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CHIGNIK SALMON STUDIES

INVESTIGATIONS OF SALMON POPULATIONS, HYDROLOGY, AND LIMNOLOGY OF THE CHIGNIK LAKES, ALASKA

G.T. RUGGERONE, C. HARVEY, J. BUMGARNER, AND D.E. ROGERS

ANNUAL DATA REPORT
ANADROMOUS FISH PROJECT

to

NATIONAL MARINE FISHERIES SERVICE
CONTRACT NO. NA90-HFM673

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CHIGNIK REGIONAL AQUACULTURE ASSOCIATION

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KEY WORDS

Alec River, Alaska Peninsula, Black Lake, emerging fry, groundwater, hydrology, limnology, sockeye salmon, spawning density

INTRODUCTION

This report is a compilation of numerous studies related to Black and Chignik lakes on the Alaska Peninsula during 1991. The large fluctuations of adult salmon returning to Black Lake have been a major concern to Chignik fishermen. Ruggerone et al. (1991) described potential factors causing the large fluctuations of adult salmon. Ruggerone and Denman (1990) reported that Alec River, the primary spawning river in the Chignik system, is changing course and discharging towards Chignik Lake rather than the main body of Black Lake. The Black Lake studies reported here are related to ongoing investigations of adult salmon fluctuations and the course change of Alec River. The reader should refer to aforementioned reports to gain a better understanding of the purpose of each study described below. The studies at Chignik Lake include ongoing baseline studies. The intention of this report is to quickly communicate data collected in 1991 rather than provide a comprehensive report.

BLACK LAKE

VARIABILITY OF ADULT SOCKEYE PRODUCTION

Production of adult sockeye (*Oncorhynchus nerka*) salmon in Black Lake varies considerably more than that of Chignik Lake. During 1970-1991, annual percent deviation from mean run size of Black Lake sockeye was greater than that of Chignik Lake sockeye during 17 of 22 years (Fig. 1). The coefficient of variation of sockeye returning per spawner (R/S) in Black Lake (0.71) was 56% greater than that in Chignik Lake (0.44) during brood years[1] 1965-84 (Table 1). Escapement was relatively constant during these years and would contribute little to the variability in adult production. Return per spawner of Black Lake sockeye was 108% more variable than that of Chignik Lake sockeye during 1972-84, the time period corresponding to greater salmon production throughout Alaska (Rogers 1987). Mean residual of observed minus expected R/S, based on the Ricker recruitment relationships for Black and Chignik Lakes, was 105% greater for Black Lake (mean residual = 1.62 R/S) than Chignik lake (0.79 R/S) during 1972-84.

The variability in sockeye returning to Black Lake translates to boom or bust harvests by fishermen. During 1970-89, annual harvests of Black Lake sockeye ($\bar{x}$ = 744,000) were less than the escapement goal during 7 years ('72, '74, '75, '79, '80, '88, '89), whereas harvests of Chignik Lake sockeye ($\bar{x}$ = 810,000) always exceeded the escapement goal. The variability in R/S and harvests of Black Lake sockeye indicate that characteristics unique to Black Lake influence the relatively great variability in adult production.

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[1] A *brood year* refers to sockeye produced by parents spawning in a given year. Thus, adults returning to Chignik Lagoon over several years may belong to the same brood year (e.g., age 1.2 and 1.3 fish returning in 1990 and 1991, respectively, belong to the 1986 brood year). *Run size* refers to all sockeye that return to Chignik in a given year (a mixture of brood years), whereas *sockeye return* typically refers to fish belonging to the same brood year, i.e. fish that may enter the lagoon during several years.

Comparison of sockeye production variability between Black Lake and sockeye systems other than Chignik Lake is more difficult because enhancement activities or changes in the escapement goal or management strategy may confound the comparison. Nevertheless, we compared the coefficient of variation of sockeye R/S in Black Lake with seven lake systems in Alaska during brood years 1972-85. The coefficient of variation of sockeye R/S in Black Lake (0.69) was 52% greater on average than that of seven lake systems (range: 0.31-0.58, Table 1). Sockeye production in each lake was less variable than that of Black Lake. However, sockeye production at Coghill Lake, a small lake in the Prince William Sound region, was exceptionally high during brood years 1976 and 1977. Excluding these two adjacent brood years, sockeye production in Coghill Lake was the most stable of all lakes examined. Greater variation in escapement would enhance variability in R/S; however, coefficient of variation of escapement was lower in Black (0.25) and Chignik (0.20) lakes than other lake systems (0.33 to 0.73). Thus, the large variability of sockeye production at Black Lake cannot be explained by fluctuating escapements. These data indicate that variation in sockeye production is inherent to Black Lake.

We correlated the R/S of Black Lake sockeye with nearby sockeye systems on the Alaska Peninsula. If brood years having poor adult returns in Black Lake were also poor in other lakes, then some factor common to the lakes would likely influence mortality more than factors unique to Black Lake. During brood years 1965-86, sockeye production in Becharof, Ugashik (years 1979-86) and Chignik lakes was not correlated with that in Black Lake ($p>0.05$; $r^2<.07$). The lack of correlation is consistent with the hypothesis that considerable variability in the Black Lake sockeye run is inherent to Black Lake.

The large variability in adults returning to Black Lake does not appear to be related to mortality during the egg stage. Most spawning tributaries have low gradients and have good to excellent spawning gravel. Scouring of the spawning grounds is not a major problem in Black Lake tributaries (Dr. M. Dahlberg, NMFS, Auke Bay, Alaska, pers. comm.). Return per spawner of Black Lake sockeye during brood years 1965-86 was not correlated with average, maximum, or minimum monthly temperature at King Salmon during the winter of egg incubation (December through February, best fit: $p = .30$, polynomial $r^2 = .12$). We used temperature data at King Salmon because the records at Port Heiden near Black Lake are incomplete. Temperature at King Salmon and Port Heiden are highly correlated ($p = .001$, $r^2 = .76$). In contrast to the insignificant relationship between winter temperature during egg incubation and adult production, average winter temperature during the fry stage was slightly correlated with brood year production (Fig. 2, $p = .06$, $r^2 = .26$). Production was low during cold winters, increased during average temperature, then declined during winters with relatively high winter temperature. These data are consistent with the hypothesis that winter may be a critical period for juvenile sockeye that overwinter in Black Lake.

LAKE PERIMETER

Ground elevation adjacent to Black Lake was measured at four locations to determine the increase in wetted lake perimeter between moderate (-0.76 m) and high (-0.2 m) lake elevations. This information is needed if the level of Black Lake is to be stabilized near natural high water for the purpose of doubling sockeye habitat during the low water period. The elevation at high water is approximately 1 m above that during low water (-1.2 m). The four areas selected (Fig. 3) appeared to have the lowest elevation gain with distance from the lake. Thus, the wetted perimeters described below should represent the maximum change during a given rise in Black Lake water level.

A lake level increase from moderate to high water resulted in a wetted perimeter increase of 10 to 220 m depending on the area. A lake elevation[2] increase from -0.76 m to -0.2 m would result in a wetted perimeter increased of 10 m at the Crooked Cr. station and 85 m at the Outlet Flats station (Fig. 4). During moderate water level (-0.82 m), the first 25 m of substrate at the Outlet Flats station was unvegetated mud, and groundwater was at ground surface for 100 m from the lake. The northwest portion of Black Lake near Crater Cr. had the lowest gradient. A lake elevation increase from -0.76 m to -0.2 m would result in a wetted perimeter increase of 150 m at the N. Crater Cr. station and 220 m at the S. Crater Cr. station (Fig. 5). At moderate water level (-0.76 m), the first 25-50 m of substrate was unvegetated silt, followed by sedge and grass. A large, vegetated berm emerged 200 m from the lake at the S. Crater Cr. station. This berm rose over 2 m above lake level and was probably created over many years during exceptionally high water levels. Gradient from the water's edge to 250 m offshore during moderate water level was low and water depth shallow (1 m). Near the Crooked Cr. station, a shoal identified by breaking waves extended ~500 m beyond the sandspit that created the bay.

GROUNDWATER

The objective of measuring groundwater elevation relative to lake level was to estimate the capacity of the surrounding area to absorb water as lake level increased. This information is needed because stabilization of lake level near high water could lead to some seepage from the lake to adjacent grounds during low-water periods. Groundwater elevation was measured by transit and rod at four locations (Fig. 3) representing areas with the lowest ground surface elevation. The resulting data were also used to calculate changes in the wetted perimeter of the lake as water level increased.

Groundwater elevation increased as ground elevation increased with distance from the lake, as expected (Figures 4 and 5). Groundwater elevation adjacent to the lake also increased as lake level increased. At the Crooked Cr. station, groundwater elevation increased approximately 8 cm and 16 cm as lake level increased 15 cm and 30 cm (e.g., -.906 to -.759 m to -.608 m elevation gain) during 6-16 June and 6-26 June, respectively (Fig. 4). Distance between ground surface and groundwater increased approximately 15 cm between 10 and 100 m from the lake (Fig. 6), i.e., the gradient of groundwater was less than that of ground surface. As lake level increased from -.906 m to -.608 m, groundwater at the four stations rose from 19 cm to within 3.8 cm of the surface.

We calculated the horizontal distance to reach a 1-m gain in groundwater elevation (Fig. 7). Distance to reach a 1 m gain in water elevation increased from 60 m to 86 m with a 30-cm gain in lake elevation. Lake elevation during the low water period in fall is ~-1.1 m and the extrapolated

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[2] Lake elevation is relative to the benchmark at the outlet of Black Lake.

distance to reach a 1 m gain in groundwater elevation is approximately 43 m. On the bases of these limited measurements, loss of lake water to the surrounding substrate would not be great during events causing lake level to rise approximately 1 m over low water.

SANDSPIT

Ruggerone and Denman (1990) reported observations by Chignik residents indicating that the sandspit extending across Black Lake (Fig. 3) has grown. Discussions with FRI researchers (Dr. D. Narver, Dr. M. Dahlberg, and D. Phinney) who worked at Black Lake during the early 1960s support these observations. During the early 1960s, FRI personnel spent considerable time at Black Lake during August and September while conducting a major study on the rearing capacity of sockeye in the lake. When presented with photographs of the sandspit taken during August 1990, the former FRI researchers noted that the sandspit and Fan Cr. (new channel) delta had grown considerably.

The sandspit is an important feature in Black Lake because it crosses 80% of the lake width at low water and separates the outlet area from the main rearing area. Ruggerone and Denman (1990) suggested that the sandspit growth resulted, in part, from the rechanneling of Alec River, increased sediment transport through the new channel, and the prevailing southeasterly winds.

During June 1991, we measured the maximum elevation of the sandspit from the Alec River delta to Sand Pt., and measured the cross-sectional profile near the mid-point of the sandspit. Measurements relative to lake level were made with a transit (8x) and meter rod at 50 m intervals along the sandspit. Measurements started 750 m from Alec River delta. Within the first 750 m, the spit is relatively high and often covered by grasses. These data could be used to determine changes in the size of the sandspit during the next several years.

The sandspit (1200 m) and Sand Pt. (400 m) traversed 68% of Black Lake on 17 June, a period of moderately low water level (-.806 m, Fig. 8). The open-water area was 740 m wide but 14% of this distance (100 m) was ≤1 m. Maximum water depth in this narrow channel was 1.85 m. Sandspit elevation declined 1.4 m between 750 m and 1750 m from Alec River delta (Fig. 8). As spit elevation approached that of the lake, wind-generated water currents created shallow breaks in the spit.

Sandspit width decreased with distance from Alec River delta. A cross-sectional profile was measured at the area where the spit approached water level (1190 m). Although the spit width above water was only 4 m, the foundation of the spit was exceptionally wide (Fig. 8). The distance between the 0.5 m depth contour on each side of the spit was 60 m.

Sediment composition of the spit was coarse, loosely compacted sand within ~1300 m from the Alec River delta. The coarse sand was deposited on top of fine, compacted silt. Size composition was similar to that observed in Alec River. The rapid elevation increase shown in the longitudinal profile was composed of coarse sand. Between 900 m and 1500 m from Alec River delta, the coarse sand was highly unstable and the spit could change elevation depending on water level and wind-generated water currents.

BLACK RIVER PROFILE

The objective of the Black River profile measurements was to provide initial data that could be used to evaluate the feasibility of a weir designed to control lake level. These data could also be useful to Alaska Department of Fish & Game (ADFG) personnel if they decide to construct the floating weir at a new location. Cross-sectional profiles of upper Black River were measured by transit and rod approximately 400 m and 1100 m from Black Lake. These sites were chosen because they were close to Black Lake, river gradient and velocity were low, and the river channel was relatively wide. The left bank was ~10 m from a steep hill covered by deciduous shrubs. The right bank was considerably less precipitous and covered by grasses and deciduous shrubs (mostly willow).

Channel width of the upper site on 26 June was 142 m and maximum depth was 1.45 m (Fig. 9). The cross-channel gradient was low and the substrate was compact sand. Channel width of the lower site on 17 June was 65 m and maximum depth was 2.4 m (Fig. 10). The channel gradient between the two sites was 0.01%.

Ground elevation of the right bank at the upper site gradually increased with distance from the river. The ground surface 9 m from the river was .44 m above the river level during moderately high water on 26 June (-.608 m, Fig. 9). At 270 m from the river, the ground was .89 m above river level. The berm rose more abruptly at the lower site. Berm elevation peaked 10 m from the river and was .63 m above water during the moderately high water on 26 June (-.608 m). The right bank consisted of sand covered by grasses and some shrubs. Groundwater elevation at the lower site increased with higher river water (Fig. 10).

ALEC RIVER

Water elevation at the Alec River benchmark, located ~300 m above the confluence with the new channel, was -1.390 m on 17 June. This water elevation corresponds to -0.2 m at the outlet benchmark, i.e., ~1 m above low lake level during winter. Alec River was 0.61 m higher than the lake. Flow was relatively great and river elevation was 0.22 m higher than that during low water in August 1990.

Elevation of the sandbar that deflects Alec River flow into the new channel was -1.055 m. The bar rose 0.39 m above the river, whereas during low water in August 1990 the bar was 0.69 m above water. Maximum bar elevation was 0.08-m lower in 1991 than that during August 1990. This elevation decline was not unexpected because the bar shape and elevation will change with the waterflow.

Sediment transport in the new channel during low and high flows was calculated by hydrologist Bob Denman (see Appendix for detailed discussion). The calculations involved Yang's sediment transport equation, data and observations made during our August survey in 1990, and several assumptions. During 28 August 1990, we estimated a flow of 13.04 m^3 (460.5 cfs) in the new channel. Water flow during this period was low relative to other periods. Sediment transported during low water was estimated at 7.1 m^3/d, or the equivalent of 34 drums of 55 gallon capacity. Additional assumptions (e.g., water depth and velocity) were made to estimate sediment transport during high flows since we have not taken flow measurements during this period. The estimated sediment transport rate during high water was 67 m^3/d, or the equivalent of 322 drums of 55 gallon capacity. This transport rate was based on an average sediment concentration of 18.6 mg/L or nearly double that during low water. The estimated sediment concentration during high water appears to be low because water clarity is great during low water and poor (<0.5 m) during high water. Thus, the sediment flow rate during high water appears to be low. Additional field data, including direct sediment transport measurements during moderately high water, were collected during 1992 and will be analyzed in a forthcoming report.

Sedimentation patterns for Alec River were qualitatively evaluated given the scenario of a stable lake level near the high water mark (-.2 m elev.). High lake level would cause sedimentation of the area where Alec River splits into two channels. As the channel and delta bed elevation increased, flow would seek alternative routes. The preferred routes would be those of lowest topographic elevation and least resistance to erosion. It is likely that new channels would be created at or near the newly formed delta.

Another aspect of inundation with respect to sedimentation patterns would be the role of wind on sediment movement. By stabilizing the lake level near high water, the sediment that once was deposited by the river near the sandspit would now be deposited thousands of feet "upstream," where wind action would likely play a less important role in spit accretion. Also, raising the lake level would inundate the spit, where wave action may erode the spit. Those portions of the old delta covered by water could also be subject to this erosion.

In summary, stabilizing the lake level near high water would cause the inundation of the existing Alec delta and the creation of a new delta near the location of the channel split. At some point in the future, new channels would be created in the delta, forming a feature similar in size and shape to the existing multi-channeled delta. Due to the elimination of lake level fluctuation, vegetation colonization of the delta would likely proceed at a faster rate than that which is occurring at the present delta.

UPSTREAM FRY MOVEMENT

Narver (1963) examined the freshwater scale characteristics of spawning sockeye from Black Lake tributaries, Black River tributaries, and Chignik Lake tributaries and beaches. First year's growth (scale radius) of age 1.3 sockeye returning in 1960 was similar between Black River (Chiaktuak Cr. and West Fork) and Chignik Lake (Clark River) spawners. First year's growth of fish returning to six areas of the Alec River drainage and Fan Cr. was consistently greater than that of Black River and Chignik Lake fish. Total freshwater growth (# circuli) of age 2.3 sockeye in 1961 was similar between Black River (Bearskin Cr.) and Chignik Lake (Clark River, Home Cr., beaches) spawners. Total freshwater growth of fish returning to Black Lake was consistently greater than that of Black River and Chignik Lake fish. Narver concluded that most fry produced in Black River tributaries migrate downriver and rear in Chignik Lake.

However, several factors indicate that some fry produced by sockeye spawning in Black River tributaries migrate upstream to rear in Black Lake. Roos (1960) observed sockeye fry near

Chiaktuak Cr. migrating upstream. Freshwater age composition of Black River tributary spawners was more similar to that of Black Lake than Chignik Lake spawners during 10 of 14 years. Furthermore, age composition of early Black River tributary spawners was most similar to that of Black Lake spawners, whereas age composition of late spawners was most similar to that of Chignik Lake spawners. Presumably, the fry produced by the early adults emerge early and migrate to Black Lake, where food production begins about 1 month before that in Chignik Lake. Differences in the early versus late age composition data support the hypothesis that early and late emerging fry stocks in the Black River tributaries evolved in response to the geologically recent formation of Black Lake (Knappen 1929). Alternatively, fry produced by the early spawning sockeye might rear in Black River before migrating to Chignik Lake.

Although Narver (1963, 1966) and Dahlberg (1968) suggest that most, if not all, fry produced by spawners in Black River tributaries migrate downstream to Chignik Lake, we believe that the rearing habitat of these fish should be clarified by visual observations. Upstream migrating sockeye fry typically migrate in slow water near the bank. Two traps were set overnight along the shore of Black River approximately 300 m and 400 m down river from the lake during 6 June. Additionally, we searched for fry by walking ~0.3 km of river above Chiaktuak Cr. and by searching the lower 100 m of Chiaktuak Cr. We did not expect to observe large numbers of fry in early June because peak emergence probably occurs in early to mid-May.

No sockeye fry migrating upstream were observed in Black River during the brief periods of sampling. Some coho (*O. kisutch*) fry and numerous pond smelt (*Hypomesus olidus*) were observed. The coho fry were holding in still-water areas primarily in the lower river. Smelt were observed at the ADFG weir on Black River and below. Pond smelt, similar in size to sockeye smolts, were initially reported as sockeye smolts by ADFG personnel installing the weir. If many fry migrate upriver, they must move before June. While searching the lower 100 m of Chiaktuak Cr., we visually observed 1 sockeye fry, 1 coho fry, 1 Dolly Varden (*Salvelinus malma*) char fry and 5 unidentified fry. An electroshocker would have facilitated the identification of the fry. Additional trapping operations should be conducted during early May 1992 to further evaluate upstream movements of sockeye fry.

CHIGNIK LAKE

LIMNOLOGY

Zooplankton, chlorophyll *a*, Secchi depth, and water temperature were sampled in Chignik Lake on 27 June. Light penetration was measured on 10 and 28 June and water temperature was measured every 2 h at the outlet of Chignik Lake between 23 June 1990 and 10 June 1991.

Chlorophyll *a* was measured at seven depths between 0 and 20 m after filtering lake water through a 1.2-μ filter (Hardy 1979). Average chlorophyll *a* was 2.0 mg/m^3 at Clark Bay and 3.2 mg/m^3 near the Black River delta. These estimates were low relative to previous years.

Species of phytoplankton in Chignik Lake were qualitatively examined in the fall after a significant flood event. Grab samples were collected at the surface near Hatchery Beach, Clark Bay, and the outlet. Algal species included *Melosira italica*, *Stephanodiscus minutula*, *Stephanodiscus niagarae*, and small forms of *Nitzschia* spp. No blue-green algae were observed. These species were also observed in a more detailed seasonal study conducted during 1983 and are typical of cold lakes with low alkalinity (S. Abella, University of Washington, Seattle, pers. comm.). The phytoplankton observed in these and other samples from Chignik Lake can be consumed by zooplankton (Infante and Edmondson 1985, Infante and Litt 1985; A. Litt, Univ. Washington, Seattle, pers. comm.).

Zooplankton were sampled at five stations (Parr 1972) by a 243-µ net pulled vertically from 40 m. This net was designed to capture large zooplankton that salmon typically consume rather than the more numerous, smaller life stages and species. Total zooplankton abundance averaged 112,600 ± 69,900 ($\bar{x} \pm$ S.D.) plankters/m^2. Cycloid copepods were most abundant (40,500/m^2), as is typical of southwestern sockeye lakes during spring, followed by rotifers (30,700/m^2), calanoid copepods (20,900/m^2), cladocerans (20,000/m^2), and other plankters (500/m^2). Among cladocerans, *Bosmina* spp. (18,700/m^2) were more abundant than *Daphnia* spp. (1,400/m^2).

Water temperature was measured continuously at 10 m by a Ryan thermograph placed near the outlet of Chignik Lake. Weekly mean water temperature increased from 8.3°C in late June 1991 to 12.2°C in late August, then declined rapidly to 0.3°C in mid-December (Fig. 11). Temperature increased gradually through winter to 1.5°C in early April, then increased rapidly to 6.5°C by mid-June 1991. Chignik Lake froze for a brief period during winter (John Lind, Chignik Lake, Alaska, pers. comm.).

Light penetration in Chignik Lake was measured by a Licor photometer during 1300-1345 h, 10 June. The sky was clear; therefore, clouds would not interfere with measurements. Light penetration declined rapidly with depth at all three stations (Fig. 12). Compensation depth (i.e., the depth at which oxygen production equals respiration or the depth to which 1% of subsurface photosynthetically active light penetrates [Schindler 1971]) increased with distance from Black River, owing to the suspended sediments flowing from the West Fork of Black River and Black Lake. Compensation depth ranged from 4.4 m to 7.8 m and Secchi depth averaged 2.1 m. Light penetration was also measured on 28 June during overcast skies. Average compensation and Secchi depths were 7.4 m and 1.7 m, respectively.

Koenings and Burkett (1987) developed a relationship between the euphotic volume of a lake (i.e. the water volume that captures 99% of incoming light) and adult run size. Euphotic volume of Chignik Lake was 153.5 million m^3, based on average compensation depth and lake surface area (22 km^2). The Koenings and Burkett model predicts an annual run size of 288,000 sockeye. However, observed run size to Chignik Lake during 1979-89 was 1,132,000 sockeye, a value 293% greater that predicted by the model. The estimated euphotic volume of Black Lake is 70 million m^3 (1.7 m depth, 41 km^2 surface area) and the predicted run size is 79,000 fish. The observed sockeye run size to Black Lake during 1979-89 was 1,194,000 fish, a value 1,400% greater that predicted by the model.

At least two factors probably contribute to the large sockeye returns to Chignik and Black lakes relative to that predicted by the model. First, both Chignik and Black lakes have high rates of primary productivity relative to other major sockeye lakes. Burgner et al. (1969) reported that primary productivity of Chignik Lake ($\bar{x} = 242$ mg C/m^2/4 h) was the highest of 21 major sockeye lakes ($\bar{x} = 59$ mg C/m^2/4 h) sampled in southwestern Alaska. Primary productivity of Black Lake (121 mg C/m^2/4 h) was third highest. The abundance of phytoplankton provides food for zooplankton, which are in turn consumed by juvenile sockeye. Growth of Chignik Lake sockeye appears to be exceptional when fish density is considered. For example, Burgner et al. (1969) developed a relationship between sockeye spawning density in the Wood River lakes and fry length on 1 September. The extrapolated size of Wood River age-0 sockeye during a spawner density of 12,500 adults/km^2 lake surface area is 38.7 mm, and the measured length of sockeye in Chignik Lake at the same density and date was 22% greater (47.2 mm). Black Lake sockeye also are relatively large when fish density is considered.

FRY EMERGENCE RATES

Daily rates of sockeye fry emerging along shoreline spawning areas of Chignik Lake have been estimated since 1986. Details of the sampling trap and procedure are provided by Ruggerone (1989). Prior to 1991, up to 45 traps were placed at four sampling areas (South Hatchery South, South Hatchery North, North Hatchery, and the Delta spawning grounds). In 1991, traps were only placed at the South Hatchery North (14 traps) and Delta spawning grounds (10 traps). The South Hatchery North area is the primary area for beach spawning sockeye salmon. A significant portion of sockeye in Chignik Lake spawn along beaches where groundwater percolates through gravel (e.g., alluvial fans).

A fry emergence index for June was calculated from traps placed at the South Hatchery North and Delta spawning grounds. The index was calculated by weighting catches at South Hatchery North by 0.8 and those at the Delta area by 0.2. Research during 1986-88 indicated that emergence peaked during early June and continued until late July, although townet catches of fry containing yolk have been made in early September. Air temperature should not have a major effect on emergence timing because groundwater in these areas is fairly constant in spring.

The average and geometric mean indices of emerging fry in 1991 (34 and 11 fry/m^2/30 d, Table 2) were considerably lower than that in 1986-88 (84 and 38 fry/m^2/30 d) but higher than that in 1989-90 (16 and 6 fry/m^2/30 d). The majority of fish emerging in 1991 should return as adults in 1995 and 1996.

FEEDING STUDIES

A pilot study was undertaken to determine whether juvenile sockeye salmon from Chignik Lake would consume food made for salmon in hatcheries and net pens. We were interested in the potential for direct feeding of sockeye salmon in Chignik Lake, primarily during periods when food might be less abundant. Little or no food is available during winter (Ruggerone et al. 1991). Early spring may be a critical period if zooplankton (mostly cyclopoid copepods that overwinter in mud) are not readily available when temperature begins to increase.

Hatchery food has improved in recent years. Salmon food can be adjusted for size, palatability, energy content, and buoyancy. Conversion rates are high: 1 g dry food will produce ~1 g fish tissue (Dr. Ron Hardy, NMFS, Seattle, WA, pers. comm.). Salmon food is sterilized and would not transmit disease to fish.

We were particularly interested in neutrally buoyant fish food because sockeye salmon in Chignik Lake would have a greater chance to consume food suspended in the water column. Moore-Clark Co. (LaConner, Washington) donated salmon food for our pilot study that was near the density of water. When place in Chignik Lake water, one diet sank and another floated on the water before slowly sinking. Neutrally buoyant food could be developed using data on the specific gravity of Chignik Lake water.

The feeding study used 40 sockeye fry collected from emergence fry traps. The fish were held in two 5 gal. aquaria and each aquaria was provided .15 to .3 g of "diet 750" per day. These feeding levels provided more than enough food. Feeding commenced on 13 June and ended on 29 June. Water temperature was 8.8 ± 0.3 °C.

Stomachs of the fish were distended throughout the test period, indicating that fish actively consumed food. Length of sockeye fry increased 3.2 mm (31.1 ± 0.1 mm to 34.3 ± 0.2 mm) and weight increased 56% (194 ± 2 mg to 303 ± 6 mg) during the 16 day period. Water content at the end of the test period was 81.5%. These data demonstrate that Chignik sockeye fry will consume processed food. Clark et al. (1991) demonstrated rapid growth of sockeye fry (0.5 mm/d) held in net pens for a two month period and fed processed food. Further research could be conducted to determine whether juvenile sockeye salmon will consume processed food in Chignik Lake.

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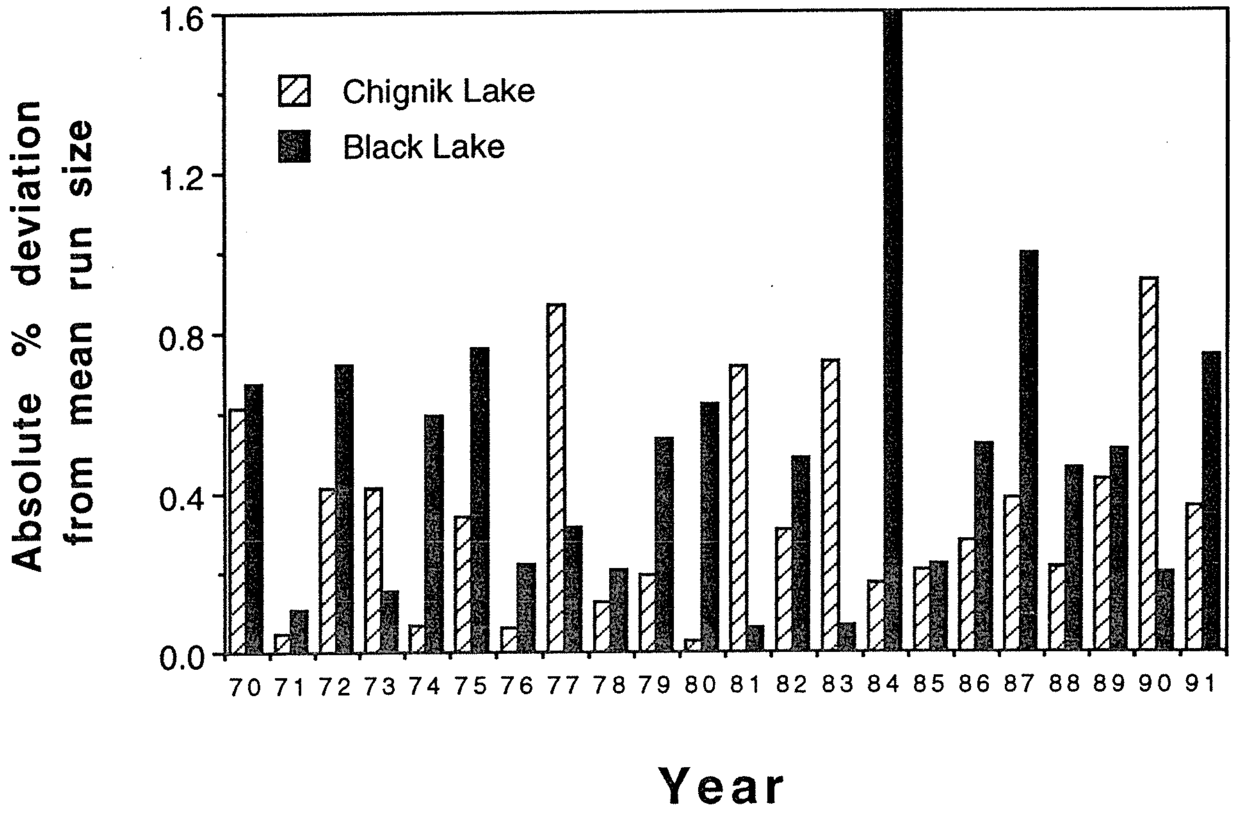


Figure 1. Comparison of the standardized annual deviation from mean run size for Black Lake and Chignik Lake sockeye salmon, 1970-1991.

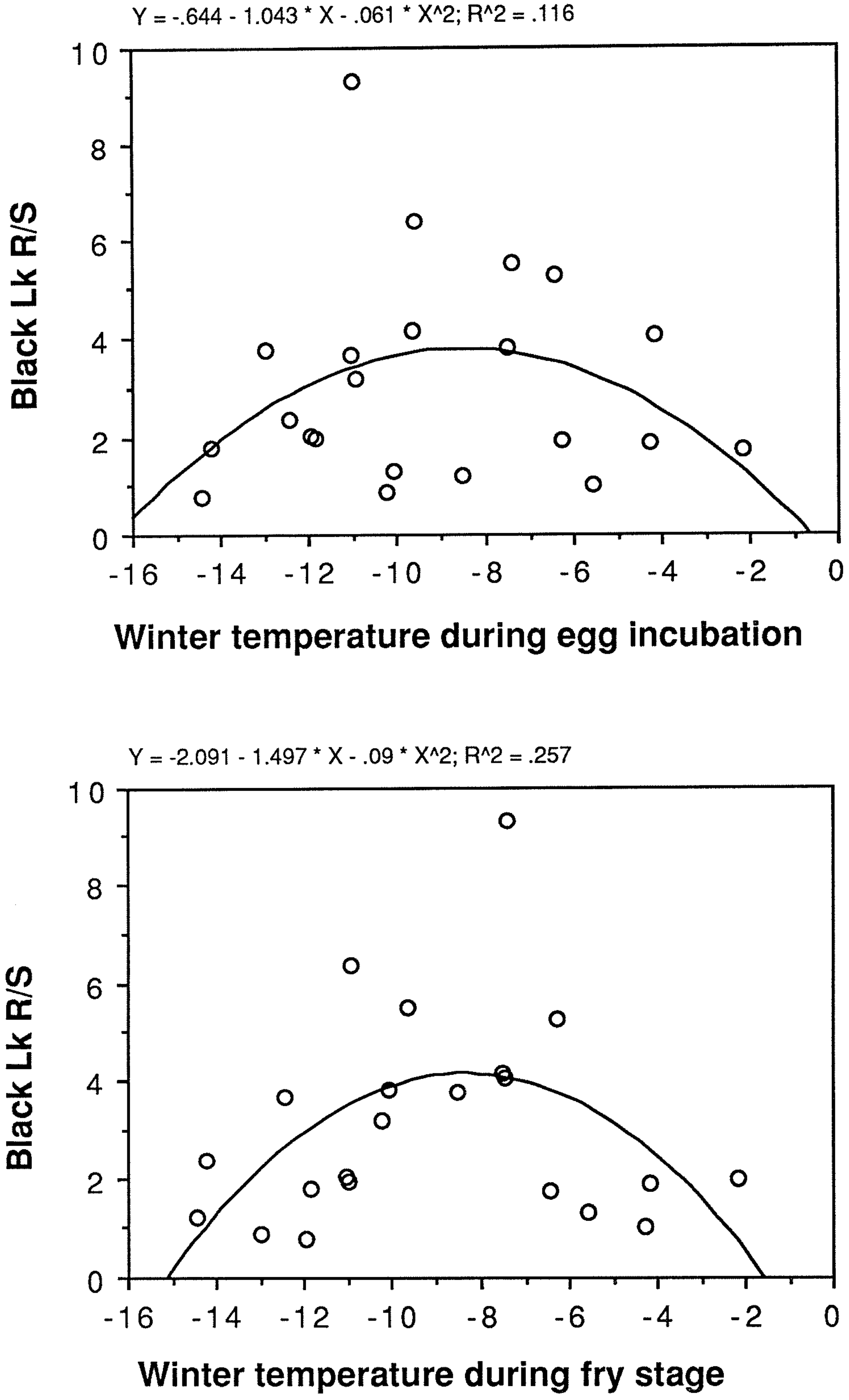


Figure 2. Return per spawner of Black Lake sockeye salmon (brood years 1965-86) in relation to average December to February temperature during the egg stage (upper graph) and fry stage (lower graph). Temperature data are from the King Salmon weather station.

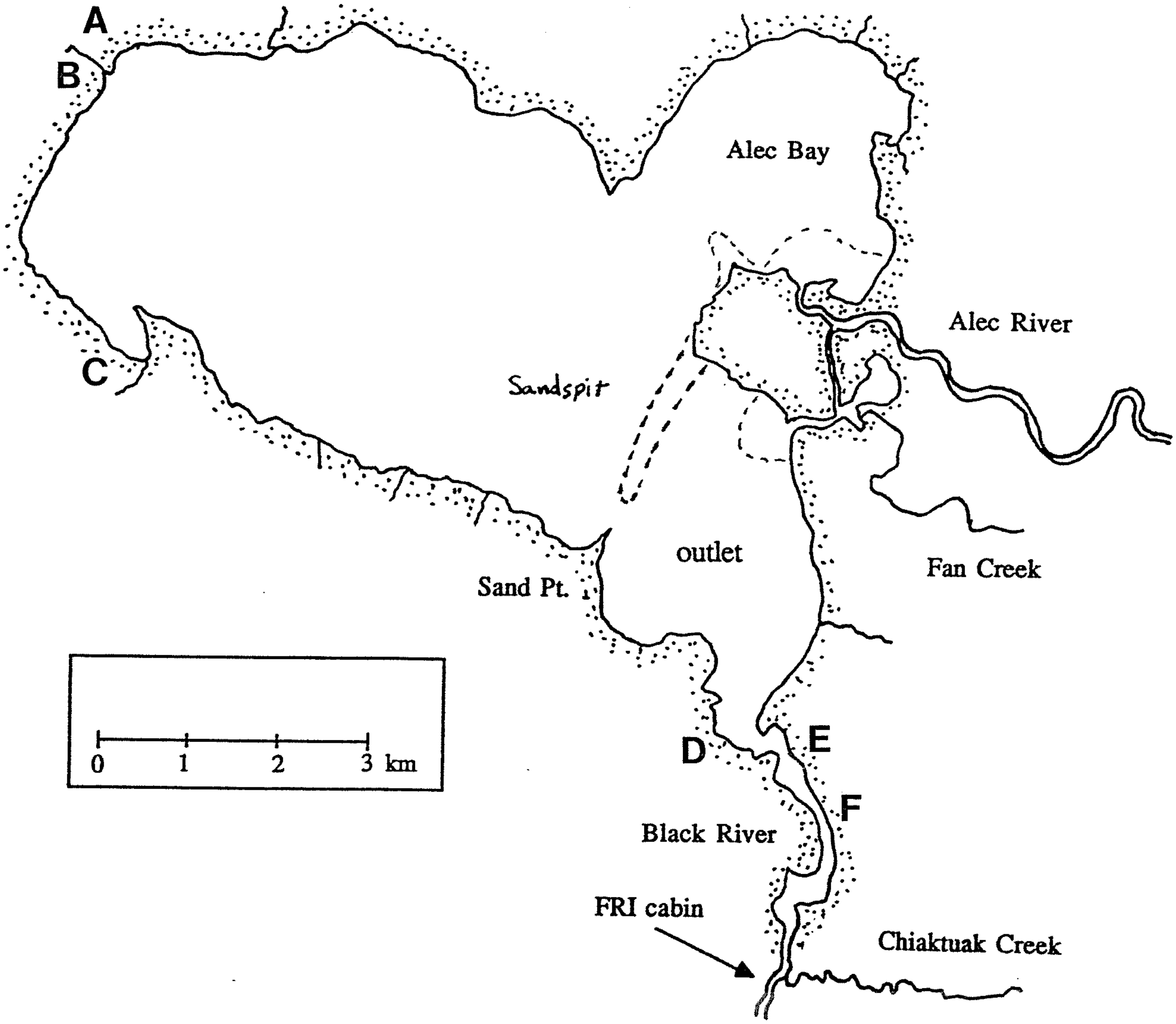


Figure 3. Map of Black Lake and sampling locations. A: North Crater Cr. station; B: South Crater Cr. station; C: Crooked Cr. station; D: Outlet Flats station; E: upper Black River site; F: lower Black River site.

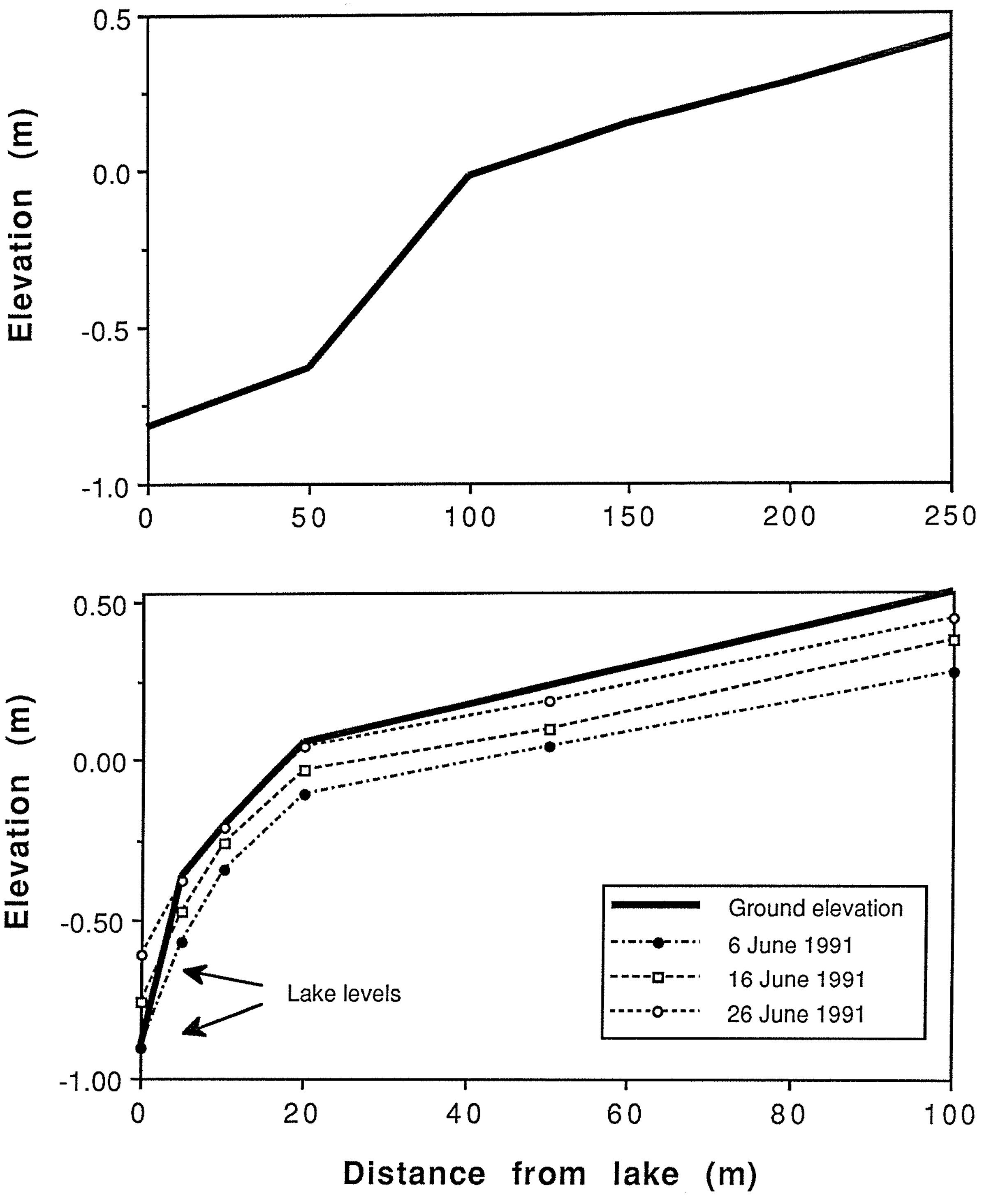
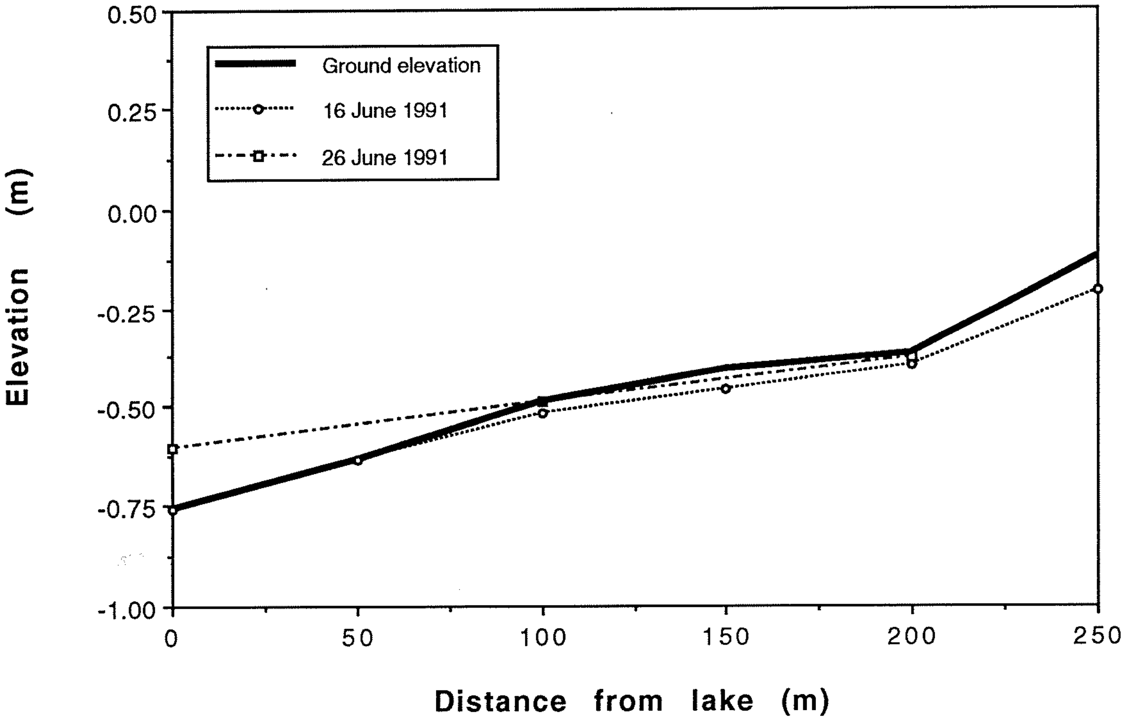


Figure 4. Changes in ground (solid line) and groundwater (dash line) elevation with distance from Black Lake. Upper and lower graphs represent the Outlet Flats and Crooked Cr. stations, respectively. Zero elevation represents the elevation of the benchmark at the Outlet of Black Lake.



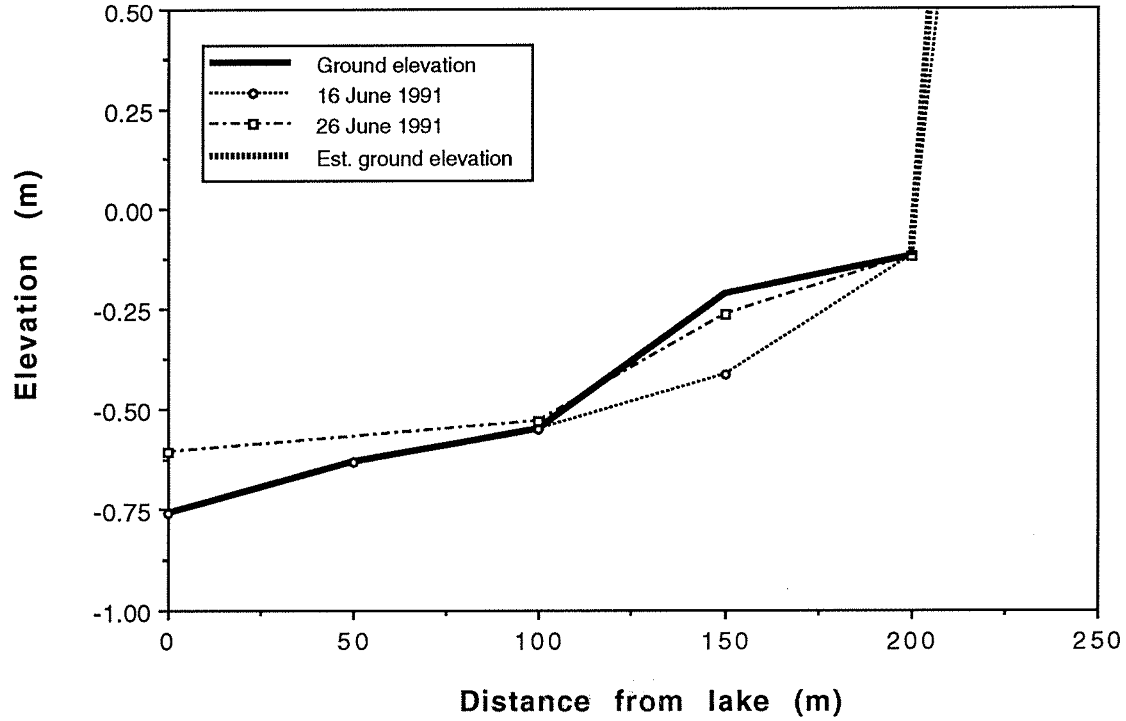


Figure 5. Changes in ground (solid line) and groundwater (dash line) elevation with distance from Black Lake. Upper and lower graphs represent the South Crater Cr. and North Crater Cr. stations, respectively.

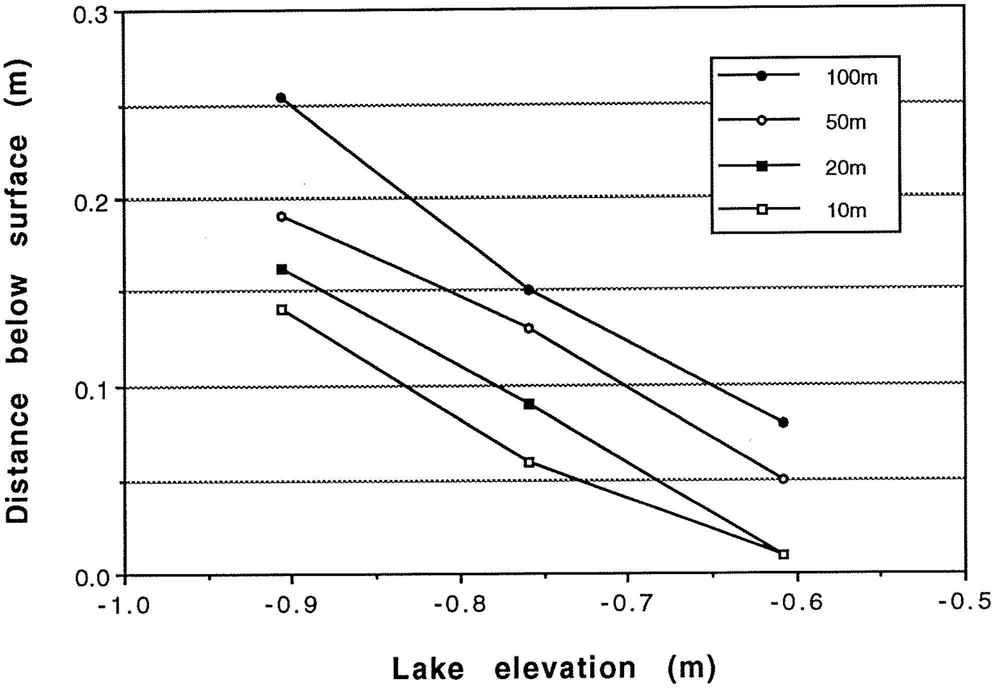


Figure 6. Relationship between water depth below the ground surface, lake elevation, and distance from the lake near Crooked Cr. The distances from the lake (10 to 100 m) were measured when lake level was at -.906 m.

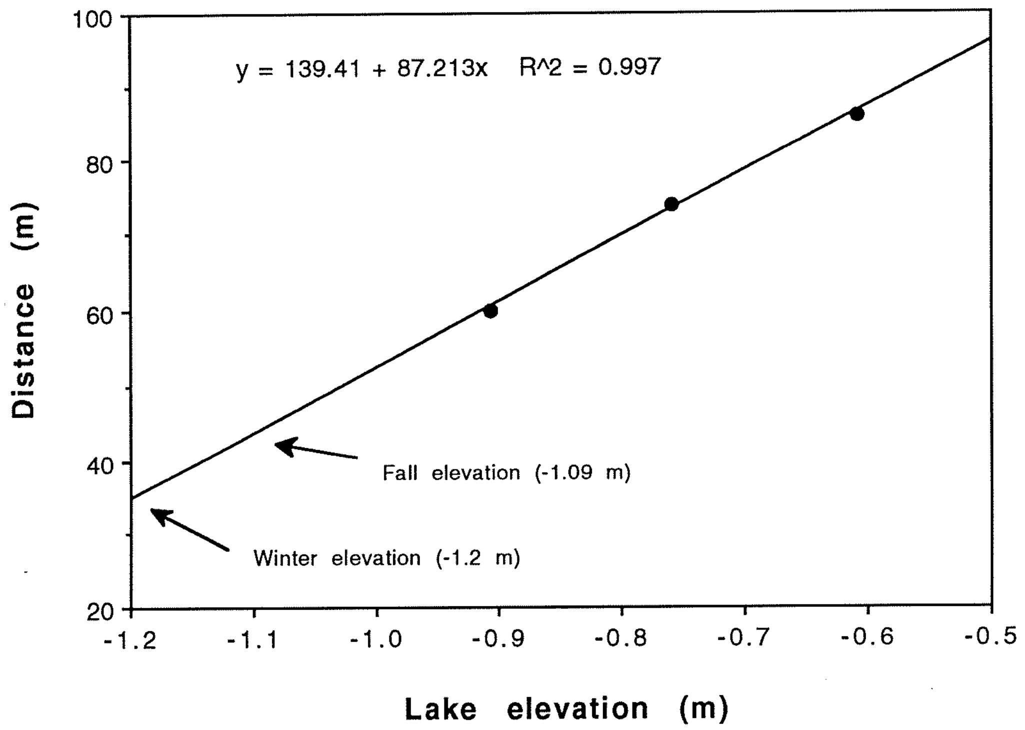


Figure 7. Horizontal distance (m) to reach a 1-m rise in groundwater elevation at several lake levels.

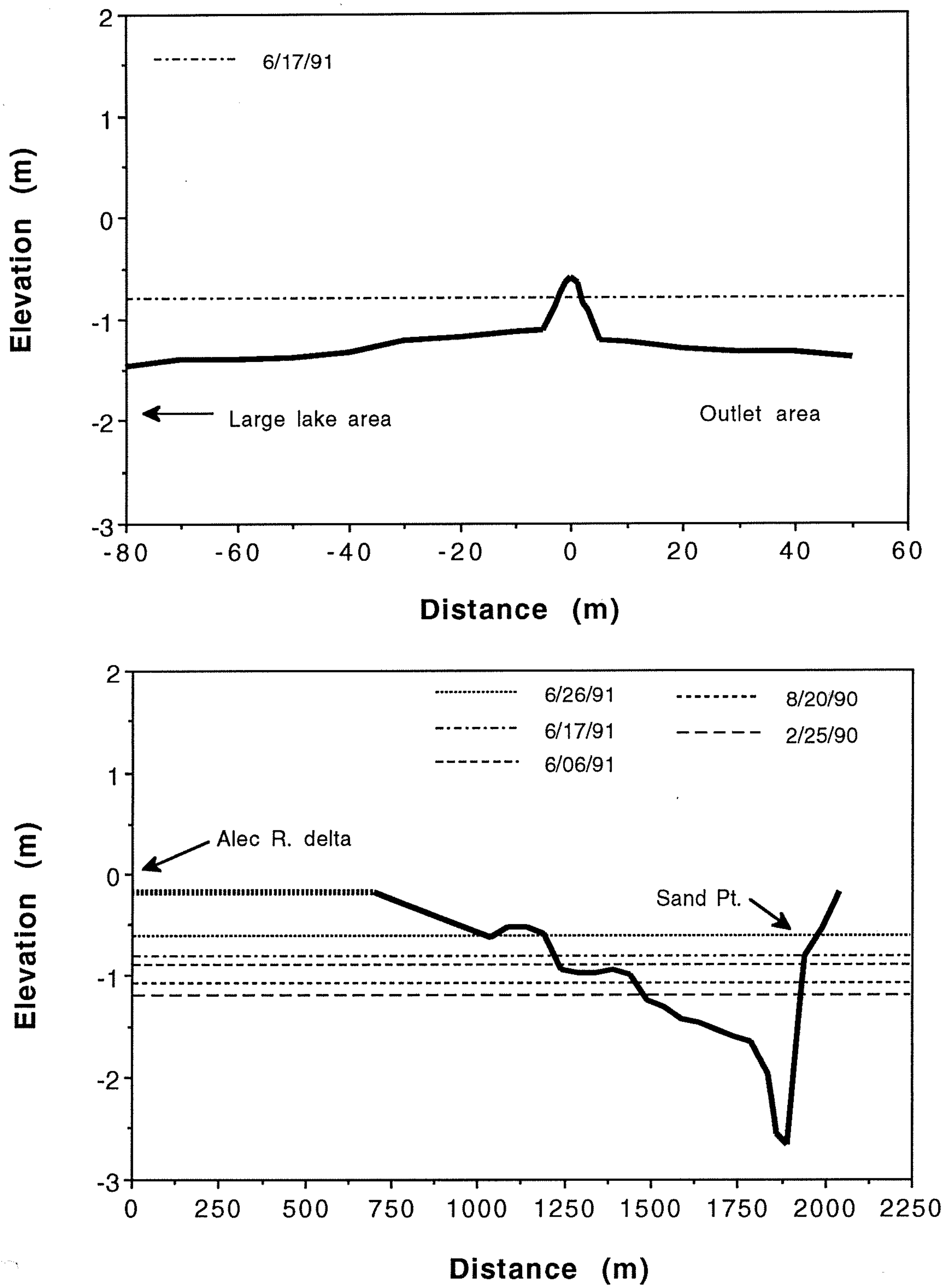
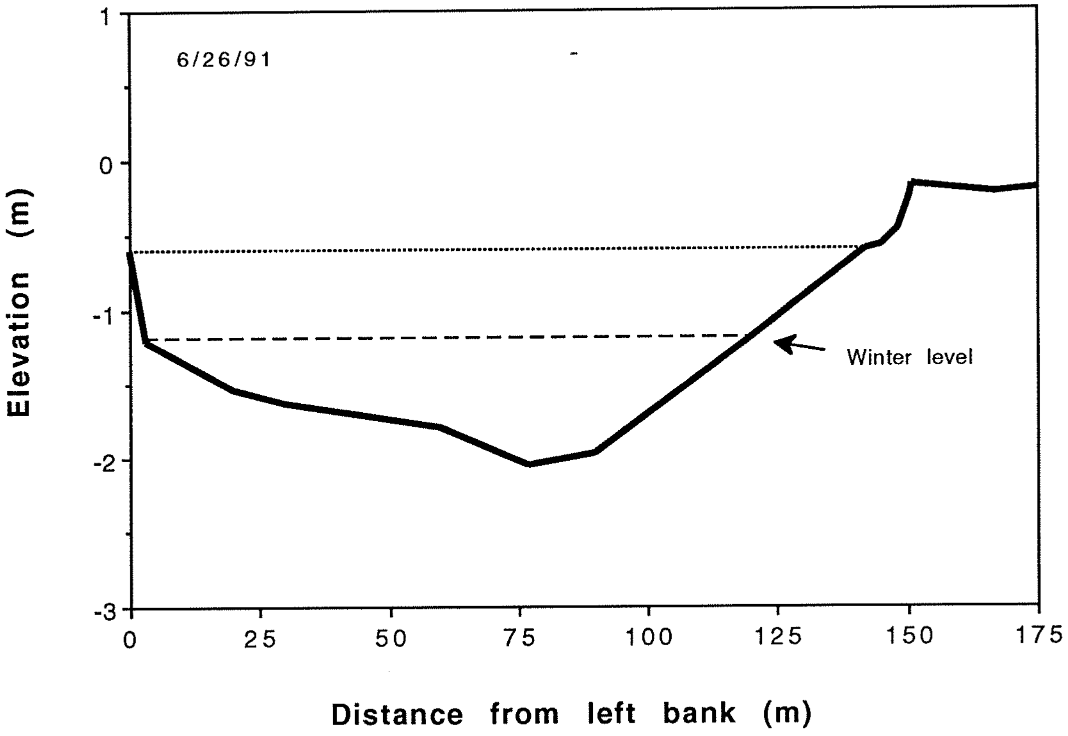


Figure 8. Cross-sectional (upper graph) and longitudinal (lower graph) view of sandspit extending from Alec River delta to Sand Pt. Measurements made on 17 June 1991. Horizontal dash lines represent lake level during other time periods.



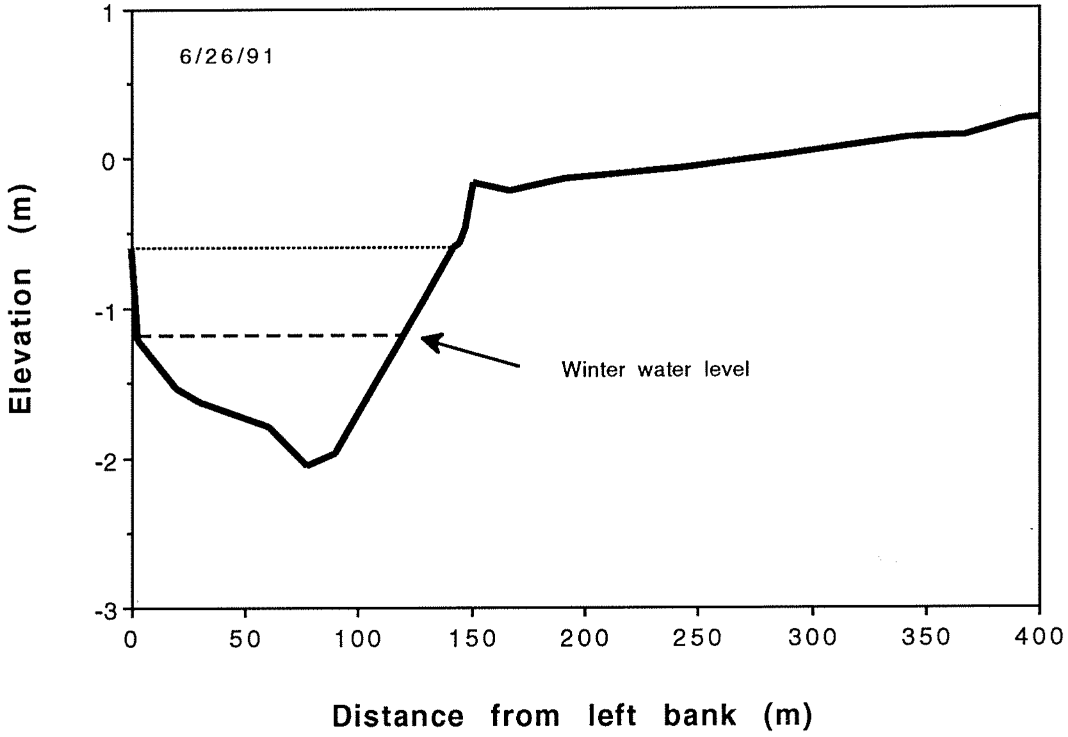


Figure 9. Cross-sectional profiles of Black River (upper graph) including the right bank (lower graph) approximately 400 m from the lake outlet. Lake level was -.608 on 26 June 1991.

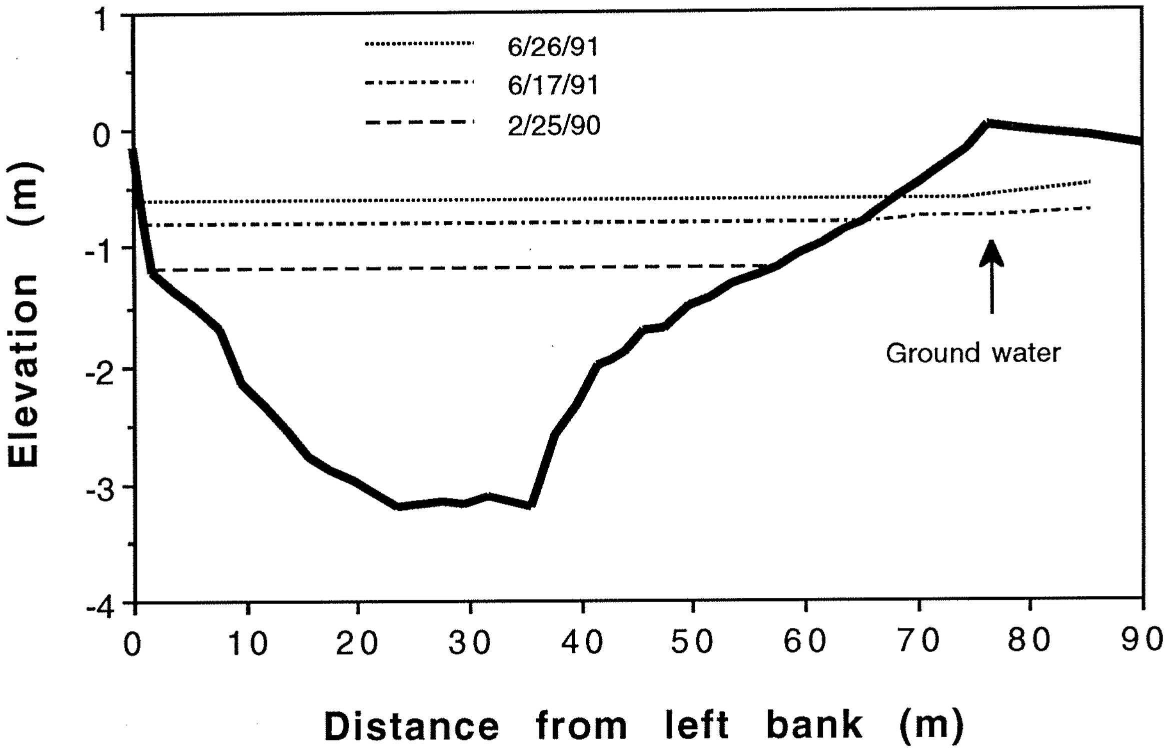


Figure 10. Cross-sectional profile of Black River approximately 1100 m below the lake outlet. Lake level on 17 June, 26 June and 25 February 1990 were -.806 m, -.608 m, and -1.2 m, respectively.

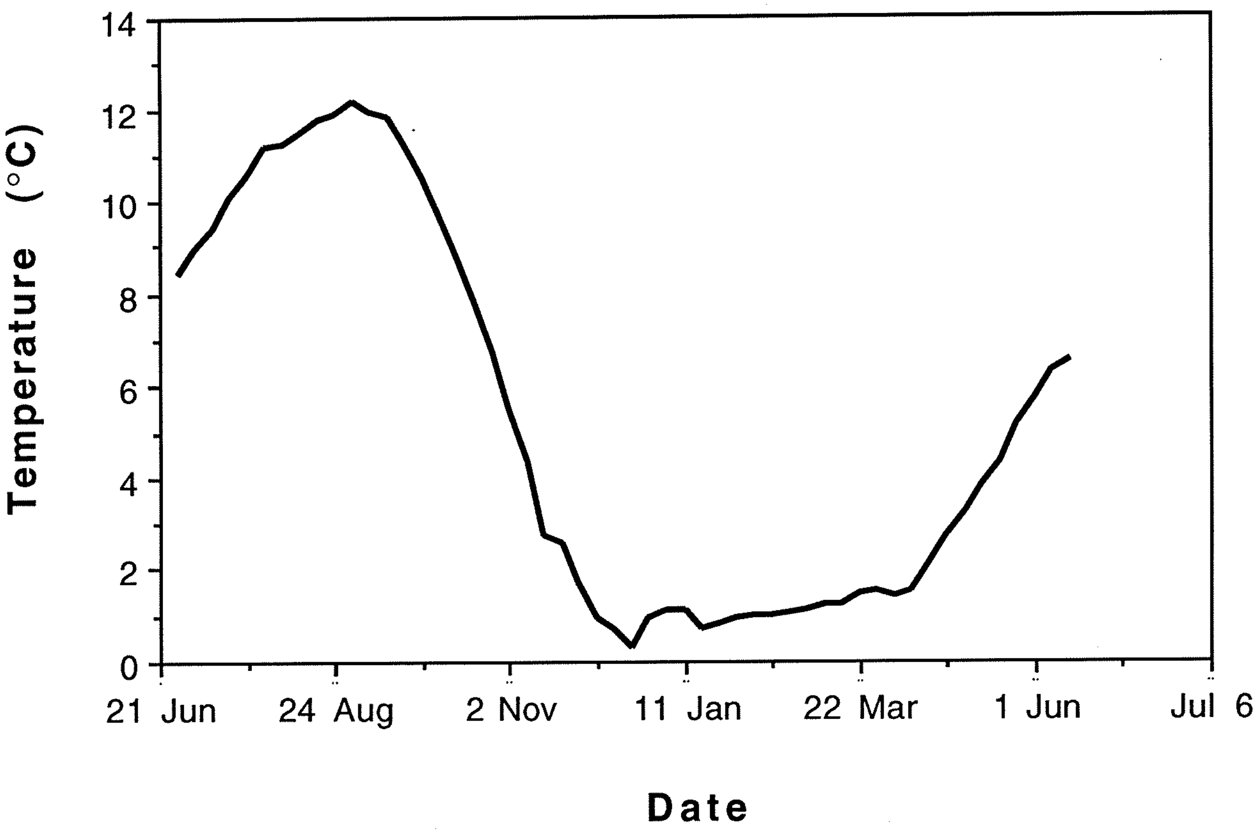


Figure 11. Weekly mean water temperature of Chignik Lake outlet during 23 June 1990 to 10 June 1991. Temperatures were measured 10 m below the surface.

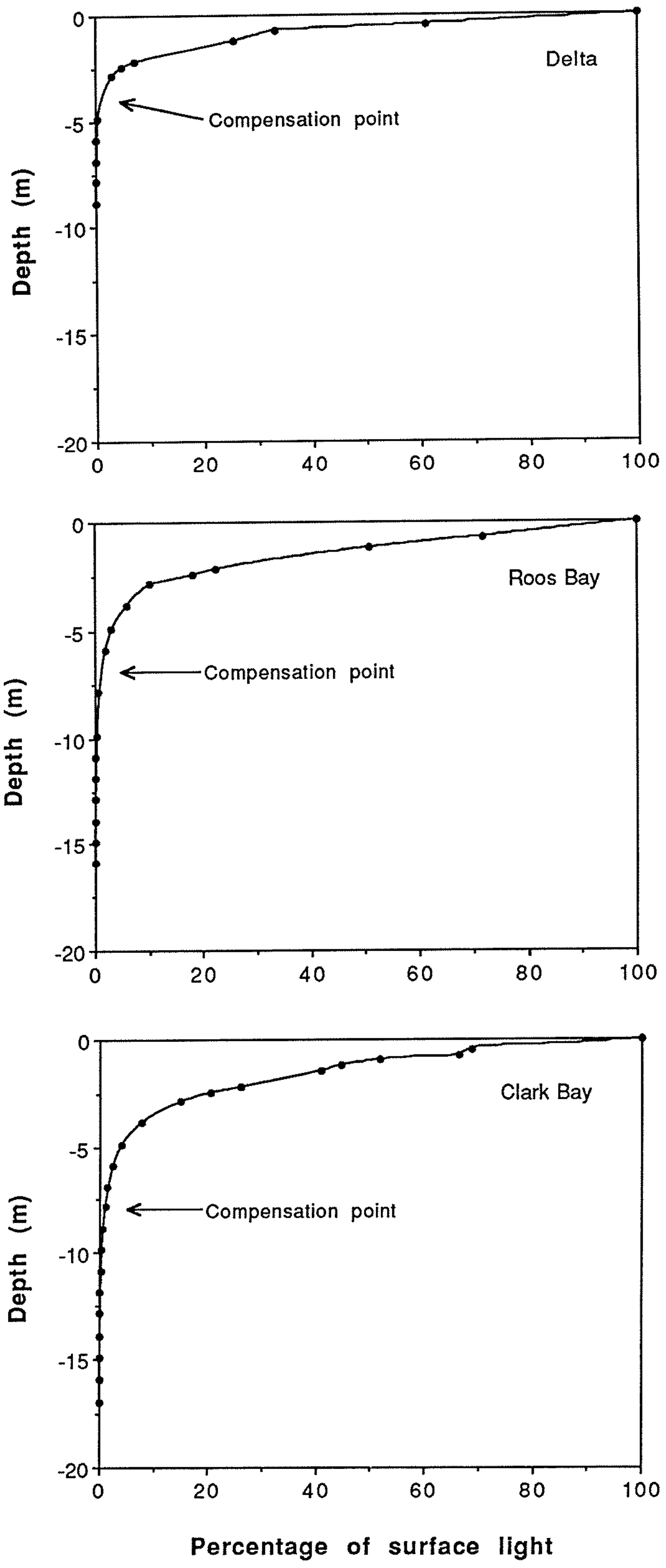


Figure 12. Light penetration measured as a percentage of surface light in three areas of Chignik Lake. Measurements taken during 1300 to 1345 h on 10 June 1990.

Table 1. Variability of adult sockeye salmon production among lake systems in western and central Alaska.

Lake system	Brood years	Return per spawner ± SD	Coef. variation
Black	1965-84	3.10 ± 2.20	0.709
	1972-84	3.38 ± 2.31	0.69
Chignik	1965-84	4.64 ± 2.06	0.44
	1972-84	3.92 ± 1.29	0.33
Wood R.	1972-85	2.83 ± 1.59	0.56
Ugashik	1979-85[a]	3.09 ± 1.30	0.42
Egegik	1972-85	7.00 ± 3.05	0.44
Red River	1972-83	2.59 ± 1.50	0.58
Kasilof	1972-84	6.10 ± 2.91	0.48
Kenai	1972-84	7.50 ± 3.69	0.49
Coghill	1972-84	7.50 ± 10.5	1.40
	excl. 1976&77[b]	3.56 ± 1.10	0.31

[a] Brood years 1972-78 were excluded from the analysis because spawning escapements were exceptionally small.

[b] Brood years 1976 and 1977 were excluded because return per spawner during these adjacent years was unusually high (19 to 39) relative to other years (1.6 to 5.5).

Table 2. Indices of emerging sockeye salmon abundance along shoreline spawning grounds of Chignik Lake during June, 1986 to 1991. Values are fry/m^2/30 days.

Year	1986	1987	1988	1989	1990	1991
Average	89	60	104	16	17	34
Geometric mean	34	37	43	5	7	11
Years when adults return	90&91	91&92	92&93	93&94	94&95	95&96

APPENDIX

TECHNICAL MEMO

TO: Greg Ruggerone, Fisheries Research Institute, U.W.
FROM: Bob Denman, Jones & Stokes Associates
DATE: April 6, 1992
SUBJECT: Alec River & Black Lake - Hydrology, Sediment Transport

INTRODUCTION

This technical memo presents the results of an initial investigation into the sediment transport capabilities of the Alec River. In addition, this memo contains the probable impacts of raising Black Lake on the fluvial sedimentation patterns at the mouth of the Alec River at Black Lake.

SEDIMENT TRANSPORT

Methodology. The most accurate method to determine sediment transport in a river system such as the lower Alec River would be to physically measure sediment transport over a variety of flow conditions. These measurements, coupled with an accurate record of river discharge, could produce a reliable annual sediment discharge rate for the river system. Given the lack of sediment transport measurements and the minimal flow data, sediment discharge formulas are the most reliable method to estimate sediment transport.

Sediment transport formulas based on flume and field data have existed since the 1950's, yielding results differing by orders of magnitude. Obviously, variation in the many factors affecting sediment transport have been difficult to quantify. Of the many types of rivers studied, the most statistically valid sediment transport data generated by formulas come from river systems like the Alec which possess relatively low gradient and small substrate. This is in part due to the relatively laminar flow exhibited by these streams (thus allowing the application of standard hydraulic principles), but also the physical ease with which field verification/calibration of data can be obtained.

In order to determine the most appropriate formula for use in the Alec River system, I investigated 10 of the most commonly used sediment transport formulas. Each of these formulas possesses its own assumptions and limits, which I weighed in determining the most applicable for the Alec. All of the equations utilize basically the same input data; namely stream geometry data such as depth, width and slope, and other parameters such as substrate size, water velocity, particle fall velocity, and shear stress associated with water and particle movement. Given the conditions in the lower Alec basin, the work by Chih Ted Yang appears to be the best suited to estimating sediment transport (Yang 1973). It should be noted that the USGS also determined that results from 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 is based on unit stream power, expressed as an expansion of the product of stream velocity and slope (Yang and Molinas 1982). As the equation is based on the ability of the stream to transport, it assumes that sediment transport is not limited by the quantity of material available for transport. Given conditions in the Alec, I believe this to be a valid assumption. While the equation is rather involved, the following variables are needed to complete the analyses:

- Particle fall velocity
- Mean particle size
- Kinematic viscosity
- Shear velocity
- Average velocity
- Energy slope
- Average flow velocity at incipient motion of particle

The product of the equation is suspended sediment concentration in ppm (which for the concentrations we are dealing with is equivalent to mg/L). It should be noted that the methodology and assumptions inherent in the equation consider both the bed-load and suspended load. In other words, the sediment concentration predicted by the equation should account for all particle movement within the river system.

Results. The first conditions input were those we encountered during the last week of August 1990. At the measured flow of 460.5 cfs (13.04 cms), the predicted sediment concentration is 10.5 mg/L. Given the clarity of the water we observed, I would say this concentration is reasonable. Assuming a sediment bulk density of 1.65 g/cc, this concentration and river flow translate into a sediment output rate of 7.1 cubic meters per day. 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.

Obviously, the key question is how the flow parameters we observed during that week relate to what happens during the remainder of the year. As you know, sediment transport is a very dynamic process, with the majority of material being transported during relatively infrequent high flow events. In order to model a higher flow, I applied the Yang equation to expected conditions during a high flow event which would roughly correspond 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 as opposed to the August 1990 average velocity of 1.7 ft/sec. Utilizing this velocity in the Yang equation, the average sediment concentration would be 18.6 mg/L. Having not seen the Alec at high flow, I cannot say whether this is an accurate number, but it appears to be on the low side.

Assuming for calculation's sake that this concentration is valid, it equates to a sediment delivery rate of 67 cubic meters per day.

Conclusions. Utilizing the Yang sediment transport formula for sand bed rivers, sediment transport rates for Alec River vary between 7 and 67 cubic meters per day. I have assumed that all sediment carried by the river eventually reaches the lake. Without flow data, it is very difficult to determine an overall annual sediment loading to Black Lake. Based on what we do know about river flow, some rough estimates are possible. If, for example, we assumed 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. Due to the obvious accretion occurring within the lake, sediment transport rates for the upper Black River are considerably less than those of the Alec.

SEDIMENTATION PATTERNS/LAKE LEVEL INCREASES

The following is a rather qualitative discussion of the probable impacts of stabilizing the level of Black Lake near high water on the sedimentation patterns at the mouth of Alec River. It is assumed that lake levels stabilized at a level zero to one meter above the present low water level. The most profound impact of this action on the sedimentation pattern would be the inundation of low elevation areas of the current delta and a portion of the lower Alec River. The resulting lowered water velocities in the inundated areas would force sediment to fall out of suspension further "up river" than that which presently occurs.

According to the information you sent me regarding lake levels and the data we took in August 1990, the proposed lake level (~0.2 m elev.) would be 69 cm above that which we observed in August. Given the gradient in the lower Alec River, this level would inundate the river to a point approximately 100 ft upstream of the channel split.

Following raising of the lake level, sedimentation within the inundated channels would commence immediately. Much of the accretion would likely occur in the area of the sand bar which divides the river at the channel split. As the channel and delta bed elevation rises, flow would seek alternative routes. The preferred routes would be those of lowest topographic elevation and least resistance to erosion. It is likely that new channels would be created at or near the newly formed delta.

Another aspect of inundation with respect to sedimentation patterns would be the role of wind on sediment movement. As we theorized in August 1990, strong winds and shallow depths may be partially responsible for the formation of the spit in Black Lake. By raising the lake level, the sediment that once was deposited by the river near the spit would now be deposited thousands of feet "upstream," where wind action would likely play a less important role in spit accretion. Also, raising the lake level would inundate the spit, where wave action may erode the spit. In fact, some of the old delta could be subject to this erosion once inundated.

In summary, stabilizing the lake level near high water would cause the inundation of the existing Alec delta and the creation of a new delta near the location of the channel split. At some point in the future, new channels would be created in the delta, forming a feature similar in size and shape to the existing multi-channeled delta. Due to the elimination of lake level fluctuation, vegetation colonization of the delta would likely proceed at a faster rate than that which is occurring at the present delta.

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