



Water Quality and Surface Hydrology of Freshwater Flow Systems in Southwest Alaska

2010 Annual Summary Report

Natural Resource Technical Report NPS/SWAN/NRTR—2011/428



ON THE COVER

West Basin of Naknek Lake, Katmai National Park and Preserve.

Photograph by: Wendy Artz, Katmai National Park

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Table of Contents

	Page
Figures.....	iv
Tables.....	vi
Abstract.....	vii
Acknowledgements.....	viii
Introduction.....	1
Methods.....	1
Study Area	1
Field Methods	3
Results and Discussion	11
Lake Clark Water Temperature	11
Naknek Lake Water Temperature	12
Naknek Lake and Lake Brooks Discharge.....	17
Telaquana Lake Discharge.....	21
Vertical Lake Profiles	23
Water Temperature	23
pH.....	27
Specific Conductivity.....	28
Dissolved Oxygen.....	29
Water Clarity.....	29
Chulitna River and Lake Clark Outlet Continuous Water Quality Monitoring.....	31
Recommendations and Conclusions	37
Literature Cited	39

Figures

	Page
Figure 1. National Park units included in the Southwest Alaska Inventory and Monitoring Network.	2
Figure 2. Lake Clark, Kijik Lake, Lachbuna Lake, and Crescent Lake in LACL.	4
Figure 3. Lake Brooks and major basins of Naknek Lake including major tributaries in KATM.....	5
Figure 4. Exit Creek area in KEFJ. Study site is denoted with a star. Gray areas represent glacial ice cover.....	6
Figure 5. GRTS sample locations on Lake Clark where vertical lake profiles were measured	7
Figure 6. GRTS sample locations on Lake Brooks and Naknek Lake where vertical lake profiles were measured	8
Figure 7. GRTS sample locations on Lachbuna Lake in LACL.....	9
Figure 8. GRTS sample locations on Crescent Lake in LACL.....	9
Figure 9. Sample locations on Kijik Lake in LACL.....	10
Figure 10. Lake Clark isotherm displaying patterns of summer stratification.	12
Figure 11. Comparison of near surface water temperatures for the North Arm and West Basin of Naknek Lake.....	16
Figure 12. Isotherm for North Arm of Naknek Lake displaying patterns of summer stratification	16
Figure 13. Isotherm for West Basin of Naknek Lake displaying patterns of summer stratification	17
Figure 14. Estimated daily discharge for Naknek Lake for period of record	18
Figure 15. Estimated daily discharge for Lake Brooks for period of record.	18
Figure 16. 2009 and 2010 open water season hydrographs for Naknek Lake plotted with period of record (2006 – 2010) mean, max and min estimated discharge	19
Figure 17. Estimated daily discharge for Telaquana Lake for period of record	21

Figure 18. Temperature profiles for select sites that were representative of each basin in Lake Clark during August sampling.	26
Figure 1. Temperature profiles of select sites within Naknek Lake and Lake Brooks	26
Figure 20. pH profiles for select sites within Naknek Lake and Lake Brooks.	28
Figure 21. Water temperature and specific conductivity profile for Lachbuna Lake.	29
Figure 22. Secchi depths for Lake Clark comparing pre-eruption (2008) and post-eruption (2009 and 2010) water clarity.....	30
Figure 23. Secchi depths for four basins in Naknek Lake and in Lake Brooks.....	31
Figure 24. Comparison of the upper and lower Chulitna River gage sites.	34
Figure 25. ADCP discharge measurements plotted with the 2010 Lake Clark open water hydrograph	35

Tables

	Page
Table 1. Summary of water temperature data for Lake Clark.	14
Table 2. Summary of water temperature data for the North Arm and West Basin of Naknek Lake between September 1, 2008 and July 31, 2010	15
Table 3. Summary of estimated lake discharge (Q) data for Naknek and Brooks Lakes during open water period for 2007 - 2010.	22
Table 4. Summary data for core parameters collected at vertical lake profile sites on Lake Clark, Naknek Lake, and Lake Brooks during summer 2010.....	24
Table 5. Summary data for core parameters collected at vertical lake profile sites on Lake Clark, Naknek Lake, and Lake Brooks during summer 2010.....	25
Table 6. Summary data for core parameters for the Chulitna River.....	32
Table 7. Summary data for core parameters for the outlet of Lake Clark	33

Abstract

The Southwest Alaska Inventory and Monitoring Network monitors freshwater systems in five national park units: Alagnak Wild River (ALAG), Aniakchak National Monument and Preserve (ANIA), Katmai National Park and Preserve (KATM), Kenai Fjords National Park (KEFJ), and Lake Clark National Park and Preserve (LACL). To date, most of our efforts have focused on field testing and modifying protocols for water quality and hydrology monitoring on high priority lake systems.

In 2010, lake profiles were measured on Lake Clark, Lachbuna Lake, Crescent Lake, Kijik Lake (LACL sites), Naknek Lake, and Lake Brooks (KATM sites) between the surface and 50 m for water temperature, pH, specific conductivity, dissolved oxygen, and water clarity. Water quality parameters were generally stable between sites throughout each lake except for water clarity. The 2009 spring eruptions of Mt. Redoubt and subsequent volcanic ash inputs into the Lake Clark system were still influencing water clarity although Secchi depths did increase compared to 2009 observations. Continuous water temperature monitoring in Lake Clark has been ongoing since September 2006 while continuous temperature monitoring on Naknek Lake was initiated in August 2008. Water temperature data from both lakes depict temporary summer stratification followed by abrupt vertical mixing due to a strong wind events in late July.

Water level and discharge measurements were continued on Naknek Lake and Lake Brooks in 2010. Water level measurements were converted into estimated lake discharge based on stage discharge rating curves developed in 2006-07 by the U.S. Geological Survey. Subsequent discharge measurements were used to refine rating curves. Continuous water quality and water level monitoring was conducted on Exit Creek (KEFJ) during two-week deployment periods (late spring and mid-summer) to examine natural variation in water quality parameters due to diel glacial melting. Diel patterns were most obvious in water temperature and specific conductivity during low flow (spring / early summer) when ground water contributions to surface flow exceed runoff contributions comprising glacial and snowmelt runoff as well as precipitation events.

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Introduction

The Southwest Alaska Inventory and Monitoring Network (SWAN) monitors freshwater systems in five national park units: Alagnak Wild River (ALAG), Aniakchak National Monument and Preserve (ANIA), Katmai National Park and Preserve (KATM), Kenai Fjords National Park (KEFJ), and Lake Clark National Park and Preserve (LACL) (Figure 1). The goal of SWAN freshwater monitoring is to document the natural variability and to monitor for potential influences of large scale anthropogenic impacts, such as climate change, on large lake systems. SWAN's primary objective is to monitor water quality and hydrologic parameters in large lake systems, including associated tributaries and outlets, in order to describe the current status and trends of limnological conditions. To date, much of SWAN's freshwater monitoring efforts have focused on protocol testing for the freshwater chemistry and surface hydrology vital signs. Specifically, methods were explored to document variability of core water quality parameters (e.g. temperature, pH, dissolved oxygen, and specific conductivity), quantify seasonal hydrograph changes during the ice-free season, and track water temperature patterns in select lakes.

Water quality monitoring efforts have focused on Lake Clark, LACL and Naknek Lake, KATM while hydrologic monitoring has taken place primarily on Naknek and Brooks Lakes, KATM. Additionally, Exit Creek within KEFJ was monitored with a water level pressure transducer equipped with a conductivity and temperature sensor. Although most SWAN freshwater monitoring takes place during the ice-free period (typically May through September), lake water temperature is monitored year-round. Water temperature has been monitored continuously in Lake Clark since September 2006 and was initiated in Naknek Lake in August 2008. This report will discuss the results of the 2010 field sampling efforts as well as summarize water temperature collected between September 2009 and September 2010 (Water Year 2010).

Methods

Study Area

During the SWAN monitoring development process, park resource staff and regional experts suggested developing a tiered system to categorize water bodies for monitoring based on management priorities, access, and system type (e.g., glacial vs. non-glacial, anadromous vs. non-anadromous). Lake Clark and Kijik Lake in LACL, Naknek Lake and Lake Brooks in KATM, and Exit Creek in KEFJ were all identified as high priority (Tier 1) water bodies for monitoring. Additionally, we collected lake profiles on Lachbuna and Crescent Lakes, both Tier 2 systems, in LACL during 2010. The Chulitna River is a major tributary to Lake Clark where we initiated river gaging and water quality monitoring in 2009.

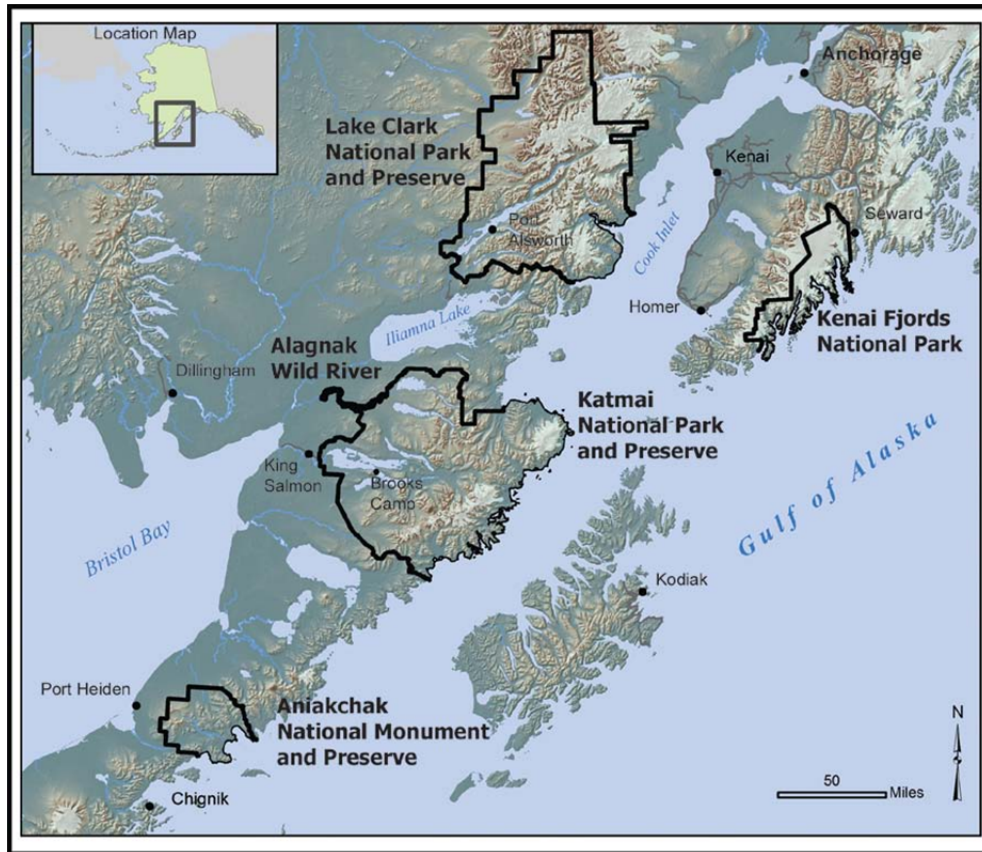


Figure 2. National Park units included in the Southwest Alaska Inventory and Monitoring Network.

Lake Clark (Figure 2) is located within the Kvichak River drainage in southwest Alaska and is the third largest lake (313 km²) in the National Park system (behind Naknek Lake and Yellowstone Lake – Yellowstone National Park). Lake Clark is a glacially-carved oligotrophic lake that is 66 km long and 5–8 km wide. It has an average depth of 103 m, a maximum depth of 280 m, and a drainage area of 7,620 km² (Young and Woody 2007). Six tributaries contribute the majority of runoff into the lake. Three tributaries are glacially fed, two are clear, and one is organically stained (Brabets 2002). Seasonal runoff from glacial tributaries is highest between June and September, which creates a turbidity gradient along the length of the lake from the turbid upstream to the relatively clear (approximately 2 Nephelometric Turbidity Units (NTU)) downstream (Brabets 2002, Wilkens 2002). The Chulitna River (Figure 2) is a low gradient (7% mean slope), organically stained river flowing from the southwest tundra region of the Lake Clark watershed. The Chulitna River has a watershed area of 2,997 km² with no glaciers and approximately 92 km² of lakes (Brabets 2002).

Kijik Lake (Figure 2) is a 4.5 km² clear water system that flows into Lake Clark through the Kijik River system. The Little Kijik River is the primary inflowing source of water for Kijik Lake. The shoreline, outlet, and inlet areas of Kijik Lake are among the most important sockeye salmon (*Oncorhynchus nerka*) spawning areas within the Lake Clark

watershed (Young and Woody 2007). Lachbuna Lake (Figure 2) is a non-anadromous glacial system located farther upstream in the Kijik River watershed. Crescent Lake (Figure 2) is an anadromous glacial lake within the Crescent River system that drains the eastern portion of LACL flowing into the Cook Inlet.

Naknek Lake and Lake Brooks (Figure 3) are located within the Naknek River drainage in southwest Alaska. Naknek Lake is the largest lake (609 km²) in the National Park system and third largest lake in Alaska (Kozlowski 2007). Naknek Lake is a bathymetrically complex system with multiple basins. The North Arm of Naknek Lake has an average depth of 63 m, maximum depth of 167 m, and receives runoff from snowmelt and wet tundra. The Iliuk Arm of Naknek Lake has an average depth of 96 m, maximum depth of 173 m, and receives water from Grosvenor Lake, glacial inputs from the Savonoski River, and ash flows from the Valley of Ten Thousands Smokes via the Ukak River (Kozlowski 2007). The East (avg. depth 27 m, max. depth 71 m) and West (avg. depth 13 m, max. depth 80 m) Basins of Naknek Lake serve as mixing areas for waters from the North and Iliuk Arms. Lake Brooks is a major lake within the Naknek system, flowing into the East Basin of Naknek Lake via the Brooks River. Lake Brooks has a surface area of 75 km², an average depth of 45 m, a maximum depth of 79 m, and receives much of its runoff from snowmelt and wet tundra (Goldman 1960, Kozlowski 2007).

Exit Creek (Figure 4) flows from Exit Glacier on the northeast end of the Harding Icefield in south central Alaska. Exit Creek flows from the terminus of the glacier for approximately 3.2 km to the confluence with the Resurrection River which enters Resurrection Bay at Seward, AK.

Field Methods

Lake temperature was monitored year-round through the use of automated temperature thermistors attached to a moored array. Thermistors recorded water temperature (°C) hourly at 5 m, 10, and every 10 m to 100 m using Onset HOBO Water Temp Pro thermistors. During summer months, a surface buoy with a thermistor was attached to the moored array so that surface temperature could be recorded. Data were downloaded once or twice annually during the open water season (between late May and late September) depending on site access logistics and staff availability.

Water quality sampling for core parameters was conducted using both discrete and continuous sampling strategies. Discrete samples were recorded for vertical lake profiles at lake sites, whereas continuous unattended sampling was employed at select tributary and lake outlet sites. Yellow Springs Incorporated (YSI) multiparameter sondes were used for all water quality measurements. A series of calibrations and error checks for temperature, dissolved oxygen, pH, and specific conductivity were performed each day before sondes were used in the field. Additionally, post-trip error checks were conducted at the end of each day during lake profile measurements and at the end of each deployment period for continuous water quality monitoring.

Continuous water level measurements were recorded with In-Situ Level Troll and Solinst Levellogger non-vented pressure transducers on the outlets of Lake Brooks, Naknek Lake, Telaquana Lake and Lake Clark and on the Chulitna River. Level data were used to estimate daily discharge for Lake Brooks, Naknek Lake and Telaquana Lake using stage / discharge rating curves that were developed by the U.S. Geological Survey Water Resources Division (USGS-WRD) in 2007. An acoustic Doppler current profiler (ADCP) was used to measure discharge on the Chulitna River and at the Lake Clark outlet throughout the open water season and a provisional rating curve was developed for the Lower Chulitna River.

Additionally, an In-Situ Aqua Troll non-vented pressure transducer equipped with temperature and conductivity sensors was used to record water level at Exit Creek. All pressure transducers were programmed to record water level (feet) hourly. Barometric loggers deployed nearby were used to compensate water level readings for atmospheric pressure.

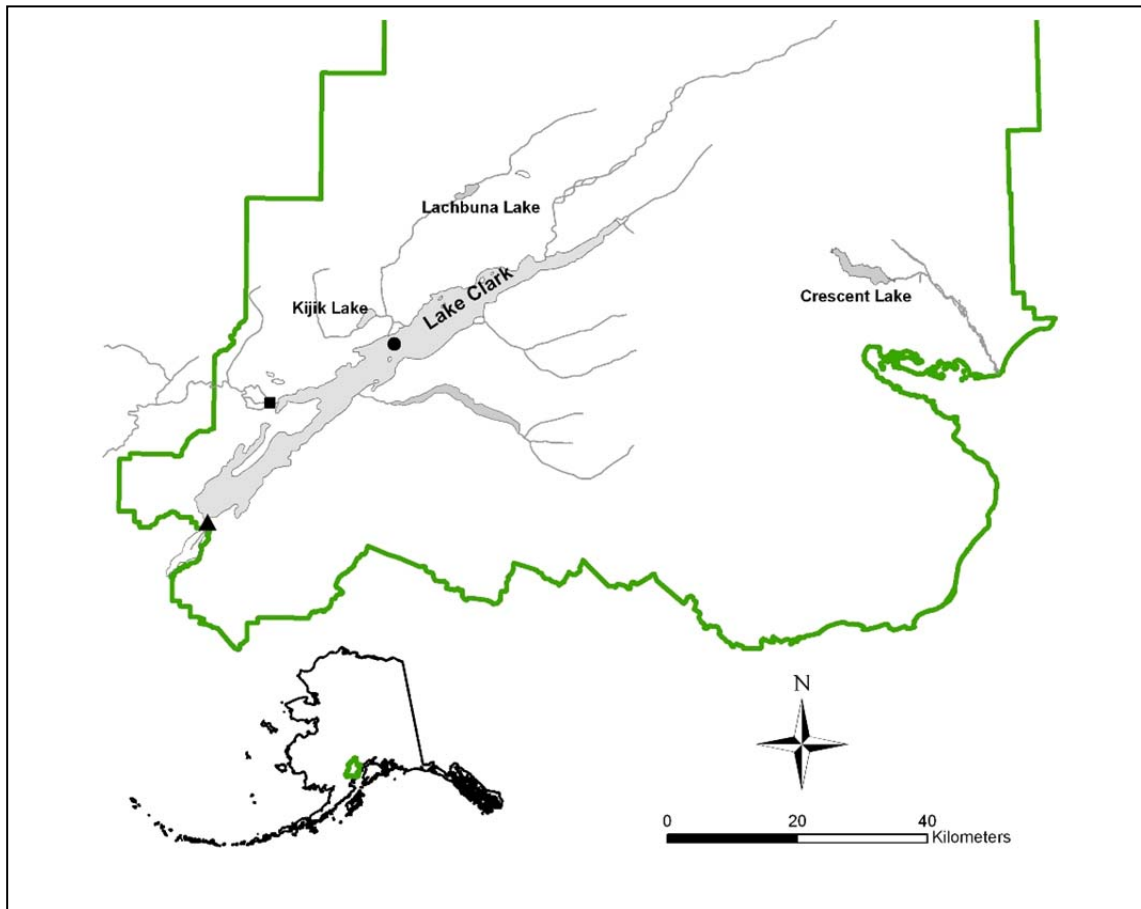


Figure 3. Lake Clark, Kijik Lake, Lachbuna Lake, and Crescent Lake in LACL. Chulitna River monitoring site (square), temperature array (circle), and lake outlet (triangle) are denoted as well.

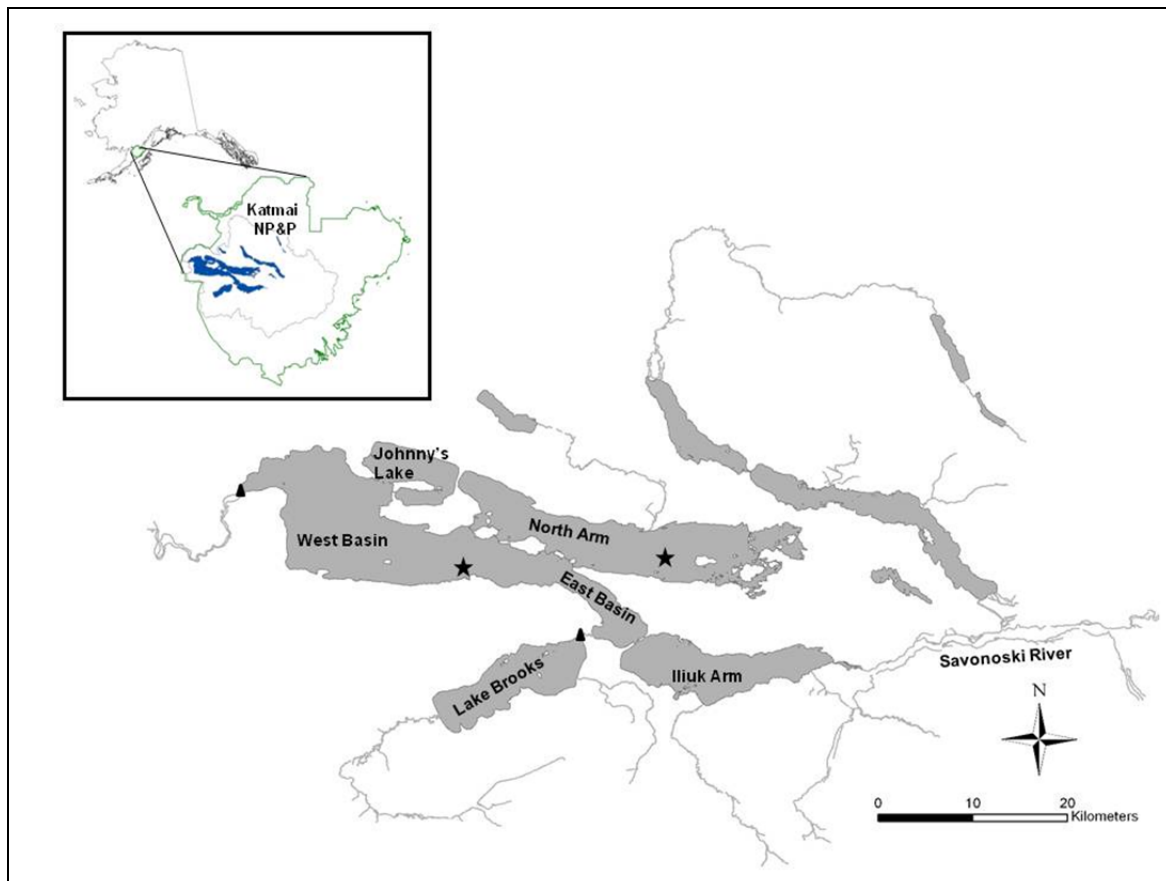


Figure 4. Lake Brooks and major basins of Naknek Lake including major tributaries in KATM. Lake outlets denoted with a triangle, temperature arrays denoted with a star.

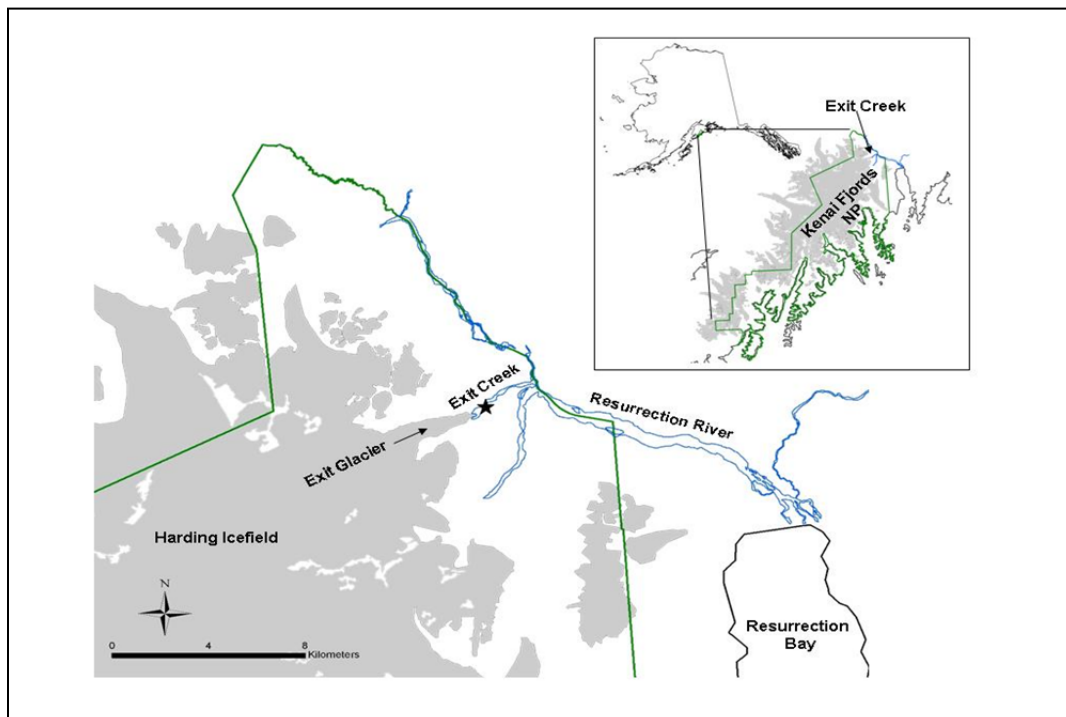


Figure 5. Exit Creek area in KEFJ. Study site is denoted with a star. Gray areas represent glacial ice cover.

Vertical lake profiles were measured on Lake Clark (Figure 5), Naknek Lake (Figure 6), Lake Brooks (Figure 6), Lachbuna Lake (Figure 7), Crescent Lake (Figure 8), and Kijik Lake (Figure 9) during the mid-summer index period (late July to late August). The mid-summer index period is defined by the period where the vertical thermal gradient is greatest (based on previous lake temperature monitoring). Sampling was conducted at general random tessellation stratified (GRTS) points on each lake (Stevens and Olsen 2004), except Kijik Lake. GRTS points were not available for Kijik Lake at the time of sampling so five randomly selected locations within the lake were sampled (Figure 9). GRTS points were created by overlaying a 1 km² grid of cells on each lake basin with a point assigned to the center of each cell in a geographic information system. A coordinate list (containing latitude and longitude) for each center point was generated and a GRTS analysis was applied to the coordinate list. The result was a list of randomly selected, spatially balanced sample locations for collecting lake profile information. Lake Clark was divided into three basins (upper, middle and lower) to consider the effects of the turbidity gradient whereas Naknek Lake was divided into five basins (West, East, Iliuk, North Arm, and Johnny's Lake) based on bathymetry and water source (glacial, ash-laden waters of the Iliuk Arm vs. non-glacial, clear waters of the North Arm). We sampled 10 sites in each basin of Lake Clark (Figure 5), 10 sites total in Lake Brooks (Figure 6) and 10 sites each in the West, East North Arm, and Iliuk Arms of Naknek Lake (Figure 6). The Johnny's Lake basin within Naknek Lake was not sampled due to time constraints. Additionally, one in every 10 sites was randomly selected for repeat sampling to track sample variability.

We used a YSI 600QS multiparameter sonde to collect water temperature ($^{\circ}\text{C}$), pH (unitless), dissolved oxygen (mg/L and % saturation), and specific conductivity ($\mu\text{S}/\text{cm}$) (collectively referred to as core parameters) between the surface and 50 m depth. Once the multi-parameter sonde was placed in water and readings stabilized, core parameters were recorded on the descent and ascent. Measurements were collected at the surface, 1 m, 2 m, 3 m, 4 m, 5 m, and every 5 meters to 50 m or the bottom, whichever was reached first. A 20 cm black and white Secchi disc was used to record water clarity at each site as well. The Secchi disc was lowered vertically into the water on the shaded side of the boat, the depth at which the disc disappeared was recorded. The disc was then lowered farther before being slowly raised; the depth at which the disc reappeared was recorded. This process was repeated two more times and Secchi depth was reported as the average of all six readings. Multiparameter sonde and Secchi disc methods were similar to those described in Hoffman et al. (2005) and USGS (2005). Information on recent precipitation, wind conditions, and overall site depth was also collected at each sample site.

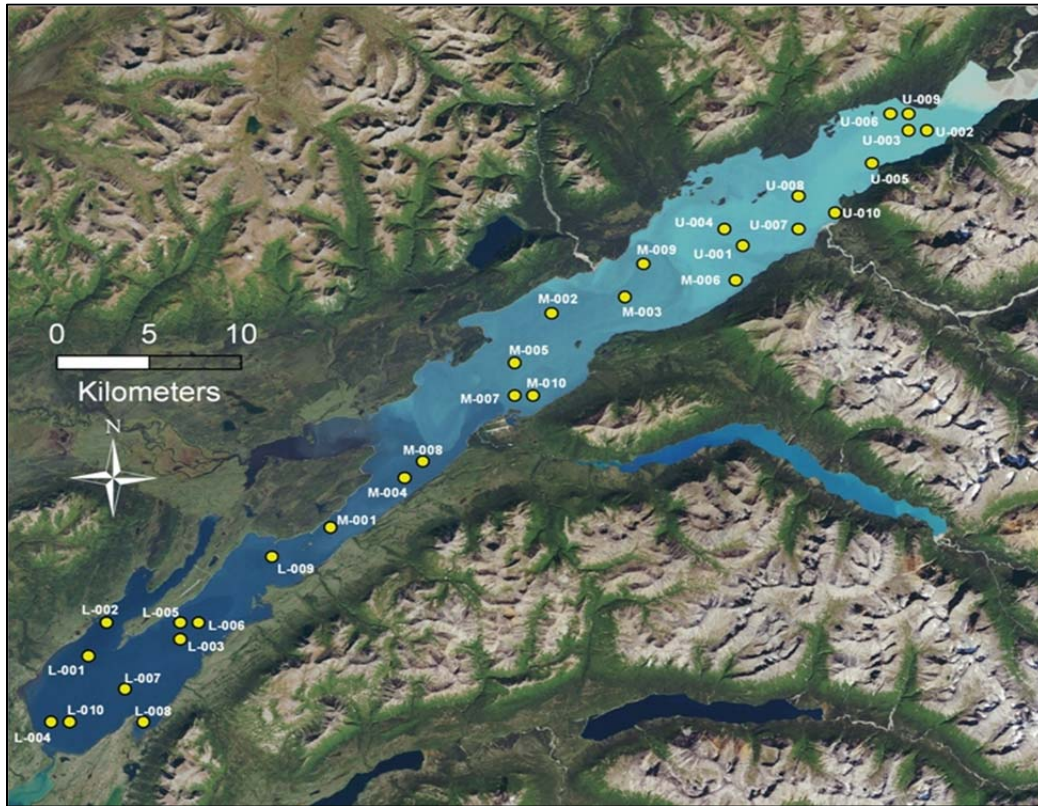


Figure 6. GRTS sample locations on Lake Clark where vertical lake profiles were measured. Note the longitudinal turbidity gradient as represented by changing water color from northeast to southwest axis.

Continuous monitoring of core parameters was conducted on the Chulitna River and at the outlet of Lake Clark from June through September using a YSI 6600 multiparameter sonde with optical dissolved oxygen and turbidity sensors. The sonde was housed inside

a polyvinyl chloride pipe which was attached to a secure steel cable and anchored to the river bank. The sonde was programmed to measure core parameters, as well as turbidity (NTU), on a 1 hour interval. At approximately one month intervals, water quality parameter readings were taken with a calibrated YSI 6600 sonde to correct for sensor drift due to fouling. Additionally, post-deployment error checks were conducted on the continuous deployment sonde to measure sensor calibration drift (Wagner et al. 2006). Dataset corrections for sensor fouling and drift correction were applied using AQUARIUS Time Series software (<http://www.aquaticinformatics.com/>).

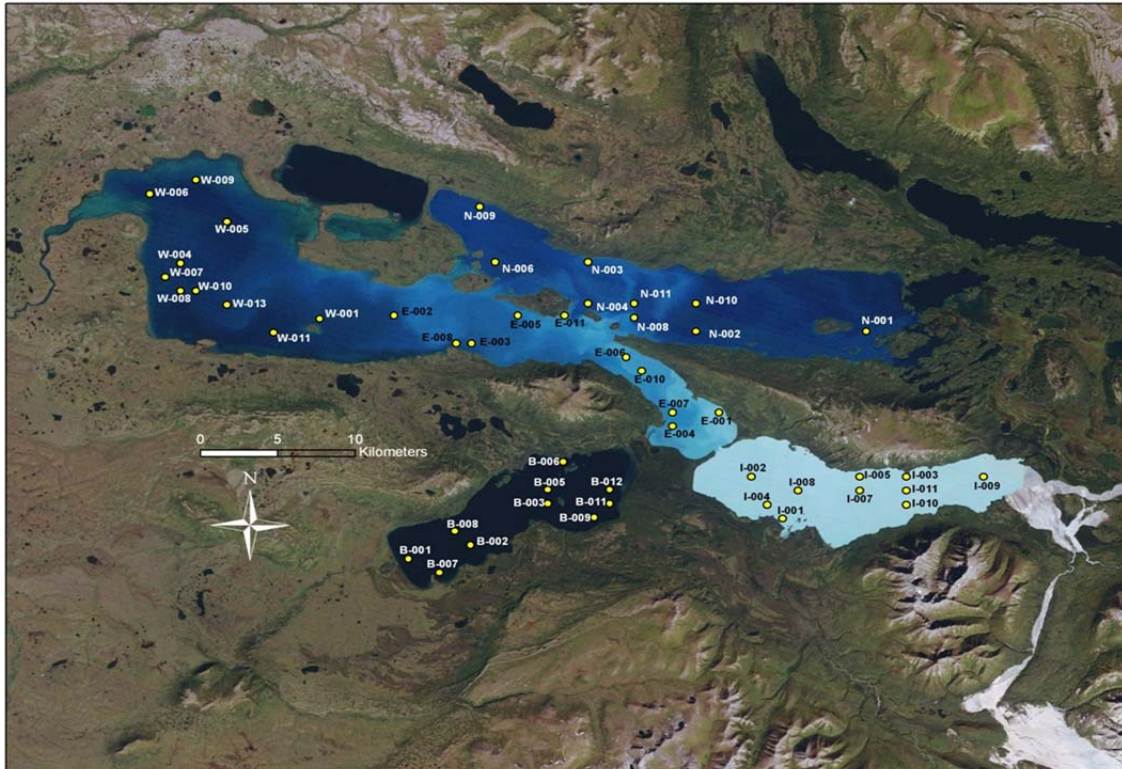


Figure 7. GRTS sample locations on Lake Brooks and Naknek Lake where vertical lake profiles were measured. Note the stark contrast in water clarity between lake basins; the highly turbid Iliak Arm is pale blue. Darker water indicates increased water clarity.

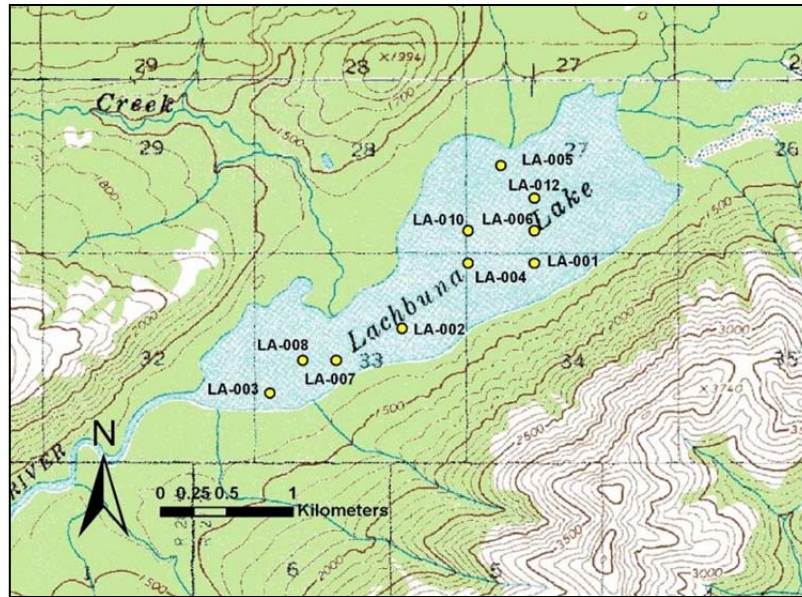


Figure 8. GRTS sample locations on Lachbuna Lake in LACL.

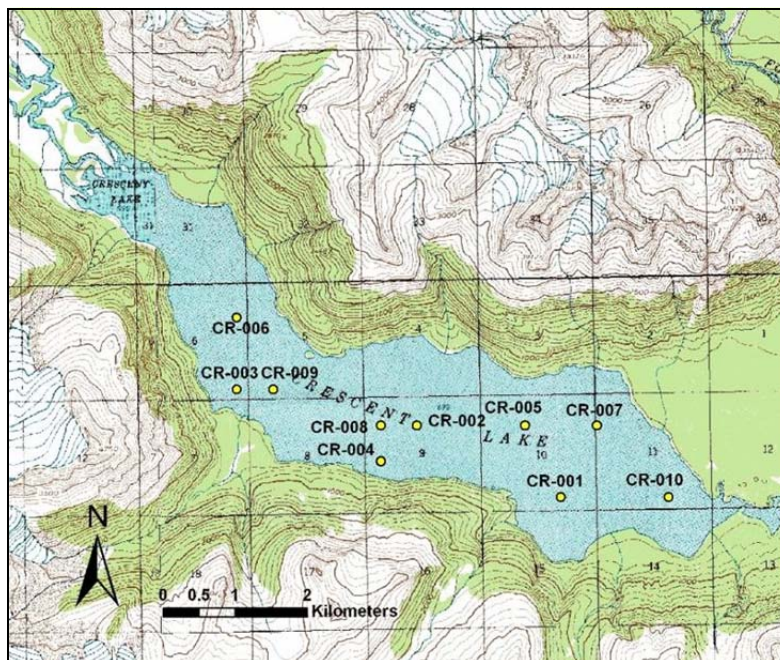


Figure 9. GRTS sample locations on Crescent Lake in LACL.

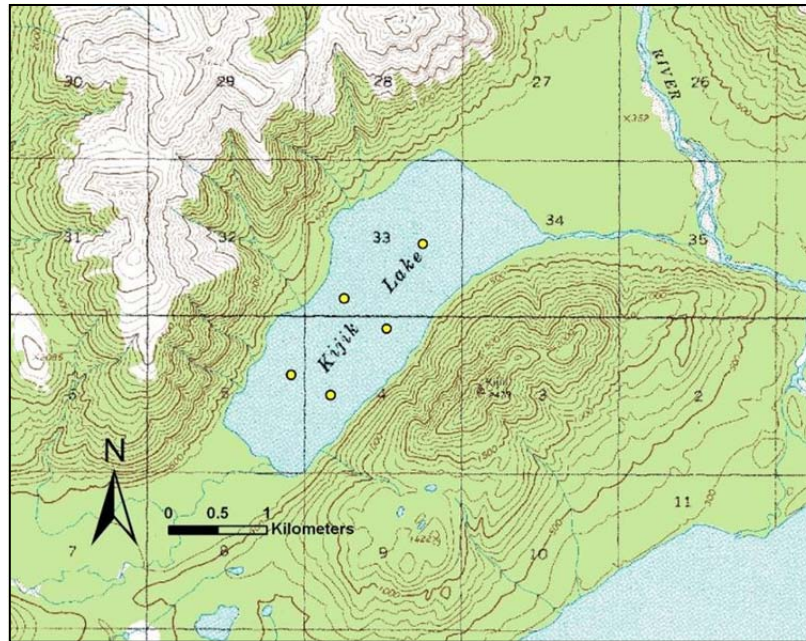


Figure 10. Sample locations on Kijik Lake in LACL.

Results and Discussion

Lake Clark Water Temperature

Water temperature in Lake Clark has been continuously monitored since September 2006. Our analysis compares 2009/2010 observations with data from the previous three years (Table 1). Generally speaking, 2009/2010 water temperatures for Lake Clark were characterized by a warm fall / early winter and a cool summer. Monthly maximum average daily temperatures for October through December 2009 were at or above the upper end of the period of record (September 2006 – September 2010), indicating relatively warm fall conditions and slow cooling conditions. Warm conditions continued into January with a maximum average daily temperature of 3.2 °C. These warm conditions were also observed in the monthly degree days for October through January 2009. Freeze-up for Lake Clark occurred on January 21, 2010, which is approximately one to two weeks later than previous years (National Park Service *unpublished data*). After lake freeze-up, temperature conditions were similar to previous years from February through May. This period represents a time of relatively stable thermal conditions in Lake Clark as the discrepancy between maximum and minimum average daily temperatures is low compared to other months. Summer conditions in 2010 were cool with maximum average daily temperatures below the range in the SWAN period of record. Additionally, the warmest 24-hour and 7-day period in 2010 were not observed until mid-September, a month later than previous years, and were several degrees lower than previous 24-hour and 7-day highs (Table 1). Temperature array data were downloaded most recently on September 16, 2010. As such, we were unable to conduct analysis later into the year so it is possible the actual warmest 24-hour period in 2010 occurred later than we report here. The cool summer conditions are also evident in the temperature isotherm (Figure 10). While Lake Clark stratified during the summer of 2010, the strength of this stratification is not as strong as observed in previous years. July air temperatures at the Port Alsworth, AK remote automated weather station (RAWS) (<http://www.raws.dri.edu/wraws/akF.html>) were 16.13 ± 5.89 °C (mean $\pm$ 1 SD) in 2009 compared to 11.64 ± 3.61 °C (mean $\pm$ 1 SD) in 2010. Mean temperatures for July were slightly above (2009) and below (2010) the 30 year July mean of 13.4 °C. Solar radiation in July 2010 was also lower than July 2009 with mean values of 142 W/m² and 235 W/m², respectively (<http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?akAPAL>). Reduced solar radiation, associated with increased cloud cover, and increased glacial runoff are possible reasons for cooler near-surface lake temperatures in 2010.

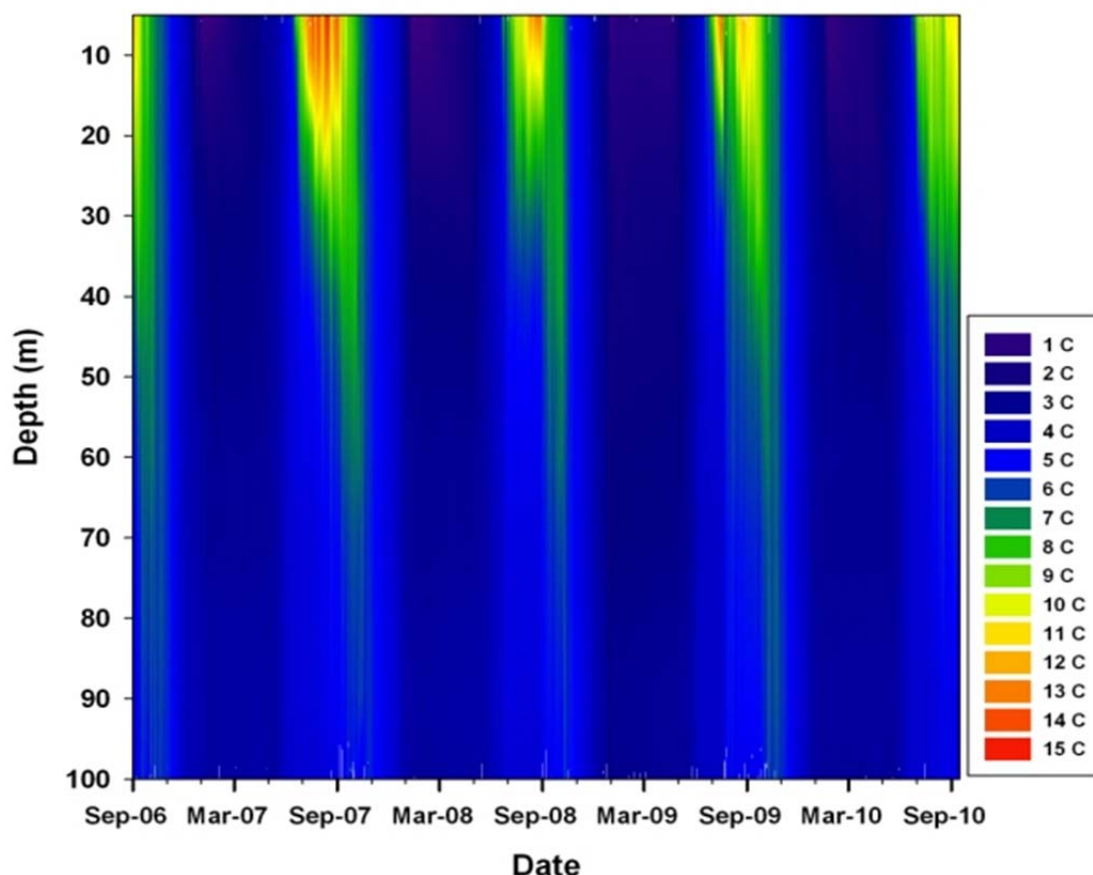


Figure 11. Lake Clark isotherm displaying patterns of summer stratification.

Naknek Lake Water Temperature

Water temperature monitoring in Naknek Lake was initiated in August 2008. This discussion will focus on comparing the 2008/2009 and the 2009/2010 datasets for each basin (Table 2). With few exceptions, maximum and minimum average temperatures for each month were higher in both basins in the fall and winter of 2009 and fall of 2008, similar to observations on Lake Clark. Though perhaps not as obvious when comparing maximum and minimum average temperatures, the warm pattern continues through the spring when monthly degree days are examined. However, as was observed for Lake Clark, summer (June and July) temperatures in 2010 were lower than in 2009. In fact, July maximum average temperatures for the North Arm and West Basin were several degrees lower in 2010 compared to 2009 observations (Figure 11). These observations from Naknek Lake and Lake Clark are indicative of cooler summer conditions in 2010 across the region than the previous summer as opposed to any lake-specific differences. Temperature array downloads occurred in early August for Naknek Lake, thus we did not calculate the warmest 24-hour and 7-day period observed for 2010 as lake temperatures were likely still increasing following the data download.

Temperature patterns between the two basins display the bathymetry differences of the deeper North Arm (mean depth 63 m, volume 63 km³) and the much shallower West Basin (mean depth 13 m, volume 13 km³) with the North Arm warming slower during spring and cooling slower during fall (Figure 11). Additionally, summertime stratification is more pronounced in the North Arm where deeper, cooler waters allow for a greater thermal gradient even though near surface temperatures are slightly cooler than the West Basin (Figure 12). The shallower West Basin is prone to frequent vertical mixing of the water column due to wind events resulting in a more uniform thermal gradient (Figure 13). Wind events play a vital role in thermal mixing of the North Arm as well. In 2009 we documented the results of a large regional wind event extending from Lake Clark to Katmai in late July that abruptly lowered near surface temperatures in Naknek Lake and Lake Clark (Shearer and Moore 2010). On July 9, 2010 a more localized event was observed within the North Arm dataset (Figure 12) and to a lesser extent in the West Basin dataset (Figure 13). Maximum hourly wind gust data for July 9, 2010 for the Pfaff Mine, Alaska RAWS from the Western Regional Climate Center (<http://www.raws.dri.edu/wraws/akF.html>) was 100.8 kph. Consequently, wind generated disturbance within Katmai resulted in decreasing near-surface lake temperatures from 10.3 ± 0.2 °C (mean $\pm$ 1 SD) on July 8, 2010 to 5.8 ± 0.5 °C on July 10, 2010 in the North Arm of Naknek Lake.

Table 1. Summary of water temperature data for Lake Clark. Analyses based on near surface temperature data. Range represents the highest and lowest observations for each month from September 1, 2006 – August 31, 2010.

Month	Max. Avg. Daily Temp ¹ mean (1 SD ⁴); °C		Min. Avg. Daily Temp ² mean (1 SD ⁴); °C		Monthly Degree Days ³	
	Range	2009-10	Range	2009-10	Range	2009-10
September	10.2 – 13.5	10.9 (0.0)	6.4 – 7.9	7.9 (0.4)	236 – 292	296
October	7.4 – 8.1	8.0 (0.1)	4.9 – 5.8	5.8 (0.1)	190 – 205	217
November	4.9 – 5.7	5.8 (0.1)	3.2 – 4.5	4.3 (0.0)	127 – 148	151
December	3.6 – 4.4	4.2 (0.0)	0.5 – 2.5	2.4 (0.4)	76 – 116	110
January	0.7 – 2.7	3.2 (0.1)	0.0 – 0.3	0.3 (0.0)	8 – 27	54
February	1.1 – 1.9	1.3 (0.0)	0.1 – 0.7	0.5 (0.0)	14 – 38	24
March	1.1 – 2.4	1.6 (0.0)	0.6 – 1.4	1.1 (0.2)	28 – 65	43
April	2.0 – 3.4	2.3 (0.1)	0.8 – 2.0	1.6 (0.0)	34 – 83	56
May	3.6 – 4.3	3.5 (0.1)	1.8 – 3.0	2.3 (0.1)	89 – 108	91
June	8.4 – 9.9	8.5(0.5)	3.6 – 4.0	3.5 (0.1)	155 – 204	150
July	11.0 – 15.0	10.5 (0.4)	5.9 – 8.9	8.6 (0.1)	285 – 395	291
August	12.1 – 15.9	11.0 (0.3)	8.1 – 10.5	8.2 (0.4)	320 – 403	300

Year	Hottest Day date	Hottest Day 24-hr mean (1 SD); °C	Hottest Week dates	Hottest Week 7-day mean (1 SD); °C
2007	August 13 th	15.9 (0.4)	Aug. 10 th - 17 th	14.7 (0.8)
2008	August 18 th	13.5 (0.5)	Aug. 22 nd - 29 th	13.0 (0.5)
2009	July 18 th	14.1 (0.4)	July 14 th – July 20 th	13.4 (0.6)
2010 ⁵	September 16 th	11.2 (0.1)	Sept. 10 th – 16 th	10.9 (0.2)

¹ Based on highest 24-hour average

² Based on lowest 24-hour average

³ Difference between daily mean temperature and 0 °C summed for each month

⁴ Standard deviations < 0.05 are reported as 0.0

⁵ Data only available to September 16, 2010

Table 2. Summary of water temperature data for the North Arm and West Basin of Naknek Lake between September 1, 2008 and July 31, 2010. Analyses based on near surface temperature data. Standard deviations < 0.05 are reported as 0.0.

	Max. Avg. Daily Temp ¹ mean (1 SD); °C		Min. Avg. Daily Temp ² mean (1 SD ⁴); °C		Monthly Degree Days ³	
	North Arm					
Month	2008-09	2009-10	2008-09	2009-10	2008-09	2009-10
September	12.0 (0.1)	11.9 (0.1)	7.3 (0.1)	10.1 (0.0)	304	336
October	9.6 (0.0)	10.1 (0.0)	6.2 (0.0)	7.7 (0.1)	239	272
November	6.2 (0.0)	7.6 (0.0)	4.1 (0.0)	5.0 (0.0)	158	192
December	4.1 (0.1)	5.0 (0.0)	0.9 (0.1)	3.2 (0.0)	98	125
January	1.2 (0.1)	3.2 (0.0)	0.7 (0.0)	0.6 (0.1)	26	56
February	1.0 (0.0)	1.5 (0.0)	0.7 (0.0)	0.8 (0.1)	21	31
March	1.3 (0.0)	1.8 (0.0)	1.0 (0.0)	1.5 (0.0)	37	52
April	2.0 (0.1)	2.5 (0.7)	1.4 (0.0)	1.8 (0.0)	46	62
May	3.8 (0.0)	3.9 (0.0)	2.1 (0.1)	2.6 (0.0)	93	98
June	9.4 (0.2)	9.5 (0.1)	3.9 (1.0)	3.9 (0.1)	191	189
July	15.8 (0.3)	10.7 (0.1)	6.8 (0.2)	6.5 (0.6)	365	267
August	12.2 (0.1)		8.2 (0.3)		344	
	West Basin					
Month	2008-09	2009-10	2008-09	2009-10	2008-09	2009-10
September	12.6 (0.1)	12.4 (0.1)	9.7 (0.0)	9.8 (0.0)	328	345
October	9.8 (0.0)	9.7 (0.1)	4.1 (0.4)	7.1 (0.1)	216	275
November	4.6 (0.4)	7.0 (0.1)	0.6 (0.1)	1.4 (0.1)	67	109
December	1.4 (0.0)	1.8 (0.2)	0.4 (0.0)	0.5 (0.2)	31	38
January	0.7 (0.0)	1.6 (0.1)	0.2 (0.0)	0.1 (0.0)	14	20
February	1.1 (0.0)	1.5 (0.0)	0.6 (0.0)	0.5 (0.0)	23	26
March	1.4 (0.0)	2.0 (0.0)	1.0 (0.0)	1.3 (0.1)	41	51
April	2.3 (0.2)	2.8 (0.1)	1.5 (0.0)	1.8 (0.1)	50	67
May	6.8 (0.1)	6.6 (0.2)	2.3 (0.1)	1.5 (0.3)	118	115
June	12.1 (0.2)	12.4 (0.2)	6.1 (0.2)	6.5 (0.2)	275	280
July	16.1 (0.1)	12.2 (0.1)	11.9 (0.1)	10.4 (0.7)	439	341
August	13.4 (0.1)		11.7 (0.2)		387	

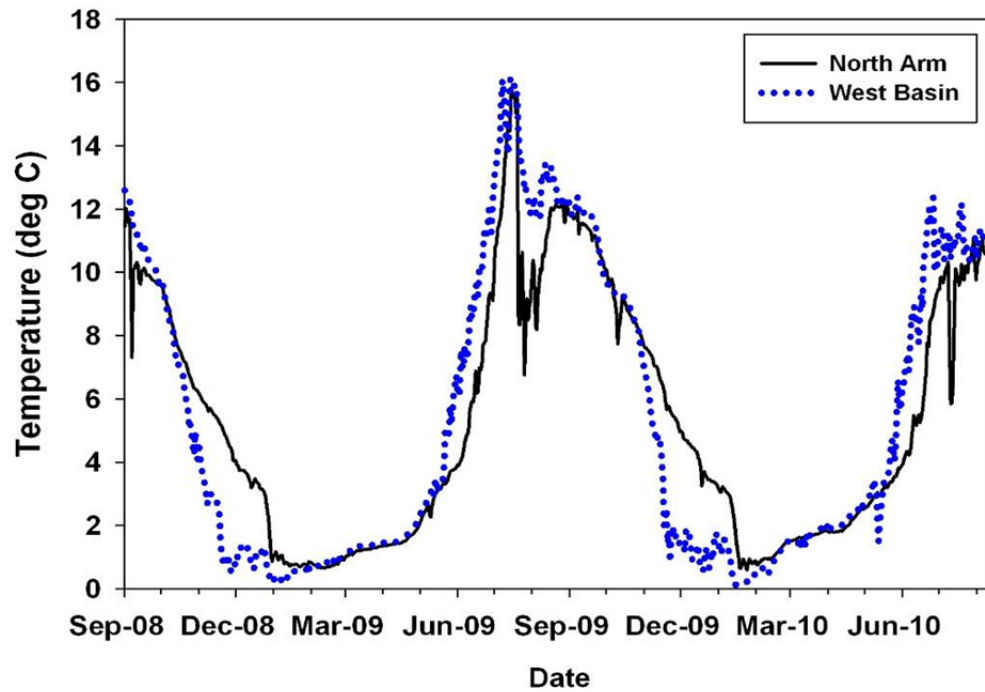


Figure 12. Comparison of near surface water temperatures for the North Arm and West Basin of Naknek Lake.

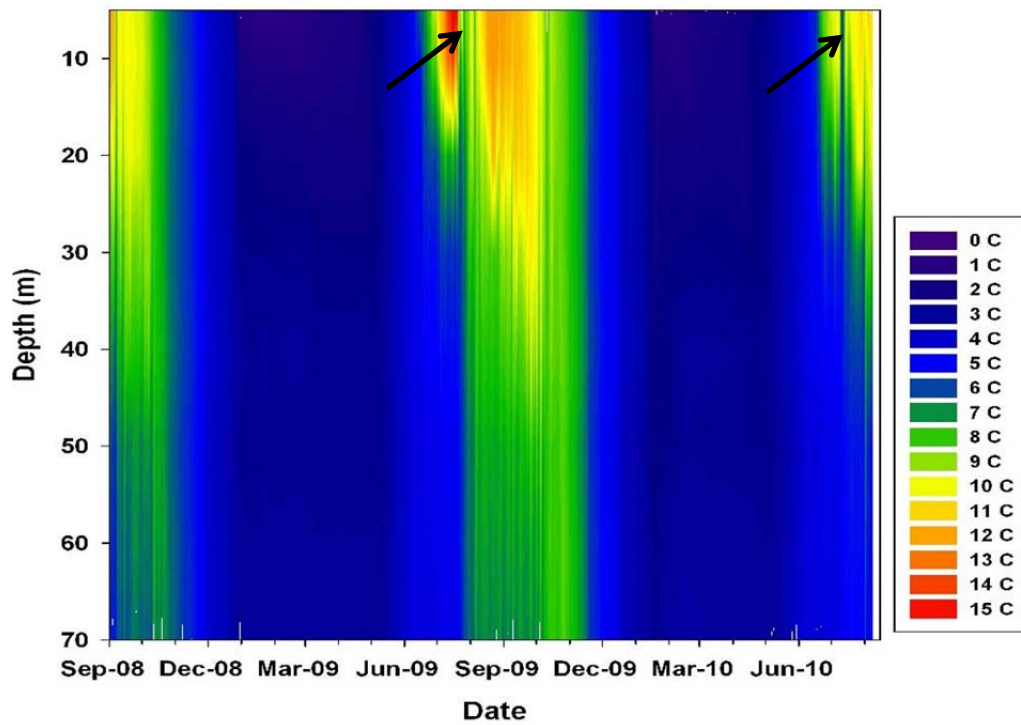


Figure 13. Isotherm for North Arm of Naknek Lake displaying patterns of summer stratification. Arrows indicate wind disturbance events (July 21, 2009 and July 9, 2010).

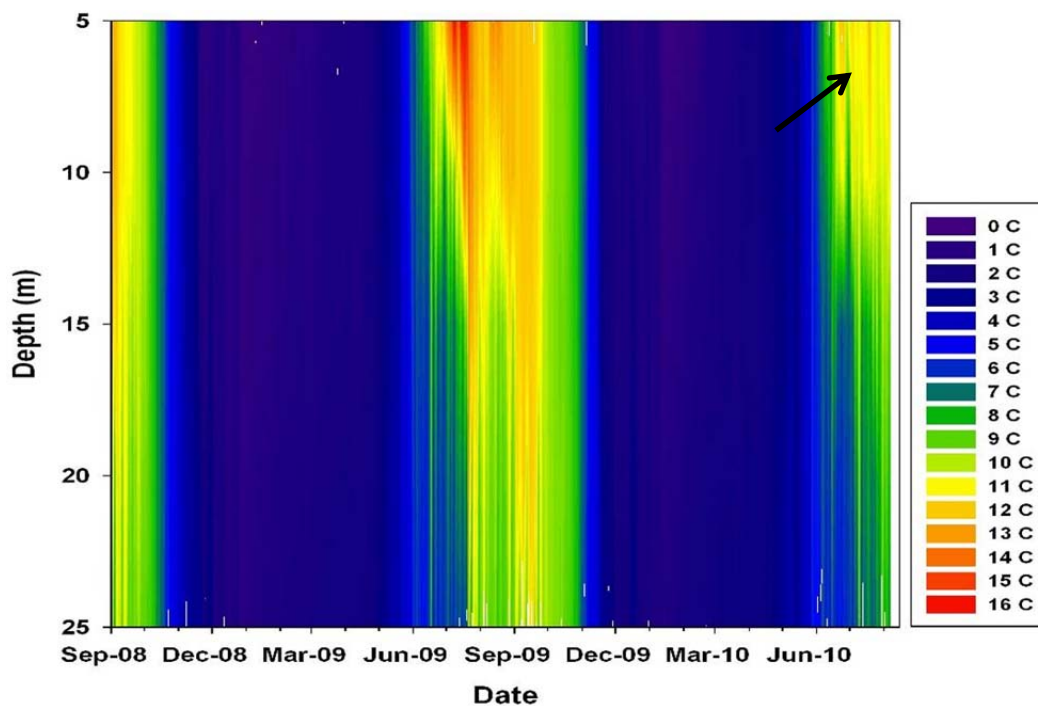


Figure 14. Isotherm for West Basin of Naknek Lake displaying patterns of summer stratification. Arrow indicates July 9, 2010 wind disturbance event.

Naknek Lake and Lake Brooks Discharge

Daily lake discharge was estimated for the open water period (May – September) for Naknek Lake and Lake Brooks using stage / discharge rating curves developed by the U.S. Geological Survey Water Resources Division over a two year period (Table 3). The seasonal hydrograph for Naknek Lake shows an early season rise through May and June in response to snowmelt runoff. Discharge tends to level off and remain stable throughout the summer months due to inputs from precipitation and glacial runoff (Figure 14). Maximum discharge for the water year occurs in August or September. In contrast, Lake Brooks often has two distinct peaks (Figure 15). The first peak occurs in June in response to snowmelt runoff. Lake levels often decline in June and July and rise again later in the summer in response to precipitation. Maximum discharge can occur in either of these two peaks. During years in which there is significant snow pack, maximum discharge occurs during the first peak. In years where snowpack is light and summer precipitation approaches or exceeds the 30-year mean, maximum discharge occurs later in the summer.

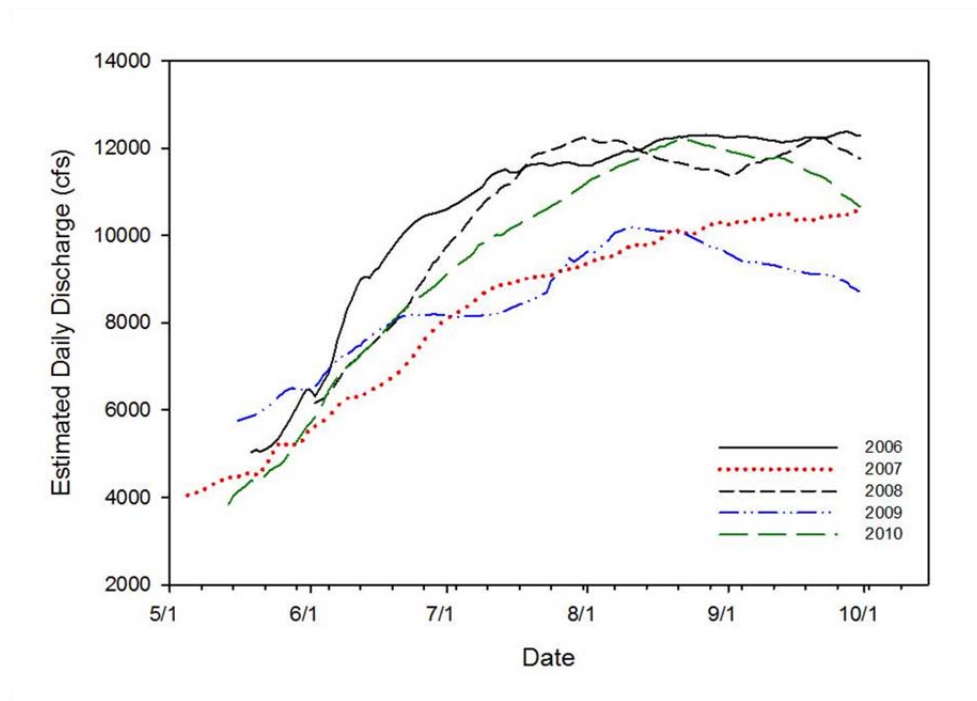


Figure 15. Estimated daily discharge for Naknek Lake for period of record. Data are displayed as a five day moving average to remove the effects of wave action.

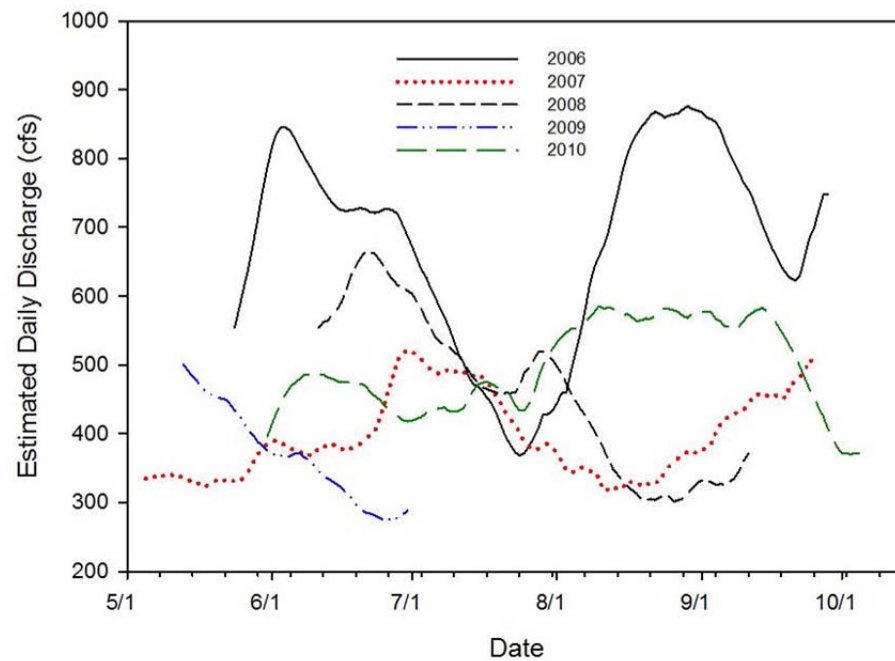


Figure 16. Estimated daily discharge for Lake Brooks for period of record.

Although the overall pattern of the open water season hydrograph for Naknek Lake is fairly consistent from year to year, discharge estimates can vary widely (Figure 16). The rising limb of the 2010 hydrograph was close to the 5-year minimum low due to water deficit conditions that persisted throughout the summer and fall of water year 2009 and into the winter and spring of water year 2010. Seasonal water deficits ranged from a high of -10.64% (summer 2009) to -4.33% (spring 2010) based on the 30 year seasonal mean precipitation totals (data obtained from National Weather Service, King Salmon Office). Overall, the combined seasonal water deficit for water year 2010 was -20.68%. This was in contrast to the start of the 2009 open water season, which was preceded by slightly higher seasonal precipitation totals in winter and spring, and warm weather resulting in a rapid rising limb of the hydrograph with discharge values approaching the 5-year maximum. These hydrograph patterns were also observed in Lake Clark where the 2009 rising limb exceeded the 10-year maximum, whereas the 2010 rising limb was well below the 10-year mean (NPS unpublished data).

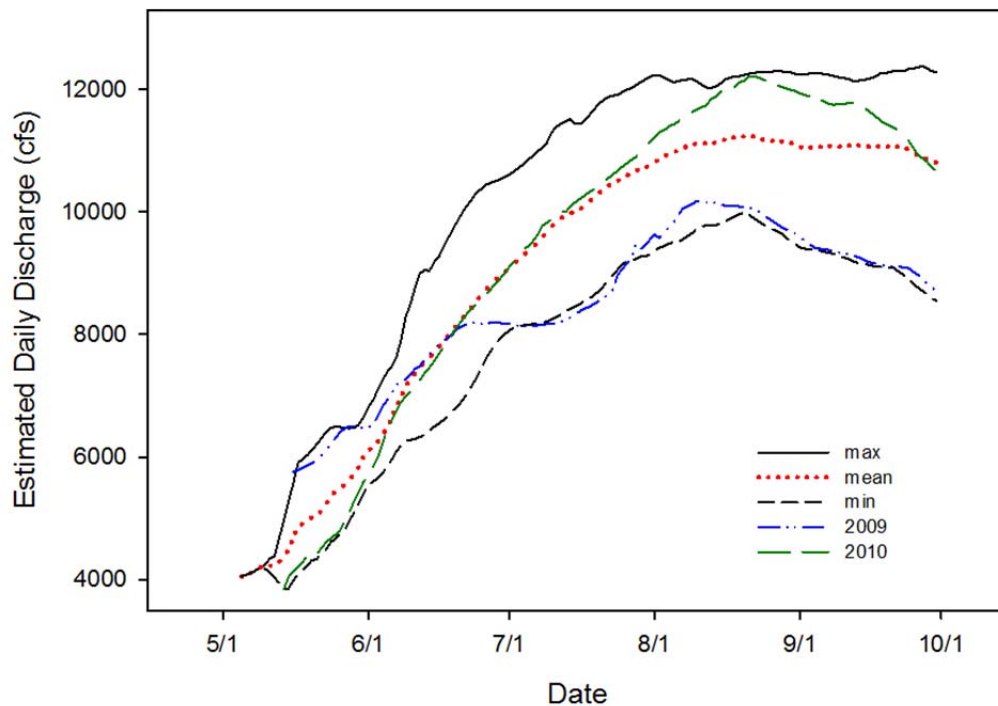


Figure 17. 2009 and 2010 open water period hydrographs for Naknek Lake plotted with period of record (2006 – 2010) mean, max and min estimated discharge. Data are displayed as a five day moving average to remove the effects of wave action.

The summer season (June – August) precipitation total for water year 2010 was 221 mm in King Salmon, only slightly less than the 30-year mean of 224 mm; however, the July and August monthly totals exceeded the 30-year monthly totals by 22 mm and 29 mm, respectively. This excess precipitation resulted in increased discharge in late July and

into August, which approached the 5-year maximum. In 2009, the hydrograph dropped quickly and by early July was close to the 5-year minimum for the remainder of the open water season (Figure 16). The Lake Clark hydrographs were very similar; by mid-August the 2010 hydrograph was close to the 10-year maximum, whereas the 2009 hydrograph had fallen below the 10-year mean (NPS unpublished data).

In Lake Brooks, maximum discharge occurred during late August (Table 3) indicating that it was driven by summer precipitation. Peak snowmelt runoff occurred in early June. The SWAN period of record (2006 – 2010) indicates that Lake Brooks discharge is highly variable compared to Naknek Lake. The Lake Brooks watershed is significantly smaller and therefore the lake exhibits a quicker hydrologic response to runoff and precipitation inputs. Although two peaks are clearly evident, the timing and magnitude of these peaks vary widely from year to year. In 2006, 2007 and 2010, the snowmelt and precipitation-driven peaks were similar in magnitude, but varied in timing from year to year (Figure 15). Maximum discharge occurred during snowmelt runoff in 2008 and 2009 whereas the late season peak was significantly lower. Discharge data for 2009 was limited due to the extremely low water levels, which left the pressure transducer out of the water.

Several discharge measurements were made on Naknek River in 2010 to check the accuracy of the rating curve developed in 2007. We used the U.S. Geological Survey Water Resources Division boat-based method (Smoot and Novak 1968) with a Price AA current meter. Three measurements were collected during the rising limb of the hydrograph and one measurement was collected later in the season during high flow. The low-flow measurements were consistent with the current rating curve; however, the high-flow measurement showed a slight deviation from the rating curve. The Price AA current meter is not the best device for measuring discharge in this river reach due to the configuration of the reach and the sluggishness of the flow within the individual cells. Future measurements will be made using our recently acquired RiverSurveyor M9 ADCP unit.

Over the last two years, the National Weather Service (NWS) has been collecting water level data at Lake Camp, the site of the Naknek Lake pressure transducer. Data collection for 2009 was spotty – level measurements started late in the season and were not collected daily; however, the 2010 record includes daily level measurements starting in late April. These daily measurements were plotted with pressure transducer levels collected at the same time and a linear regression was applied for the full record of the 2010 data set and the available data for 2009. The regressions were very similar and show promise for using the NWS daily values early in the season to estimate discharge during the time when the pressure transducer is not yet submerged. This would extend the Naknek Lake hydrograph several weeks and provide a better estimate of the magnitude and timing of the rising limb.

Telaquana Lake Discharge

Telaquana Lake is a Tier 3 lake and as such is a lower priority for monitoring. However, the lake cabin is staffed by volunteers who record daily lake level readings from staff gages that were installed by the USGS-WRD as part of the rating curve development in 2007. Water level at the lake outlet has been intermittently measured using pressure transducers. Estimated daily discharge was calculated for the period of record (2006 – 2010) using the daily lake level readings (Figure 17). The Telaquana Lake hydrograph displays a high degree of inter-annual variability. Because Telaquana is a glacially fed alpine lake, the onset of snowmelt runoff is later than in lower elevation lakes and typically peaks in late June or early July. The peak was several weeks earlier in 2009 due to the early onset of unseasonably warm temperatures. Several peaks varying in magnitude and timing occur throughout the open water season and appear to be associated with both glacial runoff and precipitation inputs. In most years of the five year dataset no distinct late season peak emerged.

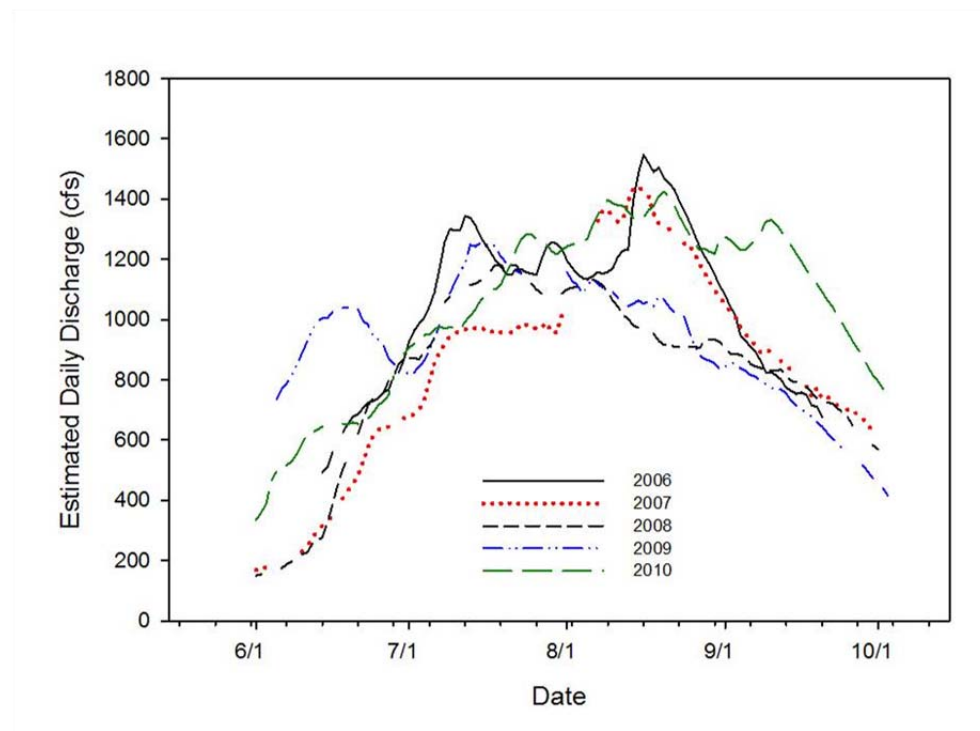


Figure 18. Estimated daily discharge for Telaquana Lake for period of record. Breaks in the data indicate periods when gage readings were not recorded.

Table 3. Summary of estimated lake discharge (Q) data for Naknek and Brooks Lakes during open water period for 2007 - 2010.

Month	Avg. Monthly Q mean (1 SD); cfs ¹				Max. Monthly Q cfs				Min. Monthly Q cfs			
	2007	2008	2009	2010	2007	2008	2009	2010	2007	2008	2009	2010
Brooks Lake												
May	343 (21)		440 (47)		398		523		321		363	
June	414 (57)	610 (43)	317 (37)	461 (25)	525	671	376	494	363	518	266	415
July	445 (52)	500 (36)		460 (35)	512	588		545	348	434		396
August	343 (25)	350 (55)		572 (15)	387	469		610	278	290		542
September	456 (40)	351 (29)		511 (74)	551	402		588	373	322		363
Naknek Lake												
May	4,671 (542)		6,328 (329)	4,265 (640)	5,753		6,996	5,826	3,948		5,758	3,718
June	6,817 (749)	7,912 (1,052)	7,882 (376)	7,681 (944)	8,142	9,831	8,334	9,127	5,610	6,163	7,061	5,826
July	8,923 (327)	11,320 (770)	8,804 (619)	10,249 (581)	9,395	12,313	10,010	11,280	8,226	9,822	8,116	9,226
August	9,924 (302)	11,797 (273)	7,948 (262)	11,867 (291)	10,505	12,235	10,284	12,246	9,424	11,301	9,351	11,312
September	10,438 (166)	11,870 (267)	9,042 (289)	11,444 (415)	10,752	12,361	9,424	11,925	10,191	11,305	8,424	10,504
Year	Peak Q date		Peak Q cfs		Peak 7-day Avg. Q dates				Peak 7-day Avg. Q Mean (1SD);cfs			
Brooks Lake												
2007	September 20 th		551		June 26 th – July 2 nd				517 (8)			
2008	June 20 th		671		June 17 th – June 23 rd				660 (9)			
2009	May 9 th		523		May 9 th – May 15 th				493 (19)			
2010	August 30 th		610		August 6 th – August 12 th				583 (9)			
Naknek Lake												
2007	September 30 th		10,752		September 24 th – September 30 th				10,558 (156)			
2008	September 20 th		12,361		September 16 th – September 22 nd				12,204 (123)			
2009	August 4 th		10,284		August 3 rd – August 9 th				10,174 (65)			
2010	August 21 st		12,245		August 18 th – August 24 th				12,185 (75)			

¹ cfs = cubic feet per seconds

Vertical Lake Profiles

Tables 4 and 5 provides a statistical summary of core parameters averaged across sites within each basin of Lake Clark and Naknek Lake, and averaged across the entire lake for Lake Brooks, Lachbuna Lake, Crescent Lake and Kijik Lake. Summary results for each parameter are discussed individually for each lake.

Water Temperature

Lake Clark surface water temperatures displayed the pattern we would expect with the lowest mean temperature in the upper lake which receives runoff from several large rivers with glacial sources and a high mean temperature in the lower lake, which is more shallow and receives runoff from low lying non-glacial drainages (Figure 18). We observed the opposite pattern in previous years (Shearer and Moore 2009, Shearer and Moore 2010) with warmer mean temperatures nearest glacial inputs. Cumulative August precipitation totals for the Port Alsworth, AK RAWS (<http://www.raws.dri.edu/wraws/akF.html>) were 48.16 cm in 2010 compared to 11.86 cm in 2009. Additionally, Lake Clark water levels were considerably higher in August 2010 compared to the previous two summers (J. Shearer *personal observation*) indicating increased tributary runoff into the lake. The cooler, wetter conditions observed in 2010 likely resulted in runoff from glacial and non-glacial sources playing a larger role in dictating Lake Clark's thermal characteristics compared to previously years (e.g. 2008 and 2009). However, upper, middle and lower basin temperature profile differences are only separated by approximately 1°C at any given depth (Figure 18). As such, between basin differences in temperature profiles may be a reflection of within lake variability, especially given the spatial distance between upper basin and lower basin sites (59.6 km between the upper-most and lower-most Lake Clark GRTS sites).

Table 4. Summary data for core parameters collected at vertical lake profile sites on Lake Clark, Naknek Lake, and Lake Brooks during summer 2010. Values represent the median between all depth intervals at a site averaged across all sites within the lake basin.

Parameter	Lake Clark			Naknek Lake			Lake Brooks	
Statistic	Upper Basin	Middle Basin	Lower Basin	East Basin	West Basin	Iliuk Arm	North Arm	
Water Temperature (°C)								
Mean	8.20	8.94	9.96	10.74	11.67	7.84	9.90	10.14
Standard Deviation	0.40	0.59	0.46	0.52	0.45	0.43	0.48	0.47
Maximum	9.02	9.62	10.82	11.66	12.33	8.90	10.43	10.70
Minimum	7.70	7.73	9.47	10.11	10.95	7.45	9.09	9.32
pH (standard units)								
Mean	7.69	7.66	7.70	7.96	7.99	7.77	7.87	7.83
Standard Deviation	0.02	0.03	0.03	0.05	0.02	0.03	0.03	0.04
Maximum	7.73	7.71	7.76	8.02	8.04	7.84	7.92	7.92
Minimum	7.67	7.61	7.66	7.88	7.96	7.75	7.81	7.78
Specific Conductivity (µS/cm)								
Mean	62	62	63	139	139	144	141	78
Standard Deviation	0	0	0	1	1	1	1	0
Maximum	62	63	62	140	140	145	142	78
Minimum	62	62	62	136	138	143	140	77
Dissolved Oxygen (mg/L)								
Mean	12.18	11.67	11.81	11.84	11.25	12.45	11.91	11.77
Standard Deviation	0.12	0.27	0.22	0.12	0.15	0.11	0.12	0.10
Maximum	12.38	12.18	12.04	11.97	11.56	12.60	12.09	11.94
Minimum	11.99	11.36	11.44	11.64	11.05	12.26	11.68	11.65
Dissolved Oxygen (% Sat)								
Mean	103.3	100.8	104.5	106.6	103.6	104.8	105.3	104.7
Standard Deviation	0.6	0.3	0.2	0.9	0.5	0.5	0.4	0.4
Maximum	104.2	103.3	106.1	108.3	104.7	105.6	106.0	105.4
Minimum	102.3	99.7	100.1	105.2	103.1	104.2	104.6	104.1
Secchi Depth (m)								
Mean	1.06	1.46	2.66	3.19	5.23	0.53	6.19	10.24
Standard Deviation	0.11	0.23	0.54	1.25	0.66	0.07	2.14	0.62
Maximum	1.20	1.91	3.96	4.73	6.05	0.65	9.75	10.96
Minimum	0.87	1.16	1.96	1.10	4.18	0.41	2.74	9.29

Table 5. Summary data for core parameters collected at vertical lake profile sites on Kijik, Lachbuna, and Crescent Lakes during summer 2010. Values represent the median between all depth intervals at a site averaged across all sites within the lake basin.

Parameter Statistic	Kijik Lake	Lachbuna Lake	Crescent Lake
Water Temperature (°C)			
Mean	9.42	9.56	8.53
Standard Deviation	0.23	0.20	0.82
Maximum	9.80	10.04	9.62
Minimum	9.15	9.31	7.30
pH (standard units)			
Mean	7.70	7.68	7.15
Standard Deviation	0.05	0.02	0.08
Maximum	7.74	7.71	7.24
Minimum	7.62	7.66	6.97
Specific Conductivity (µS/cm)			
Mean	71	72	27
Standard Deviation	0	0	0
Maximum	71	73	28
Minimum	71	72	27
Dissolved Oxygen (mg/L)			
Mean	11.14	11.03	11.69
Standard Deviation	0.13	0.04	0.11
Maximum	11.35	11.08	11.84
Minimum	11.02	10.96	11.53
Dissolved Oxygen (% Sat)			
Mean	102.5	96.8	99.9
Standard Deviation	0.3	0.3	1.0
Maximum	103.0	97.6	101.2
Minimum	102.0	96.4	98.2
Secchi Depth (m)			
Mean	9.37	1.51	0.81
Standard Deviation	0.50	0.09	0.07
Maximum	10.01	1.65	0.94
Minimum	8.60	1.41	0.73

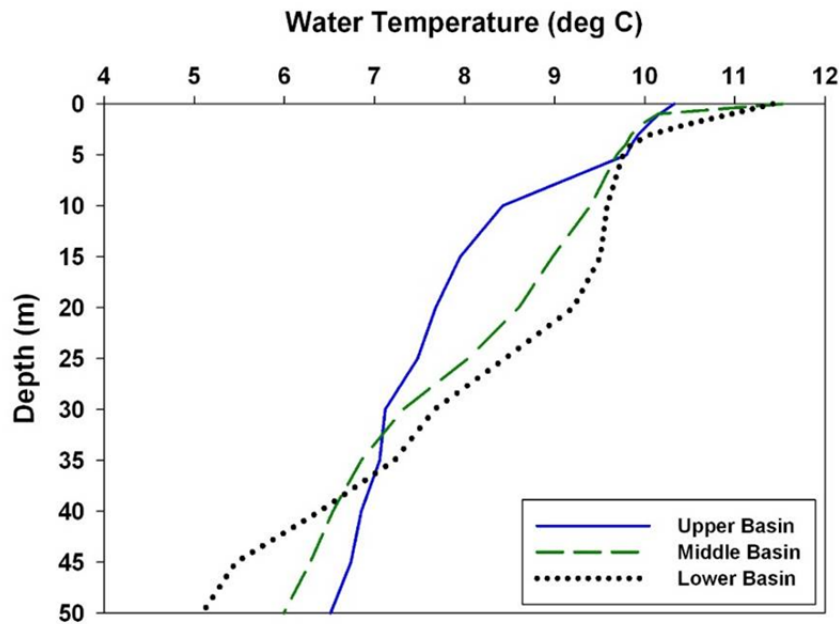


Figure 19. Temperature profiles for select sites that were representative of each basin in Lake Clark during August sampling.

Water temperatures within Naknek Lake ranged between 7.45 °C in the Iliuk Arm to 12.33 °C in the West Basin while Lake Brooks temperatures ranged between 9.32 °C and 10.70 °C (Table 4). Vertically, temperature profiles among basins in Naknek Lake were similar, although the shallow nature of the West Basin prohibits comparison to the greater depths of the other basins (Figure 19). The Iliuk Arm of Naknek Lake receives glacial runoff and ash-laden runoff from the nearby Valley of Ten Thousand Smokes (Kozlowski 2007), creating extremely turbid conditions within this basin. High surface reflectance of turbid waters in the Iliuk Arm (Edmundson and Mazumder 2002) combined with the cooler glacial meltwater from the Savanoski River may be responsible for water temperatures exhibiting less of a thermal gradient compared to the less turbid East Basin or North Arm (Figure 19).

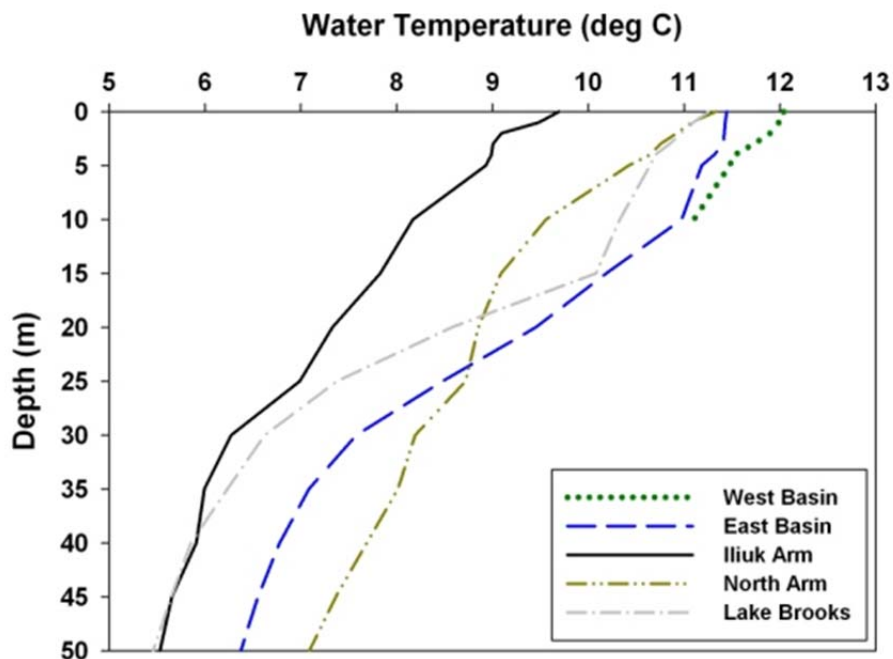


Figure 20. Temperature profiles of select sites within Naknek Lake and Lake Brooks.

pH

pH was relatively stable between basins in Lake Clark ranging between a minimum of 7.61 in the lower basin to a maximum of 7.76 in the middle basin (Table 4). Kijik and Lachbuna Lakes, both contributing basins to Lake Clark, had pH values similar to those observed within Lake Clark. Naknek Lake pH ranged between 7.75 in the Iliuk Arm and 8.04 in the West Basin with Lake Brooks pH falling between this range (Table 4).

These values are similar to those reported by LaPerriere (1997). All lakes exhibited a decrease in pH with depth (Figure 20). This pattern is likely explained by the photosynthetic depletion of dissolved carbon dioxide in the euphotic zone where phytoplankton production is highest, thus slightly reducing the amount of carbonic acid in water (Wetzel 2001). Differences in the euphotic zone and wind mixing among basins likely explain why some pH declines were greater (e.g. Lake Brooks) than others (e.g. Iliuk Arm). Goldman (1960) reported the euphotic zone of Lake Brooks to average 46 m whereas Naknek Lake averaged 16 m with considerable variation as sites within the East Basin and Iliuk Arm were combined.

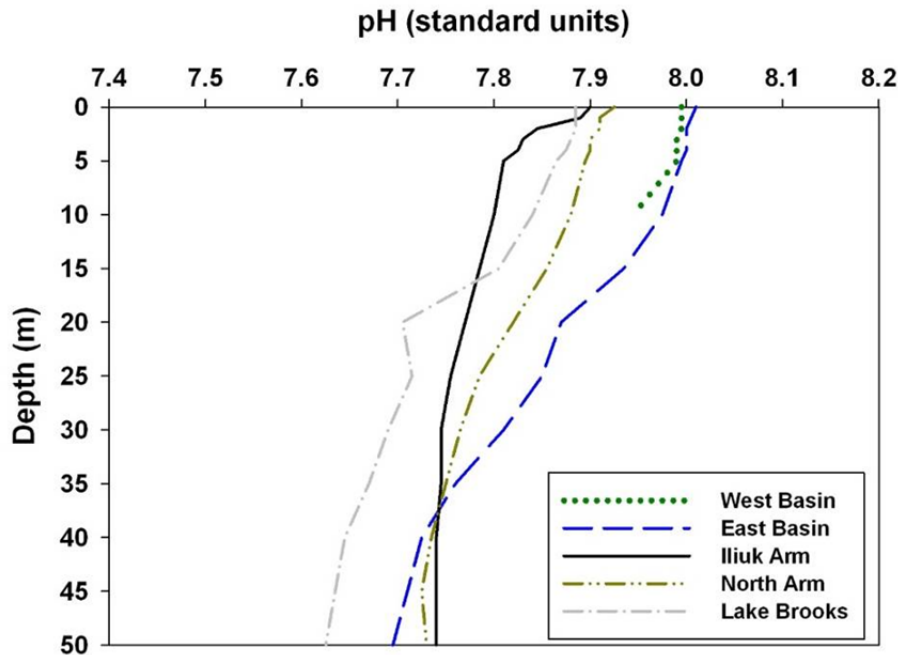


Figure 21. pH profiles for select sites within Naknek Lake and Lake Brooks.

Specific Conductivity

Similar to pH, specific conductivity remained stable throughout most lakes (Tables 4 and 5). Even along depth gradients within lake basins, specific conductivity only deviated by 1 or 2 $\mu\text{S}/\text{cm}$ from the basin average for most sites. One exception to these observations was Lachbuna Lake where specific conductivity at the surface ranged from 72 to 73 $\mu\text{S}/\text{cm}$ and 85 to 87 $\mu\text{S}/\text{cm}$ near the bottom (Figure 21).

In past years we've observed a relatively large vertical specific conductivity gradient at one particular site often associated with influences from a nearby tributary (Shearer and Moore 2010). However, all profiles measured within Lachbuna Lake displayed this same pattern. The longer water remains in contact with soils the greater potential for leaching of ions, thus groundwater tends to have a higher specific conductivity than surface runoff (Wetzel 2001). Given the observed spatial pattern within Lachbuna Lake we suggest groundwater infiltration throughout the lake basin is contributing to the higher specific conductivity values near the bottom.

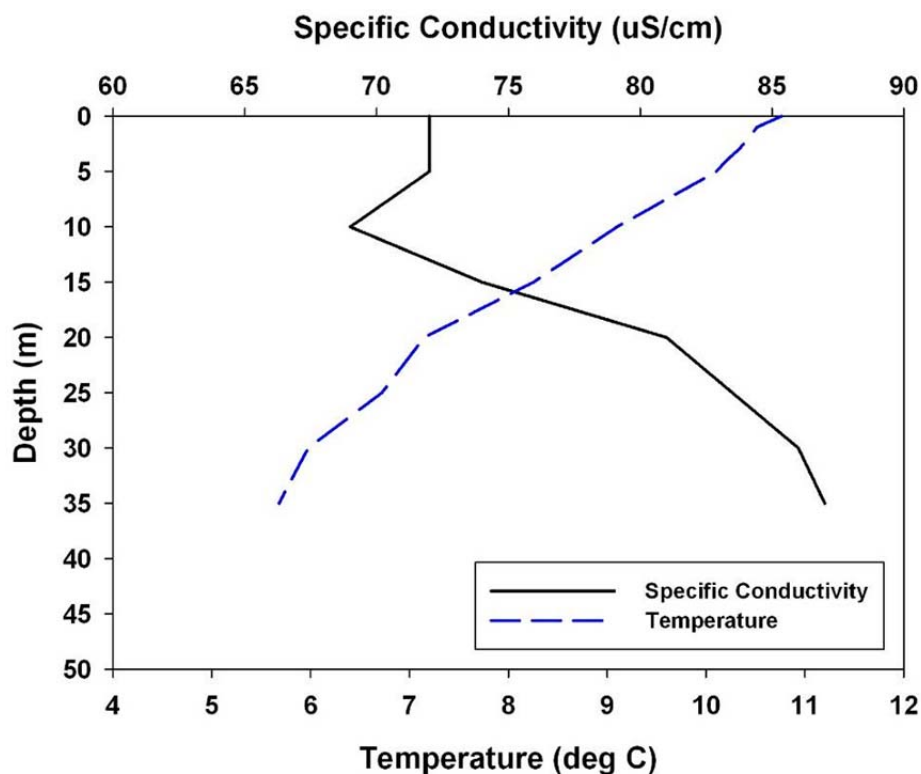


Figure 22. Water temperature and specific conductivity profile for Lachbuna Lake.

Dissolved Oxygen

Dissolved oxygen concentrations and percent saturation were high and near or above saturation levels for all lakes profiled (Tables 4 and 5). Generally speaking, dissolved oxygen profiles were orthograde, common among oligotrophic lakes (Wetzel 2001), where oxygen concentrations increased as water temperature decreased with depth. Past lake profiling measurements on Lake Clark have documented certain sites with super-saturated dissolved oxygen levels (Wilkens 2002, Shearer and Moore 2009) with no clear explanation to the mechanism(s) creating this physical occurrence. Further, in 2009 we observed super-saturated dissolved oxygen levels at several sites where several days prior dissolved oxygen saturation was only slightly above 100% at those same sites (Shearer and Moore 2010). We suggest that a combination of atmospheric conditions, primarily barometric pressure, combined with wind-driven internal circulation results in these super-saturation events. The frequency at which these events occur is unknown and would require a more intensive sampling schedule than our synoptic profiling design can provide.

Water Clarity

Water clarity conditions varied among lake basins primarily in response to the predominant surface runoff sources (Tables 4 and 5). In 2009 we documented the lake-wide effects that volcanic ash from Mt. Redoubt played in reducing water clarity within Lake Clark (Shearer and Moore 2010). In August 2010, approximately 16 months following the Mt. Redoubt eruptions, the turbidity gradient that usually characterizes

Lake Clark (Brabets 2002) was starting to emerge again although not as distinctly as pre-eruption conditions (Figure 22). Water clarity continues to vary widely within Naknek Lake (Figure 23); we observed Secchi depths ranging from 0.41 m in the Iliuk Arm to 9.75 m in the North Arm. Lake Brooks had Secchi depths ranging from 9.29 m to 10.96 m (Table 3). The between year differences observed within the East Basin of Naknek Lake may be a reflection of higher lake levels during the August 2010 sampling period. The East Basin is located down lake of the Iliuk Arm, which receives both glacial and ash-laden runoff. Periods of increased runoff combined with strong southerly / southeasterly winds result in greater mixing in the East Basin as turbid water from the Iliuk Arm moves down lake. In 2009 wind conditions prevented us from making accurate Secchi depth measurements at half the profiling sites in the West Basin (Shearer and Moore 2010). In 2010 we experienced similar wind conditions; however, we were able to hold the boat in position with an anchor. The reduced boat drift allowed for more accurate measurement of Secchi depths and likely explains the difference from 2009 observations.

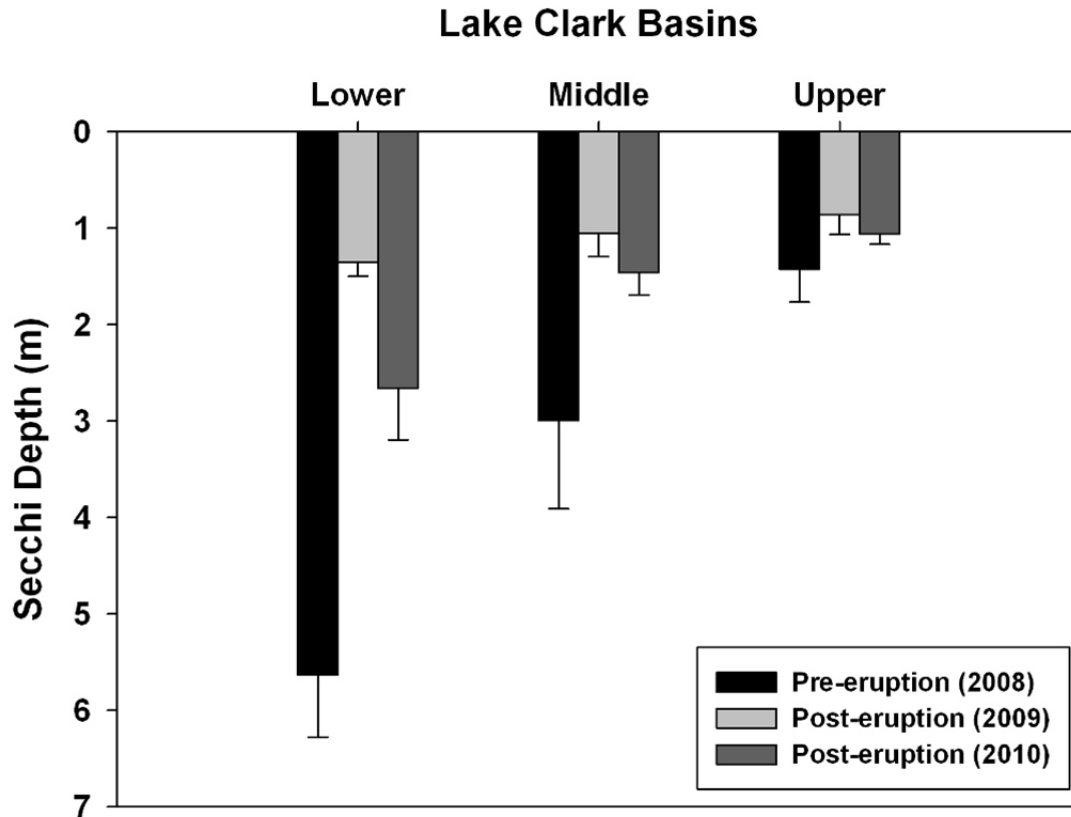


Figure 23. Secchi depths for Lake Clark comparing pre-eruption (2008) and post-eruption (2009 and 2010) water clarity.

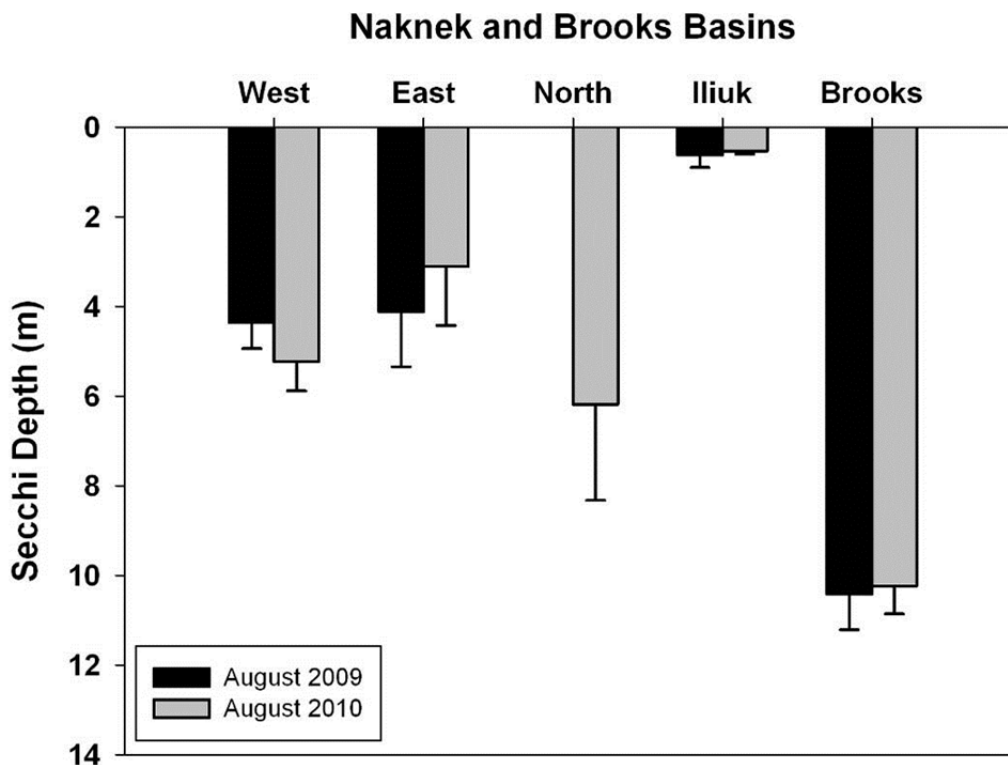


Figure 24. Secchi depths for four basins in Naknek Lake and in Lake Brooks.

Chulitna River and Lake Clark Outlet Continuous Water Quality and Discharge Monitoring

Water quality conditions in the Chulitna River (Table 6) and Lake Clark outlet (Table 7) were relatively stable among sampling periods, except for water temperature. Water temperatures increased as summer progressed, a direct reflection of increased solar radiation. The range between the maximum and minimum for each water quality parameter was relatively small for the Lake Clark outlet. Additionally, reported values were very similar to those conditions observed throughout Lake Clark during vertical lake profiles. This suggests that the Lake Clark outlet may be an integrative reflection of lakewide conditions and thus an ideal monitoring location to capture short-term variability in parameters that is not captured in synoptic lake profile sampling. One exception is that turbidity conditions at the Lake Clark outlet are very clear (Table 7) and do not reflect the turbidity gradient that typically exists within the lake. Instrument failure from early July to mid-August on the Chulitna River resulted in no data being collected during that timeframe, thus preventing a more complete summary of water quality conditions for the sample location.

Table 6. Summary data for core parameters for the Chulitna River.

Parameter	June 8 – July 6	Aug.19 – Sept. 14	Sept. 17 – Oct. 2
Statistic			
Water Temperature (°C)			
Mean	13.23	10.89	7.91
Standard Deviation	1.67	1.02	2.03
Maximum	16.16	13.03	9.89
Minimum	10.42	9.51	4.76
pH (standard units)			
Mean	7.56	7.48	7.46
Standard Deviation	0.10	0.06	0.57
Maximum	7.73	7.56	8.18
Minimum	7.32	7.32	6.60
Specific Conductivity (µS/cm)			
Mean	77	72	77
Standard Deviation	4	4	1
Maximum	83	80	78
Minimum	70	73	76
Dissolved Oxygen (mg/L)			
Mean	10.80	10.66	11.58
Standard Deviation	0.37	0.32	0.45
Maximum	11.40	11.22	12.45
Minimum	10.07	10.01	11.11
Dissolved Oxygen Saturation (%)			
Mean	103.5	96.7	97.5
Standard Deviation	3.3	1.7	1.7
Maximum	108.9	100.1	99.3
Minimum	95.2	94.0	94.1
Turbidity			
Mean	4.1	0.5	1.0
Standard Deviation	3.6	0.4	1.0
Maximum	14.0	1.8	2.6
Minimum	1.2	0.0	0.0
Stage (ft)			
Mean			
Standard Deviation			
Maximum			
Minimum			
Parameter	Greatest Diel Fluctuation*		
	Date	Range	
Water Temperature (°C)	June 21 st	6.62	
pH (standard units)	June 22 nd	0.76	
Specific Conductivity (µS/cm)	June 16 th	4	
Dissolved Oxygen (mg/L)	June 21 st	2.15	
Dissolved Oxygen Saturation (%)	June 21 st	34.2	
Stage (ft)	June 16 th	24.6	

* Based on hourly measurements over a 24-hour period.

Table 7. Summary data for core parameters for the outlet of Lake Clark. Water quality parameters were recorded hourly nearly continuously from June 8 – September 30.

Parameter Statistic	June	July	August	September
Water Temperature (°C)				
Mean	5.24	6.28	9.60	9.51
Standard Deviation	0.49	1.35	1.16	0.46
Maximum	6.07	9.64	11.38	10.20
Minimum	4.27	6.07	6.79	8.12
pH (standard units)				
Mean	7.62	7.64	7.72	7.76
Standard Deviation	0.02	0.06	0.09	0.05
Maximum	7.66	7.75	7.88	7.85
Minimum	7.58	7.54	7.57	7.67
Specific Conductivity (µS/cm)				
Mean	64	63	63	63
Standard Deviation	0	0	0	0
Maximum	64	64	64	64
Minimum	64	63	63	63
Dissolved Oxygen (mg/L)				
Mean	12.70	12.45	11.65	11.62
Standard Deviation	0.08	0.14	0.26	0.09
Maximum	12.82	12.660	12.21	11.80
Minimum	12.56	11.96	11.29	11.43
Dissolved Oxygen Saturation (%)				
Mean	100.9	101.1	102.1	101.6
Standard Deviation	1.3	1.8	1.2	1.5
Maximum	103.1	104.7	104.5	104.3
Minimum	98.4	97.7	100.0	99.2
Turbidity				
Mean	1.3	0.2	0.3	1.3
Standard Deviation	1.0	0.4	0.4	1.2
Maximum	5.1	0.9	1.2	7.1
Minimum	0.7	0.0	0.0	0.0
Stage (ft)				
Mean				
Standard Deviation				
Maximum				
Minimum				
Parameter	Greatest Diel Fluctuation*			
	Date		Range	
Water Temperature (°C)	July 26 th		4.57	
pH (standard units)	July 26 th		0.26	
Specific Conductivity (µS/cm)	multiple dates		1	
Dissolved Oxygen (mg/L)	October 12 th		0.77	
Dissolved Oxygen Saturation (%)	July 26 th		8.22	
Stage (ft)				

* Based on hourly measurements over a 24-hour period.

Estimated discharge measurements from the Lower Chulitna River (SWAN monitoring site) were compared with the Upper Chulitna River (USGS gaging site #15298040) for the open water period (Figure 24). The lower river site is heavily influenced by backwater effects of Lake Clark, especially early in the season when the rising water of Lake Clark moves up into Chulitna Bay, resulting in a hydrograph that mimics Lake Clark (Shearer and Moore 2010). The effect of the regional water deficit early in the season is evident in the upper river hydrograph, whereas the rising limb of the lower river reflects the influx of lake water moving up stream. In addition, the upper river displays a rapid response to precipitation events that is not observed in the lower river. The upper river site is approximately half the width of the lower river site, which is likely a contributing factor to the hydrologic differences that are observed between the two sites.

Four discharge measurements taken at the Lake Clark outlet were plotted on the 2010 open water hydrograph for Lake Clark (Figure 24). These measurements were obtained using the acoustic Doppler current profiler (ADCP) and except for the measurement obtained on August 2, 2010, are well correlated with the rating curve developed by the USGS (Brabets 2002). Additional measurements will be taken next year in an effort to extend the rating curve to low lake levels.

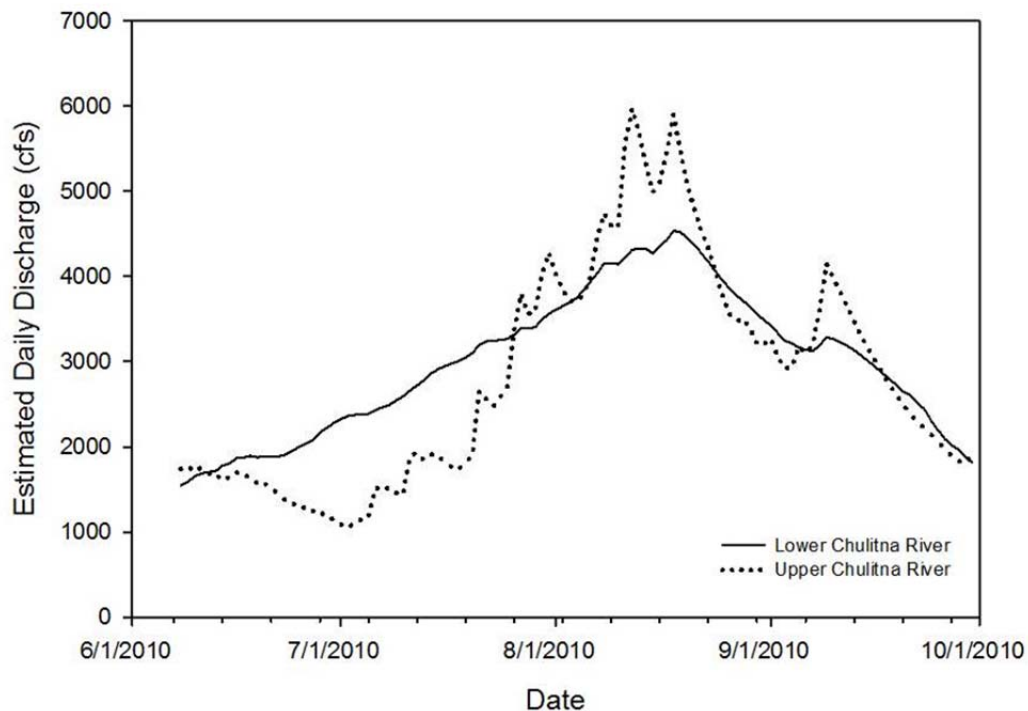


Figure 25. Comparison of the upper and lower Chulitna River gage sites.

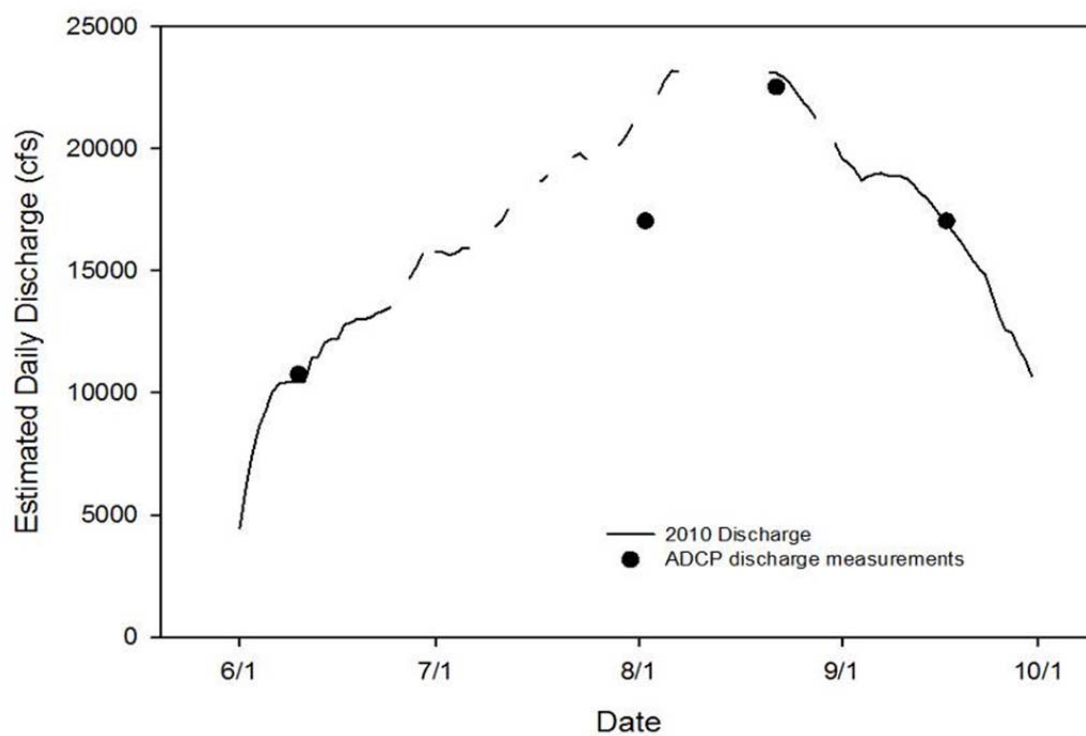


Figure 26. Acoustic Doppler current profiler discharge measurements plotted with the 2010 Lake Clark open water hydrograph. Breaks in the hydrograph indicate days in which data were not collected.

Recommendations and Conclusions

The inclusion of Tier 2 lakes within the water quality sampling schedule in 2010 provided us with an indication of the overall logistical considerations needed to fully complete an entire field season of water quality sampling. All Tier 2 (and Tier 3) lakes are only accessible via float plane and thus sampling these systems requires additional planning and costs typically not considered when sampling Lake Clark or Naknek. The Tier 2 lakes sampled in 2010 all had a boat (but no motor) available for transport on the lake which reduced the number of flights needed to transport staff and sampling equipment to study lakes. Generally speaking, a Cessna 206 float plane (approximate 800 lb. payload) is sufficient to transport two field crew members, a boat motor, and sampling equipment to and between lakes. If the field crew must transport an inflatable raft, either two flights with a Cessna 206 or one flight with a Dehavilland Beaver float plane (approximate 1,200 lb. payload) would be required. Both options result in increased operational costs. In 2011 we anticipate sampling the same Tier 2 lakes as we sampled in 2010 and thus operational costs should be similar. It is important to note that while budgetary constraints are an important aspect to consider in program operation, we will continue to place crew safety above all other considerations. Therefore, unforeseen expenses may occur as field trips are cancelled or rescheduled due to weather restrictions, thus adding to operational costs. Previous field season expenses will only provide an approximation of future operational costs.

We attempted to monitor river stage, water temperature, and specific conductivity in Exit Creek (KEFJ) with a non-vented pressure transducer; however, the instrument became detached from its anchor and buried in sediment resulting in unusable data. This incident mirrors similar experiences we have had in previous attempts to collect continuous water quality and hydrology data for Exit Creek. The dynamic nature of this glacial stream makes instrument deployment and recovery challenging. Additionally, the cost of lost and damaged equipment may not be worth the benefit of the data acquired. Though our original intent was to collect stage and discharge data to develop a stage / discharge rating curve for this stream, we have been unable to measure discharge at all but the lowest flows due to swift currents during mid-summer flows. Without adequate discharge data, a rating curve cannot be developed. We will continue to work with KEFJ staff and discuss other options for long-term monitoring that require less dependence on instream instrument deployment. One possible alternative may be the use of time-lapse photography of the Exit Creek stream corridor that displays the progression and timing of glacial melting, stream rise, peak flows, and freeze events. Similar time-lapse systems are being used by SWAN to record phenology of different vegetation zones.

Our monitoring design places a great deal of emphasis on using automated data loggers to record environmental conditions. This practice is especially advantageous in remote settings where repeated access to sample sites by field crews is costly and logistically challenging. However, this practice presents the challenge of securely deploying and leaving data loggers unattended in a dynamic environment subject to potential debris flows, sedimentation, and freeze / thaw cycles. Data loggers also must be recovered at a later time for data downloading and maintenance prior to data analysis and reporting.

Our inability to relocate the lower Lake Clark temperature array in 2010 is an example of the inherent risks associated with deploying automated data loggers in these environments. The loss of data loggers is costly from two perspectives: 1) data are lost, inhibiting our ability to synthesize data and report on environmental observations, and 2) loggers must be replaced adding to the operational costs of monitoring.

The testing and use of an acoustic Doppler current profiler in 2010 revealed a promising method for measuring river discharge at non-wadeable sites. This technology proved much more user-friendly and logistically easier compared to our previous method of using a Price AA current meter. Ideally, boats set up with a Price AA current meter are tethered to a taut cable that spans the river channel, thus anchoring the boat as water velocity is measured. Wide river reaches prevent us from using a tethered cable at our discharge measurement sites. The boat is held in position by the boat operator, who uses the motor to actively maintain position. This method introduces a great deal of error and variability into the data. The acoustic Doppler current profiler uses sonar technology and operates from a moving platform, eliminating the need to maintain position during measurements, greatly improving measurement accuracy.

To date we have maintained an excellent safety record while conducting monitoring activities in the field. However, the wilderness setting and inherent hazards associated with operating on large lake systems requires us to continually seek new and improved methods for safe field activities as well as continually re-evaluate current procedures. We will continue to work with experienced park staff to gain additional knowledge and expertise in operating a variety of watercraft to navigate lake and riverine systems. In the past our park dispatch check-ins / updates have varied depending on park requirements and situational needs. In 2011 we will explore additional methods to allow field crews to update park dispatch on location and status on a more frequent basis.

Since 2009 we have summarized water quality and surface hydrology data together in the same annual summary reports. However, in the interest of keeping these reports useful to park staff and not overly burdensome to report authors, we anticipate separating water quality and surface hydrology data in subsequent reports, especially as monitoring efforts expand. We anticipate reporting on water quality data in odd years (e.g., 2011 field season, 2013 field season, etc) and surface hydrology data in even years (e.g., 2012 field season, 2014 field season, etc). Each report will summarize data from the previous two field seasons. For example, the 2013 water quality annual summary report will present data from the 2012 and 2013 field seasons. We anticipate that five year synthesis reports will provide a comprehensive analysis of water quality and surface hydrology data together within the same report, especially since these two vital signs are integrally linked in terms of watershed dynamics.

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