in Black River were 65x greater during the 1960s compared to 1992-1993. Catches of smolts per fry were 123x greater during the 1960s compared to 1992-1993. These data suggest that considerably more sockeye salmon overwintered in Black Lake during the 1960s compared with the 1990s. This conclusion is consistent with comments by FRI researchers in the 1950s and 1960s, who indicated most salmon overwintered in Black Lake. Spring growth of yearling sockeye salmon in Black Lake can be substantial because the lake warms rapidly during spring. Analysis of spring freshwater growth of adult Black Lake salmon scales (age 1.3) indicated growth was significantly greater during the 1960s compared with the recent period, suggesting more fish overwintered in Black Lake during the early period.

In contrast to the 1960s, almost no sockeye salmon overwintered in Black Lake during the 1990s. Seven years of sampling under the ice of Black Lake during winter did not reveal a single sockeye salmon. Daily sampling of Black River during spring and summer 1992 and 1993 with multiple fyke nets and a rotary screw trap captured only a few yearling smolts. These data and others indicate essentially no sockeye salmon presently overwinter in Black Lake.

Sampling of sockeye salmon under the ice of Chignik Lake during winter revealed significant numbers of Black Lake sockeye salmon, which were identified in Chignik Lake by length at age analysis. This stock identification technique has been successfully used when making forecasts of adult salmon runs. Comparison of stock composition under the ice using length at age analysis and genetic stock identification revealed almost identical percentages.

Experiments during winter demonstrated that sockeye salmon do not tolerate 24-hour exposure to low dissolved oxygen as well as coho salmon. For example, survival of sockeye salmon declined rapidly as oxygen content declined below 30% saturation (4 mg/l), whereas no coho salmon died at this and lower oxygen levels. The results of this experiment were consistent with observation that coho were abundant in Black Lake during winter and they preferred bottom habitat, which was relatively warm, but low in dissolved oxygen.

Oxygen profiles throughout Black Lake during February demonstrated that oxygen content varied considerably from year-to-year. Oxygen content reached its lowest level in 1992 when the water column below 50 cm (1.6 ft) was below 57% saturation, which is the threshold level for maintaining healthy salmon populations. In contrast, in 1993 ice on Black Lake was thin and contained numerous holes and oxygen content exceeded 57% at all depths.

The effect of low winter oxygen on numbers of adult sockeye salmon returning to Black Lake was examined by comparing returns of age-1.3 salmon (the dominant age group) with oxygen content of Black Lake during juvenile rearing. The return of adult sockeye salmon significantly declined as oxygen content in the water column decreased. Adult returns were approximately 1.5 million salmon when oxygen content was high, but only approximately 0.5 million salmon when oxygen content was low.

<u>Competition Between Black and Chignik Lake Sockeye Salmon</u>

Studies during the 1960s and early 1970s demonstrated that sockeye salmon growth in Chignik Lake is density-dependent, indicating large emigrations of Black Lake sockeye salmon likely have an adverse effect on Chignik Lake sockeye growth and possibly survival. Comparison of Chignik Lake and Black Lake sockeye run size (i.e., all age-x.3 components from same smolt year) indicated that large Chignik Lake runs since approximately 1977 occurred primarily when Black Lake runs were average or below average (<1.2 million fish). The negative curvi-linear relationship indicated emigration of Black Lake sockeye fry adversely affected yearling salmon rearing in Chignik Lake.

Analysis of freshwater scale pattern growth of adult Chignik Lake sockeye salmon (age 2.3) indicated spring growth of juvenile salmon during the year of smoltification was reduced during years of high abundance of Black Lake salmon. This relationship suggests successful winter emigrations of Black Lake salmon, along with previous spring and summer migrations, adversely affected juvenile growth of Chignik Lake salmon. Emigration of Black Lake fry, which are similar in size to Chignik Lake yearlings, did not appear to significantly affect growth of age-0 fry in Chignik Lake, based on scale growth, but emaciated and dying age-1 and age-2 salmon have been observed during the spring following large migrations from Black Lake. The effect of Black Lake fry on growth of Chignik Lake yearlings provides a mechanism for the inverse relationship between Chignik Lake and Black Lake runs.

Chignik Adult Returns Relative to Other Watersheds

Harvests

Sockeye salmon production in the Chignik Lake system relative to other systems in western and central Alaska was compared in an effort to determine whether Chignik salmon production has increased as much as other stocks. Chignik sockeye salmon harvests, excluding interceptions, increased 128% from 1964-1976 to 1977-2002, whereas the average harvest increase for 11 other fisheries was 349%. Only harvest of Kvichak sockeye salmon lagged behind the Chignik harvests. The Chignik percentage increase was 126% when estimated interception harvests were added to the Chignik management area harvest. Thus, on average, harvests of other fisheries after the mid-1970s regime shift increased approximately 2.7 times more than Chignik harvests.

This finding suggests that sockeye salmon production in the Chignik watershed lagged significantly behind that of most other major watersheds in western and central Alaska. It supports the hypothesis that significant changes in Black Lake habitat have led to lower salmon runs.

Variability in Production

Ruggerone and Rogers (1989) hypothesized that the shallow depth of Black Lake may lead to highly variable adult runs. Variability in return per spawner (R/S) of Black Lake sockeye salmon was compared with that of 11 other stocks during brood years 1965-1995. Variability in R/S of the 11 sockeye salmon stocks, as measured by coefficient variation, increased with greater variability in spawning escapement. Coefficient of variation of Black Lake spawning escapement was low (27.5%) and the predicted variation in R/S, based on the regression analysis, was 28.9%. However, the observed Black Lake R/S coefficient of variation (60.8%) was significantly greater than expected (28.9%). Thus, Black Lake productivity was highly variable compared to other sockeye salmon stocks in western and central Alaska. This finding supports the hypothesis that the shallow depth of Black Lake creates an unstable habitat that leads to variable survival. Variability in sockeye salmon survival appears to be related to year-to-year fluctuations in dissolved oxygen under the ice of Black Lake during winter, fluctuations in survival of juvenile sockeye salmon attempting to emigrate from Black Lake during winter, and emigration of fry to Chignik Lake during spring and summer.

Potential Mitigation of Habitat Degradation in Black Lake

Available information indicates Black Lake habitat has changed significantly since the late 1960s. Favorable climate and ocean rearing conditions have masked the effect of habitat degradation on total production of sockeye salmon, but several studies provide evidence that habitat degradation has led to a reduction in the capacity of the Chignik watershed to support sockeye salmon. Observations of Black Lake during recent years suggest that habitat is continuing to degrade.

The concept of stabilizing Black Lake water level at a moderately high level in an effort to enhance sockeye runs has been discussed since the mid-1970s. The potential benefits of lake level stabilization are 1) reduced potential for high mortality due to low oxygen levels in the lake during winter, 2) greater carrying capacity of the lake, leading to less salmon emigration to Chignik Lake during spring through winter and to less inter-stock competition, and 3) greater percentage of Alec River flowing to the north channel and the main lake rearing area, thereby allowing more salmon fry to directly enter the main rearing area. Higher water level during winter will likely increase the percentage of the water column having adequate oxygen content, but this relationship has not been quantified. Although some research suggests declining lake level and high salmon densities stimulate fry emigration to Chignik Lake, other studies show factors such as flooding, can stimulate tremendous emigrations. Rapid change in lake level probably contributed to fry emigration during the flood, but this event shows that it is difficult to predict how sockeye salmon would respond to lake stabilization. Lake stabilization would not enhance water volume forever because significant sediment transport in Alec River would gradually lead to shallowing of Black Lake. Although lake stabilization is likely to have a beneficial effect on sockeye salmon production, assuming engineering works as intended, it is important to note that interactions between salmon, habitat and climate are complex. Thus, it is difficult to quantify the potential benefit to adult production that may be associated with lake stabilization.

Engineering plans to stabilize lake level have not been developed, but there are several critical issues that must be addressed if plans were developed. First, soils surrounding the lake outlet are highly porous and subject to erosion. The lake outlet control point is critical to maintaining the current lake level and this area must be protected from further erosion. Second, in water structures must allow upstream and downstream passage of juvenile and adult salmon, other fishes, and boats. Third, tests must be conducted to determine whether the soils could maintain higher water levels. Fourth, structures must be able to withstand significant forces of ice scouring, currents and wind.

Re-channeling of Alec River back into the north channel was discussed in the early 1990s. Potential benefits include transport of fry to the main lake area rather than the lake outlet area and localized increase in dissolved oxygen during winter. These potential benefits appear to be less than that of lake stabilization, which would also help shift Alec River back into the north channel. Structures placed in Alec River to divert water would be subjected to high erosion potential given the moderate water velocities and volcanic sand substrate. Techniques to encourage the river to naturally shift toward the north channel were previously discussed, but this concept was not fully evaluated.

Additional potential mitigation measures are discussed in the report, including dredging, diversion of the West Fork River, hatchery production, and supplemental feeding. There are no simple solutions for restoring habitat or enhancing Chignik sockeye salmon runs. All actions involve risks and uncertainties and the cost-benefit ratio is difficult to evaluate. However, a simulation model could be developed to explore potential outcomes from a range of interacting variables on sockeye salmon behavior and survival.

No Action

A key question is what will happen to Chignik salmon runs if no action is taken. This is not an easy question to accurately answer, but I will attempt to do so since it is an obvious question. Salmon production in the Chignik watershed is still high and it still produces significant harvests. I believe that it will continue to produce similar runs in the near future as long as climate remains favorable.

Nevertheless, significant changes in habitat during the past 40 years have been documented, and incremental changes will continue in Black Lake, Alec River and Black River. The shallowing of Black Lake is a natural process that will continue to evolve and influence sockeye production. Lake shallowing will be associated with greater exposure of the outlet sand spit that inhibits movement of fry from the outlet area to main lake rearing area. Lower lake level will lead to more emergent fry entering the lake outlet rather than the main lake because Alec River flow will shift to the outlet area. Greater fry abundance in the lake outlet area will likely lead to greater emigration to Chignik Lake during spring and summer, even though Black Lake remains an excellent rearing habitat for juvenile salmon during summer. Lower lake level during winter will lead to more frequent episodes of low oxygen in the water column of Black Lake, which may lead to more frequent failures of adult sockeye salmon runs.

Slowly, a larger percentage of juvenile Black Lake sockeye will become more dependent on Chignik Lake for rearing. This process is apparent now as very few sockeye salmon presently overwinter in Black Lake, whereas many overwintered there in the 1960s. Black Lake remains an excellent rearing habitat during open water periods, although its unique conditions lead to significant migrations of fry to Chignik Lake. Large migrations of fry from Black Lake to Chignik Lake can presently lead to increased competition, reduced growth, and increased mortality of juveniles originating from Chignik Lake spawning areas. Greater migrations of Black Lake fry during spring and summer would lead to greater competition and reduced adult returns of Chignik Lake sockeye salmon. Chignik Lagoon is currently an important rearing habitat and its importance to salmon growth and survival may increase if growth of Chignik salmon declines in response to less rearing in Black Lake. To some extent, Chignik Lagoon provides a buffer to habitat degradation in Black Lake and high rearing densities in Chignik Lake. However, Chignik Lagoon habitat cannot mitigate the mortality of salmon that occurs during winter and spring in Black and Chignik lakes.

Sockeye salmon production is influenced by the interaction of climate and habitat. During the past 25 years, winter conditions have been relatively mild compared with earlier years, leading to longer growing seasons in the lakes and greater growth and survival at sea. Effects of habitat degradation may become more apparent if climate switches back to conditions of the 1950s when winters were long and cold and salmon runs were small. Winter low oxygen content in Black Lake could become a more frequent event. However, nobody knows for certain what the climate will be 10 years from now. Thus, the near-term outlook for sockeye salmon production in the

Chignik watershed is continuation of the highly variable runs that occurred during the 1990s, assuming weather patterns remain similar.

The long-term outlook for Chignik salmon runs is for gradually declining runs relative to other systems. However, given the large variability in annual salmon runs, this long-term decline may not be large enough to detect without comparison of Chignik salmon runs with other sockeye runs in western and central Alaska. As described in this document, favorable climate and ocean conditions can mask the effects of adverse habitat changes in freshwater. Effects of habitat degradation on salmon runs will likely become more apparent during periods of unfavorable climate and ocean conditions, as demonstrated by the sharp decline in salmon runs in the Pacific Northwest during the past 30 years. Chignik fishers will continue to harvest sockeye salmon unless climate reverts back to conditions such as in the 1950s when runs were often less than the existing spawning escapement goals. Monitoring of channel migration in the lower Alec River, flow control features (natural sill) in the lake outlet, and winter conditions of Black Lake will be important for detection of significant rapid changes in habitat that may occur.

INTRODUCTION

The Chignik watershed has supported a significant sockeye salmon fishery in the Chignik Management Area along the south side of the Alaska Peninsula since the late 1800s (Fig. 1). Salmon and the associated commercial fishery provide the primary economic input for villages in the Chignik management area (Chignik Bay, Chignik Lagoon, Chignik Lake, Perryville). Chignik salmon also contribute to harvests by Kodiak and Southeast District Mainland fishers who are allowed to catch a percentage of Chignik salmon. Salmon are widely used for subsistence and they are a key cultural resource. Sockeye salmon originating from the Chignik watershed is the key species affecting the livelihood of Chignik area residents and other individuals that come to Chignik to participate in the commercial fishery or to assist with processing of the catch.

The Fisheries Research Institute (FRI), University of Washington, established a salmon research station at Chignik Lake in the mid-1950s. Chignik was selected for research because it supported a significant sockeye salmon fishery and it provided a comparison with FRI research in Bristol Bay and Kodiak. The primary goals of FRI research were to identify factors affecting salmon survival, develop methods to assist management of the salmon harvests, and to make recommendations regarding spawning escapement goals. Some of the key research topics at Chignik included: 1) carrying capacity studies to develop and/or evaluate spawning escapement goals (Narver 1966, Dahlberg 1968, Burgner et al. 1969, Parr 1972, Phinney 1968, Burgner and Marshall 1974, Ruggerone and Rogers 1998, 2003, Ruggerone et al. 1999), 2) stock identification studies based on stock specific timing (Dahlberg 1968), scale pattern analysis (Narver 1963, Marshall 1978, Conrad 1983), and genetic stock identification (Ruggerone 1997a, Templin et al. 1999), salmon run size and run timing forecasting (Parker 1986, Ruggerone 1997b, Chasco 2003), and effects of predator-prey interactions on sockeye salmon production and management (Roos 1959, 1960, Ruggerone 1989a,b,c, 1992a, Ruggerone and Rogers 1992).

During the mid- to late 1980s, residents of the Chignik Lake village (Bill Lind, Johnny Lind, Elia Lind and others) began to raise concern regarding the increasingly shallow water of Black Lake. These changes were also observed by FRI researchers and residents of other nearby villages who flew over the lakes. During the 1990s, the Chignik Regional Aquaculture Association (CRAA) funded a number of studies to evaluate changes in Black Lake and sockeye salmon production in the Chignik watershed. These studies included quantification of fry and smolt emigration from Black Lake to Chignik Lake during spring and summer (1992 and 1993), quantification of smolt emigration from Chignik Lake (1993-present), channel migration of Alec River, evaluation of effects of low dissolved oxygen on sockeye salmon survival in Black Lake, and re-evaluation of spawning escapement goals. Additionally, a lake enrichment survey was conducted based on the recommendations of Drs. O. Mathisen (University of Alaska) and J. Koenings (ADFG), who suggested that the small size and survival of Chignik sockeye salmon smolts might be enhance through lake enrichment. In addition to these biological studies, CH2M-Hill conducted an engineering feasibility survey of the Black Lake area in an effort to determine whether 1) the level of Black Lake could be increased by construction of a small sill near the outlet of Black Lake, and 2) channel migration of lower Alec River could be controlled. This preliminary 1993 engineering study revealed potential difficulties for constructing an outlet control structure (or sill) and diverting Alec River. Further investigation was halted until further information could be gathered on the effects of habitat changes on sockeye salmon.

CRAA is reconsidering approaches to restore Chignik sockeye salmon habitat and has requested a synthesis of information related to changes in Black Lake habitat and its consequences for salmon production. The purpose of this report is to 1) document changes in the physical characteristics of Black Lake since the 1950s, 2) describe the effects of these changes on sockeye salmon production and survival, and 3) evaluate the potential for enhancing salmon production in the Chignik watershed. Potential enhancement projects considered by CRAA are control of Black Lake water level during low water periods, control of Alec River channel migration, dredging of Black Lake, re-diversion of the West Fork River, hatchery production of sockeye salmon, and supplemental feeding of sockeye salmon in Chignik Lake.

Description of Chignik Watershed

The Chignik watershed consists of two lakes on the Alaska Peninsula (56° 16'N Lat., 158° 50'W Long.; Fig. 1) draining south to Chignik Lagoon and the Gulf of Alaska. Chignik Lake is small (22 km^2), relatively deep (64 m) and is situated between precipitous mountains on the south side of the peninsula. Black Lake (~41 km^2) is a shallow depression (< 6.4 m in the 1960s) on the north side of the peninsula that flows into Chignik Lake via Black River (Burgner et al. 1969). Chignik River connects Chignik Lake to Chignik Lagoon, which is a shallow and moderately large area that is significantly influenced by tidal exchange. Breakup of ice on Chignik Lake and Black Lake generally occurs in April to early May and March to April, respectively. Ice cover may be patchy or non-existent in mild winters. Frequent and strong winds continually mix the water column of these lakes during spring and summer and inhibit stratification of the water column. Water level is typically low during winter and late summer, but relatively high following snowmelt and rain during late spring and late fall. Water temperature during spring and summer typically ranges from approximately 5-13°C in Chignik Lake and from 9-18°C in Black Lake. Water transparency in both lakes decreases from spring to summer and is generally low in Chignik Lake (1-4 m Secchi disk measurements) due to high standing crop of phytoplankton and glacial runoff from Mt Veniaminof, and exceptionally low in Black Lake (<1-2 m Secchi disk measurements) due to phytoplankton and turbidity from strong winds and shallow depth. Chignik Lake has a relatively small littoral zone whereas Black Lake is primarily littoral habitat. Macrophytes (primarily *Potamogeton* sp.) are abundant in the outlet and Alec Bay areas of Black Lake from mid-summer to fall, but they are not present in Chignik Lake.

Chignik Sockeye Salmon Life History and Production

Adult sockeye salmon return to the Chignik watershed over an exceptionally long period compared with most other sockeye systems. Sockeye salmon begin migrating up Chignik River in late May and continue entering the system in October and beyond. The early run in June primarily migrates to spawning tributaries of Black Lake. Smaller numbers of early run salmon return to spawn in Black River tributaries (Dahlberg 1968), and the progeny of these fish rear in Chignik Lake (Narver 1963, 1966, Harvey 1994). During the 1960s, tag and recovery studies (Dahlberg 1968) indicated the Black Lake run was typically over by July 20; however, scale pattern studies since 1978 indicated some Black Lake salmon returned in late July and August (Conrad 1983, Witteveen and Botz 2003)[1] and in 2002 two of 78 radio-tagged salmon in August and September were observed in Alec River (Black Lake stock; Anderson 2003). Adult salmon returning to Chignik Lake tributaries and lake shoreline spawning areas enter freshwater from late June through October and beyond. Salmon originating from Black Lake spawning areas typically spend one winter in freshwater and three winters at sea, whereas salmon originating from Chignik Lake spawning areas typically spend two winters in Chignik Lake and three winters at sea. Black River tributaries produce early and late salmon runs; early run salmon typically spend one winter in freshwater whereas late run salmon spend two years in freshwater (Narver 1963, Ruggerone 1994). Chignik Lagoon provides additional rearing habitat for juvenile sockeye salmon, especially slower growing fish and some age-0 salmon (Phinney 1968, Iverson 1966, Ruggerone et al. 2000, Finkle and Bouwens 2001, Bouwens and Finkle 2003).

Burgner et al. (1969) compared sockeye salmon systems in western and central Alaska during the 1960s and concluded that the Chignik lakes had the highest standing crop of phytoplankton and primary productivity rate among all the examined lakes. High primary productivity in the Chignik watershed was likely linked to the volcanic soils compared with sedimentary soils of mainland lakes. Both Black and Chignik lakes have high densities of juveniles, which reflect the exceptionally high density of parent spawners per lake surface area. Although size of juvenile sockeye in the lakes is somewhat small, Burgner et al. (1969) noted that growth was relatively high in relation to parent spawning density per lake surface area. Burgner et al. noted that sockeye salmon in the 1960s fully utilized only approximately 77% of the Black Lake surface area because much to the lake is too shallow, thereby further contributing to higher density in the lake. Thus, high primary productivity in the Chignik watershed supports salmon prey (zooplankton and insects), and high densities of juveniles which grow relatively fast given the high density of fish in the lakes.

Chignik sockeye salmon runs exhibit long-term trends that are characteristic of salmon runs in western Alaska. Chignik salmon runs were large during the early portion of the 1900s, averaging 1.86 million salmon during 1922-50 (Fig. 2). Salmon runs were especially variable during this early period due to highly variable spawning escapements, which resulted from the 50% harvest rate policy specified by the White Act. Abundance declined during the mid-1900s, averaging 1.1 million salmon during 1951-1975. During 1976-2002, sockeye salmon runs were relatively high, averaging 2.66 million salmon. On average, the Black Lake run represented 50% of the total Chignik run.

Chignik sockeye salmon productivity (return per spawner) was recently reviewed by Ruggerone et al. (1999). Chignik salmon productivity was moderate during the early 1900s, low during the mid-1900s, and high since the mid-1960s (Fig. 3). Productivity trends were similar between Black Lake (Fig. 4) and Chignik Lake stocks (Fig. 5), although variation in productivity of the Black Lake sockeye salmon was relatively high. Return per spawner of Black Lake sockeye salmon averaged 3.2±3.1(SD) during brood years 1922-1945, 2.4±1.8 during 1946-1965, and

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[1] Scale studies since 1978 sometimes observed scale patterns during late July and August that were more associated with Black Lake versus Chignik Lake scale standards (R. Conrad and G. Ruggerone observations). However, during the early period of scale analysis the tag recovery data were believed to be more reliable and returns to Black Lake were believe to be small during late July and August in most years.

3.1±1.9 during 1966-1996. Return per spawner of Chignik Lake sockeye salmon averaged 2.5±1.6 during brood years 1922-1945, 1.7±0.9 during 1946-1965, and 4.4±1.9 during 1966-1996. Variability in R/S declined over the years in response to stabilization of spawning escapements.

The patterns of sockeye salmon runs and productivity by stock and for the total Chignik system do not show a decline that might be expected with significant changes in Black Lake habitat that have been reported. However, all salmon runs in western and central Alaska have exhibited significant increases in run size and productivity since the mid-1970s (Rogers 2002). Greater salmon runs have been associated with a climate shift that occurred during 1976/77, leading to significant changes in many species abundance (Anderson and Piatt 1999) and to greater growth of salmon at sea (Rogers and Ruggerone 1993, Ruggerone et al. 2003). The climate shift that enhanced salmon growth and survival throughout Alaska may have masked adverse changes in freshwater habitat. Thus, more detailed analysis within the Chignik Lakes is needed to evaluate the effects of Black Lake habitat changes on production and productivity of Chignik sockeye salmon. This detailed analysis is the subject of this report.

PHYSICAL HABITAT OF BLACK LAKE

Geologic History

The Alaska Peninsula is a region of numerous, active volcanoes. Volcanic activity, glaciation, and deglaciation undoubtedly have had a significant effect on the formation of Black Lake. Late Wisconsin glacial ice caps in the western Alaska Peninsula and on large islands in the Aleutians began retreating from sea level about 12,000 years ago and deglaciation was complete about 10,000 years ago (Miller and Smith 1987). Knappen (1926) noted that the north side of Black Lake is a terminal moraine of a glacier that once filled the valley of the West Fork River. This glacier pushed northward of the present location of Black Lake and created a relatively level moraine approximately 50 ft high in places. Knappen suggested that Alec River and possibly the West Fork River originally flowed into the Bering Sea rather than to Chignik Lake. However, the developing moraine ponded these streams and created a lake, which eventually overflowed southeastward to Chignik Lake. Based on observations of berms several hundred meters from the shore of Alec Bay, Buffington (2001) suggested the size of Black Lake in geologic time was much larger than present.

Miller and Smith (1987) collected field data to determine dates of caldera forming eruptions of major volcanoes along the Aleutian arc. Based on carbon-14 dating, Veniaminof caldera was formed approximately 3,700 years ago. The size of the eruption was exceptionally large, producing a volume exceeding 50 km^3. Flows from this eruption extended 50 km from the caldera rim on the Bering Sea side. On the Pacific Ocean side, ash flows entered bays and estuaries. This huge eruption likely had a major effect on Black Lake approximately 3,700 years ago.

Perimeter of Black Lake

Aerial photographs of the Black Lake area during 1953 (June 23), 1957 (June 23-24), 1962 (June 18), 1983 (August), 1991 (October), and 1993 (late May)[2] along with numerous additional photographs taken since 1989 provide visual documentation of changes in Black Lake. During the 1950s and early 1960s, the wetted surface area of the lake extended to the lake berm along the perimeter of the lake (see photographs in Appendix). This is most obvious along the western lake shore where little of the sandy beach is apparent in the early photographs, but extensive beach area is present during the 1990s. The pond next the western shore of Black Lake was relatively full in the 1950s and it was relatively close to the wetted edge of Black Lake compared with that during the 1990s. During summer 2001, the distance from the wetted lake surface to the western shore berm ranged from 374 m to 480 m depending on location (avg. 426 m or 1400 ft) at a lake level of –1.08 m (Table 1). Similar measurements were recorded by Ruggerone et al. (1992). A number of visual observations since the mid-1980s suggests lake level has not reached the old berm, even during high water periods. Since the early 1950s the lake perimeter has retracted approximately 400 m along this low gradient shoreline, based on numerous visual observations in addition to the quantitative measurements provided here.

Lake perimeter changes are also apparent at the Alec River delta. The 1950 photographs show the lake perimeter extended up to the existing lake berm, whereas photographs taken during the 1990s show considerable dry land between the berm and wetted lake area (see photographs in Appendix). During summer 2001, the distance from the wetted lake surface to the Alec River delta berm in Alec Bay was 978 m (3207 ft) at a lake level of –1.01 m (Table 1; Ruggerone et al. 2001). These measurements were taken along the newly exposed Alec Bay sandspit (see discussion below). Distance to the grass-to-sand transition, which is more representative of the delta area in terms of distance from the berm to the lake, was 382 m (1253 ft) (FRI benchmark elevation: -0.97 m). Thus, Black Lake has retreated considerably from the Alec River delta area in addition to the western shore area.

A large shallow pond near the confluence of Fan Creek and the Alec River south channel provides further visual evidence that lake elevation and ground water level has declined since the 1950s. In the 1950s, this pond was approximately 100% larger than that shown in the 1983 photographs (see Appendix photographs). Similarly, the size of the small pond near the base of the outlet sand spit has shrunk approximately 50% and it is considerably further from the lake compared with that during the 1950s.

At the head of Black River, the present lake level does not approach the more subtle berm shown in the 1950s aerial photographs along the right bank. During summer 2001, the lake was 89 m (292 ft) from the right bank berm; lake level was moderately low based on recent measurements (Table 1). Immediately across the river channel a large cove is present in the lee of the current. No vegetation was present in the cove through at least 1993. However, in 2000, dense water tolerant vegetation (horse tails and grasses) filled the cover area. Another cove is present along the right bank immediately downstream from the river head. During the low water period of

[2] During 1993, numerous high resolution aerial photographs of the Chignik watershed were taken to assist engineering work at Black Lake and a study involving the effects of beaver colonization on salmon habitat. Most of these aerial photographs are currently maintained by G. Ruggerone.

September 2002 this cove was dry and grass was beginning to colonize the area indicating greater exposure during recent years. Thus, the lake outlet and river head show evidence of a receding shoreline of Black Lake. As noted below in this document, the receding shoreline of Black Lake and upper Black River is believed to be related to down-cutting of the upper Black River channel.

Changes in the lake perimeter in other areas, such as the cobble northern shore formed by the terminal moraine, are less apparent because the shoreline is steeper and it rises abruptly above the lake. The southern shore is relatively low gradient but changes in lake perimeter are not apparent along much of this shoreline. The southern shoreline experiences less wave action and the soil is mostly peat and sand. After discussing this issue with Dr. T. Papanicolaou (University of Iowa, Dept. Civil and Environmental Engineering), I suspect that the substrate along the south shore may have subsided in response to lower Black Lake elevation because there is less evidence of a high berm elevation that would have contained high lake levels. Potentially, the lower water table resulting from the lower lake elevation may have led to compression of the soils near the outlet of Black Lake (Dr. T. Papanicolaou, pers. comm.).

Aerial photographs indicate the elevation of Black Lake may have been even higher hundreds of years ago (Buffington 2001). Much of the lower Alec River and Fan Creek areas, which are currently low elevation marshlands, may have been extensions of Black Lake before being filled in by sediment and further exposed by lowering lake level (see Appendix photographs). The eastern edge of Alec Bay near the islands has either filled from Alec River sediment or has become exposed by lowering lake elevation prior to the 1950s. This is apparent when viewing the suspected ancient shoreline extending from the edge of the bay east toward Alec River valley. At Sand Pt, along the southern shore of the lake, exceptionally high water apparently created berms that extend approximately 75 m from the shoreline shown in the 1950s photographs (see Appendix photographs). The largest most distinct berm extends inland from Nick and Virginia Aleck's cabin on Sand Pt.

Depth Surveys of Black Lake

Depth surveys of Black Lake were conducted in 1960, 1978, 1983, 1989, 1990, and 1992. The number of depth measurements varied among the surveys and standardization of depths to a benchmark was not attempted until 1989[3]. The surveys having the greatest detail and likely the accuracy were conducted in 1960 and 1992. The 1960 survey was part of an extensive survey of western Alaskan lakes conducted during the early 1960s (Burgner et al. 1969), whereas the 1992 survey was conducted to re-establish lake level profiles and water volume estimates (Ruggerone et al. 1993).

During 30 June 1960, average and maximum depths of Black Lake were 2.6 m (8.5 ft) and 6.4 m (21 ft), respectively (Table 2). Lower average and maximum depths were estimated in 1978 and 1983. During 1989-1992, average depth of Black Lake was 1.26-1.94 m (4.1-6.4 ft) or approximately 0.97 m (3.2 ft) less than that in 1960. Maximum depth during the recent period

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[3] Ruggerone established a benchmark at the outlet of Black Lake in 1989 because this location was much more accessible than the benchmark established on the bluff above Hydro Pt.

was 2.9-4.1 m (9.5-13.4 ft) or approximately 2.8 m (9.2 ft) less than that in 1960. These values were not adjusted for differences in lake level, but they suggest a significant decline in lake depth over time.

FRI archive log books were examined in an attempt to standardize the depth measurements to the 1960 lake fullness. Records indicated the 1960 depth estimates were taken during above average water level, therefore up to 0.7 m[4] was added to water depth measurements during 1978-1990 (Table 2). After standardizing water level to above-average levels (-0.6 m bench mark), average depth during 1989-1992 was approximately 0.66 m (2.2 ft) less than those during 30 June 1960, whereas maximum depth was approximately 2.4 m (7.8 ft) less. Thus, average and maximum depths declined approximately 25% and 37%, respectively from 1960 to 1989-1992 (Table 2). Essentially identical values of depth decline were produced when 1992 values were compared with the 1960 values.

A depth survey of Black lake was conducted during 2001 and 2002 (Chasco et al. 2003) and the results became available immediately prior to completion of this report. Average depth during 2001-2002 was 1.8 m (-0.6 m lake level). Comparison of standardized (-0.6 m) mean depth during 2001-2002 with that during 1992 suggests average depth may have declined 6%. The greatest decline occurred within the deepest part to the lake (> 3 m) (see their Table 15). Chasco et al. noted that differences in methodology may have accounted for differences in lake depth, but the decline in depth is consistent with other observations during the past 10 years.

The depth measurements suggest that maximum depth of Black Lake (near Hydro Pt) experienced greater change compared with average depth. This suggests that the maximum depth of the lake was likely affected by re-suspension and movement of sediments in response to wind-driven currents, shallow lake level, and sediment input from Alec River. This concept appears reasonable since the commonly strong winds at Black Lake will re-suspend sediment in the shallower parts of the lake and deposit some of it in deeper areas.

Routine sampling of fishes in Black Lake using a 6’ x 6’ surface townet also indicates the depth of Black Lake has declined since the 1960s. Narver (1966) conducted numerous townet operations in Black Lake throughout the summer and fall. Sampling stations included both the outlet of Black Lake and Alec Bay. When townet operations were resumed during the early 1990s, it became obvious that the 6’ x 6’ townet was too deep to fish in the outlet and Alec Bay areas. In order to continue fishing the outlet, a 4’ x 9’ townet was built; however, sampling with this 4’ deep net led to regular fouling on the bottom and collection of large quantities of *Potamogeton* sp., an aquatic plant. Thus, tow-netting in the outlet was abandoned. During September, 2002, water level of Black Lake was exceptionally low (-1.56 m)[5] and the 6’ x 6’ townet filled with mud near the middle of Black Lake. This was the first time that the net had become fouled while sampling the main lake area.

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[4] The addition of up to 0.7 m to the depth measurements is significant since maximum fluctuation in lake level during the open water period is approximately 1.4 m.

[5] Lake level on Sept. 2, 2002 was calibrated to the standard rod height of 0.385 m above ground.

Lake Elevation and Water Volume

The US Geological Survey (USGS) established an elevation benchmark at Hydro Pt on Black Lake during 1949 (marker name: Black 1949). The elevation above sea level of the benchmark, located on a bluff adjacent to the lake, was 11.28 m (37 ft) and the corresponding lake elevation was 8.54 m (28 ft). USGS records do not indicate the relative level of Black Lake (high, medium or low water level) or the date at which the measurements were taken. Unfortunately, precision of the USGS elevation measurements were to the nearest foot rather than to the nearest cm (<1 inch).

Comparison of the lake elevation and benchmark measurements taken during 1949 with those in the recent period indicates a significant decline in lake elevation. During June 19, 2001, the USGS benchmark was 4.1 m (13.4 ft) above the lake, or 1.38 m (4.5 ft) greater than that during 1949 (Table 3), assuming no rounding error by USGS. This lake elevation difference corresponds to a decline in lake volume of approximately 49%, based on lake depth contours during 1992 (Ruggerone et al. 1993) and no loss of lake surface area. If maximum rounding error by USGS is assumed (i.e., 1 ft), then the lake elevation change between the two periods was –1.1 m (3.6 ft).

These estimates may overestimate average decline in lake elevation and volume because the relative lake level during June 2001 (-1.01 m) was relatively low and information on the lake condition during 1949 is unknown. The FRI benchmark elevation corresponding to the upper 1949 lake elevation was +0.37 m, which is nearly 0.5 m higher than the highest recorded lake level (July 1993). A lake level of +0.37 m is approximately 0.37 m above the outlet berm and would cause considerable flooding in the outlet area of Black Lake, assuming the outlet topography did not subside over time, because the elevation of the berm at the head of Black River is approximately 0.0 m (Table 1). A lake elevation change of –1.1 m (3.6 ft) between 1949 and present, which assumes maximum rounding error by USGS (and FRI benchmark elevation of +0.06 m), also appears high, based on the existing topography of the lake outlet and river head.

If both maximum rounding error by USGS and moderately high water elevation (-0.6 m) during the 1949 measurements are assumed, then lake elevation change between the two periods is –0.67 m (2.2 ft). This would correspond to a lake volume decline of 23% at moderately high water levels during both periods. This estimate is based on scenarios having somewhat low probability, i.e., maximum rounding error by USGS and moderately high water level at the time of the USGS measurement. However, this estimate of decline does appear to match the present topography of the lake outlet. If the change in lake elevation was greater than 0.67 m, then subsidence of the outlet area (right bank) (and southern shore) must have occurred; other areas of the lake have relatively high berms that could have contained higher lake elevations. The right bank of the outlet/river head area is largely volcanic sand and/or peat and it might be possible that lowering ground water as a result of lake elevation decline led to compression of the soils (Dr. T. Papanicolaou, University of Iowa, Dept. Civil and Environmental Engineering, pers. comm.). However, there is no additional evidence in support of this hypothesis.

In conclusion, lake level elevation appears to have declined approximately 0.67-1.1 m (2.2-3.6 ft), corresponding to a decline in lake volume of 23-44% (assuming no change in lake surface area). Data are not sufficient to determine the decline in water volume associated with low flow periods.

Water volume and depth of Black Lake change rapidly with changes in lake level because the lake is shallow. For example, a water elevation decline from –0.1 m to –1.4 m (FRI benchmark present range) results in a 48% decline in water volume and depth (Table 4). This estimate of water volume decline does not include changes associated with the decline in lake surface area, therefore the estimated change is minimum. The water volume and depth measurements excluded shallow areas (13% of the lake surface area) which would be affected by lake level changes.

Growth of the Sand Spits and Deltas

Outlet Sandspit

Aerial photographs of Black Lake during the 1950s do not show the presence of sandspits extending from the Alec River delta across the lake outlet and across Alec Bay (see Appendix photographs). However, the photographs show a turbidity plume in the location of the two sandspits, indicating the location of the existing sandspits was relatively shallow during the 1950s. The shallow areas of the existing sandspits were documented in the June 1960 depth survey (Ruggerone and Denman 1990). FRI researchers from the 1960s noted that the location of the outlet sandspit was shallow, but a boat with a propeller outboard could drive across the area (D. Narver and D. Phinney, pers. comm., 1990). Annual FRI maps showing the location of tow-net hauls indicate the 6' deep nets may have been towed over the outlet sandspit during 1962 and 1964 (see Appendix photographs). Narver (1966) noted that the net dragged bottom in 1961 and 1962 when sampling in the area of the sandspit.

The August 1983 aerial photograph of Black Lake shows emergence of the sandspit across the outlet of Black Lake (see Appendix photographs). The sandspit was relatively narrow and was not connected to the Alec River delta. It crossed approximately 40% of the lake surface. Lake level was probably relatively low at the time of this photograph based the size of the exposed Fan Creek delta and the tendency for lake level to be low in August.

During the 1980s, residents of the Chignik villages raised concern that Black Lake was becoming shallower and noted that the sandspit was now much more prominent. During a low water period in August 1990, the sandspit covered approximately 80% of the lake width (see Appendix photographs). Wading along each side of the sandspit indicated that depth within ~200 m of the exposed spit was < 0.6 m (2 ft), indicating the spit was wide (Ruggerone and Denman 1990).

Aerial photographs taken in 1991 and 1993 during moderate water level show that the sandspit had become a substantial feature of Black Lake (see Appendix photographs). However, much of the spit remained underwater during 1991 and 1993 and water separated it from the Alec River delta. Furthermore, no significant vegetation was present on the sandspit during 1993.

The outlet sandspit was measured in 1991, 1992 and in 2001 (Ruggerone et al. 1992, 1993). Elevation of the sandspit in 2001 tended to be lower compared with that during 1992 and 1991 (Fig. 7), and elevation during 1992 was slightly lower than that during 1991, probably due to the high water during fall 1991. Observations of the sandspit indicate that the location and shape of the spit may be slightly altered in response to water level and wind direction. Therefore, these differences probably do not reflect significant change in the elevation of the sandspit.

The length of the spit was not measurably different in 2001 compared with that during 1991 and 1992. The sandspit extended nearly 1.8 km from the Alec River delta and it inhibited water movement between the main lake and outlet except for the narrow 2 m deep channel next to Sand Pt.

Significant vegetation has developed within 1000 m of the Alec River delta since the early 1990s, as shown by comparison of aerial photographs during 1993 and photographs taken in 2001 (see Appendix photographs). Growth of vegetation and the somewhat lower elevation of the sandspit in 2001 might be an indication of continued lowering of Black Lake water elevation. Since 1990, increased growth of vegetation along the shoreline has also been observed in upper Black River (see Appendix photographs), another indicator that Black Lake water level may be continuing to decline.

Alec Bay Sandspit

Aerial photographs in the 1950s indicate the presence of a shallow sill stretching across a portion of Alec Bay (see Appendix photographs). Formation of a bar in this area is shown in the 1983 and 1993 aerial photographs. Exposure of the bar above the lake surface was first recorded during exceptionally low water conditions during 1990 (Ruggerone and Denman 1990). The bar has become exposed on a regular basis since 1999. The greater presence of the Alec Bay sandspit during recent years is likely the result of both lower average lake level and higher sandspit elevation. Previous research indicated significant sediment transport in the Alec River and this sediment contributes to the growth of both the outlet and Alec Bay sandspits (see discussion below; Ruggerone 1994)[6].

The Alec Bay sandspit was measured in 2001. A 1.4 m high berm was present at the base of the sandspit located on the Alec River delta. The Alec Bay sandspit extended approximately 1.0 km into Alec Bay (Fig. 8). Elevation declined little (<0.25 m (9.8 inches)) within 975 m of the delta berm. Thereafter, elevation declined somewhat more rapidly. The lowest elevation, corresponding to maximum depth in Alec Bay along the path of the spit, was approximately 2 m below the sandspit elevation close to the delta. This low point was approximately 1.6 km from the delta or approximately 300 m from the western Alec Bay shoreline.

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[6] Most sediment transport occurs during high water events when the distribution of flow to the two channels is nearly equal.

Alec River North Channel Delta

Aerial photographs during 1953, 1957, 1983 and 1990 show considerable enlargement of the Alec River delta (see Appendix photographs). This change in delta size is consistent with the lowering of lake elevation, sediment transport in Alec River and sediment accumulation on the delta. The most noticeable change in the delta, in addition to greater surface area, is the emergence of large stands of alder during the 26 year period from 1957 to 1983 (see Appendix photographs). In 1957, the length of the north channel below the river wye was relatively short and no vegetation was present in areas where substantial stands of alder currently grow.

Fan Cr/Alec River South Channel Delta

Aerial photographs during 1953, 1957, 1983 and 1990 clearly show enlargement of the Fan Cr/Alec River delta extending into the outlet of Black Lake. During the 1950s, no delta was visible as the lake level was relatively high. FRI biologists noted that travel across the delta by boat (propeller) was difficult because the water was shallow (M. Dalberg, pers. comm. (1990)). In 1983, the delta was large and heavily vegetated. During 1990, the vegetated shoreline extended approximately 325 m beyond the vegetated shoreline of 1953 and 1957 (Ruggerone and Denman 1990). The unvegetated, exposed portion of the delta, which changes with lake water level, extended an additional 300 m into Black Lake during the low water period in August 1990. Thus, during this low water period the edge of Black Lake was 625 m (2,025 ft) from the 1950s berm near the river confluence.

Alec River Channel Migration

Lower Alec River splits into two channels approximately 1700 km upstream from the lake. The north channel discharges into Alec Bay and the south channel discharges into the lake outlet. Aerial photographs during 1953 and 1957 compared with those during 1993 show that the south channel has changed. During the 1950s, the south channel split into two narrow channels then converged near the confluence with Fan Cr (see Appendix photographs). The two channels are shown on the 1963 USGS topographic map. Since at least 1983, the south channel flows through one channel. M. Dahlberg, who worked with FRI at Chignik during 1960-1965, noted that the south channel was narrow ("two boat lengths wide" or approximately 10 m). Two photographs from the 1950s show the upstream entrance to the south channel was narrow (see Appendix photographs). Presently, the channel is approximately 30 m wide, suggesting considerable widening of the channel since the early 1960s.

The right bank of the south channel immediately downstream of the Alec River wye is susceptible to erosion. The vertical bank, which typically extends 1.5 m or more above the water, is largely soft soil and volcanic sand; little vegetation other than grasses help to protect the bank from Alec River flows, which are deflected into the south channel by the recently-formed large sandbar at the Alec River wye. In 1992, ten erosion monitoring stations were established along the right bank so that bank erosion could be quantified. Annual measurements of erosion indicated that approximately 0.30 m of the right bank is lost per year, depending on location (Table 5). This represents an increase in river width of approximately 1% per year based on the current width of 30 m. Greatest erosion is occurring at the river wye and along the river bend approximately 150 m downstream from the wye. Significant sloughing and sinking of the wye occurred during 1997-1998.

Aerial photographs during the 1950s and 1983 do not show the presence of the large sandbar located at the Alec River wye (see Appendix photographs). The 1983 aerial photograph shows the presence of a sandbar along the right bank of the main channel, but nearly all water flowed between the small vegetated island and this bar. In contrast, during a low flow period in 1990, a large sandbar had formed near mid-channel. The recently-formed large sandbar at the river wye deflects Alec River water into the south channel, especially during low flows. In 2003, the sandbar enlarged considerably. This will likely lead to more rapid erosion along the upper right bank of the south channel and increased flow into the lake outlet area (see below).

Factors Influencing Changes in Black Lake Morphology

Factors influencing changes in lake elevation and lake depth were discussed in previous reports (Denman and Ruggerone 1994, Ruggerone 1994, Ruggerone et al. 2001, Buffington 2001).

Channel Migration of West Fork River

An aerial photograph from 1953 shows a major channel of the West Fork River discharging into Black River approximately 1.9 km below Chiaktuak Cr and approximately 4.5 km below the lake outlet (see Appendix photographs). The West Fork River transports significant quantities of volcanic sand originating along the slopes of Mount Veniaminof and a large accumulation of sediment is shown at the confluence of the West Fork River and Black River in the 1953 photograph. The West Fork delta extended into Black River and appears to constrict the flow since the Black River channels appears narrow at this location, possibly influencing the exceptionally high water elevation of Black River (compared with levels in recent years). However, the high water elevation is not likely due to a flood event since the photograph shows sand and grass covered channels without water. Immediately below the confluence, Black River splits into two channels. Discharge of the West Fork River at this location is consistent with observations by Virginia Aleck (pers. comm.), a resident of Chignik Lake Village.

The West Fork River shifted downstream toward Chignik Lake in the late 1960s (V. Aleck; A. Shaul, ADFG, pers. comm.). The shift appears to be associated with substantial changes in the Black River approximately 100-200 m downstream from the 1953 West Fork River delta. Residents of Chignik Lake Village and Arnie Shaul (ADFG) recall the development of a temporary waterfall in Black River. This waterfall created a 1.1 m (3.5 ft) vertical drop extending the entire width of Black River. It was located near small islands between the West Fork River and the first vertical bluff. The waterfall was present for approximately one year, but residents are uncertain about the exact duration. It was first noticed during a hunting trip shortly after a heavy rain event. Boaters traveling upstream to Black Lake had to pull their skiff around the waterfall along the bank of the river. Although many residents of the village recall the Black River waterfall, there are no photographs and the specific dates of its development and decline are unknown.

The appearance of the Black River waterfall appears to have coincided approximately with channel migration of the West Fork River and it may have been associated with a shift in the mainstem channel of the Black River. Aerial photographs from the 1950s and 1990s show that the mainstem Black River immediately below the dry West Fork channel shifted to the left (looking downstream). Presently, the river channel is left of two small islands that were mid-channel in the 1950s. The waterfall may have been created near these islands when the left bank eroded, possibly depositing a large piece of bank across the narrow river channels at the islands. This description is consistent with observations of Bill Lind[7], who described the waterfall as being created by a large piece of bank sloughing into Black River. The waterfall may have been exacerbated by the loss of sediment from the West Fork River. Disappearance of the waterfall may have resulted from gradual erosion of the collapsed bank and the Black River channel, and loss of sediment from the West Fork River.

Aerial photographs of the1953 West Fork River taken during the early 1990s show that this channel became dry and overgrown with alder, willow, and grasses. The elevation of Black River is considerably lower today compared with that shown in the 1953 photograph. Presently, Black River flows through a single channel downstream of the dry West Fork rather than splitting into two channels. The old channels that carried water in 1953 are "hanging" at least 1.5 meters above the surface of Black River (see Appendix photographs). I have never seen the river flowing through these "hanging" channels since coming to Chignik in 1984. It is also apparent from the comparison of historical and current photographs that the current Black River has migrated further north compared to its position in 1953 since it is to the left of the two small islands shown in the 1953 photograph.

It is probable that upper Black River and Black Lake was maintained at a higher water elevation by the high sediment load of the West Fork River that constricted the Black River channel and reduced its capacity to carry water from Black Lake. Buffington (2001) shows diagrams of this effect[8]. Removal of the sediment and water carried by the Black River likely contributed to down-cutting and increased gradient in the upper river, leading to greater capacity to transport water from Black Lake. Over time, channel degradation appears to have worked upriver to Black Lake, eventually leading to the lower lake level that is present today.

Evidence of past degradation of the Black River channel is quite apparent and degradation appears to actively continuing since the river banks are actively eroding (Buffington 2001). River bars immediately upstream of the old West Fork River and immediately below Chiaktuak Cr have been colonized by perennial vegetation since. These bars are much more prominent today compared with that when I first began frequent trips to Black Lake in 1985. For example, the large bar immediately below Chiaktuak Cr had little vegetation during 1993 when FRI operated a fyke net at the bar. In 2003, this large bar was covered with dense willow and the bar now appears to be evolving into the right river bank as Black River continues to erode existing banks while cutting a deeper channel. I have observed substantial changes in Black River during the past 15 years. Colonization of vegetation on these bars is consistent with extensive colonization of vegetation in the river outlet area and on the outlet sandspit. Colonization of

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[7] Bill Lind, Chignik Lake Village, lived in the Chignik Lake area for much of his life and he was most knowledgeable about the watershed. He described this event to me during the early 1990s.

[8] Denman and Ruggerone noted that this hypothesis could be tested with HEC backwater calculations (HEC 1982).

vegetation suggests the water surface elevation of Black Lake and Black River is continuing to decline.

Sedimentation of Black Lake

Alec River transports large quantities of volcanic sand that contributes to the shallowing of Black Lake. Sediment transport was first estimated by Ruggerone et al. (1992) using a sediment transport model developed by Yang (1973). Yang's equation is based on unit stream power, expressed as an expansion of the product of stream velocity and slope (Yang and Molinas 1982). The model assumes that sediment transport is not limited by the quantity of material available for transport. Given conditions in Alec River, this appears to be a valid assumption. Yang's sediment transport formula for sand bed rivers have proven to exhibit the highest statistical correlation to field measurements for rivers whose physical parameters are similar to those of the Alec (USGS 1989). Yang's equation incorporates both the bed-load and suspended load.

At the measured Alec River flow of 460.5 cfs (13.04 cms) in August 1990, the predicted sediment concentration was 10.5 mg/L. This estimate appeared reasonable given clarity of water observed in the river. Assuming a sediment bulk density of 1.65 g/cc, this concentration and river flow translate into a sediment output rate of 7.1 m^3/d. Over the course of a year, this equates to about 2591.5 cubic meters if flow were to remain at a constant 13.04 cms. However, sediment transport is a very dynamic process, with the majority of material being transported during relatively infrequent high flow events.

In order to model sediment transport a higher flow, Yang's equation was applied to expected conditions during a high flow event which roughly corresponded to bank-full conditions. These bank-full conditions include an average water depth of 4 ft, instead of the August 1990 depth of 1.75 ft. Based on channel geometry, slope, and roughness, the anticipated average velocity during this high flow event would be 3.36 ft/sec (Ruggerone et al. 1992) as opposed to the August 1990 average velocity of 1.7 ft/sec. Utilizing this velocity in the Yang equation, the average sediment concentration was estimated to be 18.6 mg/L, or 67 m^3/d. Ruggerone et al. (1992) thought this estimate was low. Assuming sediment transport ranged from 7 to 67 m^3/d and there were 3 months of low flow (7 cubic meters/day), 2 months of high flow (67 cubic meters/day), and 7 months of moderate flow (30 cubic meters/day), the total annual sediment production would be 10,950 cubic meters, or approximately 50,000 55-gal drums of sediment.

In 1992, sediment transport along the bottom of the south channel was measured by a Helly-Smith bedload sampler (Emmett 1980). A 56 cm^2 area was sampled for one minute every two meters across the channel. Sediment transport was measured during two flood events during 5 June and 28 June, 1992 (Ruggerone et al. 1993). Transport of bottom sediment during the subsiding flood event on 5 June (30.4 m^3/s or 1,074 cfs) was 46.8 m^3/d or the equivalent of 225 55-gal drums (Table 6). Most of the sediment was medium sand that had a density of 1.25 g/cc. Concentration of suspended sediment was 66 mg/l, which would produce 138 m^3/d (663 55-gal drums of silt). In contrast, sediment transport during rising water (18.5 m^3/s or 652 cfs) of the smaller flood event on 28 June produced twice the amount of sediment (105.6 m^3/d) or the equivalent of 481 55-gal drums. As expected, the majority of sediment transport occurred during increasing flow of the river. Nearly all transport of sand occurred within 7.5 cm of the bottom, i.e. the height of the bedload sampler but transport of suspended sediment was significant.

Modeling and field estimates of sediment transport indicate considerable sediment transport in Alec River. Field estimates suggested the modeling transport estimate during high flow was likely low. Due to the obvious accretion occurring within Black Lake, sediment transport rates for the upper Black River are considerably less than those of the Alec, and sediment transport in Alec River will contribute to the shallowing of Black Lake. Relatively low transport of sediment from the lake to Black River is expected because heavier sediment is trapped by the lake and significant transport of suspended sediment occurs only during strong northwest winds. Sediment transport would need to be much higher than 10,950 cubic meters per year to significantly affect overall lake depth. Nevertheless, high transport likely contributed to expansion of the two deltas and sandspits. Wind driven water currents have a significant influence on the shape of sandspits in the lake outlet and Alec Bay. Dr. T. Papanicolaou (University of Iowa, Dept. Civil and Environmental Engineering) was recently contracted by CRAA to further examine the issue of sediment transport and sedimentation in the Black Lake watershed.

<u>Beaver Colonization</u>

During the late 1950s to late 1960s few beaver (*Castor canadensis*) were present in the Chignik watershed (Afonie and Annie Takak, Virginia Aleck, Chignik Lake Village; D. Phinney, WDFW, pers. comm. *in* Denman and Ruggerone 1994). Beaver activity in this area increased through the 1970s and 1980s, and Bricker (1977), an ADFG biologist, noted potential blockages of Chignik streams. Concurrent with the arrival of beaver was the noticeable decline in the water level and depth of Black Lake. In the 1980s, residents of Chignik expressed concern that beaver activity, beaver ponds and associated wetlands might have influenced the shallowing of Black Lake. Residents were also concerned about the effects of beaver activity on the spawning habitat of sockeye salmon. Thus, Denman and Ruggerone (1994) evaluated the effects of beaver colonization on the hydrology of Black Lake and on the spawning habitat of sockeye salmon.

A total of 450 dams was counted from aerial photographs of the Chignik watershed (October 1991 and May 1993), of which 318 dams were observed in the Black Lake drainage and 132 dams in the Chignik Lake drainage. Ground surveys indicated small dams not observed in the aerial photographs represented <10% of the total. Beaver dams were observed where stream gradient, discharge, and velocity were low. Creeks with dams typically had a spring season discharge of 5-20 cubic feet per second (ft^3/s).

The impact of beavers on the levels of Black Lake and Alec River was determined using a water balance approach. Beavers were assumed to impact water levels through possible alteration of the wetland and open water storage function, evapotranspiration rates (i.e., water lost to the atmosphere via evaporation and plant respiration), and groundwater export functions. Denman and Ruggerone (1994) concluded that beavers colonization had a minor effect on the shallowing of Black Lake.

Comparison of data from the 1967 Chignik sockeye salmon spawning catalog (Phinney 1970), developed prior to the colonization of beaver, with creeks presently having beaver dams indicated most beaver dams are located on streams that previously had few or no spawning by sockeye salmon. Denman and Ruggerone (1994) estimated that <2% of the sockeye spawning habitat and <1% of the spawning population was adversely affected by beaver dams. Nevertheless, a few creeks that once cumulatively contained up to 5,000 spawning sockeye salmon were completely blocked by dams. Blocked creeks adjacent to Chignik Lake included Clark Bay Creek and small tributaries to Clark River. Blocked creeks in the Black Lake drainage included Lind's Creek and Cottonwood Creek in the western portion of Black Lake, and Creek 6R in the Alec River drainage. Denman and Ruggerone (1994) concluded that beaver colonization in the Chignik watershed has had little adverse effect on commercial harvests of sockeye salmon. This conclusion is based on two important factors: (1) the small amount of spawning area affected by beaver was probably less productive per unit area than the larger spawning areas that were not affected, and (2) escapement levels have remained fairly stable over the years and the addition of a few thousand sockeye salmon to the existing spawning areas would not likely reduce egg to fry survival.

In contrast to commercial harvests, subsistence harvests of sockeye salmon have been adversely affected by beaver dams. Subsistence harvests are dependent on specific creeks which are often close to the village or traditional hunting grounds. Some important traditional subsistence salmon streams have been blocked by beaver dams (Clark Bay Creek, Cottonwood Creek, and others), resulting in few or no returning salmon.

The Chignik Lakes Enhancement Study Team (CLEST), which was mostly comprised of Chignik Lake Village residents, attempted to trap beavers and remove beaver dams during 1994. However, the task was exceptionally difficult and relatively few beavers and dams were removed.

Plate Tectonics

Tectonic movement of the Pacific Plate under the Alaska Peninsula (North American Plate) is causing the Pacific Ocean side of the peninsula to rise slightly faster than the Bering Sea side (Kienle and Swanson 1983). The Pacific Plate is moving horizontally and subducting under the North American Plate at a rate of approximately 7 cm per year. Plate tectonics was evaluated by Denman and Ruggerone (1994) as a potential factor contributing to the shallowing of Black Lake. However, the rise in ground elevation during the past 30 years (a few centimeters) cannot explain the changes observed in Black Lake (Tom Miller, USGS, pers. comm. *in* Denman and Ruggerone 1994). Furthermore, the greater elevation gain on the outlet side of Black Lake would likely cause the lake to become deeper, especially at the western end. Thus, tectonic movement has not likely contributed to the shallowing of Black Lake.

Alec River Channel Migration

Alec River splits into two channels (north and south) approximately 1.7 km upstream from Black Lake. The south channel connects with Fan Creek before discharging into the outlet area and the north channel discharges into Alec Bay. The north and south channels have changed considerably since the 1950s. More water currently flows to the lake via the south channel than before, and as discussed below, this shift may have important consequences for juvenile sockeye salmon. It is highly probable that this shift is associated with the lowering of Black Lake, which enhanced the quantity of flow to the south channel, as shown below.

The percentage of flow in the south channel relative to total Alec River flow has been monitored since 1991 in an attempt to determine if flow is shifting toward the south channel (Ruggerone et al. 1993, 1999, 2000, Ruggerone 1994, FRI unpublished data 2003). During the 1992-1993, up to 65-74% of Alec River flowed into the south channel during low flow periods (<500 cfs), but less than 50% when total flow exceeded 1500 cfs (Fig. 9). During low flows, the sand bar deflected water into the south channel, whereas during high flows much of the Alec River water flowed over the sand bar and into the north channel.

Comparison of measurements during 1998-2003 with those during the 1992-1993 demonstrated that water flow in Alec River has shifted to the south channel during this brief period (ANCOVA: $n = 21$, $F = 53.569$, $P < 0.001$, $R^2 = 0.90$[9]). Analysis of covariance indicated the slope and intercept were significantly different between the two periods, indicating the flow relationship could be modeled with two distinct regression relationships as shown in Fig. 9. For total Alec River flows between 450 and 1250 cfs, approximately 4.7% more water flowed through the south channel during 1998-2003 than during 1992-1993. This finding is consistent with measurements of continued bank erosion along the south channel (Table 5), which enables water to move more efficiently into the south channel.

During 2003 significant changes were documented at the Alec River wye. The sand bar that deflects water into the south channel expanded approximately 30 ft toward the south channel. This expansion inhibited flow into the north channel and nearly blocked one of the channels leading to the north channel. Concurrently, there was considerable new erosion at specific locations in the south channel (Table 5). Given the greater size of the sand bar and its new greater ability to deflect water into the south channel, we suspect that subsequent high flow events may cause further bank erosion and shifting of flow to the south channel (Dr. T. Papanicolaou, University of Iowa, Dept. Civil and Environmental Engineering, pers. comm.). The significant increase in the size of the sand bar appeared to be related to the exceptionally low flow during early fall 2002 followed by flooding events in late fall and winter 2002.

[9] ANACOVA was restricted to flows between 300 and 1300 cfs, i.e., flows common to both periods.

CONSEQUENCES FOR SOCKEYE SALMON PRODUCTION

Changes in Black Lake habitat have potentially significant effects on sockeye salmon. Lower lake level may influence greater numbers of fry emigrating to Chignik Lake during spring through fall, which in turn may increase competition for food in the lower lake. Movement of Alec River toward the lake outlet may encourage additional sockeye salmon fry to emigrate to Chignik Lake. During winter, sockeye salmon may experience low oxygen content as a result of biochemical oxygen demand in the shallow lake. These issues and others are discussed below.

Spring and Summer Fry Emigrations

Nearly all sockeye salmon fry rearing in Black Lake originate from Alec River, although small numbers may migrate up Black River from Chiaktuak Creek (Narver 1966, Marshall et al. 1974, Ruggerone 1994, Harvey 1995). The distribution of fry migrating from Alec River to Black Lake during spring is likely influenced by flow in the north and south channels of lower Alec River. Flows during the early spring emigration (e.g., April and May) are typically low and most Alec River flow currently enters the lake outlet area rather than Alec Bay (Fig. 6). Most fry, which are small (30 mm), likely migrate with the flow and therefore enter the lake outlet area. During spring low water periods, the outlet sandspit extends across approximately 85% of Black Lake (see photographs) and it may inhibit migration of fry to the main lake body. Large numbers of fry in the outlet area may stimulate large numbers of fry migrating to Chignik Lake where salmon prey are less abundant, especially during early spring, and water temperature is much colder and less conducive to growth.

In the 1960s and 1970s FRI biologists identified large emigrations of age-0 sockeye salmon fry from Black Lake to Chignik Lake during spring and early summer (Narver 1961, 1963, 1966, Parr 1972, Marshall and Burgner 1977). Large catches of fry were periodically captured in fyke nets placed in Black River. Emigration of fry to Chignik Lake appeared to be dependent on fry density: greater migration occurred during years of high densities in Black Lake. In some years, few sockeye salmon fry appeared to migrate to Chignik Lake, based on comparisons of length at age of juveniles captured in both lakes. However, even in years of large emigrations of fry, most fry appeared to remain in Black Lake.

Further evidence of the spring/summer fry migration was provided by adult age of sockeye salmon returning to Black Lake. Narver (1963, 1966) suggested that many age-2.3 sockeye salmon returning to Black Lake represented those fry that had emigrated to Chignik Lake during their first spring and summer. This conclusion was based on scale pattern analysis of age-2.3 adults showing that first year freshwater growth of Black Lake salmon was significantly greater than that from Black River and Chignik Lake, but growth during the second year in freshwater was not different between the groups. Although Narver suggested that many of age 2.3 sockeye salmon returning to Black Lake had emigrated to Chignik Lake as fry, it is possible that some also overwintered in Black Lake before rearing in Chignik Lake during their second year.

Narver (1966) and Parr (1972) concluded that fry emigrations from Black to Chignik Lake were important population regulating mechanisms. In 1957 and 1961, large emigrations of fry from Black Lake combined with large numbers of age-1 sockeye salmon in Chignik Lake, led to severe growth suppression, starvation, and mortality. During the spring following these large emigrations, numerous dead juvenile salmon were observed along the beaches; few dead fish were observed in the lake itself but weak and emaciated fish were also observed swimming along the edge of the lake. During spring 1958, Roos (1958) concluded that "many, many thousands of sockeye salmon had died". The majority of mortalities were among age-1 salmon in 1958, but equal numbers of age-1 and age-2 fish were observed dead in June 1962. No other species were observed.

Dead juvenile sockeye salmon have been observed in Chignik Lake during other years. During mid to late 1980s, I recall Bill Lind (Chignik Lake Village) noting that he observed dead salmon during early spring before we arrived at the FRI camp. In 1990, Mike Thompson (ADFG) observed dead juvenile sockeye salmon near the upper end of Chignik Lake (Ruggerone et al. 1991). These yearling sockeye were 30% lighter at a given length compared with subyearling Wood River sockeye salmon collected during fall. In 1992, following a late ice breakup (May 16), numerous dead and emaciated sockeye salmon (age-1 and age-2) and other species were observed in Chignik Lake (Ruggerone et al. 1993). Mortality events probably occur more frequently than indicated here because fox, birds, and isopods will quickly eat the dead fish and observations are opportunistic. Most documented mortality occurred soon after ice out, but mortality may also occur under the ice.

Daily sockeye salmon fry migrations were enumerated in Black River from 15 May to 10 July 1992 (Ruggerone et al. 1993) and from 6 May to 7 December, 1993 (Ruggerone 1994). Mark and recapture tests were used to estimate trap efficiency and total migration estimates. In 1992, daily migration of sockeye fry in Black River was low (5,400±1,800 fry/day) until an estimated 160,000 fry emigrated on 31 May. The increase in migrating fry occurred before the spring rain and high water event (Fig. 10). By mid-June daily migration of fry frequently exceeded 100,000 fry/d and reached 500,000 fry/d on several occasions. Daily fry migration rates in 1992 were not related to river temperature, lake level, or wind conditions in the outlet area of Black Lake. The total estimated number of fry migrating during 15 May to 10 July, 1992, was 7 million ±830,000 (SD) fry. This estimate greatly underestimates the total emigration since sampling ended when numerous fry were still migrating[10].

In 1993, approximately 8.8 million sockeye fry emigrated from Black Lake to Chignik Lake during 6 May to 7 December. Peak emigration occurred during a nine day period in late July when approximately 4.8 million fry or 54% of the total migration left the lake. The major emigration period in 1993 corresponded to the largest rainstorm event of the year. This storm caused a significant increase in lake level and flow in Black River. Few fry migrated after the high water subsided in August through early December.

During 1992 and 1993, lengths of emigrating fry increased significantly from May through July (Fig. 11), but fry lengths were at least 5 mm greater during 1993, possibly because fry abundance was estimated to be 50% of that in 1992 (Ruggerone 1994). In 1993, fry lengths increased from approximately 32 mm in early May to 40 mm on June 1, to 48 mm on July 1, to 57 mm on July 25. On average, fry length increased 0.29 mm per day and most fry appeared to be robust.

[10] Fry traps were set both above and below Chiaktuak Creek. Fry from Chiaktuak Creek were readily identified by size and excluded from counts in the downstream trap.

After late July, 1993, length of emigrating fry captured in Black River did not increase and few fry migrated to Chignik Lake (Fig. 11). During this late summer period, approximately 33% of the captured fry were unhealthy, e.g. gill fungus, emaciated, scale loss, popeye, and unusually dark coloration (Ruggerone 1994). Prior to late July the large majority of fry were healthy. These estimates represent the first quantitative estimates of unhealthy sockeye fry emigrating from Black Lake. Another 231 fry or 4.3% of fry captured in blocking seines near the head of Black River during May-July were injured by the salmon leech (*Piscicola salmositica*). The injured fry probably originated from Black Lake. The low capture rates suggests sockeye fry were not actively migrating to Chignik Lake during this late summer period. The few unhealthy fry were likely carried downstream by current in the lake outlet. Although these unhealthy fry represented a large portion of our catches during late summer, they represented a very small proportion of the total fry population rearing in Black Lake. The frequency of unhealthy fry is not likely to increase unless temperature increases significantly (i.e., consistently greater than ~20°C).

Length and stomach fullness of sockeye fry were examined in Black Lake and in Black River on concurrent days in order to examine whether emigrating fry were a random subset of the lake population during 1993. If migrating fish were a random subset of fish residing in Black Lake, then they would have similar lengths and stomach contents. In mid-June, the average sockeye fry in Black River was 3.4 mm longer than fry captured immediately west of the Black Lake sandspit (Ruggerone 1994). During peak emigration in late July, lengths of fry in Black River were similar to estimated lengths in Black Lake. In August and September, lengths of fry in Black River were 9-16 mm smaller than fry remaining in Black Lake. Stomach fullness of sockeye fry captured in Black River (avg. 10%) was considerably lower than fry captured in Black Lake prior to and after the peak emigration period (avg. 53%). Thus, emigration was not a random subset of fish rearing in Black Lake, except for the peak emigration period that corresponded with a significant mid-summer rainstorm.

Several studies were conducted to evaluate whether the emigration of fry from Black Lake in 1993 was influenced by the large number of recently emerged fry that probably entered the outlet area of Black Lake via the south channel of Alec River. Comparison of water velocity measurements in Alec River during the fry emigration period with maximum sustainable swim speed of salmon fry indicated that <1.5% of Alec River discharge could be negotiated by sockeye fry (Ruggerone 1994). Fry may be able to negotiate currents near the river bottom where velocity is lower. The small water volume in which fry could negotiate suggested that the distribution of fry entering the lake probably resembled the distribution of flow through the north and south channels (i.e., 55%-75% of Alec River entered the south channel during fry emigration).

In 1993, Ruggerone (1994) attempted to test whether sockeye salmon fry in the south channel of Alec River had a greater likelihood of emigrating to Chignik Lake compared with fry in the north channel. During mid-May, approximately 7,300 uniquely marked sockeye salmon fry were released into the north and south channels. Approximately 8,360 fry were captured in Black River during May and June and examined for marks. No positively identified marked fish were recaptured, therefore the test of the hypothesis that fry in the south channel are more likely to migrate to Chignik Lake was inconclusive.

In summary, these data suggest that fry emigrating from Black Lake during the non-peak migration periods (i.e., August through December) may not be a random subset of the fry population in the main body of Black Lake, whereas fry emigrating during the peak period probably originated from all parts of the lake since length of migrating and rearing fry did not differ during the peak migration period. Approximately 2.5 months passed between fry entering Black Lake and peak emigration of fry from Black Lake, indicating that the distribution of Alec River water and fry entering Black Lake in 1993 may not have influenced the emigration to a great extent. Peak emigration in 1993 occurred during a major rainstorm and rising water level in Black Lake, indicating that fry emigration in 1993 was stimulated by environmental conditions. In contrast, the migration pattern in 1992 was not correlated with lake level or river flows. Burgner (1975) noted that summer fyke-net catches of fry in Black River increased as the level of Black Lake gradually declined. He suggested that declining lake level during summer may stimulate early emigration of sockeye salmon fry. These observations suggest that a number of factors can influence emigration of fry from Black Lake to Chignik Lake.

Summer Water Temperature

Black Lake water temperature increases rapidly in spring because the lake is shallow, the substrate is black, and mountains do not block solar radiation. Thermographs have been set in the deepest part of Black Lake since 1991 in order to monitor winter and summer temperatures. Maximum summer temperature near lake bottom is typically below 18°C (Fig. 12). In comparison, preferred temperature and maximum performance of sockeye salmon occurs near 12-15°C depending on acclimation temperature; sockeye may attempt to avoid temperatures exceeding 15°C (Brett 1952, Brett 1995). Lethal temperatures for sockeye salmon range from approximately 21°C at an acclimation temperature of 1°C to approximately 23°C at an acclimation temperature of 15°C. Temperatures in Black Lake near 15°C may be beneficial to growth of sockeye salmon, but higher temperatures near 18°C or below 12°C may temporarily reduce growth efficiency.

Water temperature in Black Lake is strongly influenced by air temperature. Hourly recordings of Black Lake water temperature near bottom have shown up to 1°C fluctuations in temperature within a 24 hr period. Temperature fluctuation is likely greater near the surface. Diel temperature fluctuations are not common in deep portions of sockeye lakes, although temperatures above the thermocline of deep lakes may fluctuate.

Water temperatures along the shore of Black Lake and near the surface can exceed 18°C during warm, calm periods. Narver (1966) reported that surface temperature of Black Lake occasionally reached 20°C during summer. During May 1993, while sampling fishes daily in Black River, we recorded water temperatures exceeding 15°C, even though ice was still present on Chignik Lake. Portions of Black Lake may briefly reach temperatures that are stressful to juvenile sockeye salmon (> 20°C), although such temperatures have not been regularly recorded. Most juvenile salmon can tolerate brief periods of high temperature and it is not likely that high temperatures in Black Lake would significantly affect juvenile sockeye salmon survival.

Few studies have examined preferred and lethal temperatures of migrating adult sockeye salmon in freshwater. Preferred and lethal temperatures of adult salmon are likely less than that of juvenile salmon because adults in freshwater are migrating, undergoing physiological adaptation to freshwater, and not feeding. Gilhousen (1990), who studied pre-spawning mortality of Fraser River sockeye salmon, suggested temperatures less than 15°C likely lead to maximum survival during migration. Reiser and Bjornn (1979) suggested sockeye salmon prefer 7.2-15.6°C during the spawning migration. During July 1984, ADFG (1985) aerial surveys documented pre-spawning mortality of approximately 3,000 sockeye salmon just below the outlet of Black Lake. Unfortunately, all dead salmon were washed away during a storm before ADFG could return to the river and take samples to determine the cause of death. However, air temperature was warm and upon return to Chignik I measured a temperature of 20°C in Black River. It is likely that high temperature and possibly wind-suspended debris led to the mortality of these fish. I am not aware of large mortalities of pre-spawned sockeye since 1984, but high temperatures (18°C) that occasionally occur in Black Lake during July may reduce viability of adult sockeye salmon in Black Lake and Black River. Alec River and possibly Chiaktuak Creek provide potential refuges from warm water, but Chiaktuak Creek is more than a mile below Black Lake and few Black Lake sockeye salmon appear to hold in this area. The potential effect of high water temperature on viability of eggs produced by parents encountering high temperature is unknown, but this concern has been raised in other watersheds.

Fall Fry Abundance

Relative abundance and size of subyearling sockeye salmon in Black Lake have been estimated from tow net catches during late August and September[11]. The tow net procedure utilized a 6' x6' surface net towed between two skiffs for 10 minutes (Narver 1966). During 1961-2002, 312±66 (SE) sockeye salmon fry were captured per tow[12], indicating an exceptionally high density of sockeye salmon remaining in Black Lake during fall. This catch rate was equivalent to a catch of 702 sockeye salmon per 10 minute tow by a 9' x9' townet, which is typically used when sampling juvenile sockeye salmon in western Alaskan lakes. In comparison, sockeye catch rates in Bristol Bay lakes ranged from 16 to 94 salmon per 10 min tow (51/ tow in Lake Nerka, 94/ tow in Aleknagik, 16/ tow in Lake Clark, and 57/ tow in Lake Iliamna) (Quinn et al. 2000). Thus, densities in Black Lake were approximately 12 times that of Bristol Bay lakes.

Sockeye fry catch rates in Black Lake during 1961-1973 versus 1992-2002 were compared (Fig. 13). No statistical difference in catch rates was detected between the early period (299±60 fry) and recent period (327±134 fry) ($df = 1, 21$, $F = 0.045$, $P > 0.05$). However, catch rates were much more variable during the recent period, as indicated by the high coefficient of variation (129% vs. 72%). It should be noted that tows were made in Alec Bay and in the lake outlet during the 1960s and early 1970s, whereas these areas were too shallow to sample even with the 4' x9' net during the 1990s. The exceptionally high catch rate in 2000 was associated with

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[11] Growth estimates were based on townet sampling. Studies of gear selectivity in the Wood River lakes and elsewhere indicate two-boat surface townet sampling is not influenced by sockeye size until the fish exceed 100 mm (D. Rogers, University of Washington, pers. comm..). Essentially all juvenile sockeye in the Chignik system are <100 mm and townet sampling is not likely to be size-biased.
[12] This is the arithmetic mean of annual geometric mean catch rates.

relatively high water in Black Lake during spring through fall as a result of exceptional snow pack. The moderately high catch rate in 2002 was associated with exceptionally low lake level, leading to fouling (and loss) of the 6 ft net on the bottom near the middle of the lake.

Although densities of sockeye salmon fry appear to be similar during the two periods, it is possible that lower lake volume in recent years has led to lower total abundance of fry remaining in Black Lake during fall. Narver (1966) suggested that relatively few sockeye salmon fry utilize the areas of Black Lake that are < 2 m deep (6.6 ft). He based this statement on catches of few sockeye salmon in shallow areas where the net touched bottom and few sockeye caught in areas near *Potomogeton* sp. He estimated the primary rearing habitat in the 1960s was only 77% of the total lake surface area (Burgner et al. 1969).

Narver (1966) and Parr (1972) reported that sockeye salmon fry abundance had a negative effect on the abundance of stickleback in Black Lake, but the data did not indicate sticklebacks affected growth of sockeye salmon. Nevertheless, Narver (1966) recommended increasing escapement of sockeye salmon in order to reduce abundance of sticklebacks and potential interspecific competition. As noted below, insect production had a greater effect on salmon growth in most years, but intraspecific competition and possibly temperature were probably important in some years.

Sockeye Salmon Growth in Black Lake

Narver (1966) and Parr (1972) estimated growth rate of age-0 sockeye salmon in Black Lake from spring through September, 1961-1970. Growth rate ranged from 0.20 mm/day in 1963 to 0.32 mm/day in 1968. Average growth rate was 0.25 mm/day. Parr stated that the relationship between sockeye salmon growth rate and an index of juvenile abundance in Black Lake was insignificant ($n = 10$, $r = -0.25$). Air temperature was not correlated with growth rate. Growth rate during summer was positively correlated with sockeye salmon length on June 30, suggesting that conditions affecting growth rate in Black Lake, such as prey availability, may be established early in the growing season.

Narver (1966) and Parr (1972) also tested for density-dependent growth (intraspecific competition) through comparisons of fry length and abundance indices during fall. Density-dependent growth in Black Lake was not apparent, 1961-1970. Instead, growth appeared to be related to spring insect production, which varied year-to-year.

Re-examination of the relationship between fall fry size and density of fry in Black Lake, 1961-2002 suggested growth was density-dependent, and that spring air temperature and time period also affected growth (multi-variate regression: df = 3, 18; $F = 8.877$, $P = 0.002$). In this multi-variate analysis, growth was negatively affected by sockeye abundance determined by townet operations in fall (partial $P = 0.011$), positively affected by March air temperature at Cold Bay (partial $P = 0.012$), and positively affected by factors after 1972 (partial $P = 0.039$)[13]. Greater sockeye salmon growth after 1972 might be related to fewer sticklebacks (hypothesized by

[13] The exceptional 1963 data point was excluded from this analysis because Narver thought growth was affected by unusually great abundance of smelt. Serial autocorrelation of the regression (-0.024) was insignificant. Missing data years were 1973, 1974, 1994, 1997 and 1998.

Narver (1966)) and/or longer growing season. Small salmon size during 1963 was related to a large population of pond smelt (Narver 1966) and unusually cold temperatures likely led to small salmon size in 1971 and 1972.

Diet of sockeye salmon in Black Lake has been examined on several occasions. Insects, especially pupae and adults, were the dominant prey during spring and early summer but zooplankton (*Bosmina* sp) were a significant prey during late summer and fall (Parr 1972, Ruggerone 1994, 1999, Finkle and Bouwens 2001). Stomach fullness was typically high and most sockeye salmon had consumed at least some food. Parr (1972) estimated that prey consumption in Black Lake (1968-1969) is 230% greater than in Chignik Lake, whereas Ruggerone (1994) reported prey consumption (avg. 2.2% of body wt) was 410% greater in Black Lake, 1993. Migrating salmon fry captured in Black River in 1993 contained 75% less food than fish rearing in Black Lake. Diet and growth data indicate food consumption in Black Lake was high.

Ruggerone (1994) conducted a preliminary bioenergetic modeling of food consumption of Black Lake sockeye salmon during spring, summer, and winter in order to examine weight gain or loss during winter. Modeling results indicated daily ration (% of body wt consumed per day) was high throughout spring and summer, but it decreased from 12% in May and June to 9.5% in July and early August and to 7.8% in late August and September. After early September, projected sockeye length increased from 69.3 mm (3.3 g) on 7 September (observed) to 76.7 mm (4.6 g) on 30 September. In October, growth rate declined as water temperature and food availability declined. Sockeye length at the end of October was projected to be 80 mm (5.3 g). During November, weight decline from 5.3 g to 5.0 g (-5.4%), based on a daily ration of 0.6%. During December through 1 March, an additional weight loss of 33% was projected, based on a daily ration of 0.2%. Ruggerone (1994) concluded that the estimates of weight loss during winter were biased high. Model parameters may not be appropriate for extreme winter temperatures. Using a different approach, Ruggerone (1992) estimated a weight loss of 10% for sockeye during 90 days of starvation at 1°C. These results, in addition to observations of little or no feeding under the ice (see below) and mortality during some springs, indicate juvenile sockeye salmon can loose considerable body weight from late fall through early spring and that this period is likely a critical period for salmon survival.

Salmon Overwintering in Black Lake

Surface townet catches of sockeye salmon fry in Black Lake during late August and early September, 1961-2002, indicated the majority of fry remain in Black Lake through fall rather than emigrating to Chignik Lake. Fry trapping in Black River during May to early December 1993 suggested little or no migration of fry occurred after townet sampling and prior to ice over, but only one fall period has been sampled (Ruggerone 1994).

Ruggerone (1994) reviewed historical Black River smolt data archived at the Fisheries Research Institute. Sampling of sockeye salmon smolts (i.e., yearlings) emigrating from Black Lake was infrequent until 1992 and 1993. Only 22 nights of sampling in <u>late</u> June were available for the years 1960-1965 and 1971-1974. Narver (1966), who sampled smolts for scale patterns, noted that most Black Lake smolts had left the lake by late June, based on smolt sampling in Chignik

River. Additional sampling in Black River occurred after June when fry continued to emigrate to Chignik Lake but no smolts were present (Marshall et al. 1974).

Available historical smolt catch statistics are shown in Table 7. The fyke net was typically set for only a few hours. Maximum catch during late June was 450 smolts during a 2 hr period in 1961. Catches during several nights approached or exceeded 100 smolts. These brief periods of sampling during late June captured more sockeye salmon smolts than the cumulative catch from daily sampling during May and June, 1992 and 1993. For example, only 89 sockeye smolts were captured in Black River during daily sampling from 5 May through 30 June 1993 and 266 smolts from 16 May through 30 June 1992. All smolts were captured between 14 May and 28 June; peak catches occurred during 1-10 June.

Smolts per hour of sampling in Black River were 65x greater during the 1960s compared to late June, 1992-1993 (Fig. 14; df = 1, 44, F = 10.093, $P < 0.003$). Smolts per fry were 123x greater during the 1960s compared to late June, 1992-1993 (df = 1, 44, F = 24.272, $P < 0.001$). These data suggest that considerably more sockeye salmon overwintered in Black Lake during the 1960s compared with the 1990s.

The conclusion that considerably more sockeye salmon overwintered in Black Lake during the 1960s compared with the 1990s is consistent with the observations by D. Narver (retired B.C. Fish and Wildlife, pers. comm.) and S. Marshall (retired ADFG, pers. comm.), who worked for FRI at Chignik during the 1960s and 1970s. They stated that most Black Lake sockeye salmon overwintered in Black Lake. Narver (1963), Burgner et al. (1969) and Burgner (1975) concluded that most Black Lake sockeye salmon overwintered in Black Lake during the 1950s and 1960s. They knew that many fry emigrated to Chignik Lake during spring and summer. Roos (1960) noted that yearling sockeye salmon were captured in Black Lake during May 1959. Sampling of smolts in Chignik River during 1957 revealed a large emigration of 90-95 mm age-1 smolts, which were believed to have originated from fish overwintering in Black Lake (Roos 1958b). Average size of age-1 smolts captured by fyke net in Chignik River, 1956-1959, ranged from 72-88 mm; maximum size of age-1 smolts was 100 mm (Roos 1958, 1959b, 1960b). These size estimates are considerably larger than age-1 smolts measured during 1994-2000 (range of means: 60.2-77.0 mm; Bouwens and Edwards 2001), but comparison of size data may be confounded by inclusion of small salmon (<60 mm) in recent years[14].

Smolt size in Black River varies considerably from year to year (Fig. 15). Average length of age-1 smolts ranged from approximately 75 mm in 1975 to 98 mm in 1961 and 1965. The skewed length frequency plot in 1961 suggests the estimated mean size (98 mm) may have been biased low. Roos (1959b) reported that age-1 Black Lake smolts captured in Chignik River averaged 90 mm. During late June 1960, Narver (1961) captured age-1 smolts in Black River that ranged in size from 83 mm to103 mm; considerable spring plus growth was observed on their scales. Average smolt length in four of the seven years was similar to that in 1992 (95 mm). Smolt length observed in 1993 (111 mm) was considerably greater than that previously observed, but very few smolts overwintered in Black Lake.

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[14] Smolt trap operations regularly capture small age-1 and age-0 sockeye salmon in Chignik River. Many of these fish do not appear to smolt and continue seaward migration, but instead they will rear in the lower river and upper lagoon, then migrate upstream (Roos 1960, Iverson 1966).

Sockeye salmon scale growth collected from adults, brood years 1960-1992, was examined to determine whether spring plus growth has declined in recent years, as might be expected if few smolts overwinter in Black Lake (Bumgarner 1993, Ruggerone and Rogers 1998). Spring scale growth occurs in freshwater and possibly Chignik Lagoon[15]. Spring growth of salmon overwintering in Black Lake is much greater than spring growth in Chignik Lake (Roos 1959b, Narver 1961, Ruggerone 1994), but growth in Chignik Lagoon can be significant (Phinney 1968). Spring scale growth during 1977-1992 was significantly less than that during 1960-1976 (t-test, df = 31, t = 2.787, $P < 0.01$), averaging 14% less during recent period[16]. Multi-variate regression indicated spring plus growth declined over time (partial $P = 0.001$) and increased with greater spawning escapement (partial $P < 0.01$; df = 2, 32, $F = 7.27$, overall $P = 0.003$; $R^2 = 0.33$)[17].

In summary, this analysis, in addition to the intermittent catches of smolts in Black River, suggests that a greater percentage of smolts overwintered in Black Lake during the early 1960s compared with the recent period. During the 1990s, exceptionally few sockeye salmon overwintered in Black Lake. Sampling of juvenile salmon under the ice of Black and Chignik lakes during winter (see below) provided further evidence that few sockeye salmon currently overwinter in Black Lake. Additionally, very few yearlings have been captured during spring in Black Lake during recent years (Ruggerone 1994, Bouwens and Finkle 2003). Since many sockeye salmon appear to remain in Black Lake during fall until ice cover, a key question is whether these sockeye salmon successfully emigrate to Chignik Lake.

Winter Ecology of Black Lake and Sockeye Salmon Survival

Ruggerone et al. (1991, 1992) reported that adult sockeye salmon production in Black Lake fluctuated more than that of nearby Chignik Lake and other major sockeye systems in western and central Alaska. The large run size fluctuations were hypothesized to be related to fluctuations in habitat within Black Lake, especially during winter (Ruggerone and Rogers 1989). During winter, lake level is typically low, and ice cover prevents mixing and oxygenation of the water column. It was hypothesized that biochemical oxygen demand, which was largely driven by decay of abundant aquatic vegetation and accumulation of organic matter on the bottom, could reduce oxygen content in the lake and affect sockeye salmon survival. It was further hypothesized that the shallowing of Black Lake may have exacerbated the problem of low oxygen because biochemical oxygen demand occurs near the bottom and has greater effect on the entire water column when depth is shallow. Research in the 1960s, when depth of Black Lake was greater than now, indicated many, if not most, sockeye salmon overwintered in the lake. Research during 1993 suggested that most juvenile sockeye salmon remain in the lake until at least the period of ice formation (Ruggerone 1994). Thus, a program of winter research was

[15] Scale growth typically lags behind body growth, therefore examination of juvenile scales may underestimate recent growth. Fish collected in winter do not show the winter annulus; annulus formation has been observed in spring.

[16] As noted previously, significant changes in Black River began in the late 1960s to early 1970s. The precise date of change is not known. Changes in Black Lake appeared to occurred gradually over a period of time. The dates used in the analyses were used to bracket the periods before and after change in habitat.

[17] Serial autocorrelation for this and other regressions were insignificant.

developed and studies were conducted during February 1990, 1992, 1993, 1995, 1996, 1997, and 1998 (Ruggerone et al. 1991, Ruggerone 1993, 1995, 1996, 1997, 1999). Findings of winter research relevant to changes in Black Lake habitat are summarized below. Winter reports should be consulted for additional information on the winter ecology of salmon.

Physical Habitat

Dissolved oxygen and water temperature profiles below the ice on Black Lake were measured during February 1990, 1992, 1993, 1995, 1996, 1997, and 1998. February was selected for the field study period because ice conditions are typically most stable during February. Dissolved oxygen content varied considerably from year to year, depending on the duration of ice cover, ice thickness, and water depth. Oxygen content reached its lowest level in 1992 when the water column below 50 cm (1.6 ft) was below 57% saturation (Fig. 16), which is the threshold level for maintaining healthy salmon populations (Davis 1975). Oxygen content at water depths exceeding 1.5 m (4.9 ft) was less than 25% of saturation. In contrast, in 1993 ice on Black Lake was thin and contained numerous holes and oxygen content exceeded 57% at all depths. Oxygen content during other years was between the 1992 and 1993 measurements. Deployment of a continuously recording Hydrolab oxygen sensor demonstrated that oxygen content could decline further after the February sampling period (Ruggerone 1996, 1997, 1999).

Water temperature profiles below Black Lake show that temperature near the bottom of Black Lake approached 4.0°C, then steadily decreased to 0.1°C immediately below the ice. Warm bottom water was associated with low oxygen content and low mixing of the water column. Seasonal water temperatures recorded by a thermograph deployed approximately 0.5m above lake bottom near Hydro Pt (depth 2.8-3.2 m) indicate ice forms over Black Lake soon after the water column approaches 0°C, then rises and approaches 4°C after formation of ice (Fig. 12). Spring breakup, or warm mid-winter events, are associated with a sharp decline in water temperature as the water column begins to mix and the lake is re-oxygenated.

The amount of habitat available to sockeye salmon during February was estimated from estimates of winter lake level, ice thickness and associated displacement of water, and percentage of water column exceeding 57% saturation (Davis 1975). Total water volume in the lake was based on the spring 1992 depth survey (benchmark: -0.6 m; Ruggerone et al. 1993), which enabled calculation of water volume in relation to lake elevation measurements at the outlet of Black Lake. Loss of sockeye salmon habitat during winter relative to spring 1992 water levels was calculated (Ruggerone 1999). Habitat loss during February ranged from 87% in 1992 when lake level was low, ice was thick, and oxygen content was low to 15% in 1993 when ice was thin, lake level was relatively high, and oxygen content was high (Fig. 17). During seven years of investigation, habitat loss during winter relative to spring averaged 56%±27% (S.D.). Thus, winter habitat in Black Lake varied considerably from year to year.

Sockeye Tolerance to Low Oxygen

An experiment was conducted in Black Lake to determine the tolerance of juvenile sockeye and coho salmon to varying levels of dissolved oxygen (Ruggerone 2000). Juvenile sockeye and coho salmon were captured in traps and transported in aerated containers to the study site near

Hydro Pt. Sockeye salmon were captured in Chignik Lake and all fish were in good condition at the beginning of the experiment. At the study site, 10-20 sockeye or coho salmon were placed in wire-mesh cages (6.4 mm^2 mesh, 46 cm x 23 cm), then lowered to one of several depths under the ice (up to 3.5 m) in order to expose fish to a range of oxygen concentrations. Dissolved oxygen (mg l^{-1} and %) and temperature were measured at each cage using an Orion Model 840 dissolved oxygen meter after calibration. Fish were held in the cages for 24 h, then examined for survival.

Survival of sockeye salmon during the 24 h period was 100% when the water exceeded 65% oxygen or 9.0 mg l^{-1} (Fig. 18). Sockeye survival declined to 90-97% as oxygen content declined from 65% to 34% (4.5-9.0 mg l^{-1}), then survival declined rapidly as oxygen content declined below 30% saturation (4 mg l^{-1}). At 24% saturation (3.0-3.3 mg l^{-1}), 45% of sockeye salmon survived. No sockeye salmon survived the brief exposure to oxygen concentrations below 17% saturation (2.3 mg l^{-1}).

In comparison, all coho salmon survived 24 h exposure to oxygen concentrations as low as 21% of oxygen saturation (3.1 mg l^{-1}). Furthermore, all 50 coho survived after being held for 4-5 days at 23-24% saturation (3.2-3.3 mg l^{-1}). All 22 coho captured in traps near the lake bottom and held overnight in Black Lake survived exposure to low oxygen. Eight of these coho were exposed to water containing 13-20% oxygen (1.6-3.2 mg l^{-1}) and 14 coho were exposed to 21-27% oxygen (2.8-3.6 mg l^{-1}).

This experiment demonstrated that sockeye salmon have less tolerance to low dissolved oxygen compared with coho salmon. This finding is consistent with observations of numerous coho salmon overwintering in Black Lake and the lack of sockeye salmon in the lake during winter (see below).

Juvenile Sockeye Salmon Catch Rates

Black Lake The relative abundance of fishes in Black Lake was estimated with baited commercial fry traps (6.4 mm^2 mesh, 46 cm long x 23 cm diameter) placed beneath the ice. The traps were baited with salmon eggs treated with 1% Betadyne for at least 10 minutes, then placed in a perforated plastic container. Traps were set along the oxygen profile transect extending from Sand Point to Hydro Pt. At each station, one trap was set immediately below the ice and another trap was set on the bottom. Given the low water volume of Black Lake during winter and the high density of juvenile sockeye salmon in Black Lake during fall, catch rates during winter should be exceptionally high if most sockeye salmon overwintered in Black Lake.

No sockeye salmon were captured in Black Lake in 223 trap nights during five years of investigation (1992-1998) (Table 8). This result is consistent with the exceptionally few numbers of sockeye salmon smolts captured in Black River during daily sampling in spring 1992 and 1993. During 2000-2003, ADFG captured exceptionally few yearling sockeye salmon in Black Lake using townet and beach seine methods during spring (Finkle and Bouwens 2001, Bouwens and Finkle 2003, K. Bouwens, pers. comm.). Thus, few sockeye salmon presently overwinter in Black Lake.

In contrast, juvenile coho salmon, which have a higher tolerance to low dissolved oxygen compared with sockeye salmon (Ruggerone 2000), were frequently captured in Black Lake. During 1992-1996, 5.6±1.8 coho salmon were captured per night per trap set at the bottom of Black Lake compared with 0.7±0.3 coho salmon captured immediately below the ice (Fig. 19). Coho salmon appeared to prefer bottom habitat, which was warmer and lower in oxygen content compared with near ice habitat.

Chignik Lake Baited traps were set in Chignik Lake in order to estimate the percentage of Black Lake and Chignik Lake sockeye salmon overwintering in Chignik Lake and to demonstrate that baited traps were effective in sampling sockeye salmon under ice. Traps were set in the outer portion of the lake outlet, Clark Bay, and South Hatchery Beach. Relatively few sockeye salmon inhabited waters below 10 m depth (Ruggerone 1992b, 1995, 1998)[18]. Near surface catches of sockeye salmon average 8.7±2.7 sockeye salmon per night per trap in 185 trap nights during five years of investigation (Table 8). These data show that the baited traps were effective at capturing juvenile sockeye salmon.

Length at age analysis was used to identify stock of origin of juvenile sockeye salmon inhabiting Chignik Lake during February. This method, which relies primarily on visual separation of stocks based on length at age, can provide a reasonably accurate method for identifying Black versus Chignik Lake stocks because juvenile sockeye salmon inhabiting Black Lake grow more rapidly compared with those in Chignik Lake (Narver 1963, 1966, Parr 1972)[19]. In order to verify this methodology, juvenile sockeye salmon collected in Chignik Lake during February 1998 were preserved for genetic stock identification. Baseline genetic analyses were conducted in 1996-97 (Ruggerone 1997a, Templin et al. 1999). Length at age analysis of 402 juvenile sockeye salmon indicated Black Lake sockeye salmon (age-0 and age-1 combined) represented 28% of the sockeye population in Chignik Lake (Ruggerone 1999), whereas genetic analysis indicated Black Lake sockeye salmon represented 33% of the population (unpublished analysis, B. Templin, ADFG Genetics Lab, pers. comm.)[20]. Thus, length at age appears to be an effective methodology for estimating stocks in Chignik Lake, but it may not always be appropriate for smolts (Bouwens and Finkle 2003) since smolts must reach a threshold size.

Essentially all Black Lake sockeye salmon were present in Chignik Lake during February 1992-1998. Length at age analysis shows that a significant percentage of sockeye salmon in Chignik Lake had originated from Black Lake (Fig. 20). For example, the percentage of age-0 sockeye salmon originating from Black Lake was approximately 71%, 33%, 90%, 29%, and 79% during 1992 and 1995-1998. The percentage of Black Lake sockeye among age-1 salmon in Chignik

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[18] For example, in February 1995, juvenile sockeye catch rates at 20-30 m were <1% of those at 0-10m.

[19] Bouwens and Finkle (2003) reported that age-specific length distributions of Black Lake and Chignik Lake smolts were unimodal during 1998-2000 and could not be separated. Stock separation is more easily accomplished when sampling juveniles in the lake during winter because lake samples include small fish that will not smolt in addition to those that will smolt during spring (see Fig. 20). Year-to-year variability in stock identification of the lake samples was minimized because aging was conducted by one individual. The lake-based stock identification estimates facilitated salmon forecast estimates from 1995 through 2001 (winter samples not collected after 1998).

[20] This analysis was based on a comparison of stock percentages estimated by the length-at-age and genetic methods; individual fish were not compared.

Lake was much lower: 1%, 6%, 3%, 8%, and 4% during 1992 and 1995-1998[21]. Chignik Lake sockeye salmon may have been somewhat over-represented in the samples because most sampling was conducted in lower Chignik Lake, which is farther from Black River. Nevertheless, stock composition data provided valuable information for pre-season forecasts of adult salmon returns (Ruggerone 1996, 1997, 1999, Ruggerone et al. 1999, 2000).

Winter Zooplankton Abundance

Zooplankton abundance was examined in both lakes during February 1990 and 1992. In Black Lake, zooplankton were sampled using a plankton pump because the lake is too shallow to sample zooplankton with vertical zooplankton hauls. In Chignik Lake, vertical hauls were made from a depth of 40 m.

Sampling of zooplankton in Chignik Lake and Black Lake during winter indicated that few prey were available for planktivorous fishes such as sockeye salmon. In Black Lake during February 1990, zooplankton were scarce in the four plankton pump samples, averaging 3 *Cyclops*, 16 *Bosmina* sp. and 2 harpacticoid copepods zooplankton per m^3 (Ruggerone et al. 1991). In 1992, only 132 *Daphnia* per m^3 were captured in two samples (Ruggerone 1992b).

In Chignik Lake during 1990, zooplankton averaged 70 zooplankters per m^3 or 1% of that during late June 1990. In 1992, only small numbers of *Daphnia* (57/m^3) and *Bosmina* (6/m^3) were captured. Daphnia and Bosmina were not expected during February because adults generally die during winter, leaving eggs to hatch during spring.

Thus, as expected, few planktonic prey were available for sockeye salmon in Black and Chignik lakes during winter.

Winter Sockeye Salmon Food Habits and Appetite

Food habits of sockeye salmon and other fishes were examined during February 1990, 1992, and 1995. In 1990, stomach contents of 161 sockeye, 90 coho and 17 chinook salmon and 66 Dolly Varden char captured in Chignik Lake indicated that almost no food was consumed by the fish (Table 9). Only 5% of sockeye, 24% of coho, 12% of chinook and 2% of char contained food. The average weight of prey (chironomid larvae, bivalves, copepods and insects) consumed by sockeye was 0.1 mg or <0.01% of their body weight. Weight of prey consumed by coho, chinook and char was <0.3% of their body weight. Coho consumed chironomid larvae and unidentified fish, char consumed fish (sockeye), and chinook consumed Oligocheate worms. Debris (rocks and wood), some of which may have originated from casings of caddis fly larvae, was frequently found in coho (21%), chinook (18%), char (9%) and, to a lesser extent, sockeye (3.7%). These non-digestible items were more abundant than food in the stomachs.

During February 1992, 134 sockeye salmon and numerous other fishes were examined for food habits. Only 1.5% of the sockeye contained food (unidentified organic matter) and average prey

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[21] Age-1 salmon collected during winter do not show evidence of the winter annulus. Age-1 fish captured during winter will become age-2 fish during spring after formation of the winter annulus.

weight was 0.1±0.05 mg (Table 10). Other fishes contained little or no food. In Black Lake, 18.9% of coho consumed prey (6.7 mg/fish), of which 58% was amphipods.

During February 1995, approximately 30% of 94 sockeye salmon contained prey, but they averaged only 0.2±0.1 mg of food (Table 11). Prey content relative to sockeye body weight was <0.01%. The primary prey of sockeye salmon was the copepod, *Cyclops* sp.

Feeding experiments were conducted under the ice of Chignik Lake to determine whether sockeye salmon would consume prey during winter, if it were available (Ruggerone 1997c, 1999). Experiments were conducted during February 1997 and 1998 by pumping semi-buoyant commercial salmon food under the ice, then setting traps after approximately 24 hrs of feeding. This approach under-estimated feeding rates because some fish may have entered the traps before feeding.

During 1997, the percentage of sockeye salmon body weight (wet) represented by commercial food during winter was 4.6% and individual sockeye salmon contained up to 320 mg of commercial diet. In contrast, the percentage of sockeye salmon body weight (wet) represented by wild prey during summer 1993 was 0.56% in Chignik Lake and 2.2% in Black Lake (Fig. 20). Thus, sockeye salmon feeding on commercial diet during winter contained eight times more food than sockeye feeding on wild prey in Chignik Lake during summer .

During 1998, the percentage of fish observed feeding on the commercial diet ranged from 13% after two days of feeding to 80% after three days (Table 12). After three days of feeding, prey weight averaged 47 mg, or 2.1% of body weight. The commercial diet appeared to attract sockeye salmon. The number of sockeye per trap averaged 38 fish at the feeding station compared with 12 fish at the outlet abundance station (500 m away).

Consumption of commercial diet during winter 1998 was compared with consumption of natural prey (mostly zooplankton) by sockeye salmon in Chignik Lake during summer 1993. In Chignik Lake, sockeye contained relatively little natural food during summer (17.1 mg per fish) compared with sockeye during winter (up to 47 mg per fish during the second and third days of feeding).

In summary, sockeye salmon consume very little prey during winter because few prey are available. Feeding experiments with commercial salmon food demonstrated that sockeye salmon will readily consume prey during winter if it is available.

<u>Effects of Low Winter Oxygen on Adult Returns</u>

The effect of low winter oxygen on numbers of adult sockeye salmon returning to Black Lake was examined by comparing returns of age-1.3 salmon with oxygen content of Black Lake during juvenile rearing. Age 2.x adults were excluded from the analysis because many are believed to represent fish that overwintered in Chignik Lake (Narver 1966). Age- 1.3 is the dominant age returning to Black Lake.

The return of adult sockeye salmon significantly declined with increasing percentage of the water column containing low oxygen (i.e., 57% of saturation; Davis 1975) (Fig. 22; n = 6, R^2 = 0.80, P <0.05), but this relationship was based on only six data points. No other variables (e.g., parent escapement, lake level, avg. winter air temperature) contributed significant information to the regression. Adult returns were approximately 1.5 million salmon when oxygen content was relatively high and only approximately 0.5 million salmon when oxygen content was low (17% of the water column contained water exceeding the 57% saturation threshold). This relationship excluded the 1995 winter value because these fish returned as adults during the 1997/1998 El Nino, which created highly unusual and adverse conditions for adult sockeye salmon (Kruse 1998). Immature salmon did not appear to be strongly influenced by the El Nino event.

The percentage of water column containing low oxygen was negatively correlated with temperature coefficient of variation in Black Lake during December 10 to February 28, 1992-1998 (Fig. 23; n = 5, R^2 = 0.84, P<0.05). This relationships occurs because water temperature under the ice declines during warm periods that cause openings in the ice and mixing of the water column. The inverse relationship between oxygen content and temperature variability under the ice enabled further testing of the oxygen depletion hypothesis by inclusion of winter conditions during 1999. Return of age-1.3 sockeye salmon to Black Lake increased significantly as the temperature variability increased (Fig. 23; n = 6, R^2 = 0.83, P<0.05), providing further evidence that oxygen depletion affects sockeye salmon survival in Black Lake.

Recent observations indicate that juvenile sockeye salmon attempt to migrate from Black Lake during winter because very few fish remain in the lake by late winter and spring. Sampling of the fry migration during early winter was very difficult due to ice flows, but in 1993 a screw trap was operated in Black River near Chiaktuak Cr until ice formation in early December (Ruggerone 1994). Very few sockeye fry migrated between the time of tow netting in the lake during early September and early December, indicating the majority of Black Lake fry remained in the lake at that time. Although we have only one year of early winter sampling, these data suggest the major fry migration occurs between ice formation and late winter. The hypothesis stemming from these observations is that the majority of fry survive and migrate downstream to Chignik Lake in years of high oxygen content under the ice. During years of low oxygen, some of these fry do not survive and do not migrate to Chignik Lake. Dead sockeye fry have not been observed in Black Lake or Black River during winter, but this is not surprising since the lake is typically covered in ice and scavengers (e.g., isopods) would likely consume them prior to ice out.

Competition Between Black and Chignik Lake Sockeye Salmon

Density-Dependent Growth in Chignik Lake

Zooplankton abundance in Chignik Lake (381,000 m^{-2}) is high compared to sockeye lakes in central and southeast Alaska (228,000 ± 48,000 m^{-2}) (Kyle 1991) and western Alaska (250,000 m^{-2} for 60 m haul) (D.E. Rogers, unpublished data). However, body sizes of zooplankton were small compared with those in other sockeye salmon lakes, indicating predation is intense (Kyle 1991, Ruggerone 1994, Ruggerone et al. 2000). For example, in 1994 average size of *Bosmina*

(0.35 mm) was under the elective threshold for sockeye salmon (0.40 mm). Biomass of zooplankton in Chignik Lake is low (Bouwens and Finkle 2003).

Narver (1966) and Parr (1972) reported that juvenile sockeye salmon growth in Chignik Lake was density-dependent. During 1961-1970, the estimated growth rate of age-1 sockeye salmon declined sharply with increasing abundance of sockeye salmon in the lake ($n = 9$, $P < 0.05$; Fig. 24). However, following Parr's study, Burgner and Marshall (1974) added two additional data (1971 and 1972) that lowered the significance of the relationship ($n = 11$, $P = 0.069$). Temperature during 1971 and 1972 was exceptionally cold and temperature likely affected growth in 1971 and 1972 more than salmon density. No evidence of competition with sticklebacks or smelt in Chignik Lake was detected. These data suggest food availability in Chignik Lake was reduced by higher densities of sockeye salmon, but other factors such as seasonal immigration of Black Lake fry and temperature, also affected growth rate of age-1 sockeye salmon in Chignik Lake.

The large emigration of age-0 sockeye salmon from Black Lake to Chignik Lake, which may occur at varying periods during spring and summer, increases competition for prey in Chignik Lake. Age-0 sockeye salmon from Black Lake were similar in size to age-1 sockeye in Chignik Lake and diet was likely similar. Black Lake sockeye salmon compete for prey in Chignik Lake after migrating during spring or summer. Additional competition may occur during early spring if Black Lake sockeye salmon successfully migrate to Chignik Lake during winter (see analysis below). As discussed previously, the winter migration appears to occur between the period of ice formation and February when sampling indicated few sockeye salmon remaining in the lake during the 1990s.

Chignik smolts are small compared to most other sockeye systems. Burgner (1987) provided size at age for sockeye smolts from many stocks around the Pacific Rim. Average length of age-1 (68 mm or 2.8 g) and age-2 (78 mm or 3.9 g) smolts leaving the Chignik watershed during the 1990s (Bouwens and Edwards 2001) was less than that of other sockeye systems, except for glacial watersheds or those that are highly oligotrophic (Burgner 1987, Edmundson and Mazumder 2001). The small size of Chignik smolts is related to the high density of spawners that produce numerous juveniles that inhabit the lakes, which in turn exert intense predation pressure on zooplankton. In contrast to other watersheds where smolt size is small, primary production and plankton standing crop in the Black and Chignik lakes are exceptionally high (Burgner et al. 1969). Zooplankton production in Chignik Lake must be high in order to support the high density of sockeye salmon, but production has not been quantified.

<u>Chignik Lagoon as a Secondary Rearing Habitat</u>

Phinney (1968) conducted studies of juvenile sockeye salmon utilization of Chignik Lagoon. He reported that the lagoon is an important rearing habitat for sockeye salmon, especially for smaller sockeye salmon smolts. Non-smolting sockeye salmon also use the upper lagoon/lower Chignik River for rearing, then migrate back up Chignik River (Iverson 1966). Recent studies confirm its use for rearing and feeding (Ruggerone et al. 2000, Finkle and Bouwens 2001). Chignik Lagoon provides an important secondary rearing habitat before migration into the ocean, and it likely contributes to survival at sea of Chignik smolts, which are relatively small at age.

Age Composition of Adult salmon

Narver (1966) suggested that the return of age-2.x sockeye salmon to Black Lake represent juvenile sockeye salmon that migrated to Chignik Lake as age-0 fish during spring. Estimates of early migration of Black Lake fry are not available, but freshwater age composition of adult salmon returning to Black Lake might reflect the percentage of fry migrating to Chignik Lake during early spring. If the shallowing of Black Lake has led to an increase in early migrants, then greater percentage of age-2.x fish might be expected in the adult returns. However, this relationship is complicated because spring growth of fry emigrating from Black Lake can be substantial (Ruggerone 1994) and these fish may not migrate as age-2 smolts, as suggested by Narver.

A shift in freshwater age composition of Black Lake sockeye salmon was tested by using age composition of Black Lake sockeye salmon sampled on the spawning grounds and at the outlet of Black Lake. Multi-variate regression indicated the percentage of age-2.x salmon returning to Black Lake increased over the years, 1964-2002 (partial $P = 0.025$), and decreased with larger run size (partial $P = 0.030$; $df = 2, 35$, $F = 3.412$, $P < 0.05$, $R^2 = 0.17$), although there is considerable variability in the relationship. Age composition based on fish sampled at the outlet of Black Lake and on the spawning grounds is more representative of Black Lake salmon than age composition shown in brood tables, which is based on run reconstruction of Chignik and Black Lake runs using scale pattern analysis of age 1.3 and 2.3 sockeye salmon and other methods prior to 1978[22].

This analysis suggests changes in Black Lake habitat may have influenced a shift toward older sockeye salmon. However, spawning density has increased during the recent period and may have also influenced a shift to older juvenile sockeye salmon, whereas high temperatures in recent years would favor a shift toward younger salmon.

The number of adult sockeye salmon returning to Black Lake in relation to freshwater age composition was examined. Sockeye salmon returns significantly declined with greater percentages of salmon spending two years in freshwater ($n = 27$, $F = 29.19$, $P<0.001$; Fig. 25). If Narver's hypothesis regarding the effect of spring emigrations of fry on freshwater age is correct, then this relationship suggests fish having early migrations have lower probability of survival (however, see comment above). Alternatively, the relationship might reflect high mortality of age-1.x sockeye salmon in years of low oxygen content in Black Lake leading to lower returns and high percentages of age-2.x salmon that overwintered in Chignik Lake.

Age composition of Chignik Lake sockeye returns during the past several decades was examined. No statistical difference in the percentage of age-2.x sockeye salmon returning to Chignik Lake was observed between brood year periods 1960-1976 and 1977-1996 ($n = 31$, $P > 0.05$), even though spawning escapement to Chignik Lake has significantly increased and additional sockeye salmon may be emigrating from Black Lake. Analysis of scale patterns

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[22] Bumgarner (1993) examined age composition based on brood tables and reported that the percentage of age-2.x sockeye salmon had increased in the adults returns to both Chignik and Black lakes, largely in response to a shift in age composition prior to the mid-1960s.

collected from adult salmon indicated first year growth of sockeye salmon in Chignik Lake increased significantly during the recent period (df = 30, t = 3.987, $P < 0.001$), apparently in response to higher temperatures and longer growing seasons (Bumgarner 1993). Favorable growth of fry either inhibited additional age-2 sockeye salmon rearing in Chignik Lake or high numbers of Black Lake and Chignik Lake sockeye rearing in the lake led to additional mortality of age-2 sockeye salmon. Scale analysis indicated second year growth in Chignik Lake did not differ between the periods ($P > 0.05$), whereas spring growth of age-2 smolts was significantly less during the recent period (df = 30, t = 2.206, P = 0.035). Scale growth of fry and yearlings co-inhabiting Chignik Lake were not correlated, a finding that is unique among sockeye systems (Ruggerone and Rogers 2003).

Spring scale growth of age-2 Chignik Lake smolts was inversely related to the adult return of Black Lake salmon that co-inhabited Chignik Lake as juveniles (df = 1, 30, F = 8.48, $P < 0.01$), suggesting that age-1 Black Lake salmon affect growth of age-2 smolts during or prior to seaward migration. Age-1 Black Lake salmon are similar in size to age-2 Chignik salmon and the two stocks likely compete for prey. These data suggest that Black Lake fry primarily affect Chignik yearlings rather than fry, a finding that is consistent with evidence from adult returns (see below).

During 1977-1996, greater adult returns to Chignik Lake were positively correlated with the percentage of age-2.x sockeye in the return (df = 1, 19, F = 5.464, P = 0.031). This relationship supports the hypothesis that age-2.x sockeye are key to strong Chignik Lake runs. Salmon grow slowly in Chignik Lake and factors that adversely affect growth during the second rearing season and during the following spring may adversely affect survival and abundance.

<u>Evidence from Adult Sockeye Returns</u>

FRI scientists suggested that emigration of age-0 sockeye fry from Black Lake during spring through early winter can negatively affect growth and survival of Chignik Lake sockeye salmon (Narver 1966, Parr 1972, Burgner 1975). This conclusion was based on evidence of density-dependent growth in Chignik Lake. Adult return data also suggest emigration of Black Lake fry can affect survival of Chignik Lake salmon (Ruggerone 1994, 1995, 1999). A plot of Chignik Lake sockeye run size on Black Lake sockeye run size (i.e., all age-x.3 components from same smolt year) indicates that large Chignik Lake runs since 1976 occur primarily when Black Lake runs are average or below average (<1.2 million fish; Fig. 26). The run in 1999, in which the runs to both lakes were relatively large, is the primary exception to this trend. However, the large runs in 1999 followed two years of exceptionally low runs to both lakes, suggesting that prey availability relative to juvenile abundance may have been relatively high. In 1995, *Bosmina* and *Daphnia* abundances were exceptionally high (Ruggerone et al. 2001) and size of Chignik Lake age-2 smolts in 1996 were slightly above average (Ruggerone 1997c, Bouwens and Edwards 2001). Thus, salmon returning in 1999 experienced favorable growing conditions in Chignik Lake.

The negative effect of Black Lake sockeye on Chignik Lake sockeye production during 1977-2002 appears to have its greatest effect on age-2.3 rather than age-1.3 fish returning to Chignik Lake because numbers of age-1.3 fish from Chignik Lake are not inversely related to age-x.3

sockeye returning to Black Lake, whereas age-2.3 fish are inversely related (Fig. 27). Total brood production of the two lakes was less correlated (Ruggerone 1995). Thus, Chignik sockeye salmon appear to be affected by Black Lake salmon from the previous brood year.

In contrast to the inverse relationship between Chignik and Black Lake runs during recent years, Chignik Lake runs were positively correlated with Black Lake runs during 1922-1976 (Fig. 26). These relationships suggests Black Lake salmon that overwinter in Chignik Lake have had a significant effect on Chignik Lake salmon, whereas smolts originating from Black Lake (earlier time period) had little effect. As noted in previous documents (Dahlberg 1968, Ruggerone 1994, 1995, 1999), the accuracy of these early adult return data may be less reliable than more recent data because stock identification procedures were based on simplistic assumptions.

Chignik Adult Returns Relative to Other Watersheds

Harvests

Rogers (1995) reviewed sockeye salmon production in the Chignik Lake system relative to other systems in western and central Alaska in an effort to determine whether Chignik salmon production had increased as much as other stocks. Rogers noted that all sockeye salmon runs in western and central Alaska had increased since the mid-1970s, therefore evaluation of the status of the Chignik stock should be based on changes relative to other stocks rather than the time series of Chignik salmon production.

During 1964-1976, the average catch in the Chignik fishery (excluding interceptions) ranked fifth behind Kvichak, Naknek, Egegik, and Cook Inlet. Chignik catches exceeded those in Ugashik, South Peninsula, North Peninsula, Wood River, Nushagak District, Togiak, and Kodiak fisheries. However, during 1990-1995, Rogers noted that Chignik harvests were smaller than all systems except Igushik and Togiak, i.e., two small watersheds. The percentage increase in Chignik catch (146%) between 1990-1995 and 1964-1976 was lower than that of all other fisheries. Part of the lag in Chignik catches was explained by increased interception catches in recent years. However, total run size, including estimated interception catches, of Chignik runs increased less than all other stocks except Kvichak, which is the largest producer of sockeye salmon. Rogers noted that the highly variable R/S of the Black Lake run and the recent degradation of habitat may have adversely affected the Chignik sockeye salmon run relative to other systems.

The harvest analysis by Rogers was updated for this report to include harvests from 1964 to 2002. Chignik sockeye salmon harvests, excluding interceptions, increased 128% from 1964-1976 to 1977-2002, whereas the average harvest increase for 11 other fisheries was 349% (Table 13). Only harvest of Kvichak sockeye salmon lagged behind the Chignik harvests. The percentage Chignik increase is 126% if estimated interception harvests are added to Chignik total. Thus, on average, harvests of other fisheries after the mid-1970s regime shift increased approximately 2.7 times more than Chignik harvests.

This finding suggests that sockeye salmon production in the Chignik watershed lagged significantly behind that of most other major watersheds in western and central Alaska. It supports the hypothesis that significant changes in Black Lake habitat have led to lower salmon runs.

Variability in Production

Variability in R/S of Black Lake sockeye salmon was compared with that of eight other stocks[23] during brood years 1965-1984 (Ruggerone et al. 1992). The variability in R/S of Black Lake sockeye salmon was higher than all other stocks, including the Chignik Lake stock, suggesting that factors unique to Black Lake was influencing high variability in survival. This analysis and other observations led to the investigations of Black Lake sockeye salmon during winter in order to determine whether winter conditions in the shallow Black Lake may be responsible for the high variation in survival.

Re-analysis of Black Lake R/S variability, brood years 1965-1995, supports the initial finding that Black Lake sockeye salmon productivity is unusually variable. Variability in R/S of 11 sockeye salmon stocks, as measured by coefficient variation, increased linearly with greater variability in spawning escapement (Fig. 28; $P < 0.001$). Coefficient of variation of Black Lake spawning escapement was low (27.5%) and the predicted variation in R/S, based on the regression analysis, was 28.9%. However, the observed Black Lake R/S coefficient of variation (60.8%) was significantly greater than the expected value (28.9%) ($P < 0.05$). Thus, Black Lake productivity is highly variable compared to other sockeye salmon stocks in western and central Alaska after accounting for variability in spawning escapement. This finding supports the hypothesis that the shallow depth of Black Lake creates an unstable habitat that leads to variable survival. Variability in sockeye salmon survival appears to be related to year-to-year fluctuations in dissolved oxygen under the ice of Black Lake during winter and fluctuations in survival of juvenile sockeye salmon attempting to emigrate from Black Lake during winter.

POTENTIAL MITIGATION OF HABITAT DEGRADATION IN BLACK LAKE

Available information indicates Black Lake habitat has changed significantly since the late 1960s. Favorable climate and ocean rearing conditions have masked the effect of habitat degradation on total production of sockeye salmon, but the studies described above provide evidence that habitat degradation has likely led to a reduction in the capacity of the Chignik watershed to support sockeye salmon.

Available information also indicates that the Black Lake watershed is continuing to change. The lake appears to be getting shallower as a result of continued water level decline and sedimentation from Alec River. This is evident from encroaching vegetation along the lake and upper river shorelines and along the outlet sandspit, and the emergence of the Alec Bay sandspit in recent years. Alec River is continuing to shift toward the lake outlet, possibly in response to the declining lake level.

During the past 12 years, we have monitored some of the changes in Black Lake and have had discussions with Chignik fishers and ADFG biologists on potential options to mitigate these

[23] Chignik Lake, Red Lake, Kenai R., Kasilof, Coghill, Wood River, Ugashik, and Egegik.

changes. Obviously, there are no easy solutions and any action is likely to be highly controversial. In the text below, I discuss the potential effects of several mitigation measures that have been discussed in the past. In some cases, I raise concerns about engineering aspects of the mitigation measure so that engineers can address these issues if the action is pursued.

Increase Lake Volume by Construction of Sill at Lake Outlet

The concept of enhancing Black Lake sockeye salmon runs by increasing water volume in Black Lake was first discussed by Burgner (1975), former Director of the Fisheries Research Institute. Dr. Burgner and graduate student Scott Marshall noted that significant numbers of sockeye salmon fry emigrate from Black Lake to Chignik Lake in response to 1) high densities of fry in Black Lake, 2) loss of limnetic habitat due to falling water levels during summer, and 3) exclusion of sockeye fry from littoral areas by threespine and ninespine sticklebacks. They stated that average Black Lake depth was 3 m (9.8 ft) and 44% of the lake area was < 2 m deep (6.6 ft). Falling water level during summer reportedly reduced the capacity of the lake to support sockeye salmon fry because a decline in water level of 1 m would reduce lake volume by approximately 33%, based on calculations at that time. Previously, Narver (1966) suggested both competition for food and space were likely important mechanisms affecting Black Lake salmon. They apparently did not consider oxygen content to be a problem as it was not mentioned in the reports. Thus, Burgner hypothesized that maintaining the level of Black Lake near the spring water level (full basin) would increase the carrying capacity of the lake, thereby enhancing total production of Chignik sockeye salmon. This hypothesis was based on the concept that maintaining spring-time lake volume would reduce emigration to Chignik Lake and reduce competition for prey in Chignik Lake (Narver 1966, Parr 1972), thereby enhancing growth and survival of Chignik Lake sockeye salmon. Burgner noted that maintaining high lake levels would "probably increase total production but it is unknown whether this increased production would exceed the new carrying capacity of the system and continue to produce an emigration" of fry to Chignik Lake. Nevertheless, Burgner suggested that emigration of fry would be the same size or less.

A formal engineering investigation to evaluate dam construction was not conducted by FRI in the 1970s, but Scott Marshall spoke with Dr. Milo Bell, a fisheries engineer at the University of Washington, regarding the potential feasibility of constructing a small dam near the outlet of Black Lake. Dr. Bell suggested that the small dam may fail to maintain Black Lake at spring water level because the soils near the lake outlet were porous and water would likely seep around the dam (S. Marshall, pers. comm., 12/2002).

Ruggerone and Denman (1990) and Ruggerone et al. (1990) revisited the concept of enhancement by increasing water volume after noting significant changes in Black Lake, including shallow depth, growing sandspit across the outlet of Black Lake, and channel migration of Alec River. They referenced the dam construction concept developed by Burgner (1975). The potential benefit of stabilizing lake level near the high water mark was discussed, including concepts previously described by Burgner. Additionally, it was hypothesized that potential winterkill of juvenile sockeye salmon, as a result of low oxygen during winter, would likely be reduced if lake level was maintained near the high water mark.

The two primary benefits of maintaining lake level at a higher level were hypothesized by Ruggerone and Denman (1990) to be 1) reduced fry migration to Chignik Lake during spring and summer, and 2) reduced winterkill because biochemical oxygen demand would impact less of the water column if lake depth was greater. These hypotheses were based on the knowledge that Black Lake is a good rearing habitat during spring, summer, and fall and it was desirable to encourage sockeye salmon to stay in Black Lake, if winter conditions did not increase risk of mortality.

Winter studies conducted since 1990 indicate winter oxygen conditions can affect survival of Black Lake sockeye salmon. Research has not observed mortality under the ice of Black Lake, but it has shown sockeye salmon are more vulnerable to low oxygen than coho salmon, and adult sockeye returns to Black Lake are higher when oxygen content of Black Lake during juvenile rearing is high. Maintaining high oxygen content in Black Lake during winter would likely be beneficial to the survival of sockeye salmon. One method to increase oxygen content in Black Lake is to maintain the lake at a higher level so that biochemical oxygen demand impacts less of the water column. Quantification of oxygen content of Black Lake after stabilization of the lake elevation at a higher level has not been attempted. One factor to consider in such an evaluation is the effect of the depth at which phytoplankton does not produce additional oxygen (i.e., compensation depth; assumed to be 1% of photosynthetically active surface light). During 1995, when no snow covered the ice, compensation depth was approximately 3 m (Ruggerone 1995). ADFG has noted that biochemical oxygen demand might increase if areas of vegetated shoreline are flooded (K. Bouwens, pers. comm.), but it appears that relatively little vegetated shoreline would be flooded by a lake elevation that maintained water near a moderate to high natural level (e.g., -0.3 m to -0.6 m, FRI benchmark).

It was initially hypothesized that higher lake elevation would lead to less spring and summer emigration of fry to Chignik Lake. Reduced competition would be most beneficial to Chignik Lake sockeye salmon, which are relatively small and have lower condition factor compared with Black Lake juveniles. Research since 1990 supports the effects of competition on growth and survival in Chignik Lake. However, it remains unclear whether stabilization of lake level near the high water mark would inhibit fry emigration. Burgner (1975) and Marshall (1977) noted that fry emigration appeared to increase as lake level declined through summer, suggesting that migration was in response to increasing density of fry. However, in 1992 and 1993, declining lake level was not correlated with fry emigration (Ruggerone 1994). Instead, in 1993, a significant surge in migrating fry was associated with a mid-summer flood event that caused lake level to suddenly increase. Possibly, current from the north and south channels of the Alec River stimulated fry to alter their rheotaxis and migrate with the current. Diet and size data collected on migrating fry during non-flood periods indicated migrating fry were not a subset of the entire lake population. These data indicate that insufficient information is currently available to predict whether stabilization of lake level would significantly reduce fry emigration, but it appears more likely than not that fewer salmon would migrate if lake level was maintained at a higher level.

A third potential benefit of maintaining higher lake level is that it would likely result in more water flowing through the north channel rather than the south channel of Alec River, at least initially. Greater flow through the north channel would allow more fry to directly enter the main lake rearing area and it would provide a localized oxygen source during winter. I have not made calculations of lake level effects on discharge through the two channels but the low elevation difference between the river wye and Black Lake would suggest this result is possible. Higher lake level would also cause more sediment in Alec River to settle out before reaching Black Lake. The effect of sedimentation near the river wye on channel migration has not been determined.

CH2M-Hill examined potential methods for stabilizing the level of Black Lake. In 1994, CH2M-Hill conducted pilot tests for constructing a geo-web sill across the outlet control point. Fieldwork included evaluating potential anchoring methods for the geo-web. Some anchoring methods tested were unsuccessful and others showed promise. The CH2M-Hill-CRAA contract was discontinued after the anchoring tests, in part, due to costs and fisher concerns involving the effects of ice forces and channel/bank stability in the outlet reach.

During a CRAA meeting, CH2M-Hill engineers expressed concern about construction of a large concrete dam structure in the outlet of Black Lake where soils are soft. Subsequent fieldwork by CH2M-Hill indicated the soil in the outlet were not as soft and unstable as originally thought, (C. McCallum, CRAA, pers. comm..). As noted above, Dr. M. Bell (retired FRI) suggested that construction of a dam at the lake outlet may not maintain lake level because water would seep around the dam through the porous soils (S. Marshall, IDFG, pers. comm., 12/2002). After conducting a number of winter studies at Black Lake it is obvious that wind and ice can cause significant scouring of the shoreline. Any structure at the outlet would need to sustain annual scouring by wind-driven ice. Likewise, placement of geo-web material would need to withstand encapsulating ice, strong wind, water current, and potential disturbances by bears. The integrity of the channel substrate must be maintained in the outlet as this area appears to control lake level during low water periods.

A structure across the outlet of Black Lake would need to allow upstream and downstream movement of juvenile and adult fish, as well as boats. Harvey (1994) and Harvey et al. (1997) documented significant upstream migrations of smelt, threespine stickleback, and ninespine stickleback along the banks of Black River during spring. These fish utilize Black Lake for spawning and rearing. Sockeye salmon fry from Chiaktuak Cr were hypothesized to migrate upstream to Black Lake because the early adult run to the creek is largely age-1.3 fish (i.e., similar to Black Lake adults), whereas the late run is age-2.3. Also, J. Roos (former FRI biologist) observed upstream migrating fry near Chiaktuak Cr in the 1950s. Rheotaxis experiments by Harvey suggested Chiaktuak sockeye fry attempted to move upstream in Black River water and downstream in creek water, but few fry were observed migrating upstream against the mild river current during 1992 and 1993. Greater velocity since the late 1960s, as a result of channel degradation, may have inhibited small upstream migrations of sockeye fry in recent years. Narver (1966) suggested that most progeny Black River tributary spawners rear in Chignik Lake.

In summary, this analysis suggests that stabilization of Black Lake level might enhance sockeye salmon production in the Chignik watershed. However, interactions between salmon and habitat are complex and it is difficult to accurately predict the effects of habitat modification on adult salmon production. Possibly, a simulation model could be developed to explore interactions of multiple factors affecting sockeye behavior and survival, but this effort is beyond the current scope. Changes in run size as a result of lake enhancement would likely be difficult to detect without a focused effort to evaluate salmon population change. Nevertheless, the key question is whether lake level stabilization can be engineered without exacerbating the lake level problem or inhibiting upstream fish movement. Answering this question will require good communication between engineers familiar with the Alaskan environment, Chignik residents, and biologists familiar with the unique qualities of Black Lake. Protection of the lake control point in the outlet is essential since disruption of this area could lead to lower lake level.

Lake Dredging

Dredging a portion of Black Lake is another option that could increase the volume of Black Lake. The likely dredging location would be near Hydro Pt, which is the deepest part of Black Lake. A deeper Black Lake may result in a greater percentage of the water column having higher oxygen content because biochemical oxygen demand occurs near the bottom of the lake. Lake dredging could have the same general effect as raising lake level, except dredging would have no effect on Alec River channel migration.

Obviously, the logistics of dredging would be difficult in the remote Black Lake area and costs would likely be great. Key environmental issues include disposal of the dredge spoils, suspension of sediments during dredging operations, disruption of aquatic insect habitat (e.g., chironomids, which are important salmon prey), and possible injury to some juvenile salmon and other fishes.

Alec River Diversion

Flow in lower Alec River is gradually shifting to the south channel, which discharges to the outlet of Black Lake rather than Alec Bay and the main lake area. A measurable change was detected during the past 10 years. The shift is believed to be influenced by lowering of Black Lake elevation during the past several decades. Greater flow and greater fry entering the lake outlet may lead to increased emigration of fry to Chignik Lake during spring or to reduced prey consumption due to crowding if fry remain in the outlet area for some period of time. During low lake level periods, such as spring when fry are migrating downstream, the lake outlet sandspit crosses up to 85% of the lake and may inhibit movement of fry back into the main lake area. Although significant numbers of fry leave Black Lake during spring, we do not know the extent to which fry emigration has been exacerbated by the shifting Alec River channel. In a feasibility study, Ruggerone (1994) attempted to evaluate this issue by marking and releasing fry in the north and south channels of Alec River, but too few fry were marked in order to achieve some recoveries in Black River and the results were inconclusive. It is likely that there has been some effect on fry migration.

Another potential benefit of re-channeling Alec River back into Alec Bay is enhanced water circulation during winter. Alec River is the primary water source for Black Lake and during winter it transports oxygenated water to the lake. However, as discussed above, approximately 70% of Alec River discharges to the lake outlet area during low flow periods such as winter. Discharge of 100% of Alec River to Alec Bay would likely have a localized beneficial effect on dissolved oxygen content in Alec Bay and along the west side of the outlet spit.

A key concern is that Alec River may continue to shift toward the lake outlet area and eventually bypass Black Lake. The lake outlet sandspit has grown considerably over the past 20 years, but it would not seal off Black Lake even if 100% of Alec River discharged into the outlet. Inflow from Crater Cr, Crooked Cr, and others would maintain the narrow channel near Sand Pt. However, it is likely that 100% discharge of Alec River into the lake outlet would lead to greater fry emigration to Chignik Lake, thereby affecting Chignik salmon production. Given this concern, we initiated annual monitoring of bank erosion and the shifting Alec River channel in 1990 (see discussion above).

In 1993, CH2M-Hill[24] evaluated the potential for diverting Alec River back into the north channel leading to Alec Bay. Initially, they told CRAA that they had an innovative approach that would use existing flow in the river to excavate the wye sandbar and naturally encourage flow to Alec Bay. However, when presenting their findings to CRAA at a meeting, CH2M-Hill discussed the use of deflectors to push water into the north channel. This approach was thought to have a low probability of success given the large water volume of Alec River, high water velocity, high sediment transport, and unstable sand substrate.

Another option for diverting Alec River to Alec Bay is to cut a new channel extending from the bend above the river wye to the old lake shore in Alec Bay. This alternative would require substantial effort and would involve great disruption of habitat. However, this alternative might provide the greatest likelihood for diverting 100% of Alec River flow into Alec Bay.

There is an interaction between lake level and the percentage of water flowing into the north and south channels. Greater flows to the south channel occur when the lake level and Alec River flow are low. Maintaining lake level at a somewhat higher level would likely enhance water flow to the north channel.

West Fork Diversion

As discussed above, the lowering of Black Lake elevation is likely related to the channel migration of the West Fork River. If so, an obvious question is whether diversion of the West Fork River back to the 1950s channel would enhance water volume in Black Lake.

Re-diversion of the West Fork River by itself does not appear to be a reasonable option for two key reasons. First, the West Fork River is a highly migratory channel that has gradually shifted toward Chignik Lake for hundreds of years. This is evident from old channels shown in aerial photographs of the area. West Fork River carries a tremendous sediment load and maintaining a channel directed at upper Black River would be exceptionally difficult in this remote area. During winter, ice dams and scour events would likely reshape the river channel and cause it to migrate. Control of the West Fork River channel migration would likely require construction of large bank revetments similar to those used to control flooding of rivers in populated areas.

[24] No report was produced by CH2M-Hill.

Second, diverting the West Fork River into the 1950s channel would increase sediment load and water flow into Black River (below Chiaktuak Cr) and would likely raise river level somewhat, but it would not likely lead to lake elevations that occurred during the 1950s. The Black River channel has cut considerably deeper since the West Fork River confluence shifted downstream. Diverting the West Fork River into the 1950s channel would not cause the upper river elevation to increase significantly because sediment would be exceptionally slow to accumulate upstream of the confluence because sediment leaving Black Lake is primarily suspended sediment rather than bottom sediment. Thus, re-diversion of the West Fork River would not likely restore the elevation of Black Lake to that during the 1950s. However, re-diversion of the West Fork River and addition of sediment to the upper river channel might lead to higher lake level.

Alter Spawning Escapement Goals

Ruggerone et al. (1999) re-evaluated Black Lake and Chignik Lake spawning escapement goals using a Ricker recruitment curve approach. Preliminary attempts to include the adverse effect on Chignik Lake sockeye of premature emigration of Black Lake fry in the recruitment analysis were not successful, possibly because there is considerable error among the less-dominant age classes in the brood table and because the effect is nonlinear. They concluded that the existing goals were reasonable.

Hatchery Production

On occasion CRAA has discussed building a sockeye salmon hatchery in the Chignik Management Area. The Chignik watershed still produces a significant harvests of native sockeye and other salmon, therefore hatchery operation and production must meet strict goals before it is advisable to construct a hatchery. First, supplementation of Black Lake, Chignik Lake or Chignik Lagoon with hatchery fry is not recommended because these habitats presently support high densities of salmon and hatchery supplementation would undoubtedly impact growth and survival of the native stocks. Second, harvests of hatchery sockeye salmon must be isolated from native fish harvests because mixed stock harvests can lead to over harvest of the native stocks. Third, straying of adult hatchery salmon to native fish spawning grounds must be nil. Interbreeding of hatchery and native salmon will alter the genetic composition of the native stock. Although the outcome of interbreeding is often difficult to predict, sufficient evidence is available to suggest that interbreeding can impact production of the native stock.

Hilborn and Eggers (2000) suggested that pink salmon hatcheries in Prince William Sound have not lead to increased harvests. Instead, they suggest hatchery production has replaced rather than augmented native salmon production because native stocks have declined. They emphasized that harvests of hatchery salmon must be isolated from native runs and that hatchery and native salmon should not overlap during early marine life. In contrast, Wertheimer et al. (2001) argued that Prince William Sound hatcheries have lead to greater harvests even though they recognized that hatcheries have led to somewhat smaller native salmon runs. The lesson from these case studies is to be cautious.

Effects of hatchery production on salmon growth and survival at sea has long been identified as a concern, but few studies have examined relationships. Recently, Ruggerone et al. (2003)

presented evidence showing that Asian pink salmon compete with Bristol Bay sockeye salmon, leading to reduced growth, reduced smolt-to-adult survival, and significantly smaller sockeye salmon runs (e.g., 59 million fewer Bristol Bay salmon during the recent 20 year period). In the Columbia River, Levin et al. (2001) suggested that hatchery releases of fall chinook salmon adversely impact native chinook salmon during years of low ocean productivity. In Babine Lake, British Columbia, smolt-to adult survival of sockeye salmon declined with greater numbers of smolts produced by both spawning channel and natural sources (Hilborn 1992), implying that competition and reduced growth led to lower survival.

In summary, it would likely be difficult to construct and operate a sockeye salmon hatchery in a manner that did not impact native Chignik salmon stocks. Hatchery production does not appear to be a viable alternative for enhancing harvests while maintaining production of native salmon runs.

Supplemental Feeding to Enhance Overwinter Survival

Feeding studies have been conducted under the ice of Chignik Lake to determine whether sockeye salmon would readily consume high energy commercial salmon food. Little or no feeding occurs under the ice because no food is available. Studies indicated considerable weight loss during winter even at near freezing temperatures (Ruggerone 1999). The goal of supplemental feeding is not to enhance growth, but rather to provide sufficient energy to offset the losses that occur during periods of low food availability. It was hypothesized that maintaining body condition during winter would enhance survival. Hatcheries in Alaska often feed juvenile salmon up to twice per week during winter at temperatures near 1°C (T. Meyers, ADFG Chief Pathologist, pers. comm..).

Feeding trials during winter demonstrated that sockeye salmon were attracted to the stations and they readily consumed commercial salmon food (Ruggerone 1997c, 1999). Stomach contents after feeding on commercial food during winter were considerably greater than that of sockeye salmon feeding in Black and Chignik lakes during summer (Fig. 21). The key to successful feeding is buoyant salmon food because sockeye salmon in Chignik lake are distributed close to the ice.

Some Chignik fishers have expressed concern that providing commercial feed to sockeye during winter could be detrimental because 1) unwanted hormones and antibiotics might be added to commercial feed, 2) disease may be carried by the commercial diet, and 3) feeding may disrupt salmon bioenergetics. However, commercial feed does not contain added hormones or antibiotics (unless so desired) nor do they contain disease. Ruggerone (1999) reviewed literature on the bioenergetics issue, but could find no evidence that feeding once or twice during winter would be detrimental to salmon in Chignik Lake. K. Bouwens, ADFG, raised the concern that feeding under the ice during winter might lead to “gut fungus.” However, “gut fungus” in juvenile fish is typically caused by over feeding in hatchery raceways, followed by consumption of moldy feed on the raceway bottom (T. Meyers, ADFG Chief Pathologist, pers. comm.; K. Johnson, Idaho Dept Fish and Game Chief Pathologist, pers. comm.). This situation would not occur in Chignik Lake because the fish would be fed only once or twice during winter and uneaten food would settle to the bottom where it is not readily available to sockeye salmon, which are concentrated in the upper 10 m of the water column.

The potential benefit of supplemental feeding under ice on sockeye salmon survival and adult production is unknown, but it is likely that experiments could be established to test whether supplemental feeding is beneficial to Chignik sockeye salmon. If successful, supplemental feeding might help mitigate the adverse effect of immigrating juvenile sockeye salmon from Black Lake.

<u>No Action</u>

A key question is what will happen to Chignik salmon runs if no action is taken. This is not an easy question to accurately answer, but I will attempt to do so since it is an obvious question. Salmon production in the Chignik watershed is still high and it still produces significant harvests. I believe that it will continue to produce similar runs in the near future as long as climate remains favorable.

Nevertheless, significant changes in habitat during the past 40 years have been documented, and small incremental changes will continue in Black Lake, Alec River and Black River. The shallowing of Black Lake is a natural process that will continue to evolve and influence sockeye production. Lake shallowing will be associated with greater exposure of the outlet sand spit that inhibits movement of fry from the outlet area to main lake rearing area. Lower lake level will lead to more emergent fry entering the lake outlet area rather than the main lake because Alec River flow will shift to the outlet area. Greater fry abundance in the lake outlet will likely lead to greater emigration to Chignik Lake during spring and summer, even though Black Lake remains n excellent rearing habitat for juvenile salmon during summer. Lower lake level during winter will lead to more frequent episodes of low oxygen in the water column of Black Lake, which may lead to more frequent failures of adult sockeye salmon runs.

Slowly, a larger percentage of juvenile Black Lake sockeye will become more dependent on Chignik Lake for rearing. This process is apparent now as very few sockeye salmon presently overwinter in Black Lake, whereas many overwintered there in the 1960s. Black Lake remains an excellent rearing habitat during open water periods, although its unique conditions lead to significant migrations of fry to Chignik Lake. Chignik Lagoon is currently an important rearing habitat and its importance to salmon growth and survival may increase if growth of Chignik salmon declines in response to less rearing in Black Lake. To some extent, Chignik Lagoon provides a buffer to habitat degradation in Black Lake and high rearing densities in Chignik Lake. However, habitat in Chignik Lagoon cannot mitigate winter and spring mortality in Black and Chignik lakes.

Sockeye salmon production is influenced by the interaction of climate and habitat. During the past 25 years, winter conditions have been relatively mild compared with earlier years, leading to longer growing seasons in the lakes and greater growth and survival at sea. Effects of habitat degradation may become more apparent if climate switches back to conditions of the 1950s when winters were long and cold and salmon runs were small. Winter low oxygen content in Black Lake could become a more frequent event. However, nobody knows for certain what the climate will be 10 years from now. Thus, the near-term outlook for sockeye salmon production in the Chignik watershed is continuation of the highly variable runs that occurred during the 1990s, assuming weather patterns remain similar.

The long-term outlook for Chignik salmon runs is for gradually declining runs relative to other systems. However, given the large variability in annual salmon runs, this long-term decline may not be large enough to detect without comparison of Chignik salmon runs with other sockeye runs in western and central Alaska. As described in this document, favorable climate and ocean conditions can mask the effects of adverse habitat changes in freshwater. Effects of habitat degradation on salmon runs will likely become more apparent during periods of unfavorable climate and ocean conditions, as demonstrated by the sharp decline in salmon runs in the Pacific Northwest during the past 30 years. Chignik fishers will continue to harvest sockeye salmon unless climate reverts back to conditions such as in the 1950s when runs were often less than the existing spawning escapement goals. Monitoring of channel migration in the lower Alec River, flow control features (natural sill) in the lake outlet, and winter conditions of Black Lake will be important for detection of significant rapid changes in habitat that may occur.

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Table 1. Distance from wetted lake surface to 1950s berm and elevation of berm relative to lake and FRI benchmark. Elevation measurements taken on calm day (June 18 & 19, 2001) when lake elevation was moderately low (FRI benchmark: -1.08 m to -1.01m). See Ruggerone et al. (1992) for graphic representations of shoreline slope in these areas.

	Distance: water to berm (m)	Berm base height above lake (m)	Berm top height above lake (m)	Berm elevation (m)
Western shore	374	0.66	2.68	1.60
Western shore	480	0.79	2.40	1.32
Alec Bay: Old FRI cabin	NA	1.02	2.20	1.12
Alec Bay: River delta spit	978	0.36	1.56	0.55
Head of Black River	89	0.70	1.09	0.01

Table 2. Average and maximum depth of Black Lake, 1960-1992. Note: the 1989-1992 values were standardized to a moderately high water level (-0.6 m) rather than the exceptionally high water level assumed by Ruggerone and Denman (1990). The standardization approach was employed in order to minimize the possibility of overestimating the decline in lake depth over the years since all depth observations after 1960 were substantially deeper than more recent estimates. Sources: Narver 1961, Burgner et al. 1969, Ruggerone and Denman 1990, Ruggerone et al. 1991, Ruggerone et al. 1993, Ruggerone 1999. Copy of FRI archive files also held by Ruggerone.

Date	Avg. depth (m)	Max. depth (m)	Correction factor (m)	Standardized avg. depth (m)	Standardized max. depth (m)	Source
30-Jun-60	2.6	6.4	0	2.6	6.4	Narver 1961; FRI Archive
17-Sep-78	2.1	4.1	0.2	2.3	4.3	FRI Archive
17-Aug-83	1.5	3.4	0.5	2.0	3.9	FRI Archive
15-Jun-89	1.7	3.8	0.23	1.93	4.2	Ruggerone et al. 1991
25-Feb-90	1.26	2.9	0.7	1.96	3.8	Ruggerone et al. 1991
15-Jun-92	1.94	4.1	0	1.94	4.1	Ruggerone et al. 1993
1989-1992 v. 1960:	-0.97	-2.80		-0.66	-2.37	
	-37%	-44%		-25%	-37%	

Table 3. Comparison of Black Lake elevation during 1949 (also shown in 1963 topographic map) and June 2001 based on the USGS benchmark at Hydro Pt. The 1949 elevation is 1.57 ft higher than the maximum recorded flood level in the 1990s (FRI lake level = -0.11 m on July 23, 1993; next highest level was -0.21 m on June 6, 1993; Ruggerone 1994). The USGS measurements were reported to the nearest foot, therefore calculations were made assuming maximum rounding error (1 ft). A third set of calculations were made assuming maximum rounding error and moderately high lake conditions during the 1949 survey. Data source for 1949 data: USGS topographic map; web page.

Year	Elevation above sea level (m)	USGS Benchmark (m)	FRI benchmark (m)	Distance: USGS benchmark to lake (m)
1949 (avg.)	8.54	11.28	0.37	-2.74
1949 (max error)	8.38	11.43	0.06	-3.05
1949 (max error & moderately high water)			0.46	-2.65
19-Jun-01		11.28	-1.01	-4.1
	moderately high water:		-0.60	-3.7
Average USGS values:				
Elevation Change (m):				-1.38
Volume Change (%):				-49%
Maximum rounding error:				
Elevation Change (m):				-1.07
Volume Change (%):				-44%
Maximum rounding error & moderately high water (-0.6 m):				
Elevation Change (m):				-0.67
Volume Change (%):				-23%

Table 4. Changes in the water volume of Black Lake from 1963 to 1992 based on lake elevations ranging from –0.10 m to –1.55 m. Two sets of calculations are shown: 1) assumes average water conditions and no rounding error by USGS (values reported to nearest foot); 2) assumes maximum rounding error (1 ft total). Volume estimates do not account for changes in lake surface area. Extreme shallow areas representing on average 13% of area were excluded from calculations. Sources: Ruggerone 1994, 1999, unpublished analysis.

Lake level (FRI bench mark)	Volume (m^3)	% of Maximum	% Loss v. 1949	% Loss relative to -0.10 m elevation	ave depth (m) (w/o shallowest 13%)	Comment
		1949 benchmark and 1963 lake elevation				
0.37	112,778,700	100%	0%		3.18	1949 benchmark; 1963 topo; relative lake level unknown
0.06	101,784,550	100%	0%		2.87	Assumes maximum rounding error by USGS
		Recent Period				
1) Lake volume range based on average USGS measurements:						
-0.1	96,110,150	85%	15%	0%	2.71	1990s maximum recorded flood level
-0.3	89,017,150	79%	21%	7%	2.51	High water
-0.6	78,377,650	69%	31%	18%	2.21	Typical spring, but moderately high
-0.9	67,738,150	60%	40%	30%	1.91	Moderately low; common late summer and early fall
-1.1	60,645,150	54%	46%	37%	1.71	Low water
-1.4	50,005,650	44%	56%	48%	1.41	Low water (winter, fall)
-1.55	44,685,900	40%	60%	54%	1.26	Exceptionally low water (9/2002)
2) Lake volume range based on maximum USGS rounding error:						
-0.1	96,110,150	94%	6%		2.71	1990s maximum recorded flood level
-0.3	89,017,150	87%	13%		2.51	High water
-0.6	78,377,650	77%	23%		2.21	Typical spring, but moderately high
-0.9	67,738,150	67%	33%		1.91	Moderately low; common late summer and early fall
-1.1	60,645,150	60%	40%		1.71	Low water
-1.4	50,005,650	49%	51%		1.41	Low water (winter, fall)
-1.55	44,685,900	44%	56%		1.26	Exceptionally low water (9/2002)

Table 5. Estimates of bank erosion along the upper reach of the south channel of Alec River, 1992-2003.

		Minimum distance from stake to river bank (m)												Present	Total	Change per
Stake	Location	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2002	2003	condition	change (m)	year (m)
Wye Pt																
1	Wye Pt.			4.00	3.40	3.40	2.96	2.80	1.20	1.20	missing	missing		sunken	-2.80	-0.35
2				4.40	3.10	3.00	2.60	2.53	1.70	1.60	1.17	1.17	1.17	at river	-3.23	-0.29
3	(near S. channel)			3.25	3.00	3.00	2.20	1.78	0.80	0.80	ND	0.80	0.80	sunken	-2.45	-0.25
					-0.72	-0.03	-0.55	-0.22	-1.14	-0.03	-0.43	0.00	0.00		-2.83	-0.30
Straight channel																
1	(rebar)	3.3	3.10	2.85	2.53	2.20	1.10	1.08	0.60	0.60	0.60	0.00	0.80	new 2003	-3.30	-0.28
2	Discharge area		2.37	2.30	1.95	1.30	0.90	0.90	0.90	0.13	0.13	0.00	0.62	new 2003	-2.37	-0.22
				-0.16	-0.34	-0.49	-0.75	-0.01	-0.24	-0.39	0.00	-0.36			-2.84	-0.25
River bend																
1	upriver		8.30	7.65	7.60	5.40	5.32	5.32	5.35	5.35	5.35	5.20	5.20	vertical	-3.10	-0.26
2			10.30	9.95	9.08	8.20	7.80	7.80	7.10	6.65	6.65	6.60	6.10	vertical	-4.20	-0.35
3			10.30	9.75	9.70	9.70	9.50	9.45	8.90	8.60	8.60	6.90	6.47	sloping	-3.83	-0.32
4			15.10	13.95	13.70	13.40	13.40	12.15	12.15	12.15	12.15	12.15	12.15	undercut	-2.95	-0.25
5			12.50	12.50	11.55	11.40	11.00	10.70	10.50	10.15	10.15	9.70	8.95	sloping	-3.55	-0.30
6			9.20	8.75	8.70	7.60	7.35	7.40	6.75	6.75	5.49	5.40	5.20	undercut	-4.00	-0.33
7	down river		6.70	6.60	6.43	6.25	5.90	5.80	6.10	3.50	3.50	3.50	3.50	beaver tunnel	-3.20	-0.27
				-0.46	-0.34	-0.69	-0.24	-0.24	-0.25	-0.53	-0.18	-0.35	-0.27		-3.55	-0.30
Left bank Pt.																
1	Lt. bank Pt.	2.5	2.50	2.20	1.90	1.80	1.70	1.40	1.15	1.10	1.09	missing	missing		-1.40	-0.13
			0.00	-0.30	-0.30	-0.10	-0.10	-0.30	-0.25	-0.05	-0.01					

Table 6. Sediment transport estimates in the south channel of the Alec River during two high water event (Ruggerone et al. 1993).

Date	South channel flow (cfs)	Bottom sediment transport (m^3/day)	Suspended sediment transport (m^3/day)	Notes
6/5/92	1074	47	138	subsiding flow
6/28/92	652	106	NA	rising flow

Table 7. Summary of historical sockeye smolt catch data for Black River. All fish captured by fyke net, except in 1993 both fyke net and screw trap were used. Sources: FRI archives, Ruggerone (1994).

Year	Date	Location	Hours fished	Number of sockeye fry	Number of sockeye smolt	Number of sockeye per hr fry	Number of sockeye per hr smolt
1960	16-Jun	near Chiaktuak Cr.	4.75	152	117	38.0	29.25
1960	22-Jun	near Chiaktuak Cr.	7.50	3,000	40	750.0	10
1960	26-Aug	near Chiaktuak Cr.	3.75	4	0		
1960	5-Sep	near Chiaktuak Cr.	3.50	0	0		
1961	18-Jun	near Chiaktuak Cr	2.00	5,000	450	2500.0	225.0
1961	26-Jun	near Chiaktuak Cr	2.00	200	107	100.0	53.5
1962	20-Jun	near Chiaktuak Cr	4.00	44	31	11.0	7.8
1963	14-Jun	near Chiaktuak Cr	3.75	420	0	112.0	0.0
1963	25-Jun	near Chiaktuak Cr	6.25	52	40	13.0	10.0
1964	16-Jun	near Chiaktuak Cr	2.00	53	32	26.5	16.0
1964	18-Jun	near Chiaktuak Cr	1.25	0	7	0.0	5.6
1964	26-Jun	near Chiaktuak Cr	4.00	14	0	3.5	0.0
1964	27-Jul	near Chiaktuak Cr	ND	221	3		
1965	14-Jun	near Chiaktuak Cr	4.00	30	95	7.5	23.8
1965	15-Jun	near Chiaktuak Cr	4.00	34	92	8.5	23.0
1971	21-Jun	lower river	54.25	0		0.0	0.0
1971	23-Jun	lower river	40.50	1		0.3	0.0
1971	25-Jun	lower river	71.10	0		0.0	0.0
1971	25-Jun	lower river	71.00	0		0.0	0.0
1972	26-Jun	lower river	17.50	2		0.5	0.0
1972	29-Jun	lower river	47.50	1		0.3	0.0
1974	26-Jun	above Chiaktuak Cr	24.66	27	0	6.8	0.0
1974	28-Jun	above Chiaktuak Cr	35.50	10	0	2.5	0.0
1974	29-Jun	below Chiaktuak Cr	35.75	4	0	1.0	0.0
1974	30-Jun	below Chiaktuak Cr	23.75	342	0	85.5	0.0
1992	May	below Chiaktuak Cr	160	3,589	35	22.4	0.22
1992	June	below Chiaktuak Cr	270	19,730	224	73.1	0.83
1993	May	below Chiaktuak Cr	260	2,786	12	10.7	0.05
1993	June	below Chiaktuak Cr	300	8,062	77	26.9	0.26

Table 8. Catch rates of juvenile sockeye salmon in Black and Chignik lakes, February 1992-1998. Values are number captured per night per trap in waters less than 4 m deep (± 1 SE). Chignik Lake catches were made in the Hatchery Beach, Clark Bay, and Outlet areas, which were regularly sampled each year; see annual reports for catches in other areas and at greater depths. Unstable, drifting ice severely reduced catch efficiency in 1993. During 1998, unsafe travel conditions on Black Lake prohibited daily checking of traps.

	Black Lake		Chignik Lake	
Year	Trap Nights	Salmon/night/trap	Trap Nights	Salmon/night/trap
1992	55	0	43	14.3±1.9
1995	39	0	39	9.7±2.0
1996	20	0	26	0.6±2.3
1997	29	0	42	4.9±1.9
1998	80	0	35	14.1±1.70
Avg.	45	0	37	8.7±2.7

Table 9. Food habits of sockeye, coho and chinook salmon and Dolly Varden char in Chignik Lake during February 1990.

	Sockeye	Coho	Chinook	Char
No. sampled	161	90	17	66
Ave. length (mm)	63	93	76	117
Range (mm)	45-88	47-144	61-84	80-157
Ave. weight (g)	2	9.3	4.3	15.5
% feeding	5	24	12	2
Total prey wt. (mg)	0.1	2.2	9.4	12.7
Geom. prey wt. (mg)	<0.1	0.2	<0.1	<0.1
% of body wt.	<0.01	0.04	0.22	0.07
Prey weight (mg)				
Chironomid larvae	<0.1	0.8	0	0
Stonefly nymph	0	<0.1	0	0
Insecta	<0.1	0.3	<0.1	0
Oligocheate	0	0	9.4	0
Bivalve	<0.1	0.1	0	0
Copepod	<0.1	0	0	0
Gastropod	0	0	0	0
Fish	0	0.7	0	12.7
U.I.	<0.1	0.2	0	0
Debris	0.1	2.7	2.6	5.5

Table 10. Food habits of juvenile sockeye salmon and other fishes in Chignik Lake during February 1992. Total prey weight given as mean ± standard error.

	Sockeye	Coho	Chinook	Char	3-spine stickleback	Sculpin
No. sampled	134	109	19	48	58	51
Ave. length (mm)	67.6	90.3	75.3	98.8	62.2	79.5
Range (mm)	55	75	18	107	31	46
Ave. weight (g)	2.8	7.9	4.3	10.4	2.6	8.4
% feeding	1.5	9	0	22.9	32.8	37.3
Total prey weight (mg)	0.1±0.05	3.1±1.8	0	13.1±4.4	9.8±2.8	17.8±5.0
Geom. prey weight (mg)	0	0.2	0	1.3	1.6	2.4
‰ of body weight	0	0.3	0	1.6	3.6	2.2
Prey weight (mg)						
Chironomid larvae	0	0	0	0	0	0
Caddisfly larvae	0	0.5	0	12.9	0	1.4
Oligochaete	0	0	0	0	0	0
Bivalve	0	0	0	0	0	0.6
Gastropod	0	0	0	0	0	7.1
Copepod	0	0	0	0	0	0
Isopod	0	0	0	0	0	2
Fishes	0	1.6	0	0	0	0
Unidentified Insecta	0	0	0	0.1	0	0
Unidentified Organic	0.1	1	0	0	9.8	6.7
Inorganic	0	0.2	0.4	0.5	0.9	1.9

Table 11. Food habits of juvenile sockeye salmon and other fishes during February 1995. The sockeye and char were captured in Chignik Lake; coho were captured in Black Lake. Total prey weight given as mean ± standard error.

	Sockeye	Char	Coho
No. sampled	94	3	30
Avg. length (mm)	61.7	106.3	97.1
Range (mm)	40-103	78-128	
Avg. weight (g)	2.4		11.1
% feeding	30	0	73
Total prey weight (mg)	0.2±0.1	0	62.8±16.1
Geom. prey weight (mg)	0.1	0	14.5
% of body weight	0.01	0	0.6
Prey weight (mg)			
Chironomid larvae	<0.1	0	23
Caddis fly larvae	0	0	0.9
Bivalve	0	0	0.3
Gastropod	0	0	0
Copepod (Cyclops)	0.2	0	0
Isopod	0	0	0
Fishes	0	0	31.1
Unidentified Insecta	<0.1	0	5.3
Unidentified Organic	0	0	0
Inorganic (rocks)	0.4	0	0

Table 12. Comparison of sockeye consumption of commercial salmon food during winter 1998 with observed food consumption in Chignik and Black lakes during summer 1993. Ruggerone (1999).

Date	n	Sockeye Weight (g)	% feeding	Food in stomach (mg)	Food as % Body Wt.	Caloric Content	Calories per gram of fish
			Winter Feeding with Commercial Food				
2/6/98	48	2.7	13%	7.1	0.3%	10	3.4
2/7/98	10	2.9	80%	46.7	1.6%	65	22.5
2/8/98	21	2.2	57%	47.3	2.1%	66	28.2
			Summer Food Habits in Chignik Lake				
1993	111	3.22	76%	17.1	0.5%	10	3.2
			Summer Food Habits in Black Lake				
1993	175	3.24	87%	64.5	2.0%	38	12.2

Table 13. Relative changes in sockeye salmon harvests (millions) in western and central Alaska. Analysis updated from Rogers (1995).

	Salmon harvest (millions)				Percent change			
	1	2	3	4	From 1	From 2	From 1	From 1
Location	64-76	77-88	90-02	77-02	to 2	to 3	to 3	to 4
Alaska Peninsula								
Chignik Inshore	0.69	1.55	1.65	1.59	123	7	138	128
Igvak x .80	0.10	0.19	0.21	0.19	96	7	110	96
Stepovak x .80	0.04	0.11	0.10	0.10	193	-9	166	169
Chignik w/Interceptions	0.83	1.85	1.97	1.88	123	6	136	126
South Peninsula	0.61	1.78	2.28	2.06	191	28	271	237
North Peninsula	0.30	1.75	2.29	2.02	488	31	668	578
Ugashik	0.29	2.12	2.71	2.45	624	28	829	737
Egegik	1.18	4.26	9.65	7.02	262	127	720	497
Naknek	0.95	2.21	3.28	2.74	134	48	247	190
Mainland								
Kvichak	4.02	6.64	5.23	6.12	65	-21	30	52
Wood River	0.49	1.62	2.48	2.04	228	53	404	314
Nushagak District	0.85	3.42	4.47	3.90	304	30	426	360
Togiak	0.15	0.40	0.41	0.39	162	3	169	157
Bristol Bay Total Inshore	7.39	18.87	25.25	22.43	155	34	241	203
excl. Kvichak	3.37	12.22	20.02	16.31	263	64	494	384
Kodiak (excl. Fraser Lk & enha	0.47	1.51	3.85	2.67	222	154	717	468
Upper Cook Inlet	1.01	3.68	3.39	3.59	263	-8	234	254
Alaska Total (excl. Chignik)	11.64	30.61	42.01	36.78	163	37	261	216
excl. Kvichak	7.62	23.97	36.78	30.66	215	53	383	303

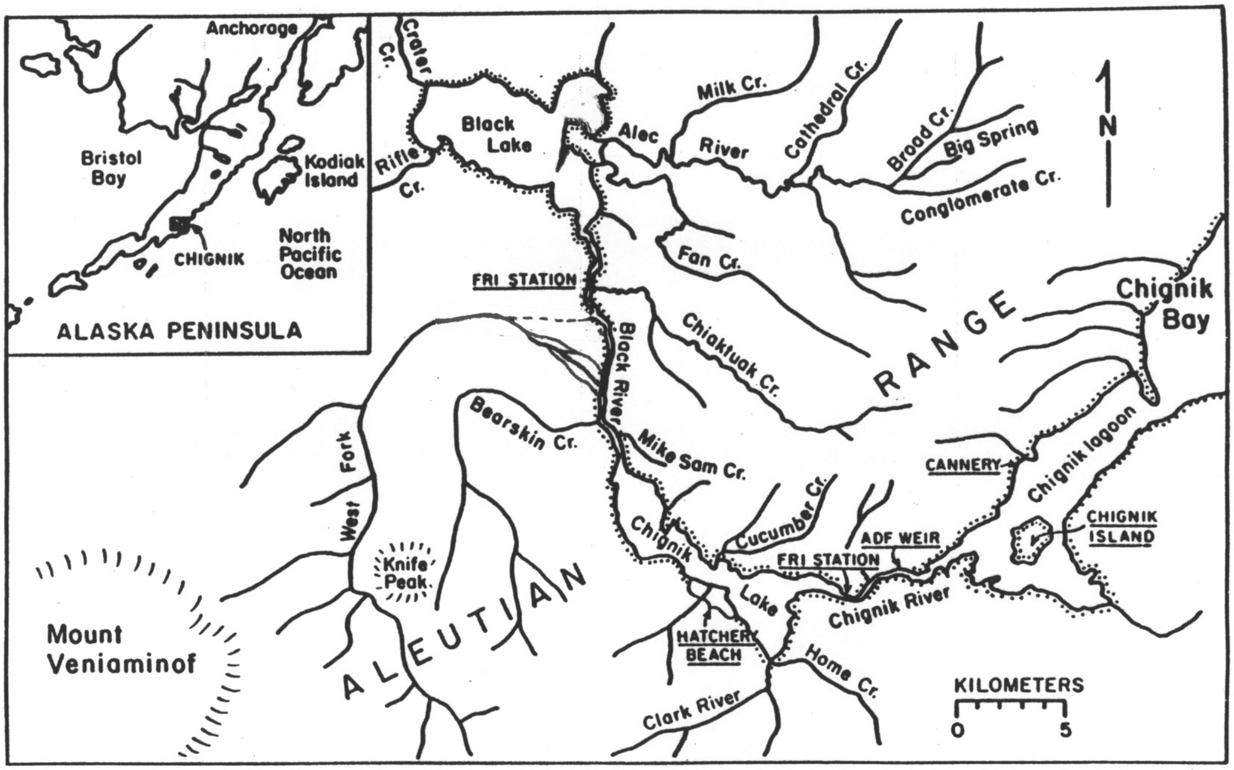

Fig. 1. Map of the Chignik watershed.

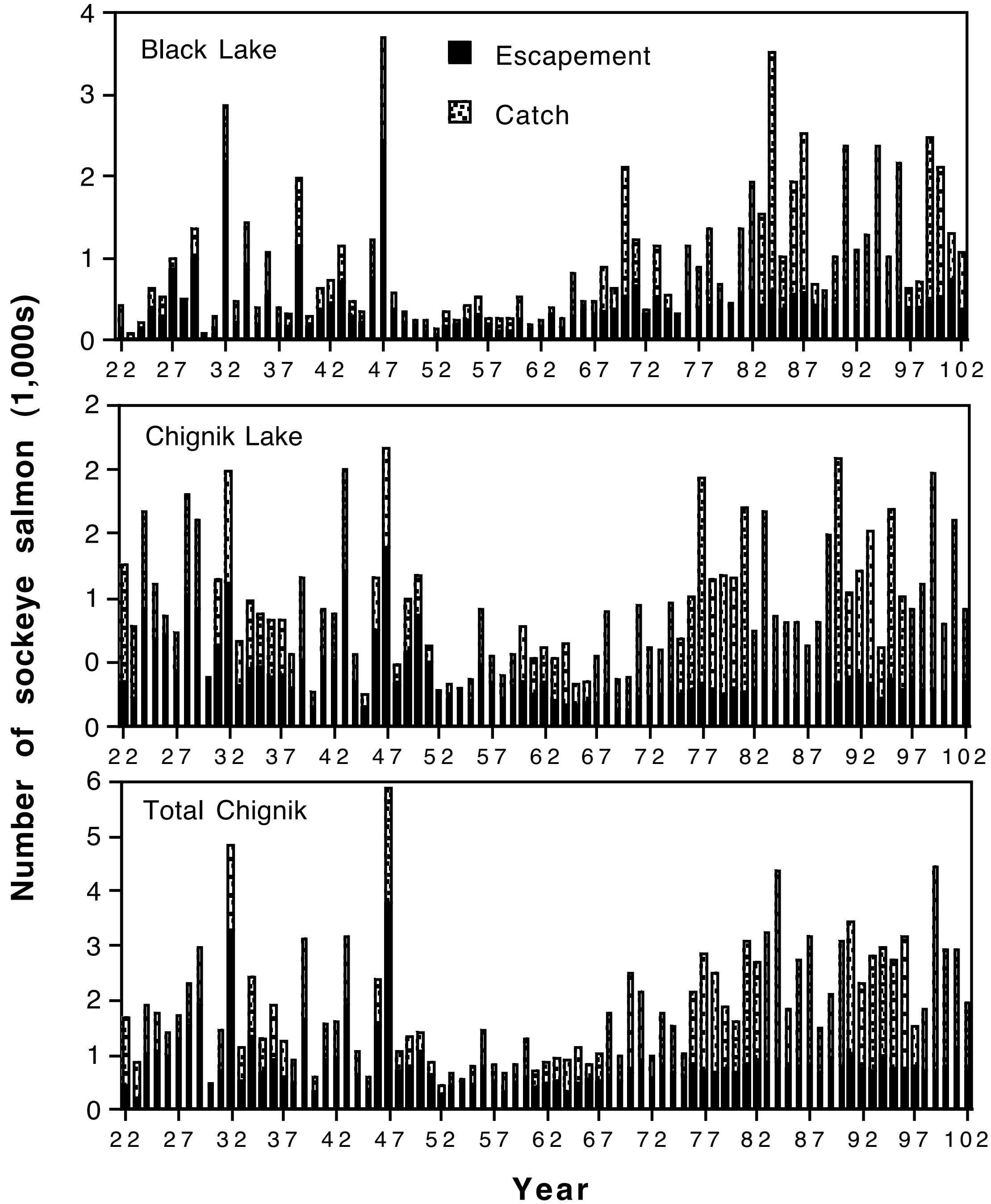

Fig. 2. Catch, spawning escapement and total run of Chignik Lake and Black Lake sockeye salmon, 1922-2002. Catch values include Cape Igvak and Southeast Mainland interception harvests of Chignik salmon prior to July 25 (i.e., 80% of total; beginning in 2002 the pre-July 26 sockeye salmon catch near Cape Igvak was assumed to be 90% Chignik-bound salmon). Data Source: K. Bouwens, ADFG.

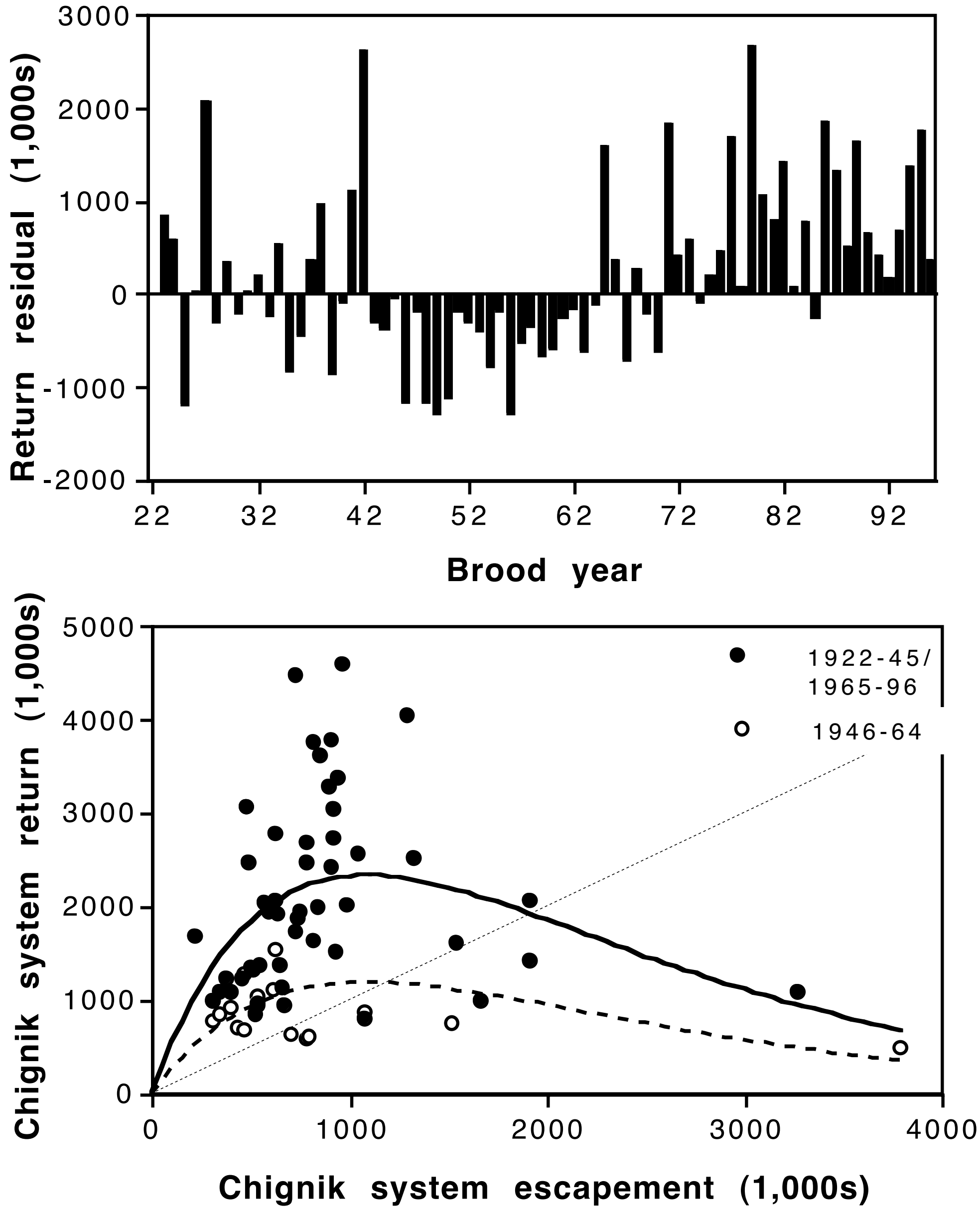

Fig. 3. Time series of residual (observed - predicted) return per spawner values for Chignik sockeye salmon, brood years 1922-1996 (upper graph). Observed sockeye returns produced by the parent spawning escapement during two periods of productivity (lower graph). Residuals and regressions based on Ricker regressions. Source: Ruggerone et al. 1999, including updated values.

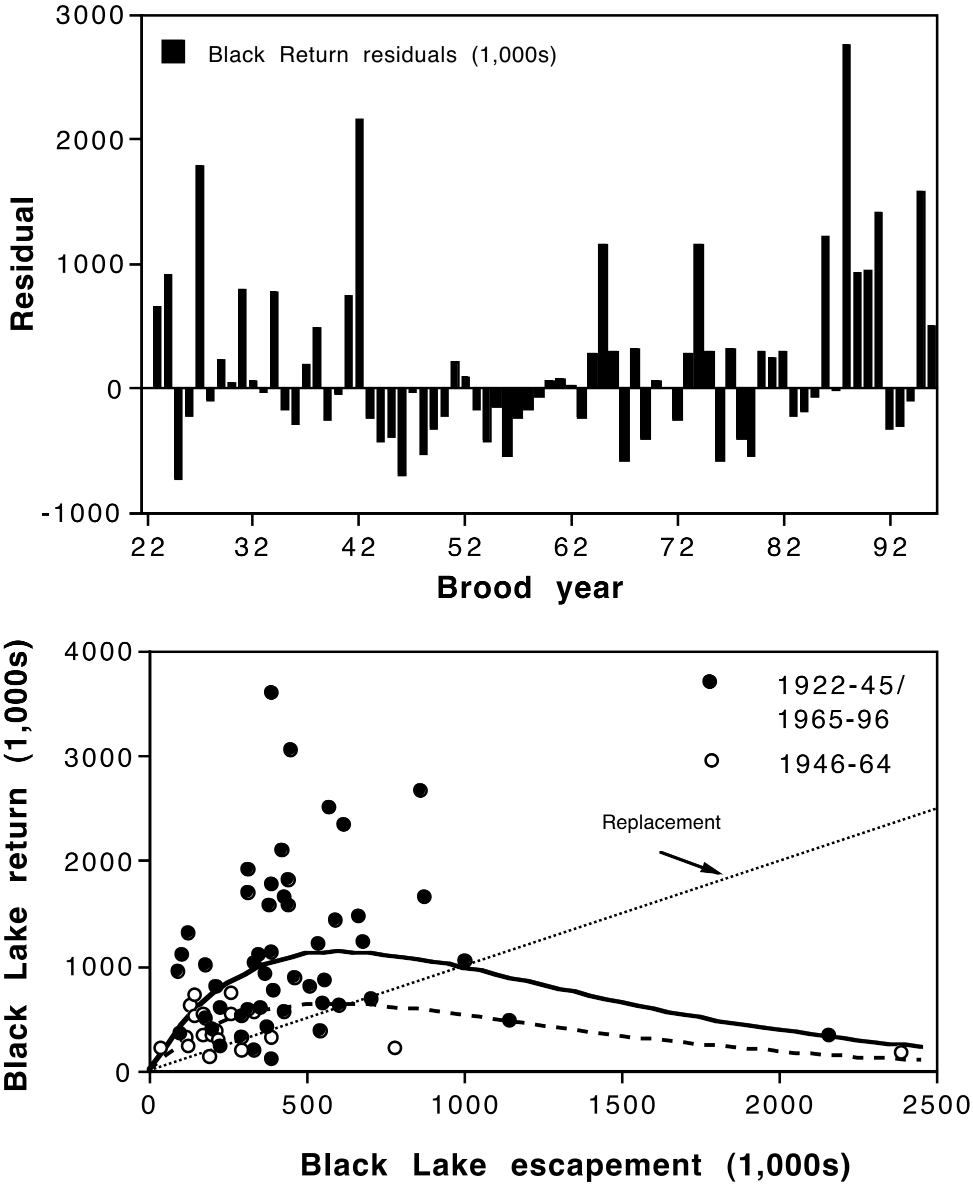

Fig. 4. Time series of residual (observed - predicted) return per spawner values for Black Lake sockeye salmon, brood years 1922-1996 (upper graph). Observed sockeye returns produced by the parent spawning escapement during two periods of productivity (lower graph). Residuals and regressions based on Ricker regressions. Source: Ruggerone et al. 1999, including updated values.

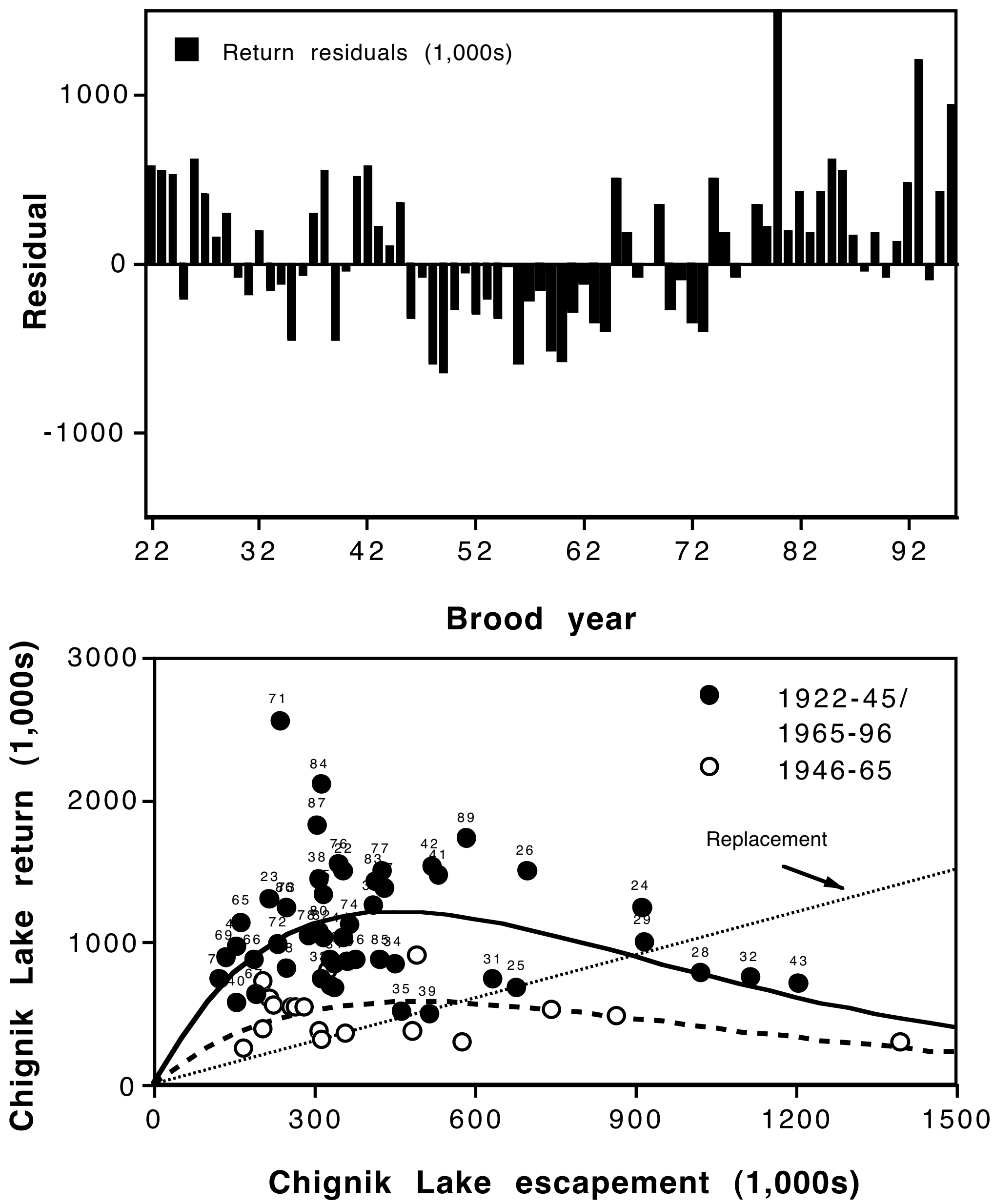

Fig. 5. Time series of residual (observed - predicted) return per spawner values for Chignik Lake sockeye salmon, brood years 1922-1996 (upper graph). Observed sockeye returns produced by the parent spawning escapement during two periods of productivity (lower graph). Residuals and regressions based on Ricker regressions. Source: Ruggerone et al. 1999, including updated values.

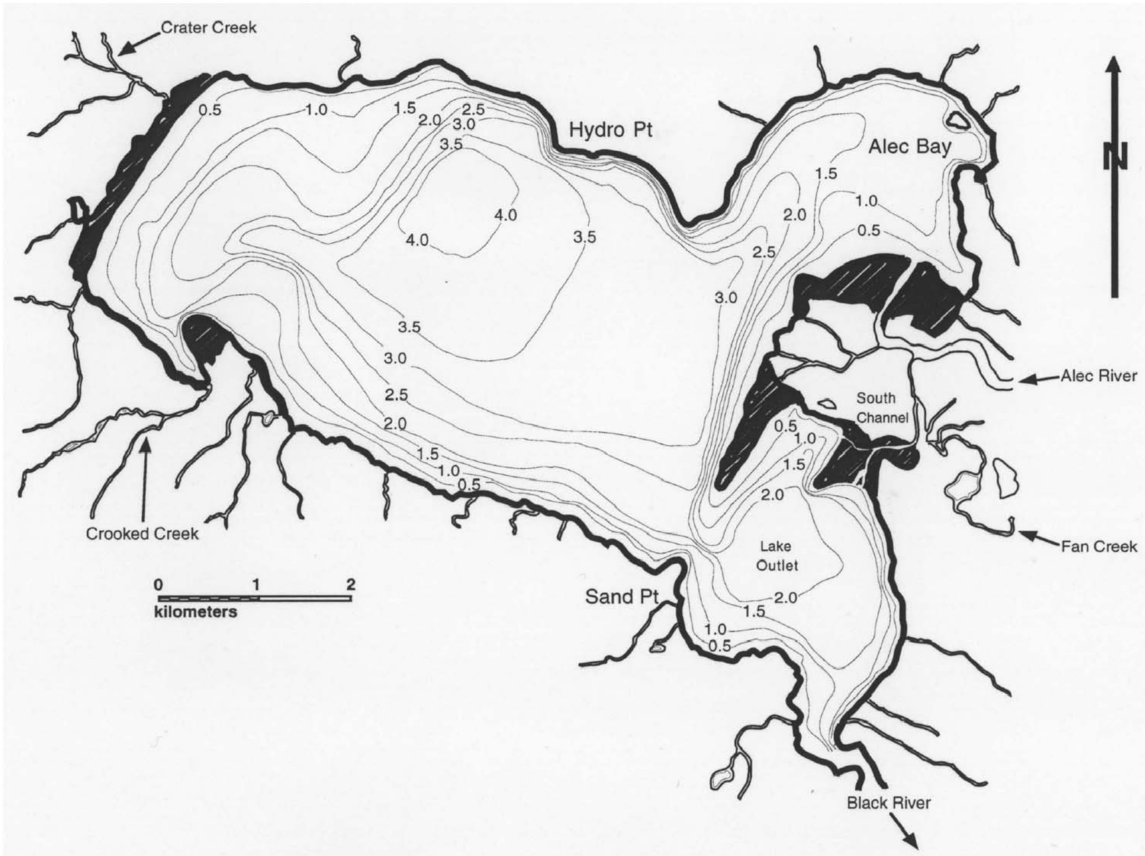

Fig. 6. Depth contours of Black Lake (0.5 m intervals). Measurements taken during June 1992; water elevation: -0.6 m. Shaded regions identify exposed areas that were underwater in the 1950s (Ruggerone et al. 1993).

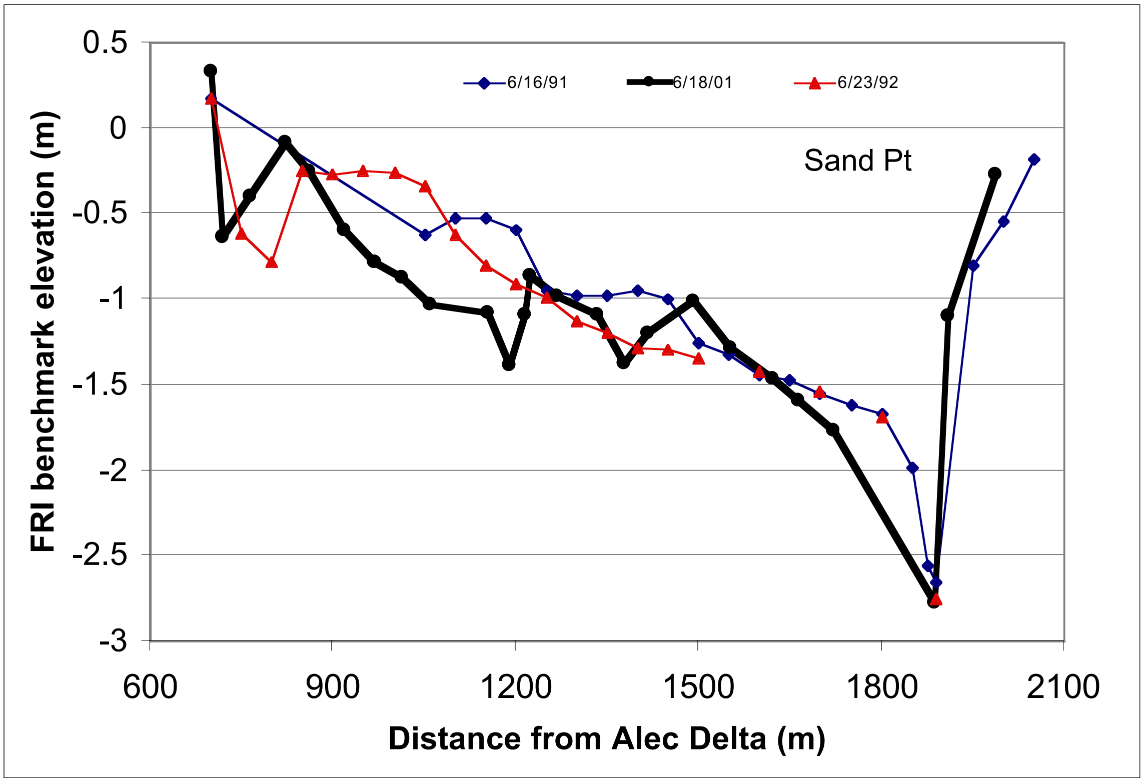

Fig. 7. Elevation of the Black Lake outlet sandspit during 1991, 1992, and 2001 (Ruggerone et al. 1992, 1993). The sandspit area between the Alec River delta and 700 m is relatively flat and elevation is lower than 0.3 m. In 2001, vegetation was present up to 860 m from the delta. Water surface elevation at the FRI benchmark was –0.80 in 1991, -0.68 in 1992, and –1.07 in 2001.

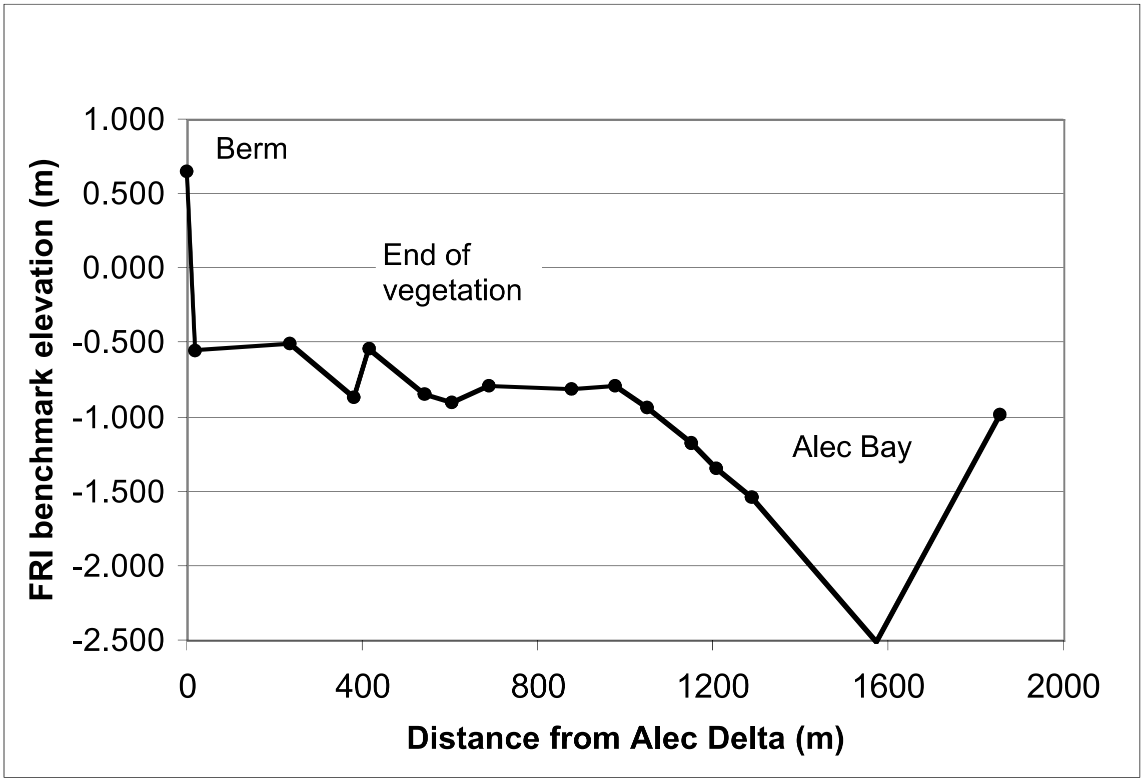

Fig. 8. Elevation of the Alec Bay sandspit during June 2001. Vegetation was present up to 380 m from the delta. Water surface elevation at the FRI benchmark was –0.91 after adjusting for a northwest wind.

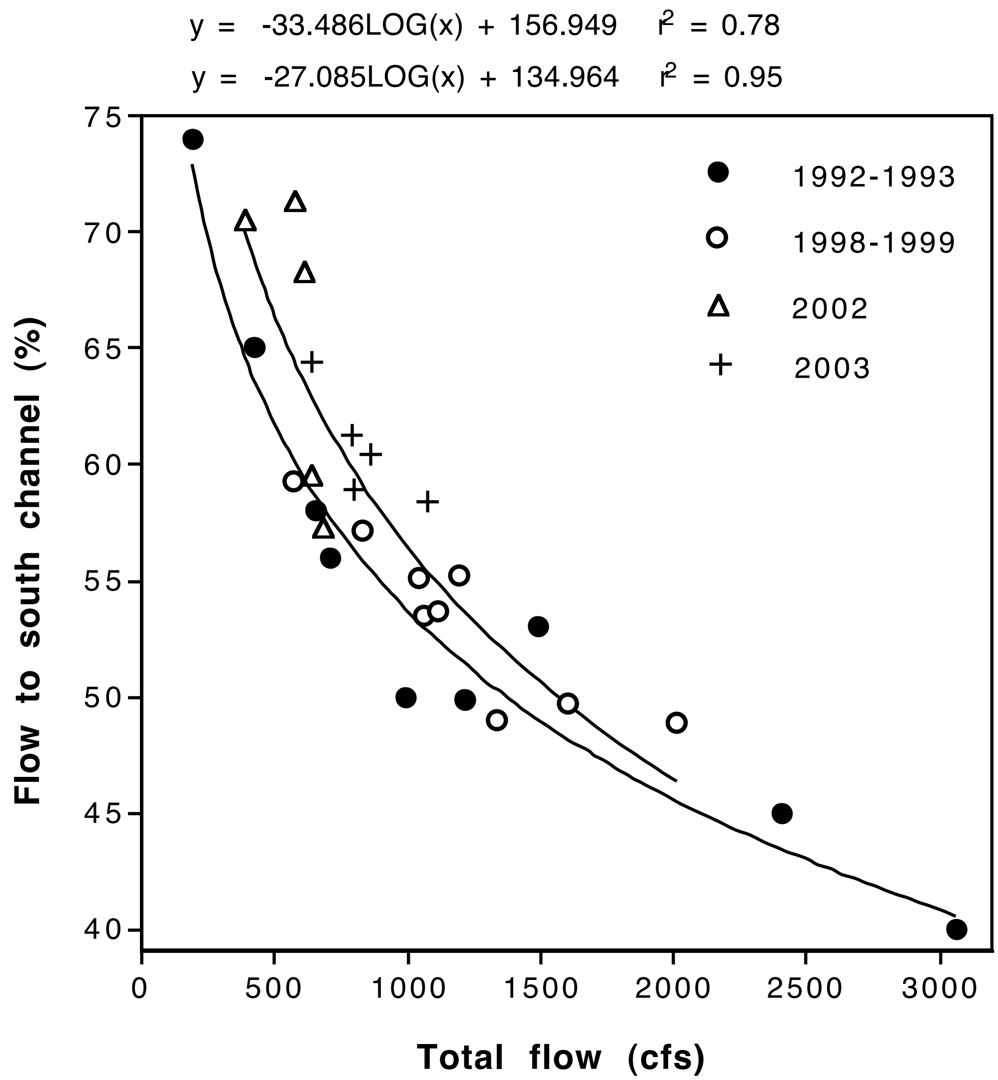

Fig. 9. Percentage of Alec River flow entering the south channel in relation to total flow in Alec River during 1992-1993, 1998-1999, and 2002-2003. Lower regression line represents 1992-1993 data and upper line represents 1998-2003 data.

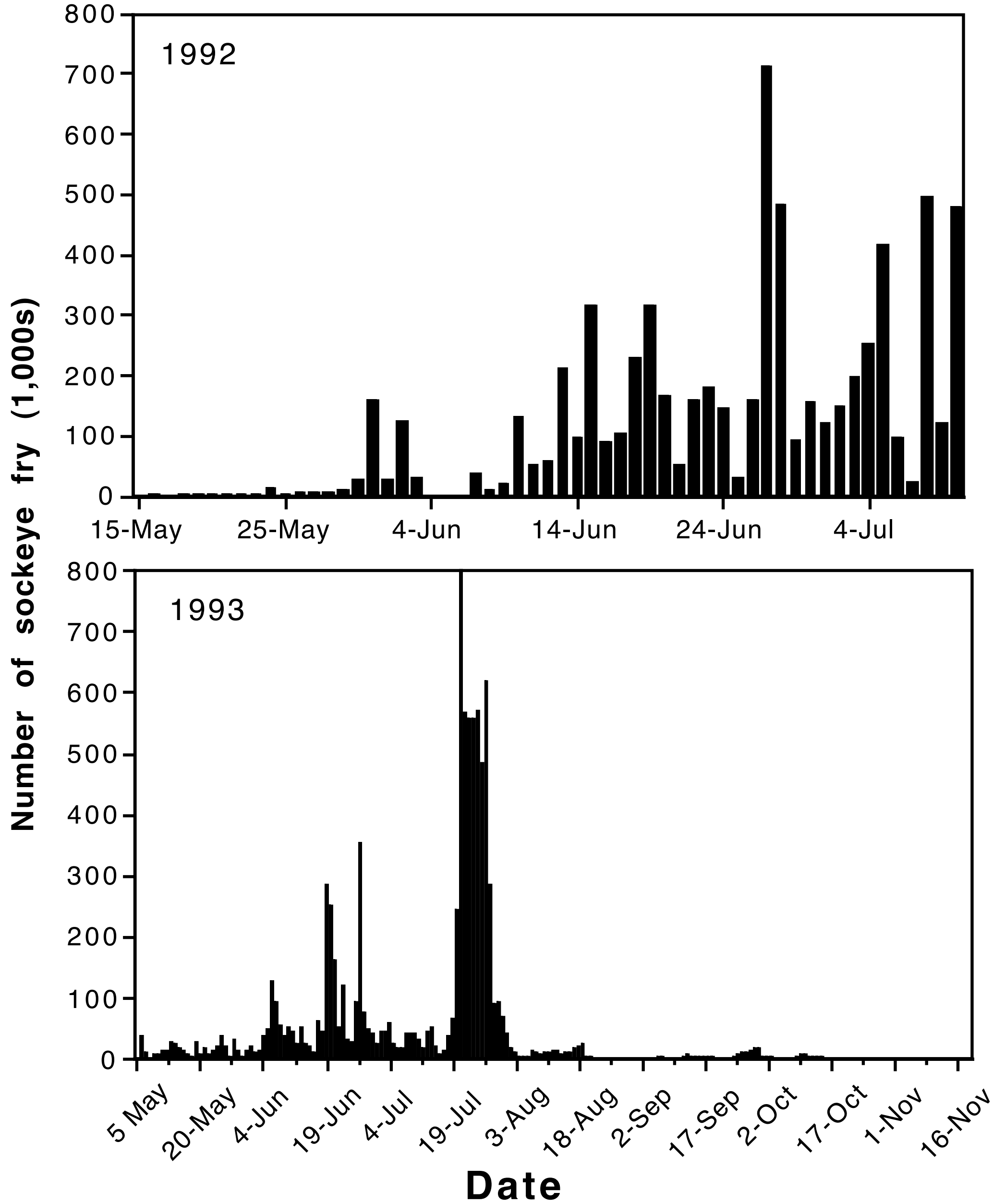

Fig. 10. Time series of total daily sockeye salmon fry emigration from Black Lake during May 15 - July 10, 1992 and from May 6 - November 19, 1993. Total emigration estimates based on mark and recapture studies. During August 30-Sept. 4, 1992, daily migrations averaged 9.8 fry per day. Sources: Ruggerone et al. 1993, Ruggerone 1994.

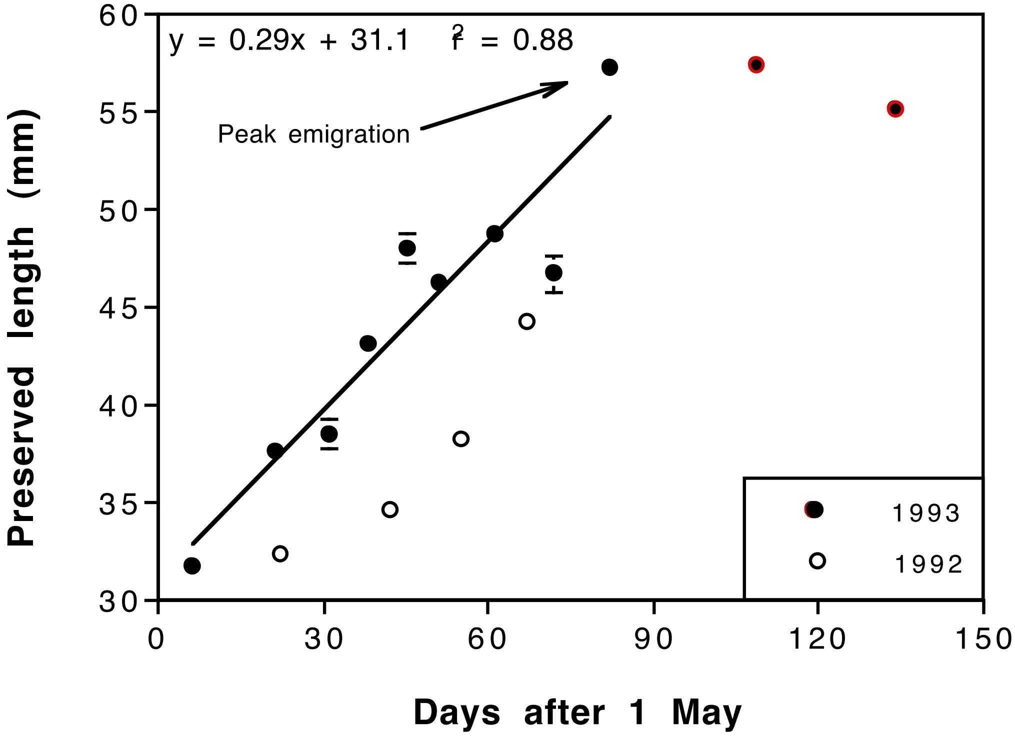

Fig. 11. Time series of mean length (±SE) of fry emigrating from Black Lake during 1993 and 1992 (captured in Black River traps). Regression line represents 1993 data during May through July; size did not change in August and early September. Small SE values (<±0.8 mm) are hidden by the data point. Source: Ruggerone 1994.

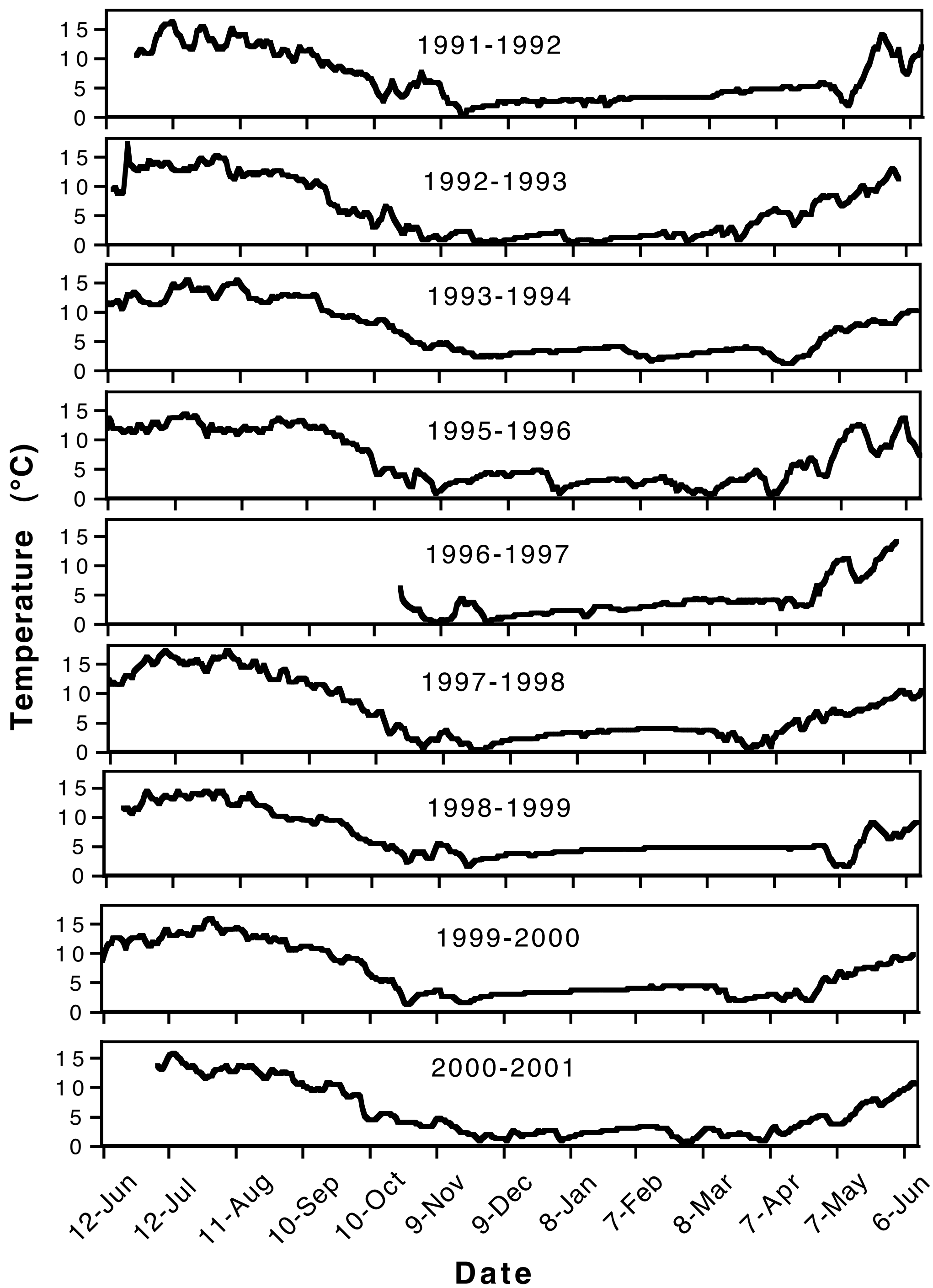

Fig. 12. Time series of mean daily water temperatures in Black Lake, 1991-2001. Thermograph set approximately 0.5 m from bottom near Hydro Pt, the deepest area of the lake.

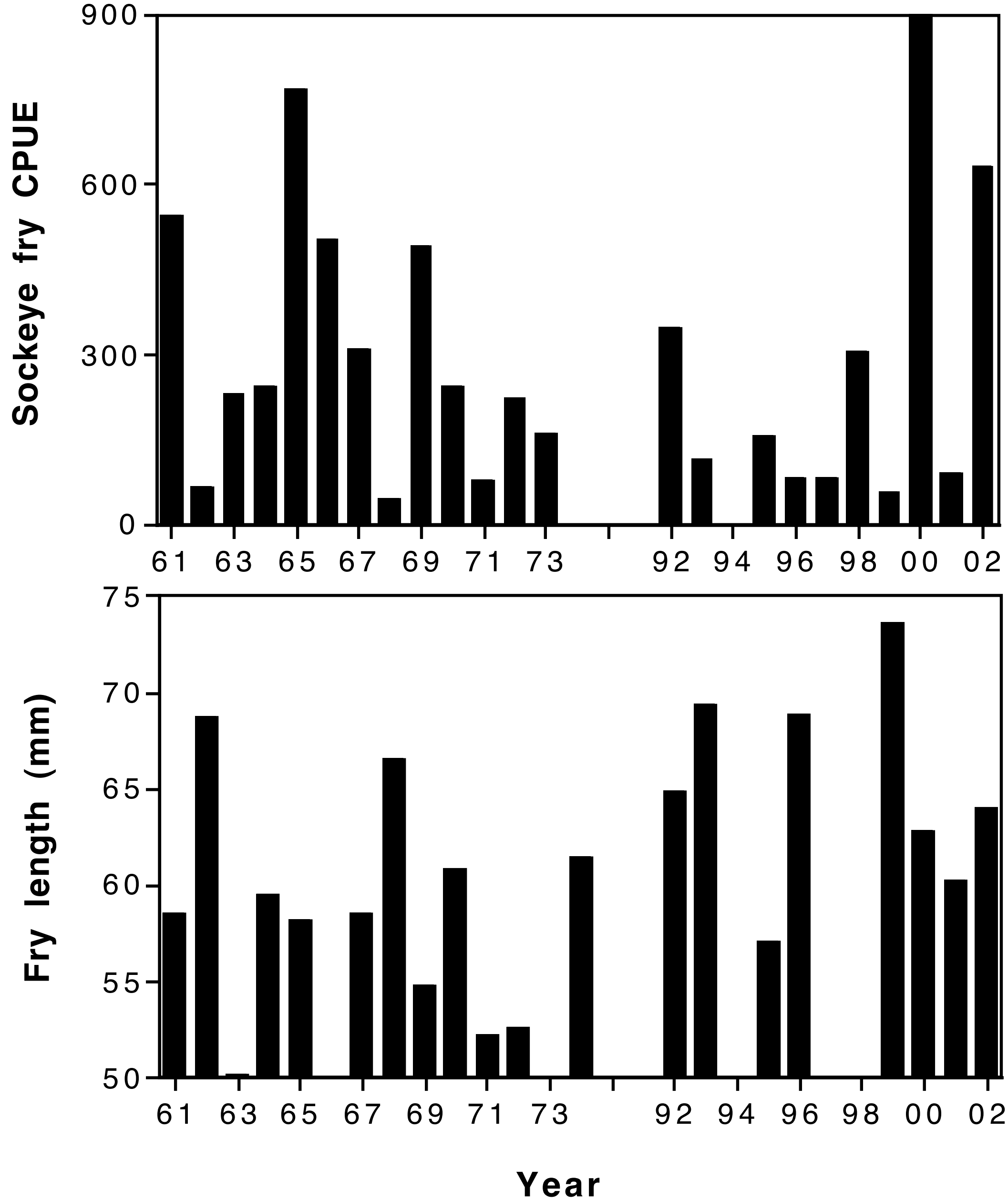

Fig. 13. Time series of sockeye salmon fry townet catches and lengths in Black Lake during late August and early September, 1961-2002. No tow-netting records for Black Lake during 1973-1991 were available. Tow-netting in 1994 (not shown) used a single boat townet, which is not comparable to the two-boat operation employed in most years.

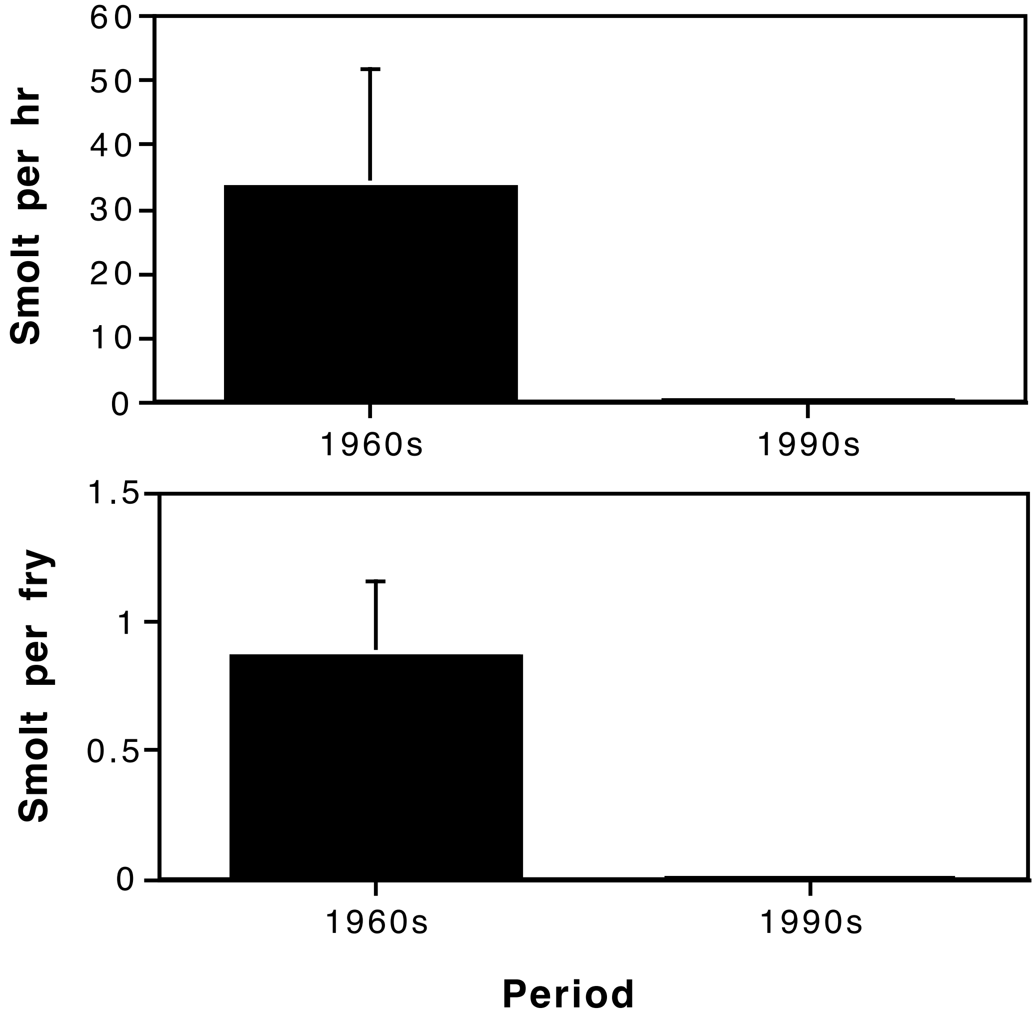

Fig. 14. Comparison of sockeye salmon smolts capture rates in Black River during the 1960s and 1990s.

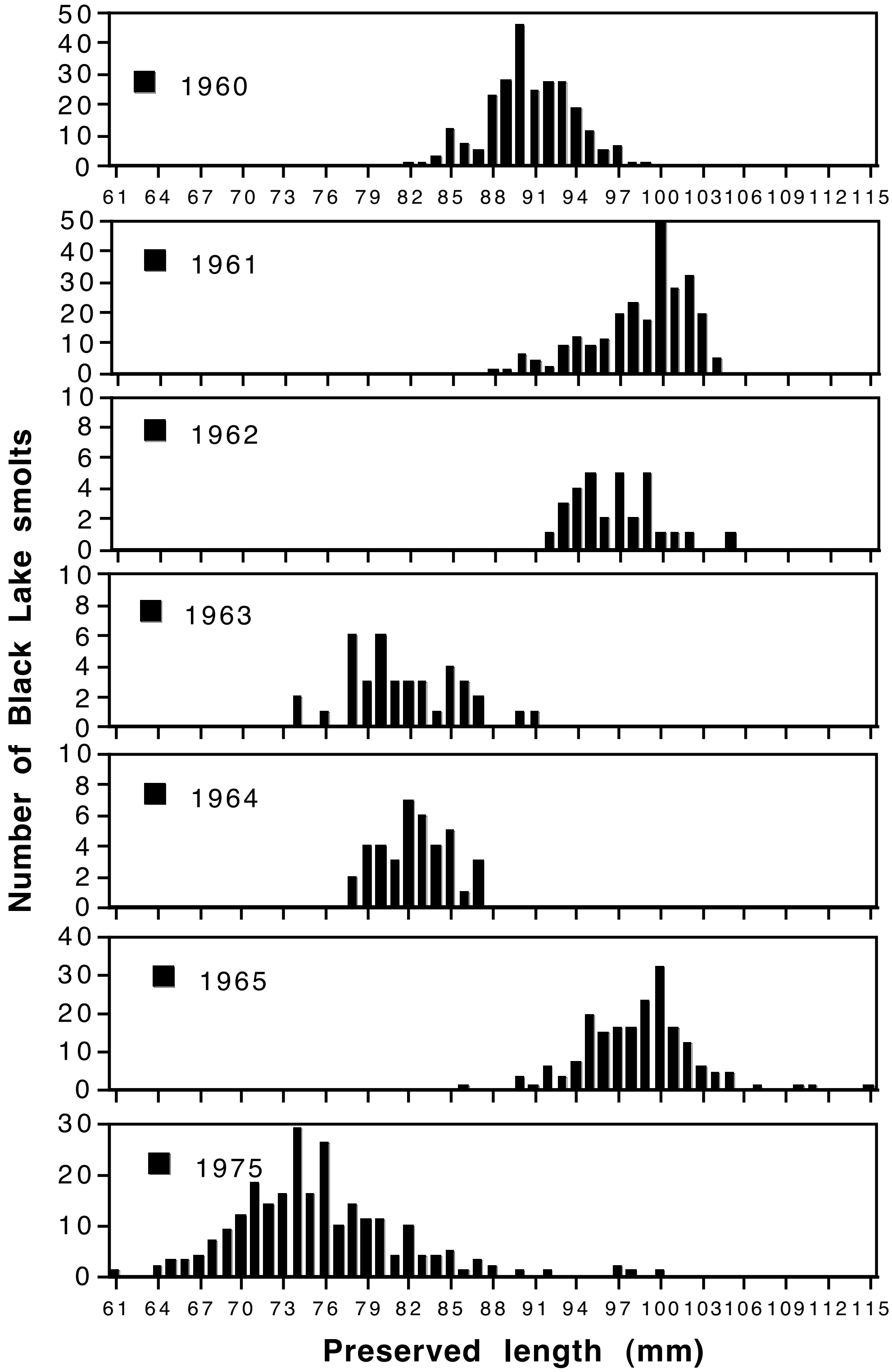

Fig. 15. Length frequency distributions of sockeye salmon smolts captured in Black River, 1960-65 and 1975. CPUE data not available for 1975. Sources: Ruggerone 1994, FRI archive.

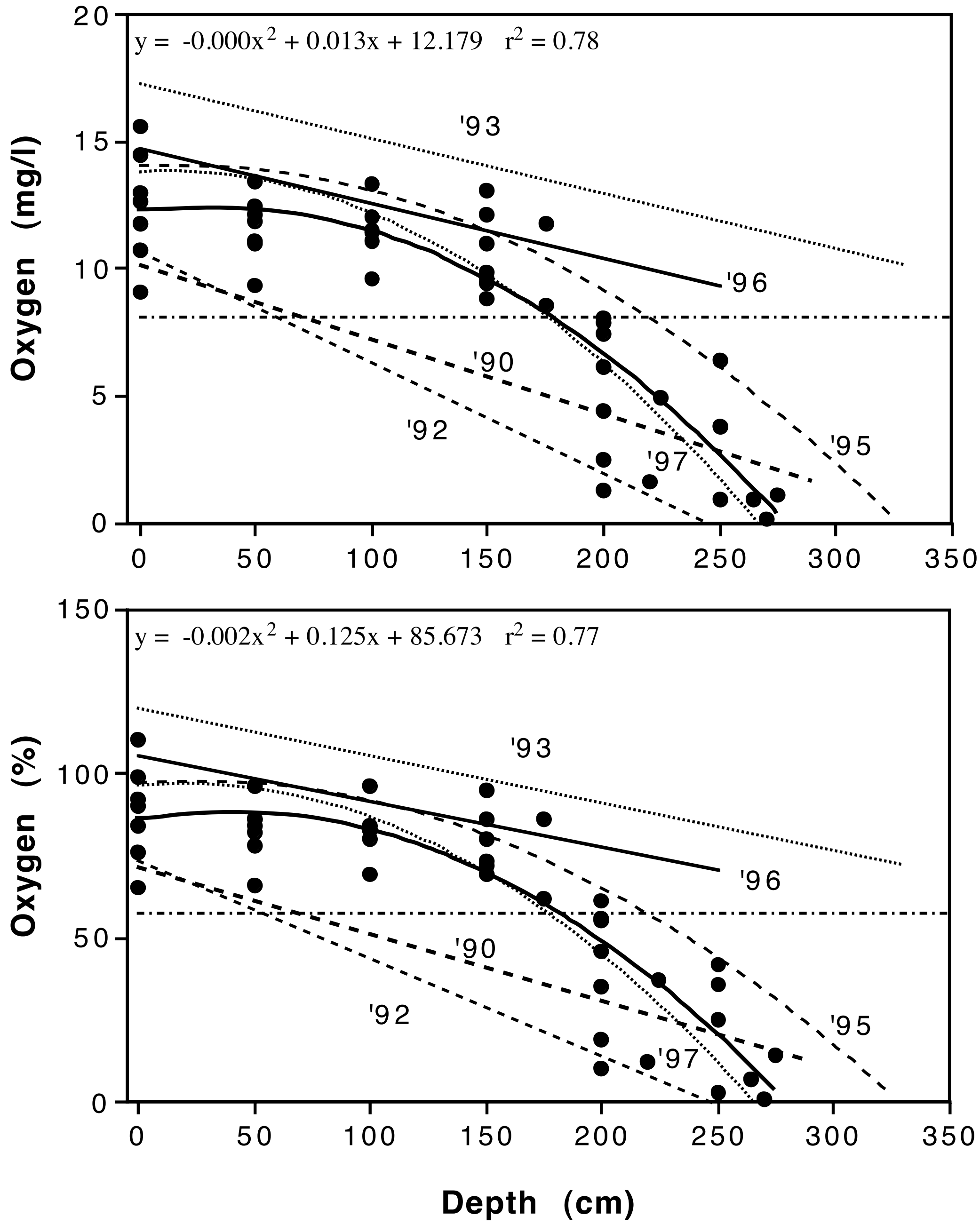

Fig. 16. Relationships between oxygen level and depth below ice in Black Lake during February 1992, 1993, 1995, 1996, 1997 and 1998. Horizontal line at 8 mg/l and 57% refers to threshold for maintaining healthy salmon (Davis 1975). Regression equations and values are shown for data collected in 1998.

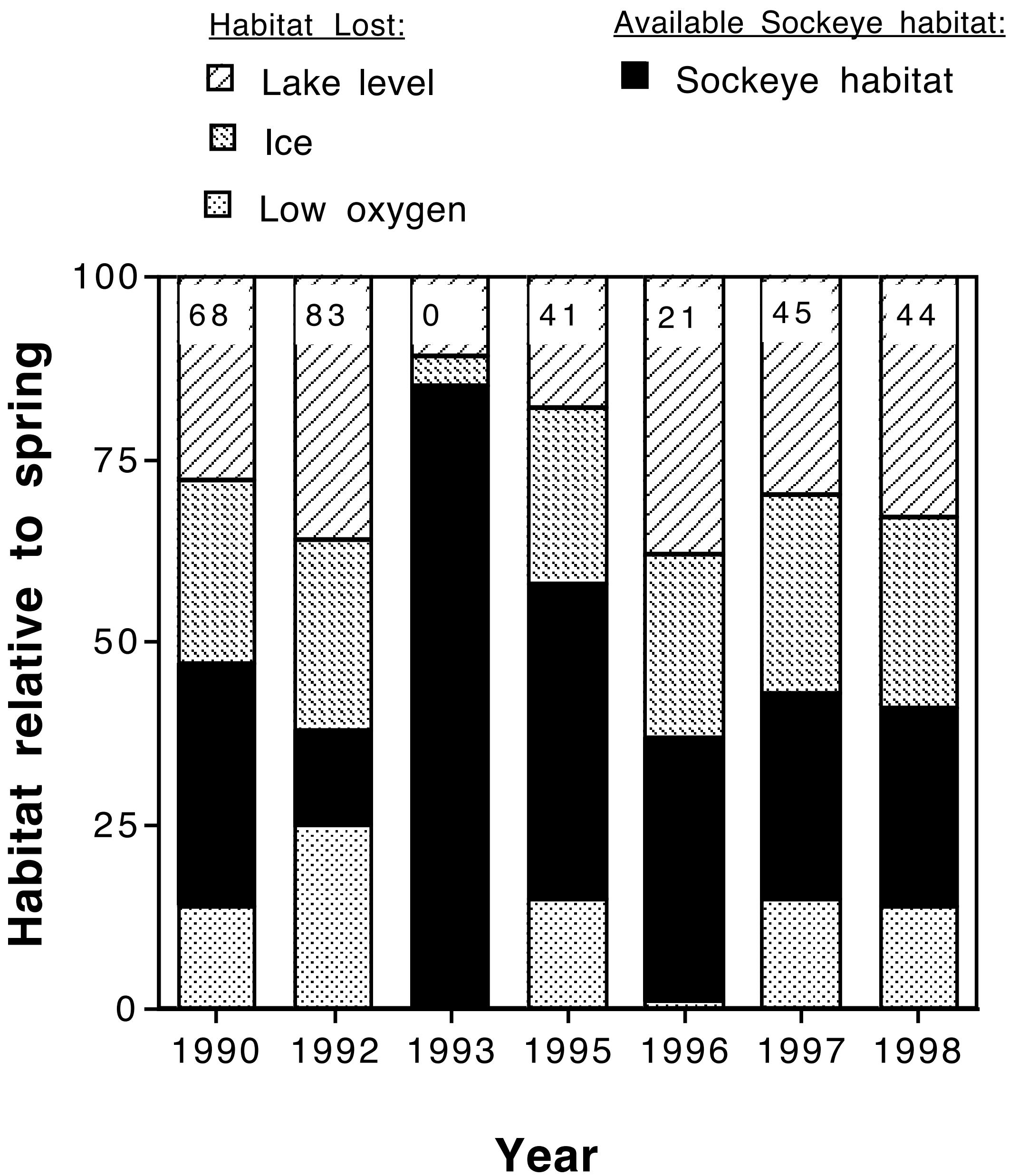

Fig. 17. Percentage of sockeye salmon habitat available during February 1990, 1992, 1993, 1995, 1996, 1997, 1998 and associated habitat losses from low lake level, ice thickness, and low oxygen (<57%) relative to spring 1992 (lake elevation: -0.6 m). Numeric values represent the percentage of water column containing low oxygen (<57%).

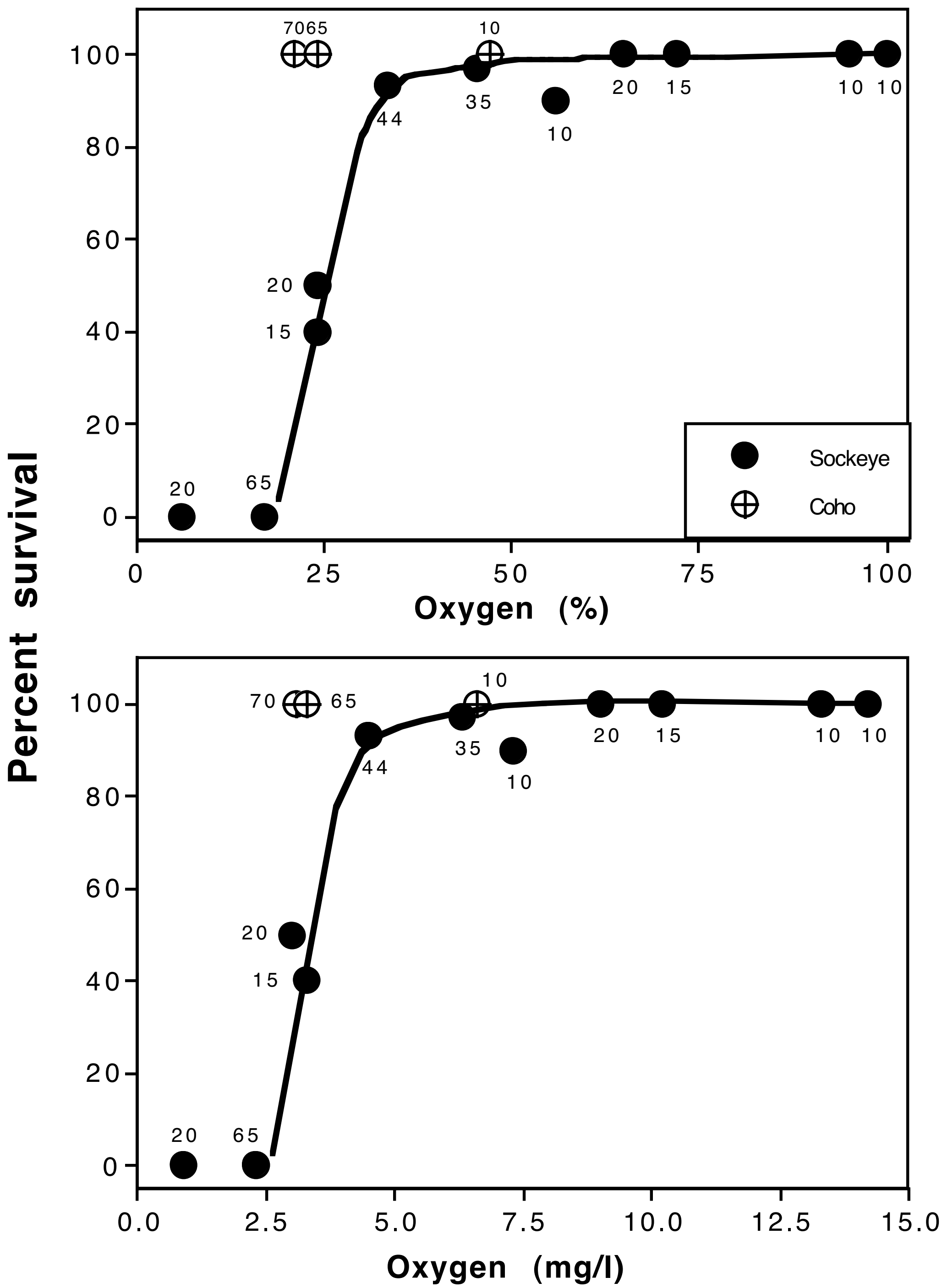

Fig 18. Survival of juvenile sockeye and coho salmon in Black Lake at oxygen concentrations ranging from to 6% to 100% saturation (upper graph) and 0.9 to 14.2 mg l^{-1} (lower graph). All salmon were held in cages and re-examined 24 hours later. Samples size is shown adjacent to each value. Line drawn by hand. Source: Ruggerone (2000).

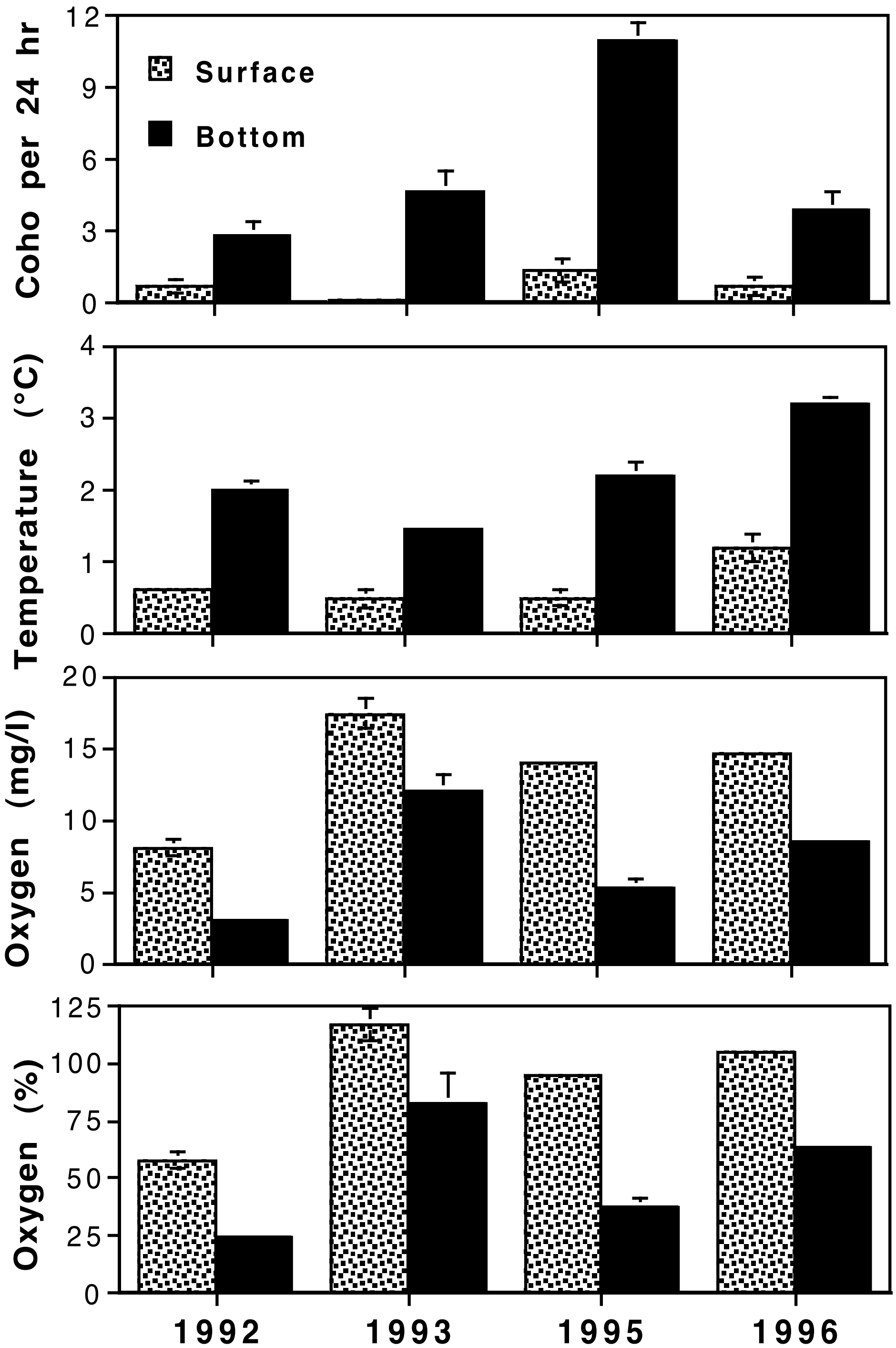

Fig. 19. Comparison of coho salmon catch rates with oxygen content and temperature of water near the ice and the bottom of Black Lake during 1992, 1993, 1995 and 1996. Values are means ± SE. Source: Ruggerone (1996).

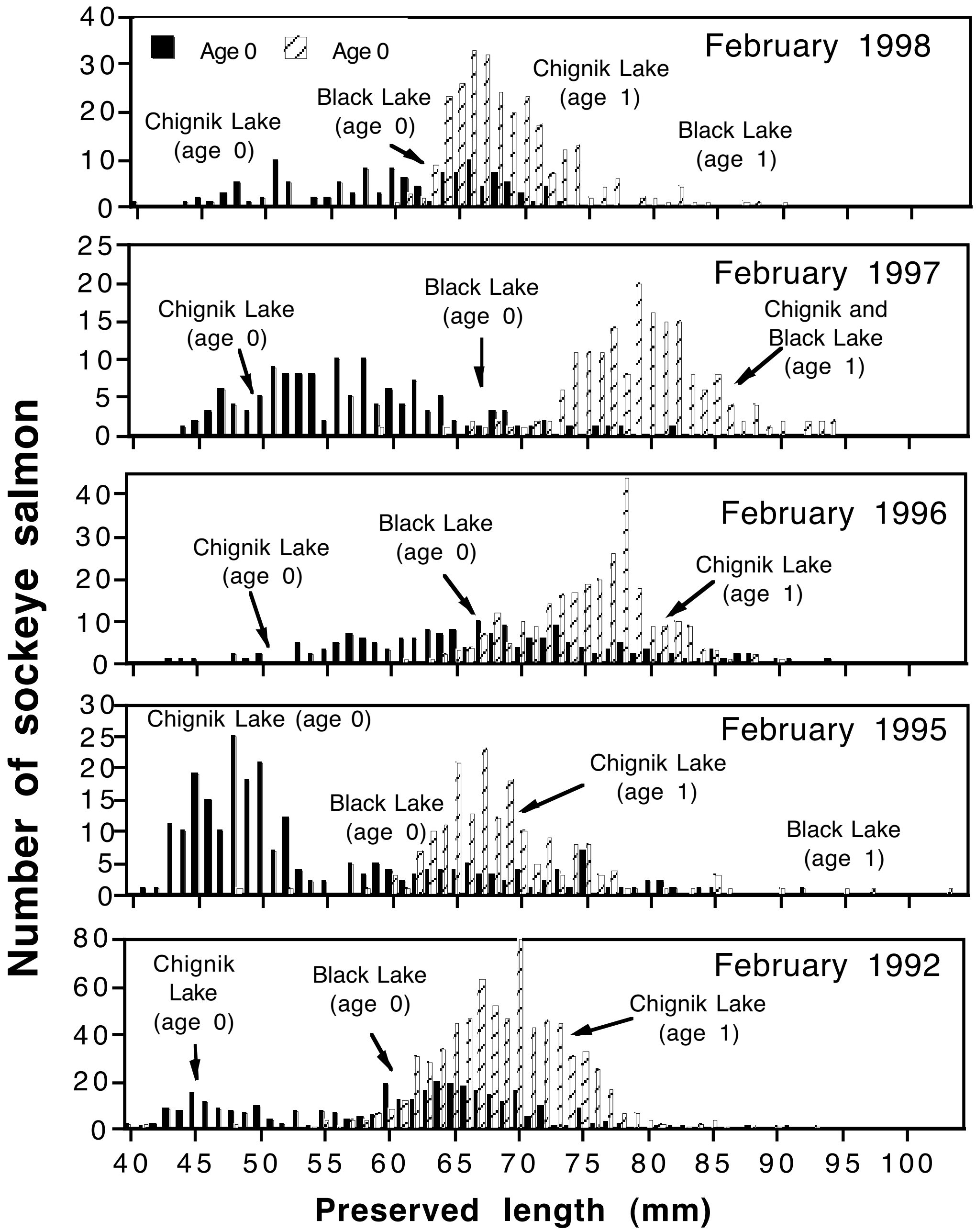

Fig. 20. Length at age frequency distribution of sockeye salmon captured in Chignik Lake during February 1998, 1997, 1996, 1995 and 1992. The dominant stock of each mode is indicated. Source: Ruggerone (1999).

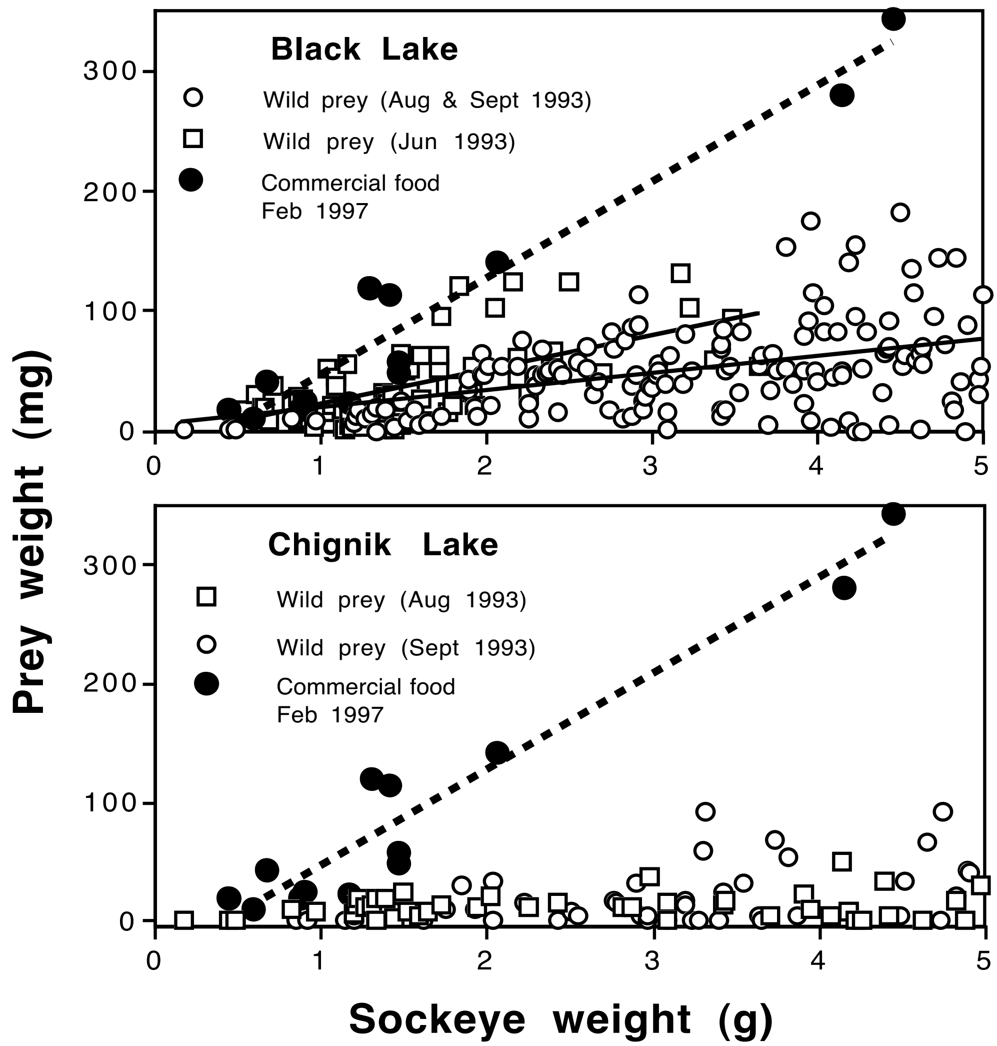

Fig. 21. Stomach contents of sockeye salmon when feeding on wild prey in Black (upper graph) and Chignik (lower graph) lakes during summer compared to contents when feeding on commercial food in Chignik Lake during winter, 1997. Regression lines shown. Source: Ruggerone (1997c).

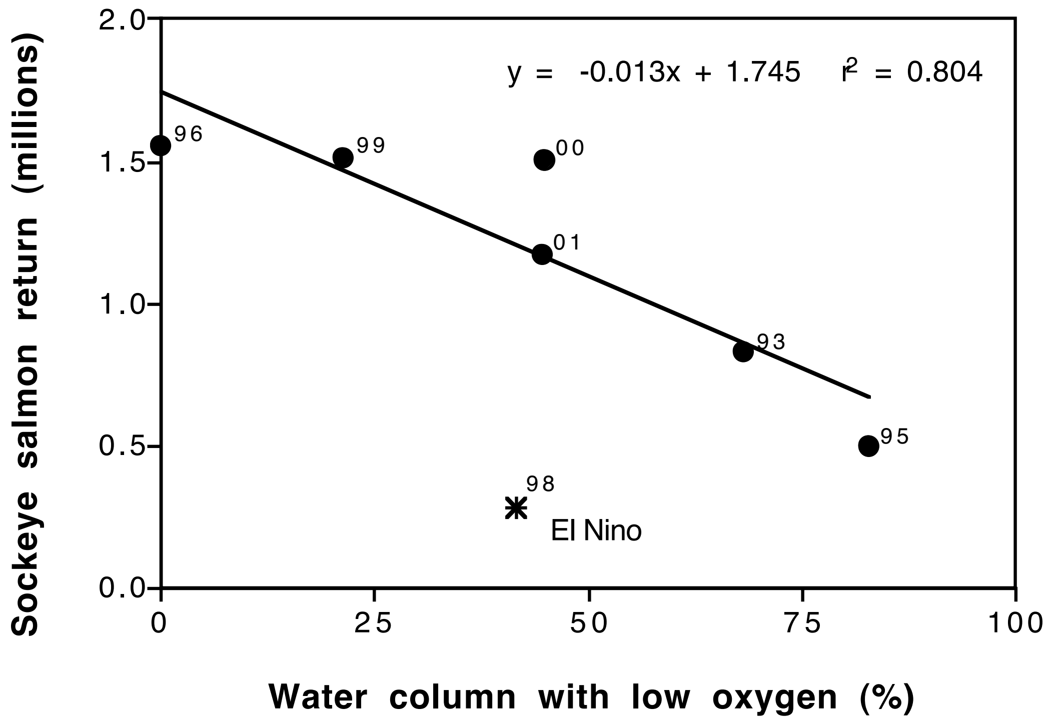

Fig. 22. Relationship between the return of age 1.3 sockeye salmon to Black Lake in relation to the percentage of Black Lake containing oxygen less than 57% of saturation during February, 1990-1998, excluding 1991 and 1994 when no sampling was conducted. Number of age 1.3 sockeye based on estimate of total run and age composition at outlet of Black Lake. Return from the 1995 winter excluded from regression because it was likely adversely affected by the 1997/1998 El Nino (Kruse 1998).

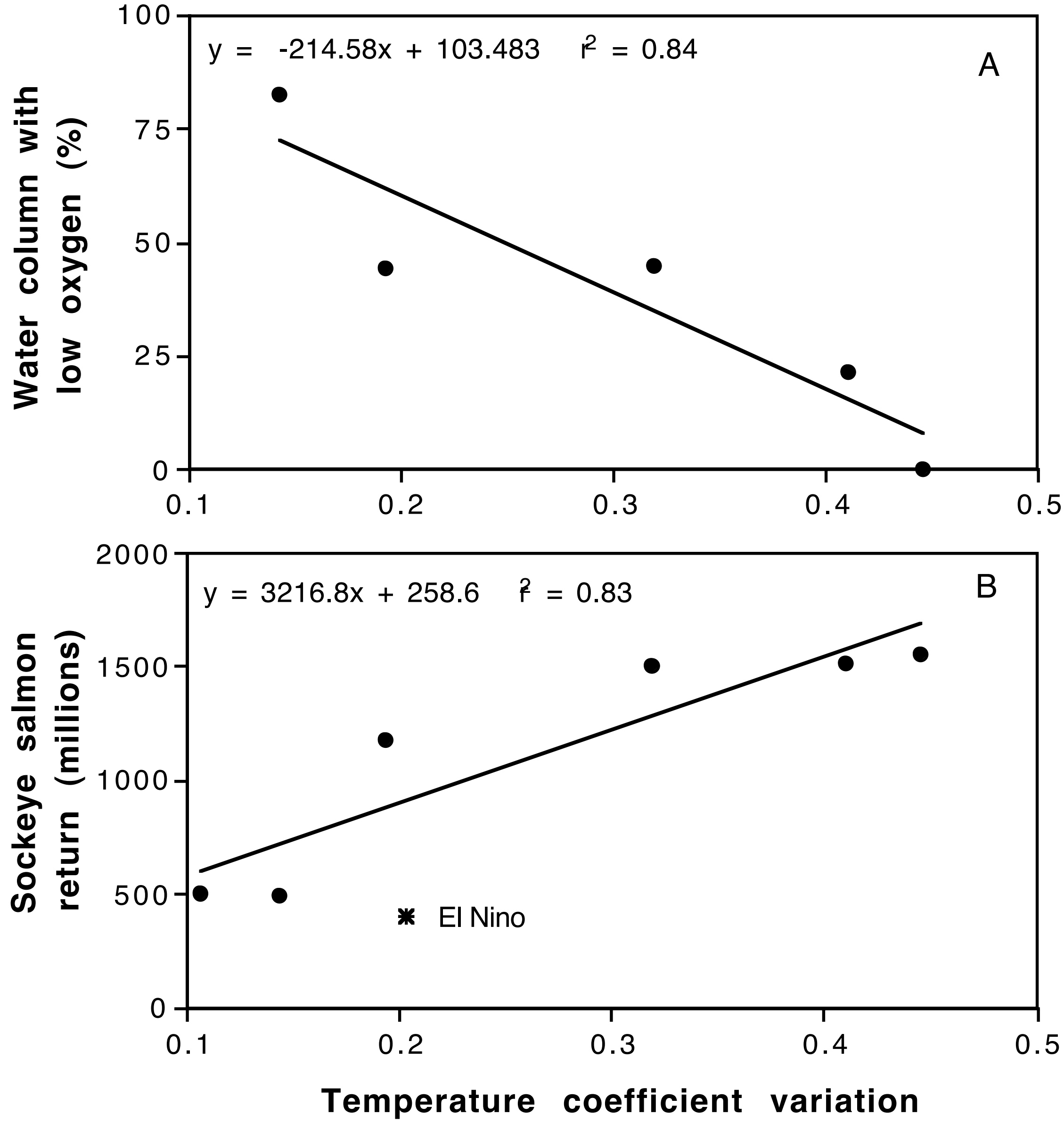

Fig. 23. Relationship between the water column with oxygen <57% (A), age-1.3 sockeye salmon return to Black Lake (B) and the coefficient of variation of water temperature in Black Lake during December 10 to February 28. Winter years when temperature data were available include 1992, 1993, 1994, 1996, 1997, 1998, and 1999. Return from the 1994 winter excluded from regression because it was likely adversely affected by the 1997/1998 El Nino (Kruse 1998).

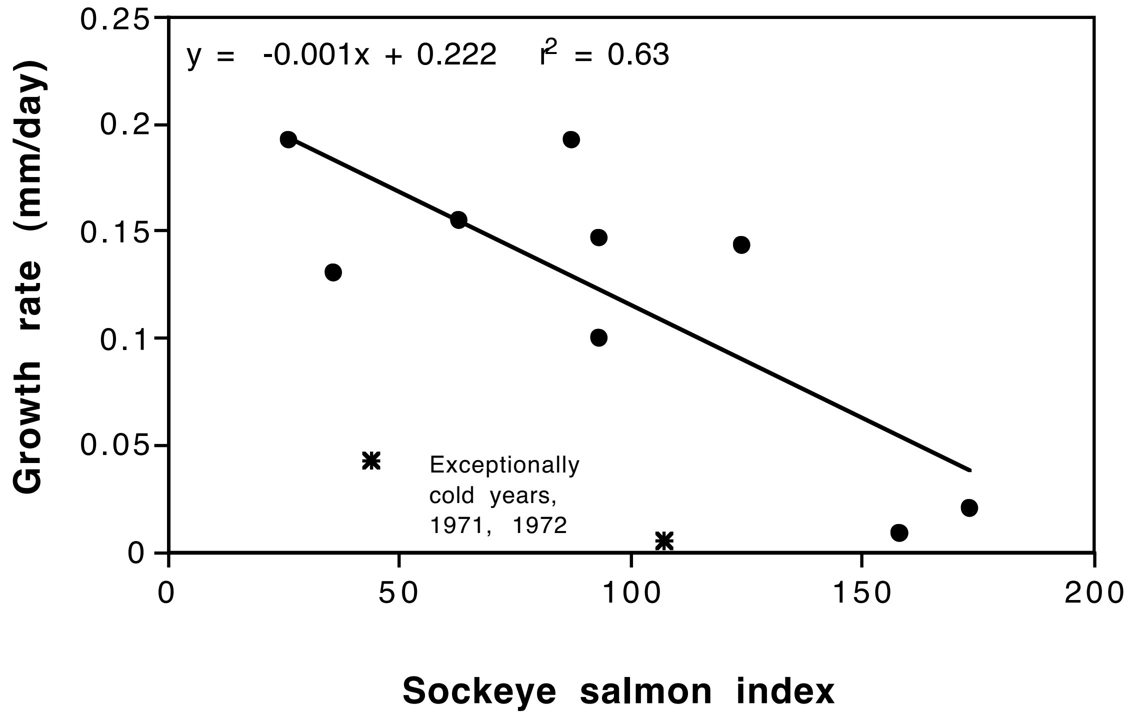

Fig. 24. Relationship between growth rate of age-1 sockeye salmon in Chignik Lake and an index of abundance (age-0 and age-1 combined). Growth during 1971 and 1972 was exceptionally low and corresponded to exceptionally cold growing seasons. Data sources: Parr (1972), Burgner and Marshall (1974).

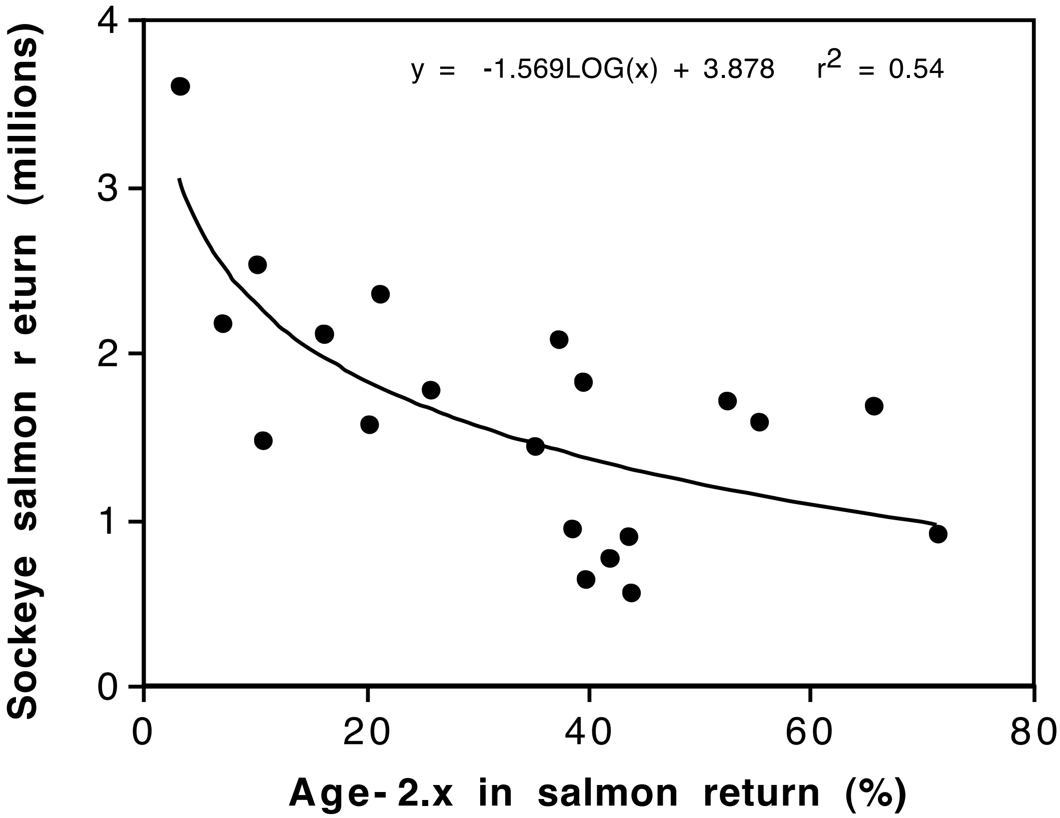

Fig. 25. Return of sockeye salmon to Black Lake in relation to the percentage of the return represented by age-2.x salmon. Time period is brood years 1977-1996. $n = 20$, $F = 21.054$, $P < 0.001$.

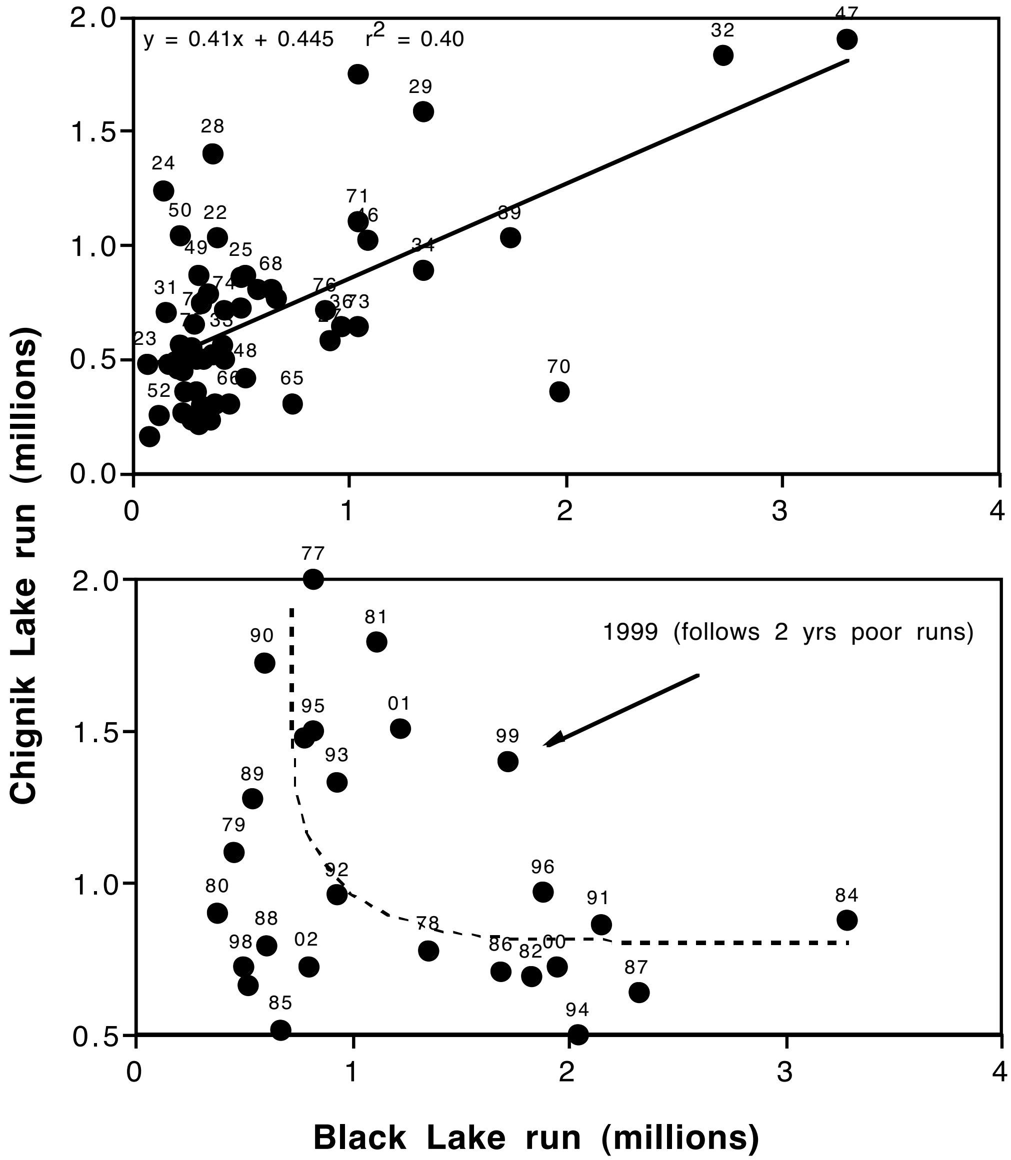

Fig. 26. Relationship between the run of age-1.3 and -2.3 sockeye from Black Lake and the run of age-1.3, -2.3, and -3.3 sockeye from Chignik Lake. The year of return for both lakes is shown above each value. The upper graph shows returns during 1922-1976. The lower graph represents years 1977-2002. Line in lower graph drawn by hand. Stock separation techniques were less precise prior to runs beginning 1978. Source: Ruggerone (1995, 1997, 1999).

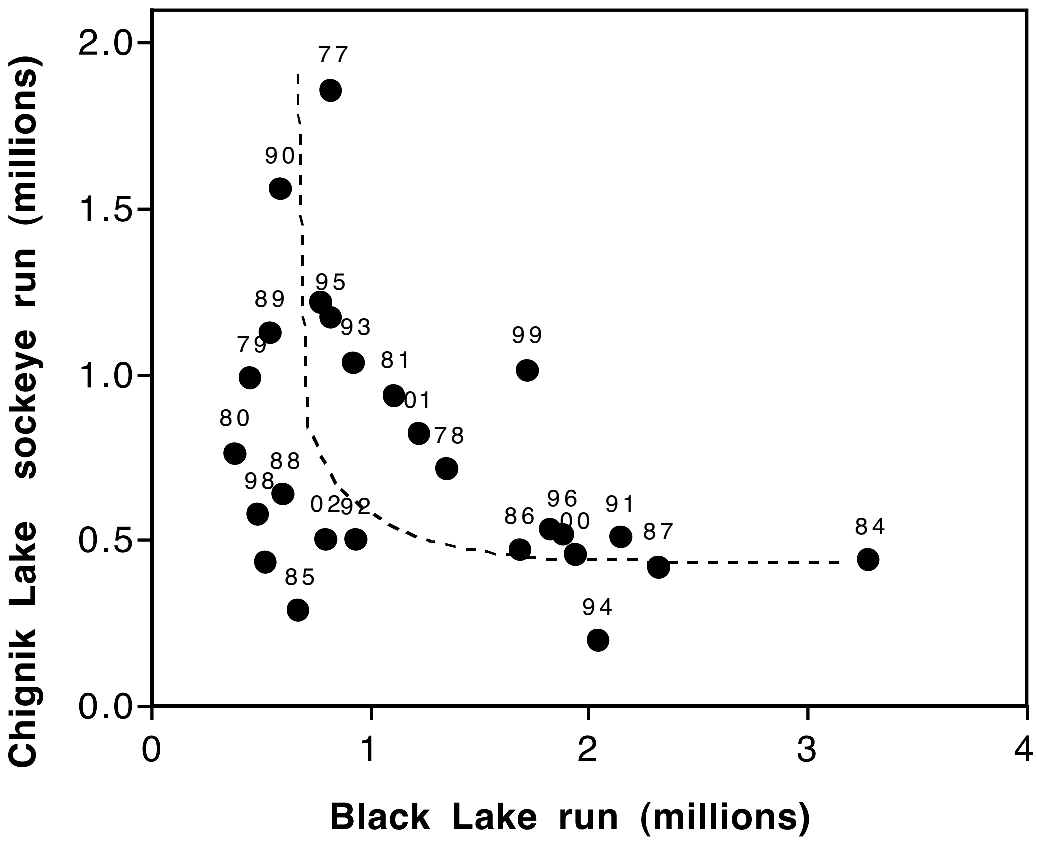

Fig. 27. Relationship between the run of age-1.3 and -2.3 sockeye from Black Lake and the run of age-2.3 sockeye from Chignik Lake, 1977-2002. Line drawn by hand. The year of return for both lakes is shown above each value.

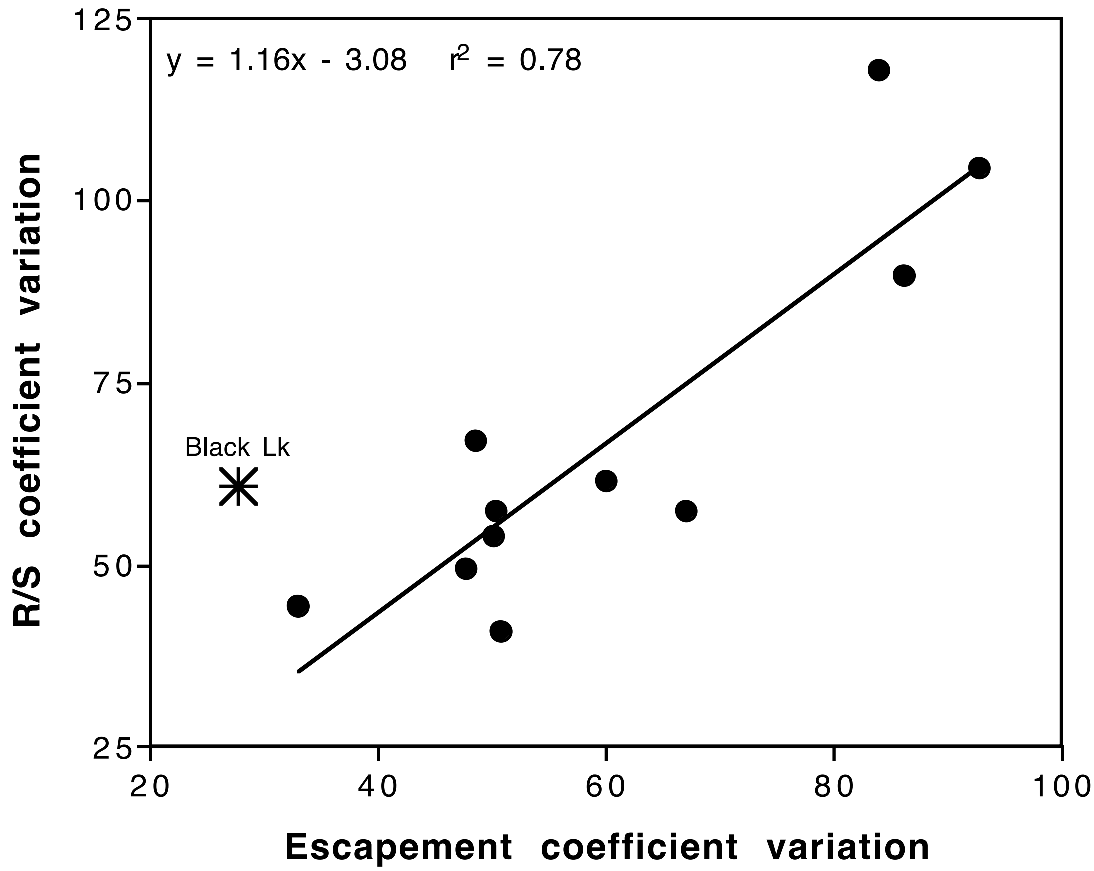

Fig. 28. Comparison of the coefficient of variation of Black Lake sockeye salmon return per spawner (R/S) with that of eleven other sockeye systems in western and central Alaska (Chignik Lake, Egegik, Igushik, Kasilof, Kenai, Kvichak, Naknek, Ayakulik, Togiak, Ugashik, Wood). The regression relationship was based on brood years 1965 to 1995 for all stocks except Kenai, Kasilof and Ayakulik, which had slightly fewer values during the early time period.

APPENDIX