Fishery Data Series No. 14-33

Autonomous Lake Mapping and Limnological Assessment of Karluk Lake, 2013

by

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and

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August 2014

Alaska Department of Fish and Game **Divisions of Sport Fish and Commercial Fisheries**

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Weights and measures (metric)

centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)

cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd

Time and temperature

day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s

Physics and chemistry

all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General

Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat or long
monetary symbols (U.S.)	$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	*E*
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	$\log_2$, etc.
minute (angular)	'
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	"
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

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August 2014

This report was prepared by Heather Finkle and Darin Ruhl under award #NA09NMF4380373 from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, administered by the Alaska Department of Fish and Game. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration, the U.S. Department of Commerce, or the Alaska Department of Fish and Game.

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This document should be cited as:
Finkle, H., and D. C. Ruhl. 2014. Autonomous salmon lake mapping and limnological assessment of Karluk Lake, 2013. Alaska Department of Fish and Game, Fishery Data Series No. 14-33, Anchorage.

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ABSTRACT

This report presents the results of limnological data collected to describe abiotic and biotic water quality parameters that influence the growth, survival, and sustainability of wild juvenile sockeye salmon from Karluk Lake on Kodiak Island. During 2013, traditional means of limnological data collection were implemented and an autonomous underwater vehicle (AUV) that collects high-resolution spatial and temporal limnological data was deployed in Karluk Lake. AUV missions were run in Karluk Lake each month between May and September, excluding August, concurrent with traditional means of collecting limnological data. AUV-collected limnological data consisted of pH, chlorophyll, dissolved oxygen, and temperature profiles. Depth readings and side-scan sonar imagery were also recorded every second during the AUV missions. Traditionally collected limnological samples consisted of temperature, light penetration, and dissolved oxygen depth profiles; zooplankton; and water samples at depth. Water samples were processed and analyzed in a laboratory for pH; alkalinity; and total phosphorous, total filterable phosphorous, filterable reactive phosphorous, nitrate + nitrite, ammonia, total Kjeldahl nitrogen, silicon, chlorophyll-*a*, and phaeophytin-*a* concentrations. Analysis of AUV data revealed variability in physical conditions over area and depth in Karluk Lake. Temperature effects appear to be influenced by lake bathymetry. Similarly, primary production occurs below the epilimnion. For Karluk Lake, low levels of silicon coincided with seasonally high zooplankton biomasses, which peaked in July, indicating silicon was a vital nutrient for lake productivity. Notably, high phytoplankton biovolumes coincided with above-average TKN concentrations.

Key words: AUV, Karluk Lake, sockeye salmon, limnology, bathymetry, zooplankton.

INTRODUCTION

Understanding the dynamics of ecological conditions in lake systems over time and space is vital for modeling and predicting types and levels of productivity for a given body of water (Bilby et al. 1996; Kyle 1992; Stockner and MacIsaac 1996). Adult catch and escapement data are often the only data available for modeling salmon productivity. However, spawner-recruit models fail to identify mechanisms that influence run failure or success. Similarly, these data are often unable to explain why run size fluctuates over time. Auxiliary data have become increasingly important for managing fisheries because salmonid returns and survival are often affected by habitat conditions. Limnological data are vital for revealing changes in salmon productivity caused by their freshwater rearing environment, where salmon are most susceptible to mortality as juveniles. Few lake systems on Kodiak Island and the Alaska Peninsula, however, possess robust limnological datasets that allow the assessment of the effects of lake rearing conditions upon salmonid survival. This report summarizes the efforts of the Alaska Department of Fish and Game (ADF&G) to reestablish baseline data and improve the quality of limnological data collected from Karluk Lake (Figure 1).

Limnological sampling includes the collection of temperature, dissolved oxygen, pH, light penetration, nutrient, and zooplankton data. Collection of these data enable reestablishment of baseline lake habitat conditions. These data allow for comparisons between lake conditions and adult returns. In turn, these analyses may identify rearing conditions that are favorable for juvenile sockeye salmon and why those conditions exist.

This project also sought to enhance the quality of data collected where possible. Although traditionally collected data sets are valuable, they are limited in their scope to describe whole-lake conditions because ecological properties observed on a small spatial scale may not be apparent on larger scales and vice versa (Kiffney et al. 2005). In large or deep lakes, such as Karluk Lake, data from one or two sampling stations may not accurately reflect the variability of conditions throughout the whole lake (Finkle and Ruhl 2012). A simple way to improve the assessment of whole-lake conditions and parameter variability in lakes is by using an autonomous underwater vehicle (AUV) because it can collect limnological data from a substantially greater area in a fraction of the time that traditional methods would require.

The Yellow Springs Instrument © (YSI) Ecomapper[1] AUV, acquired by the department with Pacific Coast Salmon Recovery Fund monies in 2009, is a free-swimming robot that collects geo-referenced (latitude, longitude, and depth) water temperature, dissolved oxygen, turbidity, pH, chlorophyll, and blue-green algae data (Figure 2). The AUV possesses an onboard computer that stores and runs a user-plotted mission. Once deployed, the global positioning system (GPS) unit located in the antenna on top of the AUV guides it along the plotted course when not submerged underwater. On diving missions, which can reach depths as great as 61 m (200 feet), the AUV follows a compass heading to the next waypoint. In addition, the AUV possesses a side-scan sonar system capable of generating bottom profile imagery and detecting fish presence in lakes. The sensor array can be programmed to collect data at varying intervals, recording measurements every second for a mission up to 4 hours long. Because all data points are geo-referenced by location and depth, physical characteristics can be mapped and compared to side-scan sonar imagery of fish presence to help identify preferred habitats. These data maps ultimately allow for relatively quick, high-resolution visual assessments of habitat quality and variability in an entire lake.

Bathymetric data are very useful for assessing salmon productivity. Several quantitative models exist that rely on accurate estimates of lake volume or area to calculate optimal levels of escapement for maximizing production (Koenings and Burkett 1987; Koenings and Kyle 1997). Bathymetric data collected by the AUV since 2009 have been used to remap Karluk Lake (Finkle and Ruhl 2011). The euphotic volume or zooplankton biomass models (Koenings and Burkett 1987; Koenings and Kyle 1997) used to assess salmon escapement goals for this system yielded substantially different estimates of optimal salmon escapement when using the re-estimated lake volume (Finkle and Ruhl 2011). Continued collection of bathymetric data will further enhance our knowledge of Karluk Lake morphology.

Reestablishing baselines and increasing the spatial and temporal metrics of limnological data for Karluk Lake will eventually lead to better modeling of stock productivity, helping resource managers sustain maximum yields of Alaska’s salmon stocks. This report summarizes the traditional limnological data collection and AUV water quality mapping in Karluk Lake during 2013.

METHODS

Karluk Lake was sampled for limnological data from May through October 2013. The sampling schedule for 2013 is outlined in Table 1. Three stations were sampled in Karluk Lake (Figure 3). Water and zooplankton samples and data on temperature, dissolved oxygen, and light penetration were gathered at all stations. Each station’s location was logged with a GPS and marked with a buoy. Sampling was conducted following protocols established by Ruhl (2013). AUV sampling events were conducted once a month from May through September, excluding August, over the field season. Because of the size of Karluk Lake, multiple missions were required during sampling events to map lake parameters. The timing of AUV missions overlapped with that of traditional limnological sampling.

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[1] Product names are included for completeness but do not constitute endorsement.

TRADITIONAL LIMNOLOGICAL SAMPLING

Physical Data – Temperature, Dissolved Oxygen, and Light Penetration

Water temperature (°C) and dissolved oxygen (mg/L) levels were measured with an YSI ProODO dissolved oxygen and temperature meter. Readings were recorded at 0.5 m intervals to a depth of 5 m and then increased to 1 m intervals. Upon reaching a depth of 25 m, the intervals were increased to every 5 m up to a depth of 50 m. A mercury thermometer was used to ensure the meter functioned properly. Measurements of photosynthetically active radiation (PAR) were taken with a Li-Cor© Li-250A light meter and Li-Cor© Underwater Quantum (UWQ) photometer above the surface, at the surface, and at depths proceeding in 0.5 m intervals until reaching a depth of 5 m. Readings were then continued at 1 m intervals until 0 µmol s^{-1} m^{-2} light penetration was reached. The mean euphotic zone depth (EZD) was determined (Koenings et al. 1987) for the lake. Temperature and dissolved oxygen measurements at 1 m were compared to assess the physical conditions in the euphotic zones of the lake. Secchi disc readings were collected from each station to measure water transparency. The depths at which the disc disappeared when lowered into the water column and reappeared when raised in the water column were recorded and averaged.

Water Sampling – Nutrients, Phytoplankton, pH, and Alkalinity

Using a Van Dorn bottle, 4 to 8 L of water were collected from the epilimnion (depth of 1 m) and hypolimnion (30 m) at each station. Water samples were stored in polyethylene carboys, refrigerated, and initially processed within 12 hours of collection following the methods of Ruhl (2013).

Unfiltered water samples were decanted into labeled, acid-washed, 500 ml polyethylene bottles and frozen for future analysis of particulate nitrogen and phosphorous.

One-liter samples were passed through 4.25 cm diameter 0.7 µm Whatman™ GF/F filters under 15 to 20 psi vacuum pressure for particulate N and P analyses. For chlorophyll-*a* analysis, 1 L of lake water from each depth sampled was filtered through a 4.25 cm diameter 0.7 µm Whatman™ GF/F filter, adding approximately 5 ml of $MgCO_3$ solution to the last 50 ml of the sample water during the filtration process. Upon completion of filtration, all filters were placed in individual Petri dishes, labeled, and stored frozen for further processing at the ADF&G Kodiak Island Laboratory (KIL) in Kodiak. Approximately 500 mL of water from each carboy was filtered separately from the chlorophyll-*a* designated sample and stored and frozen in a labeled, acid-washed, 500 mL polyethylene bottle.

Phytoplankton samples were taken from unfiltered lake water collected at 1 m. Exactly 100 mL of the unfiltered lake water was poured into an amber polypropylene bottle with 2.0 mL of Lugol's acetate, sealed, and stored at room temperature. Estimates of biovolume were processed by BSA Environmental Services, Inc. in Beachwood, Ohio.

The water chemistry parameters of pH and alkalinity were assessed with a temperature-compensated pH meter. One hundred milliliters of lake water were titrated with 0.02-N sulfuric acid following the methods of Thomsen (2008).

Water analyses were performed at the ADF&G KIL for total phosphorous (TP), total ammonia (TA), total filterable phosphorous (TFP), filterable reactive phosphorous (FRP), nitrate + nitrite, and silicon using a SEAL AA3 segmented flow autoanalyzer in accordance with the manufacturer's methodologies. Chlorophyll *a* and phaeophytin *a* were assessed using a Genesis 5 spectrophotometer following the methods outlined by Ruhl (2013). Water samples were sent to the University of Georgia Feed & Environmental Water Laboratory for total Kjeldahl nitrogen (TKN) analysis. Nutrient data were analyzed via linear regression and compared to published ratio values to indicate trophic level interactions and levels of lake productivity.

Zooplankton – Abundance, Biomass, and Length

One vertical zooplankton tow was made at each limnology station with a 0.2 m diameter, 153-micron net from a 50 m depth to the lake's surface. Each sample was placed in a 125 ml polyethylene bottle containing 12.5 ml of concentrated formalin to yield a 10% buffered formalin solution. Samples were stored for analysis at the ADF&G KIL. Subsamples of zooplankton were keyed to family or genus and counted on a Sedgewick-Rafter counting slide. This process was replicated 3 times per sample, and then counts were averaged and extrapolated over the entire sample. For each plankton tow, mean length (±0.01 mm) was measured for each family or genus with a sample size derived from a Student's *t*-test to achieve a confidence level of 95% (Edmundson et al. 1994). Biomass was calculated via species-specific linear regression equations between dry weight and unweighted- and weighted-average length measurements (Koenings et al. 1987). Zooplankton data were compared to physical and nutrient data via linear regression and published values of length and biomass.

AUV SAMPLING

In 2013, sampling of Karluk Lake with the AUV consisted of multiple successful missions in May, June, July, and September. August missions were not attempted because of unforeseen staffing limitations. All AUV missions were plotted in VectorMap software on the most recent geo-referenced images available for Karluk Lake (example shown in Figure 4) and then loaded onto the AUV's onboard computer via its own wireless network. Missions were plotted to avoid overlap and increase area coverage to maximize data accuracy for bathymetric mapping. Each deployment and retrieval followed the YSI Ecomapper operation manual (YSI 2009). Physical parameters of temperature (°C), dissolved oxygen (mg/L), pH, and chlorophyll (µg/L) were measured every 1 second along the plotted sampling grid throughout Karluk Lake. In addition, bottom profiles and fish presence or absence were obtained with the side-scanning sonar. It should be noted that in assessing fish distribution, speciation was not possible from the side-scan sonar imagery. Data were downloaded to a field computer and reviewed following each mission.

AUV DATA ANALYSIS

All data were edited for erroneous measurements. Spurious data were omitted from analyses. Traditionally collected limnological data were averaged by month, where applicable, for inseason comparisons. Physical data were plotted against depth for each month.

AUV data for Karluk Lake was divided into 3 regions (Upper, Middle, and Lower; Figure 3) to address homogeneity of lake conditions. Average values for each region were compared within and between months. Maps to display spatial and temporal variability of all AUV data were created using the Surfer 9 software package. Bathymetric maps were generated from the depth and coordinate data, also using the Surfer 9 program; lake statistics such as area, volume, and mean and maximum depth were also estimated from the bathymetric data. Side-scanned sonar images were reviewed and fish locations were recorded and plotted on lake maps for each month. Fish locations were also overlaid on maps of AUV collected physical and nutrient data.

Traditionally collected limnological and AUV data were compared, where possible, either graphically or statistically by region and month. Estimates of percent difference of lake volume and area were compared between the two methods of data collection. AUV bathymetric data were also employed in an euphotic volume model (Koenings and Burkett 1987) to estimate rearing capacity and optimal escapement for sockeye salmon.

RESULTS

Detailed limnological data for Karluk Lake are presented in Appendix A.

TRADITIONAL LIMNOLOGICAL SAMPLING

Physical Data

The average 1 m temperature in Karluk Lake was 10.0 °C (Table 2). The warmest temperature occurred in July (16.3 °C), and the coolest was in May (3.6 °C; Table 2 and Figure 5). Dissolved oxygen readings taken at a depth of 1 m were the lowest in July and August (10.7 mg/L) and the greatest in May (14.2 mg/L), averaging 11.9 mg/L over stations during the sampling season (Table 3; Figure 5). The euphotic zone depth (EZD) was estimated from light penetration data, which was at its deepest in September (25.6 m) and shallowest in June (20.1 m; Tables 4 and 5). The seasonal average of the EZD was 23.4 m (Table 5; Figure 6). The euphotic volume (EV) was greatest in September (797×10^6 m^3; Table 5).

Water Sampling

All data presented in this section were collected from a 1 m depth.

Water chemistry measurements were variable for Karluk Lake during 2013; pH ranged from 7.15 in September (Station 7) to 8.77 in June (Station 4) at Karluk Lake. The seasonal pH values averaged 7.96 (Table 6). Seasonal TP averaged between 2.9 µg/L P in August and 6.8 µg/L P in May with a seasonal mean of 5.0 µg/L P (Table 6). Of the photosynthetic pigments, chlorophyll *a* averaged between 0.53 µg/L in July and 2.51 µg/L in May over the sampling season with a seasonal average of 1.16 µg/L (Table 6). Seasonal average total nitrogen (TKN plus NO_3+NO_2) concentrations were greatest in September (1,246.3 µg/L) and lowest in June (918.4 µg/L; Table 6). Silicon concentrations averaged 135.4 µg/L over the sampling season, ranging between 65.4 (May) and 173.0 (September) µg/L (Table 6). Phytoplankton biovolume was greatest in May (242,749 mm^3/L) and lowest in July (29,604 mm^3/L; Table 7). Diatoms (Bacillariophyta) were the predominant species on average having the greatest biovolumes in May, September, and October (Table 7). In comparison to phytoplankton biovolumes from 2004 to 2006 and 2010 to 2012, 2013 biovolumes were the second greatest (109,705 mm^3/L) behind 2012 (417,719 mm^3/L; Table 8).

Zooplankton

The 2013 average abundance of Karluk Lake zooplankton was greatest in September (1,433,917 zooplankton/m^2), with the lowest monthly concentration of 1,025,478 zooplankton/m^2 in June (Table 9). The species composition was composed predominately of the copepod *Cyclops* throughout the season. *Daphnia* were the most abundant cladoceran, reaching their greatest abundance (296,267 zooplankton/m^2) in October (Table 9). Other zooplankton species present in Karluk Lake were *Bosmina*, *Diaptomus*, and *Harpaticus*. *Cyclops* had the most ovigerous individuals during a given month (84,218 zooplankton/m^2 in June; Table 9).

The seasonal weighted-average zooplankton biomass for 2013 in Karluk Lake was 1,807 mg/m^2 and ranged from 1,501 mg/m^2 in September to 2,304 mg/m^2 in July (Table 10). Karluk Lake maintained monthly zooplankton biomasses well over 1,000 mg/m^2 during the sampling season (Table 10). *Cyclops* had the greatest biomass (seasonal weighted average of 708 mg/m^2) of any species, either egg- or non-egg–bearing, in Karluk Lake during 2013 (Table 10).

Ovigerous *Diaptomus* were the longest zooplankton (seasonal weighted average of 1.20 mm) collected during 2013 (Table 11). Ovigerous zooplankton were longer than their non-ovigerous counterparts for all identified species, excluding *Bosmina*. Non-ovigerous *Cyclops* ranged from 0.56 to 0.71 mm and non-ovigerous *Bosmina* exceeded 0.40 mm in all sampled months (Table 11).

AUV SAMPLING

Physical Data

For each month, surface temperature and dissolved oxygen varied minimally from region to region (Tables 12 and 13; Figures 7 and 8). The Lower region had the coolest surface temperatures in May. The Upper region had the warmest surface temperatures, which occurred in July (Table 12; Figure 7). The greatest difference in temperature across regions was 4.5 °C between the Middle and Lower regions during June at a depth of 1 m. Surface dissolved oxygen concentrations were the greatest in May in the Middle region and the lowest in the Middle region during July (Table 13; Figure 8). The greatest difference in dissolved oxygen concentrations across regions was 1.14 mg/L between the Middle and Lower region 1 m readings during June.

Monthly temperature depth profiles indicated that Karluk Lake was mixing in May and September, stratifying in June, and completely stratified in July and August with the hypolimnion at its deepest (~20 m) during August (Figure 7). The greatest temperature difference between the surface and first 5 m of depth was 3.1 °C in the Middle region during July (Table 12). Dissolved oxygen concentrations generally varied minimally over depth (Figure 8). June dissolved oxygen concentrations showed the most heterogeneity across regions.

Water Sampling

The highest pH measurement, 9.10, occurred in Karluk Lake’s Upper region during May (Table 14; Figure 9). The Middle region had the lowest pH measurement (8.03) in September. Average pH values over depth were generally greater in the Upper region during May and July, and in the Lower region during June and September (Table 14). Monthly measurements of pH were consistent over depth in each region, with the exception of pH depth profiles from the Lower region during May and September (Figure 9).

Average surface chlorophyll concentrations were generally higher in June and at their lowest in September (Table 15; Figure 10). September chlorophyll concentrations were on average consistent across regions and depths, ranging from 1.14 to 1.83 μg/L (Table 15; Figure 10). From May through July, chlorophyll concentrations varied minimally among regions and depths. The peak chlorophyll measurement (361.0 μg/L) was recorded from the Middle region in June.

Bathymetry

The Karluk Lake bathymetric map created with AUV data in 2009 was updated in 2012 and 2013. A maximum depth measurement of 141.8 m was recorded in Karluk Lake in 2013

(Table 16). The average depth increased from 40.9 m to 45.1 m. The volume of Karluk Lake also increased from 1,843 x 10^6 m^3 (2012) to 1,907 x 10^6 m^3 (Table 16).

Sonar Imagery

The lowest apparent densities of fish present in Karluk Lake occurred in May and July with average depths of roughly 23.5 m. Side-scan sonar imagery indicated fish presence throughout Karluk Lake in June and September (Figure 11) ranging in depth from 0.72 m to a maximum seasonal depth of 60.1 m. Aggregations of fish in May and July were detected primarily in the Upper and Middle regions of the lake.

COMPARISON OF SAMPLING METHODS

Comparisons of physical data collected by the AUV to the data collected by traditional methods revealed variability among Karluk Lake temperatures, dissolved oxygen, pH, and chlorophyll concentrations over depth, space, and time (Tables 12 through 15). Specifically, pH was generally greater when measured by the AUV; AUV-measured dissolved oxygen concentrations were typically lower over depth and time (Figures 8 and 10).

DISCUSSION

PHYSICAL DATA

Traditional and AUV temperature depth profiles indicated a spring turnover event occurred during May. A fall turnover event occurred during September in Karluk Lake. A weak thermocline (the plane of maximum temperature decline relative to depth; Wetzel 1983) developed in June and was strongly defined in July and August. Timing of lake turnover and stratification events greatly affects ecosystem dynamics and will be expounded upon in this section as it becomes germane to the discussion.

Dissolved oxygen concentrations from the surface to the hypolimnion were at suitable levels for rearing fishes in Karluk Lake through the sampling season. Differences did exist between traditionally collected data and AUV-collected dissolved oxygen data. This may be in part to the variability that naturally occurs in systems and the ability of the collection methods to accurately represent lake conditions over space and time. Instrument sensitivity should not affect results because both probes are of the same type, from the same manufacturer, and calibrated following the same protocol.

Changes in phytoplankton species composition mediated by physical factors such as reduced water clarity can negatively affect zooplankton consumption and assimilation rates (Wetzel 1983; Kerfoot 1987; Kyle 1996). Cladocerans, which are selective feeders, can have periods of reduced growth or reproduction in the absence of preferred forage (Dodson and Frey 2001). Similarly, Kirk and Gilbert (1990) noted that suspended particles that reduced water clarity dilute food concentrations in the water column, reducing cladoceran population growth rates. For Karluk Lake zooplankton, water clarity historically has not been an issue, as evidenced by an average summer euphotic zone depth (EZD) greater than 20 m and increasing cladoceran biomasses through the summer.

WATER SAMPLING

Oligotrophic lakes are preferred habitat for rearing sockeye salmon (Carlson 1977; Carlson and Simpson 1996). Limnological data from traditional and AUV collection methods indicated that

Karluk Lake could be classified as having oligotrophic (low) production levels as defined by several trophic-state indices (Carlson 1977; Forsberg and Ryding 1980; Carlson and Simpson 1996).

Nutrient data may be used to indicate limitations in aquatic environments. A comparison of total nitrogen (TN) to total phosphorous (TP) is a simple indicator of aquatic ecosystem health because both are necessary for primary production (Wetzel 1983; UF 2000). Nitrogen-phosphorous ratios of less than 10:1 typically indicate nitrogen limitations in oligotrophic lakes (UF 2000; USEPA 2000). Karluk Lake consistently had TN:TP molar ratios exceeding 10:1, indicating phosphorous limitations. The TN:TP molar ratio should, however, be objectively considered as an indicator of lake health. Because phytoplankton link nutrients and consumers in a food web, they are often used as indicators of aquatic ecosystem health and bottlenecks (Cottingham 1999). For example, Chrysophyta thrive in low nutrient conditions while Pyrrhophyta can form dense blooms when nitrogen and phosphorous concentrations are high (Watson et al. 1997). From 2010 to 2013, Chrysophytes were either absent or a minor component of the phytoplankton biovolume. Similarly, Pyrrhophyta biovolume exploded in 2012 and 2013, concurrent with elevated TKN levels in Karluk Lake. Diatom production was also at historical highs in 2012 and 2013. This information suggests that nutrient limitations may be better assessed relative to phytoplankton because each species has different nutrient uptake rates and demands (Interlandi and Kilham 2001; Tilman et al. 1982).

It is also unclear whether the nutrient concentrations that were measured are what were available or left over from photosynthetic processes. Uncertainty surrounds what concentrations of nutrients have precipitated out of the euphotic zone and are awaiting a turnover event to reintroduce them where they can be used. Interestingly, the seasonal average TN:TP molar ratio from 1 m samples (541:1) were consistently greater than the seasonal average from samples collected from the hypolimnion (380:1). This suggests that there may be a deep chlorophyll maximum (DCM; Barbiero and Tuchman 2004), which is a layer just below the thermocline or in the upper part of the hypolimnion where there are strong gradients of light, oxygen, and nutrients that accumulate chlorophyll. When considered in conjunction with other limnological components, the DCM may help to explain trophic interactions in the lake.

Although nitrogen and phosphorous are important drivers of lake primary productivity, productivity must also be assessed respective to other lake attributes. Beyond nitrogen and phosphorous, silicon is a vital nutrient for phytoplankton production: diatoms require silicon for bodily structure and reproduction (Vinyard 1979, Wetzel 2001). Primary consumers such as copepods graze upon diatoms (Turner et al. 2001). Thus, if silicon concentrations affect diatom production, they may also influence the abundance of copepods. Diatoms have been the predominate taxa of phytoplankton in Karluk Lake (Tables 7 and 8). Average silicon concentrations were relatively low in Karluk Lake compared to historical values from Karluk and other Kodiak Island lakes (Finkle 2012), suggesting that diatoms are utilizing silicon for their metabolic demands and that silicon is an integral nutrient for phytoplankton production.

A comparison of the photosynthetic pigment, chlorophyll *a*, to its byproduct, phaeophytin *a*, showed that chlorophyll-*a* concentrations were proportionally high all season (ranging from 3.0 to 7.6 chlorophyll *a* to 1 phaeophytin *a*). This signifies that algal levels were generally adequate for supporting primary consumption because the potential for algal (phytoplankton) growth, existing as chlorophyll *a*, was available for photosynthesis. Conversely, when primary production is taxed by either overgrazing or poor physical conditions, phaeophytin-*a* levels tend to exceed chlorophyll-*a* levels (COLAP 2001). That chlorophyll-*a* levels were greater than phaeophytin-*a* levels may also suggest that primary production of chlorophyll was slightly ahead of its consumption. Lakes with relatively high chlorophyll-*a* to phaeophytin-*a* ratios and high zooplankton biomasses, such as Karluk Lake, support this hypothesis.

Relative to depth, chlorophyll *a* was 2 to 5 times more concentrated below the euphotic zone than at 1 m when the lake was stratified in June, July, and August (Table 6). Because the euphotic zone depth did not exceed 26 m and the nutrient samples were collected at 30 m, this result supports the hypothesis that a DCM exists and may function as another area of lake productivity beyond the euphotic zone (Barbiero and Tuchman 2004). In light of these data, nutrients did not appear to be a limiting factor in Karluk Lake in 2013. Furthermore, the AUV located patches of high chlorophyll concentrations, signifying that primary production may be greater than indicated from traditional sample collection methods.

Review of the traditionally collected pH data suggested that both phytoplankton and temperature may influence pH in Karluk Lake. Warmer temperatures release hydrogen ions from water molecules, decreasing pH. In contrast, photosynthesis uses dissolved carbon dioxide (CO_2), which acts like carbonic acid (H_2CO_3) in water. The removal of carbon dioxide through photosynthesis, in effect, reduces the acidity of water and therefore pH increases creating a more basic, or alkaline, environment, which is the opposite effect of warming water temperatures (Wetzel 1983). Karluk Lake experienced its highest pH levels concurrent with high levels of phytoplankton and cooler temperatures, indicative of nutrient consumption during photosynthesis. High temperatures in June, July, and August possibly lowered pH when the phytoplankters were at their lowest concentrations.

In comparison to AUV-collected data, pH values from traditional collection methods were generally similar between methods. Because 1 m pH readings were collected in situ from the traditional sampling station using a portable pH meter from the same manufacturer as the AUV, the differences in pH values may be attributed to the spatial variability of lake conditions as opposed to sampling methods.

ZOOPLANKTON

Planktivorous fishes, such as sockeye salmon, can exert top-down pressures on zooplankton communities (Kyle 1996; Stockner and MacIsaac 1996). This type of predation can result in changes to the zooplankton species composition (Helminen and Sarvala 1997; Donald et al. 2001; Thorpe and Covich 2001). Specifically, copepods can enter a state of diapause as an egg or copepodid in response to overcrowding, photoperiod, or predation (Thorpe and Covich 2001). Average monthly biomass estimates for Karluk Lake were high and composed predominately of copepods. The high monthly biomasses were typically well above the satiation level of 1,000 mg/m^2 for rearing salmonids (Mazumder and Edmundson 2002). The cladoceran, *Bosmina*, also serves as an indicator of overgrazing when its length falls below the juvenile sockeye salmon elective feeding threshold size of 0.40 mm (Kyle 1992; Schindler 1992). Respective of physical and nutrient data and the relatively large abundance of *Bosmina* > 0.40 mm in size, overgrazing seems unlikely to limit zooplankton production.

Phytoplankton species composition and production are dependent on nutrient availability; shifts in plankton species composition are often mediated by changes in nutrient concentrations (Graham et al. 2004). Although temperature and phosphorous have been identified as limiting factors for some lakes, silicon concentrations are distinctly tied to zooplankton production in

Kodiak lakes (Finkle 2012). Kodiak lakes with low silicon concentrations consistently had high zooplankton biomasses, whereas lakes with high silicon concentrations had low zooplankton biomasses (Figure 12). Diatoms require silicon for reproduction and for creating cell walls (Wetzel 2001). Diatoms are also favored forage of copepods, which are abundant in Kodiak lakes with relatively low silicon concentrations. Data collected between 2010 and 2013 indicated that diatoms were highly abundant and had the greatest biomass of phytoplankton species in Karluk Lake (Table 8). This information suggests that zooplankton rely upon diatoms to provide the nutrition that facilitates their success in Karluk Lake. Copepods in particular can take advantage of the primary production in the DCM as they can vertically migrate to the hypolimnion to graze upon the concentrated phytoplankton (Barbiero et al. 2000).

AUV Imagery and Bathymetry

Side-scan sonar data collected from each month indicated fish presence in Karluk Lake, with the exception of August when no missions were run. Fish observed in May and July were located mainly in the Upper and Middle regions of the lake and were generally small, which may indicate the presence of sockeye or coho (*O. kisutch*) salmon smolt, Dolly Varden *Salvelinus malma* juveniles, or stickleback. Similarly, larger-sized fish were detected near tributary streams and spawning shoals in July and September, which may have been adult sockeye salmon or Dolly Varden returning to their spawning locations.

It should be noted that detection of fish location was limited to the path that the AUV scanned. Additionally, although individual fish can be discerned in the imagery, species cannot be identified and enumeration is not possible because any overlap of schooling fish precludes accurate counts and the ability to estimate species composition.

Bathymetric data collected in 2013 was added to the Karluk Lake AUV bathymetry data set that has been collected since 2009. There were minimal increases in the estimates of lake area, volume, mean depth, or maximum depth with the inclusion of 2013 data.

The AUV volume data estimated from this study, when limited to the euphotic zone depth, showed the greatest volume of water capable of photosynthesis coincided with the lowest biomass of green (Chlorophyceae) and golden-brown (Chrysophyceae) algae. Diatoms, the most abundant phytoplankton, were not significantly correlated ($P = 0.47$, $R^2 = 0.14$) with the euphotic zone depth.

Conclusions

Karluk Lake is deep, clear, and relatively low in nutrients but supports healthy phytoplankton and zooplankton production. These conditions raise the question as to whether the nutrient and zooplankton levels seen in Karluk Lake are what is available or what is left over from consumption. This question is important to ask because changes in nutrient levels can precipitate changes in each level of an aquatic food web (Carpenter et al. 2010) and therefore affect the success of salmon populations vital to many user groups.

Increases in nutrient levels can intensify trophic cascades, altering the relationships between forage bases and prey (Hansson et al. 1998; Lathrop et al. 2002). After examining relationships among seasonal averages of phosphorous and chlorophyll relative to zooplankton, weak trends were apparent that at low phosphorous ($R^2 = 0.42$, $P < 0.0001$) and chlorophyll ($R^2 = 0.36$, $P = 0.0026$) concentrations, higher zooplankton biomasses occurred. These relationships suggest that phosphorous is being utilized for photosynthesis and chlorophyll is being consumed by zooplankton, and because zooplankton were abundant, the nutrient and chlorophyll levels seen may be what remain unutilized.

In light of the AUV chlorophyll data, it is also possible that patchiness of primary production may not be captured by the traditional sampling methods and underestimate available resources. AUV data indicated areas of variable chlorophyll concentrations across Karluk Lake when the lake was stratified in July and August of 2012. Similarly, data from May 2013 showed concentrations of chlorophyll near the outlet of a known salmon spawning stream that were much greater than those from samples collected at the buoy stations. The close proximity of the concentrated AUV chlorophyll data to known salmon spawning streams also suggested that nutrients derived from salmon carcasses were released into the lake, contributing to algal production. It is unlikely that the variability in chlorophyll concentrations would be attributed to the analysis method because the AUV produced similar results to the traditionally collected data when sampling in near the buoy stations.

Similarly, the existence of a DCM in Karluk Lake may also temper any resource limitations because nutrient concentrations below the epilimnion may contribute to lake productivity. A significant relationship exists between phosphorous and chlorophyll (2006, 2009 to 2013 data) in the epilimnion during August stratification ($R^2 = 0.92$, $P = 0.00001$). Similar strong relationships also existed below the epilimnion (30 m) in August ($R^2 = 0.53$, $P = 0.04$) and September ($R^2 = 0.91$, $P = 0.0002$). With the exception of samples collected in 2005, no hypolimnion phytoplankton data are available for Karluk Lake to quantify the presence or absence of species better suited to low light conditions or able to migrate between the DCM and epilimnion. However, 30 m chlorophyll concentrations in 2013 were on average twice as much as those collected from 1 m and diatom species known to function well in low-light conditions (*Cyclotella bodanica*; Wehr and Sheath 2003) were abundant in 1 m phytoplankton samples.

Zooplankton data may address DCM productivity to some extent. For example, in Lake Superior, cladocerans such as *Daphnia* and *Bosmina* were confined to the top 20 m of the water column, and copepods were found well below the epilimnion (Barbiero and Tuchman 2004). The copepod *Cyclops*, which is a relatively strong swimmer (Thorpe and Covich 2001), has been the predominate zooplankton taxa in Karluk Lake, and thus may be taking advantage of DCM productivity. Separate plankton tows from 50 m and from the bottom of the epilimnion (~20 m) were taken during lake stratification in June, July, and August to assess the DCM hypothesis. Analysis of these samples revealed a greater June abundance of *Bosmina* and *Daphnia* in the epilimnion than from 50 meters. In addition, the copepod biomass was substantially greater from the 50 m tows than from the 20 m tows during lake stratification. This supports the idea that a DCM developed in late June and that zooplankton were utilizing a relatively concentrated algal forage base. Continued collection of zooplankton samples, AUV missions through the thermocline and samples of epilimnion and hypolimnion phytoplankton and water would further clarify differences in lake productivity relative to the DCM.

Another important component of Karluk Lake productivity is the timing of peak zooplankton abundance and biomass. Koenings and Burkett (1987) indicated that zooplankton biomass peaked twice, once each in May and September between 1979 and 1985. Asynchrony between the peak blooms and fry emergence was hypothesized to have negatively affected juvenile condition and survival, leading to poor adult returns (Koenings and Burkett 1987). Review of historical data has shown that between 1981 and 1996, zooplankton biomass was at its greatest in

September for 6, and in May for 2, of those 16 years; however, from 1999 to 2013, the peak biomass has occurred between mid-June and August for 11 of those 15 years. The causes of the shift in the timing of the zooplankton bloom are uncertain, but the recent lower spring biomasses may indicate hatch-bloom synchrony as emergent fry consume and thus reduce the standing crop of zooplankton (Sommer 1996). This also implies healthy rearing conditions exist for juvenile sockeye salmon, because spring zooplankton biomasses generally approached or exceeded the satiation level and continued to increase into the summer.

The lack of strong seasonal relationships between variables in Karluk Lake highlights the intricacy among factors that can influence productivity and the inherent need for continued study. Because primary production is the base of a food web, any changes in it may significantly affect higher trophic levels such as secondary or tertiary consumers (Milovskaya et al. 1998). In some lake systems, a negative change in rearing conditions at these levels can cause migratory behavior or decreased juvenile sockeye salmon freshwater survival (Parr 1972; Ruggerone 1994; Bouwens and Finkle 2003). Thus, it is important to know and understand patterns of resource abundance and habitat usage to effectively manage a system and conserve its resources. Continued limnological observation of Karluk Lake is necessary for identifying whether its rearing habitat may have deleterious effects upon its rearing salmonids.

ACKNOWLEDGEMENTS

Numerous individuals helped make the Karluk Lake Limnology project a success. Darin Ruhl did an outstanding job of scheduling, collecting, and processing samples. Kyle Shedd and Kayla Bevaart helped with data collection, analysis, and database development. Melony Lechner provided logistic and field support. Thanks go to Jack Napier for supporting submariner efforts since the 1940s. The Kodiak National Wildlife Refuge provided flight support and use of the Camp Island facilities; particular thanks go to Bill Pyle, Bill Leacock, and Kevin Van Hatten. Cecilia Curtis, Debbie Maas, Teresa Tavel, Robin Gardner, and Lori Ryser provided project and administrative support. Kathy Greer polished this report with her publication expertise. Darin Ruhl, Mary Loewen, Natura Richardson, Nick Sagalkin, and an anonymous peer insightfully reviewed this document and get superstar status for their help. References to trade names do not imply endorsement by the Alaska Department of Fish and Game.

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TABLES AND FIGURES

Table 1.–Sampling dates and methods used for Karluk Lake, 2013.

Sample dates	Methods
20-May	AUV
21-May	W, Z
18-Jun	AUV
19-Jun	AUV
20-Jun	W, Z, AUV
24-Jul	AUV
25-Jul	W, Z, AUV
21-Aug	W, Z
26-Sep	AUV
27-Sep	W, Z, AUV
21-Oct	W, Z

Note: W = water sampling, Z = zooplankton sampling, AUV = AUV sampling.

Table 2.–Monthly average temperature (°C) measurements from Karluk Lake, 2013.

	Month						Seasonal
Depth (m)	May	June	July	August	Sept	Oct	Average
0.1	3.6	10.1	16.5	13.5	9.0	7.5	10.0
0.5	3.6	10.1	16.3	13.5	9.0	7.5	10.0
1	3.6	10.1	16.3	13.5	9.0	7.5	10.0
1.5	3.6	10.1	16.1	13.5	9.0	7.5	10.0
2	3.6	10.0	16.0	13.5	9.0	7.5	9.9
2.5	3.6	10.0	16.0	13.5	9.0	7.5	9.9
3	3.6	9.9	15.7	13.5	9.0	7.5	9.9
3.5	3.6	10.0	15.4	13.4	9.0	7.5	9.8
4	3.6	9.8	15.3	13.4	9.0	7.5	9.8
4.5	3.6	9.5	15.2	13.4	9.0	7.5	9.7
5	3.6	9.1	15.0	13.4	9.0	7.5	9.6
6	3.6	9.0	14.3	13.3	9.0	7.5	9.5
7	3.6	8.9	13.8	13.2	9.0	7.5	9.3
8	3.6	8.9	13.1	13.1	9.0	7.5	9.2
9	3.6	8.7	12.5	13.0	9.0	7.5	9.1
10	3.6	8.5	11.6	12.9	9.0	7.5	8.9
11	3.6	8.4	11.1	12.4	9.0	7.5	8.7
12	3.6	8.1	10.2	12.1	9.0	7.5	8.4
13	3.6	8.0	9.6	11.3	9.0	7.5	8.2
14	3.6	7.4	9.3	10.8	9.0	7.5	8.0
15	3.6	7.0	9.0	10.6	9.0	7.5	7.8
16	3.6	6.6	8.7	10.3	9.0	7.5	7.6
17	3.6	6.4	8.3	9.7	8.9	7.5	7.4
18	3.6	6.3	8.1	9.0	8.9	7.5	7.2
19	3.6	6.2	7.6	8.5	8.9	7.5	7.1
20	3.6	6.0	7.4	8.1	8.9	7.5	6.9
21	3.6	5.8	7.1	7.7	8.9	7.5	6.8
22	3.6	5.7	6.9	7.4	8.9	7.5	6.7
23	3.6	5.4	6.6	7.2	8.8	7.5	6.5
24	3.6	5.3	6.4	7.0	8.8	7.5	6.4
25	3.6	5.2	6.2	6.9	8.7	7.5	6.4
30	3.6	5.0	5.8	6.4	8.5	7.5	6.1
35	3.6	4.8	5.5	6.0	7.7	7.5	5.8
40	3.6	4.6	5.3	5.6	7.2	7.5	5.6
45	3.6	4.5	5.1	5.4	6.8	7.4	5.5
50	3.6	4.5	4.9	5.1	6.5	7.4	5.3

Table 3.–Monthly average dissolved oxygen (mg/L) measurements from Karluk Lake, 2013.

	Month						Seasonal
Depth (m)	May	June	July	August	Sept	Oct	Average
0.1	14.2	13.0	10.6	10.7	11.2	11.5	11.9
0.5	14.2	13.0	10.7	10.7	11.2	11.5	11.9
1	14.2	13.1	10.7	10.7	11.2	11.5	11.9
1.5	14.2	13.1	10.8	10.7	11.2	11.4	11.9
2	14.2	13.1	10.8	10.7	11.2	11.4	11.9
2.5	14.2	13.1	10.8	10.7	11.2	11.4	11.9
3	14.2	13.2	10.9	10.7	11.1	11.4	11.9
3.5	14.2	13.1	10.9	10.7	11.1	11.4	11.9
4	14.2	13.2	10.9	10.7	11.1	11.4	11.9
4.5	14.2	13.3	11.0	10.7	11.1	11.4	11.9
5	14.2	13.5	11.0	10.7	11.1	11.4	12.0
6	14.1	13.6	11.1	10.7	11.1	11.4	12.0
7	14.1	13.6	11.2	10.7	11.1	11.3	12.0
8	14.1	13.6	11.5	10.7	11.1	11.3	12.1
9	14.1	13.7	11.7	10.7	11.0	11.3	12.1
10	14.1	13.8	11.8	10.7	11.0	11.3	12.1
11	14.0	13.8	12.0	10.8	11.0	11.3	12.2
12	14.0	13.9	12.3	10.9	11.0	11.3	12.2
13	14.0	13.9	12.5	11.3	11.0	11.2	12.3
14	14.0	13.9	12.6	11.4	11.0	11.2	12.3
15	14.0	13.9	12.6	11.5	11.0	11.2	12.4
16	14.0	13.8	12.7	11.7	10.9	11.2	12.4
17	13.9	13.8	12.7	11.8	10.9	11.2	12.4
18	13.9	13.9	12.7	11.9	10.9	11.1	12.4
19	13.9	13.9	12.9	12.0	10.9	11.1	12.4
20	13.9	13.8	12.8	12.1	10.9	11.1	12.4
21	13.9	13.8	12.9	12.1	10.9	11.1	12.4
22	13.8	13.7	12.9	12.1	10.8	11.1	12.4
23	13.8	13.7	12.9	12.1	10.8	11.0	12.4
24	13.8	13.7	12.8	12.1	10.8	11.0	12.4
25	13.8	13.6	12.8	12.1	10.8	11.0	12.3
30	13.7	13.4	12.7	12.0	10.8	10.9	12.2
35	13.6	13.2	12.5	11.9	10.7	10.9	12.1
40	13.5	13.1	12.4	11.8	10.6	10.8	12.0
45	13.4	13.0	12.3	11.8	10.6	10.7	11.9
50	13.3	12.8	12.2	11.7	10.5	10.6	11.9

Table 4.–Monthly average light penetration (µmol s^{-1} m^{-2}) measurements from Karluk Lake, 2013.

	Date						Seasonal
Depth (m)	21-May	20-Jun	25-Jul	21-Aug	27-Sep	21-Oct	Average
0.1	133.3	383.3	889.7	158.7	54.2	53.0	278.7
0.5	117.1	316.7	774.3	135.4	38.6	41.1	237.2
1	107.9	285.0	654.0	108.7	34.6	30.1	203.4
1.5	99.1	281.0	580.0	91.7	26.9	25.0	183.9
2	95.2	247.7	510.3	80.8	24.9	23.0	163.6
2.5	84.7	222.3	428.7	72.5	22.5	20.6	141.9
3	74.0	189.0	381.7	64.4	21.2	18.7	124.8
3.5	65.1	141.0	345.0	60.1	19.7	17.1	108.0
4	61.0	112.5	314.7	56.3	18.3	16.0	96.5
4.5	54.7	101.8	287.0	51.9	17.4	15.2	88.0
5	49.3	94.6	252.3	48.8	16.5	14.1	79.3
6	45.1	89.1	216.3	41.8	14.6	12.3	69.9
7	38.1	59.4	180.3	35.5	12.6	10.3	56.0
8	31.5	48.4	152.3	30.3	10.7	8.7	47.0
9	25.4	42.2	127.8	25.9	9.1	7.1	39.6
10	20.9	31.1	106.0	22.0	7.6	5.9	32.3
11	17.3	26.2	81.8	18.4	6.5	5.0	25.9
12	14.2	24.4	70.4	16.0	5.5	4.2	22.4
13	11.3	21.0	58.6	13.1	4.7	3.6	18.7
14	9.0	13.6	47.8	10.9	4.0	3.0	14.7
15	7.4	10.8	38.6	9.1	3.4	2.4	11.9
16	6.1	8.7	30.0	7.6	2.8	2.1	9.6
17	5.0	6.9	25.6	6.4	2.4	1.7	8.0
18	4.1	5.6	21.2	5.4	2.0	1.5	6.6
19	3.4	4.5	16.6	4.5	1.7	1.3	5.3
20	2.9	3.6	13.5	3.8	1.4	1.0	4.4
21	2.4	3.0	10.9	3.2	1.2	1.0	3.6
22	2.0	2.4	8.9	2.7	1.0	0.7	3.0
23	1.7	2.0	6.9	2.3	0.8	0.6	2.4
24	1.4	1.6	5.7	1.9	0.7	0.5	2.0
25	1.1	1.3	4.7	1.6	0.6	0.4	1.6
26	1.0	1.1	3.8	1.3	0.5	0.7	1.5
27	0.8	0.9	3.0	1.1	0.4	0.5	1.2
28	0.6	0.8	2.5	0.9	0.4	0.3	1.0
29	0.5	1.1	2.0	0.7	0.4		0.9
30							

Table 5.–Monthly average euphotic zone depth and euphotic volume estimates for Karluk Lake, 2013.

Month	Euphotic zone depth (m)	Euphotic volume (x 10^6 m^3)
May	24.17	760
June	20.05	635
July	21.96	692
August	25.08	785
September	25.63	797
October	23.22	732

Table 6.–Monthly and seasonal station averages of water chemistry data at depth from Karluk Lake, 2013.

Depth	Sample type	May	June	July	August	September	October	Seasonal average	SE
1 meter									
	pH	8.25	8.68	8.21	7.77	7.32	7.55	7.96	0.08
	Alkalinity (mg/L $CaCO_3$)	20.3	22.4	23.1	22.8	23.9	23.4	22.7	0.21
	Total phosphorous (µg/L P)	6.8	5.1	3.1	2.9	5.6	6.5	5.0	0.28
	Total filterable phosphorous (µg/L P)	1.8	1.9	1.6	2.7	1.9	2.8	2.1	0.09
	Filterable reactive phosphorous (µg/L P)	0.8	0.9	1.1	0.9	0.5	1.5	1.0	0.06
	Total Kjeldahl nitrogen (µg/L N)	985.3	896.7	999.7	1179.3	1219.7	1062.7	1057.2	20.49
	Ammonia (µg/L N)	9.0	6.2	25.2	24.1	11.3	5.3	13.5	1.48
	Nitrate + nitrite (µg/L N)	49.8	21.7	1.7	1.9	26.6	53.6	25.9	3.74
	Organic silicon (µg/L)	65.4	125.0	166.2	153.3	173.0	129.7	135.4	6.55
	Chlorophyll *a* (µg/L)	2.51	1.17	0.53	0.64	1.17	0.91	1.16	0.12
	Phaeophytin *a* (µg/L)	0.33	0.39	0.14	0.18	0.35	0.21	0.27	0.02
Hypolimnion									
	pH	8.20	8.47	7.93	7.78	7.41	7.65	7.91	0.06
	Alkalinity (mg/L $CaCO_3$)	20.4	21.7	22.7	22.8	24.3	23.7	22.6	0.23
	Total phosphorous (µg/L P)	7.0	6.2	7.2	4.5	6.4	7.8	6.5	0.19
	Total filterable phosphorous (µg/L P)	2.0	2.0	1.8	2.0	1.8	2.7	2.0	0.06
	Filterable reactive phosphorous (µg/L P)	0.8	0.8	0.6	0.7	0.9	1.4	0.9	0.05
	Total Kjeldahl nitrogen (µg/L N)	703.0	948.0	1099.3	1126.0	1185.0	1150.7	1035.3	30.38
	Ammonia (µg/L N)	9.1	10.3	48.6	50.3	12.3	6.0	22.8	3.46
	Nitrate + nitrite (µg/L N)	50.8	45.5	39.3	37.8	36.2	55.8	44.2	1.31
	Organic silicon (µg/L)	198.9	101.4	129.9	132.9	145.5	97.4	134.3	6.13
	Chlorophyll *a* (µg/L)	3.19	2.29	3.09	2.19	1.12	0.91	2.13	0.16
	Phaeophytin *a* (µg/L)	0.44	0.77	0.64	0.28	0.22	0.29	0.44	0.04

Table 7.–Monthly phytoplankton biovolumes by phylum for Karluk Lake, 2013.

	Month						Seasonal average
Phyla	May	June	July	August	September	October	(mm^3/L)
Bacillariophyta	176,894	30,864	6,108	3,549	96,079	34,896	58,065
Chlorophyta	6,136	61,324	20,981	523	2,868	3,088	15,820
Chrysophyta	2,382	1,234	524	15,359	8,771	4,916	5,531
Cryptophyta	1,175	277	-	967	8,637	3,030	2,348
Cyanobacteria	382	403	455	232	2,878	4,213	1,427
Euglenophyta	1,012	-	1,441	7,616	-	3,155	2,204
Pyrrophyta	54,768	-	94	1,536	89,462	-	24,310
Monthly total	242,749	94,102	29,604	29,783	208,694	53,298	109,705

Table 8.–Annual seasonal average phytoplankton biovolumes by phylum for Karluk Lake, 2004-2006 and 2010-2013.

Phyla	Seasonal average (mm³/L)							Historical average
	2004	2005[a]	2006	2010[a]	2011	2012	2013	
Bacillariophyceae (Diatoms)	40,933	42,630	12,480	7,697	4,365	108,971	58,065	39,306
Chlorophyta	961	2,373	235	670	5	17,547	15,820	5,373
Chrysophyta	5,498	5,575	7,629	806	60	-	5,531	3,586
Cryptophyta	3,538	4,490	2,380	305	18	94,561	2,348	15,377
Cyanobacteria	54	19	3	5	45	2,331	1,427	555
Dinophyta	-	-	-	-	103	-	-	15
Euglenophyta	-	236	1,129	-	3	60,150	2,204	9,103
Haptophyta	6,915	6,600	5,608	-	-	-	-	2,732
Pyrrhophyta	9,347	12,925	12,550	4,299	-	134,159	24,310	28,227
Total	67,246	74,847	42,013	13,783	4,600	417,719	109,705	104,273

[a] May samples were not collected.

Table 9.–Monthly average zooplankton abundance (number/m²) from Karluk Lake, 2013.

Taxon	Date						Seasonal average
	21-May	20-Jun	25-Jul	21-Aug	27-Sep	21-Oct	
Copepods:							
Diaptomus	60,775	88,464	173,921	171,267	210,169	311,837	169,405
Ovig. *Diaptomus*	-	-	-	9,908	-	-	1,651
Cyclops	745,223	728,946	391,698	360,226	354,897	351,292	488,713
Ovig. *Cyclops*	70,594	84,218	80,370	58,740	23,708	16,454	55,681
Harpaticus	-	-	-	708	-	-	118
Nauplii	249,779	52,371	101,822	199,575	404,879	261,766	211,699
Total copepods:	1,126,371	953,999	747,811	800,425	993,653	941,348	927,268
Cladocerans:							
Bosmina	10,483	14,862	118,940	243,454	158,462	114,119	110,053
Ovig. *Bosmina*	2,654	2,831	708	708	1,172	1,239	1,552
Daphnia longiremis	10,041	11,323	148,377	220,099	217,755	296,267	150,644
Ovig. *Daphnia longiremis*	1,017	2,123	17,162	53,079	28,397	23,355	20,855
Immature cladocerans	9,156	40,340	118,874	99,788	34,479	52,548	59,197
Total cladocerans:	33,351	71,479	404,061	617,127	440,265	487,527	342,301
Total copepods + cladocerans	1,159,722	1,025,478	1,151,871	1,417,551	1,433,917	1,428,875	1,269,569

Table 10.–Monthly average zooplankton biomasses (mg/m^2) from Karluk Lake, 2013.

Taxon	Date						Seasonal average	Seasonal weighted average
	21-May	20-Jun	25-Jul	21-Aug	27-Sep	21-Oct		
Copepods:								
Diaptomus	206	417	732	359	349	418	413	379
Ovig. *Diaptomus*	-	-	-	71	-	-	12	12
Cyclops	1,256	1,032	682	498	398	472	723	708
Ovig. *Cyclops*	256	382	332	253	104	81	235	233
Harpaticus	-	-	-	1	-	-	0.1	0.1
Total copepods:	1,718	1,830	1,746	1,182	851	971	1,383	1,332
Cladocerans:								
Bosmina	20	26	229	387	273	206	190	189
Ovig. *Bosmina*	8	7	1	1	1	1	3	3
Daphnia longiremis	20	28	259	312	309	423	225	225
Ovig. *Daphnia longiremis*	5	11	69	134	67	62	58	58
Total cladocerans:	52	72	558	835	650	692	477	475
Total copepods + cladocerans	1,771	1,902	2,304	2,017	1,501	1,663	1,860	1,807

Table 11.–Seasonal averages of zooplankton lengths (mm) from Karluk Lake, 2013.

Taxon	Date						Seasonal average length	Weighted average length
	21-May	20-Jun	25-Jul	21-Aug	27-Sep	21-Oct		
Copepods:								
Diaptomus	0.91	1.03	0.98	0.77	0.71	0.67	0.85	0.79
Ovig. *Diaptomus*	-	-	-	1.20	-	-	1.20	1.20
Cyclops	0.68	0.66	0.71	0.64	0.56	0.63	0.65	0.65
Ovig. *Cyclops*	1.00	1.11	1.07	1.09	1.10	1.13	1.08	1.07
Harpaticus	-	-	-	0.53	-	-	0.53	0.53
Cladocerans:								
Bosmina	0.43	0.41	0.46	0.41	0.42	0.44	0.43	0.43
Ovig. *Bosmina*	0.55	0.52	0.36	0.44	0.36	0.36	0.43	0.47
Daphnia longiremis	0.69	0.65	0.64	0.58	0.59	0.58	0.62	0.60
Ovig. *Daphnia longiremis*	1.02	1.07	0.96	0.76	0.74	0.78	0.89	0.79

Table 12.–Karluk Lake AUV and traditionally collected mean temperature data, by depth, month, and region, 2013.

Region	Depth (m)		May AUV	May Traditional	June AUV	June Traditional	July AUV	July Traditional	August AUV	August Traditional	September AUV	September Traditional
Upper												
	Surface	°C	4.3	4.0	11.6	11.3	17.3	17.0	ND	13.6	9.2	9.1
		SD	0.36	-	0.50	-	0.87	-	ND	-	0.11	-
	1-m	°C	4.1	4.0	11.3	11.3	16.6	16.9	ND	13.6	9.2	9.2
		SD	0.19	-	0.44	-	0.90	-	ND	-	0.12	-
	5-m	°C	3.9	4.0	10.2	11.0	14.4	15.5	ND	13.6	9.2	9.3
		SD	0.09	-	0.78	-	0.48	-	ND	-	0.12	-
Middle												
	Surface	°C	4.0	3.4	12.2	9.5	17.3	16.1	ND	13.5	9.4	9.2
		SD	0.62	-	1.22	-	1.17	-	ND	-	0.16	-
	1-m	°C	3.6	3.4	12.3	9.4	15.9	16.0	ND	13.5	9.3	9.2
		SD	0.46	-	1.11	-	0.50	-	ND	-	0.17	-
	5-m	°C	4.4	3.4	10.6	8.2	14.2	14.8	ND	13.3	9.4	9.2
		SD	0.33	-	0.23	-	0.15	-	ND	-	0.07	-
Lower												
	Surface	°C	3.3	3.4	8.2	9.5	16.4	16.3	ND	13.4	9.2	8.6
		SD	0.02	-	1.79	-	0.59	-	ND	-	0.11	-
	1-m	°C	3.3	3.4	7.8	9.5	15.6	15.9	ND	13.4	9.2	8.6
		SD	0.02	-	1.35	-	0.29	-	ND	-	0.10	-
	5-m	°C	3.3	3.4	6.9	8.2	15.2	14.8	ND	13.3	9.1	8.6
		SD	0.02	-	0.78	-	0.27	-	ND	-	0.16	-

Note: Traditionally collected data values are from a sample size of one precluding SD calculation.

Table 13.–Karluk Lake AUV and traditionally collected mean dissolved oxygen data, by depth, month, and region, 2013.

Region	Depth (m)		May AUV	May Traditional	June AUV	June Traditional	July AUV	July Traditional	August AUV	August Traditional	September AUV	September Traditional
Upper												
	Surface	mg/L	13.04	14.19	12.22	12.42	10.44	10.61	ND	10.63	10.70	11.21
		SD	0.18	-	0.29	-	0.12	-	ND	-	0.04	-
	1-m	mg/L	13.07	14.19	12.74	12.43	10.65	10.62	ND	10.62	10.68	11.18
		SD	0.06	-	0.52	-	0.30	-	ND	-	0.02	-
	5-m	mg/L	13.07	14.14	12.70	12.52	10.86	10.90	ND	10.59	10.67	11.11
		SD	0.05	-	0.46	-	0.30	-	ND	-	0.03	-
Middle												
	Surface	mg/L	13.17	14.20	12.13	13.07	10.42	10.64	ND	10.72	10.69	11.15
		SD	0.10	-	0.29	-	0.16	-	ND	-	0.09	-
	1-m	mg/L	13.11	14.20	12.06	13.17	10.66	10.71	ND	10.71	10.69	11.16
		SD	0.06	-	0.47	-	0.26	-	ND	-	0.03	-
	5-m	mg/L	13.21	14.16	12.52	13.73	10.86	11.05	ND	10.73	10.71	11.10
		SD	0.05	-	0.17	-	0.10	-	ND	-	0.02	-
Lower												
	Surface	mg/L	13.33	14.21	13.08	13.08	10.54	10.60	ND	10.70	10.67	11.19
		SD	0.04	-	0.35	-	0.10	-	ND	-	0.04	-
	1-m	mg/L	13.33	14.21	13.20	13.10	10.91	10.74	ND	10.71	10.64	11.18
		SD	0.02	-	0.23	-	0.26	-	ND	-	0.02	-
	5-m	mg/L	13.31	14.16	13.27	13.53	10.81	11.01	ND	10.69	10.62	11.12
		SD	0.02	-	0.19	-	0.30	-	ND	-	0.03	-

Note: Traditionally collected data values are from a sample size of one precluding SD calculation.

Table 14.–Karluk Lake AUV and traditionally collected mean pH data, by depth, month, and region, 2013.

			May		June		July		August		September	
Region	Depth (m)		AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional
Upper												
	Surface	pH	9.10	-	8.77	-	8.47	-	ND	-	8.53	-
		SD	0.23	-	0.14	-	0.08	-	ND	-	0.21	-
	1-m	pH	9.04	8.32	8.79	8.63	8.43	8.16	ND	7.76	8.41	7.48
		SD	0.14	-	0.08	-	0.09	-	ND	-	0.12	-
	5-m	pH	9.01	-	8.81	-	8.46	-	ND	-	8.37	-
		SD	0.15	-	0.08	-	0.10	-	ND	-	0.16	-
Middle												
	Surface	pH	8.60	-	8.65	-	8.43	-	ND	-	8.27	-
		SD	0.11	-	0.14	-	0.09	-	ND	-	0.10	-
	1-m	pH	8.60	8.14	8.58	8.77	8.34	8.21	ND	7.82	8.25	7.33
		SD	0.11	-	0.14	-	0.20	-	ND	-	0.08	-
	5-m	pH	8.50	-	8.61	-	8.28	-	ND	-	8.03	-
		SD	0.03	-	0.06	-	0.11	-	ND	-	0.11	-
Lower												
	Surface	pH	8.69	-	9.05	-	8.50	-	ND	-	8.78	-
		SD	0.11	-	0.15	-	0.08	-	ND	-	0.35	-
	1-m	pH	8.65	8.30	9.06	8.63	8.25	8.25	ND	7.74	8.63	7.15
		SD	0.09	-	0.10	-	0.23	-	ND	-	0.21	-
	5-m	pH	8.59	-	9.02	-	8.30	-	ND	-	8.52	-
		SD	0.13	-	0.09	-	0.27	-	ND	-	0.30	-

Note: Traditionally collected data values are from a sample size of one precluding SD calculation.

Table 15.–Karluk Lake AUV and traditionally collected mean chlorophyll data, by depth, month, and region, 2013.

			May		June		July		August		September	
Region	Depth (m)		AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional
Upper												
	Surface	µg/L	1.58	-	2.24	-	2.97	-	ND	-	1.83	-
		SD	5.93	-	5.65	-	11.05	-	ND	-	4.82	-
	1-m	µg/L	1.78	2.24	1.62	0.96	1.50	0.64	ND	0.64	1.14	1.44
		SD	1.46	-	1.10	-	0.87	-	ND	-	0.80	-
	5-m	µg/L	1.16	-	1.23	-	1.26	-	ND	-	1.14	-
		SD	0.80	-	0.69	-	0.72	-	ND	-	0.36	-
Middle												
	Surface	µg/L	4.65	-	7.41	-	1.97	-	ND	-	1.50	-
		SD	20.50	-	30.15	-	7.69	-	ND	-	1.61	-
	1-m	µg/L	1.48	2.72	1.42	1.28	1.13	0.32	ND	0.64	1.45	0.96
		SD	1.15	-	1.05	-	0.85	-	ND	-	1.03	-
	5-m	µg/L	1.49	-	1.49	-	1.30	-	ND	-	1.41	-
		SD	1.09	-	1.05	-	0.94	-	ND	-	1.03	-
Lower												
	Surface	µg/L	1.51	-	2.17	-	1.32	-	ND	-	1.40	-
		SD	1.74	-	6.61	-	1.23	-	ND	-	1.10	-
	1-m	µg/L	1.43	2.56	0.71	1.28	0.58	0.64	ND	0.64	1.61	1.12
		SD	1.07	-	18.00	-	0.39	-	ND	-	1.14	-
	5-m	µg/L	1.49	-	1.25	-	1.48	-	ND	-	1.36	-
		SD	0.95	-	0.78	-	1.27	-	ND	-	0.95	-

Table 16.–Karluk Lake bathymetry statistics, 2013.

Bathymetry statistic	
Area (m^2)	37,284,000
Volume (m^3)	1,907,330,000
Maximum depth (m)	141.8
Average depth (m)	45.1

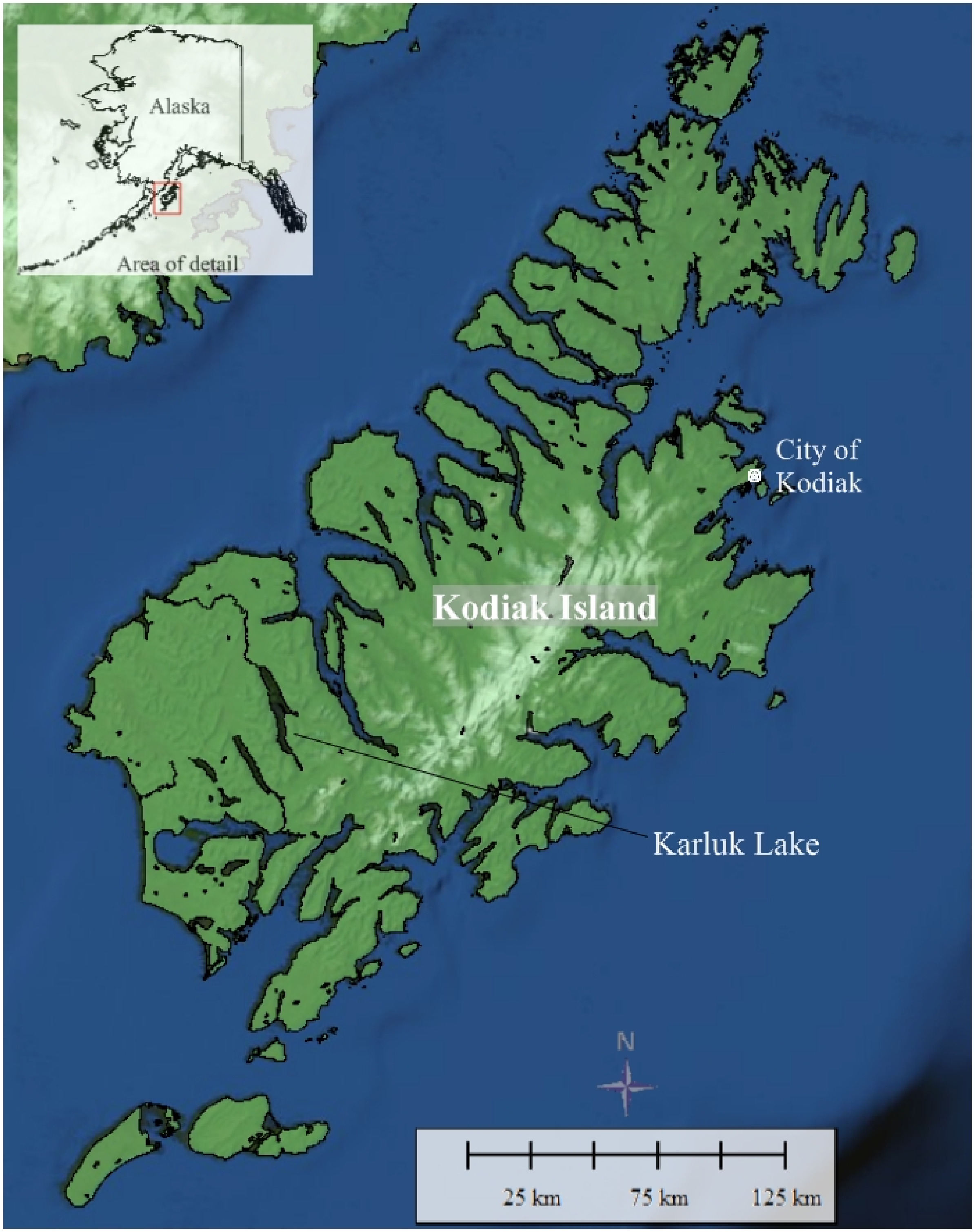


Figure 1.–Map of Kodiak Island, Alaska, highlighting Karluk Lake's location.

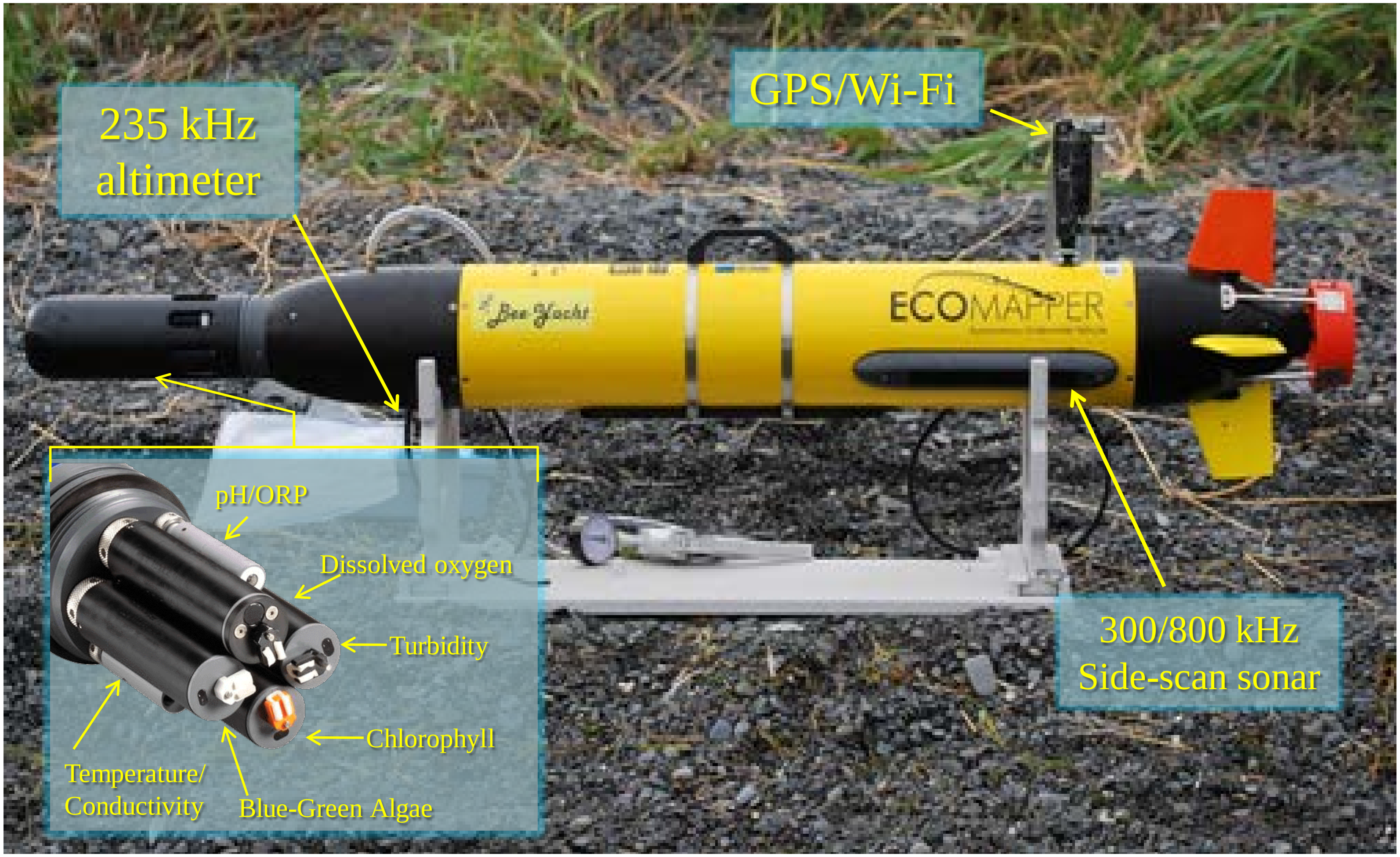


Figure 2.–The AUV and its features.

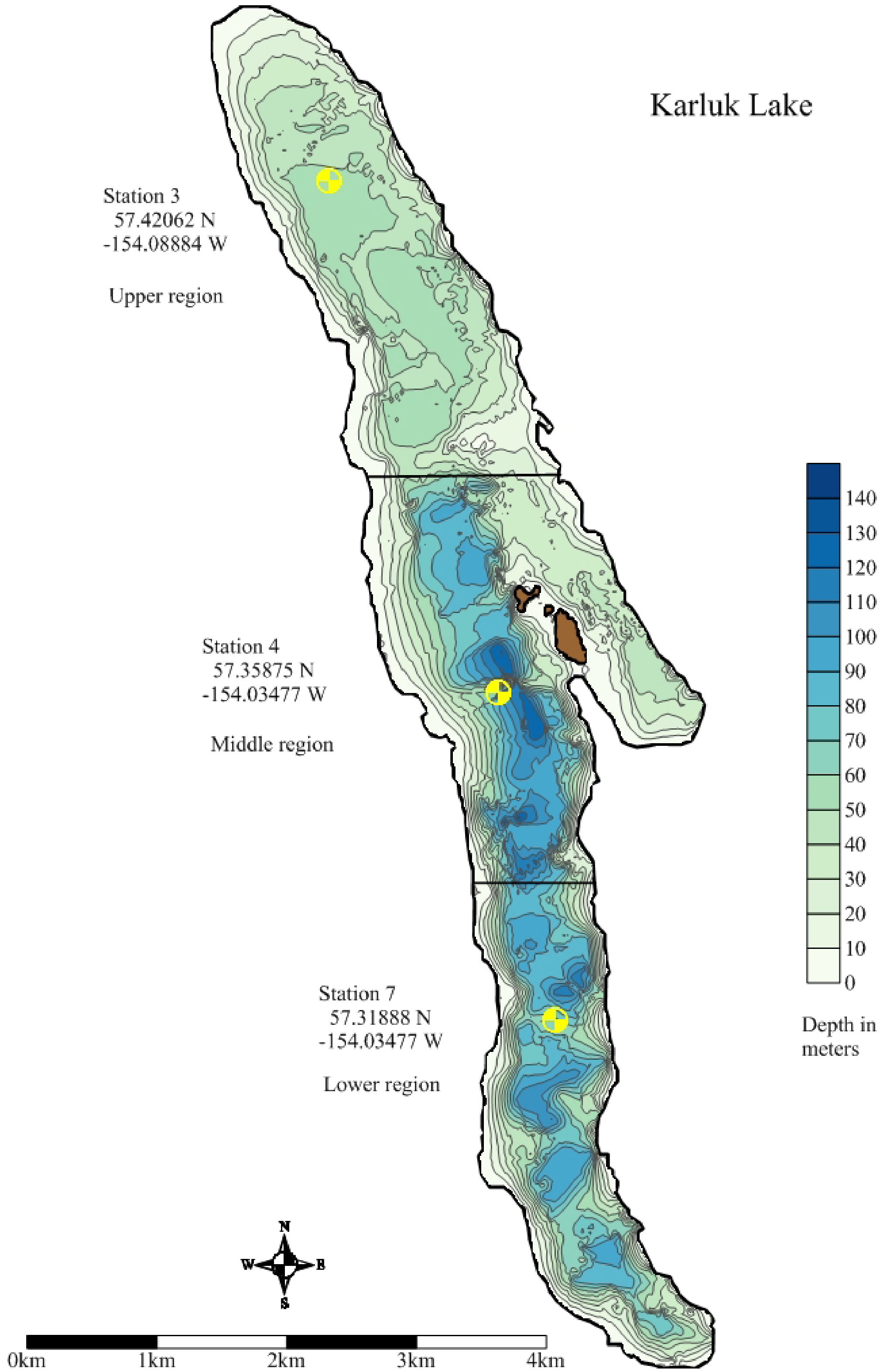


Figure 3.–AUV sampling regions and locations of traditional sampling stations for Karluk Lake, 2013.

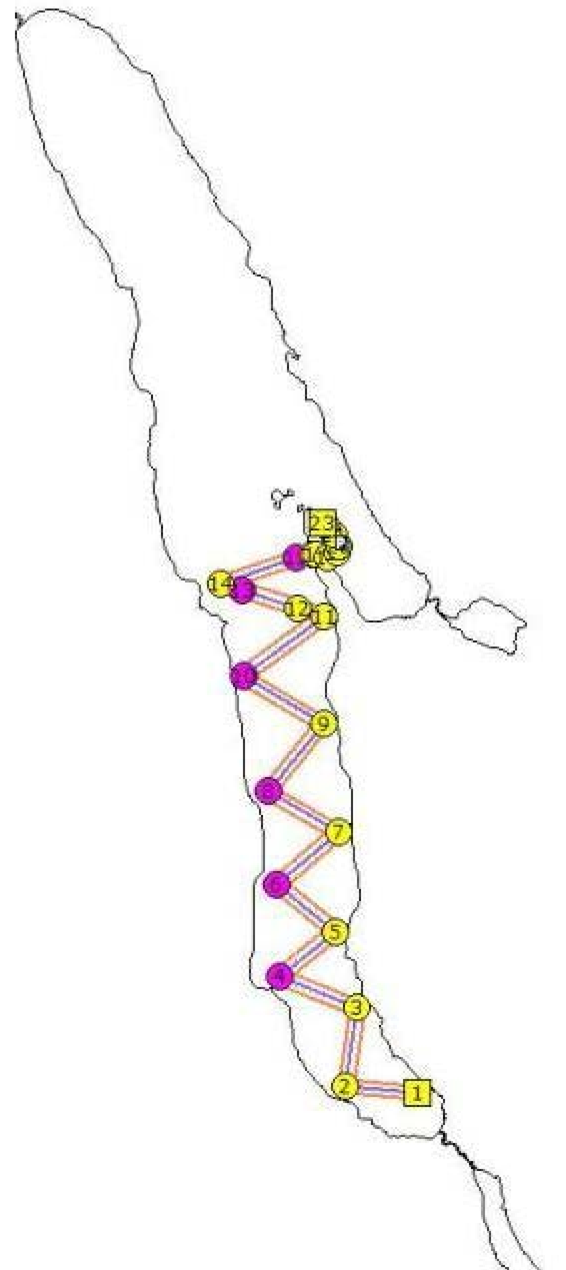


Figure 4.–Example of an AUV mission plotted in Karluk Lake using VectorMap software.

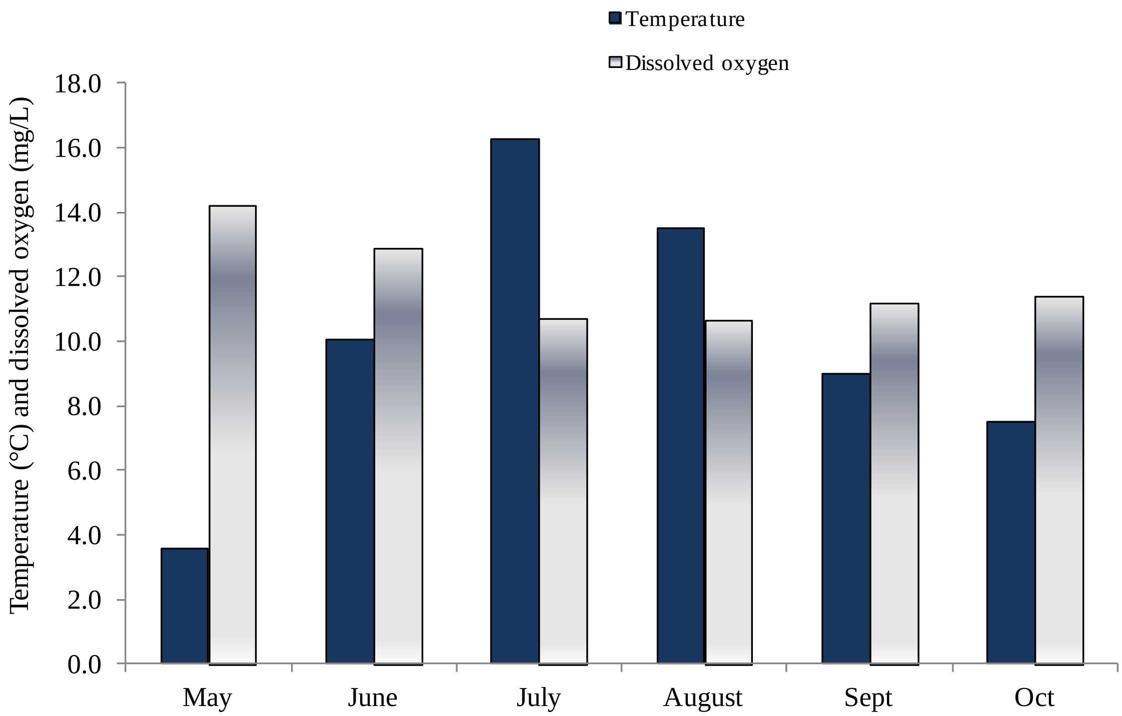


Figure 5.–Seasonal average 1 m temperature and dissolved oxygen measurements from Karluk Lake, 2013.

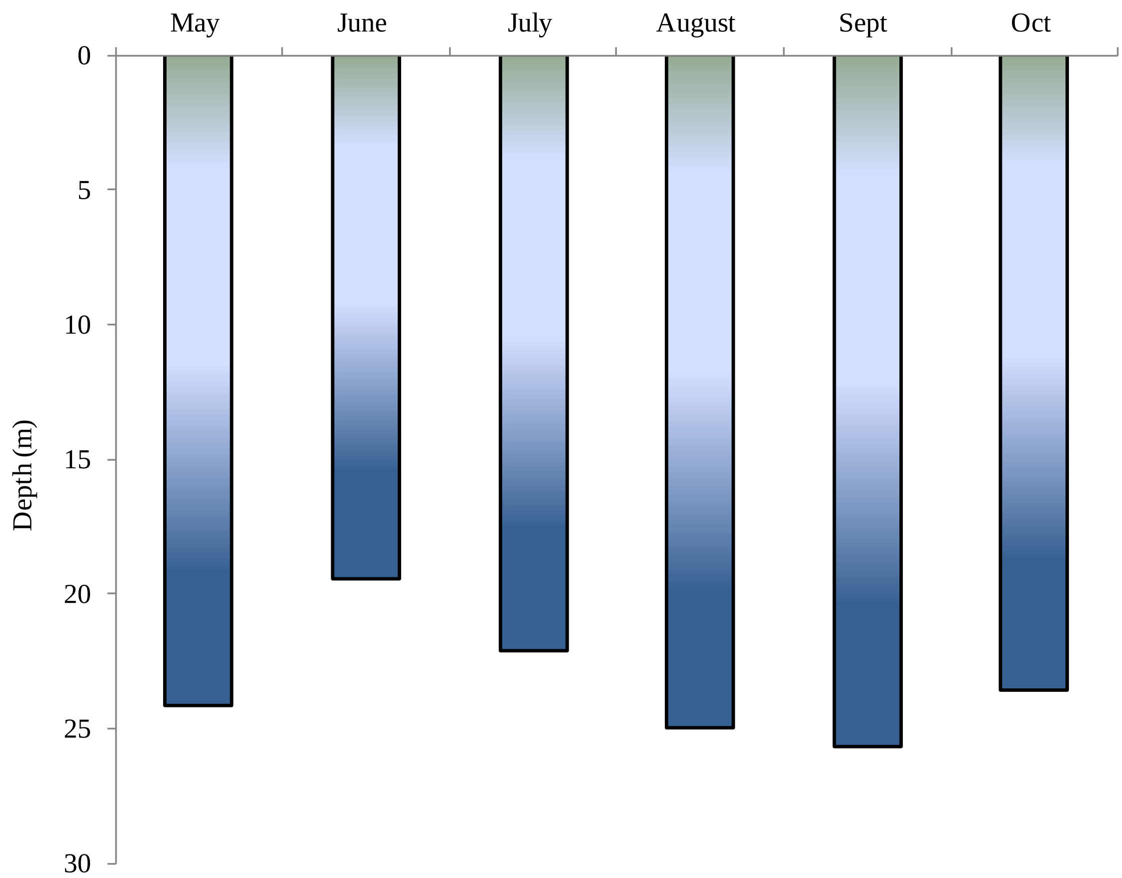


Figure 6.–Seasonal average euphotic zone depth (EZD) for Karluk Lake, 2013.

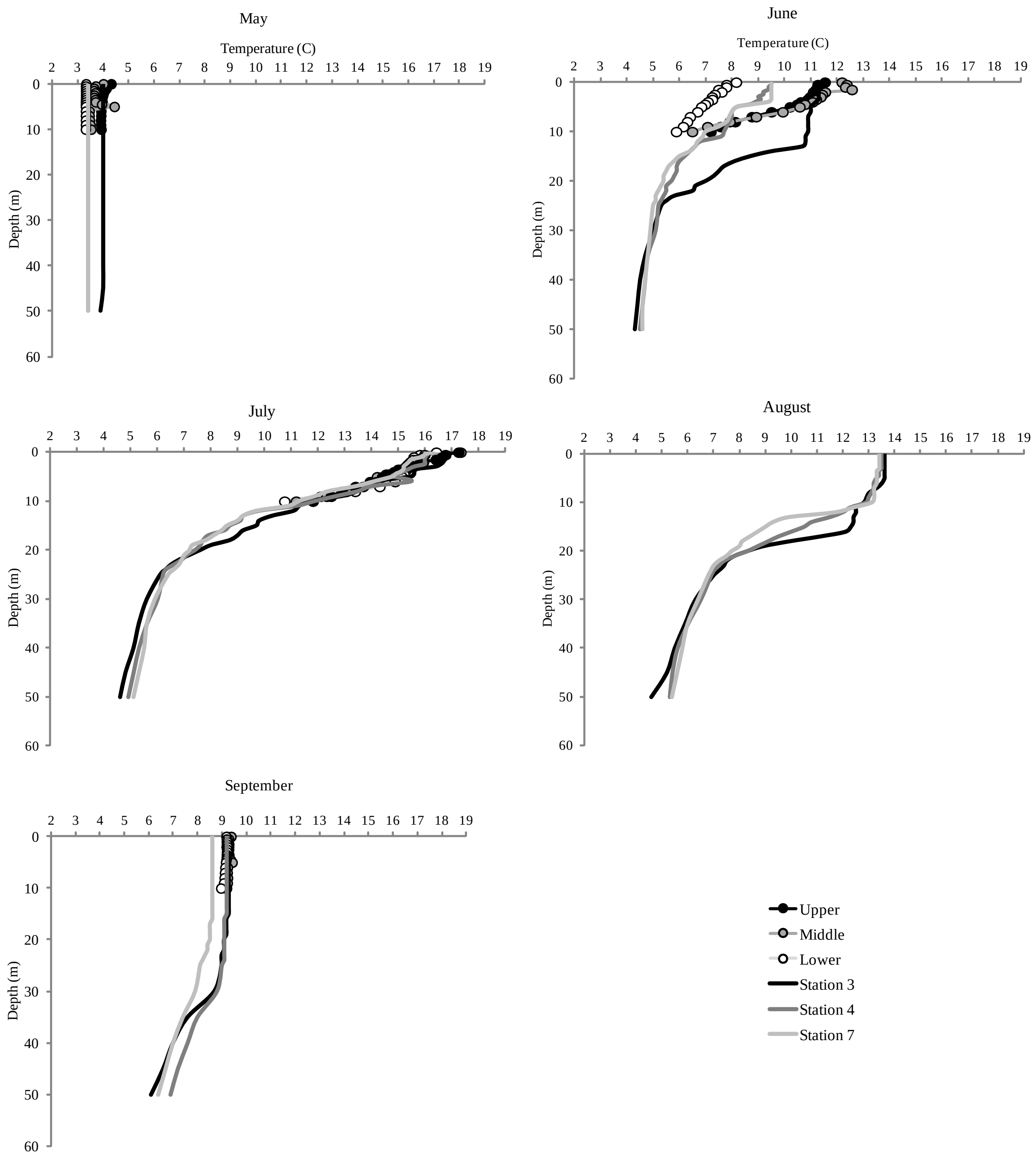


Figure 7.–Karluk Lake AUV (Lower, Middle, Upper) temperature depth profiles by month compared to traditionally collected (Stations 3, 4, and 7) data, 2013.

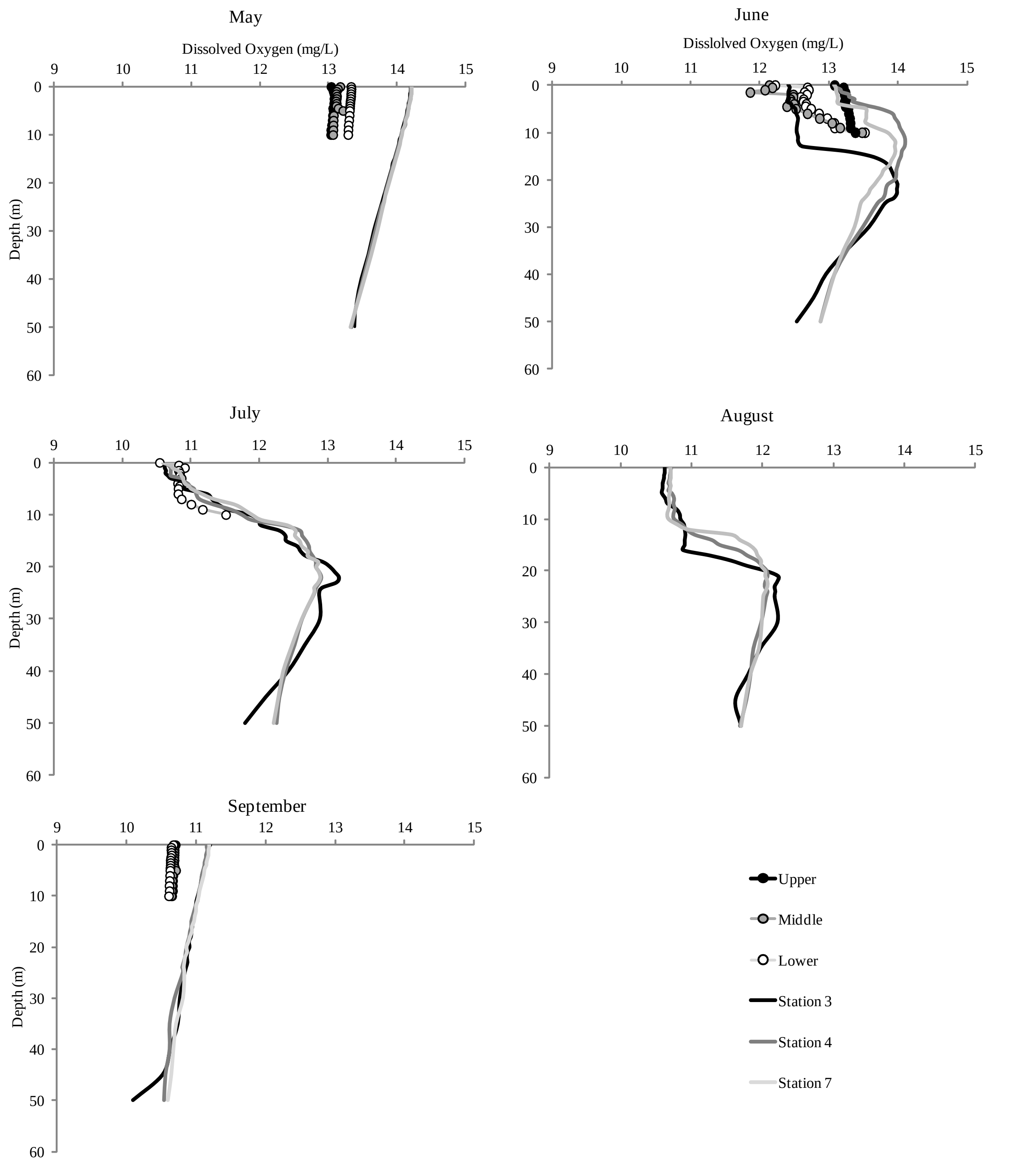


Figure 8.–Karluk Lake AUV (Lower, Middle, Upper) dissolved oxygen depth profiles by month compared to traditionally collected (Stations 3, 4, and 7) data, 2013.

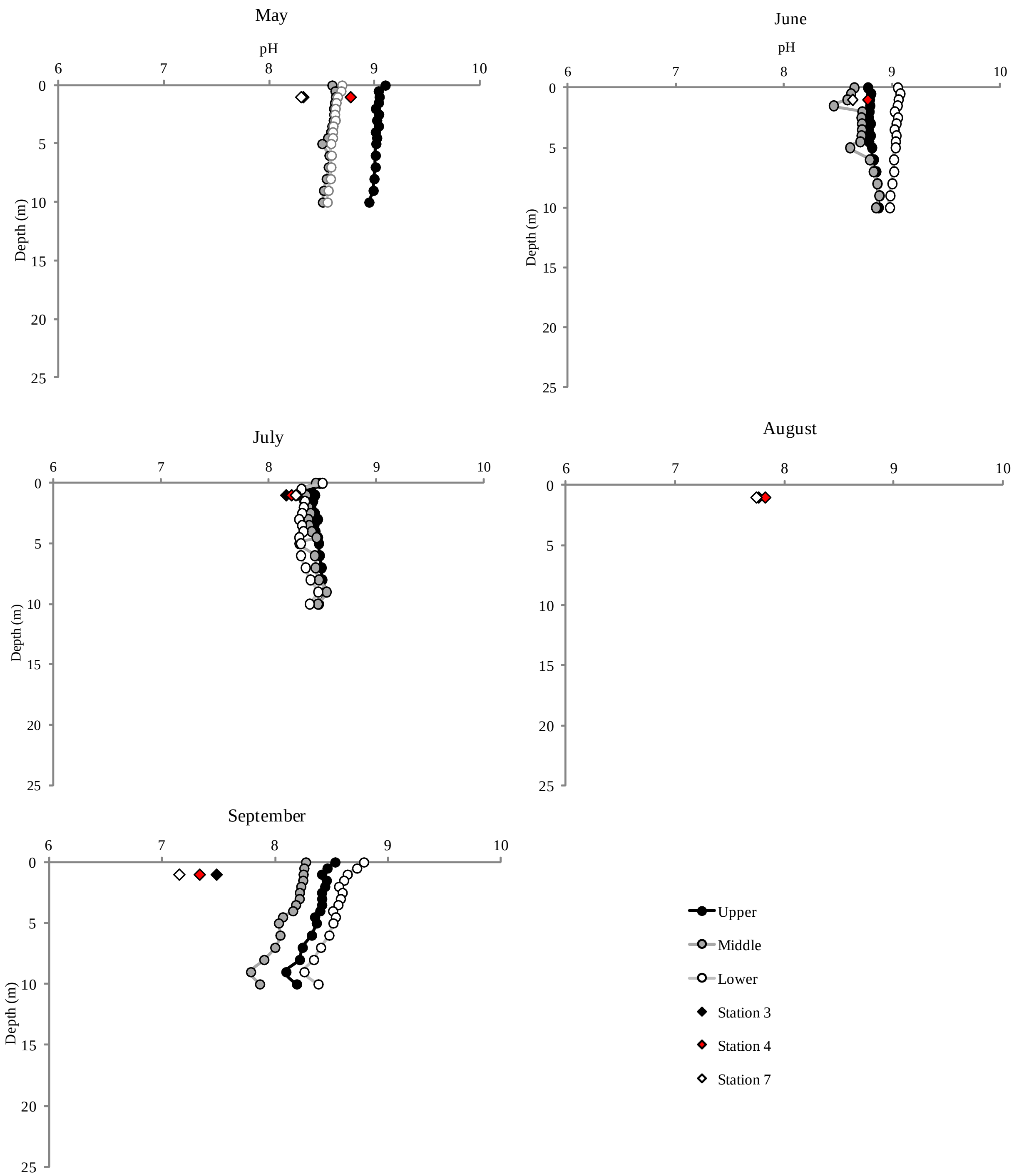


Figure 9.–Karluk Lake AUV (Upper, Middle, Lower) pH depth profiles by month compared to traditionally collected (Stations 3, 4, and 7) data, 2013.

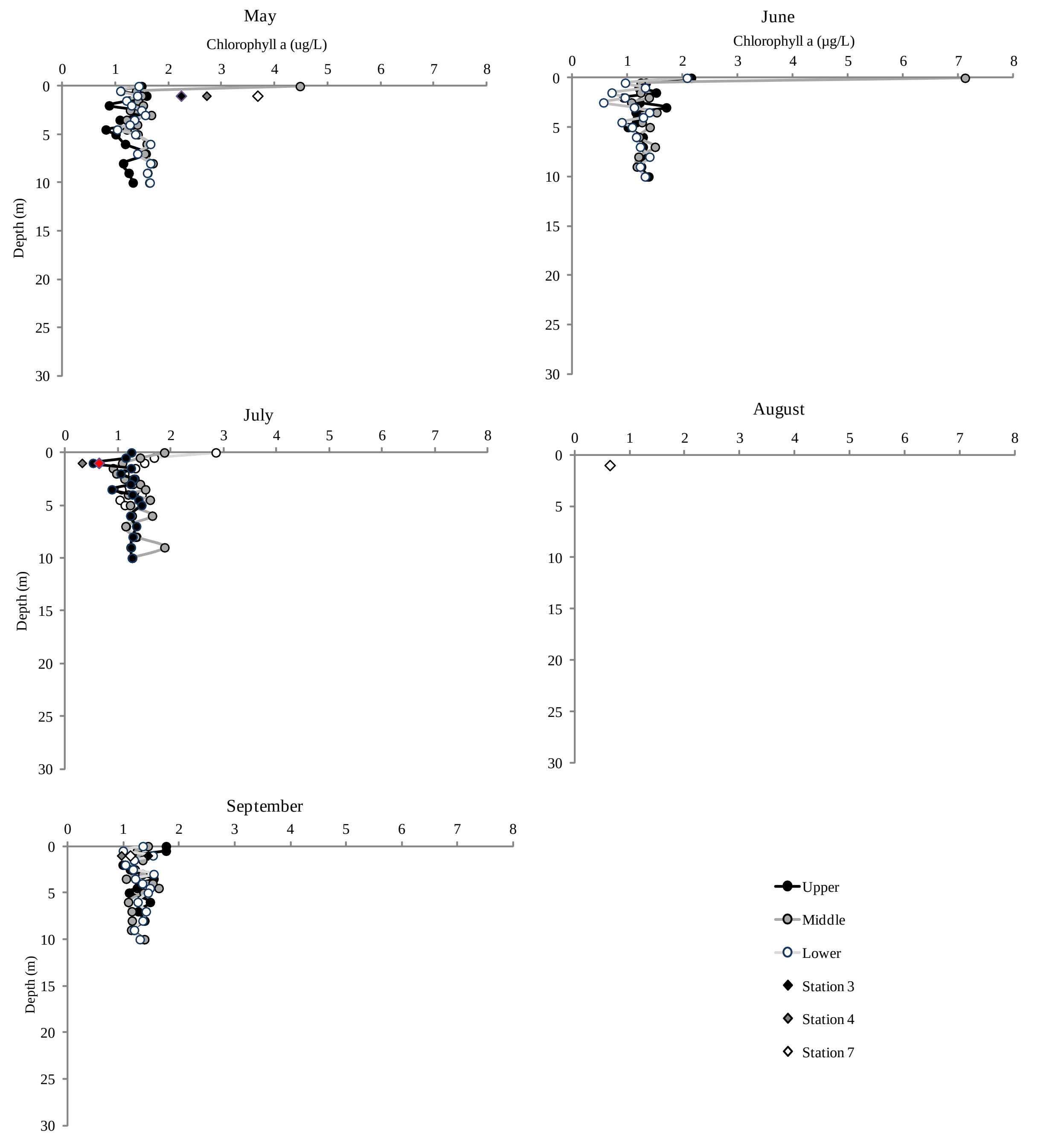


Figure 10.–Karluk Lake AUV (Upper, Middle, Lower) chlorophyll-*a* depth profiles by month compared to traditionally collected (Stations 3, 4, and 7) data for May through September, 2013.

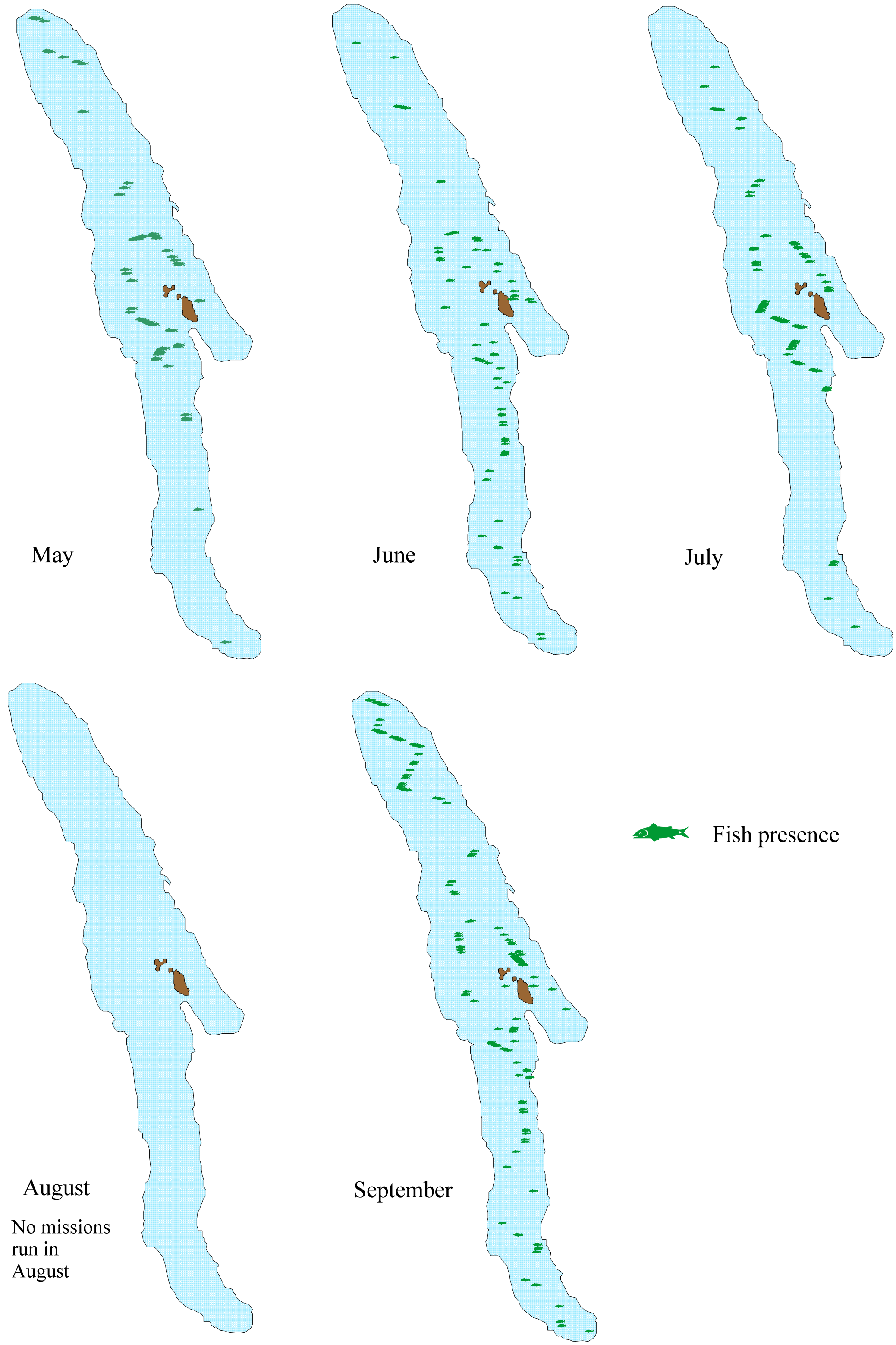


Figure 11.–Map of fish presence by month in Karluk Lake, 2013.

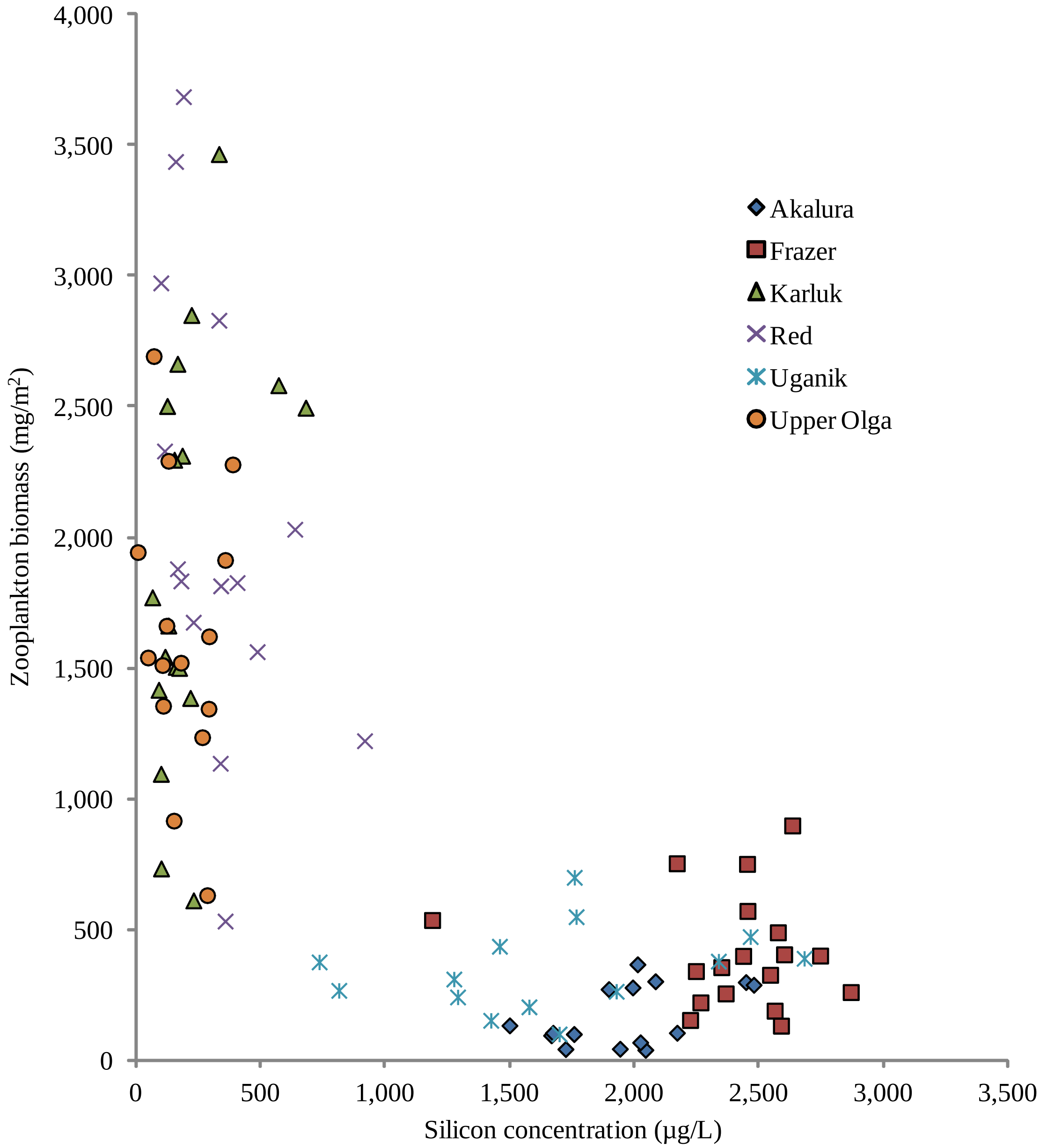


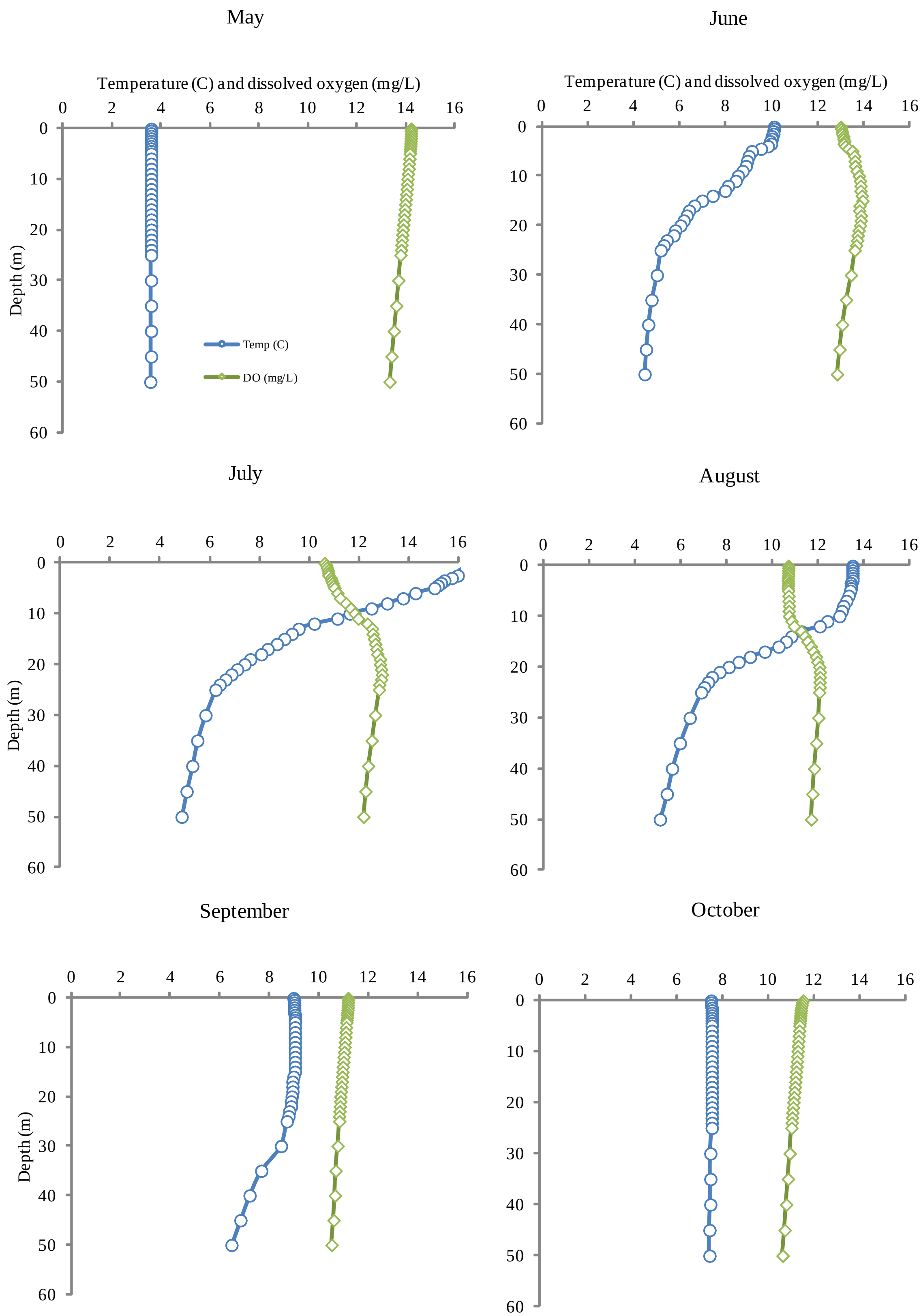
Figure 12.–Monthly zooplankton biomasses relative to silicon concentrations for six Kodiak lakes between 2011 and 2013.

APPENDIX A. KARLUK LAKE MONTHLY LIMNOLOGICAL DATA

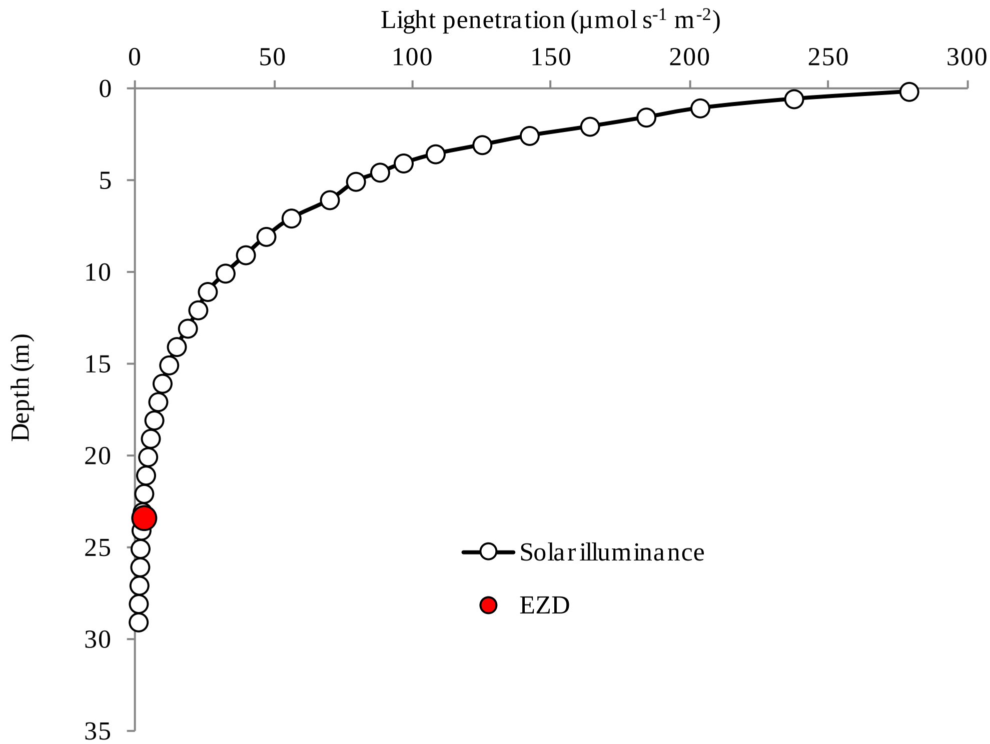
Appendix A1.–Monthly and seasonal averages of 1 m temperature and dissolved oxygen, euphotic zone depth (EZD), and Secchi measurements from Karluk Lake, 2013.

Sample type	May	June	July	August	September	October	Seasonal average
Station 3							
1-m Temperature (°C)	4.0	11.3	16.9	13.6	9.2	7.6	10.4
1-m Dissolved oxygen (mg/L)	14.2	12.4	10.6	10.6	11.2	11.5	11.8
EZD (m)	23.9	17.8	23.2	25.5	25.9	22.3	23.1
Secchi depth (m)	7.0	7.0	12.0	8.5	6.5	9.8	8.5
Station 4							
1-m Temperature (°C)	3.4	9.8	16.0	13.5	9.2	7.5	9.9
1-m Dissolved oxygen (mg/L)	14.2	13.2	10.7	10.7	11.2	11.5	11.9
EZD (m)	24.3	19.9	21.3	25.9	25.5	22.4	23.2
Secchi depth (m)	8.0	7.0	12.0	8.3	7.3	10.8	8.9
Station 7							
1-m Temperature (°C)	3.4	9.5	15.9	13.4	8.6	7.4	9.7
1-m Dissolved oxygen (mg/L)	14.2	13.1	10.7	10.7	11.2	11.4	11.9
EZD (m)	24.3	22.5	21.3	23.8	25.5	25.0	23.7
Secchi depth (m)	6.3	7.3	10.8	8.3	7.0	9.8	8.2

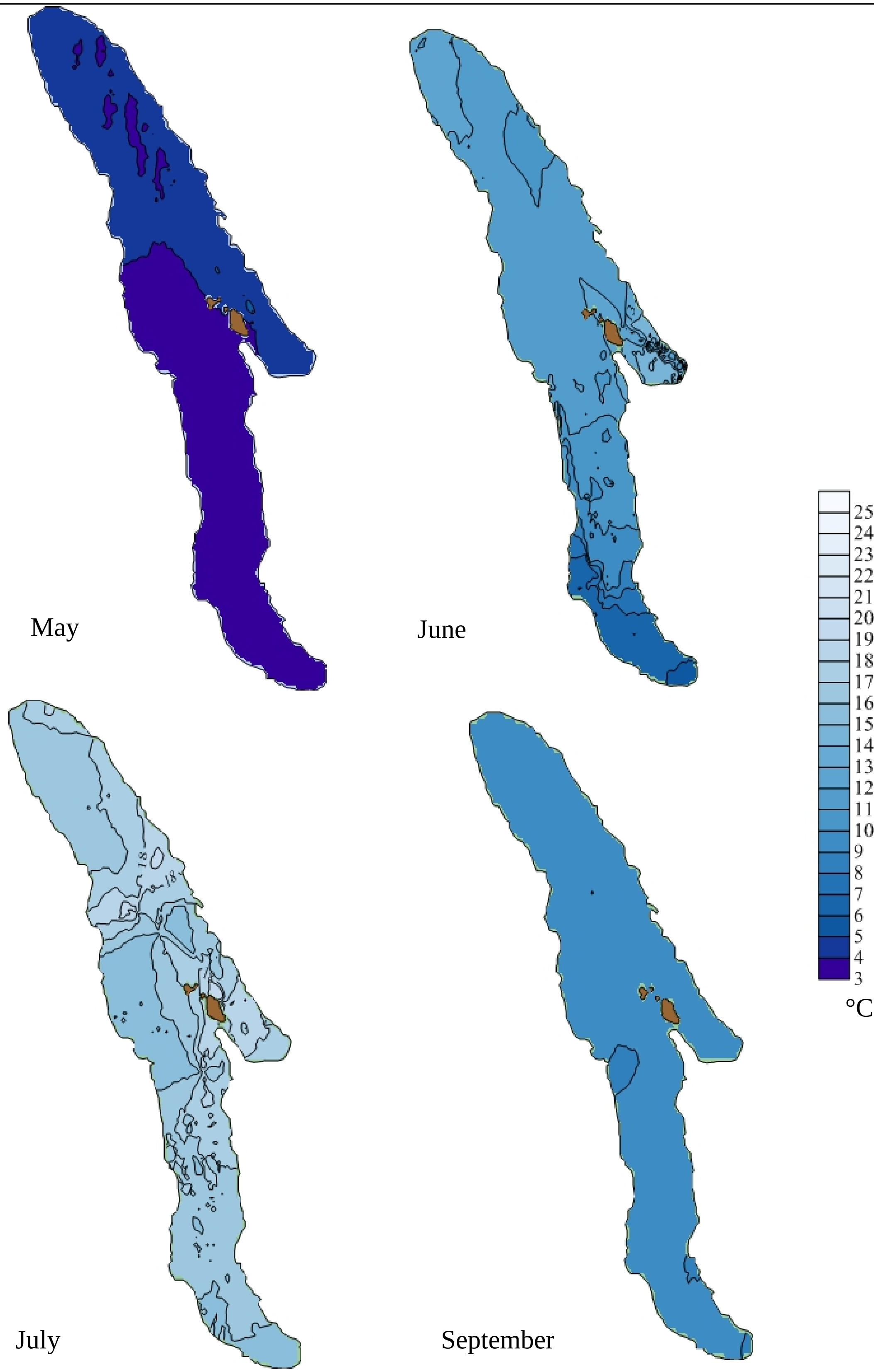
Appendix A2.–Temperature and dissolved oxygen depth profiles by month for Karluk Lake, 2013.



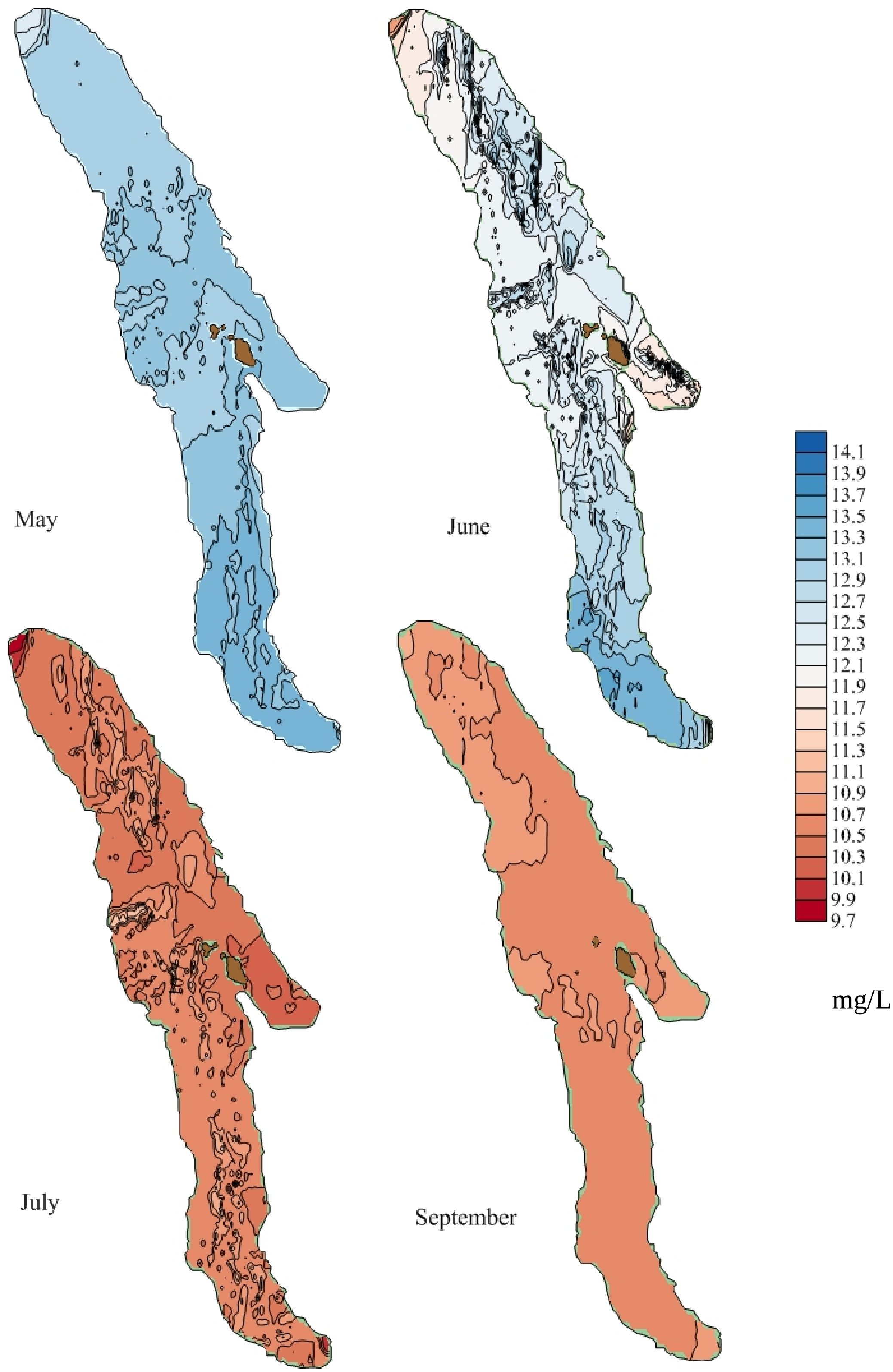
Appendix A3.–Average monthly solar illuminance profile for Karluk Lake, 2013.



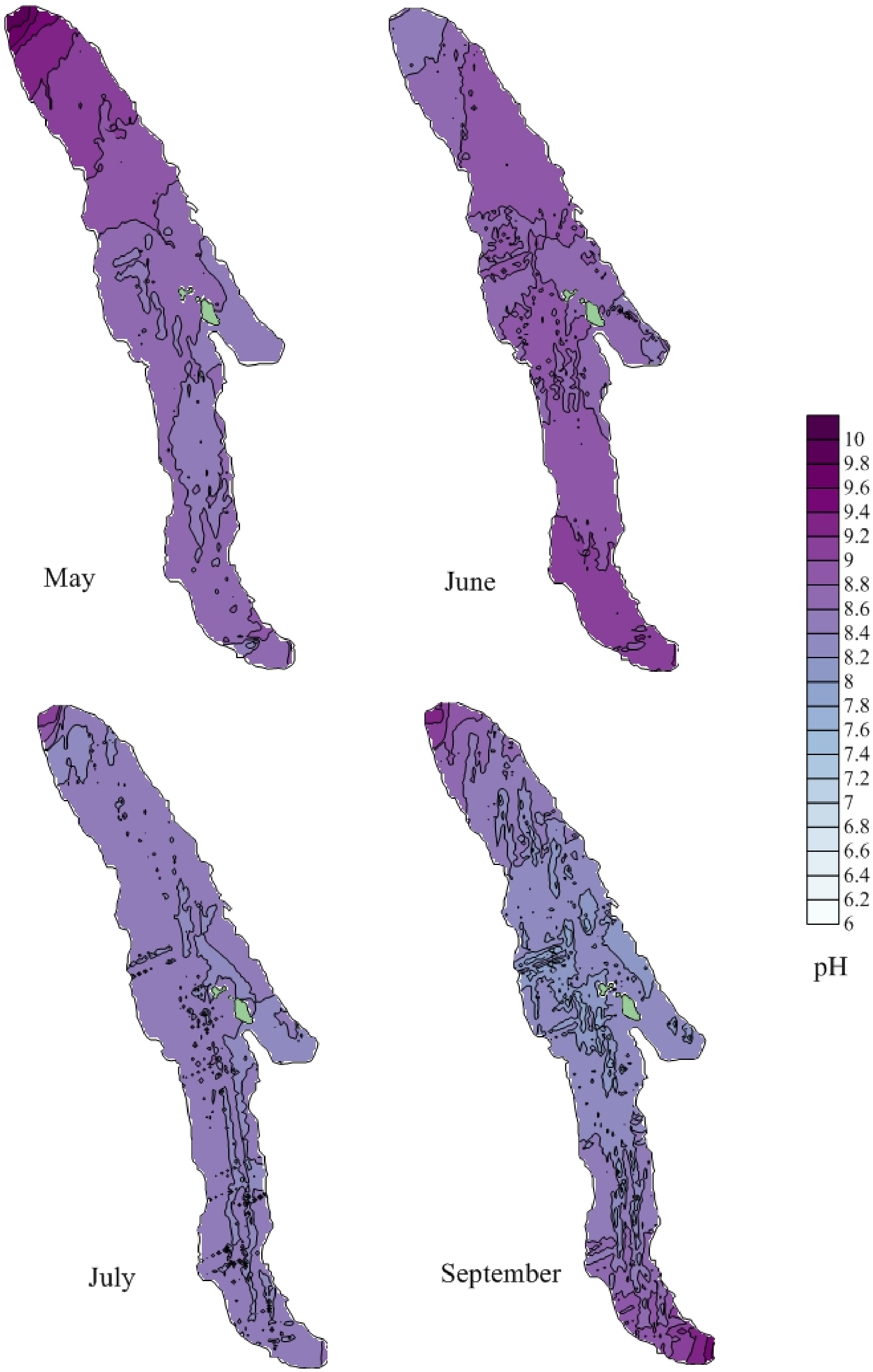
Appendix A4.–Karluk Lake AUV surface temperatures by month, 2013.



Appendix A5.–Karluk Lake AUV surface dissolved oxygen concentrations by month, 2013.



Appendix A6.–Karluk Lake AUV surface pH by month, 2013.



Appendix A7.–Karluk Lake AUV surface chlorophyll concentrations (µg/L) by month, 2013.