



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

2008 Annual Summary Report

Natural Resource Technical Report NPS/SWAN/NRTR—2009/199



ON THE COVER

Neacola River confluence with Kenibuna Lake in Lake Clark National Park and Preserve.
Photograph by: Jeff Shearer, Southwest Alaska Network

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Jeff Shearer
Claudette Moore

National Park Service
Southwest Alaska Network
240 W. 5th Ave.
Anchorage, AK 99501

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Abstract

The Southwest Alaska Inventory and Monitoring Network monitors freshwater systems in five national park units: Alagnak Wild River, Aniakchak National Monument and Preserve, Katmai National Park and Preserve, Kenai Fjords National Park, and Lake Clark National Park and Preserve. To date, most of our efforts have focused on protocol testing for water quality monitoring on Lake Clark and hydrologic monitoring on Naknek and Brooks Lakes.

In 2008, 30 randomly selected, spatially balanced lake profile sites on Lake Clark were measured monthly from June through August between the surface and 50 m for water temperature, pH, specific conductivity, dissolved oxygen, and water clarity. Water quality parameters were stable between sites and months throughout the lake although water clarity decreased with proximity to glacial tributaries and as summer progressed, reflecting increased glacial melting due to increased air temperatures and solar radiation. Continuous water temperature monitoring in Lake Clark has been ongoing since September 2006. Water temperature data depict summer stratification and reverse stratification during winter, but there have been no indications of thermocline development. Water temperature monitoring was expanded to Naknek Lake in August 2008 but data were not available for analysis during the preparation of this report.

Water level and discharge measurements were continued on Naknek and Brooks Lakes in 2008. 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 while discharge measurements were used to refine rating curves. Continuous water quality and water level monitoring was conducted on Exit Creek from June 9, 2008 to September 30, 2008 to examine natural variation in water quality parameters due to diel glacial melting. Little variation in water quality parameters was observed that could be attributed directly to diel glacial melting. Early to mid-September precipitation events, and subsequent increased stream flow, was responsible for much of the variation observed within the data set.

Monitoring in 2009 will focus on incorporating water chemistry analytical methods and tributary monitoring with lake profile and continuous water temperature monitoring to develop a more comprehensive approach to examine large freshwater flow systems (e.g. large lakes and their corresponding components – tributaries, outlets, and contributing lakes).

Acknowledgements

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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) and quantify seasonal hydrograph changes during the ice-free season.

Much of the water quality monitoring efforts have focused on Lake Clark, LACL while hydrologic monitoring has taken place primarily on Naknek and Brooks Lakes, KATM. Additionally, protocol testing for continuous deployment of multi-parameter sondes was conducted in Exit Creek, KEFJ. Though 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. This report will discuss the results of the 2008 protocol testing efforts as well as summarize water temperature data from the past several years.

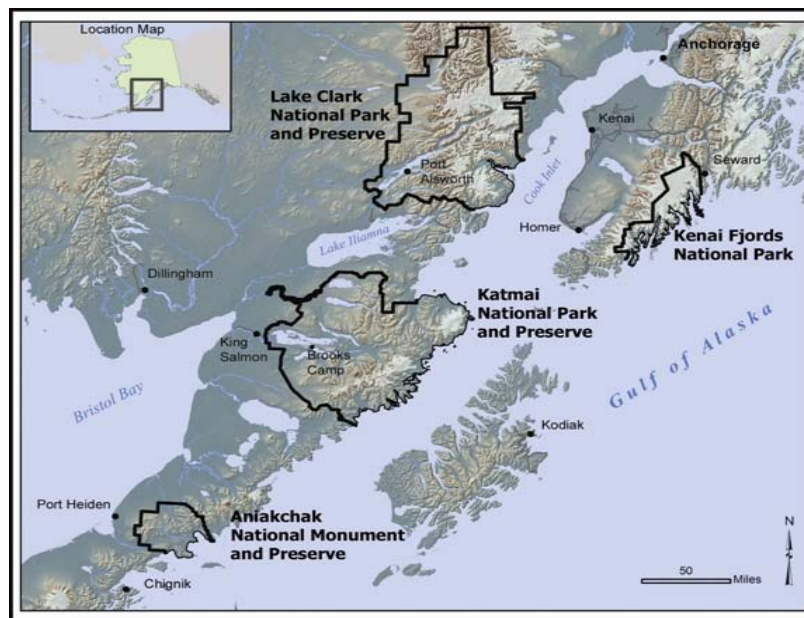


Figure 1. National Park units included in the Southwest Alaska Inventory and Monitoring Network.

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). Lakes Clark and Kontrashibuna in LACL, Naknek and Brooks Lakes in KATM, and Exit Creek in KEFJ were all identified as high priority (Tier 1) water bodies for monitoring. No SWAN monitoring took place on Lake Kontrashibuna in 2008 and this lake will not be discussed further in this report.

Lake Clark (Figure 2) is located within the Kvichak River drainage in southwest Alaska and is among the largest lakes (313 km²) in the National Park system. 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).

Naknek and Brooks Lakes (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 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. Brooks Lake is a major lake within the Naknek system, flowing into the East Basin of Naknek Lake via the Brooks River. Brooks Lake 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.

Field Methods

Water quality sampling focused on protocol testing for vertical lake profiles and continuous multi-parameter sonde deployment. Yellow Springs Incorporated (YSI) multi-parameter sondes were used for all water quality measurements. A series of calibrations and error checks for temperature, dissolved oxygen, pH, and specific

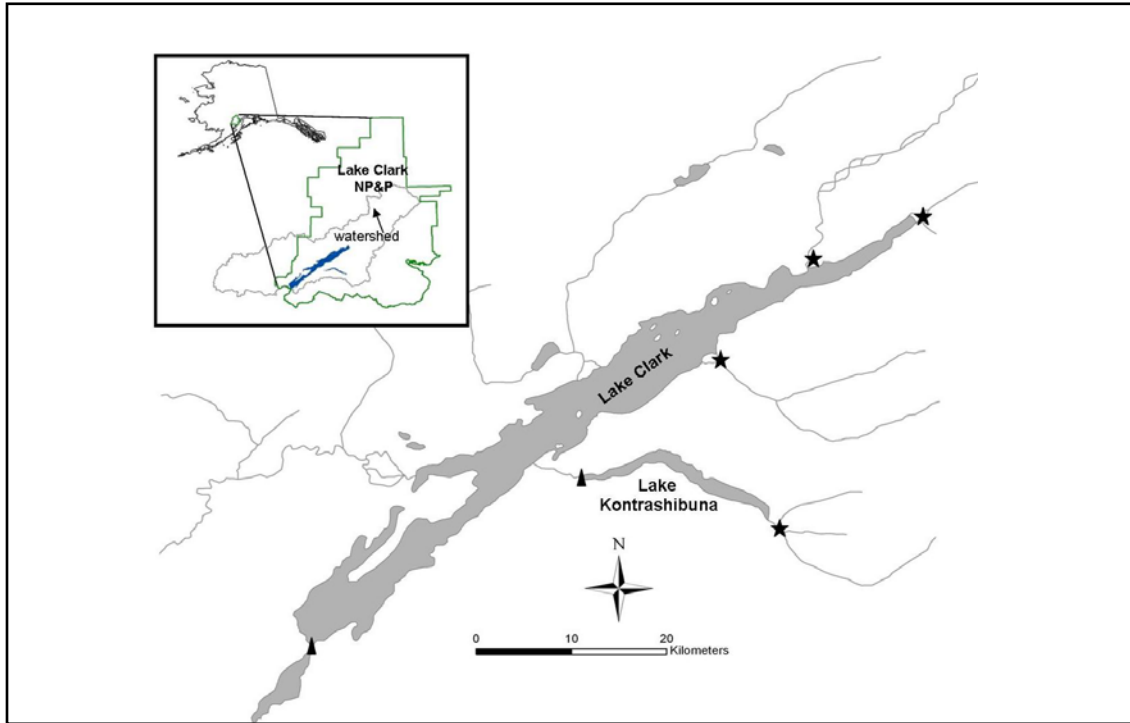


Figure 2. Lakes Clark and Kontrashibuna including major tributaries in LACL. Glacial tributaries (star) and lake outlets (triangle) are denoted as well.

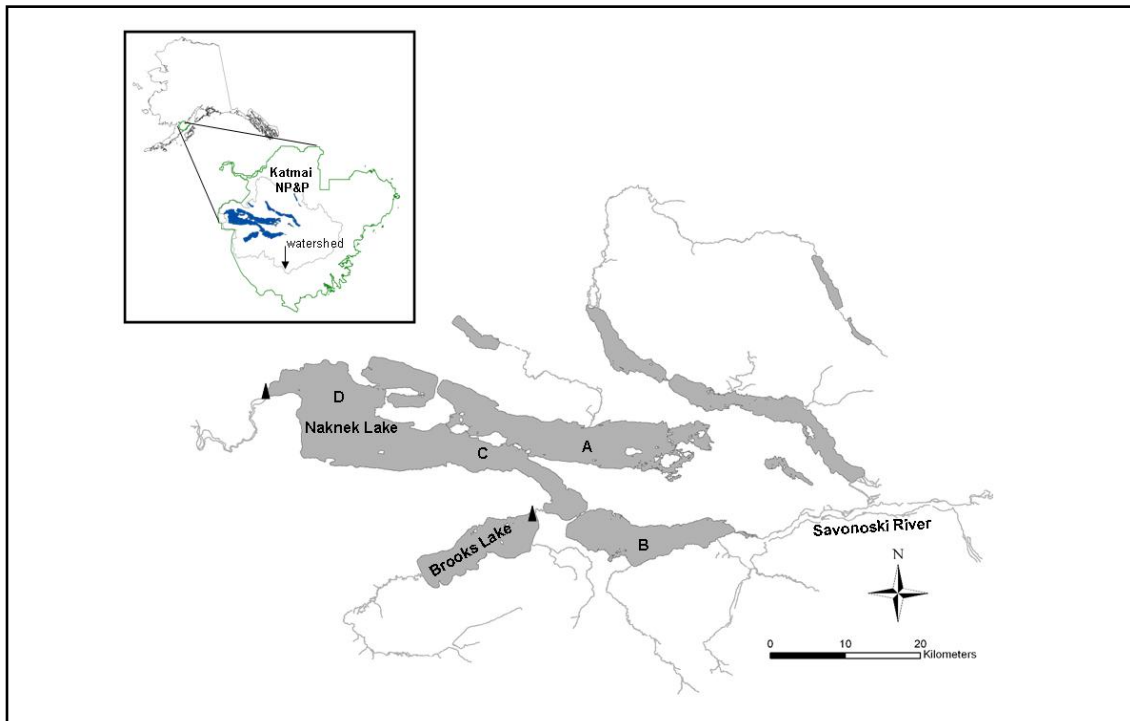


Figure 3. Naknek and Brooks Lakes including major tributaries in KATM. Naknek Lake basins include the North Arm (A), Iliuk Arm (B), East Basin (C), and West Basin (D). Lake outlets denoted with a triangle.

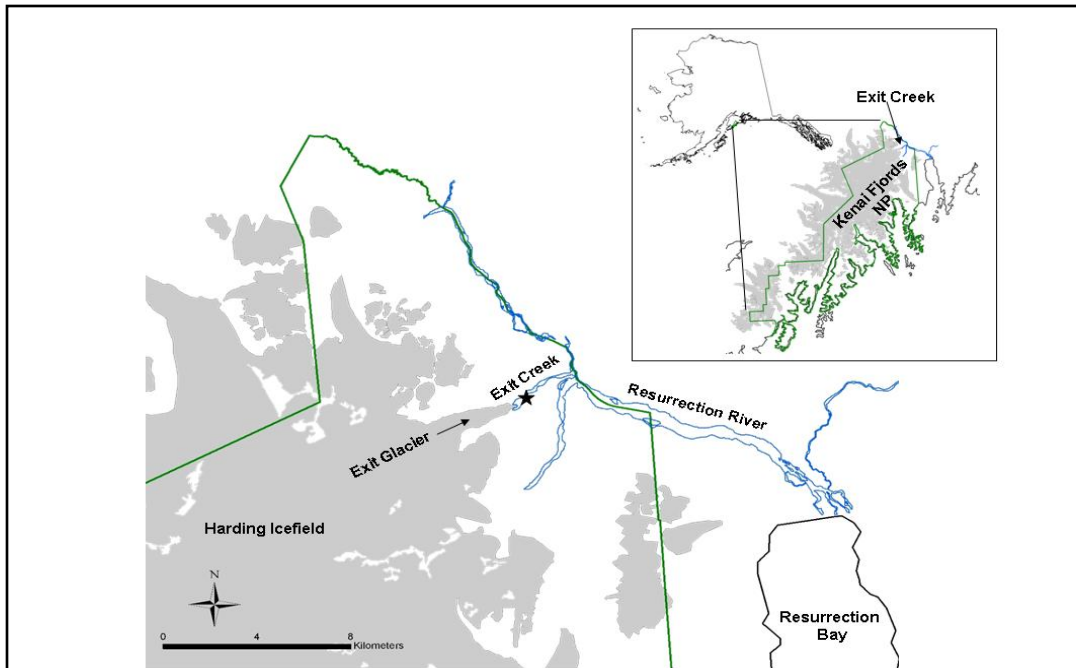


Figure 4. Exit Creek area in KEFJ. Study site is denoted with a star. Gray areas represent glacial ice cover.

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 to evaluate sensor drift.

Lake temperature was monitored continuously 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 meter to 100 m, then every 20 meters to the bottom. Onset HOBO Water Temp Pro thermistors were used to depths less than 120 m while Onset Stowaway TidBit thermistors are used at depths below 120 m. During summer months, a surface buoy with a thermistor was attached to the moored array so that surface temperature can be recorded. Data were downloaded twice annually (once in late May / early June and once in late September).

Continuous water level measurements were taken with In-Situ Level Troll pressure transducers on the outlets of Brooks and Naknek Lakes. These two locations are among the sites the U.S. Geological Survey Water Resources Division developed stage / discharge rating curves for SWAN in 2007. Additionally, a Solinst Levellogger pressure transducer 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 for post-deployment correction of water level readings for atmospheric pressure.

Vertical lake profiles were measured monthly on Lake Clark from June through August. The lake was divided into three basins (upper, middle and lower) to consider the affects of the turbidity gradient. Sampling was conducted at general random tessellation

stratified (GRTS) points on the three lake basins (Figure 5). 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. We sampled 10 sites in each basin of the lake. We used a YSI 600QS multi-parameter sonde to collect water temperature (°C), pH (unitless), dissolved oxygen (mg/L and % saturation), and specific conductivity (µS/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 a 1-minute interval on the descent and ascent 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.

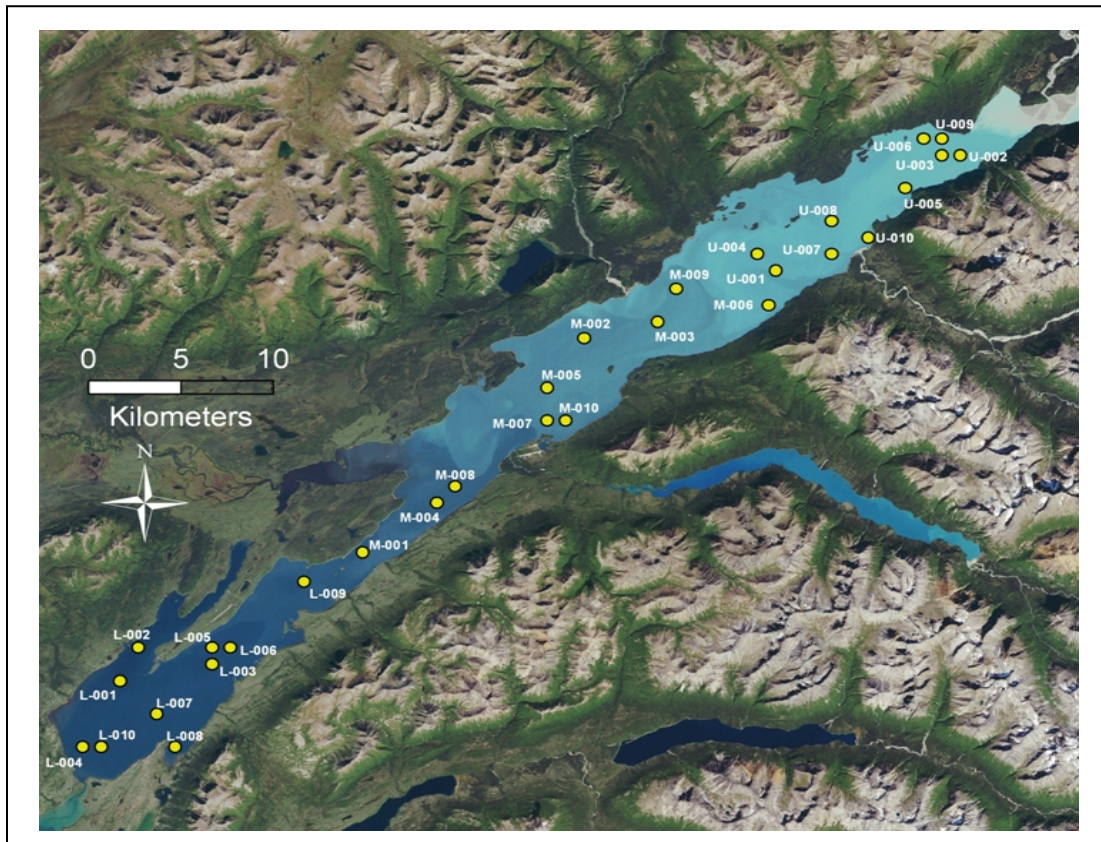


Figure 5. GRTS sample locations on Lake Clark where vertical lake profiles were measured. Note longitudinal turbidity gradient.

Continuous monitoring of core parameters was conducted on Exit Creek from June through September using a YSI 6600V2 multi-parameter sonde with optical dissolved oxygen and turbidity sensors. The sonde was placed inside a polyvinyl chloride pipe housing which was then attached to a concrete block (approximate weight 45 kg) and placed in the channel thalweg. The sonde was programmed to measure core parameters, including turbidity (NTU), on a 1-hour interval. Periodic in-situ readings were taken with a calibrated YSI 600QS multi-parameter sonde to provide an independent data set to correct for sensor drift on the continuous deployment sonde.

Results and Discussion

Lake Clark Water Temperature

Water temperature in Lake Clark has been continuously monitored since September 2006 (Table 1). Maximum average daily temperatures were higher for summer months in 2007 than 2008 although minimum average daily temperatures were similar for winter months in both years. Monthly degree days (MDD) also show warmer summer temperatures in 2007 than 2008. For example, 403 and 292 degree days were recorded for August and September 2007, respectively, compared to 378 and 190 degree days recorded for August and September 2008. Although no thermocline (herein defined as a change of ≥ 1 °C per meter depth) has been observed within the dataset, Lake Clark does show patterns of summer stratification (Figure 6 and 7). Additionally, inverse stratification occurred from late December through mid-April both years along with two periods of isothermy (uniform temperature throughout the water column) from November through early December and in May. During limnological studies of Lake Clark, Chamberlain (1989) and Wilkins (2002) both reported similar patterns to those described above. Chamberlain (1989) reported a maximum temperature of 13 °C and a minimum temperature of 0 °C, similar to the 13.7 °C (maximum) and 0.7 °C (minimum) reported by Wilkins (2002). Based on mixing patterns and seasonal presence of ice cover, Lake Clark is best classified as a discontinuous cold polymictic lake. Lewis (1983) defines discontinuous cold polymictic lakes as ice-covered part of the year, ice-free above 4°C and stratified during the warm season for periods of several days to weeks, but with irregular interruption by mixing. Other large lakes in southwest Alaska share this classification as frequent storms with strong winds result in deep mixing of waters (LaPerriere 1997).

Naknek and Brooks Lakes Discharge

Lake discharge was estimated for Naknek and Brooks Lakes based on stage / discharge rating curves developed by the U.S. Geological Survey Water Resources Division (Table 2). Naknek Lake discharge was considerably higher in the summer of 2006 than 2007 with 2006 minimum discharge exceeding 2007 maximum discharge for each respective month (Figure 8, Table 2). Brooks Lake displayed a similar trend except for the month of July where flows were similar between 2006 and 2007 (Figure 9, Table 2). Peak estimated discharge for Naknek Lake occurred on October 17, 2006 and October 4, 2007. The peak 7-day average (based on a moving average) occurred approximately during the same time for both years as well: October 12-18, 2006 and October 6-12, 2007 (Table 2).

Table 1. Summary of water temperature data for Lake Clark between September 1, 2006 and September 24, 2008. Analyses based on data collected at five meter depth interval.

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		
	2006	2007	2008	2006	2007	2008	2006	2007	2008
January		0.7 (0.1)	2.7 (0.0)		< 0.1 (0.0)	0.1 (0.0)		8	22
February		1.9 (0.1)	1.1 (0.1)		0.7 (0.1)	0.1 (0.0)		38	14
March		2.4 (0.0)	1.5 (0.1)		1.4 (0.2)	0.6 (0.1)		65	37
April		3.4 (0.5)	2.3 (0.1)		2.0 (0.1)	1.2 (0.3)		83	56
May		4.3 (0.1)	3.7 (0.1)		3.0 (0.2)	1.8 (0.3)		108	92
June		9.9 (0.5)	8.4 (0.9)		4.0 (0.0)	3.6 (0.0)		204	155
July		15.0 (0.9)	11.0 (0.5)		8.9 (0.3)	7.2 (0.3)		395	285
August		15.9 (0.4)	13.5 (0.5)		10.3 (1.2)	10.5 (0.3)		403	378
September ⁵	11.1 (0.1)	13.5 (0.3)	10.2 (0.2)	7.7 (0.4)	7.9 (0.5)	6.4 (0.6)	276	292	190
October	7.5 (0.2)	8.1 (0.1)		5.8 (0.0)	5.5 (0.0)		205	204	
November	5.7 (0.0)	5.6 (0.0)		3.8 (0.0)	4.5 (0.0)		141	148	
December	3.8 (0.0)	4.4 (0.0)		0.5 (0.1)	2.5 (0.1)		79	116	
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	13.4 (0.2)		Aug. 22 nd - 29 th	13.0 (0.5)				

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 2008 results based on September 1st – September 24th dataset; full month dataset not available at time of analysis.

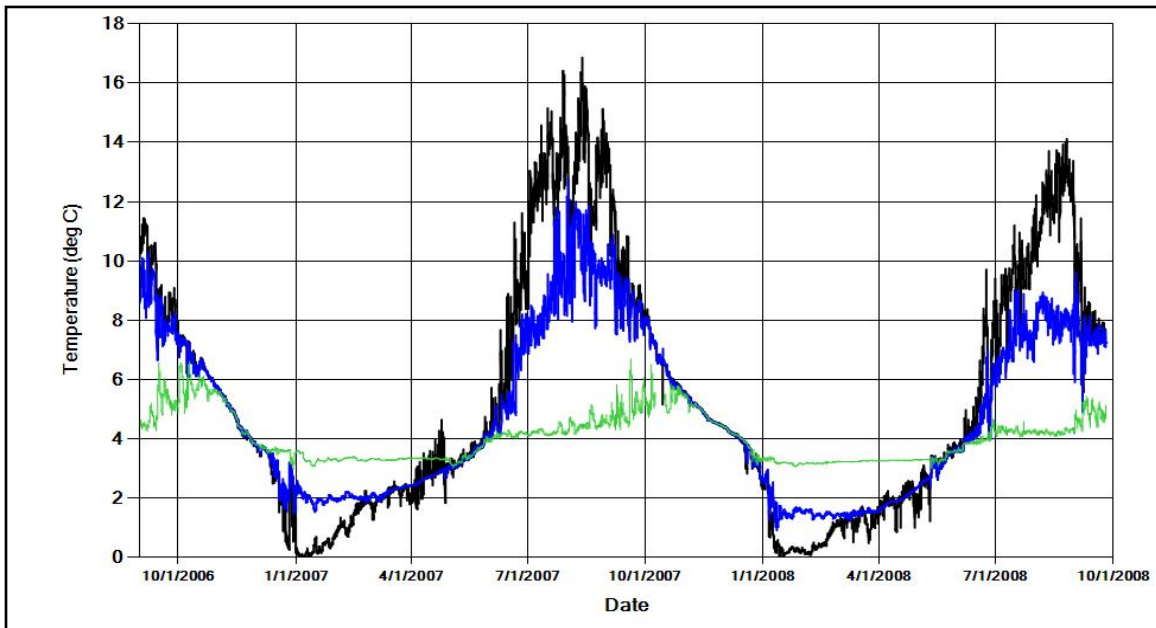


Figure 6. Water temperature data for Lake Clark between September 1, 2006 and September 24, 2008. Data from 5 m (black), 20 m (blue), and 100 m (green) depth intervals.

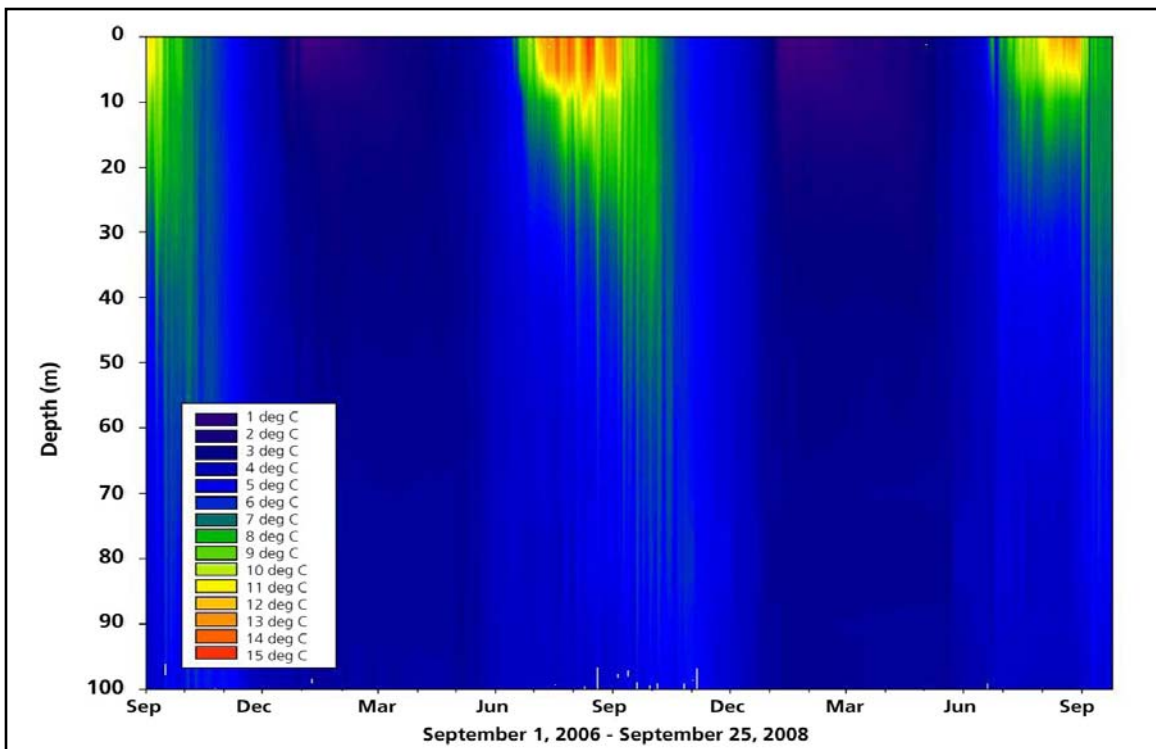


Figure 7. Lake Clark isotherm displaying patterns of summer stratification.

Table 2. Summary of estimated lake discharge (Q) data for Naknek and Brooks Lakes during ice-free period in 2006 and 2007.

Month	Avg. Monthly Q mean (1 SD); cfs ¹		Max. Monthly Q cfs		Min. Monthly Q cfs	
	2006	2007	2006	2007	2006	2007
Brooks Lake						
May		343 (21)		398		321
June	743 (54)	414 (57)	859	525	663	363
July	470 (83)	445 (52)	638	512	357	348
August	761 (134)	343 (25)	892	387	478	278
September ²	725 (81)	456 (40)	871	551	611	373
Naknek Lake						
May		4,671 (542)		5,753		3,948
June	9,220 (1,369)	6,817 (749)	10,638	8,142	5,624	5,610
July	11,415 (313)	8,923 (327)	11,843	9,395	10,724	8,226
August	12,098 (210)	9,924 (302)	12,338	10,505	11,685	9,424
September	12,244 (91)	10,438 (166)	12,417	10,752	12,052	10,191
October	12,699 (450)	10,650 (325)	13,426	11,072	11,836	9,722
Year	Peak Q date	Peak Q cfs	Peak 7-day Avg. Q dates	Peak 7-day Avg. Q mean (1 SD); cfs		
Brooks Lake						
2006	August 28 th	892	Aug. 26 th – Sept. 1 st	871 (14)		
2007	September 20 th	551	June 26 th – July 2 nd	517 (8)		
Naknek Lake						
2006	October 17 th	13,426	Oct. 12 th – Oct. 18 th	13,242 (153)		
2007	October 4 th	11,072	Oct. 6 th – Oct. 12 th	10,982 (47)		

¹ cfs = cubic feet per second² Based on September 1, 2006 – September 26, 2006 time period.

Peak estimated discharge for Brooks Lake was more erratic, occurring on August 28th and September 20th for 2006 and 2007 respectively with the peak 7-day average occurring between August 26 – September 1, 2006 and June 26 – July 2, 2007 (Table 2). The relatively rapid rise of the Naknek Lake discharge in early summer followed by a period of gradually increasing discharge through September (Figure 8) is a reflection of spring snowmelt coupled with summer precipitation that result in peak lake levels, and subsequently discharge, in early fall. The Brooks Lake hydrograph (Figure 9), however, reflects a different flow regime marked by a late spring / early summer peak due to snow melt and a late summer / early fall peak due to precipitation. Naknek Lake receives both glacial meltwater and non-glacial surface runoff whereas Brooks Lake only receives precipitation, and snowmelt to a lesser extent (Kozlowski 2007). Glacial melt increases throughout the summer months with increasing solar radiation, resulting in stage peaks that occur later in summer than systems driven exclusively by snowmelt and precipitation. Multiple large lakes drain into Naknek Lake, including Grosvenor (73 km² surface area) and Coville (31 km² surface area) Lakes. All of these lakes serve as “control points” that dampen flood events upstream in the watershed, resulting in a prolonged, less-erratic release of water into Naknek Lake downstream. Brooks Lake has no other contributing lake basins within its watershed, and thus flows into and out of the lake are likely subject to more immediate responses to localized precipitation events.

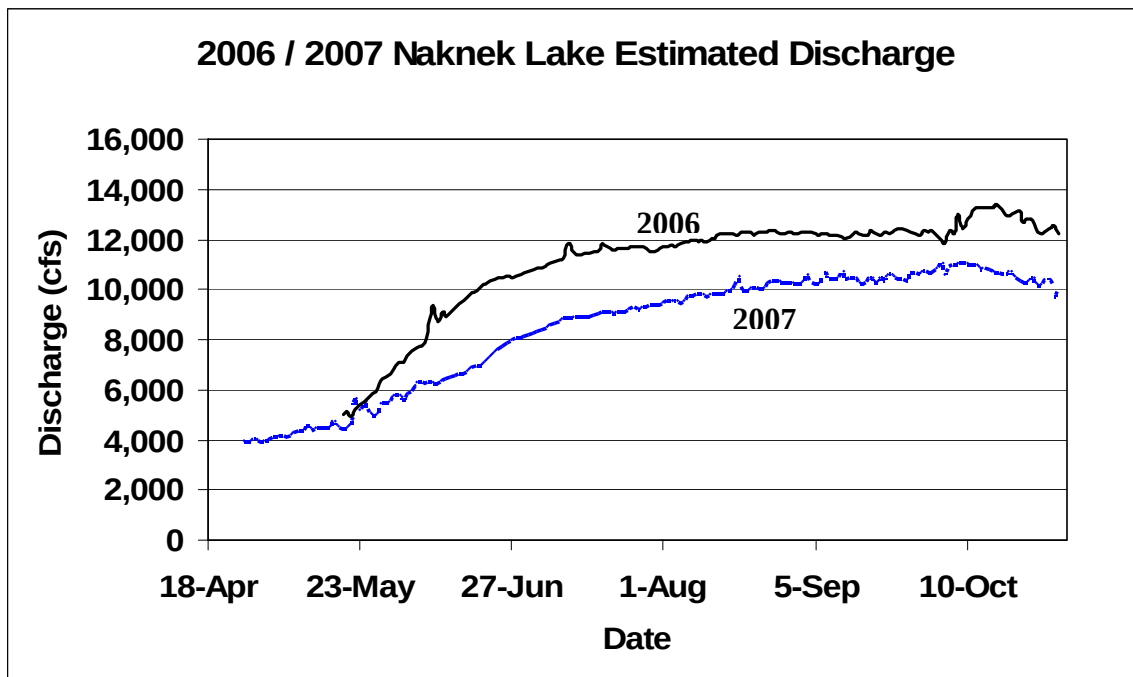


Figure 8. Estimated discharge for Naknek Lake for 2006 (black) and 2007 (blue).

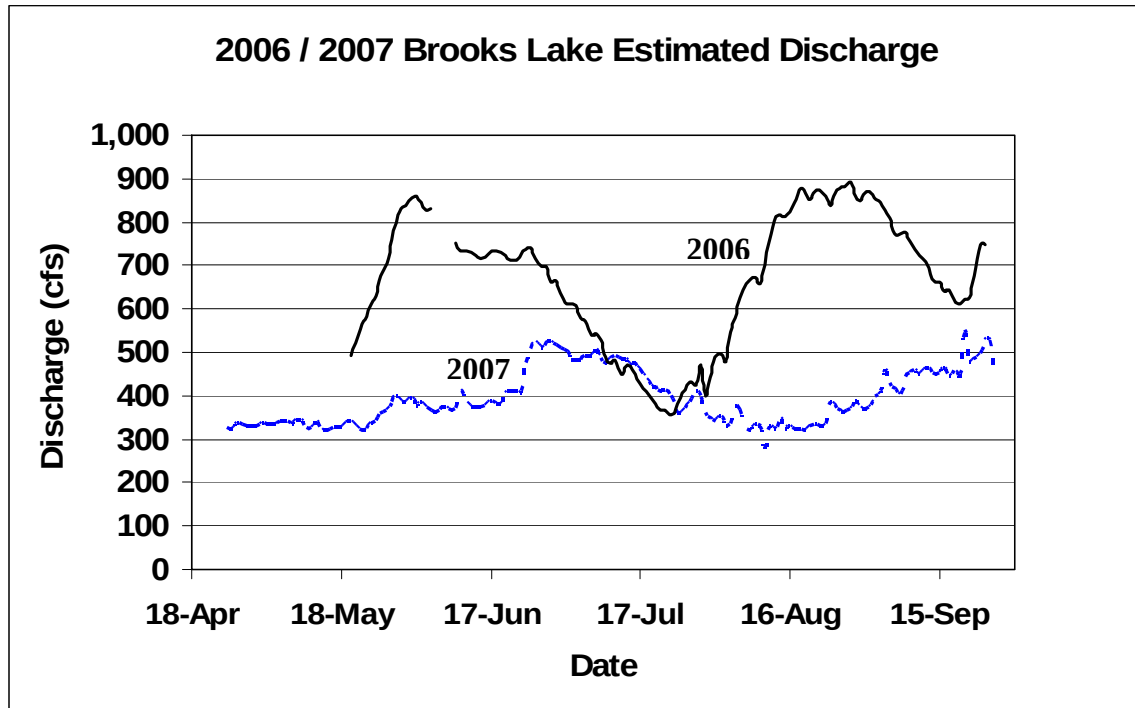


Figure 9. Estimated discharge for Brooks Lake for 2006 (black) and 2007 (blue).

Lake Clark Vertical Lake Profiles

Table 3 provides a statistical summary of core parameters averaged across sites within each portion of the lake for each month. Summary results for each parameter are discussed individually below.

Water Temperature

Water temperature displayed a larger degree of variation between basins of the lake and months compared to other parameters measured, ranging between an average of 5.22 °C in the middle basin in June and an average of 11.67 °C in the lower basin in August (Table 3). Although we collected lake profiles throughout the entire lake, no thermocline was detected along any profile during any month, even at site U-004 in the upper basin of the lake during August which displayed the greatest temperature range (14.15 °C at the surface to 5.14 °C at 50 m) of any recorded profile (Figure 10). Previous limnological studies on Lake Clark (Chamberlain 1989 and Wilkins 2002) reported similar temperature ranges, although Chamberlain (1989) did report a weak thermocline developing briefly in July. In their analysis of thermal regimes for 60 subarctic, Alaskan lakes, Edmundson and Mazumder (2002) indicate that water temperature should remain relatively uniform as relative depth changes for glacial lakes in comparison to clear lakes that should display a more distinct separation of epilimnion, metalimnion, and hypolimnion layers over a range of relative depth. They reason that the high surface reflectance of glacial silt in conjunction with cold, turbid meltwater entering the basin at depth counteracts heat accumulation. However, we did not observe this pattern in the

Table 3. Summary data for core parameters collected at vertical lake profile sites on Lake Clark for 2008. Values represent the median between all depth intervals at a site averaged across all sites within that lake basin for each month.

Parameter Statistic	Upper Basin	June Middle Basin	Lower Basin	Upper Basin	July Middle Basin	Lower* Basin	Upper Basin	August Middle Basin	Lower Basin
Water Temperature (°C)									
Mean	5.88	5.22	5.83	9.07	8.60		10.97	10.79	11.67
Standard Deviation	0.90	0.92	1.19	0.24	0.75		0.98	0.79	1.60
Maximum	11.11	9.20	10.21	12.70	11.16		14.15	14.07	13.52
Minimum	4.04	3.90	4.15	4.72	4.79		5.12	5.04	4.76
pH (standard units)									
Mean	6.98	7.31	7.33	7.35	7.52		7.42	7.44	7.63
Standard Deviation	0.15	0.04	0.06	0.03	0.09		0.06	0.04	0.10
Maximum	7.45	7.40	7.52	7.55	7.68		7.63	7.76	7.77
Minimum	6.85	7.00	7.18	7.22	7.26		7.26	7.20	7.37
Specific Conductivity (µS/cm)									
Mean	63.0	62.6	61.8	62.4	62.2		61.5	62.6	62.1
Standard Deviation	0.4	1.4	0.6	0.6	0.4		0.7	0.5	0.3
Maximum	64.0	66.0	64.0	64.0	64.5		63.5	64.0	64.5
Minimum	59.5	53.0	60.5	58.5	49.0		55.0	59.0	62.0
Dissolved Oxygen (mg/L)									
Mean	13.11	13.66	13.31	11.82	13.75		11.70	11.71	11.91
Standard Deviation	0.12	0.56	0.14	0.33	1.11		0.23	0.26	0.41
Maximum	13.48	14.30	13.50	12.47	16.30		13.29	13.28	13.54
Minimum	12.27	11.60	12.39	11.53	11.93		11.00	10.82	11.28
Dissolved Oxygen (% Sat)									
Mean	105.4	107.7	106.7	103.1	117.7		106.0	105.7	109.0
Standard Deviation	1.3	4.9	2.1	3.2	8.6		0.2	1.0	0.8
Maximum	114.3	116.2	111.4	106.9	133.7		107.2	109.1	112.1
Minimum	100.6	88.0	99.4	97.0	101.8		104.3	95.6	103.8
Secchi Depth (m)									
Mean	2.76	5.82	6.86	2.35	3.83		1.43	3.00	5.63
Standard Deviation	1.21	1.07	0.62	1.37	0.86		0.35	0.91	0.65
Maximum	5.08	7.09	7.85	3.87	5.25		1.96	4.37	6.39
Minimum	1.36	3.78	6.02	1.00	2.69		1.03	1.86	4.59

* Lower portion of lake not sampled in July.

glacially influenced upper basin of Lake Clark. When we compare a relatively clear water site in the lower basin (site L-010; 5.67 m Secchi depth; 50.7 km to nearest glacial tributary) with a glacially turbid site in the upper basin (site U-002; 1.14 m Secchi depth; 5.7 km to nearest glacial tributary) the temperature profiles display nearly identical patterns, albeit the glacially influenced site has slightly warmer water at depth (Figure 11). One possible explanation for this observed pattern is that wind mixing and internal circulation within Lake Clark may be substantial enough to create relatively uniform conditions between lake basins.

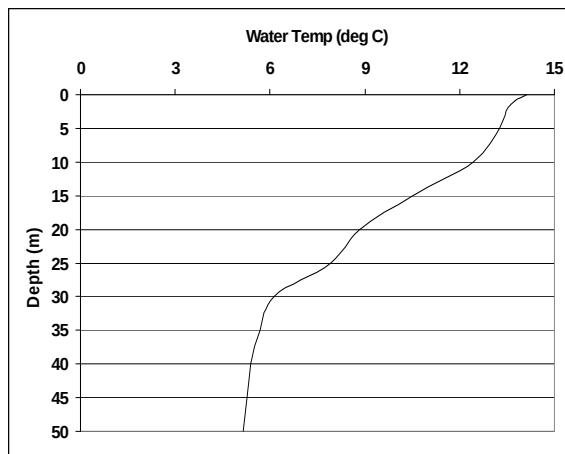


Figure 10. Temperature profile for site U-004 in August on Lake Clark.

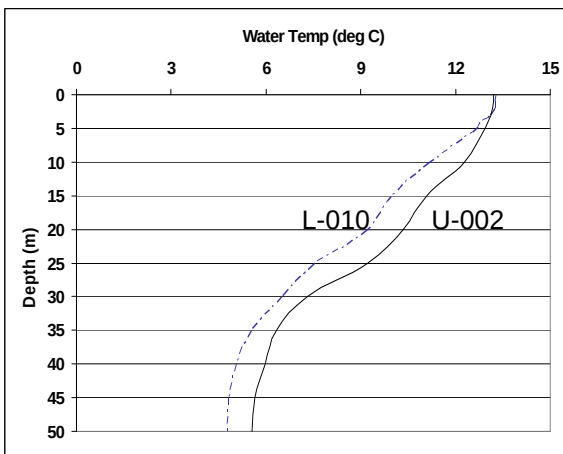


Figure 11. Water temperature profiles for two sites on Lake Clark in August.

pH

pH was relatively stable between basins and months ranging from an average of 6.98 in the upper basin in June to an average of 7.63 in the lower basin in August (Table 3). The greatest vertical range in pH was observed in August in the middle basin at site M-007 with a value of 7.76 at the surface and 7.30 at 50 m. pH displayed a slight increasing trend among basins as summer progressed. This pattern is most likely explained by the photosynthetic depletion of dissolved carbon dioxide in the euphotic zone, thus slightly reducing the amount of carbonic acid in water (Wetzel 2001). Wilkins (2002) made the same conclusion based on similar observations.

Specific Conductivity

Similar to pH, specific conductivity remained stable between basins and months (Table 3). Even along depth gradients, specific conductivity only deviated by 1 or 2 $\mu\text{S}/\text{cm}$ off the basin average for that month for most sites. An exception to this observation was for several sites in the upper basin in August where there appeared to be a lens of water with lower conductance between 10 and 30 m (see Figure 12 as an example). Glacial meltwater entering the upper basin from the nearby Tlikakila River is the most likely explanation for this observation. Brabets (2002) reported specific conductance and water temperature values for the Tlikakila River of 32 $\mu\text{S}/\text{cm}$ and 7.0 °C for August 1999 and 44 $\mu\text{S}/\text{cm}$ and 5.0 °C for August 2000. The higher density of the colder water from the glacial Tlikakila River would sink below the warmer surface waters of Lake Clark as

meltwater enters the basin (Figure 13), creating a lens of water with slightly lower conductance that underlies higher conductance surface waters.

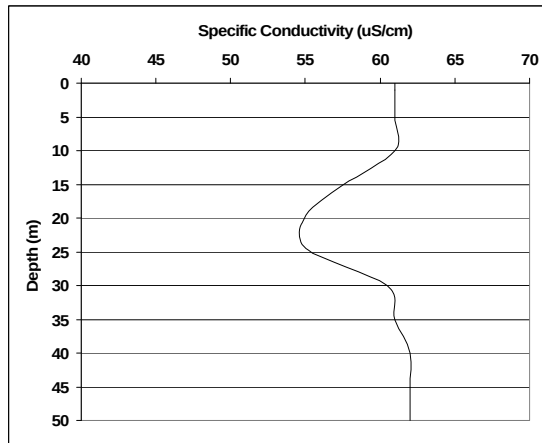


Figure 12. Specific conductivity profile for site U-009 in August on Lake Clark.

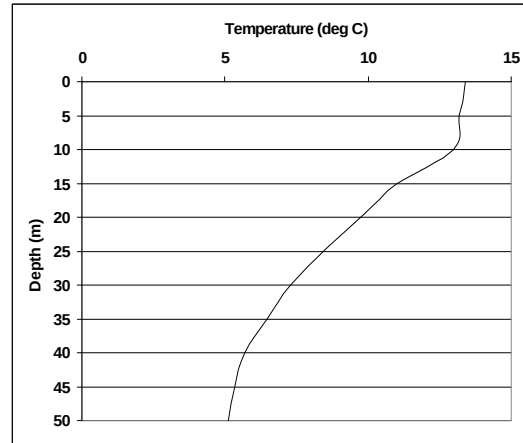


Figure 13. Water temperature profile for site U-009 in August on Lake Clark.

Dissolved Oxygen

Dissolved oxygen concentrations and percent saturation were high and close to or above saturation levels throughout the lake during all months (Table 3). Generally speaking, dissolved oxygen profiles were orthograde, common among oligotrophic lakes (Wetzel 2001), where oxygen concentrations increased as water temperature decreased with depth (Figure 14). These observations are similar to profiles measured by Wilkins (2002), who reported areas of super-saturation (percent saturation approaching 125%) at great depths (up to 110 m). Interestingly, we observed the same pattern for several middle basin profiles in August. For example, at site M-005 in July dissolved oxygen percent saturation ranged between 133.7% at the surface and 127.2% at 50 m (Figure 15). Wilkins (2002) did not have a plausible explanation for this occurrence. We are certain instrument error did not play a factor as daily calibrations and error-checks were performed on all dissolved oxygen sensors. While photosynthetic production may partially explain high percent saturation levels near the surface, this occurrence at 50 m and deeper remains uncertain. In large, deep lakes, such as Lake Clark, bacterial respiration of organic matter of phytoplanktonic origin is usually dominant over benthic decomposition (Wetzel 2001). It is possible that bacterial depletion of oxygen are minor compared to the replenishing of oxygen supplies by internal lake circulation due to strong wind events, perhaps partially explaining the observations of oxygen super-saturation at greater depths.

Water Clarity

Secchi depth data showed the distinct pattern of increasing turbidity from sites in the lower basin to the upper basin and from June through August (Table 3), a pattern observed by Chamberlain (1989) and Wilkins (2002) as well. This pattern is mostly explained by the glacial runoff entering the upper portion of Lake Clark via the Tlikakila River. The result is a silt plume that starts in the upper lake in late spring and advances towards the lower lake throughout the summer. Snow pack in the upper watershed and summer temperatures, which greatly influence glacial melting, dictate the amount of

inflow into the upper basin of Lake Clark (Brabets 2002), ultimately determining the extent to which the silt plume extends into the lower basin of the lake each year.

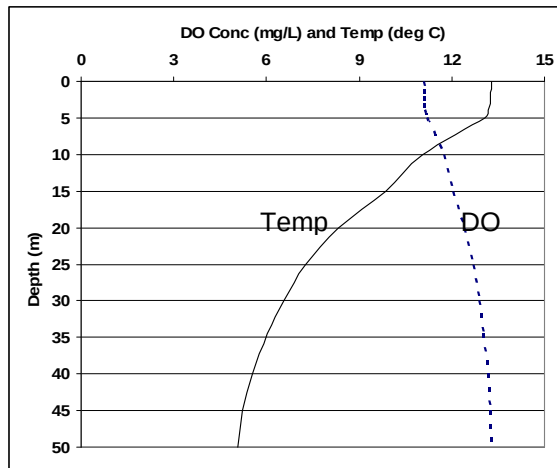


Figure 14. Dissolved oxygen and temperature profile for site M-005 in August on Lake Clark.

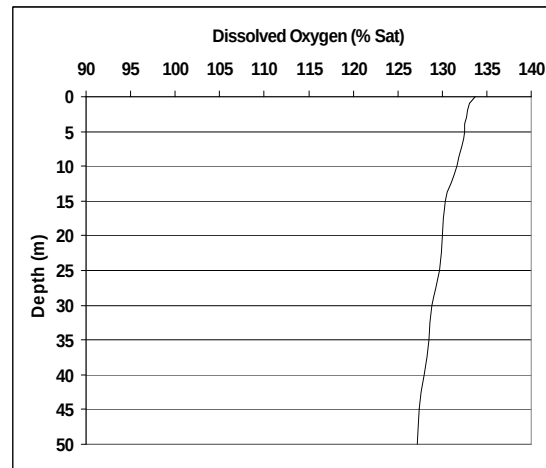


Figure 15. Dissolved oxygen profile displaying pattern of super-saturation for site M-005 in July on Lake Clark.

Exit Creek Continuous Water Quality Monitoring

Mean core parameter values were relatively stable throughout the summer months in Exit Creek (Table 4). Except for June, water temperature fluctuated less than 2 °C during the summer. In June, higher water temperatures (5.24 °C max) were recorded the first several days following sonde deployment. During this time, the sonde was positioned immediately under the water surface and thus likely more prone to solar heating prior to an increase in stream stage. Specific conductivity, pH, and dissolved oxygen fluctuated little throughout the summer while turbidity was variable. A plausible explanation for wide variation in turbidity values may be constant channel scouring above the sample site resulting in constant suspension of sediment and bed material into the current. The channel of Exit Creek between the sample site and Exit Glacier is extensively braided and constantly shifting within a broad glacial moraine. All values for water quality parameters were similar to those values reported by Bennett (2005) in a previous water quality inventory of Exit Creek and other glacial waters within KEFJ. Exit Creek stage (Figure 16) represents a typical hydrograph for glacial streams with a gradual, continued rise throughout the summer (Milner et al. 1997). Precipitation events are apparent in the stage in early to mid-September. One of the objectives for continuous monitoring in glacial systems is to assess the variability in core water quality parameters that occurs over a diel cycle in relation to daily glacial melting. Based on the Exit Creek data set, the greatest diel variability can be linked to two time periods: in early June immediately following sonde deployment and in early to mid-September during high precipitation events (Table 4). These observations suggest that within a particular year glacial melting may result in relatively constant water quality conditions, except for turbidity, while other disturbances, such as precipitation events, attribute a large portion of the natural variability observed at a sample site.

Table 4. Summary data for core parameters collected with multiparameter sonde in Exit Creek.

Parameter Statistic	June	July	August	September
Water Temperature (°C)				
Mean	1.74	1.20	1.25	1.00
Standard Deviation	0.96	0.39	0.37	0.27
Maximum	5.27	2.43	2.45	1.58
Minimum	0.61	0.54	0.61	0.09
pH (standard units)				
Mean	7.82	7.89	7.65	8.02
Standard Deviation	0.08	0.14	0.07	0.45
Maximum	8.31	8.33	7.98	9.24
Minimum	7.66	7.65	7.52	7.51
Specific Conductivity (µS/cm)				
Mean	30.0	39.3	38.7	41.2
Standard Deviation	4.3	3.4	2.3	8.8
Maximum	42.0	45.8	44.0	59.0
Minimum	23.3	33.6	34.4	29.0
Dissolved Oxygen (mg/L)				
Mean	14.58	14.83	14.76	14.30
Standard Deviation	0.29	0.12	0.14	0.51
Maximum	15.08	15.10	15.07	15.42
Minimum	13.56	14.52	14.40	13.49
Dissolved Oxygen (% Sat)				
Mean	105.3	107.0	105.9	100.6
Standard Deviation	1.5	1.0	2.1	3.9
Maximum	109.1	109.7	110.8	107.0
Minimum	101.2	104.8	102.1	94.3
Turbidity (NTU)				
Mean	122.3	179.7	87.6	200.9
Standard Deviation	87.2	58.9	40.4	159.3
Maximum	543.6	370.9	279.6	717.4
Minimum	18.9	1.2	0.2	0
Stage (ft)				
Mean	0.76	1.55	1.57	1.58
Standard Deviation	0.34	0.19	0.12	0.91
Maximum	1.24	1.92	1.88	3.13
Minimum	0.16	1.08	1.14	0.08
Parameter	Greatest Diel Fluctuation*			
	Date		Range	
Water Temperature (°C)	June 10		4.21	
pH (standard units)	Sept 14		1.38	
Specific Conductivity (µS/cm)	June 10 & 22, Sept 19		7.0	
Dissolved Oxygen (mg/L)	June 10		0.90	
Dissolved Oxygen (% Sat)	June 10 & 13		5.3	
Turbidity (NTU)	Sept 4		709	
Stage (ft)	Sept 7		0.70	

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

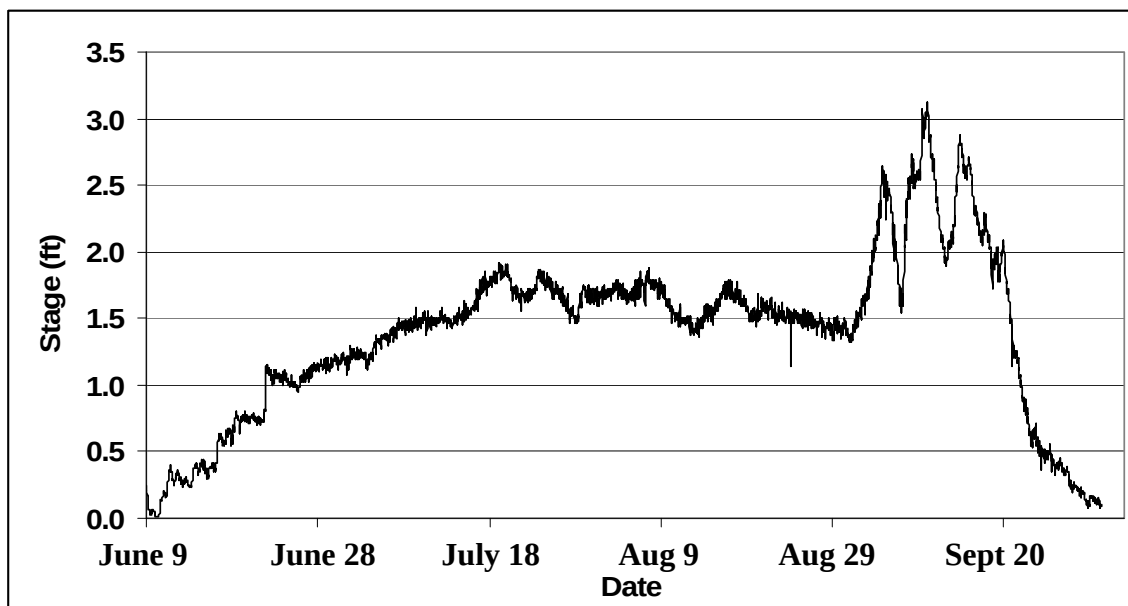


Figure 16. Stage profile of Exit Creek between June 9, 2008 and September 30, 2008.

Recommendations and Conclusions

To date, most of the water quality and surface hydrology protocol testing has taken place on Lakes Clark, Naknek, and Brooks. We will continue to focus primarily on these systems due to their importance to park management and their large spatial scale. However, we recognize the importance of monitoring smaller water bodies as well. Small, shallow basin lakes tend to operate more as a microcosm compared to large lake systems and changes are likely to first manifest themselves in these smaller systems (Larsen et al. 2004). The challenge for SWAN in the upcoming years will be to implement a scaled-down version of the water quality and surface hydrology monitoring being implemented on Lake Clark or Naknek Lake (high priority waters) on the smaller, more difficult to access lakes, such as Kijik Lake, LACL (medium priority water).

We will focus on pilot testing of SOPs for analytical parameters for water quality along with monitoring major tributaries during 2009. Additionally, we anticipate expanding our continuous monitoring of core water quality parameters to non-glacial rivers and lake outlets. Specifically, we will set up a monitoring site on the Chulitna River (tributary to Lake Clark). The Chulitna River is a major inflowing tributary to a high priority lake and is of particular interest to LACL park staff due to its proximity to a major proposed gold and copper mine. We will continue to measure vertical lake profiles on Lake Clark on multiple occasions in 2009. Our logic for sampling Lake Clark at different times during the ice-free period is to ensure we capture the range in variation of water quality that may occur during summer months and thus, to identify an index period where annual sampling can occur that will capture the greatest range of variation.

Currently, our ability to monitor surface hydrology is limited to water level measurements with pressure transducers and discharge at deep channel locations, such as lake outlets. Our current methodology of using a Price AA current meter mounted to a sounding weight on a boat prevents us from accessing and accurately measuring discharge on swift, shallow glacial rivers, which comprise a large percentage of the major tributaries flowing into large lakes within SWAN. Developing stage discharge rating curves and accurately monitoring flow conditions in these glacial rivers is critical to our surface hydrology monitoring strategy. SWAN will continue to explore the potential of acquiring an acoustic doppler current profiler for more accurate discharge measurements of glacial rivers.

One important change we will make to our continuous water quality monitoring is to the duration of sonde deployment. While we conducted independent spot checks at the continuous deployment site on Exit Creek in 2008 to correct for sensor drift, we feel that shorter deployments (approximately two weeks) will provide us with better data quality control. Our primary concern is not so much being able to correct sensor drift with independent spot checks but leaving sondes deployment for extended periods and risk sensor failure due to siltation and channel migration, especially in glacial systems. We will attempt to cover all phases of the stream's hydrologic cycle (base flow, rising, peak, and falling) with these deployments. We recognize this strategy will require additional site visits, and thus additional logistical planning, but feel it is an important change needed to acquire high quality data.

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