US Army Corps of Engineers
Alaska District

Black Lake Ecosystem Restoration Technical Report

October 2012

Executive Summary

This report investigates the physical and biological conditions at Black Lake on the Alaska Peninsula in southwestern Alaska. Black Lake provides prime rearing habitat for sockeye salmon, a critical commercial and subsistence resource to the local population. Changes observed in Black Lake over the past several decades include reduced depths and volumes. There is concern that continued reductions in depth and volume would result in harmful and unrecoverable impacts to the salmon that utilize the habitat in Black Lake. Investigations conducted as part of this study have determined that the changes observed in Black Lake are in response to geomorphic changes in the river that drains it. While Black Lake may experience further reductions in volume, the risk does not appear imminent based on recent indications that Black Lake could be approaching a new state of equilibrium. Nevertheless, continued monitoring is recommended by periodically measuring the volume of Black Lake and elevation changes in the lake's outlet and the upper reach of Black River below the lake outlet. Those measurements, coupled with an annual assessment of Chignik sockeye smolt production, would establish whether Black Lake is still degrading, and if so, the ensuing impact on system-wide sockeye production. The above measurements would also help determine whether future intervention may be warranted. Numerous structural measures were considered to alleviate the impacts of reduced depths and volumes in Black Lake to date; however, none are recommended for implementation at this time.

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Black Lake USGS data collection summary

Griffiths, J., Schindler, D., & Seeb, L.W. (2012), *Habitat connectivity and patterns of stock condition in the Chignik Watershed*.

Kaufman, Darrell, *Long-term sedimentation rate in Black Lake, Alaska, School for Earth Sciences & Environmental Sustainability, Northern Arizona University, May 2012.*

StSaviour, A. and D. Hunt. 2012. Sockeye salmon smolt investigations on the Chignik River, 2011. Alaska Department of Fish and Game, Fishery Data Series No. 12-17, Anchorage.

Introduction

Black Lake is one of two major lakes in the Chignik River drainage and supports an early run of sockeye salmon, which is critically important culturally and economically to several Native Alaskan communities. Additionally, the Black Lake sockeye run contributes to several major commercial salmon fisheries on the south side of the Alaska Peninsula and provides an important early-season food source for local wildlife, including a large brown bear population and marine mammals. While Black Lake is highly productive, averaging more than 1.2 million sockeye salmon run annually, physically the lake is quite shallow, with a maximum depth of 13.6 feet.

Reductions in the depth and volume of Black Lake have been documented in various reports and journal articles since the early 1990s. Continued depth reductions in Black Lake could detrimentally impact the quality and quantity of sockeye fry rearing habitat and is the topic of this technical report.

Background Information

Study Authority

Section 206 of the Water Resources Development Act of 1996 (PL 104-303), as amended.

Location of Project

Black Lake is a large shallow lake on the Alaska Peninsula in southwestern Alaska. Black Lake is drained by the Black River, which drains into Chignik Lake about 7.5 miles downstream. Chignik Lake is drained by the Chignik River, which drains into Chignik Lagoon, then Chignik Bay of the North Pacific Ocean. Figure 1 is an overview of this diverse project area. The closest community to Black Lake is the Native Village of Chignik Lake, which is approximately 13 miles southeast of the outlet of Black Lake. The project location is within the Lake and Peninsula Borough.

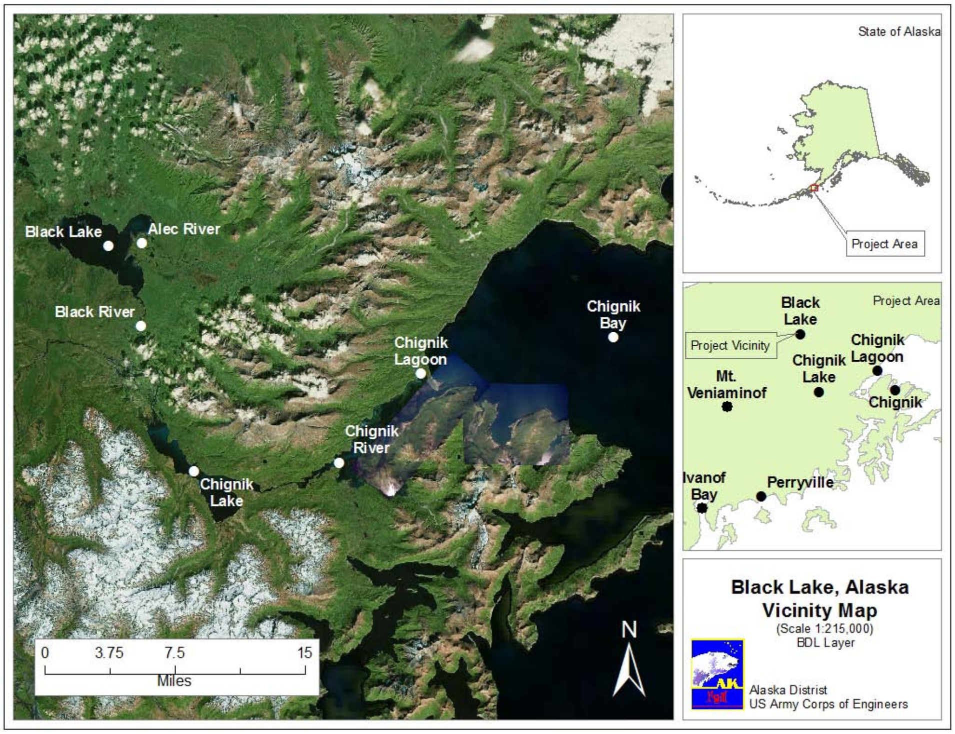

Figure 1. Black Lake drainage and local communities

Stakeholders

The Lake and Peninsula Borough

Located southwest of Anchorage along the Alaska Peninsula, the Lake and Peninsula Borough encompasses approximately 23,782 square miles of land (roughly the size of West Virginia) and 7,125 square miles of water. The Lake and Peninsula Borough was incorporated in April 1989 as a Home-Rule Borough with a manager form of government. A seven-member assembly acts as the legislative body for the borough. The borough is predominantly rural and contains 17 communities, six of which are incorporated as second-class cities. Village or Tribal Councils govern the remaining 11 communities (http://www.lakeandpen.com).

While the study was conducted at full Federal expense, the Lake and Peninsula Borough has expressed willingness to be the non-Federal cost-sharing partner for project construction if an acceptable plan is developed. The borough acted in partnership with the Chignik Regional Aquaculture Association, who requested the initiation of the study and has been the main point of contact throughout.

Local Communities

Five local communities rely upon Chignik fishery resources as a source of income and subsistence food. The communities are Chignik Lake (population 69), Chignik Lagoon (population 77), Chignik (population 102), Perryville (population 130), and Ivanoff Bay (population 7) (2011 Alaska Department of Labor Estimates). Populations in Chignik Bay and Chignik Lagoon nearly quadruple in size in the summer months due to the influx of Chignik commercial fisherman, employees of fish processing facilities, and local family summer residents. Figure 1 shows the location of the five communities as well as Black and Chignik Lakes.

Chignik Regional Aquaculture Association (CRAA)

The goal and mission statement of CRAA is as follows:

The long-term goal of the Chignik Regional Aquaculture Association (CRAA) is to increase local salmon production. In accordance, CRAA is committed to protecting, enhancing, and rehabilitating Chignik salmon resources and improving commercial fishery management and stock utilization.

Further, CRAA is committed to ensuring that traditional subsistence resources and opportunities are protected and maintained for the people of Chignik Lake, Chignik, Chignik Lagoon, Ivanoff Bay, and Perryville.

Additionally, CRAA will support product promotion, fair marketing, and harvest strategies that advance the economic foundation and commitment to the Chignik salmon fishery, absent of any financial obligations.

CRAA board members represent local commercial, sport, and subsistence fishermen, as well as local governments, tribes, and seafood processors. CRAA has served as the point of contact between the Corps and the local sponsor throughout this study.

Alaska Department of Fish & Game Division of Commercial Fisheries (ADF&G)

The mission of the ADF&G Division of Commercial Fisheries is to manage subsistence, commercial, and personal use fisheries in the interest of the general well being of the people and economy of the state, consistent with the sustained yield principle, and subject to allocations through public regulatory processes (http://www.adfg.alaska.gov).

Fishery resources of concern in this study are managed by ADF&G as part of the Chignik Management Area (CMA). The CMA includes the local communities of Chignik Lake, Chignik, Chignik Lagoon, Ivanoff Bay, and Perryville. The major effort of ADF&G in the CMA is the day to day management of the Chignik commercial salmon fishery that occurs each summer. A seasonal fish weir is constructed each season adjacent to a field station located between Chignik Lake and Chignik Lagoon from which the commercial fishery is managed. ADF&G has been an active collaborator throughout the study.

University of Washington Fisheries Research Institute (FRI)

The Fisheries Research Institute (FRI) was established in 1948 on the University of Washington campus as a base for salmon research in Alaska. They have maintained a research station, one of six in Alaska, at Chignik Lake since 1955. Early FRI work in the

Chignik Lakes formed the basis for current fisheries management in this region (http://fish.washington.edu/research/alaska/history.html#chignik). The FRI has been an active collaborator throughout the study.

Identified Problems

The local sponsor has concerns that the ongoing changes to the physical conditions of Black Lake (depth and temperature) will lead to increased competition between two sockeye salmon stocks during their juvenile life history. It is feared that under the future without project conditions, increased competition from Black Lake fry fleeing degraded habitat in Black Lake could result in lower abundance of the late-run Chignik Lake stock, resulting in an overall loss of productivity in the entire Chignik system. Another concern is increased interspecies competition between sockeye fry and resident species such as stickleback and pond smelt. The Chignik fishery is of critical importance to local subsistence and commercial fishermen as well as area wildlife.

Of particular concern for this study was answering the following questions regarding the future without project conditions.

Will Black Lake continue to become shallower and warmer?

Continued shallowing of Black Lake will further diminish the quality and quantity of sockeye fry rearing habitat, further reducing the utilization of the lake by sockeye fry. In particular, increased water temperatures due to reduced volumes and depths were a concern. Sufficient increases in water temperatures could cause salmon and other species to seek refuge in cooler water such as that provided by the deeper Chignik Lake.

What is the mechanism by which Black Lake is becoming shallower?

While all previous investigations attributed long term reductions in Black Lake depth and volume to reduced water surface elevations (WSE), it is also possible for a lake to experience reductions in depth and volume due to sedimentation. Identifying the relative contributions of lowered WSE and sedimentation to the overall reductions in depth and volume documented at Black Lake is an important consideration when considering suitable management measures for implementation.

Will geomorphic processes isolate habitat in the upper basin of Black Lake?

Further, and potentially complete, extension of a spit across Black Lake threatens to impair water circulation and sediment and nutrient transport processes, especially in the upper, principal basin of the lake. This could make it difficult for fish to utilize the upper basin of the lake. Salmon utilization of Black Lake may be reduced as a greater proportion of flows enter Black Lake from the south fork of the Alec River. With greater flows from the south fork of the Alec River, quality rearing habitat within Black Lake could be greatly reduced.

Summary of Existing Conditions

Black Lake is a large shallow lake located on the Alaska Peninsula in southwestern Alaska. The principal water source for Black Lake is the Alec River. The Alec River originates about 12 miles east of Black Lake. A large delta intruding into the lake basin from its eastern shore has formed where the Alec River and Black Lake meet. Black Lake is drained by the Black River which drains into Chignik Lake about 7.5 miles downstream. Chignik Lake is drained by the Chignik River, which drains into Chignik Lagoon, and then into Chignik Bay of the North Pacific Ocean. Figure 1 is an overview of this diverse project area. For full details, the Hydraulics and Hydrology Report, which is included as an appendix to this report, should be consulted.

Reductions in the depth and volume of Black Lake attributable to lower long-term water surface elevations (WSEs) have been published in various reports and journal articles since the early 1990s. Table 1 provides a listing of the published lake WSE decline estimates ranging between 1 and 6.5 feet. Similarly, estimates of Black Lake volume reductions have ranged from 23 to 44 percent. The basis of these reports comes from anecdotal evidence and various lake measurements tied to various datums over time. Lack of vertical control between the multiple datums made direct comparison between these different measurements problematic and added substantial uncertainty to the quantification of the losses in depth and volume documented in Black Lake.

Table 1. Published declines in Black Lake Water Surface.

Report	Source	Estimated Lake Elevation Decline	Range of Years
Conclusions of 1993-1994 Black Lake Investigations	CH2MHILL, 1994	1-2 feet	Unknown
Geomorphic Reconnaissance of the Black Lake Area, Alaska Peninsula	Buffington, 2002	4.6 feet	1963 – 2001
Rapid Natural Habitat Degradation and Consequence for Sockeye Salmon Production in the Chignik Lakes System, Alaska	Ruggerone, 2003	2.2-3.6 feet	1949 – 2003
Evaluation of the Reduction in Water Storage Capacity of Black Lake, AK	Elhakeem & Papanicolaou, 2008	At least 3.3 feet	1953 – 2008
Effects of simultaneous climate change and geomorphic evolution on thermal characteristics of a shallow Alaskan Lake	Griffiths, Schindler, Balistrieri, & Ruggerone, 2011	6.5 feet	1960 – 2011

A progressively larger portion of flow from the Alec River has been entering Black Lake via a southern channel that discharges not far from the outlet of the lake (Figure 2). A spit has been extending from the Alec River delta and currently extends across a majority of Black Lake during low water levels (Figure 2). Some fear that the spit threatens to divide the lake into two basins, effectively isolating a large proportion of the habitat available in Black Lake. There is concern that continuation of these two trends would have negative impacts upon fry utilization and access throughout Black Lake.

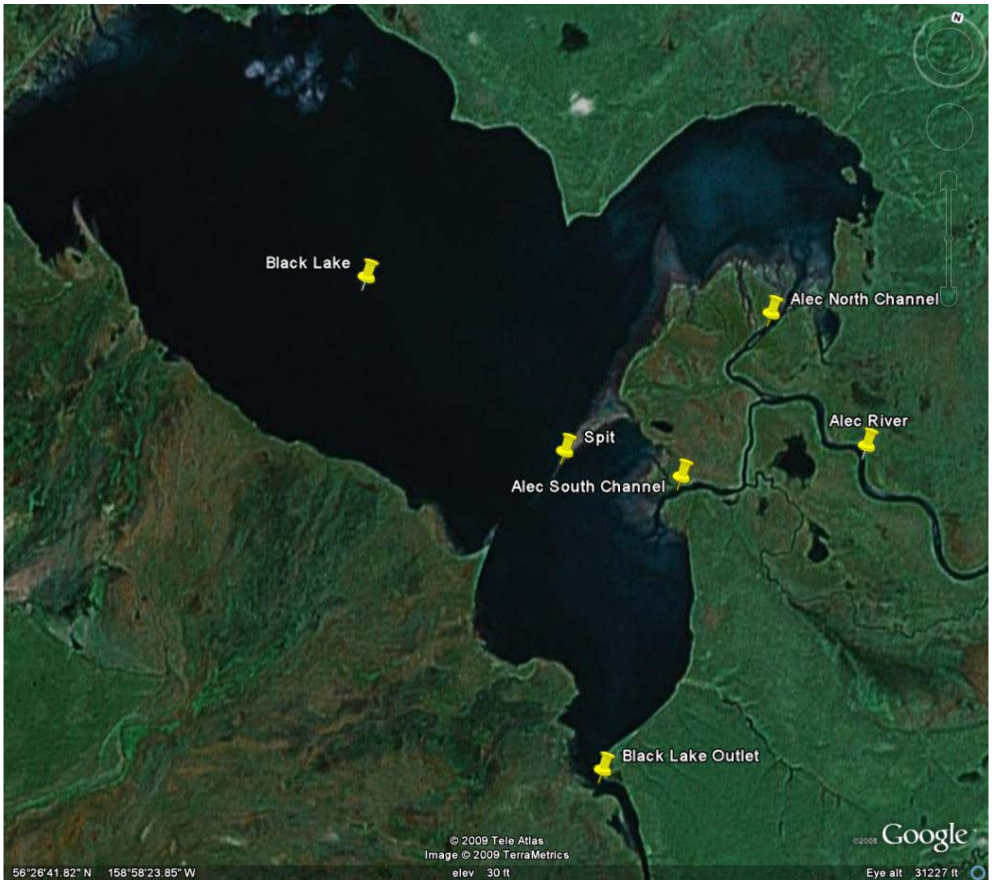

Figure 2. **Overview of Alec River and Black Lake**

Fishery Resources

Sockeye salmon are the principal salmon species returning to the Chignik/Black Lake drainage. Two runs, an early (May-July) and late run (June-September) enter the Chignik River. The early run spawns in Black Lake drainages, including the Alec River (Black Lake stock), and the late run spawns in Chignik Lake drainages, including the Black River between the lakes (Chignik Lake stock). Both runs are harvested commercially and the late run is harvested for local subsistence.

Juvenile sockeye salmon rearing in Black Lake appear to be responding to changing environmental conditions. There is evidence that when the lake was deeper, juvenile sockeye spent the winter in Black Lake. Today, indications are that most of the juvenile sockeye migrate to Chignik Lake by August, apparently in response to summer water temperatures that can approach 21° C. There is evidence that some juvenile sockeye find refuge in cooler water near creek mouths and migrate to Chignik Lake later in September.

Study funds were used to support a Fisheries Research Institute effort (Griffiths, et al 2012) to validate differences between the two salmon stocks. Data collected as part of this effort did not show a consistent statistical difference in body condition between the stocks. However, a subset of juveniles produced by Black Lake stocks seem to have a better body condition, though overall, fish that emigrated from Black Lake earlier were found to be in poorer condition after spending more time in Chignik Lake, a result that corroborates several previous studies.

Sockeye fry rearing in Black Lake have a growth advantage over sockeye fry of the same age rearing in Chignik Lake. Compared with the deeper and colder Chignik Lake, limnologically Black Lake can be very productive relatively early in the season. This early productivity can result in accelerated growth for sockeye salmon fry recently emerged from the spawning gravels in the Alec River. Black Lake fry benefit from the more or less ideal environmental rearing conditions in Black Lake until rising summer water temperatures apparently drive most of them to Chignik Lake where prey species are or can be more limited than in Black Lake. Black Lake fry are larger than Chignik fry of the same age when they enter Chignik Lake (Simmons et al in review 2012), and potentially can out-compete smaller Chignik Lake stock for available food resources, affect growth of the Chignik Lake stock, and potentially impair their freshwater survival.

The salmon fishery resources of the Chignik lakes system have been managed since the early 1900's. Early management was begun by the Federal Bureau of Commercial Fisheries and then subsequently by the Alaska Department of Fish and Game (ADF&G) since Alaska statehood in 1959. The University of Washington in Seattle created the Fisheries Research Institute (FRI) in 1948 and began work in the Chignik area in 1955 as part of ongoing Alaska salmon resource investigations. Currently, ADF&G and FRI are actively involved in Chignik salmon studies, and to a lesser but important extent, so too are the Chignik Regional Aquaculture Association and the U.S. Fish and Wildlife Service.

In addition to managing the Chignik commercial salmon fishery, ADF&G has been annually assessing the sockeye salmon smolt out-migration from the Chignik lakes system since 1994 and conducting limnological studies in Chignik and Black lakes annually from 2000. These studies provide data useful for improving system management toward the goal of ensuring that escapement levels are appropriately gauged for maximum sustainable yield. Integral to the smolt monitoring work is genetic analyses of the smolt. The aim is to allow run-specific forecasting by assigning smolt numbers to stock of origin by age class, advance escapement goal evaluation, and measure specific stock performance (production) and between-year survival variability, and also to evaluate long-term habitat changes.

Chignik sockeye smolt abundance varies annually and has averaged about 13 million for the last 18 years (Figure 3). The between-year fluctuations in smolt numbers indicate wide changeability in environmental (habitat) conditions within the Chignik drainage, which affects sockeye smolt survival and production. This level of smolt abundance indicates that the Chignik lakes system as a whole is very productive, and there is no downward trend evident at this time.

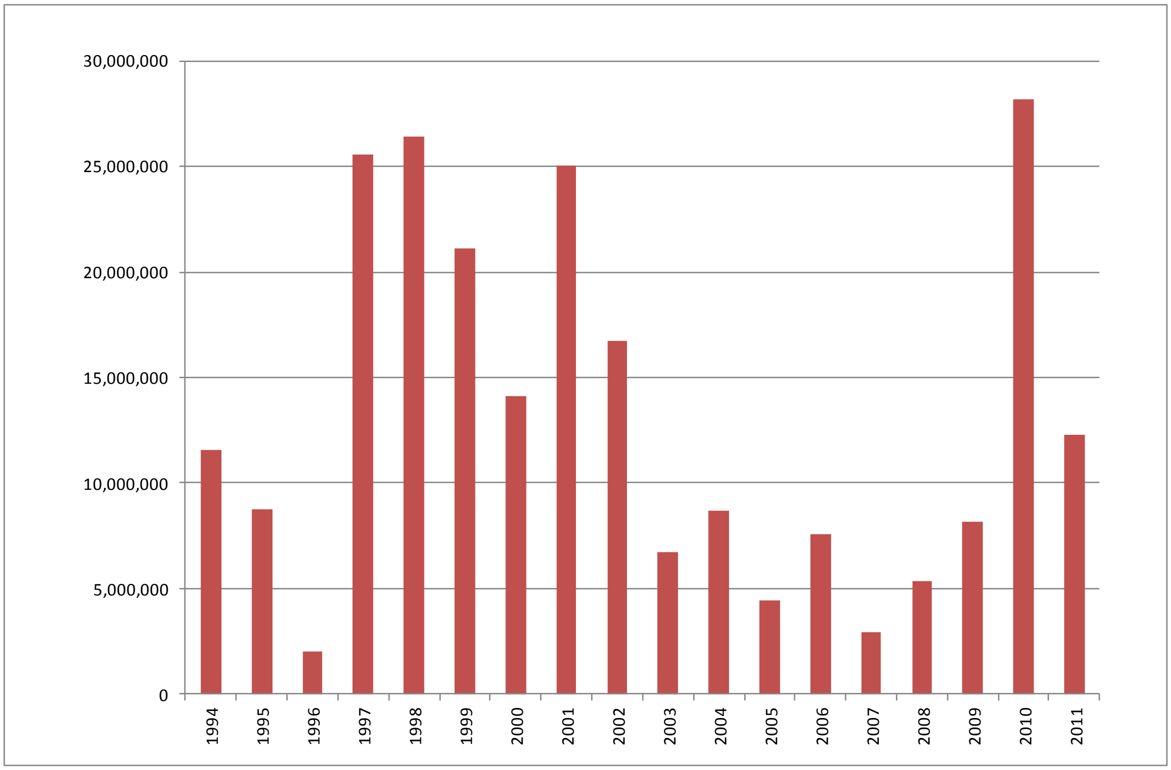

Figure 3. Annual sockeye salmon smolt emigration estimates, Chignik River 1994-2011. Emigration estimates for 1996 were underestimated. Created from data in StSaviour and Hunt, 2011

Analysis of Identified Problems

Much of the following information has been summarized from the Hydraulics and Hydrology Report, which is included as an appendix to this report. For full details, the appendix should be consulted.

Will Black Lake continue to become shallower and warmer?

As part of this study, accurate vertical and horizontal control monuments that allowed for comparison between the different historical measurements were established. A continuous lake water level (stage) gage was also installed in Black Lake. The gage record (http://waterdata.usgs.gov/nwis/uv?site_no=15297584) shows that Black Lake water levels fluctuate up to 4.5 feet on an annual basis. This period of record displays trends similar to those reported in historical documents. Lake levels rise during the spring snowmelt and then generally decrease throughout the summer, interrupted periodically with steep rises in water levels during large fall storms. Also notable in the data are daily fluctuations due to wave set-up within Black Lake. This wave set-up phenomenon is important when measuring lake water levels or when comparing historical aerial photographs. Weather conditions can change the water surface of Black Lake at a particular location within a range of approximately 3 feet (plus or minus 1.5 feet). The fact that Black Lake is subjected to weather and climate induced variations in WSE on variable time scales further complicates the comparison of historical WSE measurements.

A bathymetric survey of Black Lake was performed in 2011. The survey provided the absolute elevation of the lake bottom, as opposed to determining depths based upon the WSE at the time of the survey. A bathymetric contour map and stage (WSE) versus volume and stage versus surface area curves were generated from the data collected. This showed that at a WSE elevation of 26 feet, the average depth of the lake is 6.3 feet with a maximum depth of 13.6 feet.

To examine trends in WSE, changes in vegetation around the perimeter of the lake were used as a proxy for changes in the average WSE. To relate changes in vegetation to changes in average lake stage, two key assumptions are made: that vegetation around the lake responds to changes in average lake WSE and that the bathymetry of the lake remains relatively constant. The results of this analysis indicate that over the past 50 years, the average lake water surface elevation has decreased by approximately 1 to 2 feet. This corresponds to an average volume decrease of between 17 and 30 percent. These depth and volume reductions are less than all but one of the previous estimates documented in this report. Though the average volume appears to be declining, based on recent lake stage measurements, the water surface elevation during significant runoff events can still reach historic levels.

One of the concerns of reduced WSEs in Black Lake is an increase in water temperature due to reduced volume and depth. Sufficient increases in water temperatures could cause salmon and other species to seek refuge in cooler water such as that provided by the deeper Chignik Lake. During the course of this study, a hydrodynamic model (Griffiths, et al. 2011) was used to refine the impacts changes in lake depth and volume would have upon water temperature. The hydrodynamic model was used to simulate various future scenarios. It showed that air temperature, not depth, is the driving force determining water temperatures in large, shallow lakes subject to high wind mixing, such as Black Lake. The model predicted that small increases in WSE would actually raise water temperatures, likely due to the increase of residence time of water in the lake. With recent warming trends experienced in the region and expected to continue into the near future, it is likely that Black Lake will experience further increases in water temperature in spite of changes in WSE.

What is the mechanism by which Black Lake is becoming shallower?

While all previous investigations attributed long-term reductions in Black Lake depth and volume to reduced WSEs, it is also possible for a lake to experience reductions in depth and volume due to sedimentation. The contribution of sedimentation to the reductions experienced at Black Lake was not previously measured. Identifying the relative contributions of lowered WSE and sedimentation to the overall reductions in depth and volume documented at Black Lake is important when considering suitable management measures for implementation. To address this, sedimentations rates occurring in Black Lake for the past 50 years were estimated using lake bed coring data techniques.

A set of five sediment cores approximately 1 meter in length were sampled in Black Lake (Kaufman 2012). The tops of two cores were sampled for plutonium content to locate the depth of the onset of nuclear weapons testing (1953) and the peak of plutonium production (1963). Two cores were also analyzed for radiocarbon (^{14}C by accelerator mass spectrometry at University of California, Irvine) to generate a sedimentation-rate model that extends centuries to millennia, depending on core length and sedimentation rate. Results from the lake coring indicate that approximately 1 to 4 inches of sediment has accumulated in Black Lake since 1963. This results in a 1 to 5 percent decline in volume over the past 50 years. This represents a small proportion of the overall volume loss at Black Lake and indicates that another mechanism(s) must be accountable for a majority of the volume loss.

An often suspected cause of reduced WSE and volume in Black Lake is geological and hydrological changes in the Black River. The confluence of a sediment-laden tributary (West Fork River) to the Black River shifted downstream in the early 1960's (Buffington, 2002). Movement of the heavy sediment discharge and channel constriction of the tributary downstream in the Black River moved the Black River away from a state of equilibrium. Often, after such a disturbance, a river will respond by downcutting its channel until equilibrium is restored. Evidence of such downcutting is visible upstream from the current West Fork River confluence toward Black Lake. The evidence is extensive with numerous perched side-channels, bank erosion, and calving as far upstream as the confluence of Chiaktuak Creek (Red Salmon Creek) with the Black River, approximately 2 miles downstream of the Black Lake outlet. Signs of channel degradation diminish upstream from the confluence of Chiaktuak Creek with no visible signs of channel degradation obvious at the outlet of Black Lake.

To better understand the Black River and how it controls the WSE of Black Lake, surveys of the river were conducted in 2004 and 2011. Prior to Corps involvement, a survey was also completed in 1993. The surveyed topographic data were used to develop a hydraulic model to better understand the hydraulics of Black River. The model was built using the surveyed channel cross sections. Three separate reaches were identified in the model (Figure 4):

Reach 1 – Chignik Lake to the confluence of the West Fork
Reach 2 – Confluence with the West Fork to Chiaktuak Creek
Reach 3 – Chiaktuak Creek to Black Lake

Based on calibration and validation results, the model was considered suitable for examining the hydraulics of the Black River and responding changes to the outflow of Black Lake. The model was then used to better understand responses in the lake WSE to changes downstream in the Black River.

Based upon model results, it is believed that three mechanisms in the Black River are primarily responsible for changes in the outflow of Black Lake.

1. A shift in the inflow location of the West Fork downstream, resulting in less flow within Reach 2 and reducing the upstream back water effect. This would affect upstream WSE.

2. Rapid erosion of sediment within Reach 2 after the removal of the West Fork sediment input along this reach. Changes in the bed elevation within Reach 2 would likely affect upstream WSE.

3. Gradual long term erosion within Reach 3 as channel velocities increase as a result of mechanisms 1 and 2. Lowering of the average bed elevations within Reach 3 would affect the WSE of Black Lake.

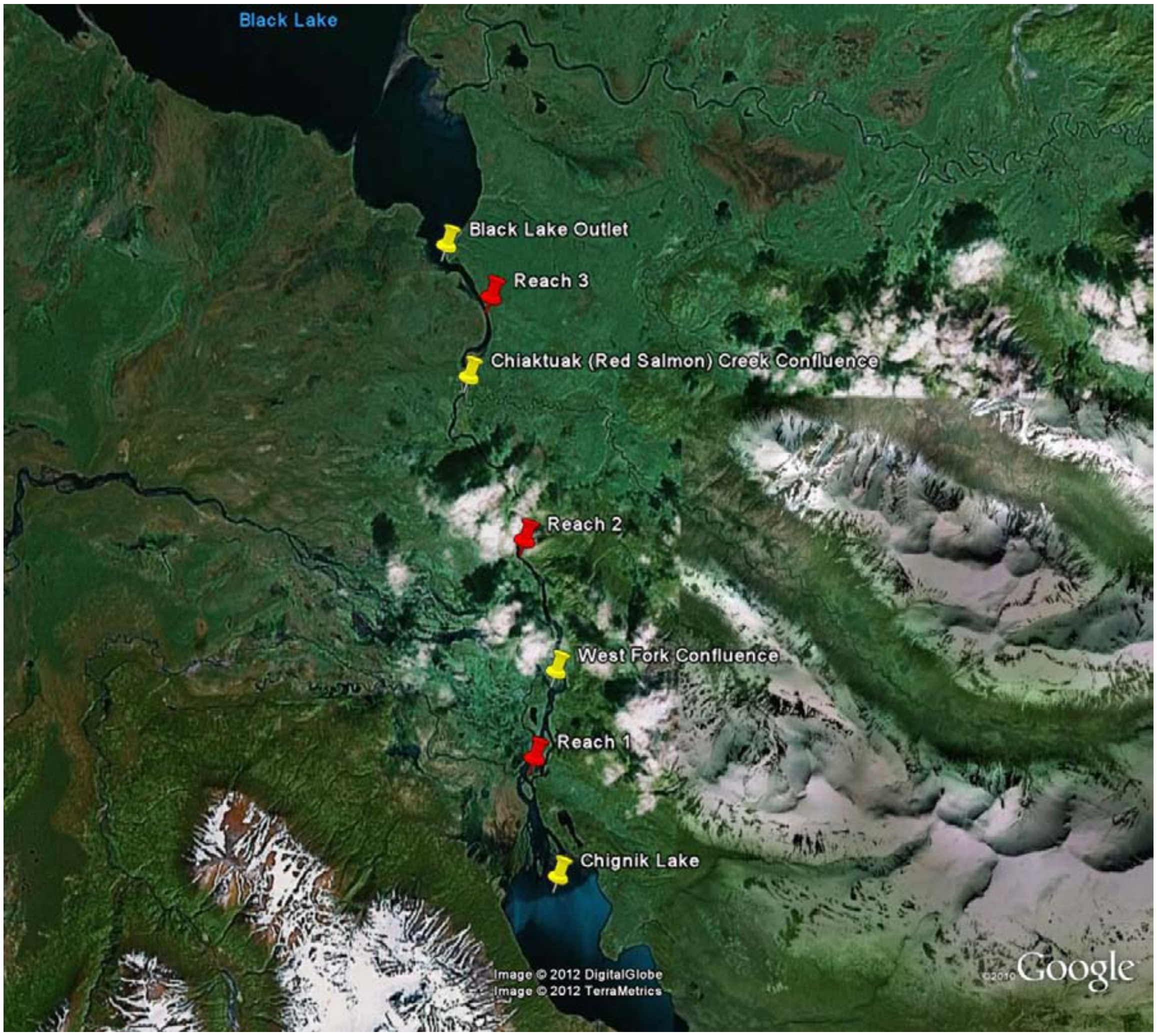

Figure 4. Black River reaches as modeled in hydraulic model

Model results show that the shift of the West Fork River, as reported, will produce changes in the WSE of Black Lake without any changes required in the upper reach of the Black River. A significant portion of the changes are a result of the decrease in the volume of water within Reach 2 and erosion of sediment within Black River when the upstream sediment supply from the West Fork was removed. These results also help to explain the channel degradation observed within Reach 2 where the historic West Fork channels are perched several feet above the Black River.

Sediment grab samples collected along the Black River indicate that Chiaktuak Creek is a source of larger-grained, erosion resistant streambed material. This is evidenced by the presence of armored point bars located immediately downstream of the confluence of Chiaktuak Creek and the Black River (Photo 1). While the river is capable of transporting finer-grained material, which is transported away, at most flows it is unable to transport the larger-grained material, which is left in the bed as ‘armor.’ The location of this erosion resistant feature agrees well with the upper extent of visible downcutting in the Black River channel.

Photo 1. Armored point bar located downstream of the confluence of Chiaktuak Creek and the Black River

Model results and physical observations indicate that lower lake water surface elevations in Black Lake are attributable to the shift in the location where the West Fork River enters the Black River. Cross section survey data collected in 2004 and 2011 imply that while the trend in lower average lake water surface elevations may continue, the rate of change may be decreasing as the Black River approaches a new equilibrium following the shift in the West Fork. It is to be expected that as the West Fork River continues to migrate across its alluvial fan, over decades and centuries, that the water levels within Black Lake will fluctuate in response to the changing bed of the Black River. The West

Fork currently appears to have migrated as far south as possible with a hardpoint preventing further migration. While no estimates have been made on when the river will migrate back towards Black Lake, if and when this does occur, we can expect to see aggradation within portions of the Black River and a subsequent response of higher WSE in Black Lake.

Will continued geomorphic processes isolate habitat available in the upper basin of Black Lake?

The U.S. Geological Survey operated stream gages on the Alec and Black rivers during a portion of this study. Streamflow data were collected from May 2004 through September 2005 (M.L. Jackson, et al. 2006**)**. Data recorded indicates the Alec River contributes approximately 68 percent of the water flowing into Black Lake. A majority of the Alec River flows through its southern delta channel into Black Lake's bay on the side of the spit closest to the lake outlet. Remaining Alec River flows travel through its northern delta channel into Black Lake on the far side of the spit from the lake outlet. A majority of the approximately 32 percent of flows into Black Lake that do not originate from the Alec River also enter the lake on the far side of the spit. These flows will be sufficient to ensure the spit remains open for the foreseeable future, even if all flows within the Alec River were to switch to its southern delta channel. Major impacts to habitat access and water circulation from further extension of the spit are not anticipated.

Risk & Uncertainty

The magnitude of depth and volume reductions of Black Lake were a source of substantial uncertainty. Previous estimates were based on anecdotal evidence and various measurements tied to various datums over time. Lack of vertical control between the multiple datums made direct comparison between these different measurements problematic and added substantial uncertainty to the quantification of the losses in depth and volume documented in Black Lake. Establishing accurate vertical and horizontal controls during the course of the study effectively reduced this uncertainty and allowed for comparison between the different historical measurements.

The caldera of Mount Veniaminof, an active stratovolcano, is approximately 20 miles southwest of Black Lake. Lahars, debris flows, and ash fall from any future eruptions could have major impacts on Black Lake and its aquatic habitat, potentially negating any improvements realized from any measures implemented.

Potential Alternative Plans

The following alternatives were considered during this study:

No Action – Future Without Project Conditions

Based on data collected to date, it is estimated that while the trend in lower average lake water surface elevations may continue, the rate of change appears to be decreasing. It is possible that the Black River may be approaching a new equilibrium following a stream channel shift in the West Fork, a tributary to the Black River. It is to be expected that as the West Fork continues to migrate across its alluvial fan over decades and centuries, the water levels in Black Lake will fluctuate in response to the changing bed of the Black River. The West Fork currently appears to have migrated as far south as possible with a hardpoint preventing further migration. While no estimates have been made on when the river will migrate back towards Black Lake, if and when this does occur, we can expect to see aggradation in portions of the Black River and a subsequent response of higher WSE in Black Lake. While further reductions in Black Lake WSE are possible, major reductions and impacts to rearing habitat are not anticipated.

Water entering Black Lake's main basin, on the opposite side of the spit from the lake outlet, will be sufficient to ensure that the spit remains open for the foreseeable future, even if all flows in the Alec River switched to its southern delta channel. Major impacts to habitat access and water circulation from further extension of the spit are not anticipated.

Control Structure at the Outlet of Black Lake

One method to raise the WSE in Black Lake is to construct a broad-crested weir extending across the river in Reach 3 of the Black River. The weir could have a lowered section in the middle to allow passage of boats and fish. The effect of this type of structure is that at low flows the center portion functions as a weir, raising the upstream WSE. At high flows, the weir flow area expands with a decreasing influence upstream. Calculations show that such a weir would increase the WSE in Black Lake by approximately 1.3 to 1.5 feet at lower flows, and 0.1 to 0.25 foot at higher bank full flows. Such a structure would only have appreciable impacts upon WSE during low flow periods, which generally occur during the winter. Since there are few juvenile sockeye salmon present in Black Lake during the winter, presumably due to high summer water temperatures in Black Lake triggering migration to cooler waters downstream, this alternative would have minimal biological benefits. In addition, hydrodynamic modeling (Griffiths 2011) showed that increases in lake depth by as much as 6.5 feet would have no appreciable impact upon water temperatures in Black Lake. Due to the remote location and difficult access to the site, construction would be expensive and challenging. Additionally, if the system did not react optimally with the weir in place, opportunities for timely and effective adaptive management would be severely limited. Further consideration of this alternative is not suggested at this time.

In-stream Control Structures in the Black River

As an alternate to placing a single structure at the mouth of Black Lake, several smaller grade control structures could be placed in the Black River to control the WSE of Black Lake. Multiple erosion resistant structures such as cross-vanes or check dams consisting of imported materials (rocks and/or logs) could be placed in the stream channel. Each structure would provide a grade control structure and would prevent downcutting of the Black River. A number of these structures placed strategically throughout the Black River could return the Black River, and subsequently Black Lake, to historical water surface elevations. Due to the difficulty and expense of constructing structures at multiple remote locations, it would be more cost effective to construct one structure at the mouth of Black Lake. Further consideration of this alternative is not recommended at this time.

Control structure in the Alec River

A diversion structure or channel could be constructed in the Alec River to increase the proportion of streamflow that drains into the north basin of Black Lake. The location of the outlet of this channel could be strategically placed to access the deepest accessible potions of the lake, potentially providing improved access to sources of cooler water and dissolved oxygen. It has been suggested that ensuring that more water flows into the north basin would ensure that the spit does not fully extend across the lake, dividing it into two separate basins. This analysis has concluded that under existing conditions, water entering Black Lake in its north basin would be sufficient to ensure that the spit remained open for the foreseeable future. Since favorable habitat located in the north basin would continue to be accessible to salmon, the overall benefits of this approach is questionable. Further consideration of this alternative is not recommended at this time.

Alec River Sediment Traps

Placement of sediment traps in the Alec River would provide a short-term reduction in sediment transport to Black Lake. It has been determined that Black Lake depths have only been reduced by 1 to 4 inches due to sedimentation over the past 50 years. Sedimentation only accounts for a small proportion of the depth reductions observed at Black Lake. Further consideration of this alternative is not recommended.

Control of Beaver Populations

Many in the community suggested that the recent expansion of beaver into the area contributed to lower water levels in Black Lake. A previous investigation (Denman and Ruggerone 1994) determined that the potential impacts from beavers on the overall hydrology of Black Lake to be minimal. No further consideration of this effort is warranted.

Dredging of Black Lake

Dredging could be used to deepen Black Lake. As opposed to a control structure at the outlet, dredging can be targeted to particular portions of the lake to maximize its impact. Selective portions of the lake could be deepened without a corresponding increase in shallow water along the margin of the lake such as would occur from a control structure. A deeper lake of this manner would provide more habitat and be less susceptible to high temperatures and depleted dissolved oxygen concentrations. This alternative does not appear to be feasible, however, due to the amount of material that would need to be removed to have an appreciable effect and the difficulty and expense to dredge at such a remote site. Further consideration of this alternative is not recommended at this time.

Monitoring Plan

Considering the documented gradual changes in the physical habitat of Black Lake, it would be beneficial to monitor some of the trends identified in this study to confirm the direction and rates of change in the future. The primary objective of such a monitoring plan should be to detect any accelerated degradation within Reach 3 of the Black River that could lead to further volume losses in Black Lake. This is the only alternative plan recommended at this time.

Preliminary Evaluation of Alternatives

Numerous structural measures were considered to alleviate the impacts of reduced depths and volumes in Black Lake. Implementation of any of these measures is not warranted at this time due to several factors;

- It appears that the Black Lake/Black River system may be approaching a point of geomorphic equilibrium following a channel shift of a tributary to the Black River. While further reductions in Black Lake WSE are possible, major reductions and impacts to rearing habitat are not anticipated.

- There is no clear correlation between the changes documented at Black Lake and the fisheries resources of the Black Lake/Chignik fishery. To what extent that these changes have reduced sockeye salmon production of Black Lake is unknown. No sustained downward trend in the fishery attributable to the reduction in depth and volume has been documented.

- Structural measures are predicted to have a minimal impact upon the thermal regime of Black Lake and hence are not expected to increase the utilization of Black Lake habitat. Future anticipated increases in air temperature are likely to have a larger impact.

Conclusion

Lower WSE in Black Lake are attributable to the shift in location where the West Fork River enters the Black River. While the trend in lower average lake WSE may continue, the rate of change appears to be decreasing, and it is possible that the Black River may be approaching a new equilibrium. It is to be expected that the water levels in Black Lake will fluctuate in response to the changing bed of the Black River. While further reductions in Black Lake WSE are possible, major reductions and impacts to rearing habitat are not anticipated. Water entering Black Lake in its main basin on the opposite side of the spit from the lake outlet will be sufficient to ensure that the spit remains open for the foreseeable future, even if all flows in the Alec River were to switch to its southern delta channel. Major impacts to habitat access and water circulation from further extension of the spit are not anticipated.

The Chignik River salmon fishery continues to be a robust salmon fishery. The Chignik River watershed began as the result of dynamic natural processes and will likely continue to be shaped by those same processes. The fishery will likely continue to shift life history strategies to account for the habitat changes accordingly. Competition between Black Lake emigrants and Chignik Lake smolt will likely continue in years when conditions increase temperatures in Black Lake. Continued monitoring of smolt outmigration and limnology in the system will provide the best way to detect changes in the early life history strategies that may be deleterious to this vital fishery.

Recommendations

Continued monitoring of smolt outmigration and limnology in the Chignik system is the best way to detect changes in the early life history strategies that may detrimentally impact the overall resources of the watershed. Such data are not confounded by variable ocean conditions and therefore are essential for linking changes in freshwater life stages and the overall health of sockeye salmon stocks. Annual collection of Black Lake water surface elevation data, combined with periodic collection of cross section data from the Black River, and satellite imagery of the region will allow early identification of any geomorphic forcings that could result in a deleterious loss of rearing habitat in Black Lake. A monitoring plan, as described in Supplemental Information, is recommended to ensure the system is approaching a state of renewed equilibrium and to identify any stressors to the system before they have irreversible impacts upon Black Lake and its fishery resources.

Continued study under Section 206 of the Water Resources Development Act of 1996 is not warranted at this time because the Authority does not facilitate monitoring efforts prior to project implementation. Thus, there is no Federal interest under the Continuing Authorities Program.

Views of the Sponsor

The sponsor, the Lake and Peninsula Borough (Borough), has worked closely with the Chignik Regional Aquaculture Association (CRAA), which has played the primary role in coordinating Black Lake research since its founding in 1991. The Borough and CRAA believe that the unusually rapid changes in the watershed that led to the significant reductions in the volume of Black Lake over the last 30 years continue to present a significant potential danger to the future salmon productivity of Black Lake. Due to the large natural variation in run size, the impacts of very different management regimes over time (e.g. Federal versus State management and Japanese high seas drift net fishing near shore versus the institution of the 200-mile limit); climate change (e.g. Pacific Decadal Oscillation and global warming); and the complex life history of salmon, it is impossible to statistically correlate declining lake volume with reductions in Black Lake salmon productivity. While the extent of any reduction in Black Lake salmon productivity over the last 30 years is unknown, it is obvious and universally acknowledged that if Black Lake volume continues to decline, even at a reduced rate, eventually Black Lake will suffer a substantial negative impact on average future salmon production.

The Borough and CRAA strongly support the recommendation of instituting a monitoring program. The monitoring program would involve continuing ongoing smolt emigration, limnological, and genetics monitoring; year-round continuous lake level measurements; updated satellite imagery of Black Lake every 2 to 5 years; and updated river cross section surveys at least every 5 years. This program should provide adequate means to discover possible ongoing negative impacts to the salmon habitat or salmon production in time to discover and implement a feasible mitigation project.

Black Lake provides the back bone of the fishing economy for the Borough communities of Chignik, Chignik Lagoon, Chignik Lake, Perryville, and Ivanof Bay as well as providing fishing opportunities to neighboring fishing areas of Kodiak and Aleutians East Borough. It is of the highest importance that the monitoring program be instituted to safeguard this critically valuable natural resource.

Views of Other Resource Agencies

The Alaska Department of Fish and Game (ADF&G) recognizes that there have been reductions to the volume of Black Lake over the past 30 years. To what extent, if any, these changes have reduced sockeye salmon production of Black Lake is unknown. However, ADF&G does recognize that at some point diminishing lake volume will indeed have negative effects upon production (Adam StSaviour, email 9/16/2011), and therefore, they support the idea of monitoring the system. ADF&G expressed support for the continued monitoring of smolt outmigration and limnology as the best means to detect deleterious effects on this vital fishery. Detecting changes in salmon early life history, as opposed to the total returns subsequent to their ocean life stage 3 years later, will provide an early warning system of potential declines in fresh water sockeye salmon production. This data will not be confounded by variable ocean conditions and can provide specific indications, such as an absence of age-1 smolt in the outmigration, which would immediately warn of impacts to Black Lake.

Based upon results of their long-term research and monitoring efforts, the University of Washington Fisheries Research Institute believes that the return of salmon to the Chignik watershed is linked to ocean conditions that are dominated by Pacific Decadal Oscillation (PDO). Low runs from 1945-1975 and high returns since 1977 have been observed throughout Alaska and Chignik. Sockeye salmon runs to the Chignik watershed averaged 1.3 million fish from 1945 to 1975 and averaged 2.5 million fish from 1977 to 2011. In recent years, the PDO has been in a more average state and this has been reflected in the run (average from 2002 to 2011 was 2.1 million fish). The relative contribution of the Black Lake and Chignik Lake stocks to the total run is variable among years. However, despite geomorphic evolution in the upper watershed, the Black Lake stock contribution to the total run has not declined over time. Between 1922 and 2011, the Black Lake stock contributed 47 percent of the annual run; in the last decade it has contributed an average of 54 percent. Overall, it appears that freshwater habitat diversity across the Chignik watershed buffers changes in the rearing environment and that stocks are sensitive to low frequency climate variation (Daniel Schindler, email 4/6/2012).

Supplemental Information

Proposed Monitoring Plan

A monitoring plan, such as the following, in addition to continuing ongoing smolt emigration, limnological, and genetics monitoring as detailed in StSaviour and Hunt (2012), would provide the necessary information to allow early identification of any potential stressors to the health of the sockeye salmon resources of the Chignik system.

Year-round continuous lake level measurements.

- It is important to monitor the level of Black Lake on a continuous basis throughout the year to establish rates and direction of WSE changes.
- These measurements should consist of a simple water level recorder installed and retrieved each year. A second redundant sensor is also recommended.
- Biweekly lake water surface measurements should be performed during the typical summer field season. These measurements should consist of a simple level loop that begins and ends at a stable COE benchmark. An inexpensive digital level is recommended for this work. All future elevation data should be collected using this consistent, GPS established, vertical datum.
- Data should be reduced and quality controlled on an annual basis with comparisons performed against prior years.

Acquisition of satellite imagery

- On a 2 to 5-year interval acquire satellite imagery of Black Lake that includes the confluence of Chiaktuak Creek on the Black River.
- Examine each image for qualitative and quantitative changes in Black Lake, the Alec Delta and Reach 3 of the Black River.

Repeated cross section surveys

- On a minimum 5-year interval perform repeated cross section surveys. The priority should be cross sections located in Reach 3 on the Black River.

References

The following studies are particularly relevant to this study. Many of them were completed as part of, or in conjunction with, this study.

Buffington, J. M. 2002. "Geomorphic Reconnaissance of the Black Lake Area, Alaska Peninsula." This report concluded that geomorphic evidence indicated a downstream shift of the confluence of the West Fork and Black rivers may be responsible for lower water surface elevations in Black Lake. Black Lake water surface elevation losses between 1963 and 2001 were estimated to be 4.6 feet. It suggested that a grade control structure of some sort located near the lake outlet may be a potential solution to further impacts. It also highlighted potential difficulties with such an approach including excessive costs, providing for fish and vessel passage, and potential failure of a structure due to earthquakes and volcanic eruptions.

Chasco, B., G. T. Ruggerone, and R. Hilborn. 2003. "Chignik Salmon Studies - Investigations of Salmon Populations, Hydrology and Limnology of the Chignik Lakes, Alaska, During 2000-2002," University of Washington. This is an annual report submitted to the National Marine Fisheries Service and Chignik Regional Aquaculture Association documenting salmon studies completed between May 2002 and April 2003. A bathymetric survey of Black Lake was completed during this particular effort and is documented in the report.

CH2M Hill. no date. "Conclusion Statement of 1993-1994 Black Lake Investigations Report." This report concluded that it could be feasible to raise the WSE of Black Lake by installing a Geo-Web across the outlet sill in an attempt to facilitate sand deposition. The project went so far as to test anchoring systems for the Geo-Web sill, but the actual structure was never installed.

Denman, Robert A. and Gregory T. Ruggerone. 1994. "Effects of Beaver Colonization on the Hydrology and Spawning Habitat of Sockeye Salmon in the Chignik Lakes, Alaska," Natural Resources Consultants, Inc. This report investigated the potential impacts upon Black Lake by the recent expansion of beaver into the area. It determined the potential impacts upon the overall hydrology of Black Lake to be minimal.

Eastman, D.E., B.J. Rogers, D.E. Rogers, and M. Duke. 1995. "An Annotated Bibliography of Fisheries Research Institute Studies at Chignik, Alaska," FRI-UW-9505 Annual Report, Anadromous Fish Project, National Marine Fisheries Service Contract No. NA36FA0276. An annotated bibliography of Fisheries Research Institute studies at Chignik, Alaska through 1994.

Elhakeem, M., and A. N. Papanicolaou. 2008. "Evaluation of the Reduction in the Water Storage Capacity of Black Lake, AK, International Journal of River Basin Management ," Vol. 6, No. 1, pp. 63-77. The Chignik Regional Aquaculture Association funded a sediment transport model of Black Lake. This paper summarizes the findings of this effort, that infilling of the lake via sedimentation is not a probable cause for observed reductions in lake depths. A water surface elevation loss of at least 3.3 feet was estimated between 1953 and 2008.

Finkle, H. and E. J. Newland. 2005. "Sockeye salmon smolt investigations on the Chignik River, 2004," Alaska Department of Fish and Game, Fishery Data Series No. 05-16, Kodiak, AK. Sockeye smolt out migration survey data.

Finkle, H. 2006. Chignik Watershed Ecological Assessment Project Season Report, 2005. Fishery Management Report No. 06-54. Alaska Department of Fish and Game, Divisions of Sport and Commercial Fisheries. This report assesses water quality, zooplankton, and catch data in 2005 to describe the mechanisms behind changes in rearing strategies and migratory behavior of juvenile sockeye salmon in Black Lake.

Griffiths, J. R., D. E. Schindler, L. S Balistrieri, and G. T Ruggerone. 2011. "Effects of simultaneous climate change and geomorphic evolution on thermal characteristics of a shallow Alaskan Lake," Journal of Limnology and Oceanography, 56 (1), 193-2005. University of Washington Fisheries Research Institute conducted thermal modeling of Black Lake to investigate the impacts of placing a control structure at its outlet to raise the elevation of the lake. Preliminary model results showed that such a structure would cause higher water temperatures, not lower temperatures as desired. Water surface elevation losses experienced by Black Lake between 1960 and 2011 were estimated to be 6.5 feet.

Griffiths, J., D. Schindler, and L.W. Seeb. 2012. "Habitat connectivity and patterns of stock condition in the Chignik Watershed." This investigation built upon previous efforts to better understand how and when different sockeye salmon stocks utilize lake habitat available in Black and Chignik lakes. The results indicate that the proportion of Black Lake sockeye salmon stock rearing in Chignik Lake is quite variable year to year. There is also no consistent difference in the health of the two stocks in Chignik Lake. The report concludes that Black Lake continues to provide highly productive rearing habitat for a portion of the Black Lake stock

Jackson, M.L., M.E. Castor, J.M. Goetz, G.L. Solin, J.M. Wiles. 2006. "Water Resources Data for Alaska, Water Year 2005," Water Data Report AK-05-1, U.S. Geological Survey, Water Resources Office, Anchorage, Alaska. The U.S. Geological Service (USGS) maintained streamflow gages each on the Alec River and at the outlet of Black Lake from May 2004 through September 2005. Daily mean discharge in cubic feet per second and water temperature in degrees Celsius are available during this period. Summary data can be found in this annual report.

Kaufman, Darrell. 2012. "Long-term sedimentation rate in Black Lake, Alaska," School for Earth Sciences & Environmental Sustainability, Northern Arizona University, May 2012. Six sediment cores were collected from Black Lake and analyzed to determine historical sedimentation rates in the lake. Sedimentation rates were low, ranging from 0.00035 in/yr to 0.13 in/yr for the past 50 years.

Ruggerone, G. 2003. "Rapid Natural Habitat Degradation and Consequences for Sockeye Salmon Production in the Chignik Lakes System, Alaska," University of Washington School of Aquatic & Fishery Sciences. This report documents the habitat changes observed at Black Lake and discusses their potential impacts upon sockeye salmon production. It identified several potential measures to mitigate negative impacts to Black Lake habitat. This investigation estimated Black Lake water surface elevation losses from 2.2 to 3.6 feet between 1949 and 2003.

Ruggerone G. T. 2003. "Photographic Documentation of Habitat Degradation in Black Lake, Alec River, and Black River, Alaska." Draft Report Prepared for: Chignik Regional Aquaculture Association, Chignik, AK. This report provides a historical photographic documentation of Black Lake. It contains dated comparison photos of lake and river features.

Simmons, R.K., T.P Quinn, L.W Seeb, D.E. Schindler, and R. Hilborn. "Changes in rearing patterns by juvenile salmon facing changing environments," Canadian Journal of Fisheries and Aquatic Sciences (in review). This study utilized genetic tools to study Black Lake and Chignik Lake juvenile sockeye salmon stock specific movement and health. It documented an earlier summer entry into Chignik Lake by Black Lake emigrant sockeye salmon fry than previously thought. This could increase the occurrences of a competitive rearing habitat in Chignik Lake. No conclusive evidence of stock specific impacts to growth was found as part of this study.

StSaviour, A. and D. Hunt. 2012. "Sockeye salmon smolt investigations on the Chignik River, 2011," Alaska Department of Fish and Game, Fishery Data Series No. 12-17, Anchorage. This report summarizes the 18th year of collection of sockeye salmon smolt monitoring and enumeration data by Alaska Department of Fish and Game. Limnological data has also been collected in Chignik and Black lakes since 2000. Analyzing such smolt enumeration and limnological data provides insight concerning overall stock status, future run strength, and how environmental factors may influence food availability, juvenile emigration timing, and overwintering habitat selection. This effort has also involved a genetic component since 2006. Genetic analyses have provided additional information about stock-specific run timing and age composition.

Westley, P. A. and R. Hilborn. 2006. "Investigations of Salmon Populations, Hydrology, and Limnology of the Chignik Lakes, Alaska, During 2004-2005," Annual Report, Anadromous Fish Project, NMFS Contract No. NP18D647C. 1 November 2005 – 30 April 2006. This report continues studies on the relative abundance and size of juvenile sockeye salmon (Oncorhynchus nerka) and the biological and physical environment for sockeye salmon in Chignik and Black Lake.

Westley, P. A., B. E. Chasco, and R. Hilborn. 2005. "Investigations of Salmon Populations, Hydrology, and Limnology of the Chignik Lakes, Alaska, During 2004-2005," Annual Report, Anadromous Fish Project, NMFS Contract No. NP18D647C. 1 November 2004 – 30 April 2005. This report continues studies on the relative abundance and size of juvenile sockeye salmon (Oncorhynchus nerka) and the biological and physical environment for sockeye salmon in Chignik and Black Lake.

BLACK LAKE HYDROLOGY AND HYDRAULICS REPORT

October 2012

Contents

ACKNOWLEDGMENTS

This report appendix was prepared by staff of the Alaska District, U.S. Army Corps of Engineers, in Anchorage, Alaska. The hydraulics and hydrology analysis was performed by Mr. Crane Johnson of the Hydraulics and Hydrology section working under Mr. Ken Eisses, Chief of Hydraulics and Hydrology and reviewed by Dr. Jon Zufelt from the Engineer Research and Development Center - Cold Regions Research and Engineering Laboratory.

Introduction

Black Lake is one of the primary rearing habitats for sockeye salmon for the entire south side of the Alaska Peninsula in the Chignik Region. Since the early 1990's there has been concern that the lake is rapidly losing volume due to a lower average water surface. The average water surface and volume of Black Lake varies dramatically on an annual time scale with what appears to be a decadal decrease in overall lake volume. This report attempts to document this loss in volume and describe the mechanisms responsible for the decline. An accurate and repeatable baseline topographic and bathymetric survey was performed as part of this investigation. This baseline survey can be used as a reference for future surveys to measure changes in the Black Lake system that may occur. The last section of this report provides engineering recommendations and a cost effective monitoring plan for this valuable habitat resource.

Geologic and Hydrologic Setting

Black Lake is on the Alaska Peninsula and drains into the Chignik River, which flows south into Chignik Lake and then out into the Gulf of Alaska on the south side of the Alaska Peninsula. Figure 1 shows a vicinity map of the Chignik area. The lake itself is in a broad low-lying area to the northeast of Mt. Veniamianoff. The lake is bordered by flat tundra, marsh, and grassland to the south, west, and north, with a portion of the northwest shoreline adjacent to terminal glacier moraines. The shoreline of Black Lake is primarily composed of fine sand with two distinct areas consisting of gravel and cobbles. The first cobble area is along the northeast shoreline below the NGS "Black" monument, and the second area is along the southeast shoreline between the mouth of the Alec River and the basin outlet. The lake is extremely shallow with rapid temperature changes throughout the summer and no measureable temperature stratification in the water column. The major tributaries into Black Lake are the Alec River, Fan Creek, and Crater Creek.

Water flows out of Black Lake down the Chignik River into Chignik Lake. The Chignik River (as shown on USGS maps) is locally known as the Black River and will be referred to as the "Black River" throughout this report. Black Lake was formed as glaciers that pushed out of the West Fork and Black River receded, with the West Fork alluvial fan encroaching against the opposite valley wall, effectively forming a dam with Black Lake situated upstream from this area (Knappen, 1929).

The drainage basin area of the Black Lake basin measured at the USGS stream gaging station along the Black River is 282 square miles. Table 1 below shows the area and estimated average annual precipitation for each drainage basin identified in this report. The first five basins listed are all tributaries of Chignik Lake and are shown on Figure 1; the last basin listed is Russell Creek, the only drainage basin with a long-term stream gage in this region of the Alaska Peninsula. The largest drainage basin that flows into Black Lake is the Alec River, which flows into the east side of Black Lake. Several other lesser drainages enter Black Lake from the northern and western sides of the lake. The Alec River drainage area was calculated to be 102 square miles. Fan Creek is a sub watershed that flows into the Alec River just upstream from Black Lake.

Average annual precipitation for each basin was estimated using the PRISM (Parameter-elevation Regressions on Independent Slopes Model) data set. This data set contains spatially gridded estimates of average monthly and annual precipitation for the climatological period 1971 to 2000 (Daly, 2009).

Table 1. Black Lake Watersheds.

Watershed	Area Square Miles	Average Annual Precipitation Inches (PRISM 2000)
Black Lake	282[2]	53
West Fork	164	82
Alec River	102[1]	76
Chiaktuak River	27	80
Fan Creek	24	67
Russell Creek	31	49

[1] USGS reports a drainage area of 123 square miles for this gage.

[2] USGS reports a drainage area of 283 square miles for this gage.

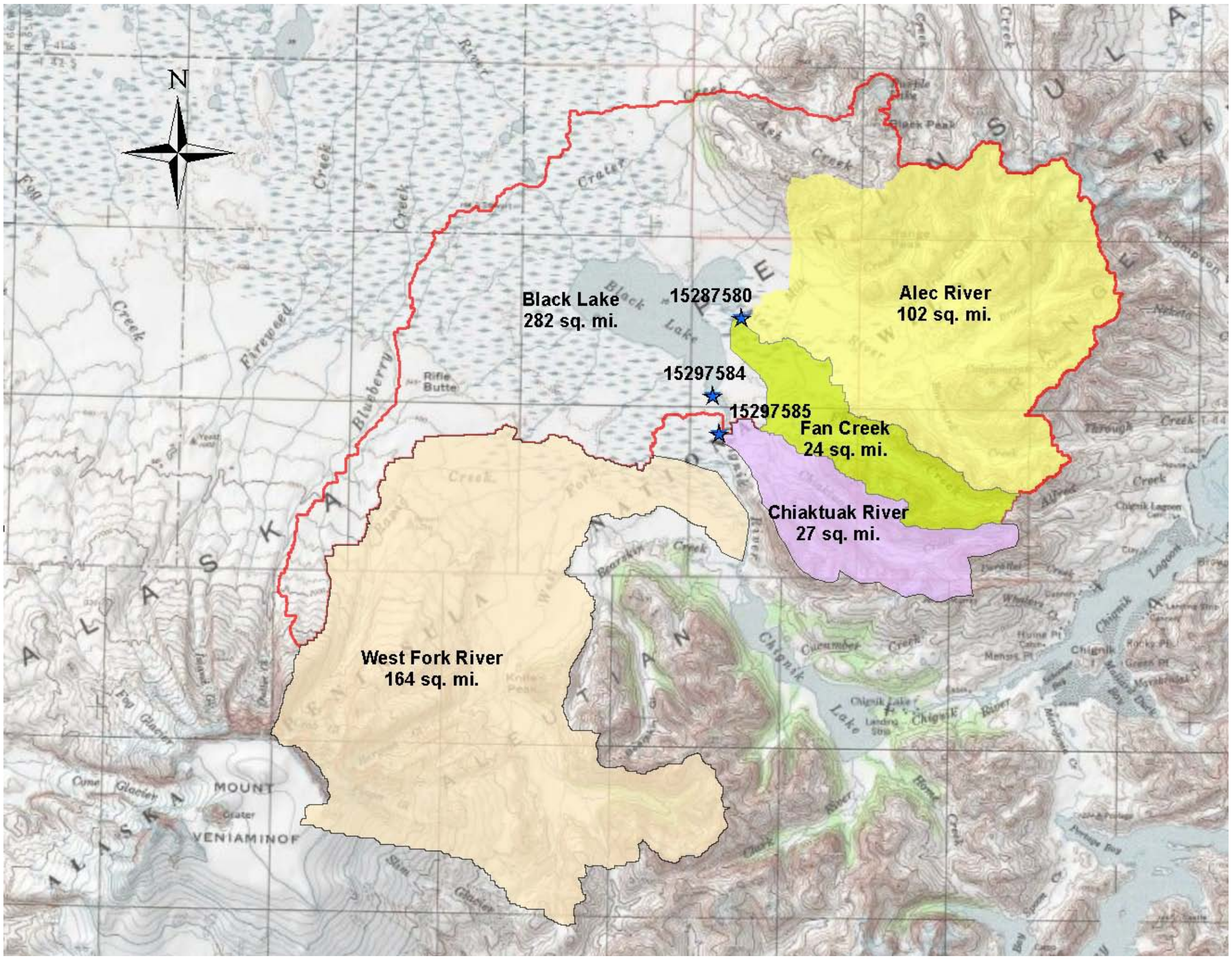

Figure 1. Black Lake Watershed Boundaries and USGS gage locations.

Assuming that, on an annual basis, the volume of water flowing into Black Lake from each sub basin is proportional to drainage area and average annual precipitation, we can determine the relative contribution of each sub watershed to the overall hydrology of Black Lake. Table 2 below provides the relative watershed contributions to Black Lake.

Table 2. Black Lake Relative Watershed Runoff Contributions

Watershed	Percent Contribution
Western Black Lake Watersheds	37%
Alec River	52%
Fan Creek	11%
Black Lake Complete	100%
West Fork River	120%

Together the Alec River and Fan Creek contribute approximately 63 percent of the water flowing into Black Lake. Based on drainage area and average annual precipitation estimated by the

PRISM model on an annual basis, the West Fork River contributes an estimated 20 percent more runoff into Chignik Lake than the Black Lake watershed.

Hydrology

In addition to estimates based on regional precipitation information, historical stream gage information can be used to also examine the relative influence of the Alec River on the hydrology of Black Lake. The USGS has maintained several stream and lake stage gages within or near the Black Lake watershed. The gages used in this study are listed in Table 3.

Table 3. Stream gages used for this study.

USGS Gage Number	Gage Name	Drainage Area (sq. mi)	USGS Gage Datum Feet NGVD 29	Available Period of Record	COE Gage Datum Feet (Surveyed)
15297580	Alec River NR Chignik AK	102 [1]	32[3]	05/19/2004-9/30/2005	16.06
15297585	Chignik River at Black Lake Outlet Near Chignik	282 [2]	59[3]	05/19/2004-9/30/2005	N/A
15297584	Black Lake Above Outlet Near Chignik Lake AK	N/A	66[3]	9/8/2010-9/30/2112	0
15297610	Russell Creek Near Cold Bay AK	31	7.65	1981-1986, 1995-2012	N/A

[1] USGS reports a drainage area of 123 square miles for this gage.

[2] USGS reports a drainage area of 283 square miles for this gage.

[3] USGS gage datum values are not surveyed.

Monthly averaged data for the stream gages installed on the Alec (15297580) and Black (Chignik - 15297585) rivers for the 2005 water year are shown in Table 4 below. The third column of the table provides the ratio between the Alec River, which flows into Black Lake, and the Black River, which flows out of Black Lake.

Table 4. Alec and Black River Discharge.

Month	Alec River Discharge (ft^3/s)	Black River Discharge (ft^3/s)	
May 2004	1,126	1,533	73%
June 2004	1,289	1,707	76%
July 2004	991	1,329	75%
August 2004	532	778	68%
September 2004	459	730	63%
October 2004	578	1,132	51%
November 2004	389	859	45%
December 2004	465	916	51%
January 2005	659	1,063	62%
February 2005	624	990	63%
March 2005	576	1,034	56%
April 2005	361	312	116%
May 2005	933	1,057	88%
June 2005	1,043.4	1,364.0	76%
July 2005	627.8	878.1	71%
August 2005	585.6	788.4	74%
September 2005	985.3	1,193.7	83%

Peak	4,640 June 4th, 2004	2,440 June 5th, 2004	
Water Year 2005	652 Runoff = 87”	965 Runoff = 46”	68%

The gage record indicates that overall the Alec River contributes a slightly higher percentage of water flowing into Black Lake than estimated based on drainage area and average annual precipitation. Direct losses and gains due to evaporation and rainfall on Black Lake were considered insignificant compared with the overall volume of water flowing from the Alec River.

The difference between the estimated ratio and measured ratio could be due to several small glaciers near the headwaters of the Alec River. These small glaciers appear to be losing mass based on a comparison of recent satellite imagery and the historical extents shown on the USGS quadrangle maps. The loss of glacier mass would provide additional runoff beyond what falls annually as precipitation. Groundwater losses and gains could also affect the relationship between the Alec River inflow and Black River outflow.

Figure 2 shows the average daily discharge for the USGS period of record for the Alec and Black rivers. As expected in a lake system, peak inflows to the lake can far exceed the peak outflows due the storage effects of the lake. The lake acts as a buffer with water going into lake storage prior to being routed downstream. Peak flow on the Alec River was 4,640 cfs on June 4, 2005. The highest report peak flow on the Alec River was estimated at over 6,000 cfs in July 1993

(Ruggerone G. T., 1994). Years with known flooding on the Alec and Black rivers are 1993, 2007, and 2011.

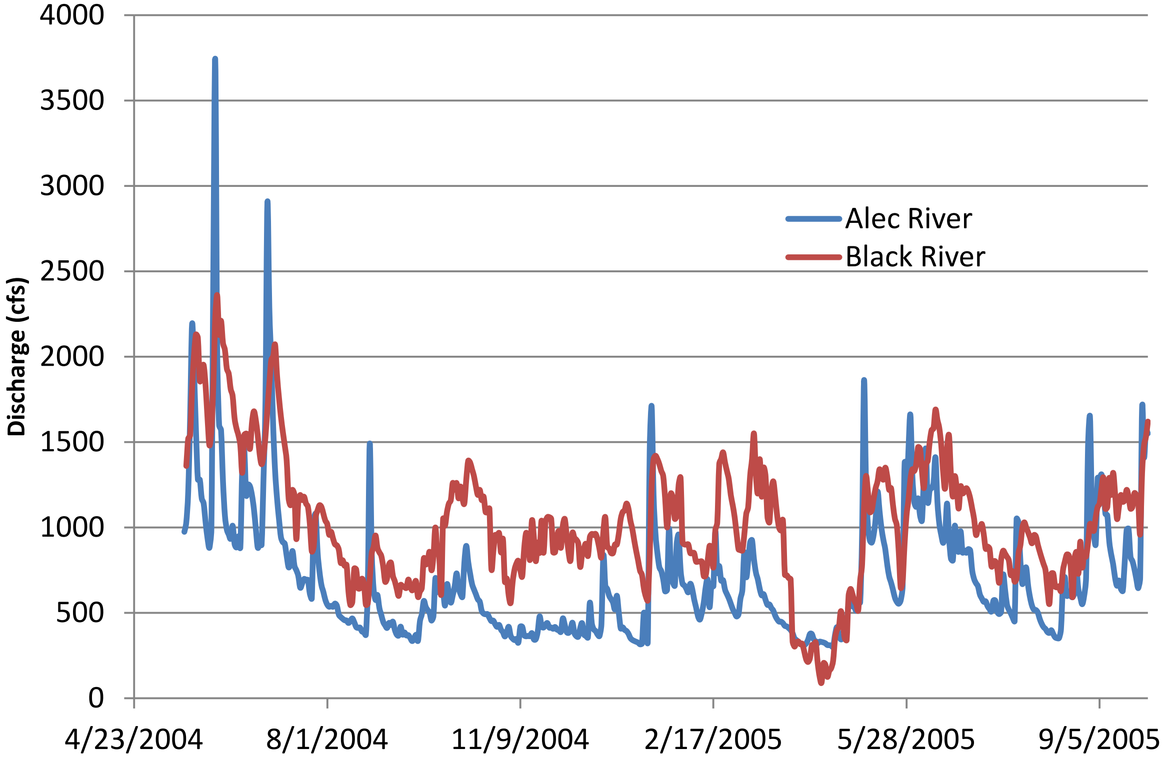

Figure 2. Alec and Black River Discharge for WY2005.

The closest two long-term precipitation gages are at Cold Bay, 170 miles to the southeast, and Kodiak, 265 miles to the northeast. Kodiak and Cold Bay both recorded more precipitation during the 2005 water year than the long-term 30-year average (2 percent and 13 percent, respectively). A similar analysis was performed for Russell Creek, which has the closest stream gage with a long-term record. This gage also showed above average volume of runoff for the 2005 water year (16 percent). Overall, it appears that the 2005 water year was slightly wetter than normal based on data from these three sites.

Lake Water Surface and Volume Changes

Changes in the long-term water surface elevation (WSE) for Black Lake have been published in various reports and journal articles since the early 1990s. Table 5 below provides a listing of the published lake water surface elevation decline estimates.

Table 5. Published declines in Black Lake water surface elevations.

	Source	Estimate Lake Elevation Decline	Range of Years
Conclusions of 1993-1994 Black Lake Investigations	CH2MHILL, 1994	1-2 feet	Unknown
Geomorphic Reconnaissance of the Black Lake Area, Alaska Peninsula	Buffington, 2002	4.6 feet	1963 – 2001
Rapid Natural Habitat Degradation and Consequence for Sockeye Salmon Production in the Chignik Lakes System, Alaska	Ruggerone, 2003	2.2 – 3.6 feet	1949 to 2003
Evaluation of the Reduction in Water Storage Capacity of Black Lake, AK	Elhakeem & Papanicolaou, 2008	At Least 3.3 feet	1953 – 2008
Effects of Simultaneous climate change and geomorphic evolution on thermal characteristics of a shallow Alaskan Lake	Griffiths, Schindler, Balistrieri, & Ruggerone, 2011	6.5 feet	1960 – 2011

The basis of these reports comes from anecdotal evidence and various lake measurements over time. Anecdotal evidence of lower lake levels over time include the declining ability to tow-net sample for juvenile salmon in Black Lake by dragging a 6.5 by 6.5-foot net pulled between two boats. Some of the earliest reports of lake depth are from the 1960's when the lake was sampled to determine fish populations. Researchers divided the lake into five areas, with tow-net sampling, using the 6.5-foot by 6.5-foot net, performed in areas A through D. The fifth area of the lake was considered too shallow for sampling. The limitations of using this large tow net were initially identified in 1975 as significantly reducing the area within Black Lake that can be sampled (Marshall & Burgner, 1975). Figure 3 shows the four areas (A-D) that were sampled in the 1960's and 1970's. This figure also provides contours for the 2-meter and 4-meter depths throughout the lake. Alec Bay, the South Alec/Fan Creek delta, and western shorelines are all identified as shallow areas. No datum is provided with this figure, making it difficult to compare subsequent bathymetric data sets.

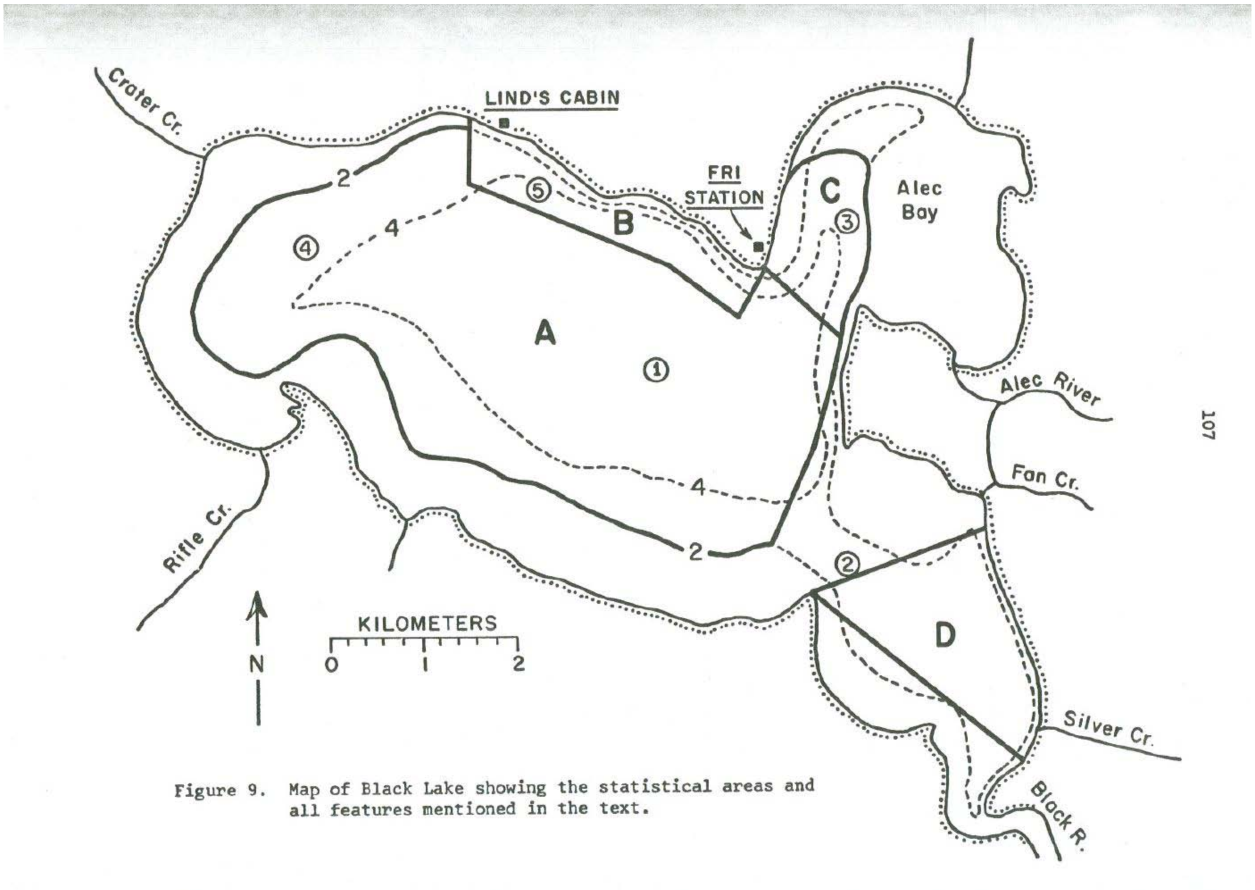

Figure 3. Map of Black Lake showing tow-net sampling areas (Narver, 1966).

As part of this study a continuous lake water level (stage) gage was installed in Black Lake in the fall of 2010. The gage record shows that Black Lake water levels fluctuate up to 4.5 feet on an annual basis (shown in Figure 4). This period of record displays trends similar to those reported in historical documents. Lake levels rise during the spring freshet and then generally decrease throughout the summer, interrupted with steep rises in water levels during large fall storms. Also notable in the data are daily fluctuations due to wave setup within Black Lake.

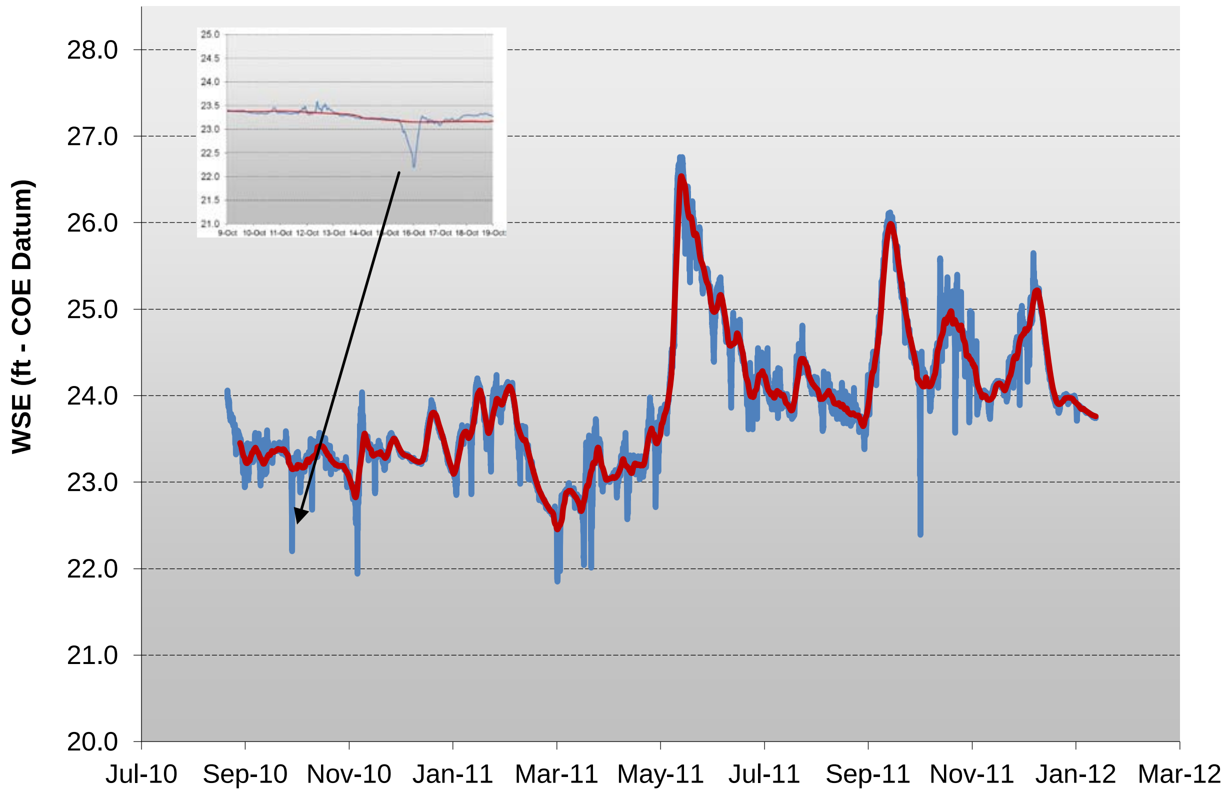

Figure 4. Black Lake provisional lake stage measurements (USGS September 2010- January 2012). Data are hourly readings (blue) with a 5-day moving average shown in red.

These wave setup events show up in the record as significant spikes in the data as a result of strong steady winds aligned with the long (NW-SE) axis of the lake. The lake stage gage is located near the outlet of Black Lake and is affected by wave setup. The inset in Figure 4 shows an event that occurred on October 16, 2010 that resulted in a 1.2-foot drop in the lake water surface elevation measured at the gage. During this drop in lake surface elevation, Port Heiden, located 36 miles to the north on the Bristol Bay side of the Alaska Peninsula, recorded steady wind speeds of up to 50 miles per hour from the southeast. This 24-hour wind event at Port Heiden corresponded to this drop measured in Black Lake. During this time, the water surface of Black Lake was essentially tilted, lower in the southeast portion and correspondingly higher in the northwest area of the lake. If we utilize a standard method to estimate wave setup within a closed basin (EM 1110-2-1420, Hydrologic Engineering Requirements for Reservoirs), the corresponding wind speed required to produce a 1.2-foot change in water surface is approximately 45 miles per hour and corresponds well to measured wind speeds in Port Heiden and the observed changes in the Black Lake water surface.

This wind tide phenomenon is important when measuring lake water levels or when comparing historical aerial photographs. Weather conditions can change the water surface of Black lake at the outlet area within a range of approximately 3 feet (plus or minus 1.5 feet). The preferred method to measure the lake water surface elevation is to continuously sample so that the error associated with wave setup can be minimized.

The average lake water surface elevation during this recent period of record (Water Year 2011) was 23.8 feet (COE datum). A similar look at the regional climate indicates that WY2011 was likely slightly drier than average with below average precipitation at Cold Bay (-10 percent) and Kodiak (-19 percent) and below average annual runoff at Russell Creek (-8 percent).

Historic Lake Water Surface Elevation Measurements

Various depth surveys and water surface elevation measurements have been conducted at Black Lake since the 1960’s with the number of measurements, temporal pattern, and vertical datum varying over time.

In 2004 the Corp of Engineers established accurate vertical and horizontal control monuments in the vicinity of Black Lake. This effort expanded the reliable vertical control points from one to seven with two new monuments adjacent to the Alec River and four new monuments near the outlet of Black Lake (Figure 5). These new vertical benchmark monuments are 20 to 30-foot-long, deep-drive aluminum rods with a magnetic survey cap and a greased PVC casing around the upper 4 feet. The primary vertical control benchmark for Black Lake is the National Geodetic Survey monument “Black PID-UW1425” located on a bluff above the northern shore of Black Lake. This monument is shown on the USGS topographic maps for the area with an elevation of 37 feet printed on the map. During the 2004 survey a GPS established elevation of 38.34 feet was calculated for “Black” and is the vertical datum for all data presented in this report. The 2004 survey also found and tied monuments from an older survey in 1993 and several historic University of Washington benchmarks that then allowed for comparisons between various lake water surface elevation data that has been gathered over time.

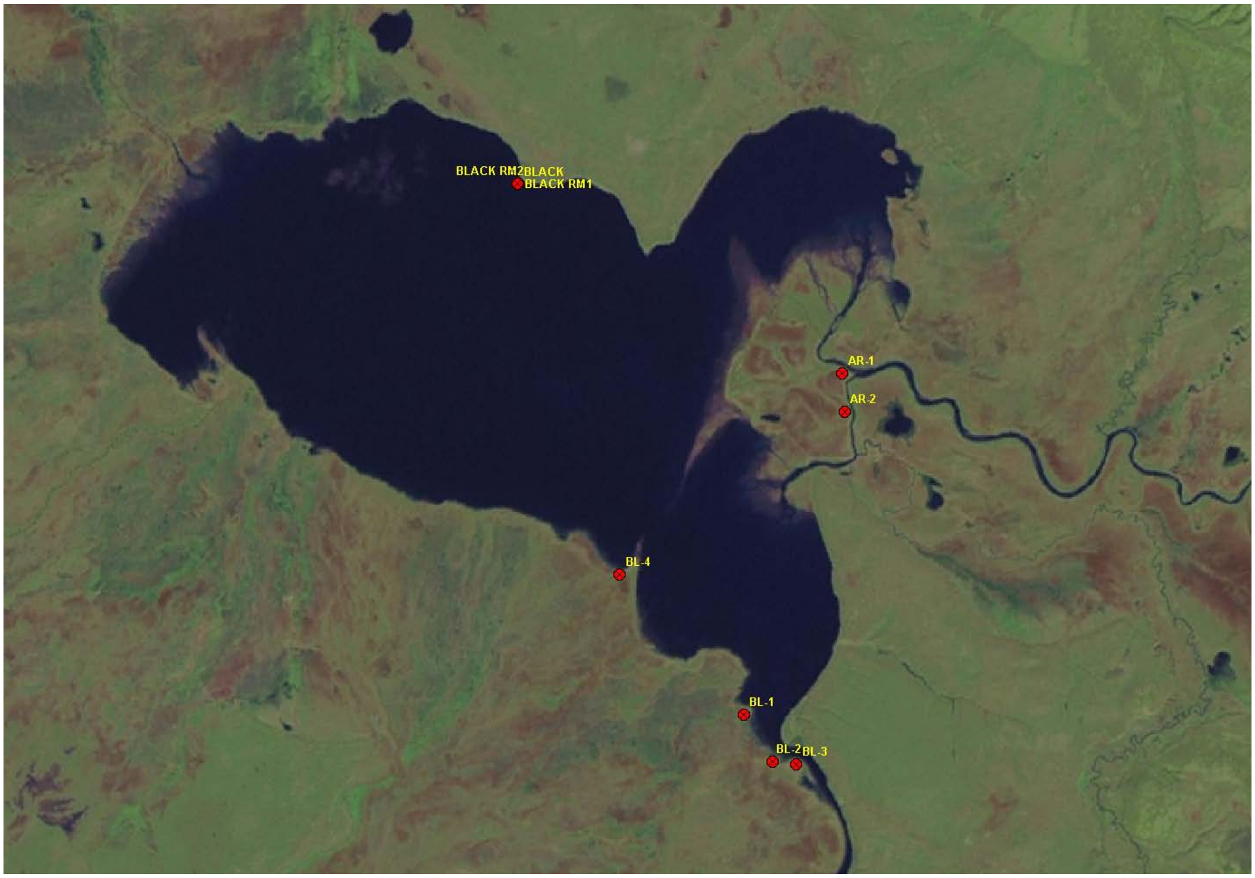

Figure 5. Black Lake COE Control Monuments.

Three differences between separate vertical datums established by CH2MHILL, Fisheries Research Institute (FRI), and the Corps of Engineers (COE) were calculated, with all historic elevations converted to the COE datum for comparison purposes. In addition to historic lake water surface elevation measurements, the Black Lake water level at separate times was estimated based on a series of aerial and oblique photographs. Due to the gradual sloping topography of Black Lake, small changes in the water level correspond to significant changes in the lake water surface perimeter. This allows for an approximation of the lake water surface elevation based on surveyed features.

One example utilizing a 1957 aerial photograph is shown in Figure 6. The water level was estimated to be 25.5 feet based on features identified within the photograph and the 2011survey. The cross section survey over the small island visible in both photographs is shown below. The highest elevation of the island is 26.1 feet (COE datum). In addition, ground surface elevations in two areas (circled) were sampled and compared. The ground surface elevation along the eastern shores, circled in both photographs, is 26.5 feet and 25.2 feet. The lower, 25.2-foot area, was inundated in the 1957 photograph and shown as dry in the 2010 satellite image. It is likely that this lower area includes some deposited sediment from the Alec River raising the ground surface. The other two areas appear to be stable and outside the influence of the Alec Delta. The water surface elevation measured by the University of Washington on the day the satellite image was collected (June 17, 2010) was 24.9 feet.

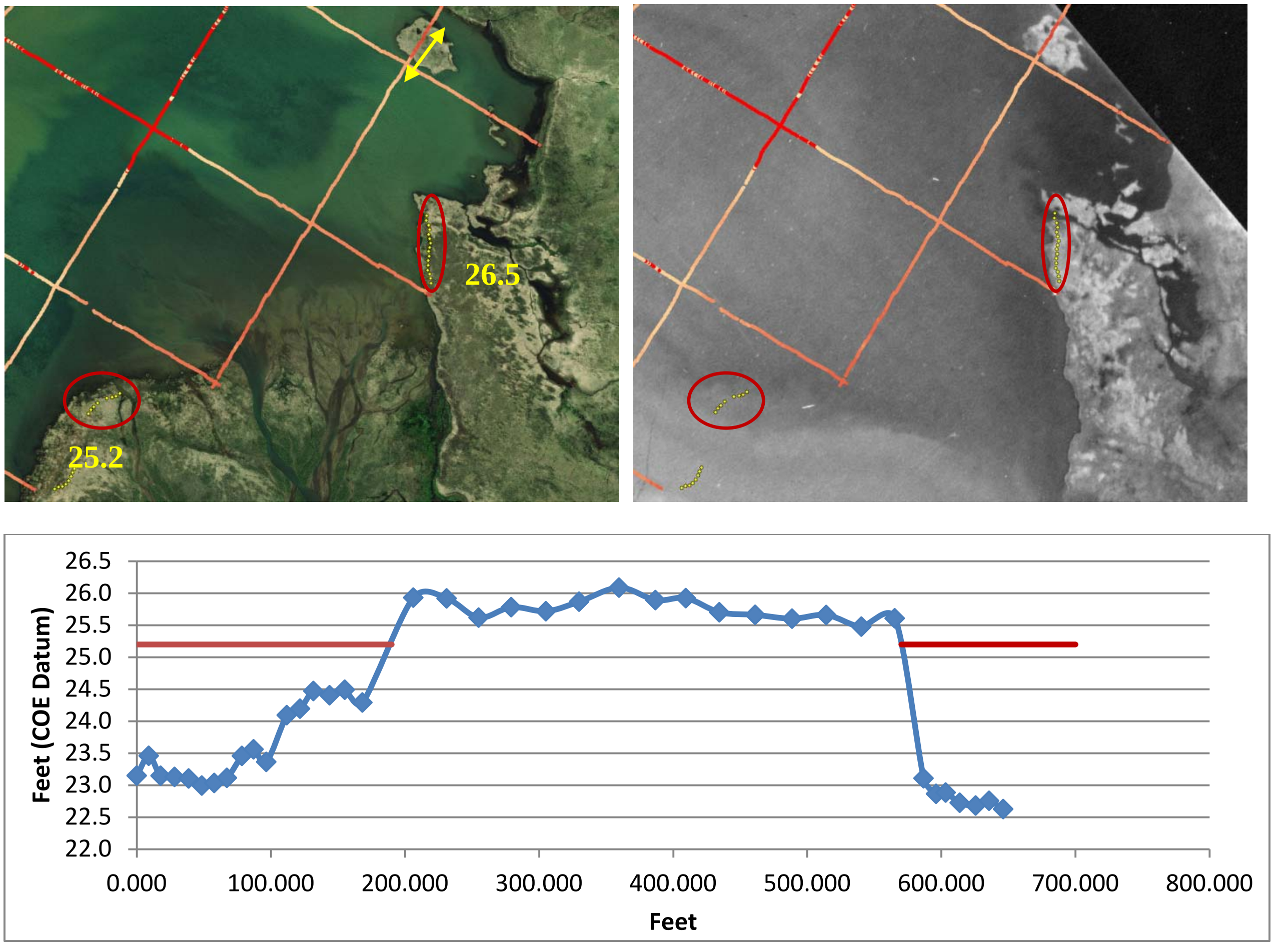

Figure 6. Example of water surface elevation estimation from aerial photographs. 2010 Satellite image on the left with 1957 aerial photograph on the right. A survey transect (bottom) traversed the small island that is visible in both photographs.

[1] These values are described in the source reference, accuracy was not verified.

Table 6 and Figure 7 list the measured lake water surface elevations. All measurements were adjusted to the COE datum established in 2004.

Table 6. Black Lake water levels.

Date	Water Surface Elevation (COE DATUM)	Source
7/1/1949	29.3[1]	Rapid Natural Habitat Degradation and Consequences for Sockeye Salmon Production in the Chignik Lakes System, Alaska October 2003 Table Page 18.
6/23/1953	27.0	Aerial Photograph Interpretation
6/24/1957	25.5	Aerial Photograph Interpretation
8/26/1983	26.0	Aerial Photograph Interpretation
Feb-90	24.3[1]	Chignik Winter Study, 1998, pg8
10/21/1991	25.0	Aerial Photograph Interpretation
Feb-92	23.7[1]	Chignik Winter Study, 1998, pg8
6/1/92	26.3[1]	Chignik Salmon Studies Investigations of Salmon Populations, Hydrology, and Limnology of the Chignik lakes, Alaska, During 2000-2002 Figure 33.
Feb-93	25.6[1]	Chignik Winter Study, 1998, pg8
5/12/93	24.7[1]	CH2MHILL 1993 Electronic Survey Data File: 51293B.out
6/6/1993	27.6[1]	Rapid Natural Habitat Degradation and Consequences for Sockeye Salmon Production in the Chignik Lakes System, Alaska October 2003, Table 3.
7/23/93	27.9[1]	Rapid Natural Habitat Degradation and Consequences for Sockeye Salmon

		Production in the Chignik Lakes System, Alaska October 2003, Table 3.
Feb-95	25.1[1]	Chignik Winter Study, 1998, pg8
Feb-96	23.6[1]	Chignik Winter Study, 1998, pg8
Feb-97	24.2[1]	Chignik Winter Study, 1998, pg8
Feb-98	24.0[1]	Chignik Winter Study, 1998, pg8
6/19/01	24.9[1]	Rapid Natural Habitat Degradation and Consequences for Sockeye Salmon Production in the Chignik Lakes System, Alaska October 2003
9/1/01	23.2[1]	Rapid Natural Habitat Degradation and Consequences for Sockeye Salmon Production in the Chignik Lakes System, Alaska October 2003 Table 4
8/15/04	24.7[1]	DOWL Survey Field Book
12/5/2007	27.0	Oblique Aerial Photograph

[1] **These values are described in the source reference, accuracy was not verified.**

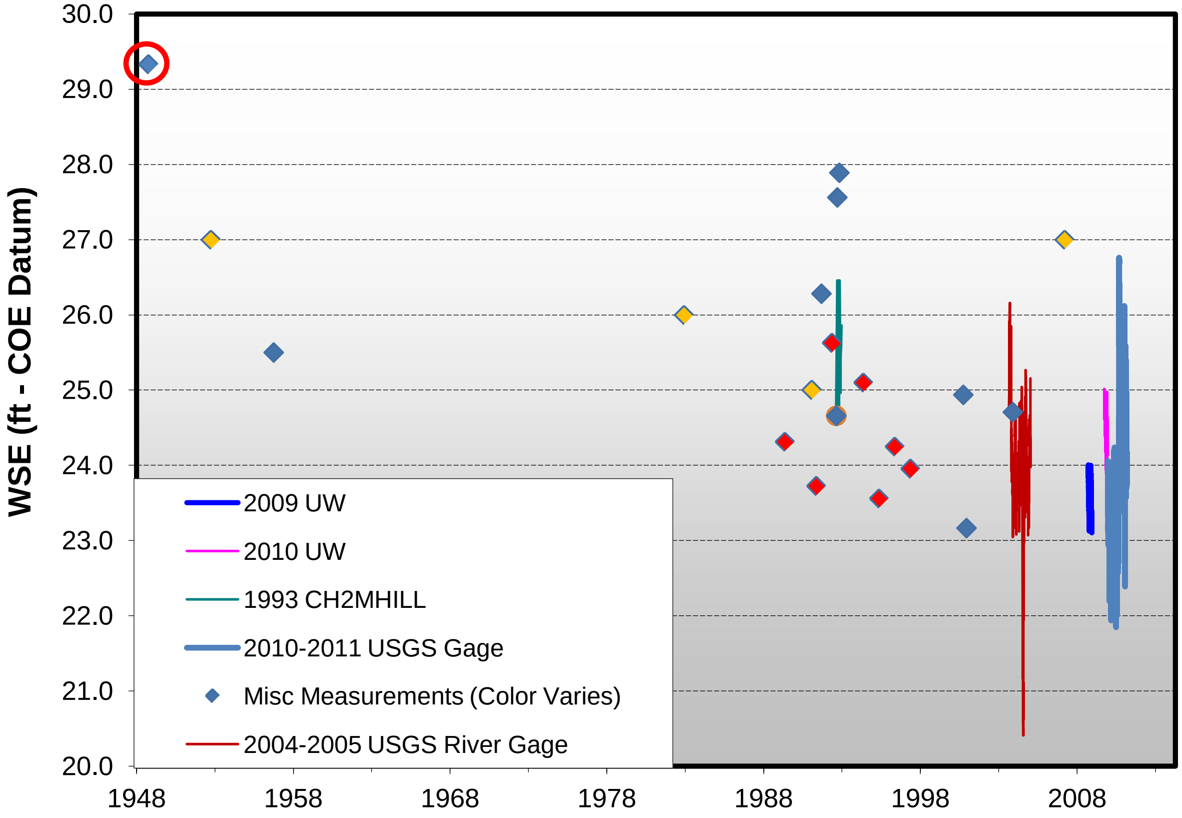

Figure 7. Black Lake Water Level Measurements over time. Four continuous water level measurements have occurred over the years and are shown. Various water level measurements from reports are included as well. Red markers indicated winter measurement, orange markers are lake level estimates from aerial photography.

The highest water surface elevation for Black Lake shown in Figure 7 was reported in 2003 (Ruggerone, 2003). This elevation was based on the USGS published quadrangle maps for Chignik B-4 and Chignik B-3. These topographic maps list an elevation of 37 feet above mean sea level for the NGS monument “Black” and a lake elevation of 28 feet above sea level for Black Lake, resulting in an estimated water surface elevation of 29.3feet (COE Datum). The original map preparation notes for these two quadrangles were obtained and reviewed. As described in the two documents (USGS, 1965), vertical control included NGS monuments and mapping control using altimetry on lakes and identifiable features in the interior of the peninsula. The original mapping notes conclude that these elevations are accurate to plus or minus 10 feet. The original USGS published lake elevation cannot be used as an accurate estimate of historic Black Lake water levels.

While it appears that there may be a downward trend in the water surface elevation for Black Lake, it would be speculative to assume this is the case based on these point measurements alone. Based on the continuous Black Lake water surface elevation measurements in 2011, there appears to be less variability during the winter months. The average of the historical February water surface elevation measurements is 24.3 feet (seven measurements between 1990 and 1998) compared with the 2011 average of 23.8 feet. The average water surface elevation in February 2011 was higher than two of the historical winter measurements and lower than five.

Based on the recent lake stage measurements and photographs from a large flood in 2007, it appears that the lake water surface elevation can reach historic levels (26.5 to 27.5 feet) during flood stages and that during the winter months levels appear to be slightly lower than was measured 15 to 20 years ago.

Trends in Lake Water Surface Elevation and Volume

The volume of Black Lake can change as a result of either a lowering of the water surface or changes in the lake bed due to sedimentation. A typical lake cross section figure is shown in Figure 8. Changes in volume can be a result of either the average water surface elevation going down over time or sediment infilling over time.

$$\Delta \text{ In Lake Volume} = \Delta \text{ Average Water Surface Elevation} + \Delta \text{ Sedimentation}$$

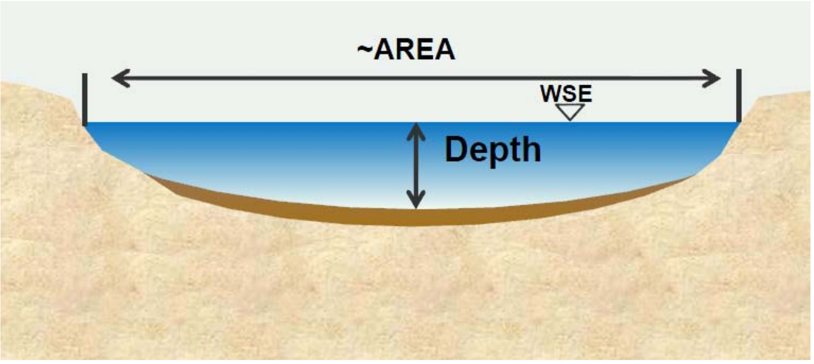

Figure 8. Typical Lake Cross Section.

Lake Sedimentation

Two methods were utilized to estimate sedimentation within Black Lake. The first method looked at the bed material sediment transport capacity of the Alec River. Bed material load is composed of sediment grains found in the stream bed. The finer wash load is only found in the stream bed in very small quantities.

Field data collected along with hydrologic data were used to estimate the annual average sediment load from the Alec River into Black Lake. It was assumed that sediment discharge on the Alec River is capacity limited and that the sediment discharge from the smaller drainages was negligible when compared with sediment discharge from the Alec River. The following method was used to estimate the average annual sediment transport into the lake:

1. A hydraulic model of a short reach of the Alec River upstream from the wye (3 cross sections) was developed. A Manning's *n* value of 0.022 was selected based on calibration using the water surface elevations measured at a flow of 350 cfs.
2. Only 1 year of gage data is available for the Alec River. This length of record is not sufficient to develop a flow duration curve; instead a regional scaling method was used to develop a flow duration curve for the Alec River (Biedenham & Copeland, 2000). A flow duration curve was developed for Russell Creek, the closest site with a long-term stream gaging record (21 years). This curve was then adjusted for use on the Alec River by using a dimensionless discharge index (Q_{2r}/Q_{2a}) based on USGS regional regression equations for the 2-year discharge at Russell Creek and Alec River respectively.
3. A bed material sediment-discharge curve was developed utilizing the simple hydraulic model, a sampled sediment grain size distribution, and Yang's equation for total sediment transport. It should be noted that during high flows bed material will be transported as bed load along the channel bottom and as suspended load within the water column. Using data from the Alec River hydraulic model and the estimated fall velocity for medium sand, we would expect that during flood flows roughly 70 percent of the bed material sediment to be transported as suspended load in the Alec River.
4. Utilizing the flow duration curve and sediment discharge curve, the calculated average annual bed material sediment load into Black Lake was 330,000 tons per year. This is larger than previous estimates likely due to differences in how flow durations were discretized.
5. The Black Lake sediment trap efficiency was estimated using the curve developed by Brune, which relates inflow water volume to water storage volume to estimate the percent of sediment trapped in the reservoir, or in this case, lake. A trap efficiency of 78 percent was selected, which is at the low end of the envelope curve for normal reservoirs. Black Lake is extremely shallow, allowing for wave action to transport bed material sediment within the lake and toward the outlet.
6. It was assumed that all wash load (silt and clay sized particles) transported by the Alec River passed through Black Lake. Most areas of Black Lake have a sandy bottom indicating that there is very little deposition of clay and silt sized particles.
7. These calculations result in an estimated 6 inches of accumulated sediment over the past 50 years.

While the above calculations are useful to determine the order of magnitude of sedimentation in Black Lake, without measured sediment transport data these calculations can have an error of up to an order of magnitude or more.

The second method used to evaluate sedimentation in Black Lake was to directly measure accumulated sediment. A set of five sediment cores approximately 1 meter in length were sampled within the main lake and outlet area. The cores were split in the field and stabilized for shipment and then photographed and logged at centimeter scale for their macro-stratigraphy, including the location of volcanic ash (tephra) beds. Magnetic susceptibility (MS) was measured on all split-core surfaces at intervals of 0.5 cm using a Bartington meter and probe. The tops of two cores were sampled for Pu content to locate the depth of the onset of nuclear weapons testing (1953) and the peak of Pu production (1963). Two cores were also analyzed for radiocarbon (^{14}C by accelerator mass spectrometry at University of California, Irvine) to generate a sedimentation-rate model that extends centuries to millennia, depending on core length and sedimentation rate. Sediment bulk density was measured at 1 cm intervals to quantify sedimentation rates in terms of mass flux (which accounts for changes in porosity) as well as thickness (which does not).

Preliminary results from the lake coring indicate that approximately 1 to 4 inches of sediment has accumulated within Black Lake since 1963. This results in a 1 to 5 percent decline in volume over the past 50 years. Final results for this study will be presented in a separate report to be published in the summer of 2012 by Northern Arizona University.

Black Lake Bathymetry

A bathymetric survey was performed in 2011 and is shown in Figure 9. The survey was completed using survey grade GPS and fathometer to measure the absolute elevation of the lake bottom. This method does not rely on a flat lake water surface elevation to establish the bottom elevations; it instead relies on GPS derived elevation information together with soundings to estimate the elevation of the lake at a known point. From these point data for the lake bottom, a bathymetric contour map was generated (Figure 9) and then used to develop geometric relationships for Black Lake (stage vs. volume and stage vs. area). At a water surface elevation of 26 feet, the average depth of the lake is 6.3 feet with a maximum depth of 13.6 feet.

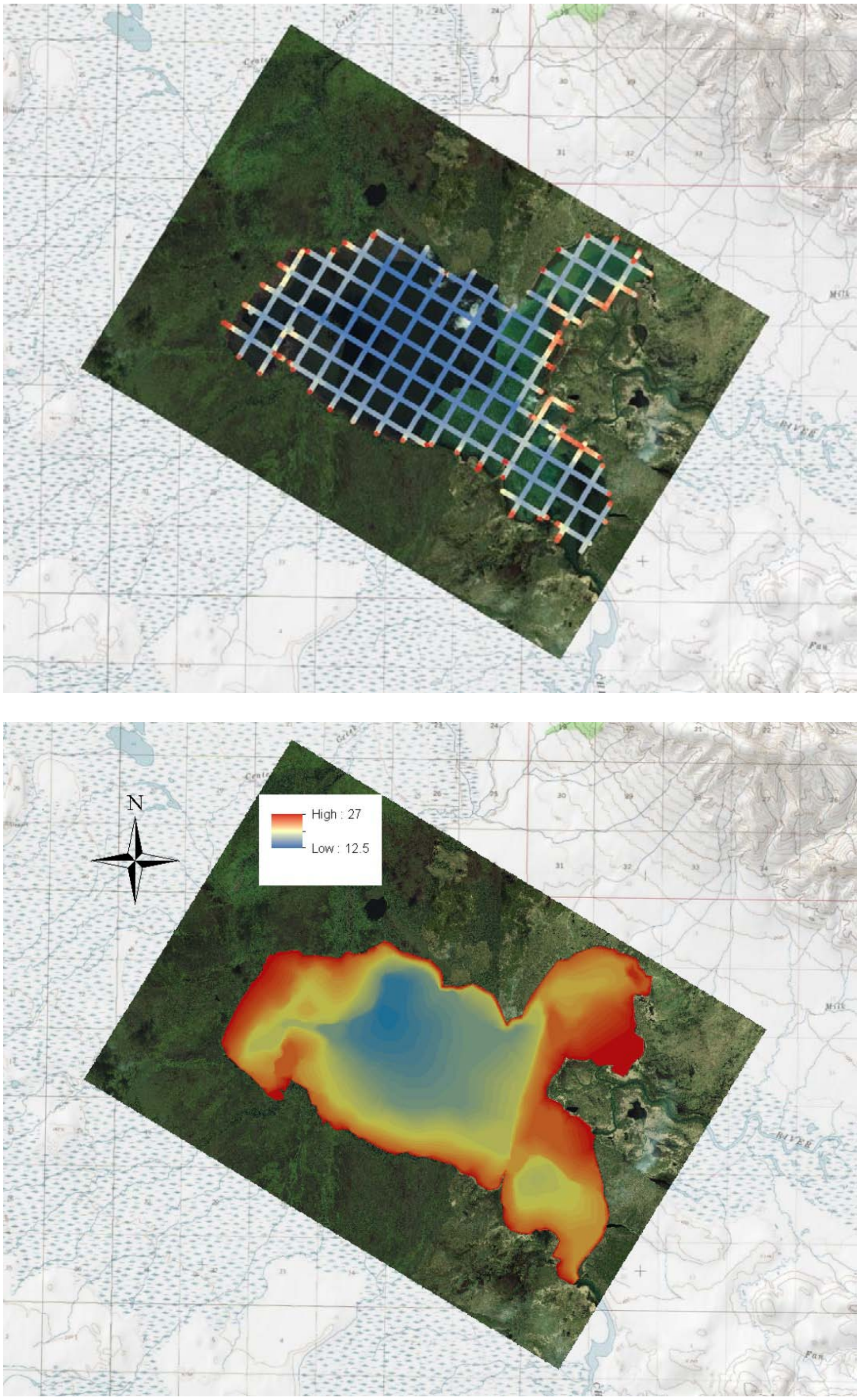

Figure 9. 2011 Black Lake survey transects (top) and bathymetric map (bottom) showing the lake bed elevations.

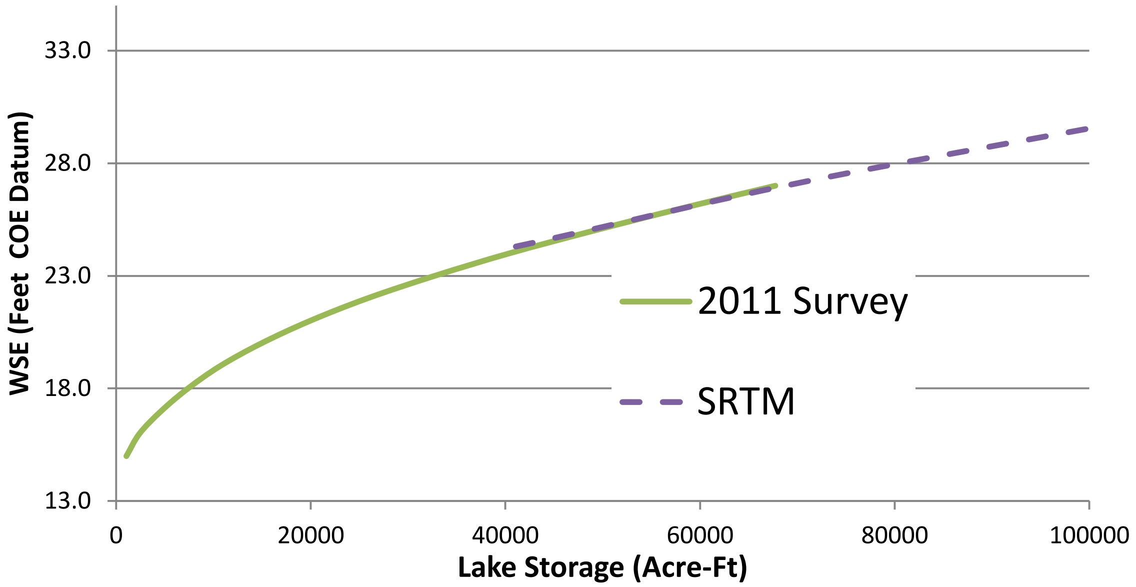

Figure 10. Black Lake storage elevation curve.

The surveyed storage elevation curve (Figure 10) was then extended using topographic data from the Space Shuttle Topography Mission (SRTM). The SRTM data was adjusted vertically until it matched the surveyed data in areas where the curves overlapped. After the vertical adjustment, the slope and shape of the SRTM storage versus elevation curve closely matched the surveyed data. The SRTM data was then used to extrapolate the volume relationship beyond the surveyed data.

Considering the various methods used to collect the historic bathymetric information and lack of a standardized datum, it is difficult to compare this dataset with the previous bathymetric datasets. Figure 11 presents two historical storage-elevation curves alongside the curve developed as part of this study.

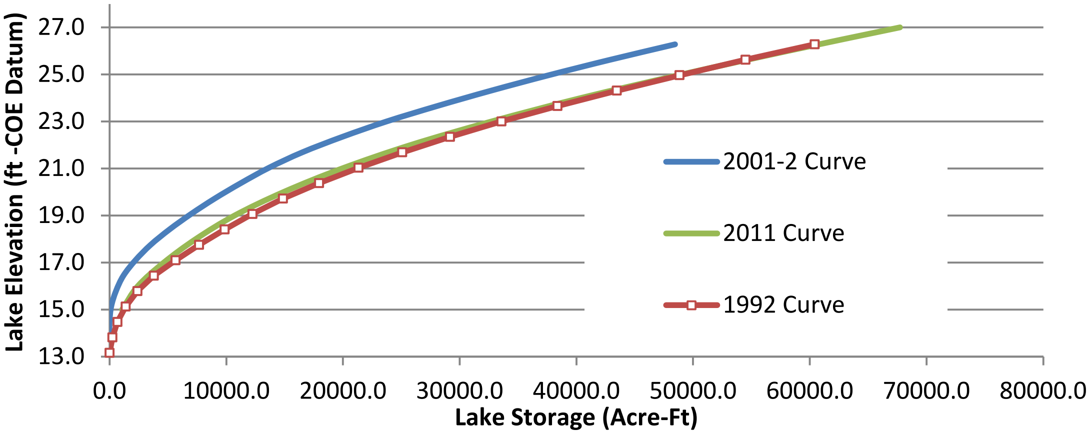

Figure 11. Comparison of elevation-storage curves.

The 1992 dataset (Ruggerone G. , 2003) was collected in June using time transects of the lake while measuring from the water surface to the bottom of the lake. This dataset compares very well to the 2011 surveyed bathymetric data. The 2001-2002 dataset (Chasco, Ruggerone, & Hilborn, 2003) was collected over the course of two summers by using a GPS and depth sounder. Considering the variability in methods and vertical datums, it is difficult to draw conclusions from these three data sets. Based on the 1992 and 2011 data, it appears that overall there may be some indication of sedimentation based on differences between the two curves.

Average Water Surface Elevation Trends

To examine trends in average annual lake water surface elevations, changes in vegetation around the perimeter of the lake was used as a proxy for changes in the average water surface elevation. In order to relate changes in vegetation to changes in average lake stage, two key assumptions are made: that vegetation around the lake responds to changes in average lake water surface elevations and that the bathymetry of the lake remains relatively constant.

A series of seven aerial and satellite images was examined over the last 50 years with an estimate of the perimeter vegetation line established for each image. The polygon area was then calculated and an elevation assigned based on the surveyed surface area versus elevation curve. The elevation calculated cannot be considered a water surface elevation but rather a proxy for the average water surface. The values were then reduced by subtracting the median of the range measured. Results of this analysis are shown in Table 7and Figure 12.

Table 7. Proxy lake elevation estimates.

Year	Proxy Elevation (Feet)	Source
1957	0.95	Black and white photograph
1975	0.83	Satellite imagery (Landsat)
1983	0.4	High altitude photography
1988	0.2	Satellite imagery (Landsat)
2000	-0.2	Satellite imagery (Landsat)
2003	-0.6	Satellite imagery (Landsat)
2010	-1	Satellite imagery (Geo-Eye)

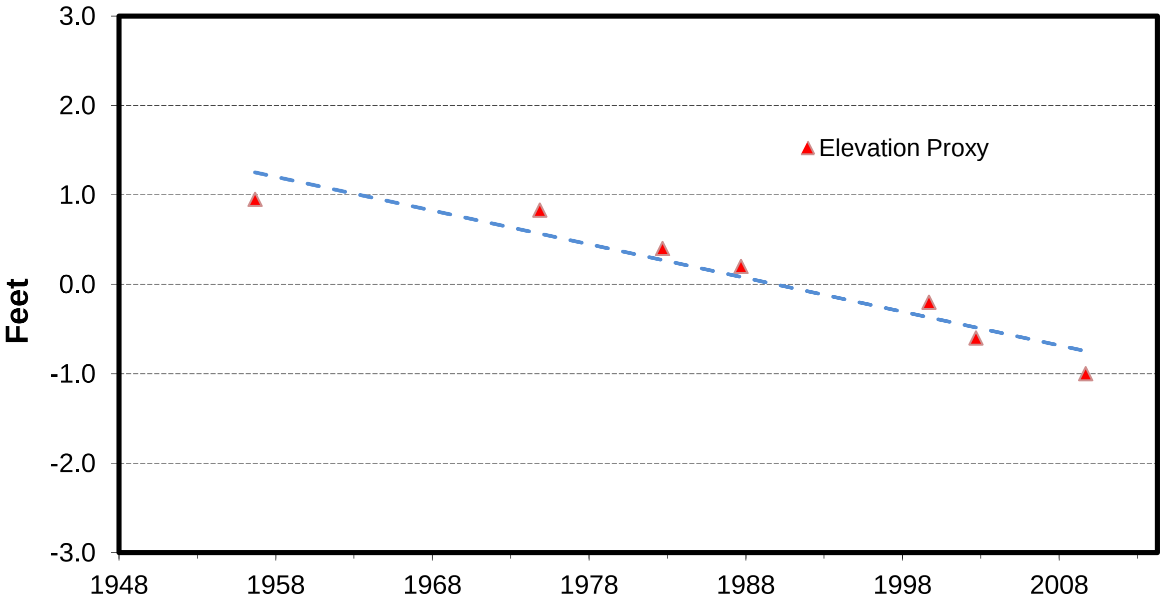

Figure 12. Changes in proxy lake elevation.

This estimate of the average decline in lake water surface elevation includes changes due to delta progradation at the mouth of the Alec River where there have been significant changes in the vegetation line around Black Lake. The actual changes in average annual water surface elevation are likely less than this estimate due to the fact that some of the vegetation changes are a result of delta progradation and not from a lower lake water surface elevation.

One key area of the lake where the vegetation line has likely shifted due to changes in the average lake water surface elevation and not delta progradation is the northwestern end of the lake. Figure 13 shows an aerial photograph from 1957 and a satellite image from 2010. Lake bathymetry transects from 2011 are shown for reference in both images. Figure 14 shows the cross section highlighted in yellow. Two key points are shown on the cross section: the first is the vegetation line that is visible in the 2010 satellite imagery and the second is the water level at the time the image was acquired (September 10, 2010). Careful examination of the 1957 photograph shows that the wind was strong enough from the southeast to produce waves with white caps, indicating that the lake water surface is likely elevated along this margin of the lake in the photograph.

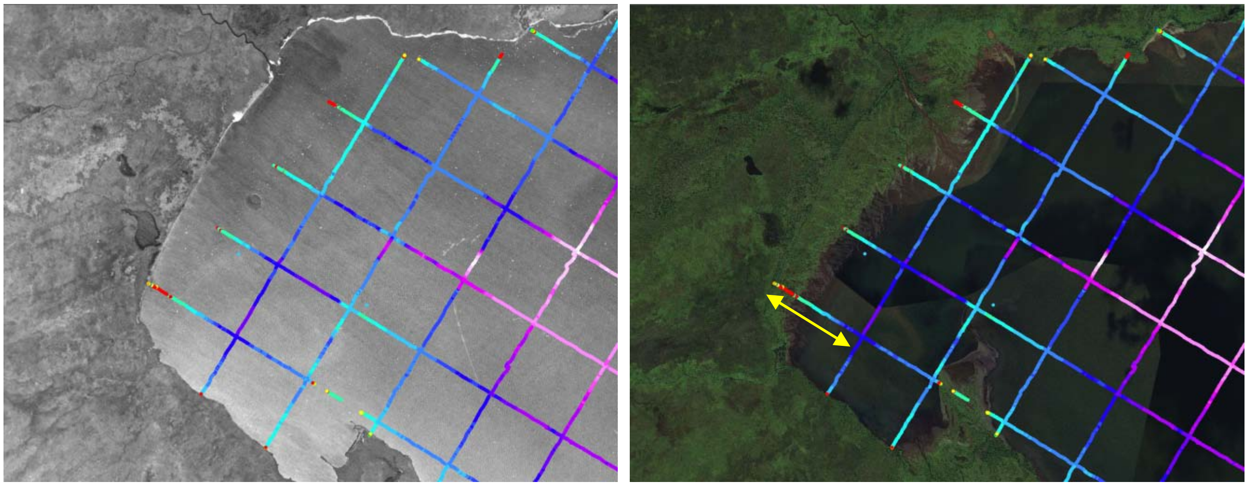

Figure 13. North End of Black Lake (1957 Left, 2010 Right). Water level during the 2010 image was approximately 23.7 feet (COE Datum) based on the USGS lake stage gage.

A 2-foot reduction in lake water surface elevation results in a roughly 1,000-foot change in the location of the water's edge along this northwest lake perimeter. The green band shown in Figure 14 shows the variation in water levels measured from 2010 to 2011 at the USGS gage.

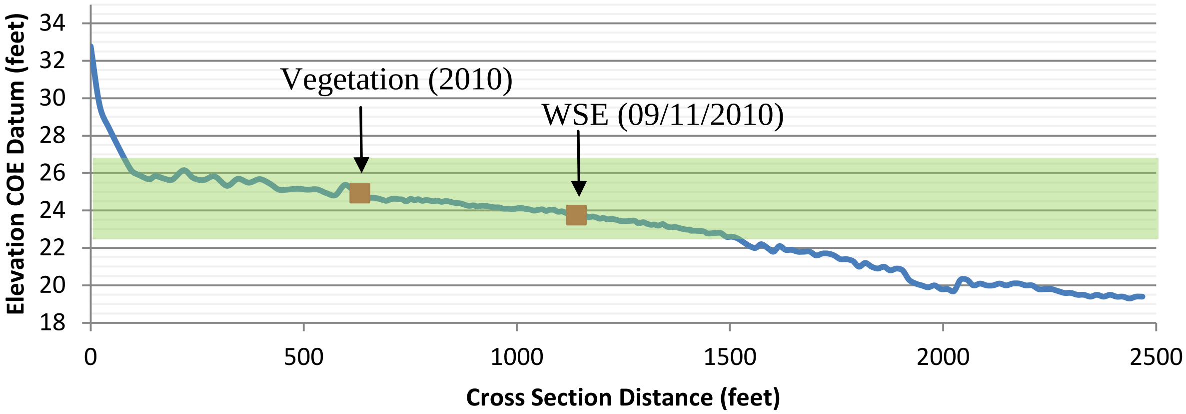

Figure 14. Cross Section along northwest edge of Black Lake. Profile location shown in Figure 14 with a yellow arrow. The green band shows the variation in water levels recorded at the USGS outlet stage gage (15297584).

The results of this analysis indicate that over the past 50 years the average lake water surface elevation has decreased by approximately 1 to 2 feet. This corresponds to an average volume decrease of between 17 and 30 percent. Though the average volume appears to be declining, based on recent lake stage measurements, the water surface elevation during significant runoff events can still exceed historic average water levels.

A drop in the average water surface elevation of the lake, also known as a base level lowering, would also result in degradation in the longitudinal profiles of tributaries that flow into Black Lake. Channel incision and changes to the longitudinal profile are common responses to a lowered downstream base level. Several tributaries surrounding Black Lake show signs of deep incision; however, these tend to be found in the areas shown on the USGS quaternary map as marine terrace deposits and glacial till deposits. The high bluff to the southeast of Black Lake is classified as a marine terrace deposit, which is commonly fronted with wave cut scarps (Detterman, Miller, Yount, & Wilson, 1981). The incised channels through these areas could be a result of the glacial rebound of the Alaska Peninsula. Estimates indicate that the Alaska Peninsula has rebounded 45 feet on the Bristol Bay side and 90 feet on the Pacific Ocean side. There has been some discussion about long-term changes in Black Lake being a result of glacial uplift and/or plate tectonics. Ruggerone (2003) investigated this theory and concluded that uplift due to plate tectonic movement results in greater elevation gain near the lake outlet and would likely cause Black Lake to become deeper. Plate tectonics and glacial rebound are likely not contributing to the long-term shallowing of Black Lake.

The longitudinal profile of the Alec River was surveyed to find supporting evidence for changes in the average water surface elevation for Black Lake. Under equilibrium conditions, the longitudinal profile of an alluvial river would be expected to be upward concave with the slope of the river flattening downstream. The longitudinal profile (Figure 15) for the Alec River shows a slight grade break approximately 3.5 miles upstream from Black Lake. Upstream from this grade break the river exhibits the expected concave upward profile. There are no other obvious grade breaks or knick points along the profile. This provides additional evidence of the decline in the average water surface elevation of Black Lake.

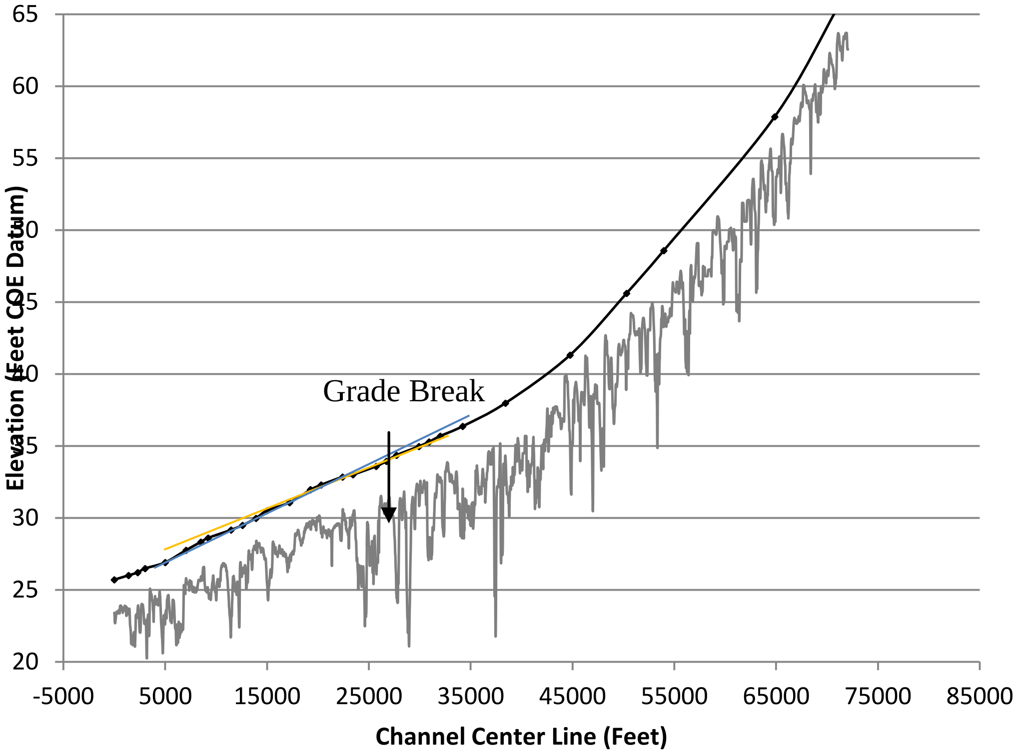

Figure 15. Alec River longitudinal profile

In addition to changes in the longitudinal profile, a river can respond with changes in pattern, roughness, and shape in response to base level changes.

Black Lake Water Level Controls

As with any reservoir or lake the water surface elevation is controlled by:

- Volume of water flowing into the lake
- Direct water losses and gains (precipitation, infiltration, and evaporation)
- Relationship between water storage and the lake water surface elevation
- Relationship between lake water surface elevation and water flowing out of the lake (outlet rating curve)

The volume of water flowing into the lake will vary over time due to changes in many direct factors such as precipitation, temperature, and reduction in glacier runoff. Long-term changes, such as changes in vegetation, in the watersheds can also affect the volume of water that flows into Black Lake.

Previous studies have characterized the outlet of Black Lake as a weir to estimate the relationship between outflow and the lake water surface elevation. Generally, flow out of Black Lake is tranquil with no obvious sill or weir at the outlet or within the upper reach of the Black River. The stage versus discharge relationship of Black Lake is controlled by the channel hydraulics of the upper Black River rather than a typical lake outlet sill.

The confluence of the West Fork River used to enter the Black River farther upstream than at the present moment. Knappen (1929) described how the high sediment load of the West Fork River created the alluvial fan that dams the outlet of Black Lake and establishes the water level of the lake. Figure 16 shows a present day braid of the West Fork flowing into the Black River and depositing sediment in the Black River channel. It is to be expected that as the West Fork River migrates across this alluvial fan, over decades and centuries, that the water levels in Black Lake will fluctuate in response to the changing bed of the Black River.

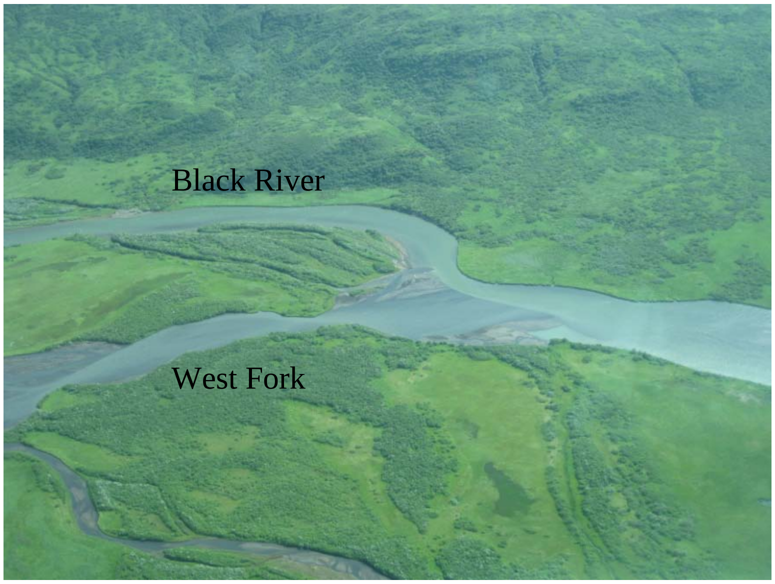

Figure 16. Confluence of the West Fork and Black River showing deposition of sediment in the Black River Channel.

Examining the oldest known map of the Black Lake area (Figure 17) shows that in 1925 the West Fork River was braided, with the first major tributary flowing into the Black River approximately ¾ of a mile downstream of Chiaktuak River. Today, the first major tributary flows into the Black River approximately 3.5 miles downstream from the Chiaktuak River.

Ruggerone (Ruggerone G. T., 2001) describes that the shift in the Black River occurred in the late 1960’s or early 1970’s. Just after the shift local residents reported a waterfall forming across the entire width of the Black River that impeded boat traffic for several years before gradually disappearing.

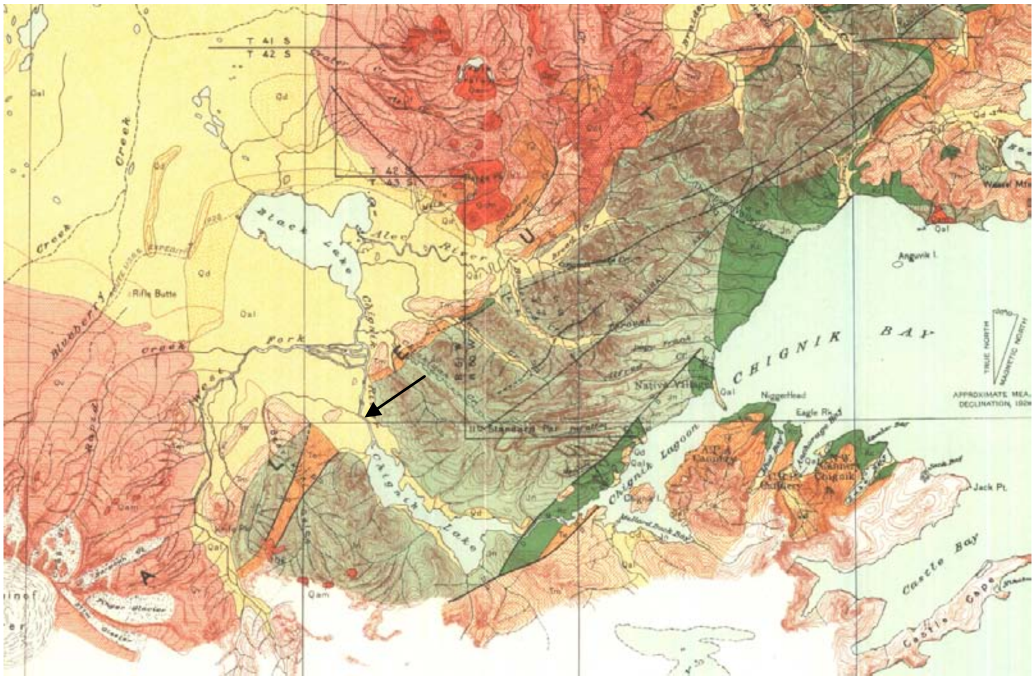

Figure 17. 1929 Geologic Map of the Black Lake area (Knappen & Sargent, Geologic Map of the Aniakchak District Alaska, 1929). Arrow shows the approximate location West Fork Confluence with Black River today (shown in Figure 18).

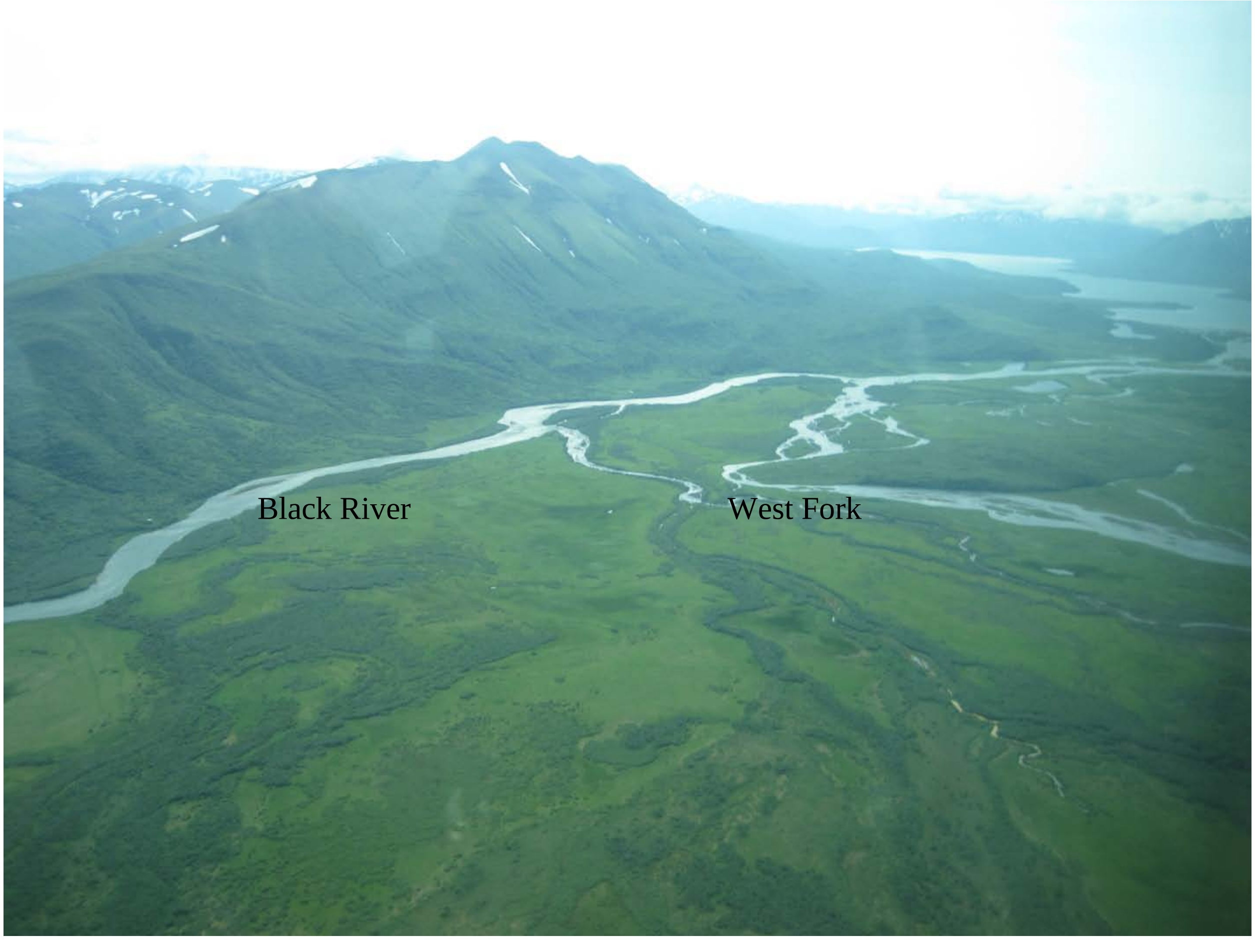

Figure 18. Confluence of the West Fork River and the Black River as seen in 2011.

Upstream from the West Fork the Black River tends to be a single thread channel with obvious signs of degradation noticeable between the current confluence of the West Fork and the confluence with Chiaktuak Creek. Signs of degradation include near vertical channel side banks and perched historic West Fork side channels. The perched inverts are estimated to be on the order of 3 to 5 feet above the current Black River water surface.

Signs of channel degradation diminish upstream from the confluence of Chiaktuak Creek, with no visible signs of channel degradation obvious near the outlet of Black Lake.

Black River Longitudinal Profile

To better understand the Black River and how it controls the stage discharge relationship of Black Lake, a survey of the river was conducted in 2011. This channel survey included cross sections and a longitudinal water surface profile. The longitudinal profile is shown in Figure 19. Several key observations are made from these data:

- The longitudinal profile of the Black River is convex, consistent with a degrading river.
- The average channel slope between Black Lake and Chignik Lake is 0.0004 ft/ft.

- There are several obvious breaks in the average channel slope along the river:
  - Black Lake to Chiaktuak Creek 0.0001 ft/ft
  - 1.5 mile section below Chiaktuak Creek 0.0005 ft/ft
  - Old West Fork confluence to the New Location 0.0003 ft/ft
  - New West Fork confluence to Chignik Lake 0.0008 ft/ft.

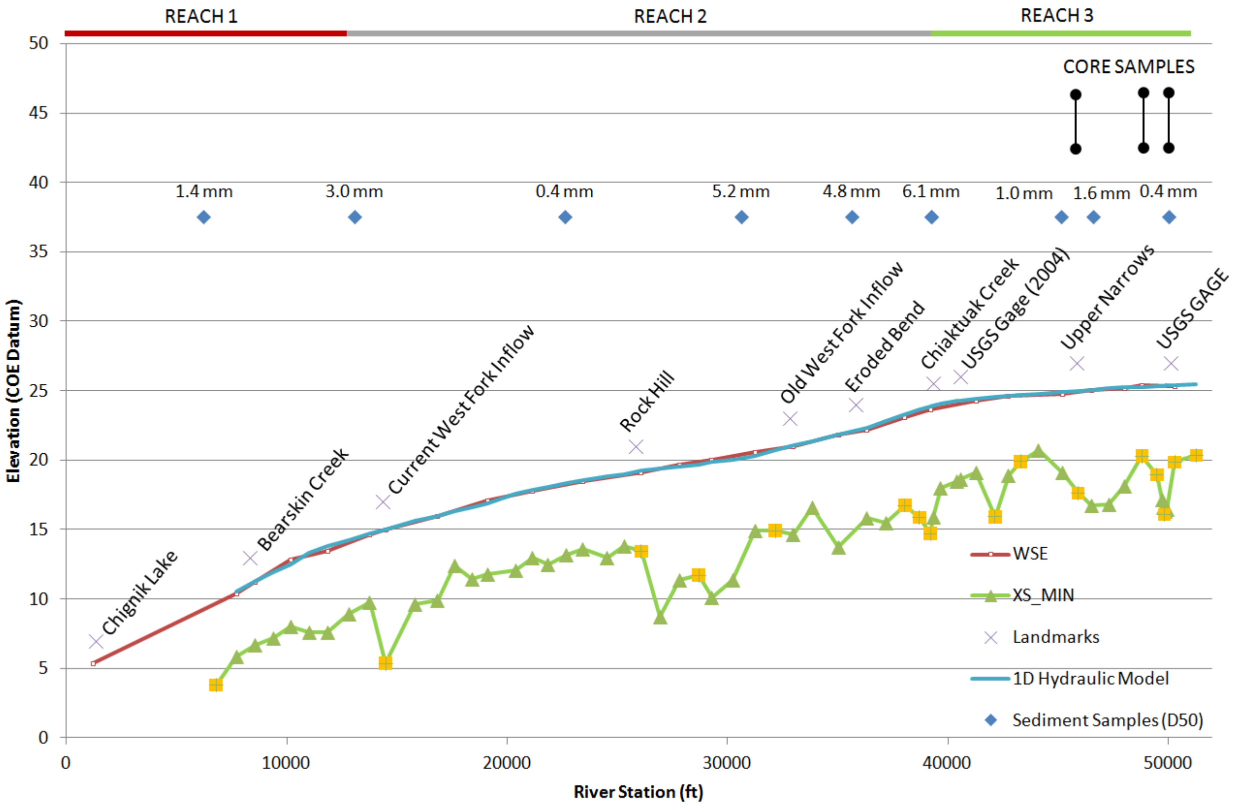

Figure 19. Black River Longitudinal Profile. Cross sections marked with a '+' are repeated cross sections from earlier surveys. Prominent locations are identified and the D50 grain size for bar grab samples is shown above the profile along with the locations of three river bed core samples.

Black River Hydraulic Model

The surveyed topographic data was used to develop a hydraulic model to better understand the hydraulics of Black River. The model was built using the surveyed channel cross sections. Three separate reaches were identified in the model:

- Reach 1 – Chignik Lake to the Confluence of the West Fork.
- Reach 2 - Confluence with the West Fork to Chiaktuak Creek.
- Reach 3 – Chiaktuak Creek to Black Lake.

Lateral inflows for Chiaktuak Creek and the West Fork River were estimated and included in the hydraulic model. It was estimated that flows in Chiaktuak Creek were equal to 10 percent of the flow in the Black River based upon concurrent measurements during low flow conditions by the Univeristy of Washington. The measured ratio of Chiaktuak flows to Black River ranged from 8 to 13 percent. Lateral inflow for the West Fork was estimated based on the runoff ratios developed previously and shown in Table 2. It was estimated that flow in the West Fork was equal to 120 percent of the flow into the Black River. The actual ratio of flows between the Black River and both the Chiaktuak and West Fork River is expected to be variable with the tributaries, contributing more during peak flood events and less during drier periods.

Initial estimates for the channel Manning's *n* were made using standard methods for each reach (Arcement & Schneider, 1990) and then values were adjusted for each reach to match the surveyed water surface. The final *n* values for reaches one through three were 0.027,0.027, and 0.024, respectively. The calibrated model had a maximum water surface difference of 0.33 foot between the modeled and measured water surface elevations and a root mean squared error of 0.15 foot.

The model was then validated within the upper portion of the river by comparing historical discharge measurements from 2004 and 2005 at varying flows with the model results. The modeled rating curve (Figure 20) generated using the 2011 survey data compared very well with the measured discharge versus stage data.

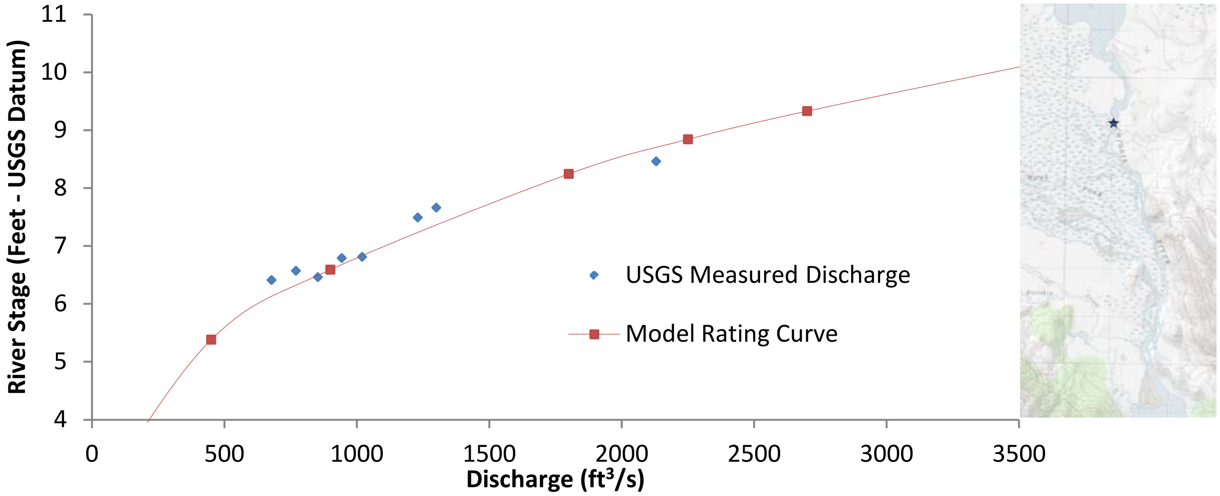

Figure 20. Modeled rating curve in Reach 1 compared with measure discharge data. Inset shows the comparison location.

Based on the calibration and limited model validation, the model was considered suitable for examining the hydraulics of the Black River and changes to the outlet rating curve for Black Lake. The model was then used to better understand responses in the lake water surface elevations to changes downstream.

It is proposed that three mechanisms are primarily responsible for changes in the Black Lake outlet stage versus discharge relationship.

1. Shift in the inflow location of the West Fork downstream resulting in a change in water volume in Reach 2. This will affect the upstream water surface elevations.

2. Rapid erosion of sediment in Reach 2 after the removal of the West Fork sediment input along this reach. Changes in the bed elevation in Reach 2 *will likely* affect the upstream water surface elevations.
3. Gradual long-term erosion in Reach 3 as channel velocities increase as a result of mechanisms 1 and 2. Lowering of the average bed elevations in Reach 3 *will* affect the water surface elevation of Black Lake.

Changes in the stage versus discharge relationship of Reach 3, also known as a rating curve, results in changes in average lake volume. A downward shift in the rating curve, as a result of degradation, would result in lower average lake stages and volumes.

Modeled Changes in the Black River

To evaluate these three possible mechanisms several modifications were made to the hydraulic model inflows and geometry. These results were then compared with the original existing conditions model. A flow of 2,700 cfs was used for the comparisons. This corresponds to peak Black Lake water surface elevations (and discharge) measured during this past water year. The three scenarios used for comparison were:

- Existing conditions.
- Black River with the West Fork inflow shifted upstream to the estimated historical location, same geometry as existing conditions.
- West Fork shifted upstream and additional sediment included so that a layer approximately 3 feet thick exists in the location of the reported waterfall (just upstream from Old West fork inflow).

Water surface profiles for these three scenarios are shown in Figure 21, with the changes in Black Lake water surface elevations listed in Table 8.

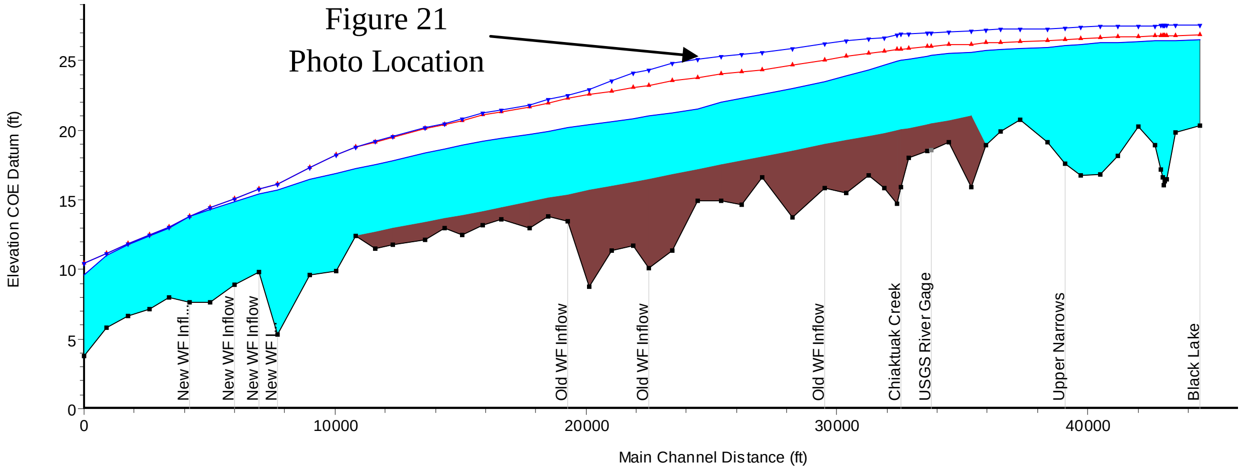

Figure 21. Black River hydraulic model (Flow = 2,700 cfs). Blue (bottom) filled WSE represents the current existing conditions. The red (middle) water surface profile results from the West Fork shifting to a farther upstream inflow. The Blue (top) includes the shifted West Fork and additional sediment (as shown in brown) within the channel.

Table 8. Comparison of changes in the Black River hydraulics

Scenario	Black Lake @2700 cfs		River Station 31239 @ 2700 cfs	
	Stage (feet)	Δ (feet)	Stage (feet)	Δ (feet)
Existing Conditions	26.4	~	21.6	~
Higher West Fork Inflow	26.8	0.4	23.8	2.2
Higher West Fork w/Sediment	27.5	1.1	25.1	3.5

These results show that the dramatic shift of the West Fork River, as reported, will produce changes in the water surface elevation of Black Lake immediately without any changes required in the upper reach of the Black River. A significant portion of the changes are a result of the decrease in the volume of water in Reach 2 and erosion of sediment in Black River when the upstream sediment supply from the West Fork was removed. These results also help to explain the channel degradation observed in Reach 2 where the historic West Fork channels are perched above the Black River. It has been reported that these channels are perched several feet above the current Black River. An example of a perched channel is shown in Figure 22.

Figure 22. Perched tributary channel along the Black River right bank approximately 1 mile downstream from Chiaktuak Creek.

The modeling results show the degradation observed in Reach 2 cannot be used to directly estimate degradation at the lake outlet.

The erosion of the West Fork deposited sediment, described as a waterfall by local residents, occurred within an oversteepened reach also known as a knickpoint. The term knickpoint refers to an abrupt change in the longitudinal profile of a stream, with a steeper slope immediately downstream (Brush & Wolman, 1960). A knickpoint in a channel in which no material is being transported will remain intact indefinitely. A knickpoint in a stream flowing over readily erodible material would be obliterated rapidly. Knickpoints in natural streams exist at all stages between these two extremes. Figure 23 shows several combinations of resistant and non-resistant stream bed material response to upstream knickpoint migration.

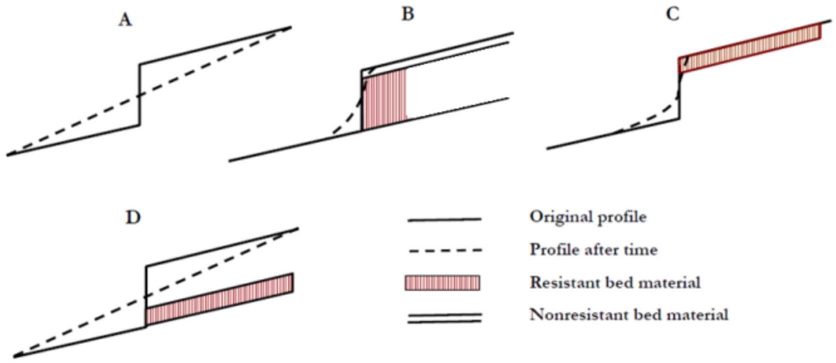

Figure 23. Various combinations of resistant and nonresistant bed material on knickpoint migration. (Brush & Wolman, 1960)

The anecdotal reports of the dramatic shift in the West Fork combined with a waterfall forming in the Black River and then rapidly disappearing indicate that initially the knickpoint in the Black River was in highly erodible material. Based on sediment samples and a visual inspection of mid channel river sand bars, the West Fork transports medium to coarse sands. Deposits of this material in the Black River would be highly erodible. The waterfall observed on the Black River after the shift was likely a result of a knickpoint in bed material similar to configuration A in Figure 23.

Black River Sediment Transport

Nine separate sediment grab samples were collected in July 2011 from similar geomorphic features along the Black River to develop an understanding of bed material transport within each reach. If armoring was present, the samples were collected below the armor layer. A location map and complete sediment sampling results are shown in Appendix B. The sampled median grain size along the Black River (shown in Figure 19) indicates that the largest sediment sizes occur just downstream from Chiaktuak Creek. The median sampled grain for reaches 1 and 2 varied between medium and large sand (0.4 and 3.0 mm). The median size increased just downstream from Chiaktuak Creek in the over steepened area to fine gravel (4.8 to 6.1 mm).

Visible armoring was observed in the bars immediately downstream from Chiaktuak Creek. The median sampled grain size in the upper section of the Black River, Reach 3, was medium sand (0.4 to 1.6 mm).

Using the 1D hydraulic model for the Black River, bed-shear stress and stream power were examined between Chignik Lake and Black Lake. Figure 24 shows the bed-shear stress in the existing Black River at a discharge of 2,700 cfs as well as a comparison of stream power between the current existing conditions and the historical scenario (shift in West Fork + sediment) modeled. Stream power decreases dramatically in Reach 2 with a noticeable increase in stream power in the knickpoint area. Farther upstream in Reach 3, stream power is similar between the historic scenario and current conditions

The average bed-shear stress in reaches 1 and 2 is between 0.1 and 0.15 lb/ft^2. Utilizing shields criteria for incipient motion, there is sufficient shear stress to mobilize and begin to transport the median grain sizes found in the Black River grab and core samples. The grab samples collected just downstream from Chiaktuak Creek contain larger sediment grain sizes with approximately 8 percent of the material larger than ¾-inch gravel and a D84 size of between 14.8 and 15.3 mm. A bed-shear stress of approximately 0.16 to 0.20 lb/ft^2 is required to initiate motion of these larger particles. In this area, as the river transports the smaller particles from this over steepened area, the river bed will become armored with the larger particle sizes remaining. The remaining larger particles will armor the river bed, reducing stream bed degradation. Armoring was visible in the point bars (Figure 25) just downstream from Chiaktuak Creek.

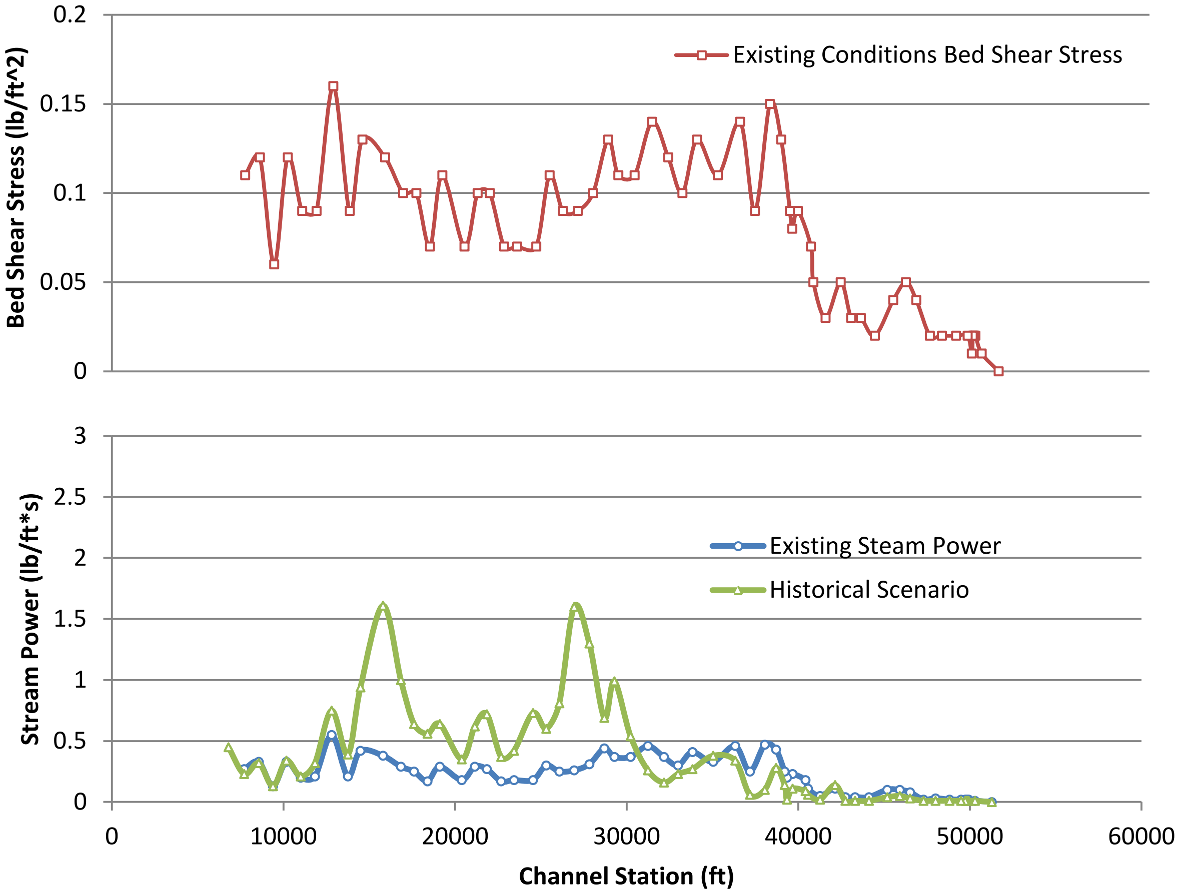

Figure 24. Comparison of stream power (2,700 cfs) between existing conditions and historical scenario (bottom) and the calculated bed shear stress for the existing conditions model (top).

These modeling results indicate that sediment transported by Chiaktuak Creek likely becomes an erosion resistant feature once deposited in the Black River, creating a situation similar to configuration B in Figure 23. The larger particles transported by Chiaktuak Creek armor the bed of Black River, increasing the average grain size of the stream bed, enabling them to resist the bed surface shear forces.

Figure 25. Black River point bar downstream from Chiaktuak Creek showing visible armoring.

A second potential erosion resistant feature was identified through core samples taken in Reach 3 of the Black River. The core sample locations are shown in Figure 19. One core (Core Site 6) shows 48 inches of medium sand with a consistent grain size throughout the 4-foot core. Two cores (Core Site 5 and 4) consisted of similar medium sands in the upper 24 inches. However, the lower sections of these two cores consisted of fine-grained material consisting of 76 and 78 percent silt.

The critical shear stress required to mobilize fine-grained material varies widely. Assessing erosion resistance of cohesive materials by flowing water is complex due to the difficulties in characterizing the strength of the electro-chemical bonds that define the resistance of cohesive materials. One study in the Yalobusha River basin in Mississippi found two distinct fine-grained clay formations in the watershed. One formation had a measured critical shear stress of 0.03 lb/ft^2 , and the second formation had a critical shear stress of 3.82 lb/ft^2. Papanicolaou (2008) suggests that 0.21 lb/ft^2 is an appropriate critical shear stress for a cohesive, well compacted sediment layer. Considering the relatively low bed-shear stresses modeled in the upper portion of Reach 3 of the Black River, cohesive sediment layers in this reach may also prevent degradation of the river bed, and depending upon the cohesive strength of the soil, could also prevent upstream migration of a knickpoint. Figure 26 shows a picture of the sediment sampled between 24 and 48 inches below the stream bottom. The material was classified as silt.

Figure 26. Sample from 24 to 48 inches below the channel bed at Core Site 5.

Black River Cross Section Comparison

To further examine the stability of the Black River, the cross sectional surveys were compared. Cross section surveys of both the Alec River and Black River were completed in 1993, 2004, and 2011. These surveys were adjusted to the common COE datum established for Black Lake. Complete data for repeated cross sections are shown Appendix A. Seven cross sections in Reach 3 of the Black River were available from 1993 (XS-2 through XS-8). An additional nine cross sections were surveyed in 2004 and 2011. Between 2004 and 2011 two significant floods occurred. The first was in December 2007 with local residents reporting that you could almost boat from Black Lake across to the northern side of the Alaska Peninsula. The second event was during the spring of 2011. Residents indicated that this was the second highest flood in recent memory, behind the 2007 event. The Black River cross section locations are shown in Figure 27.

Table 9 shows a comparison of the thalweg elevations and average channel elevations for each cross section on the Black River. Between 1993 and 2004 all seven cross sections, located within Reach 3 (XS-2 through XS-7), showed lower average channel elevations, indicating that Reach 3 degraded over this time. On average the thalweg was 1.6 feet lower and the average channel elevation was 0.7 foot lower. However, between 2004 and 2011 the average thalweg elevation for these cross sections increased by 0.5 foot with a corresponding 0.2-foot increase in the average cross section depth. Six out of the seven original cross sections aggraded during this second period.

Overall, between 1993 and 2011 the repeated cross sections showed a 1.1-foot decrease in the average thalweg elevation and a 0.6-foot decrease in the average channel elevation. The degradation occurred generally between 1993 and 2004 with some aggradation during the period 2004 and 2011.

Between 2004 and 2011 the two cross sections just downstream from Chiaktuak Creek and one cross section immediately upstream showed signs of degradation with both a lower thalweg and lower average channel elevation.

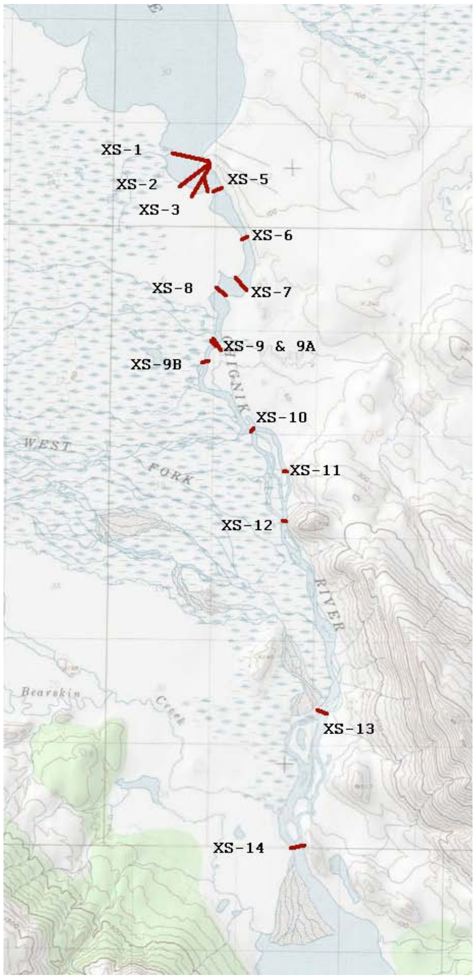

Figure 27. Location of repeated cross sections along the Black River.

Table 9. Black River Cross Section Comparison Summary. Negative values indicate that the average channel elevation has decreased.

Black River	River Station (ft)	Thalweg Elevation (ft)			Average Channel Elevation (ft)			Change in Average Elevation (ft)					
								1993-2004		1993-2011		2004-2011	
		1993	2004	2011	1993	2004	2011	Thalweg	Channel	Thalweg	Channel	Thalweg	Channel
XS-1	51275		20.9	20.3		22.9	23.1					-0.64	0.12
XS-2	50295	20.7	18.8	19.8	23.1	22.5	23.3	-1.88	-0.62	-0.90	0.18	0.98	0.80
XS-3	49826	18.4	15.3	15.7	22.8	21.9	22.2	-3.09	-0.84	-2.71	-0.54	0.38	0.29
XS-4	49483	20.7	19.0	18.7	22.7	21.9	21.9	-1.72	-0.84	-1.99	-0.81	-0.27	0.03
XS-5	48812	21.8	18.6	20.2	22.6	21.5	21.8	-3.17	-1.08	-1.56	-0.84	1.61	0.24
XS-6	45913	18.0	17.4	17.6	20.7	19.8	20.0	-0.60	-0.89	-0.35	-0.69	0.25	0.20
XS-7	43307	19.5	19.1	19.9	22.0	21.5	21.7	-0.39	-0.52	0.41	-0.33	0.80	0.18
XS-8	42142	16.5	16.6	15.9	20.4	20.1	19.4	0.08	-0.31	-0.62	-1.05	-0.70	-0.75
XS-9	39205		15.8	14.6		20.8	19.9					-1.20	-0.88
XS-9A	38703		16.7	15.7		15.5	15.2					-1.02	-0.27
XS-9B	38049		16.6	16.6		20.8	21.1					0.03	0.30
XS-10	32173		14.8	14.7		17.2	16.9					-0.06	-0.26
XS-11	28699		10.1	10.9		13.9	14.4					0.77	0.52
XS-12	26080		13.4	13.4		15.2	14.9					-0.02	-0.27
XS-13	14490		6.8	4.8		12.5	12.1					-1.96	-0.45
XS-14	6797		5.4	3.4		7.2	7.4					-1.98	0.25

Black Lake Sensitivity to Change and Maximum Lake Levels

To examine how changes downstream would affect Black Lake over time, a simple hydrologic model was developed based on the following:

- Lake stage versus storage relationship – surveyed data
- Lake discharge versus storage relationship – developed from hydraulic model
- Measured lake inflows and outflows for 2004-2005

This simple model combined with the hydraulic model of the Black River was used to evaluate how changes in the Black River affect water surface elevations in Black Lake over time. The period from May 19, 2004 through May 18, 2005 was used as the reference year for comparisons. The Alec River and Black River measured hydrographs appear to follow the typical pattern for Black Lake: high flows during the spring snowmelt period and tapering off over the summer.

Black River discharge results for the modeled and measured 2004-2005 period are shown in Figure 28. The model predicts slightly higher discharge during peak events and slightly lower values during the winter low flow periods. There is a high degree of confidence in the storage curve and the lake outlet discharge curve. Therefore, the difference between the modeled and measured outflow hydrographs are likely due to tributary inflows and possibly groundwater contributions to the lake during periods of low lake stage. Tributary flows were estimated based on average annual ratios of flow into Black Lake; however, the results suggest that during high flow periods the Alec River contributes a larger percentage of inflow and during low flow periods a smaller percentage. Physically, this could be explained by a larger portion of rainfall with the smaller tributary basins going into subsurface and groundwater layers and taking longer to flow into Black Lake.

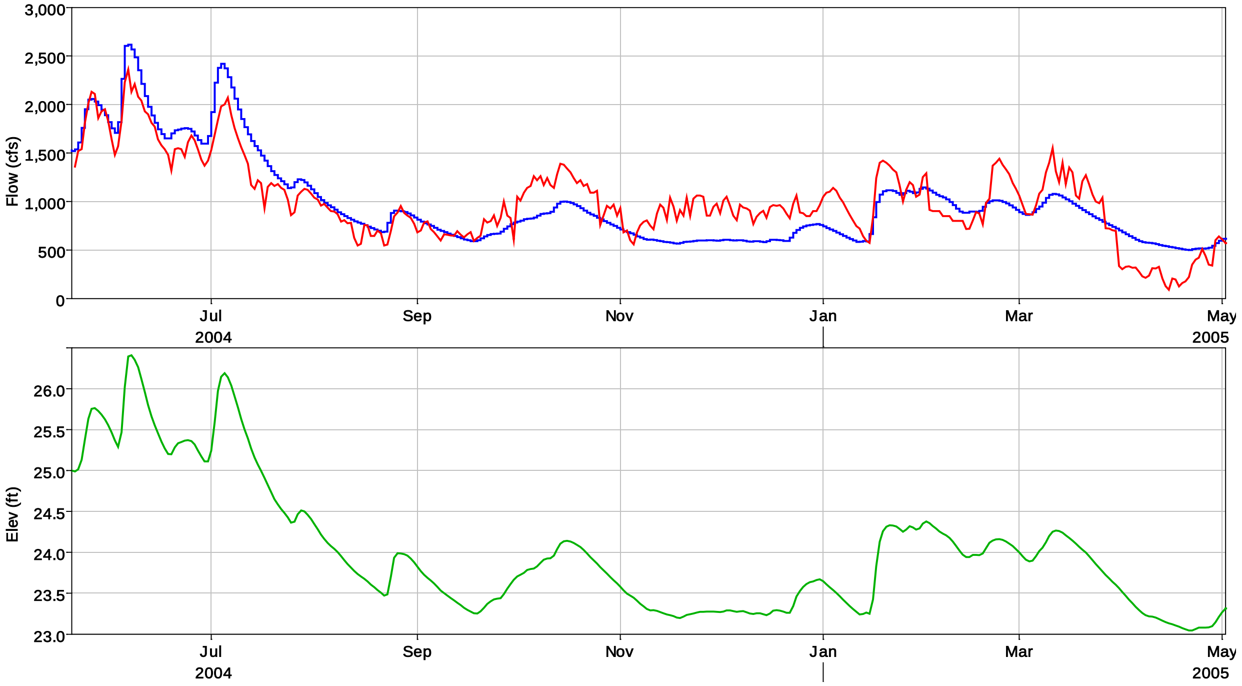

Figure 28. Comparison between modeled (blue line) and measured (red line) discharge on the Black River 2004-2005 (Top). Modeled Black Lake stage for 2004-2005 (bottom).

Black Lake Outlet Structure

To raise the water surface in Black Lake a substantial structure would be required in Reach 3 of the Black River or, alternatively, several smaller structures could be built in Reach 3.

Significantly raising the water surface upstream of an instream structure requires that the structure “choke” the river, forcing a higher water surface upstream. One typical example would be bridge abutments that project into a large river forcing a rise in the upstream water surface elevation. Another example would be in the installation of a broad crested weir.

It is unlikely that the previous attempt to alter the water surface elevation of Black Lake would have had much success. This previous attempt to raise lake levels consisted of installing a geotextile web across the channel bottom to encourage deposition of sediment near the lake outlet. While the goal of depositing sediment in this area may have been accomplished by this technique, the corresponding reduction in conveyance area would not have led to a significant increase in the upstream water levels. As an example, if the channel elevations for cross section 5, shown below in Figure 29, were raised by 1.0 foot, the corresponding change in Black Lake water surface elevations would be minimal, as shown in Table 10.

Figure 29. Black River cross section 5.

Table 10. Changes in Black Lake WSE with 1 foot of sediment accumulation at cross section 5.

Flow	Change in Black Lake WSE (feet)
450	0.17
900	0.07
1800	0.03
2250	0.03
2700	0.02
3600	0.02

A more traditional approach would be to install a broad crested weir that would extend across the river at cross section 5. The weir could have a lowered section in the middle to allow the passage of boats and fish. This modification is shown in Figure 30 along with the upstream water surface at a flow of 900 cfs down the Black River.

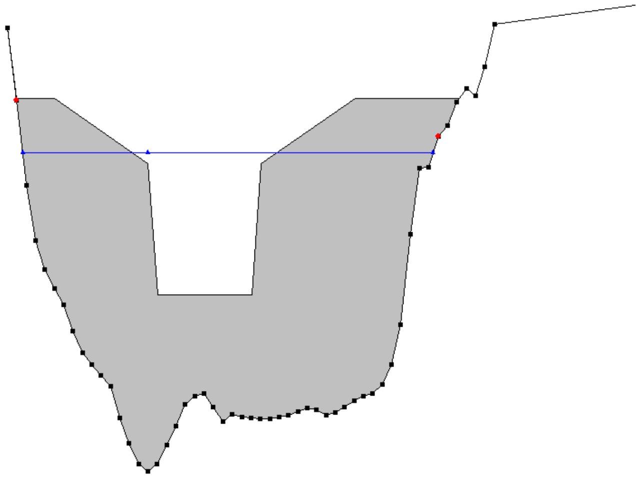

Figure 30. Cross Section 5 with compound weir.

The effect of this type of structure is that at low flows the center portion functions as a weir raising the upstream water surface elevation. At high flows the weir flow area expands with a decreasing influence upstream. A comparison of the with- and without-weir rating curves for the lake is shown in Figure 31. The curves show that at lower flows the weir increases lake water surface elevations by approximately 1.3 to 1.5 feet, and at higher bank full flows, this decreases to 0.1 to 0.25 foot.

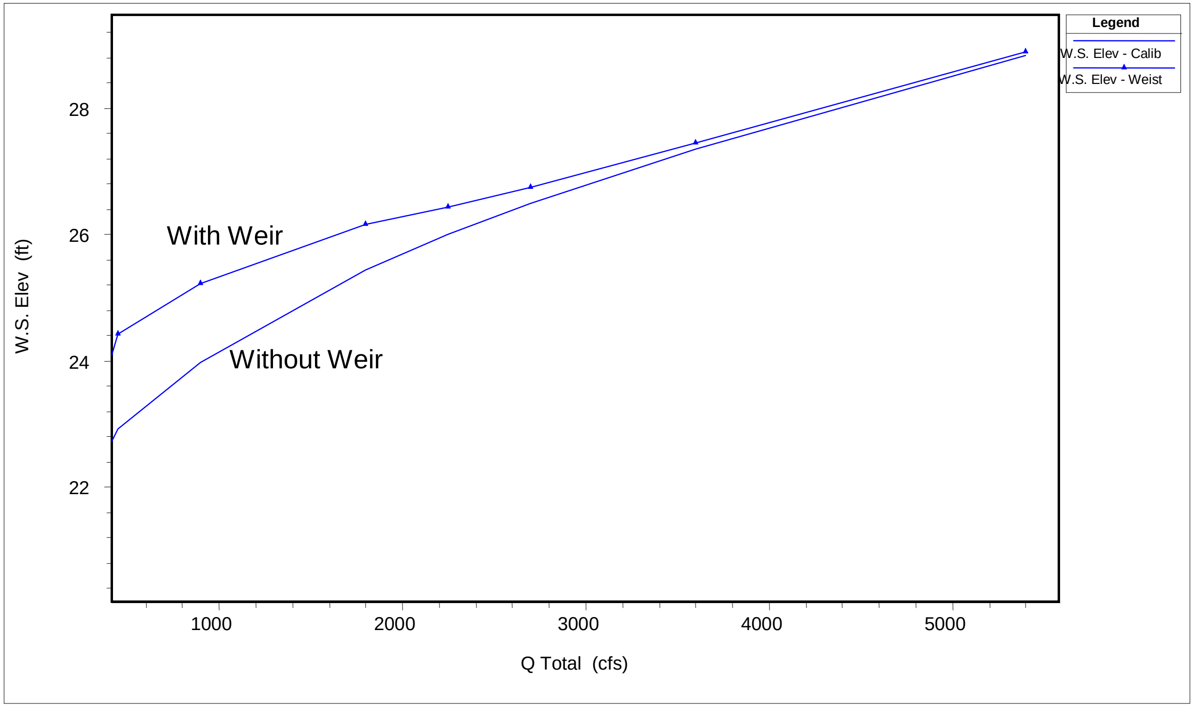

Figure 31. Lake outlet rating curve

Utilizing the hydrologic model with a modified outlet rating curve, the effect of a weir at the outlet of Black Lake was examined. The plot shows that this type of weir would effectively raise the lake water surface elevation during low flow periods with only a moderate increase at the higher lake stages.

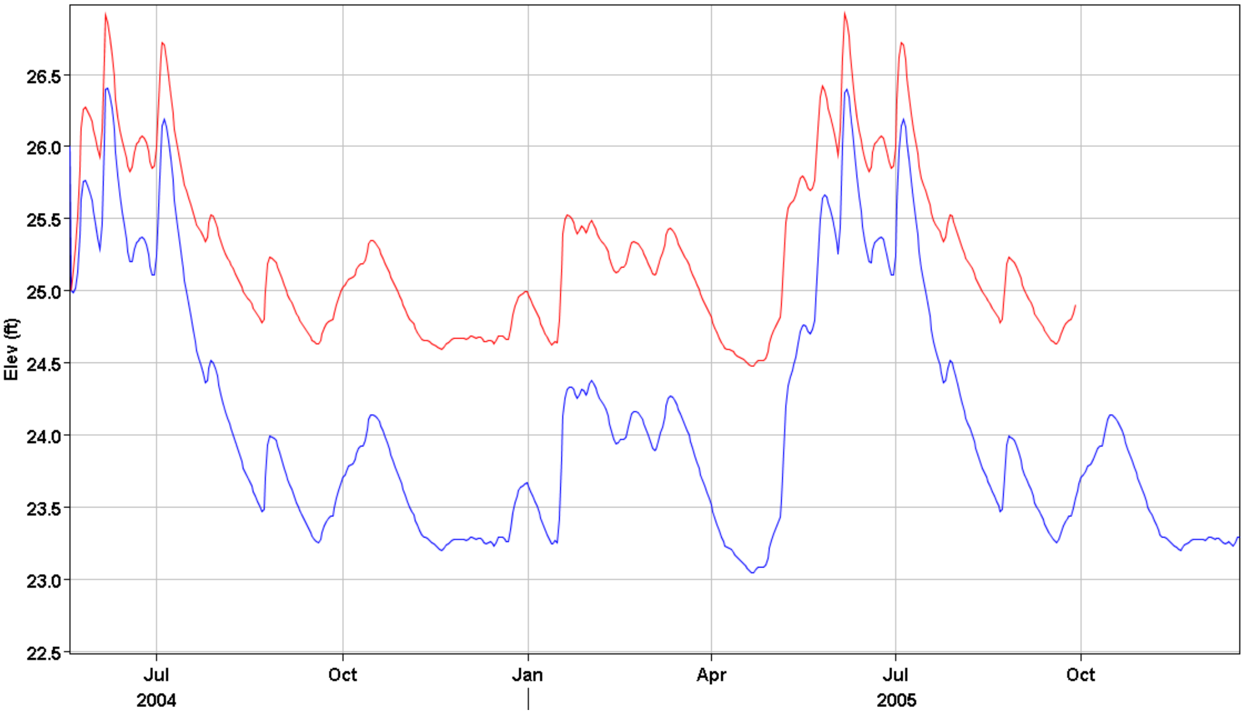

Figure 32. Comparison of 2004-2005 with a weir (RED) and without a weir (BLUE).

The weir structure impact on adult salmon fish passage is expected to be negligible at all lake stages. At low flow, when the weir is not submerged, there would be an approximately 1.5-foot difference in the water surface elevation from upstream to the side of the weir, with velocities through the opening on the order of 3 feet per second. At high lake stages the difference between the upstream and downstream water surface elevations would decrease with a slight increase in channel velocities.

Changes in the Alec River Delta

Over the past several decades there has been some concern that the mouth of the Alec River is shifting towards the south and could eventually short circuit Black Lake and empty into the upper reaches of the Black River. The original 1929 geologic map indicates that a majority of the Alec River flow empties into Black Lake through the North Alec River with a more recent 1950's aerial photograph showing flow through the North and South Alec delta channels, but also through the center of the Alec delta.

Figure 33 shows some of the changes in the Alec River delta over the past 80 years from the oldest map available in 1929 to a satellite image in 2011.

Figure 33. Alec River Delta in 1929 (Top), 1956 (Middle) and 2011 (Bottom).

The current Southern Alec River channel cannot migrate any farther south due to a high relic shoreline bluff shown on the quaternary geologic maps as a marine terrace deposit consisting of well sorted sand and gravel plateaus, ending locally with prominent wave-cut scarps. This feature is labeled in Figure 334.

Figure 34. Overhead color infrared photograph showing the marine terrace adjacent to Black Lake (top) and oblique photograph showing the same marine terrace.

The Alec delta will continue to change naturally over time as sediment from the Alec River is continually deposited near the distal edge of the delta, forcing shifts in both the magnitude of flow in the delta channels and over time the location of the channels through the delta area. The higher marine terrace adjacent to the southern Alec delta channel prevents any further migration of the channel and eliminates the possibility of the Alec River bypassing Black Lake.

Based on the estimated distribution of inflow into Black Lake, there will always be a hydrologic connection between the northern and southern areas of Black Lake. An estimated 37 percent of the water flowing out of Black Lake originates from the western Black Lake watershed.

Discussion and Conclusions

The average volume of Black Lake over the past 50 years is estimated to have decreased by approximately 25 percent due to the lowering of the average lake water surface elevation with an additional 1 to 5 percent reduction due to lake sedimentation. Lower lake water surface elevations are attributed to the shift in the location where the West Fork River enters the Black River. Based on the historical changes in lake surface area related to lake elevation, it is estimated that the slow trend in lower average lake water surface elevations may continue. However, comparisons of recent cross section data collected in 2004 and 2011 indicate that degradation may have ceased or slowed down, possibly as a result of the Black River reaching a quasi equilibrium condition following the shift in the West Fork.

The West Fork currently appears to have migrated as far south as possible with a hardpoint preventing further migration. While no estimates have been made on when the West Fork River will migrate back towards Black Lake, if and when this does occur, we can expect to see aggradation within portions of the Black River again.

Two methods were examined to raise water levels in Black Lake. The first method, proposed in 1993, would likely have been ineffective at significantly changing the lake’s water elevations. The second method is a more traditional solution that consists of a compound weir that increases water levels at low flows but still provides for similar water levels at higher flows. However, when constructability is considered in this remote area, the challenges and cost of installing a grade control structure escalate quickly. In addition to the challenges with installing such a structure, there would be no ability to adapt such a structure should the Black River continue to degrade. While it may be technically feasible to manipulate the lake water surface elevation with an outlet structure, construction of such a structure would be challenging and at a high costs.

No outlet structure is recommended at this time considering:

- the limited evidence that the rate of change in the upper reaches of the Black River is decreasing and erosion resistant layers are likely to exist in the stream bed
- the challenges and cost associated with construction in this remote area
- the inability to adaptive manage a project in this remote area
- the potential to increase summer lake temperatures if the lake depth is increased (Griffiths, Schindler, Balistrieri, & Ruggerone, 2011)

Black Lake should continue to be monitored over time to identify significant changes in the lake water surface elevation, geometry of the Alec Delta and Black Lake shoreline and base level of the Upper Black River.

Recommended Monitoring Plan

Black Lake is an important resource for the Chignik area fisheries. Considering the documented gradual changes in the physical habitat of Black Lake, it is important to continue monitoring the lake to establish the direction and rates of change in the future. The primary objective of this plan is to detect degradation within Reach 3 of the Black River.

The following monitoring plan is recommended at a minimum in addition to the typical limnology data collected by the University of Washington:

1. Conduct year-round continuous lake level measurements.
    a. It is important to monitor the level of Black Lake on a continuous basis throughout the year to establish rates and direction of WSE changes.
    b. These measurements should consist of simple water level recorder installed and retrieved each year. A second redundant sensor is also recommended.
    c. Biweekly lake water surface measurements should be performed during the typical summer field season to verify the continuously recorded data. These measurements should consist of a simple level loop that begins and ends at a stable COE benchmark. An inexpensive digital level is recommended for this work. All future elevation data should be collected using this consistent, GPS established, vertical datum.
    d. Data should be reduced and quality controlled on an annual basis with comparisons performed against prior years.
    e. The USGS publication “Stage Measurements at Gaging Stations TM 3-47” provides complete details on methods and equipment required to monitor lake stage, and USGS publication “Levels at Gaging Stations TM 3-A19” provides details on the methods and equipment required to tie the lake stage measurements into the COE elevation datum established at Black Lake.
2. Acquire satellite imagery
    a. On a 2 to 5-year interval acquire satellite imagery of Black Lake that includes the confluence of Chiaktuak Creek on the Black River.
    b. Examine each image for qualitative and quantitative changes in Black Lake, the Alec River delta and Reach 3 of the Black River.
3. Perform repeated cross section surveys
    a. At a recommended 5-year interval (or as needed) perform repeated cross section surveys. The priority should be cross sections located with Reach 3 on the Black River.

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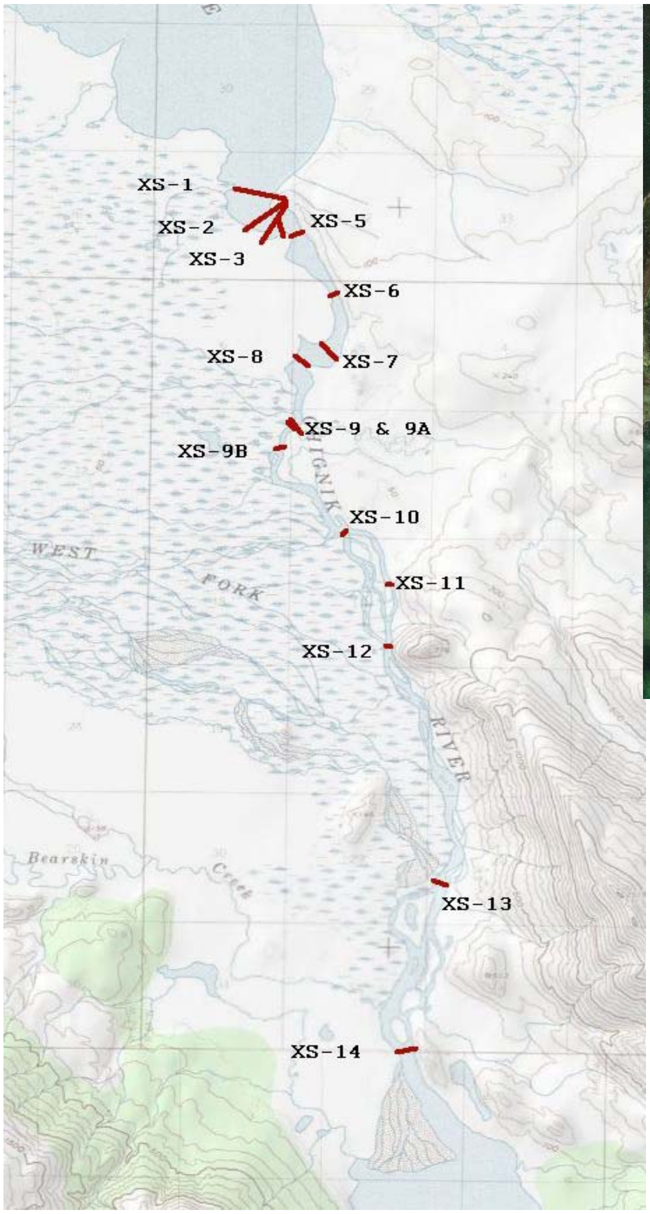
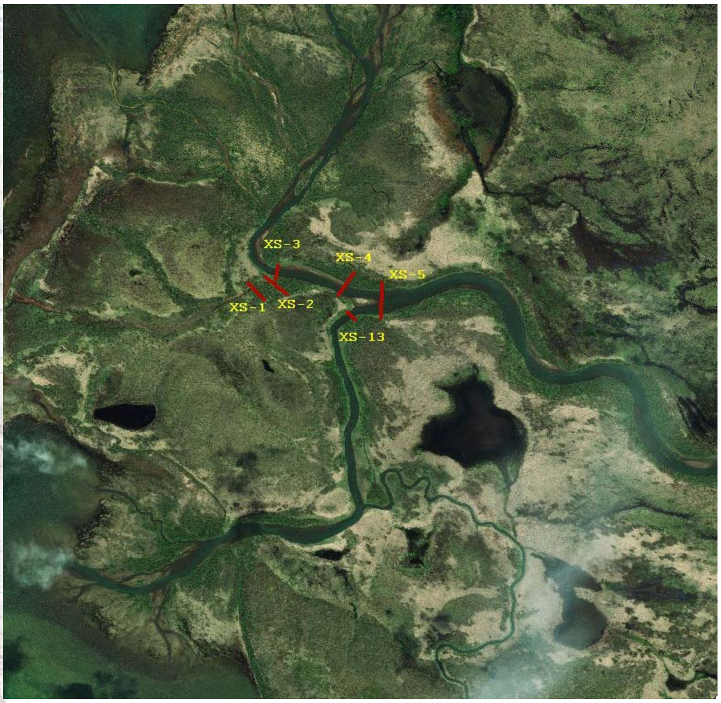
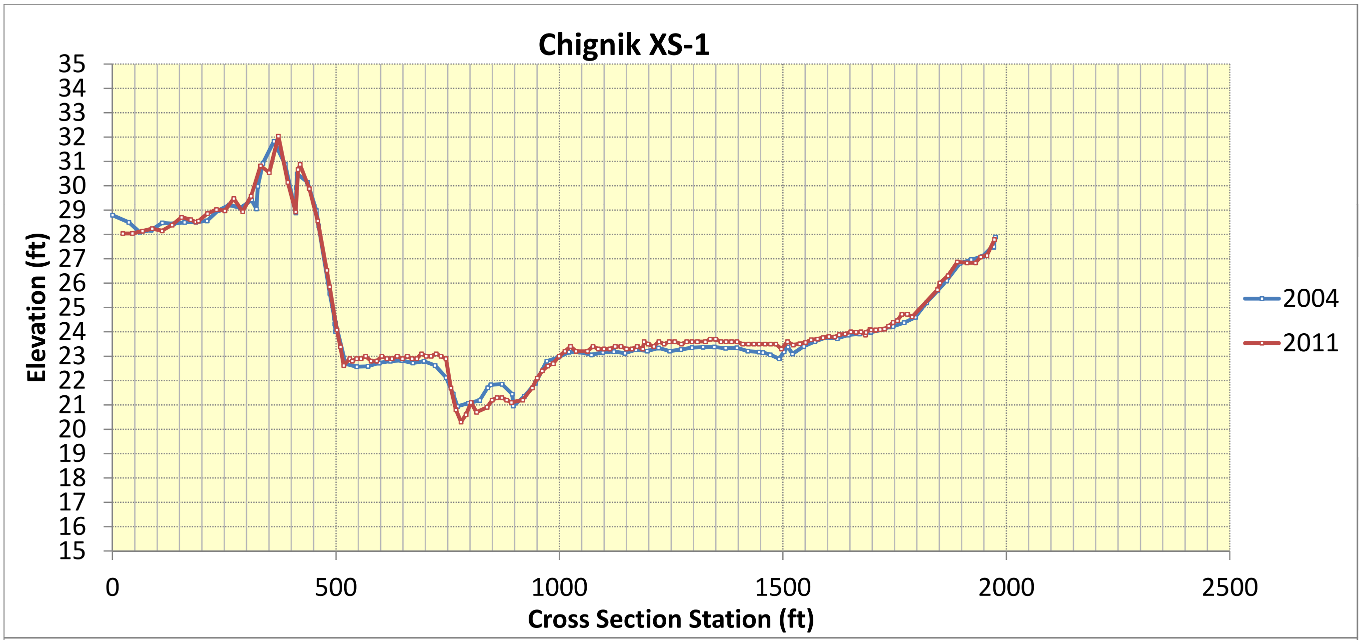
APPENDIX A: Cross Section Survey

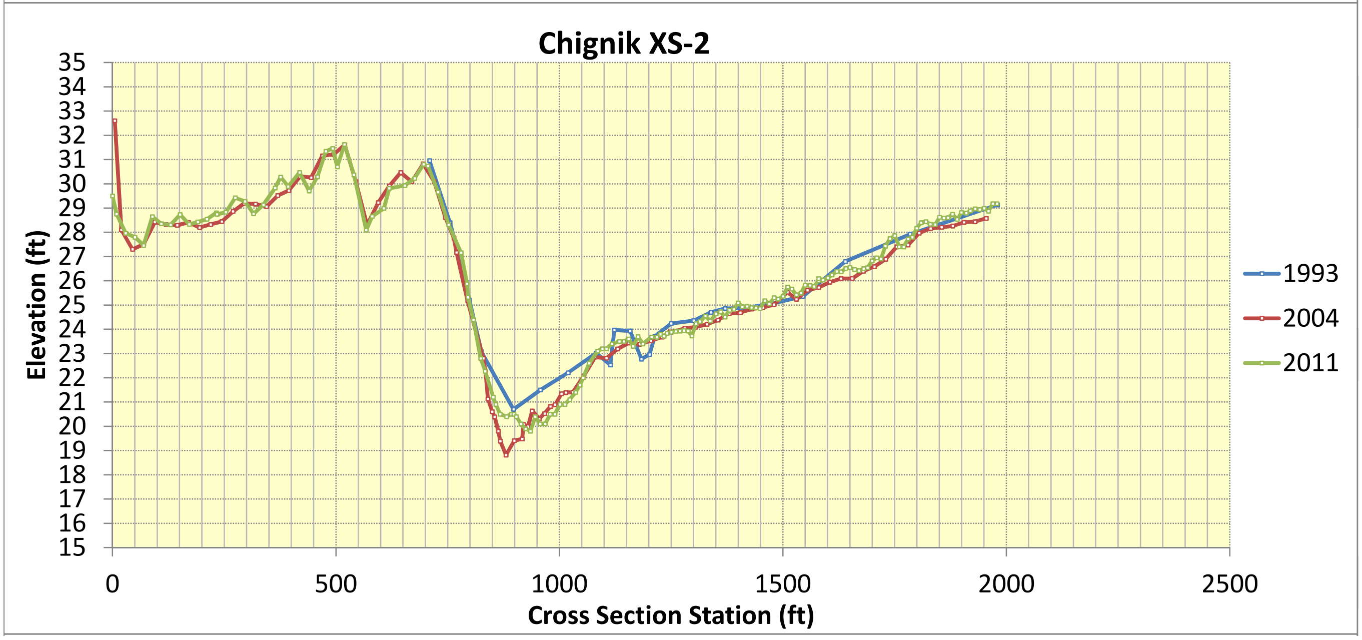
Black River	River Station (ft)	Thalweg Elevation (ft)			Average Channel Elevation (ft)			Change in Average Elevation (ft)					
								1993-2004		1993-2011		2004-2011	
		1993	2004	2011	1993	2004	2011	Thalweg	Channel	Thalweg	Channel	Thalweg	Channel
XS-1	51275		20.9	20.3		22.9	23.1					-0.64	0.12
XS-2	50295	20.7	18.8	19.8	23.1	22.5	23.3	-1.88	-0.62	-0.90	0.18	0.98	0.80
XS-3	49826	18.4	15.3	15.7	22.8	21.9	22.2	-3.09	-0.84	-2.71	-0.54	0.38	0.29
XS-4	49483	20.7	19.0	18.7	22.7	21.9	21.9	-1.72	-0.84	-1.99	-0.81	-0.27	0.03
XS-5	48812	21.8	18.6	20.2	22.6	21.5	21.8	-3.17	-1.08	-1.56	-0.84	1.61	0.24
XS-6	45913	18.0	17.4	17.6	20.7	19.8	20.0	-0.60	-0.89	-0.35	-0.69	0.25	0.20
XS-7	43307	19.5	19.1	19.9	22.0	21.5	21.7	-0.39	-0.52	0.41	-0.33	0.80	0.18
XS-8	42142	16.5	16.6	15.9	20.4	20.1	19.4	0.08	-0.31	-0.62	-1.05	-0.70	-0.75
XS-9	39205		13.7	14.6		20.8	19.9					0.86	-0.88
XS-9A	38703		16.7	15.7		15.5	15.2					-1.02	-0.27
XS-9B	38049		16.6	16.6		20.8	21.1					0.03	0.30
XS-10	32173		14.8	14.7		17.2	16.9					-0.06	-0.26
XS-11	28699		10.1	10.9		13.9	14.4					0.77	0.52
XS-12	26080		13.4	13.4		15.2	14.9					-0.02	-0.27
XS-13	14490		6.8	4.8		12.5	12.1					-1.96	-0.45
XS-14	6797		5.4	3.4		7.2	7.4					-1.98	0.25





Black River repeated cross sections (left)
Alec River repeated cross sections (top)


Chignik XS-1
Elevation (ft)
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
0
500
1000
1500
2000
2500
Cross Section Station (ft)
2004
2011


Chignik XS-2
Elevation (ft)
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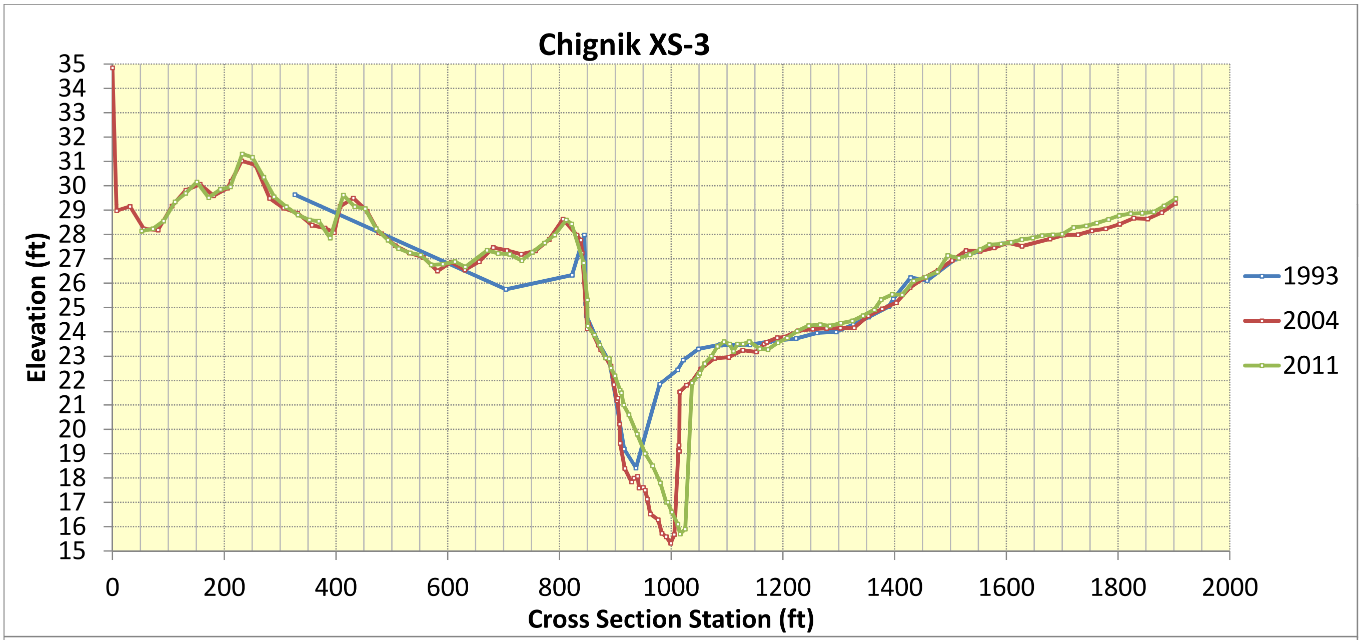
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
0
500
1000
1500
2000
2500
Cross Section Station (ft)
1993
2004
2011


Chignik XS-3
Elevation (ft)
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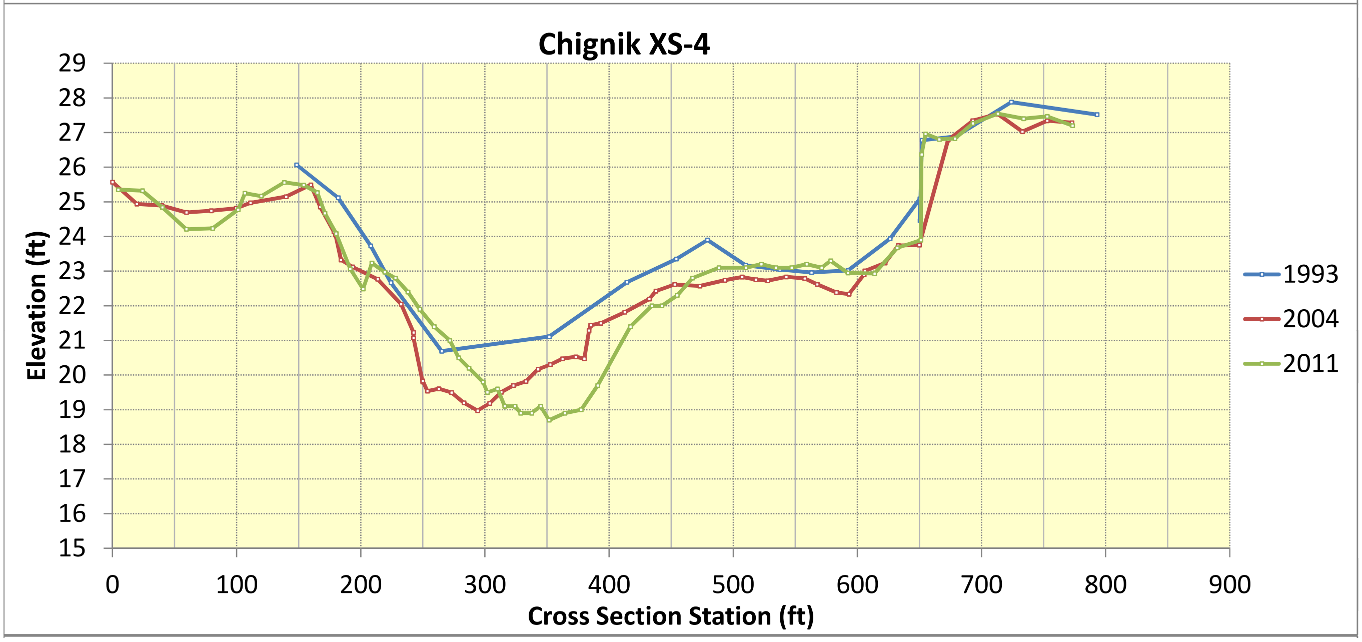
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Cross Section Station (ft)
1993
2004
2011


Chignik XS-4
Elevation (ft)
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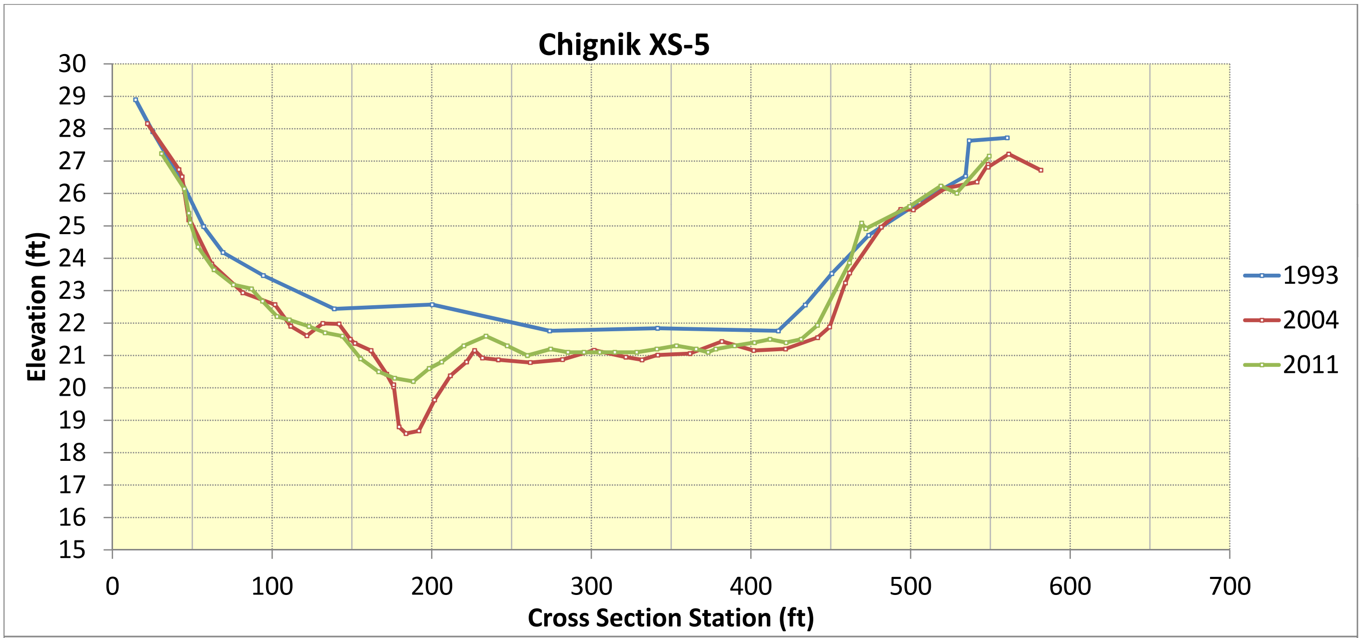
28
27
26
25
24
23
22
21
20
19
18
17
16
15
0
100
200
300
400
500
600
700
800
900
Cross Section Station (ft)
1993
2004
2011


Chignik XS-5
Elevation (ft)
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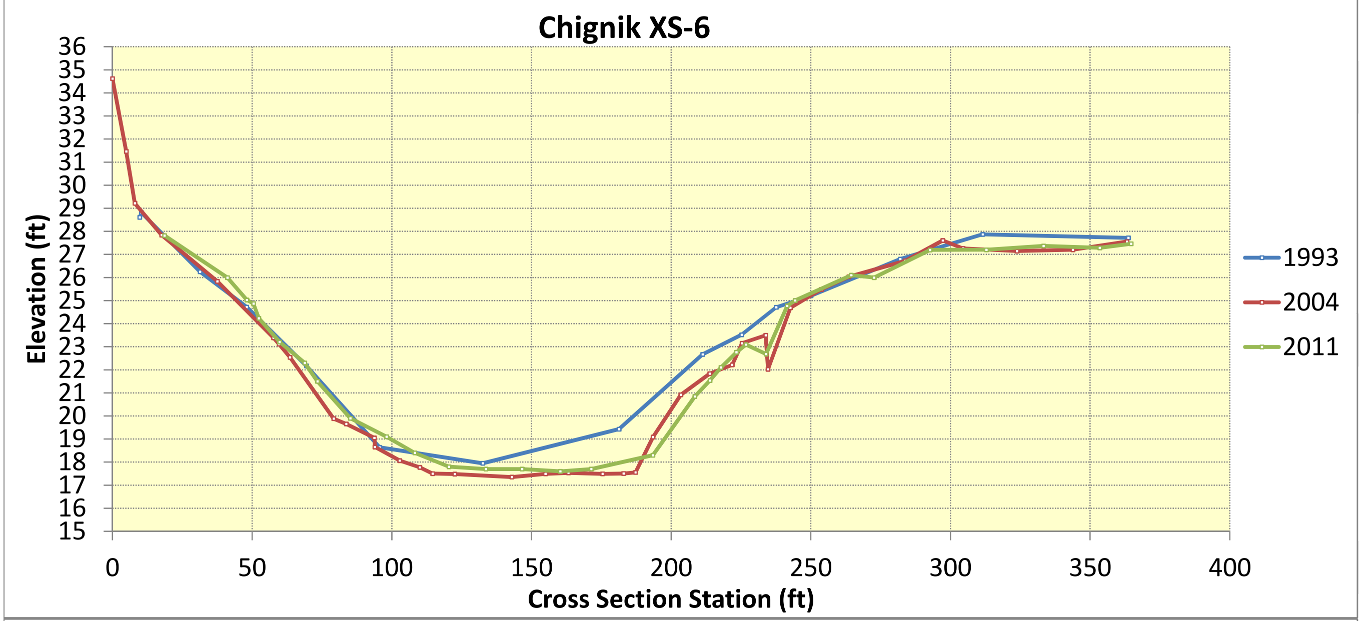
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
0
100
200
300
400
500
600
700
Cross Section Station (ft)
1993
2004
2011


Chignik XS-6
Elevation (ft)
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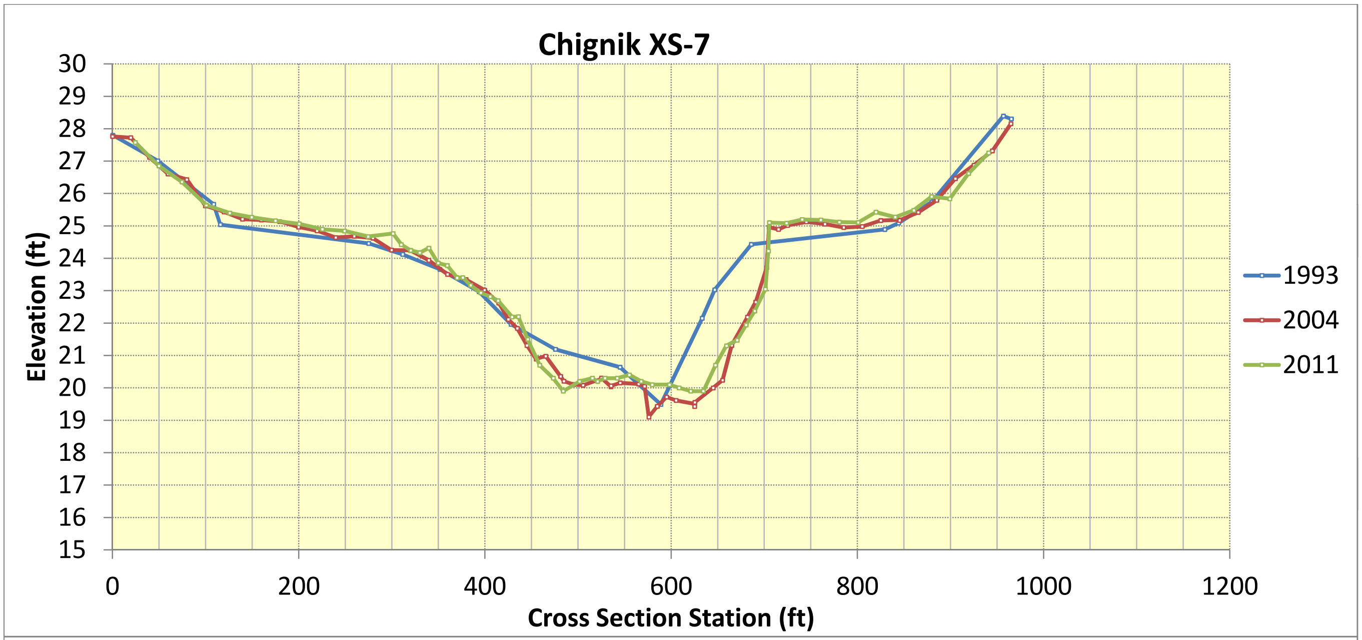
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
0
50
100
150
200
250
300
350
400
Cross Section Station (ft)
1993
2004
2011



Chignik XS-7
Elevation (ft)
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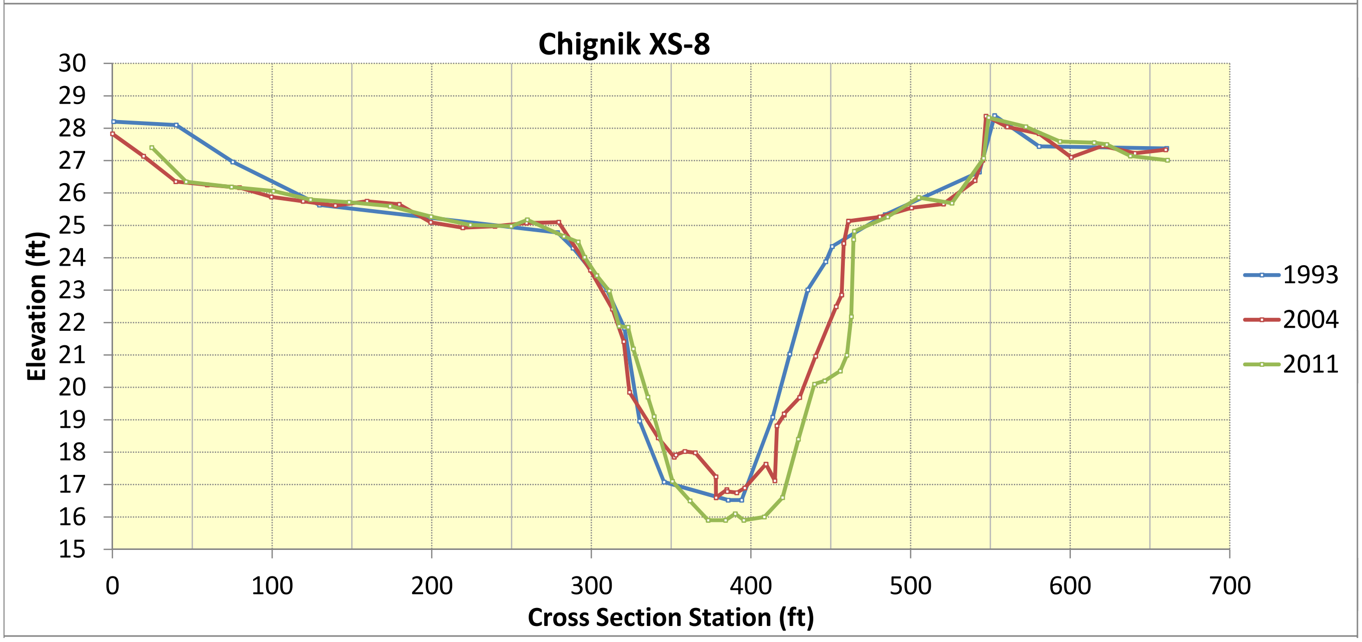
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
0
200
400
600
800
1000
1200
Cross Section Station (ft)
1993
2004
2011



Chignik XS-8
Elevation (ft)
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27
26
25
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23
22
21
20
19
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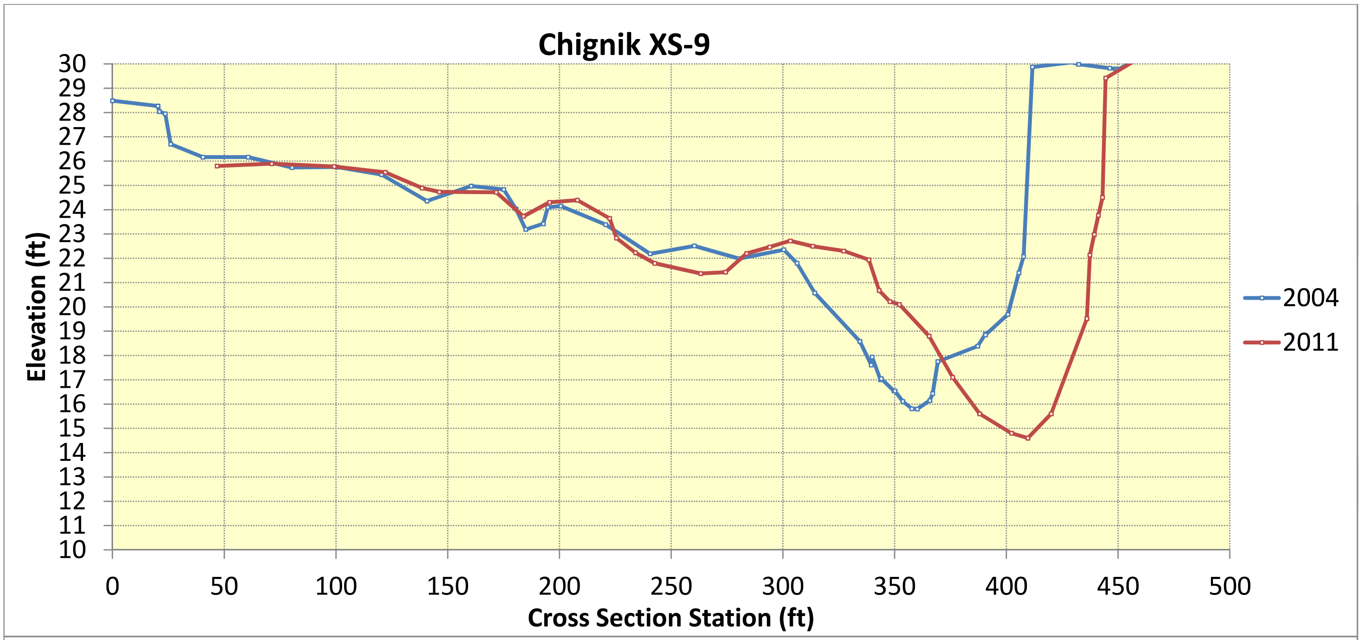
17
16
15
0
100
200
300
400
500
600
700
Cross Section Station (ft)
1993
2004
2011


Chignik XS-9
Elevation (ft)
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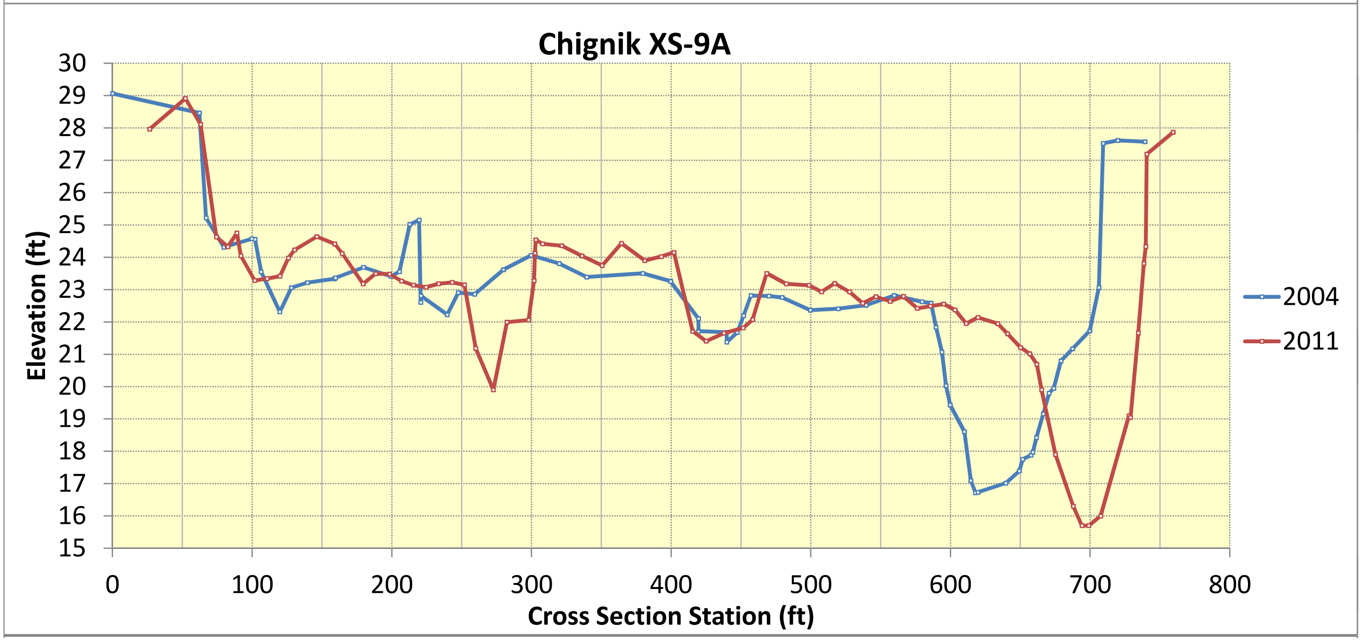
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
0
50
100
150
200
250
300
350
400
450
500
Cross Section Station (ft)
2004
2011


Chignik XS-9A
Elevation (ft)
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29
28
27
26
25
24
23
22
21
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19
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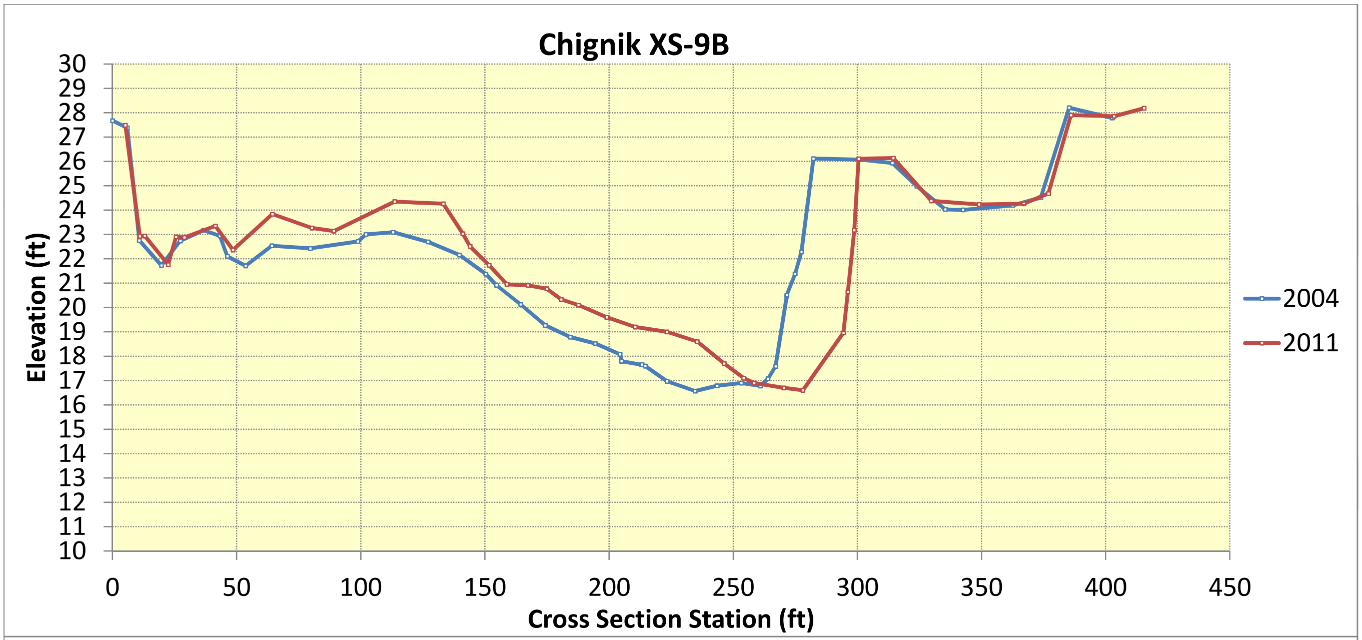
16
15
0
100
200
300
400
500
600
700
800
Cross Section Station (ft)
2004
2011


Chignik XS-9B
Elevation (ft)
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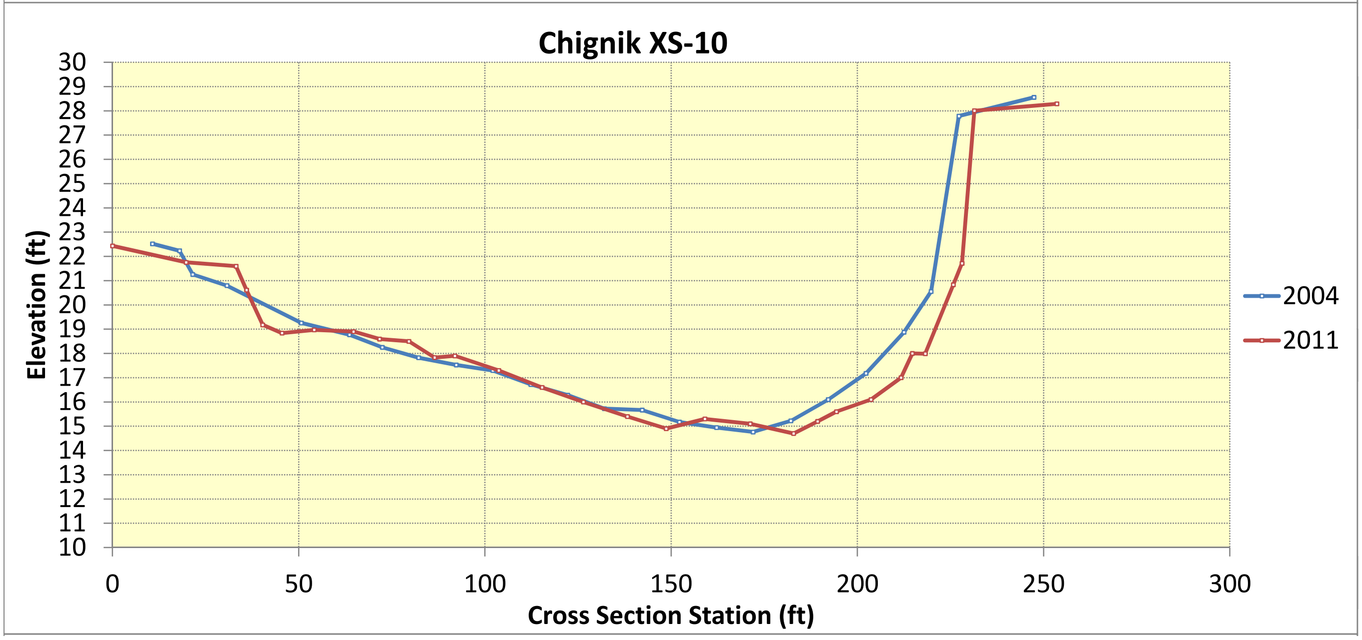
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
0
50
100
150
200
250
300
350
400
450
Cross Section Station (ft)
2004
2011


Chignik XS-10
Elevation (ft)
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28
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21
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19
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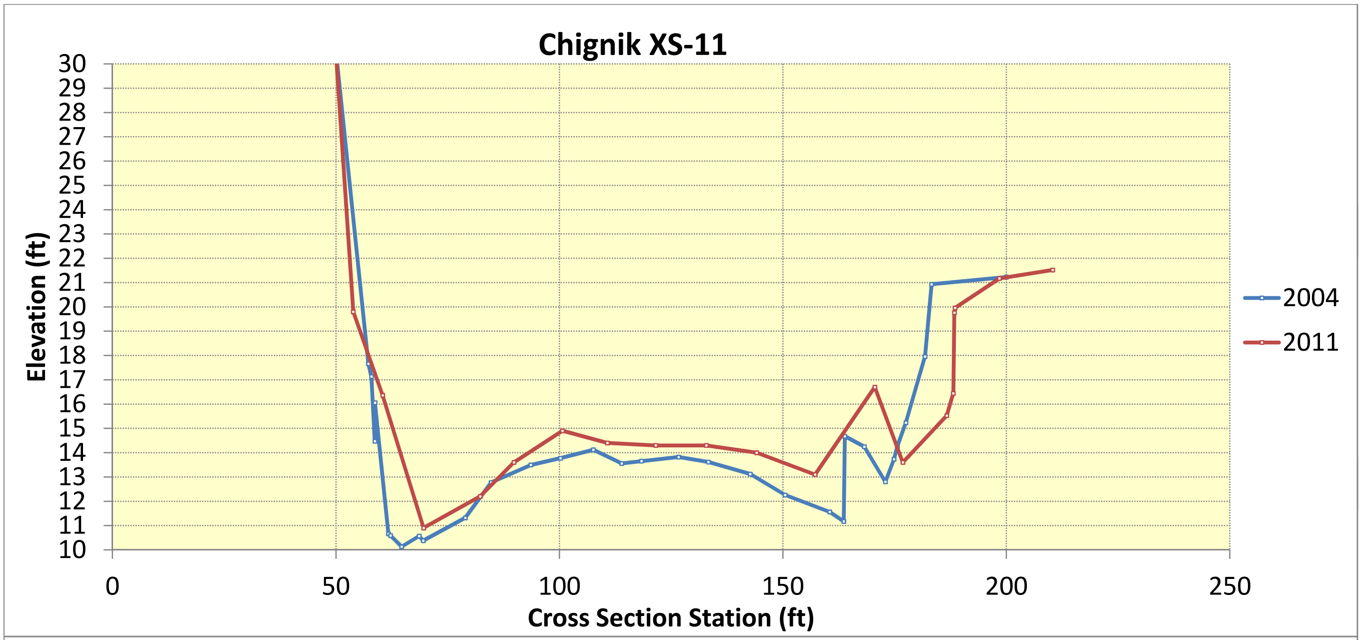
14
13
12
11
10
0
50
100
150
200
250
300
Cross Section Station (ft)
2004
2011


Chignik XS-11
Elevation (ft)
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29
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27
26
25
24
23
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21
20
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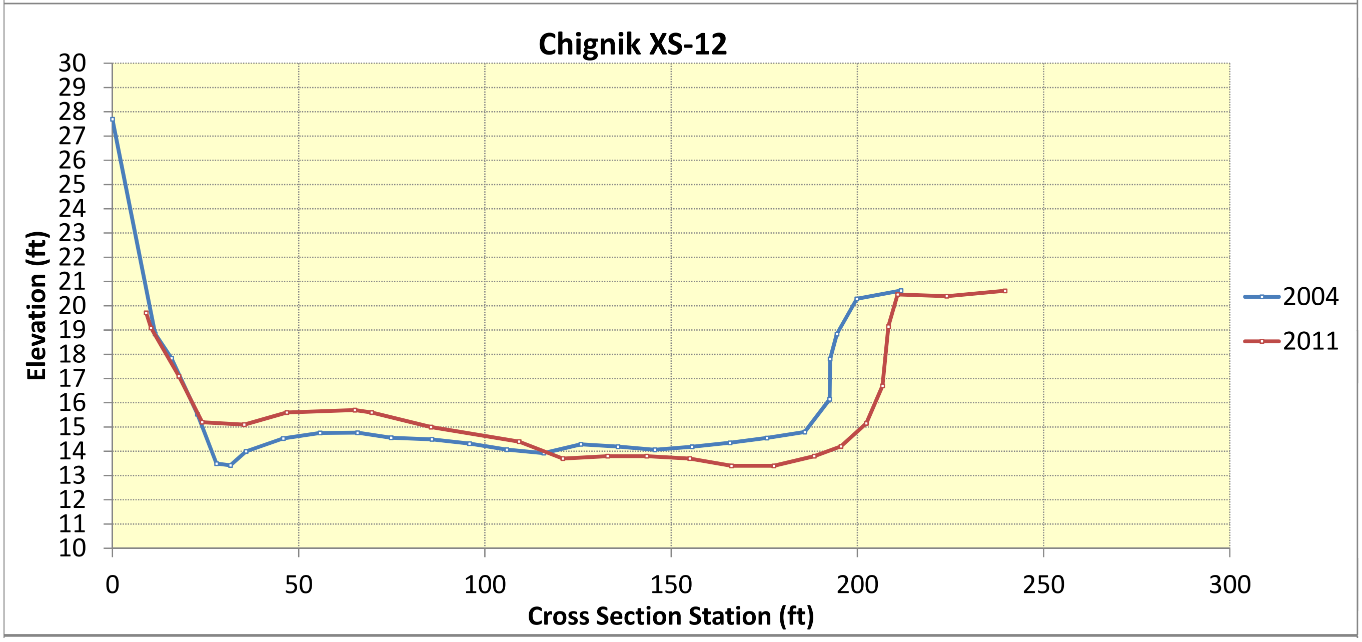
14
13
12
11
10
0
50
100
150
200
250
Cross Section Station (ft)
2004
2011


Chignik XS-12
Elevation (ft)
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29
28
27
26
25
24
23
22
21
20
19
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16
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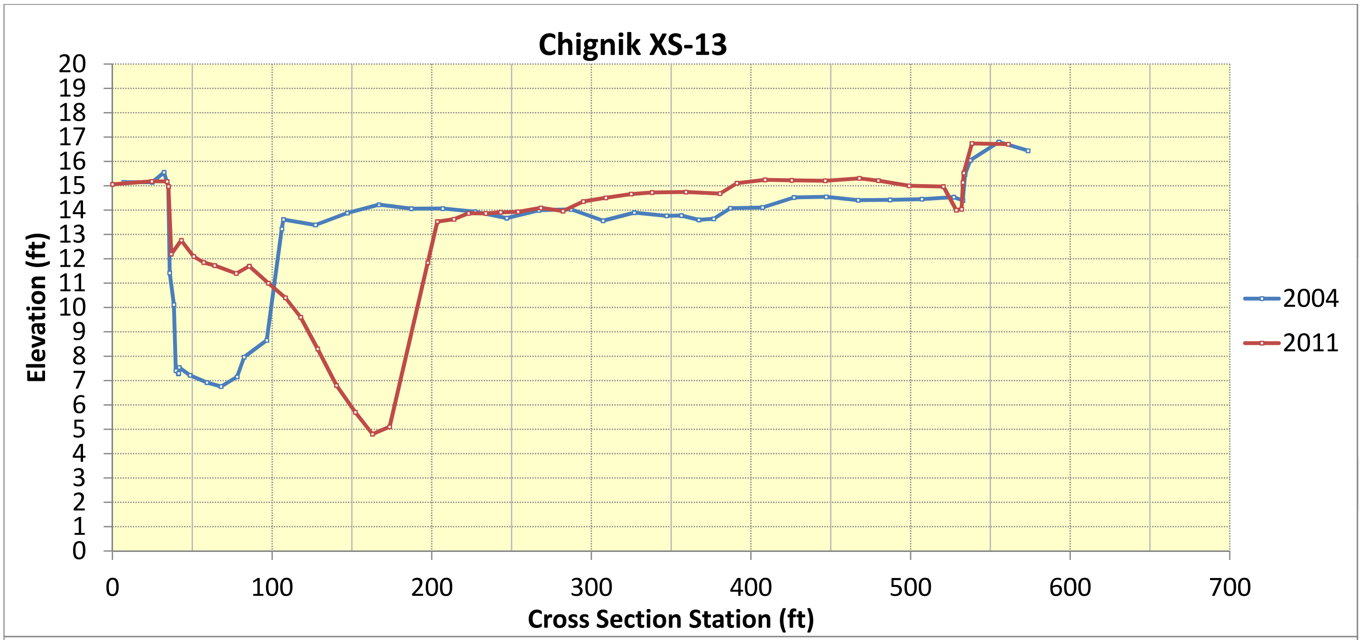
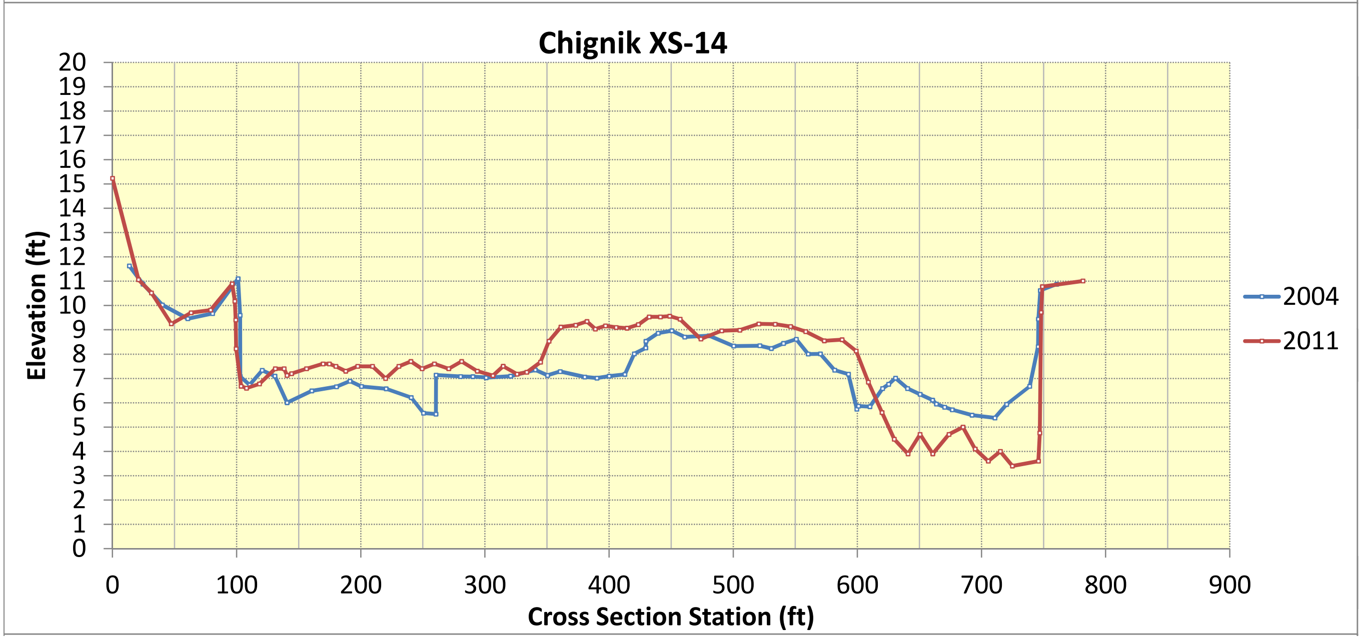
14
13
12
11
10
0
50
100
150
200
250
300
Cross Section Station (ft)
2004
2011


Chignik XS-13
Elevation (ft)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
100
200
300
400
500
600
700
Cross Section Station (ft)
2004
2011


Chignik XS-14
Elevation (ft)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
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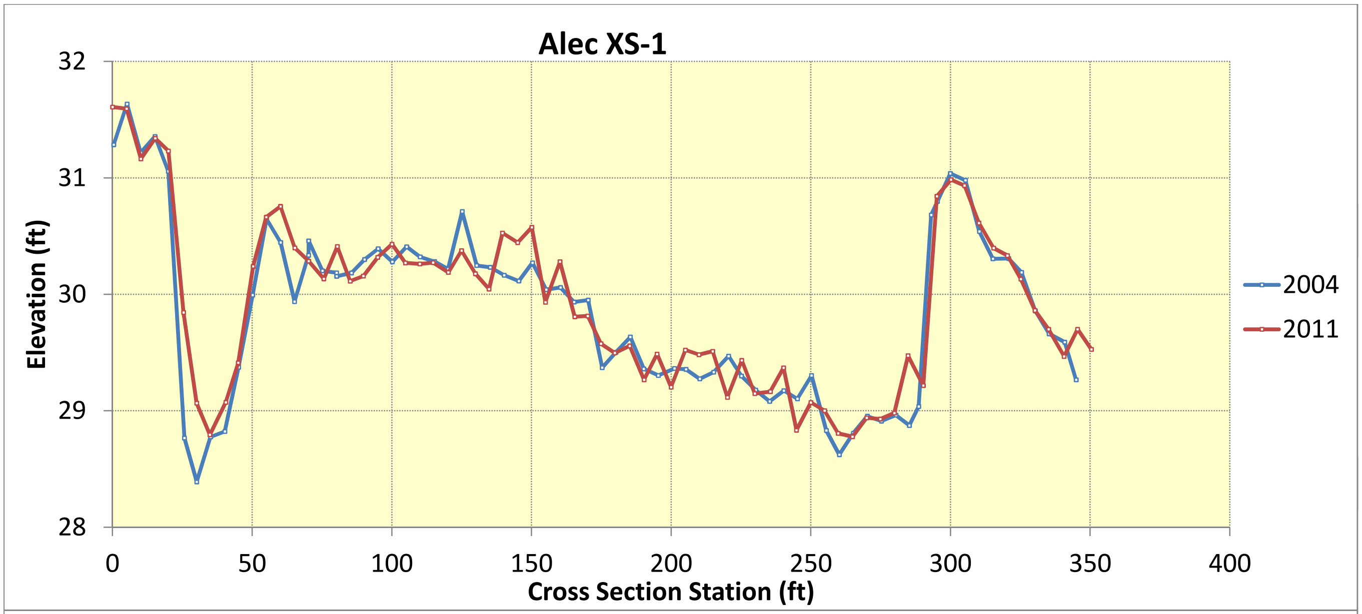
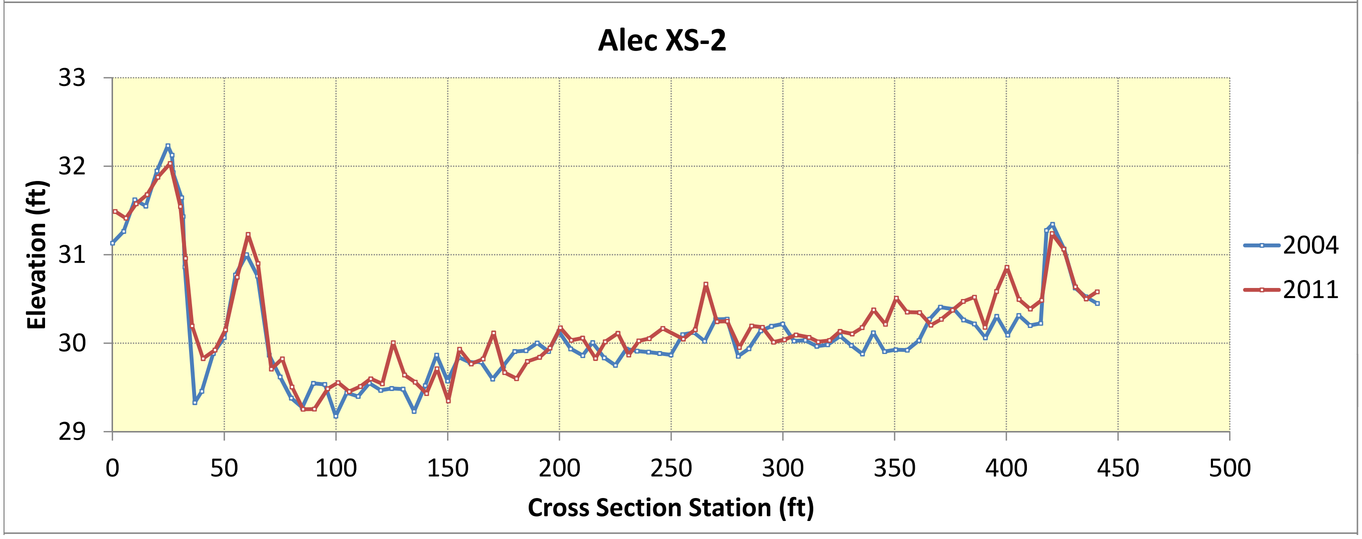
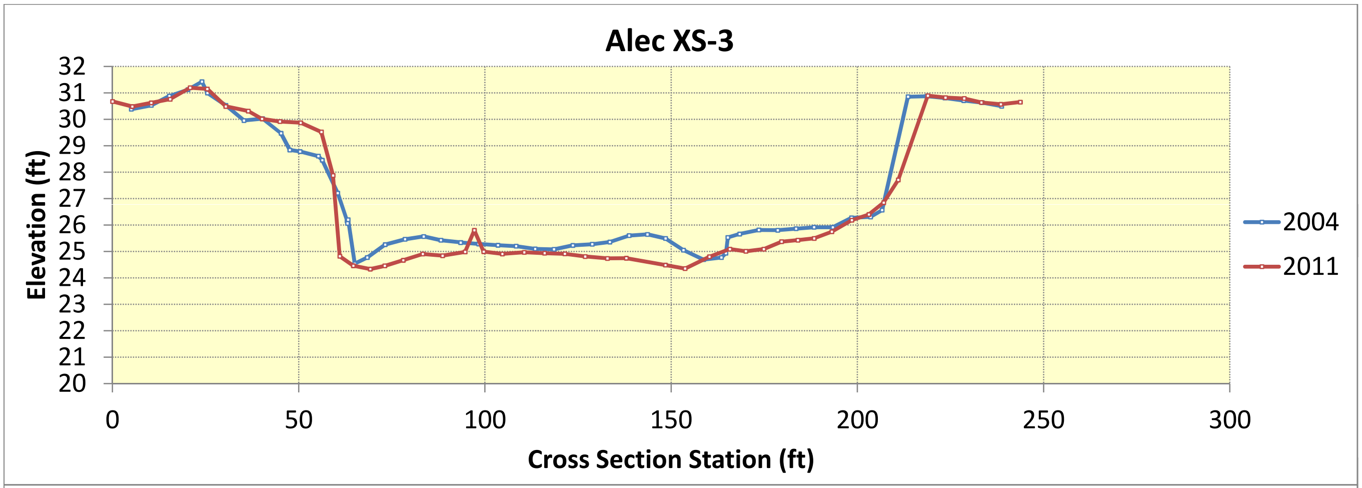
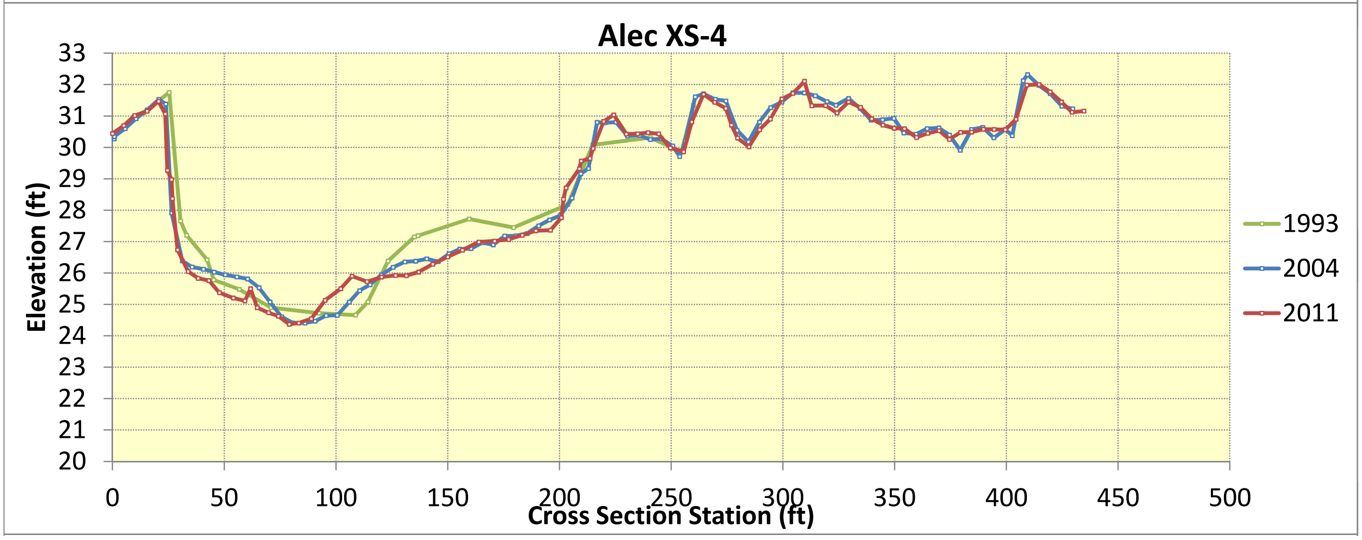
2
1
0
0
100
200
300
400
500
600
700
800
900
Cross Section Station (ft)
2004
2011


Alec XS-1
32
31
30
29
28
Elevation (ft)
0
50
100
150
200
250
300
350
400
Cross Section Station (ft)
2004
2011


Alec XS-2
33
32
31
30
29
Elevation (ft)
0
50
100
150
200
250
300
350
400
450
500
Cross Section Station (ft)
2004
2011


Alec XS-3
Elevation (ft)
32
31
30
29
28
27
26
25
24
23
22
21
20
0
50
100
150
200
250
300
Cross Section Station (ft)
2004
2011


Alec XS-4
Elevation (ft)
33
32
31
30
29
28
27
26
25
24
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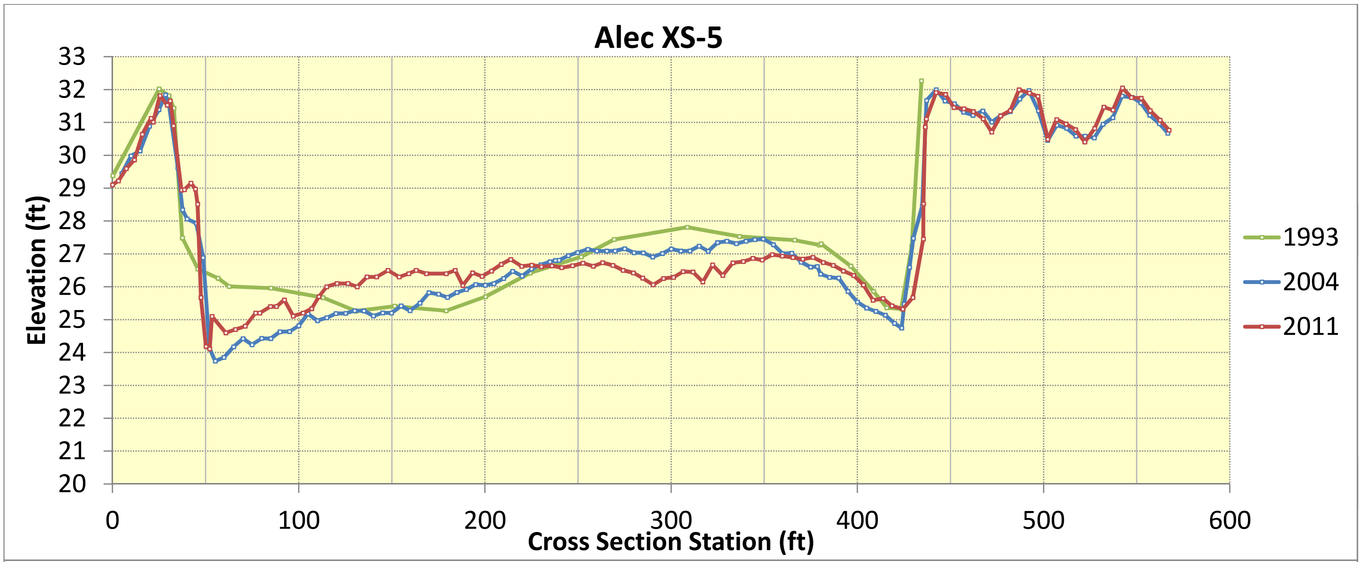
0
50
100
150
200
250
300
350
400
450
500
Cross Section Station (ft)
1993
2004
2011


Alec XS-5
Elevation (ft)
33
32
31
30
29
28
27
26
25
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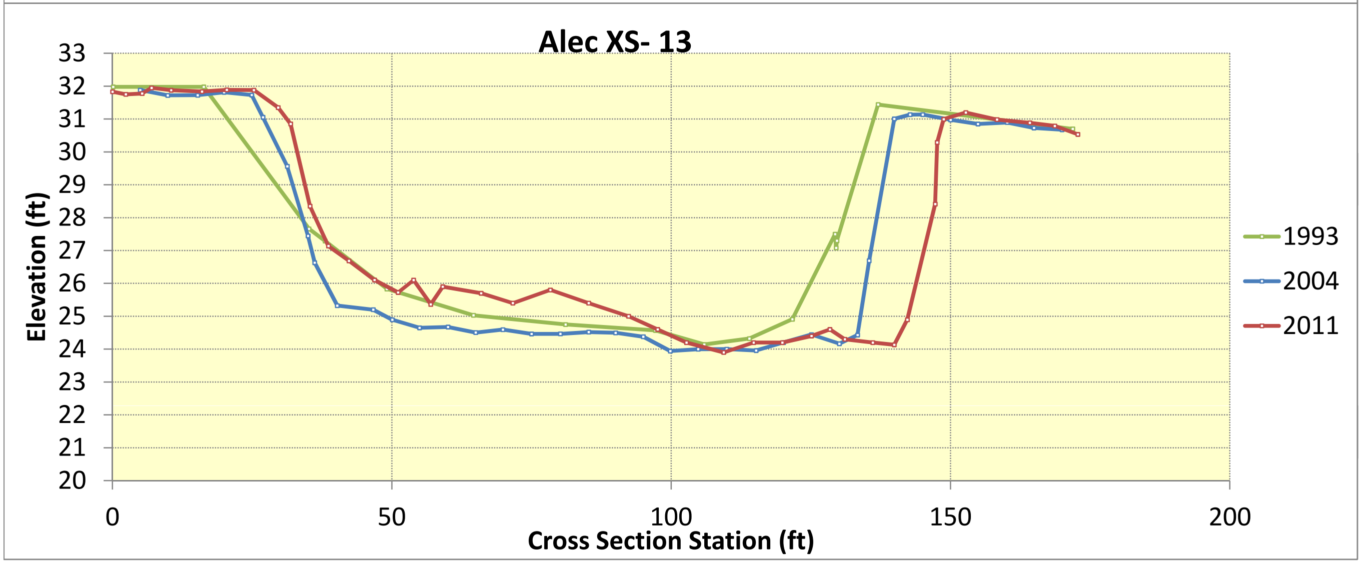
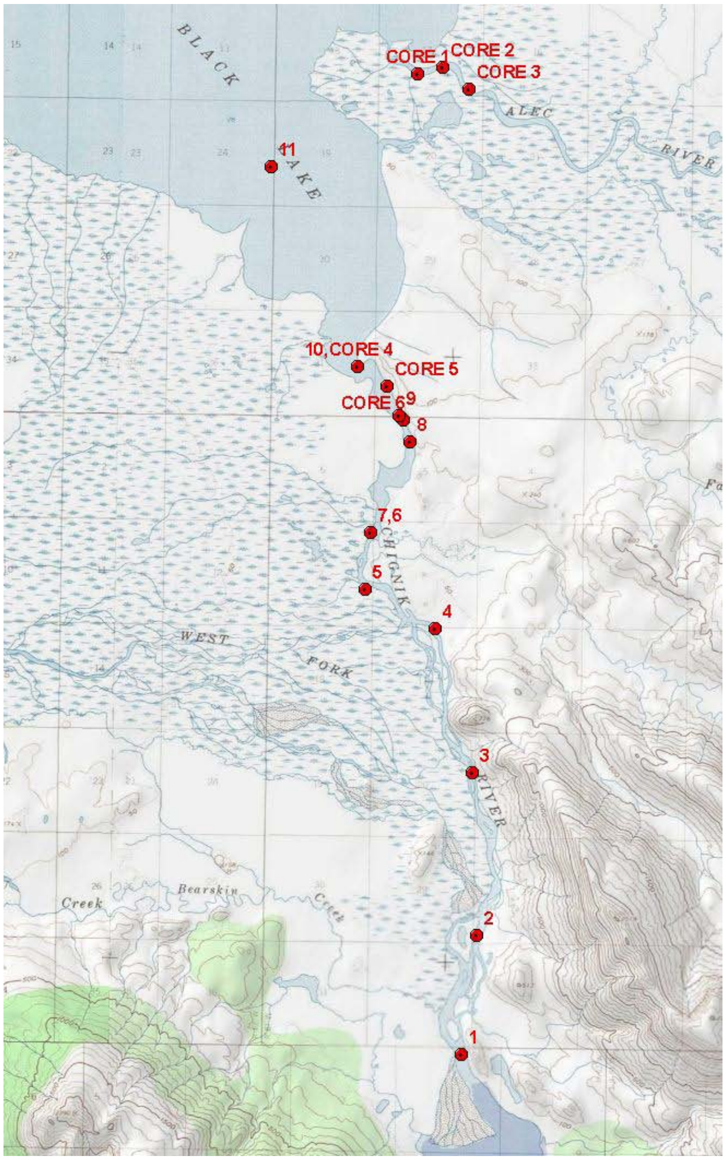
23
22
21
20
0
100
200
300
400
500
600
Cross Section Station (ft)
1993
2004
2011


Alec XS- 13
Elevation (ft)
33
32
31
30
29
28
27
26
25
24
23
22
21
20
0
50
100
150
200
Cross Section Station (ft)
1993
2004
2011

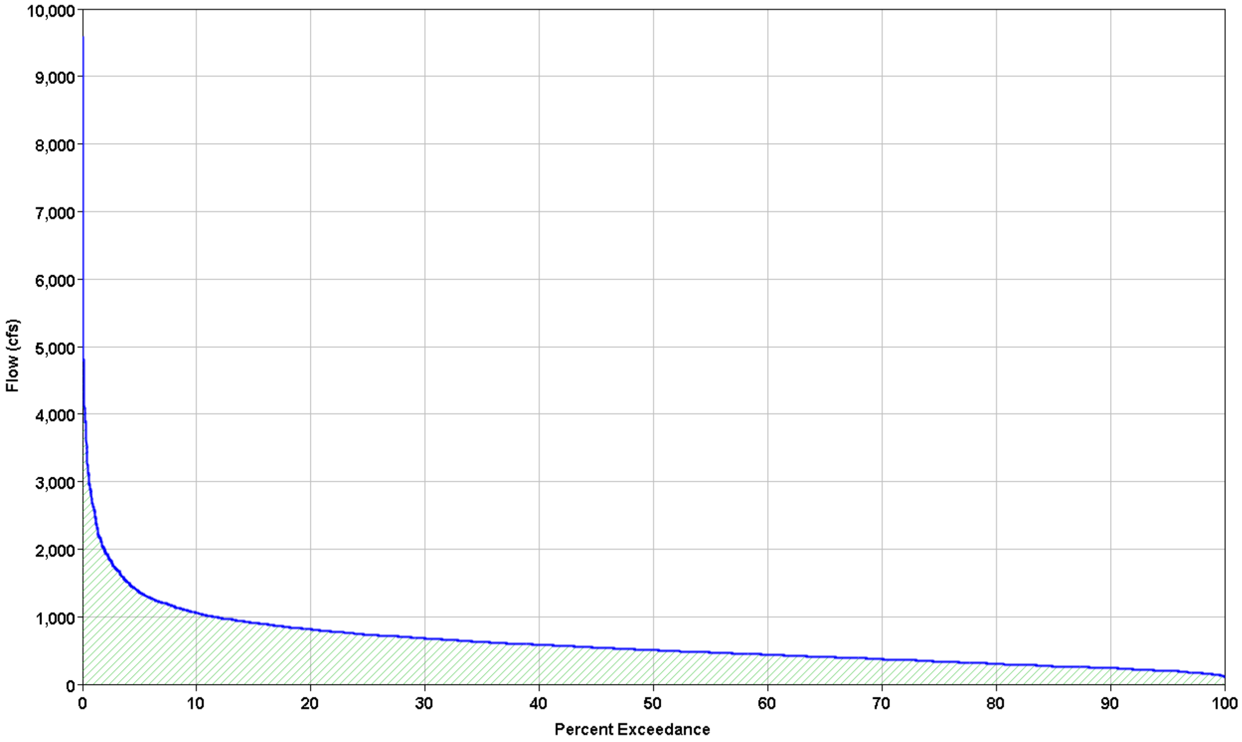
APPENDIX B: Sediment Samples

The locations of the sediment grab samples and streambed coring locations are shown below with sediment grain size characterization sheets on subsequent pages.



Sediment sample locations.

APPENDIX C: Alec River Estimated Flow Duration Curve



Estimated flow duration curve for the Alec River.