Fishery Data Series No. 12-55

Limnological Assessment of Kodiak and Alaska Peninsula Salmon Lakes, 2011

by

Heather Finkle

September 2012

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

Symbols and Abbreviations

The following symbols and abbreviations, and others approved for the Système International d'Unités (SI), are used without definition in the following reports by the Divisions of Sport Fish and of Commercial Fisheries: Fishery Manuscripts, Fishery Data Series Reports, Fishery Management Reports, and Special Publications. All others, including deviations from definitions listed below, are noted in the text at first mention, as well as in the titles or footnotes of tables, and in figure or figure captions.

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

FISHERY DATA SERIES NO. 12-55

LIMNOLOGICAL ASSESSMENT OF KODIAK AND ALASKA PENINSULA SALMON LAKES, 2011

by
Heather Finkle
Alaska Department of Fish and Game, Kodiak

Alaska Department of Fish and Game
Division of Sport Fish, Research and Technical Services
333 Raspberry Road, Anchorage, Alaska, 99518-1565

September 2012

This report was prepared by Heather Finkle 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 author(s) and do not necessarily reflect the views of the National Oceanic and Atmospheric, the U.S. Department of Commerce, or the Alaska Department of Fish and Game.

ADF&G Fishery Data Series was established in 1987 for the publication of Division of Sport Fish technically oriented results for a single project or group of closely related projects, and in 2004 became a joint divisional series with the Division of Commercial Fisheries. Fishery Data Series reports are intended for fishery and other technical professionals and are available through the Alaska State Library and on the Internet: http://www.adfg.alaska.gov/sf/publications/. This publication has undergone editorial and peer review.

Heather Finkle
Alaska Department of Fish and Game, Division of Commercial Fisheries
211 Mission Road, Kodiak, Alaska 99615, USA

This document should be cited as:
Finkle, H. 2012. Limnological assessment of Kodiak and Alaska Peninsula salmon lakes, 2011. Alaska Department of Fish and Game, Fishery Data Series No. 12-55, Anchorage.

TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

LIST OF APPENDICES

Appendix **Page**

LIST OF APPENDICES (Continued)

Appendix **Page**

LIST OF APPENDICES (Continued)

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 6 lakes on Kodiak Island and 2 lakes located on the Alaska Peninsula. Akalura, Frazer, Karluk, Red, Uganik, and Upper Station lakes were sampled on Kodiak Island while Bear and Orzinski lakes were sampled on the Alaska Peninsula. Traditional means of limnological data collection were implemented for all lakes and an autonomous underwater vehicle (AUV) that collects high-resolution spatial and temporal limnological data was deployed in Red and Uganik lakes. Four AUV missions were run in Red Lake (June, July, August, and September) and 2 in Uganik Lake (June and September) concurrent with traditional means of collecting limnological data. AUV-collected limnological data consisted of pH, chlorophyll, dissolved oxygen, temperature, and turbidity 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, nitrate + nitrite, ammonia, chlorophyll-*a*, and phaeophytin-*a* concentrations. Analysis of AUV data revealed variability in physical conditions over lake area and depth in Red and Uganik lakes. Temperature effects appear to be influenced by bathymetry for all lakes. For Kodiak lakes, low levels of silicon coincided with high zooplankton biomasses and vice versa indicating silicon was a vital nutrient for lake productivity.

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

INTRODUCTION

Understanding the dynamism 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, these data often lack the contrast to identify factors that influence run failure or success. 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 Alaska Department of Fish & Game’s (ADF&G) efforts to re-establish baseline data and improve data quality of limnological sampling conducted in 8 lakes on Kodiak Island and the Alaska Peninsula during 2011.

In 2011, this project investigated 6 Kodiak Island lakes (Akalura, Frazer, Karluk, Red, Uganik, and Upper Station lakes; Figure 1) and 2 Alaska Peninsula lakes (Bear and Orzinski lakes; Figure 2), all of which possess sockeye salmon *Oncorhynchus nerka* runs. Lakes such as Akalura, Orzinksi, Red, Uganik, and Upper Station have recent data gaps spanning over 10 consecutive years (Schrof and Honnold 2003), and would benefit from re-established limnological baselines relative to current climatic trends. Bear Lake limnological data, on the other hand, spans 13 continuous years, warranting continued data collection for comparison to adult return data.

Limnological sampling includes the collection of temperature, dissolved oxygen, pH, light penetration, nutrient, and zooplankton data. Collection of these data in all targeted lakes will re-establish a touchstone of habitat conditions in each lake. These data will also allow for comparisons of conditions between lakes respective to levels of 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 valuable, traditionally-collected data sets 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 and Uganik lakes, data from 1 or 2 stations may not accurately reflect the variability of conditions throughout the whole lake (Finkle and Ruhl 2011). 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 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 3). 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 up to every second for up to a 4-hour mission. As 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). With the AUV's capabilities for collecting geo-referenced depth data, it is possible to reassess lake volume and area, which were originally estimated over 30 years ago. Changes in lake volume could create substantially different estimates of optimal salmon escapement in the euphotic volume or zooplankton biomass models (Koenings and Burkett 1987; Koenings and Kyle 1997) used to assess salmon escapement goals for these systems.

Re-establishing baselines and increasing the spatial and temporal metrics of limnological data for Kodiak Island and Alaska Peninsula lakes will eventually lead to better modeling of stock productivity, helping resource managers sustain maximum yields of Alaska's salmon stocks. This report summarizes the second year of traditional limnological data collection in 8 western Alaska lakes and water quality mapping with an AUV in 2 Kodiak Island lake systems that support extensive sport, commercial, and subsistence salmon fisheries.

METHODS

Six lakes (Akalura, Frazer, Karluk, Red, Upper Station, and Uganik) on Kodiak Island and 2 lakes on the Alaska Peninsula (Bear and Orzinski) were sampled for limnological data during 2011 (Figures 1 and 2). The sampling schedules for 2011 are outlined in Tables 1 and 2. Each lake had 1 limnology/zooplankton sampling station, with the exceptions of Bear and Frazer lakes that each had 2 stations, and Karluk Lake, which had 3 stations (Appendices A through H). Water and zooplankton samples and temperature, dissolved oxygen, and light penetration data 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 Thomsen (2008). AUV sampling events were conducted at least 2 times in both Red and Uganik lakes over the field season. Because of the size of Uganik Lake, multiple missions were required during sampling events to map lake parameters. Mapping of Red Lake with the AUV only required a single mission per sampling event. The timing of AUV missions overlapped with that of traditional limnological sampling.

TRADITIONAL LIMNOLOGICAL SAMPLING

Physical Data - Temperature, Dissolved Oxygen, and Light Penetration

Water temperature (°C) and dissolved oxygen (mg/L) levels were measured with a YSI 55 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 20 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's calibration. Measurements of photosynthetically active radiation (PAR) were taken with a photometer above the surface, at the surface, and proceeded at 0.5 m intervals until reaching a depth of 5 m. Readings were then continued at 1 m intervals until the lake bottom or 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 and incorporated into a model for estimating sockeye salmon fry production (Koenings and Kyle 1997). 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 disappears when lowered into the water column and reappeared when raised in the water column were recorded and averaged.

Water Sampling - Nutrients, pH, and Alkalinity

Using a Van Dorn bottle, 4 to 8 L of water were collected from the epilimnion (depth of 1 m) at each station. Water samples were stored in polyethylene (poly) carboys and refrigerated until initial processing.

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 Near Island Laboratory (NIL) in Kodiak.

The water chemistry parameters of pH and alkalinity were assessed with a pH meter. One hundred milliliters of refrigerated lake water were warmed to 25°C and titrated with 0.02-N sulfuric acid following the methods of Thomsen (2008).

All filtered and unfiltered water samples were stored and frozen in clean polyetheylene bottles. Water analyses were performed at the ADF&G NIL for total phosphorous (TP), total ammonia (TA), total filterable phosphorus (TFP), filterable reactive phosphorous (FRP), nitrate + nitrite, chlorophyll *a*, phaeophytin *a*, and silicon. Water sample analyses for Orzinski Lake were restricted to chlorophyll *a* and TP because of logistic constraints associated with being a remote field camp, limited processing abilities, and increased the difficulty of shipping samples for initial processing. Bear Lake water samples were filtered and frozen at the Chignik River weir field laboratory and shipped frozen to the ADF&G NIL for nutrient analyses.

All laboratory analyses adhered to the methods of Koenings et al. (1987) and Thomsen (2008). Total Kjeldahl nitrogen (TKN) cannot be processed at the NIL and was sent to the University of Georgia Feed & Environmental Water Laboratory for processing. Nutrient data were analyzed via linear regression and compared to published ratio values.

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 1 m above the lake bottom to the 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 NIL. 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 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. Zooplankton biomass data were used to estimate escapement levels by indicating a level of juvenile production that a plankton population can maintain as a forage base following the methods of Koenings and Kyle (1997).

AUV SAMPLING

In 2011, sampling of Red Lake with the AUV consisted of 1 mission each in June, July, August, and September. Portions of the June mission data were considered suspect because mission reports indicated the AUV did not run as programmed. The Red Lake July mission was aborted because of software and mechanical errors. Successful missions were run in Red Lake in August and September. In Uganik Lake, 3 missions were run during June and another was run during September (Table 1). Successful AUV missions were not run in either lake during May because of vehicle malfunctions. All AUV missions were plotted in VectorMap software on the most recent geo-referenced images available for each 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, turbidity (nephelometric turbidity units; NTUs), and chlorophyll (µg/L) were measured every 1 second along the plotted sampling grid throughout each 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 footage. 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 Red and Uganik lakes were divided into 3 regions (Upper, Middle, and Lower; Figure 5) 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 in both lakes 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 overlain 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 2 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 each lake are presented in Appendices A through H.

TRADITIONAL LIMNOLOGICAL SAMPLING

Physical Data

Kodiak Island Lakes

The 1 m temperatures in Kodiak Island lakes ranged from 3.4°C at Upper Station Lake in May to 14.3°C at Akalura Lake in August (Table 3). Akalura Lake was seasonally the warmest averaging 11.5°C and Uganik Lake was the coolest, averaging 8.2°C (Table 3; Figure 6). Uganik Lake, unlike the other Kodiak Island lakes, did not exceed 10°C at a depth of 1 meter over the sampling season. Dissolved oxygen readings taken at a depth of 1 m were the lowest in September (10.0 mg/L at Akalura Lake) and the greatest in May (14.3 mg/L at Upper Station Lake), averaging between 11.2 to 12.4 mg/L over all lakes during the sampling season (Table 4; Figure 6). The euphotic zone depth (EZD) was estimated from light penetration data at its deepest in June and October (23.6 m at Karluk Lake) and its shallowest in September (4.6 m at Uganik Lake; Table 5). Among all lakes, the seasonal average of the EZD ranged between 7.2 and 21.3 m (Table 5; Figure 7).

Alaska Peninsula Lakes

The 1 m temperatures in Alaska Peninsula lakes ranged from 4.7°C in June at Bear Lake to 12.0°C in August at Orzinski Lake and averaged 7.0°C at Bear Lake and 10.4°C at Orzinski Lake over the summer sampling season (Table 3; Figure 6). Dissolved oxygen readings taken at a depth of 1 m were the lowest in August (11.7 mg/L at Bear Lake) and the greatest in June (13.5 mg/L at Bear Lake; Table 4). Seasonal averages of dissolved oxygen were 12.7 mg/L for Bear

Lake and 10.8 mg/L for Orzinski Lake. Input of light penetration data into a euphotic zone depth (EZD) model estimated the EZD at its deepest in June (22.4 m) and shallowest (18.0 m) in August at Bear Lake (Table 5; Figure 7). The EZD of Orzinski Lake was 16.9 m in June, and increased to 19.8 m in August, both of which exceed the measured maximum depth of 15.5 m.

Water Sampling

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

Kodiak Island Lakes

Water chemistry measurements were fairly stable for most Kodiak Island lakes during 2011; pH ranged from 7.10 in May at Upper Station Lake to 7.99 in August at Karluk Lake (Table 6). Seasonal pH values averaged between 7.33 at Uganik Lake and 7.79 at Karluk Lake. Seasonal TP averaged between 4.9 (Karluk Lake) and 16.5 (Red Lake) µg/L P over the sampling season. Uganik Lake recorded the lowest TP concentration of 2.8 µg/L P during August while Red Lake achieved a high of 22.4 µg/L P during May (Table 7). Of the photosynthetic pigments, chlorophyll *a* averaged between 0.60 (Uganik lake) and 1.70 (Akalura Lake) µg/L over the sampling season (Table 8). Of all the Kodiak Island lakes sampled, Upper Station Lake had the greatest concentration of chlorophyll *a* (2.88 µg/L in May) and Uganik Lake had the lowest concentration (0.16 µg/L in June; Table 8). Seasonal average nitrogen concentrations were greatest in Uganik Lake (363.1 µg/L) and lowest in Akalura Lake (180.1 µg/L; Table 9). Reactive silicon concentrations in Akalura, Frazer, and Uganik lakes typically exceeded 1,000 µg/L over the sampling season, whereas Karluk, Red, and Upper Station lakes maintained seasonal silicon levels below 240 µg/L (Table 10).

Alaska Peninsula Lakes

The pH in Bear Lake averaged 7.12, ranging from 7.08 in July to 7.15 in August (Table 6). No pH data were available for Orzinski Lake. Total phosphorous concentrations averaged 3.4 µg/L P for Bear Lake and 7.8 µg/L P for Orzinski Lake (Table 7). Of the Alaska Peninsula lakes, Orzinski had the greatest concentration of TP at 8.8 µg/L P during August and Bear Lake had the lowest TP concentration at 2.6 µg/L P during July (Table 7). Of the photosynthetic pigments, chlorophyll *a* averaged 0.95 µg/L in Bear Lake and 1.17 µg/L in Orzinski Lake. Orzinski Lake had the greatest concentration (2.56 µg/L in August) of chlorophyll *a* and also the lowest (0.32 µg/L in July; Table 8). The seasonal average nitrogen concentration of Bear Lake was 204.6 µg/L (Table 9). Reactive silicon exceeded 1,100 µg/L for the entire sampling season in Bear Lake (Table 10). Silicon concentrations were below 720 µg/L for Orzinski Lake during the sampling season.

Zooplankton

Kodiak Island Lakes

The 2011 seasonal average abundance of Kodiak Island zooplankton was greatest in Red Lake (1,544,188 zooplankton/m^2) with the largest monthly concentration exceeding 2 million zooplankton/m^2 in May (Table 11). The Red Lake species composition was composed predominately of the copepod *Cyclops* from May through July, which was succeeded by *Daphnia* in August and September (Appendix D7). Karluk and Upper Station lakes also supported large abundances of zooplankton that were predominately *Cyclops*. Akalura, Frazer, and Uganik lakes had average zooplankton abundances below 390,000 zooplankton/m^2, ranging from 71,975 zooplankton/m^2 (Akalura Lake) to 469,745 (Frazer Lake) zooplankton/m^2 over the sampling season (Table 11). The zooplankton species composition of Uganik Lake was predominately *Cyclops*. Akalura and Frazer lakes experienced a shift from a species composition of mainly *Cyclops* in the spring to cladocerans (either *Bosmina* or *Daphnia*) in the fall.

The greatest seasonal weighted-average zooplankton biomass in 2011 was in Red Lake (2,541 mg/m^2) and ranged from 1,833 mg/m^2 in May to 3,686 mg/m^2 in September (Table 12). Akalura Lake had the lowest seasonal weighted-average zooplankton biomass (185 mg/m^2); Uganik Lake was also low with a seasonal weighted-average zooplankton biomass of 355 mg/m^2. Karluk and Upper Station lakes generally maintained zooplankton biomasses over 1,000 mg/m^2 each month during the sampling season (Table 12).

Ovigerous *Epischura* from Upper Station Lake (seasonal weighted average of 1.66 mm) were the longest zooplankton on average collected during 2011 (Table 13). *Daphnia f*rom Akalura Lake were the longest non-ovigerous taxa on average. Non-ovigerous *Cyclops* ranged from 0.55 to 0.80 mm in the Kodiak Lakes. Non-ovigerous *Bosmina* had weighted averages greater than 0.40 mm only in Karluk Lake in all sampled months except September. The smallest zooplankton were *Chydorinae* from Red Lake, which had a seasonal weighted-average length of 0.25 mm (Table 13).

Alaska Peninsula Lakes

The seasonal average abundance of zooplankton was 805,164 zooplankton/m^2 for Bear Lake and 6,502 zooplankton/m^2 for Orzinski Lake in 2011 (Table 11). *Cyclops* were the most abundant taxa identified in Bear Lake and *Eurytemora* and *Epischura* were the most abundant taxa in Orzinksi Lake (Appendices G7 and H7). Zooplankton abundance was greatest in Bear Lake during June. August zooplankton abundance was less than July zooplankton abundance in Orzinski Lake (Table 11).

Zooplankton biomasses ranged from 2,048 mg/m^2 in June to 1,229 mg/m^2 in August in Bear Lake (Table 12). Orzinski Lake zooplankton biomasses were less than 19 mg/m^2 in July and August (Table 12). No cladocerans were netted in Orzinski Lake and less than 3 mg/m^2 of non-egg bearing *Bosmina* were collected in Bear Lake in 2011 (Table 12; Appendices G8 and H8).

Ovigerous *Cyclops* had the greatest average length (1.06 mm) of all zooplankton in Bear Lake (Table 13). The copepods *Eurytemora* (0.79 mm) and *Cyclops* (0.64 mm) were the longest zooplankton sampled from Orzinski Lake (Table 13).

AUV SAMPLING

Physical Data

Red Lake

June, August, and September surface temperature, dissolved oxygen, and turbidity were mapped for each region relative to location. Surface temperatures and dissolved oxygen concentrations measured by the AUV varied minimally from region to region (Tables 14 and 15; Figure 8). The Lower region had the warmest surface temperatures in June but was cooler than the Middle and Upper regions in August and September. Turbidity was substantially greater in all regions of the lake during September compared to August, however, the Lower region during July had the greatest turbidity measurements at all depths during the sampling season (Table 16).

Monthly temperature depth profiles indicated that Red Lake stratified in July with the hypolimnion being deepest (~18 m) in the Middle region of the lake (Figure 8). Dissolved oxygen concentrations varied minimally over depth (Figure 9). In July and September, the Lower region of Red Lake had 1 meter turbidity measurements greater than surface measurements, differing by up to 168 NTUs (Table 16).

Uganik Lake

Surface temperature, dissolved oxygen, and turbidity were mapped for June and September in Uganik Lake (Tables 17 through 19; Appendices E10 and E11). Upper region surface temperatures were cooler than the other regions in June and conversely warmer in September. Dissolved oxygen concentrations were greatest in the Upper region in both June and September. From June to September, surface temperatures increased and dissolved oxygen concentrations declined. Surface turbidity measurements were greatest in the Lower region, decreasing from the Middle to Upper regions, respectively (Table 19; Appendices E10 and E11).

Temperature and dissolved oxygen depth profiles were generally similar among regions within Uganik Lake, with the exception of the Upper Region that had fluctuating readings within the first five meters from the water's surface (Table 17; Figure 10).

Water Sampling

Red Lake

Average surface chlorophyll concentrations were generally similar between June and August AUV sampling events, however, September averages were substantially greater in each region (Table 20). With the exception of June data, average chlorophyll concentrations at the 1 m depth tended to be greater than measurements taken from the surface or 5 m depth. Maximum concentrations of chlorophyll reached 211.6 μg/L in June from the Upper region, 210.1 μg/L in July from the Lower region, 160.1 μg/L in August from the Upper region, and 265.4 μg/L in September from the Lower region. Chlorophyll depth profiles showed variability over location, depth, and time; they were generally low on average during June and August and high in July and September (Figure 11).

The average surface pH measurements in Red Lake were similar from June through August, but were noticeably lower during September (Table 21). No region consistently maintained the highest or lowest pH measurements. The Lower region had the lowest pH measurement (7.75) in September and the Upper region had the highest pH (8.16) in June. Average pH values over depth were generally greater in the Upper region during June and September (Figure 12). With the exception of July data, pH values were also fairly consistent over depth.

Uganik Lake

Average surface chlorophyll concentrations in Uganik Lake were generally low (< 3 μg/L) during the 2011 sampling season. The greatest average concentration was measured in June from the Lower region (Table 22). The variability around the surface chlorophyll measurements was also the greatest in June, as evidenced by relatively large standard deviations and maximum concentrations of 328.3 μg/L for the Upper region, 273.3 μg/L for the Middle region, and 274.8 μg/L for the Lower region. Surface pH measurements in Uganik Lake varied minimally over depth within each region but were lower in June than September (Table 23; Figure 13; Appendix E13).

Depth profiles of chlorophyll concentrations showed some variability in measurements taken from each region in September (Figure 13; Appendix E13). The Middle region appeared to have the most consistent chlorophyll measurements over depth. Depth profiles of pH were fairly homogenous (Figure 13).

Bathymetry

Red Lake

The Red Lake bathymetric map created with AUV data differed from the original bathymetric map that was created circa 1980 using a fathometer (Table 24; Figure 14). AUV lake volume estimates were 14% less than the original estimate. The original estimate of average depth was 11% more than the AUV estimate (Table 24). Visual comparison of the two versions of the Red Lake bathymetric maps showed differences in the bottom morphology over the lower two-thirds of the lake, as evidenced by the presence of deep depressions and a pinnacle in the AUV version and a more uniform bottom in the original map (Figure 14).

Uganik Lake

The Uganik AUV bathymetric statistics of lake volume and area drastically differed from those originally estimated; area increased by 334% and volume increased by 794% compared to the original estimate. The AUV-generated maximum depth for Uganik Lake was slightly less than originally estimated, however the average depth increased from 17.2 to 45.2 m (Table 24). Review of both maps revealed greater definition in bottom morphology with the newly plotted AUV map and that the lake's deepest spot shifted northwesterly from what was originally plotted (Figure 15).

Sonar Imagery

Red Lake

June imagery showed low densities of fish present in the Upper and Lower regions of the lake at an average depth of 3.2 m. Side-scan sonar imagery indicated fish presence throughout Red Lake in September (Figure 16). Aggregations of fish were greatest in the Lower region of the lake with an average depth of 13.1 m, ranging between 0.7 and 43.6 m.

Uganik Lake

June and September side-scan sonar imagery showed fish presence throughout the lake (Figure 17). Fish were detected at an average depth of 13 m in June and September. The detection depths ranged from 0.7 to 52.2 m in June and 1.2 to 39.6 m in September.

COMPARISON OF SAMPLING METHODS

Red Lake

Comparisons of physical data collected by the AUV to the data collected by traditional methods revealed that Red Lake temperature and dissolved oxygen differed minimally while pH and chlorophyll concentrations substantially varied over depth, space and time (Tables 14, 15, 20, and 21). Specifically, pH and chlorophyll were generally greater when measured by the AUV; AUV-measured dissolved oxygen concentrations were lower over depth and time (Figures 8 and 10). Region-wide comparisons of averaged AUV to traditional data showed the Lower region differed more from the other regions (Appendix D).

Uganik Lake

Comparisons of physical data collected in Uganik Lake by the AUV to data from the traditional sampling station revealed that AUV-recorded temperatures in the Upper region were typically cooler than the other regions in June but either similar or warmer in September (Table 17; Figure 11). AUV-recorded dissolved oxygen concentrations were lower in both June and September than those collected by traditional means (Table 18; Figure 11). Mean AUV pH values were less than traditionally collected data values. AUV chlorophyll values from Uganik Lake were greater than those estimated by traditional methods (Tables 21 and 22; Figure 11). Depth profiles showed temperature readings similar to one another, however, dissolved oxygen and chlorophyll profiles from Station 1 in the Middle region of the lake varied substantially from the AUV data (Figure 11).

DISCUSSION

PHYSICAL DATA

Traditional and AUV (for Red and Uganik lakes only) temperature depth profiles indicated spring turnover events occurred during May for all lakes. Fall turnover events occurred in September for all lakes except Red and Upper Station lakes, which remained stratified. No thermoclines (the plane of maximum temperature decline relative to depth; Wetzel 1983) developed in any of the study lakes prior to July. Akalura, Karluk, Red, and Upper Station lakes were the only lakes to possess distinct thermoclines for more than 2 months. Akalura Lake maintained the warmest 1 m temperatures over the sampling season, ranging on average from 1.1°C to 4.5°C higher than the other lakes, most likely because of its relatively shallow depth. Bear Lake was the coolest lake with a seasonal average 1 m temperature of 7.0°C, which may be attributed to its greater depth and lack of stratification. Timing of lake turnover and stratification events greatly affects ecosystem dynamics and will be expounded upon below as it becomes germane to the discussion.

Dissolved oxygen concentrations from the surface to the hypolimnion were at suitable levels for rearing fishes in all lakes through the sampling season. Differences existed between traditionally-collected data and AUV-collected 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. Instrument sensitivity should not affect results as both probes are of the same type and from the same manufacturer.

Akalura Lake was the only lake to possess hypoxic conditions, which occurred near the lake bottom in August. This condition, which has occurred during July and August in prior years (Edmundson et al. 1994), is not unprecedented for Akalura Lake because of several factors. When organisms die and sink to the lake bottom, their decomposition consumes oxygen (Wetzel 1983). In systems that maintain ample phosphorous and nitrogen concentrations, healthy algal growth can occur. In August, Akalura Lake possessed the highest total phosphorous concentration of all the sampled lakes. Additionally, chlorophyll levels were also greater than any other sampled lake indicating algal growth. With a sparse zooplankton consumer base, a portion of the phytoplankton that were produced during this time may have escaped consumption by zooplankton, died, sank to the lake bottom. This algal deposition may have subsequently created a hypoxic layer because of their decomposition on the lake bottom. Because Akalura Lake was stratified at this time, no oxygen was replaced in the benthos, creating a hypoxic sink.

That other lakes did not present this condition may be a result of limitations of the sampling gear to reach and measure benthic conditions, lake mixing events, limitations to phytoplankton production, or robust zooplankton communities that can effectively graze upon phytoplankton to reduce algal death and their subsequent decomposition.

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 Bear, Karluk, Red, and Upper Station lakes' zooplankton, water clarity normally has not been an issue as evidenced by an average summer euphotic zone depth (EZD) greater than 15 m. For Frazer Lake, water clarity was typically good as evidenced by an average EZD of 15.1 m, yet zooplankton biomass levels were consistently low, suggesting other ecological factors may have a greater influence on secondary production. The low average EZDs in Uganik (7.2 m) and Akalura (11.1 m) lakes may suggest turbidity influences lake productivity because zooplankton biomasses were low in these lakes (ADEC 1978, Lloyd 1987, McCabe and O'Brien 1983). An average EZD of 18.4 m was estimated for Orzinski Lake; this EZD value exceeds the maximum lake depth and suggests the entire water column of the lake is photosynthetically active.

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 the lakes sampled in this project 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 as 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). The only lake that exhibited any seasonal nitrogen limitations within the epilimnion (1 meter samples) was Akalura Lake during August. It should be noted that despite the limitations indicated by the TN:TP ratio, nitrogen and phosphorous concentrations for Akalura Lake were relatively high for being an oligotrophic lake (Carlson 1977; Forsberg and Ryding 1980, Carlson and Simpson 1996); in other words, both nitrogen and phosphorous were ample and readily available for primary production with phosphorous in greater excess than what primary producers would use. The remaining study lakes consistently had 1 m TN:TP ratios exceeding 10:1, indicating phosphorous limitations. In contrast to Akalura Lake, Red, Orzinski, Uganik, and Upper Station lakes had relatively high phosphorous concentrations for being oligotrophic lakes, with each lake possessing adequate TP levels for primary production concurrent with high TN levels (Forsberg and Ryding 1980, Carlson and Simpson 1996).

While these trends in nitrogen and phosphorous are relevant and revealing to the conditions that drive lake primary productivity, they 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. Average silicon concentrations were lowest (< 235 µg/L) in Karluk, Upper Station, and Red lakes. The average TN:TP ratio for Red Lake was low, suggesting that as silicon concentrations decreased, either nitrogen concentrations decreased or phosphorus concentrations increased. Monthly nitrogen concentrations fluctuated more than phosphorous concentrations over the sampling season, thus the phytoplankton community structure may be more dependent upon silicon and nitrogen as opposed to phosphorous. Karluk and Upper Station lakes each had 1 m TN:TP ratios that increased over the sampling season. The change in nutrient concentrations can be attributed to increased organic nitrogen (measured as TKN) rather than declines in phosphorous. Conversely, in Frazer and Bear lakes, 1 m TN:TP ratios and silicon concentrations were relatively high, which suggests these lakes may experience phosphorous limitations because phosphorous concentrations remained seasonally low and there was little variation in nitrogen levels. Uganik Lake was unique in that phosphorous concentrations were relatively high compared to the other lakes. Because nitrogen, phosphorous, and silicon were abundant in Uganik Lake, the high concentrations of available nutrients may be more indicative of physical conditions, such as turbidity or temperature, limiting primary productivity and hence nutrient consumption.

A comparison of the photosynthetic pigment, chlorophyll *a*, to its byproduct, phaeophytin *a*, showed that chlorophyll-*a* concentrations were proportionally high in all lakes [annual seasonal means ranging from 1.9 (Uganik Lake) to 10.2 (Bear Lake) chlorophyll *a* to 1 phaeophytin *a*, respectively]. This signifies that algal levels in the studied lakes were generally adequate for supporting primary consumption because the potential for algal (phytoplankton) growth existed 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 larger chlorophyll-*a* to phaeophytin-*a* ratios and low zooplankton biomasses (Akalura, Frazer, and Orzinski lakes) or small chlorophyll-*a* to phaeophytin-*a* ratios and high zooplankton biomasses (Karluk, Red, and Upper Station lakes) support this hypothesis. In light of these traditionally collected data, primary nutrients did not appear to be a limiting factor in most Westward Region lakes for their levels of productivity in 2011. Furthermore, AUV missions located patches of high chlorophyll concentrations, connoting primary production may be greater than indicated from traditional sample collection methods.

Review of the traditionally collected pH data suggested that temperature and zooplankton may influence pH in the sampled lakes. Warmer temperatures release more hydrogen ions from water molecules, decreasing pH. Uganik Lake experienced its lowest pH and warmest temperatures in August. The other study lakes reached their greatest pH concurrent with their warmest temperatures. This may be explained by nutrient availability and primary production. 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). Frazer, Karluk, Red, Upper Station, and Bear lakes each experienced their highest pH levels concurrent with their lowest levels of useable nitrogen (ammonia and nitrate + nitrite) and low levels of phosphorous, indicative of nutrient consumption during photosynthesis. The temperature-pH relationship was increasingly apparent in Uganik Lake because high concentrations of ammonia and nitrate + nitrite were readily available for photosynthesis yet chlorophyll-*a* concentrations were low indicating limited primary productivity.

In comparison to AUV-collected data, pH values from traditionally-collected methods were consistently lower for Red Lake. 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. The similarity among the Uganik Lake pH readings between AUV and traditional methods supports this.

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 copepdid in response to overcrowding, photoperiod, or predation (Thorpe and Covich 2001). Average monthly biomass estimates for Bear, Karluk, Red, and Upper Station lakes were high and composed predominately of copepods. The high biomasses for these lakes were typically well above the satiation level of 1,000 mg/m^2 for rearing salmonids (Mazumder and Edmundson 2002). The cladoceran, *Bosmina*, also indicates 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 ovigerous *Bosmina* >0.40 mm in size, overgrazing seems unlikely to limit zooplankton production for these lakes. Akalura, Orzinski, and Uganik lakes had consistently low zooplankton biomass levels that fell below or approached starvation levels (<100 mg/m^2) for rearing salmonids (Mazumder and Edmundson 2002). The average *Bosmina* length for Akalura Lake also fell below 0.40 mm. In light of prior discussion, this suggests overgrazing, nutrients, or physical conditions may negatively impact zooplankton production in Akalura, Frazer, and Uganik lakes.

While temperature and phosphorous have been identified as limiting factors for some lakes, silicon concentrations are distinctly tied to zooplankton production in all sampled Kodiak lakes. Lakes with low silicon concentrations consistently had high zooplankton biomasses whereas lakes with high silicon concentrations had low zooplankton biomasses (Figure 18). 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). Diatoms require silicon for reproduction and for creating cell walls (Wetzel 2001). Diatoms are also favored forage of copepods, which are abundant zooplankton in Kodiak lakes with low silicon concentrations. Data collected in 2010 indicated that diatoms were highly abundant and had the greatest biomass of phytoplankton species in Karluk Lake (Heather Finkle, Commercial Fisheries Biologist, ADF&G, Kodiak, *unpublished data*). This information infers that zooplankton in some Kodiak lakes rely upon diatoms to provide the nutrition that facilitate their success. For lakes such as Akalura, with low zooplankton production, this suggests that the phytoplankton species composition may not favor copepod production in addition to temperature limitations. Phytoplankton-related conditions similar to Akalura Lake may also exist in Frazer and Uganik lakes. It should be noted that Bear Lake was anomalous with respect to the silicon-zooplankton relationship as it had high concentrations of silicon and high zooplankton biomass. One explanation for this may be that Bear Lake has ample silicon contributions to the lake throughout the summer, well beyond the needs of primary and secondary producers. This is a plausible hypothesis because a strong winter storm in November 2007 caused landslides, muddying lake water and possibly adding nutrient-laden sediments to the lake. Because silicon rapidly sinks, it may have built up in the lake and been reintroduced throughout the water column with lake turnover events. Sufficient run-off from the surrounding mountains may also release silicon into the Bear Lake.

AUV IMAGERY AND BATHYMETRY

Side-scan sonar data collected from Red and Uganik lakes indicated an abundance of smolt-sized and adult-sized fish. During June, sonar imagery indicated the presence of small fish in the north and south ends of Red Lake. Vehicle malfunctions prevented full AUV coverage of Red Lake, limiting the sonar imagery to the shallower north and south ends of the lake, where the AUV could cruise the water's surface. Fish observed in June were generally small, which may indicate the presence of sockeye or coho (*O. kisutch*) salmon, Dolly Varden *Salvelinus malma* juveniles or stickleback. That their abundance declined in September may suggest they outmigrated from Red Lake or suffered a mortality event prior to the September mission. Similarly, larger-sized fish were detected near tributary streams and spawning shoals in September, which may be adult sockeye salmon or Dolly Varden returning to their spawning locations. More fish were detected throughout Red Lake in September than in June, which coincides with the departure of sockeye salmon smolt and the arrival of adult salmon.

Numerous fish, both large and small, were detected during June and September in Uganik Lake. Schools of sockeye salmon fry were observed near the surface of Uganik Lake while running the June missions, in part validating June imagery analysis of small sized fish. Sonar imagery from September may be biased towards larger fish. Uganik Lake experienced a high water event that caused the lake level to change by roughly 1 m within a 24 hr period. Although the AUV mission was conducted prior to the lake level receding when logs and branches littered the water, adult salmon-sized and larger debris may have been present in the lake before either sinking or flushing out of the system, and subsequently labeled as fish presence. Care was taken during the analysis to measure and verify if suspect imagery lengths could plausibly belong to an adult salmonid.

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 from the AUV allowed for re-estimation of lake volume and estimates of sockeye salmon productivity. The bathymetric data for Red and Uganik lakes has not been updated since it was initially mapped in the 1980s. With the exception of maximum depth, all bathymetric parameters were noticeably different between the original and updated values. Employing high-resolution aerial imagery and mapping software most likely improved estimates of lake area. Differences among the volume estimates are most likely because of the ability of the AUV to efficiently run more transects and accurately collect more data points over those transects than by traditional means. Such drastic increases in volume also stem from inaccurate original estimates of lake area and depth compounded by erroneous calculations.

The AUV volume data estimated from this study, when incorporated into an euphotic volume model of lake productivity (Koenings and Burkett 1987), resulted in a decreased point estimate of optimal escapement for Red Lake when compared to prior estimates using the original data and same model. For Red Lake, this difference was a 38% decrease (from an averaged point estimate of 296,000 fish from past analyses to the AUV-based estimate of 183,000 fish). Optimal escapement, also using AUV bathymetry data, for Uganik Lake was estimated at approximately 16,000 sockeye salmon.

CONCLUSIONS

Through the course of this study, numerous lake types and patterns of productivity have been identified on Kodiak Island and along the Alaska Peninsula. These lakes exhibited a broad range of characteristics: Akalura Lake is small, shallow and warm during the peak of summer and although nutrient rich, supports poor zooplankton production; Orzinski Lake is also small, shallow, yet nutrient depleted and cool; Bear Lake is deep, clear and rich in silicon and zooplankton; Frazer Lake is deep, clear, rich in silicon, but has relatively low phosphorous and zooplankton levels; Karluk Lake is deep, clear, relatively low in all nutrients but supports strong zooplankton production; Uganik Lake is deep, turbid, cool, and low in zooplankton production; Red and Upper Station lakes are replete with nutrients except silicon, yet zooplankton are rich.

Changes in nutrients and forage bases can significantly impact 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. Through comparisons of multiple lakes within a given region and of varying morphology, this study has elucidated patterns of ecological processes, evincing the dynamism of each lake. These unique processes reflect each lake's geomorphology. Each lake also has changing levels of primary productivity that are not only driven by their shape, but also their surrounding terrain and subsequent responses to climate. Continued limnological observation of Westward Region lakes are necessary for identifying if salmonid rearing environments may have deleterious effects upon these vital fisheries.

ACKNOWLEDGEMENTS

Numerous individuals helped make the Westward Region Limnology project a success. Darin Ruhl did an outstanding job of scheduling, collecting, and processing samples. Dawn Hunt, Casey McConnell, and Jodi Estrada helped with data collection, analysis, and database development. Aaron Poetter, Bob Murphy, Paul Horn and Steve Hakala provided logistic 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 Uganik Lake cabin: particular thanks go to Bill Pyle, Bill Leacock, and Kevin Van Hatten. Cecilia Curtis, Debbie Maas, Molly McCafferty, Teresa Tavel, Robin Gardner, and Lori Ryser provided project and administrative support. Lindsay Gann polished this report with her publication expertise. M. Birch Foster, Adam StSaviour, Aaron Tiernan, David, Barnard, Matt Nemeth, and an anonymous reviewer 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 & Game.

REFERENCES CITED

ADEC (Alaska Department of Environmental Conservation). 1978. Nationwide listing of parameters: turbidity, total dissolved solids, settleable solids, and suspended solids for waters suitable for fishing, wildlife, and recreation. ADEC, Juneau.

Bilby, R. E., B. R. Frasen, and P. A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of streams: evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences. 53:164-173.

Bouwens, K. A., and H. Finkle. 2003. Chignik watershed ecological assessment project season report, 2001. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 4K03-10, Kodiak.

Carlson, R. E. 1977. A trophic state index for lakes. Limnology and Oceanography 22(2):361-369.

Carlson, R. E., and J. Simpson. 1996. A coordinator's guide to volunteer lake monitoring methods. North American Lake Management Society.

COLAP (Congress on Lake and Pond Associations, Inc.). 2001. Standard operating procedures for chlorophyll *a* sampling. Boston, Massachusetts.

Dodson, S. I., and D. G. Frey. 2001. The Cladocera and other Branchiopoda [*In*] Ecology and systematics of North American freshwater invertebrates. 2nd Edition. J. E. Thorpe and A. P. Covich (eds.) Academic Press.

Donald, D. B., R. D. Vinebrooke, R. S. Anderson, J. Syrgiannis, and M. D. Graham. 2001. Recovery of zooplankton assemblages in mountain lakes from the effects of introduced sport fish. Canadian Journal of Fisheries and Aquatic Sciences. 58:1822-1830.

Edmundson, J. A., L. E. White, S. G. Honnold and G. B. Kyle. 1994. Assessments of sockeye salmon production in Akalura Lake. Alaska Department of Fish and Game, Division of Commercial Fisheries Management and Development, Regional Information Report 5J94-17, Juneau.

Finkle, H., and D. C. Ruhl. 2011. Assessment of Kodiak salmon lakes using an autonomous underwater vehicle, 2009. Alaska Department of Fish and Game, Fishery Data Series No. 11-29, Anchorage.

Forsberg, C., and S. O. Ryding. 1980. Eutrophication parameters and trophic state indices in 30 Swedish waste-receiving lakes. Archiv fur Hydrobiologie 88:189-207.

Graham, J. M., A. D. Kent, G. H. Lauster, A. C. Yannarell, L. E. Graham, and E. W. Triplett. 2004. Seasonal dynamics of phytoplankton and planktonic protozoan communities in a northern temperate humic lake: diversity in a dinoflagellate dominated system. Microbial Ecology 48: 528-540.

Helminen, H., and J. Sarvala. 1997. Responses of Lake Pyhäjärvi (southwestern Finland) to variable recruitment of the major planktivorous fish, vendace (*Coregonus albula*). Canadian Journal of Fisheries and Aquatic Sciences. 54:32-40.

Kerfoot, W. C. 1987. Cascading effects and indirect pathways. p. 57-69 [*In*] Kerfoot, W. C. and A. Sih. {ed.} Predation: Direct and indirect impacts on aquatic communities. University Press of New England. Hanover and London.

Kiffney, P. M., R. E. Bilby, and B. L. Sanderson. 2005. Monitoring the effects of nutrient enrichment on freshwater ecosystems. Pages 237-263 [*In*] P. Roni, editor. Methods for monitoring stream and watershed restoration. American Fisheries Society, Bethesda, Maryland.

Kirk, K. L., and J. J. Gilbert. 1990. Suspended clay and the population dynamics of planktonic rotifers and cladocerans. Ecology 71(5):1741-1755.

Koenings, J. P., and R. D. Burkett. 1987. Population characteristics of sockeye salmon (*Oncorhynchus nerka*) smolts relative to temperature regimes, euphotic volume, fry density, and forge base within Alaskan lakes. Pages 216-234 [*In*] H.D. Smith, L. Margolis, and C. C. Wood, editors. Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Canadian Special Publications in Fisheries and Aquatic Sciences. Volume 96.

Koenings, J. P., J. A. Edmundson, G. B. Kyle, J. M. Edmundson, and R. B. Burkett. 1987. Limnology field and laboratory manual: Methods for assessing aquatic production. Alaska Department of Fish and Game, Division of Fisheries Rehabilitation, Enhancement, and Development, No. 71. Juneau.

REFERENCES CITED (Continued)

Koenings, J. P., and G. B. Kyle. 1997. Consequences to juvenile sockeye salmon and the zooplankton community resulting from intense predation. Alaska Fisheries Research Bulletin 4(2):120-135.

Kyle, G. B. 1992. Assessment of lacustrine productivity relative to juvenile sockeye salmon *Oncorhynchus nerka* production in Chignik and Black Lakes: results from 1991 surveys. Alaska Department of Fish and Game, Fisheries Rehabilitation, Enhancement and Development Division Report 119, Juneau.

Kyle, G. B. 1996. Stocking sockeye salmon (*Oncorhynchus nerka*) in barren lakes of Alaska: effects on the macrozooplankton community. Fisheries Research 28 (1996) 29-44.

Lloyd, D. L. 1987. Turbidity as a water quality standard for salmonid habitats in Alaska. North American Journal of Fisheries Management 7:34-45.

Mazumder, A., and J.A. Edmundson. 2002. Impact of fertilization and stocking on trophic interactions and growth of juvenile sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. 59:1361-1373.

McCabe, G. D., and W. J. O'Brien. 1983. The effects of suspended silt on feeding and reproduction of *Daphnia pulex*. American Midland Naturalist 110:324-337.

Milovskaya, L. V., M. M. Selifonov, and S. A. Sinyakov. 1998. Ecological functioning of Lake Kuril relative to sockeye salmon production. N. Pac. Anadr. Fish Comm. Bull. No. 1: 434-442.

Parr, W. H., Jr. 1972. Interactions between sockeye salmon and resident lake fish in the Chignik Lakes, Alaska. M. Sc. thesis. Univ. of Washington, Seattle.

Ruggerone, G. T. 1994. Investigations of salmon populations, hydrology, and limnology of the Chignik Lakes, Alaska, during 1993. Natural Resources Consultants, Inc. Seattle Wa.

Schindler, D. E. 1992. Nutrient regeneration of sockeye salmon (*Oncorhynchus nerka*) fry and subsequent effects on zooplankton and phytoplankton. Can. J. Fish. Aquat. Sci. 49:2498-2506.

Schrof, S. T., and S. G. Honnold. 2003. Salmon enhancement, rehabilitation, evaluation, and monitoring efforts conducted in the Kodiak Management Area through 2001. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 4K03-41, Kodiak.

Stockner, J. G., and E. A. MacIssac. 1996. British Colombia lake enrichment programme: Two decades of habitat enhancement for sockeye salmon. Regulated Rivers: Research and Management, Vol. 12, 547-561.

Thomsen, S. E. 2008. Kodiak Island lake assessment/limnology project laboratory analysis operational plan. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional information Report 4K08-4, Kodiak.

Thorpe, J. H., and A. P. Covich. 2001. Ecology and classification of North American freshwater invertebrates. Academic Press, San Diego, California.

Turner, J. T., A. Ianora, A. Miralto, M. Laabir, and F. Esposito. 2001. Decoupling of copepod grazing rates, fecundity and egg hatching success on mixed and alternating diatom and dinoflagellate diets. Marine Ecology Progress Series 220:187-199.

UF (University of Florida). 2000. A beginner's guide to water management–nutrients. Department of Fisheries and Aquatic Sciences, Institute of Food and Agricultural Sciences, University of Florida, Gainesville. http://lakewatch.ifas.ufl.edu/LWcirc.html

USEPA (United States Environmental Protection Agency). 2000. Nutrient criteria technical guidance manual: lakes and reservoirs. Washington, D. C.

Vinyard, W. C. 1979. Diatoms of North America. Eureka. Mad River Press, Inc.

Wetzel, R. G. 1983. Limnology. New York. CBS College Publishing.

Wetzel, R. G. 2001. Limnology. San Diego. Academic Press.

YSI (Yellow Springs Instruments). 2009. YSI Ecomapper operation manual.

TABLES AND FIGURES

Table 1.–Sampling dates and methods used for Kodiak Island lakes, 2011.

Akalura		Frazer		Karluk		Red		Uganik		Upper Station	
13-May	W, Z	13-May	W, Z	24-May	W, Z	13-May	W, Z	27-May	W, Z	13-May	W, Z
16-Jun	W, Z	16-Jun	W, Z	20-Jun	W, Z	16-Jun	W, Z,AUV	22-Jun	AUV	16-Jun	W, Z
18-Jul	W, Z	16-Jul	W, Z	21-Jul	W, Z	18-Jul	W, Z, AUV	23-Jun	W, Z, AUV	18-Jul	W, Z
26-Aug	W, Z	17-Aug	W, Z	16-Aug	W, Z	26-Aug	W, Z, AUV	16-Jul	W, Z	26-Aug	W, Z
15-Sep	W, Z	15-Sep	W, Z	14-Sep	W, Z	15-Sep	W, Z, AUV	10-Aug	W, Z	15-Sep	W, Z
		13-Oct	W,Z	13-Oct	W, Z			21-Sep	W, Z, AUV		

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

Table 2.–Sampling dates and methods used for Alaska Peninsula lakes, 2011.

Bear		Orzinski	
9-Jun	W, Z	30-Jun	W, Z
9-Jul	W, Z	14-Jul	W
25-Aug	W, Z	1-Aug	W, Z

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

Table 3.–Monthly and seasonal averages of 1 m temperature (°C) measurements from Kodiak Island and Alaska Peninsula lakes, 2011.

	Month						Seasonal
Lake	May	June	July	August	September	October	average
Akalura	7.3	10.1	13.1	14.3	12.8	ND	11.5
Frazer	4.1	6.6	10.2	13.1	10.4	8.9	8.9
Karluk	4.0	7.8	11.9	12.9	9.5	8.3	9.1
Red	4.1	7.2	10.9	12.9	11.6	ND	9.3
Uganik	5.4	8.4	9.0	9.8	8.4	ND	8.2
Upper Station	3.4	6.0	10.8	13.3	11.9	ND	9.1
Bear	ND	4.7	6.3	10.1	ND	ND	7.0
Orzinski	ND	8.8	ND	12.0	ND	ND	10.4

Table 4.–Monthly and seasonal averages of 1 m dissolved oxygen (mg/L) measurements from Kodiak Island and Alaska Peninsula lakes, 2011.

	Month						Seasonal
Lake	May	June	July	August	September	October	average
Akalura	12.9	11.7	11.0	10.3	10.0	ND	11.2
Frazer	13.3	12.7	11.9	11.2	11.0	11.1	11.9
Karluk	14.2	13.5	12.0	11.2	11.6	11.6	12.4
Red	14.1	12.9	11.7	10.5	10.7	ND	12.0
Uganik	12.5	12.2	11.9	11.9	11.3	ND	12.0
Upper Station	14.3	13.3	11.7	10.6	10.6	ND	12.1
Bear	ND	13.5	12.9	11.7	ND	ND	12.7
Orzinski	ND	11.1	ND	10.6	ND	ND	10.8

Table 5.–Monthly and seasonal averages of euphotic zone depth (EZD) measurements in meters from Kodiak Island and Alaska Peninsula lakes, 2011.

	Month						Seasonal
Lake	May	June	July	August	September	October	average
Akalura	10.0	10.0	12.3	13.4	9.6	ND	11.1
Frazer	15.5	15.8	12.4	16.9	16.2	13.6	15.1
Karluk	23.6	19.2	22.9	20.1	18.3	23.6	21.3
Red	14.6	15.0	17.3	17.0	15.8	ND	15.9
Uganik	4.7	6.3	6.9	13.6	4.6	ND	7.2
Upper Station	12.9	13.9	19.6	16.3	15.0	ND	15.5
Bear	ND	22.4	19.8	18.0	ND	ND	20.1
Orzinski	ND	16.9	ND	19.8	ND	ND	18.4

Table 6.–Monthly and seasonal averages of pH measurements taken at 1 m depths from Kodiak Island and Alaska Peninsula lakes, 2011.

	Month						Seasonal
Lake	May	June	July	August	September	October	average
Akalura	7.16	7.51	7.48	7.66	7.50	ND	7.46
Frazer	7.35	7.48	7.46	7.72	7.47	7.44	7.50
Karluk	7.79	7.80	7.55	7.99	7.82	7.77	7.79
Red	7.39	7.54	7.55	7.88	7.61	ND	7.59
Uganik	7.2	7.57	7.31	7.11	7.43	ND	7.33
Upper Station	7.10	7.39	7.32	7.58	7.39	ND	7.36
Bear	ND	7.14	7.08	7.15	ND	ND	7.12
Orzinski	ND	ND	ND	ND	ND	ND	-

Table 7.–Monthly and seasonal averages of total phosphorous concentrations (µg/L) taken at 1 m depths from Kodiak Island and Alaska Peninsula lakes, 2011.

	Month						Seasonal
Lake	May	June	July	August	September	October	average
Akalura	10.9	10.0	9.7	11.5	11.6	ND	10.7
Frazer	5.0	5.7	5.2	4.2	4.5	5.7	5.0
Karluk	5.8	5.1	4.2	4.4	4.8	5.3	4.9
Red	22.4	20.6	13.4	11.2	15.1	ND	16.5
Uganik	9.8	9.3	7.2	2.8	10.8	ND	8.0
Upper Station	7.8	8.4	7.2	5.1	5.1	ND	6.7
Bear	ND	4.5	2.6	3.3	ND	ND	3.4
Orzinski	ND	7.3	7.4	8.8	ND	ND	7.8

Table 8.–Monthly and seasonal averages of chlorophyll-*a* concentrations (µg/L) taken at 1 m depths from Kodiak Island and Alaska Peninsula lakes, 2011.

	Month						Seasonal
Lake	May	June	July	August	September	October	average
Akalura	1.60	0.80	1.28	2.31	2.49	ND	1.70
Frazer	0.95	0.80	1.36	1.12	0.80	2.08	1.18
Karluk	2.45	0.64	1.07	0.37	0.59	0.80	0.99
Red	1.28	1.60	0.96	0.64	0.48	ND	0.99
Uganik	0.92	0.16	0.64	0.64	0.64	ND	0.60
Upper Station	2.88	2.24	0.80	1.28	0.96	ND	1.63
Bear	ND	1.48	0.40	0.96	ND	ND	0.95
Orzinski	ND	0.64	0.32	2.56	ND	ND	1.17

Table 9.–Monthly and seasonal averages of total nitrogen concentrations (µg/L) taken at 1 m depths from Kodiak Island and Alaska Peninsula lakes, 2011.

	Month						Seasonal
Lake	May	June	July	August	September	October	average
Akalura	184.6	191.2	195.1	104.0	225.4	ND	180.1
Frazer	177.3	173.0	128.5	156.6	173.2	208.5	169.5
Karluk	164.1	142.8	177.3	272.2	292.3	190.4	206.5
Red	340.6	217.0	172.8	228.4	403.8	ND	272.5
Uganik	524.0	416.8	291.9	286.0	296.7	ND	363.1
Upper Station	221.7	224.4	218.0	193.1	219.0	ND	215.2
Bear	ND	226.7	231.3	155.7	ND	ND	204.6
Orzinski	ND	ND	ND	ND	ND	ND	ND

Table 10.–Monthly and seasonal averages of silicon concentrations (µg/L) taken at 1 m depths from Kodiak Island and Alaska Peninsula lakes, 2011.

	Month						Seasonal
Lake	May	June	July	August	September	October	average
Akalura	1,942.0	1,499.1	1,757.5	2,012.4	2,084.2	ND	1,859.0
Frazer	2,746.0	2,633.8	2,454.3	2,563.6	1,188.6	2,247.5	2,305.6
Karluk	99.8	101.2	234.3	182.5	67.7	116.3	133.6
Red	180.3	99.7	166.5	114.7	190.3	ND	150.3
Uganik	2,337.5	1,458.8	735.1	1,275.7	814.0	ND	1,324.2
Upper Station	105.5	108.4	71.0	6.8	47.7	ND	67.9
Bear	ND	1,184.8	1,707.1	1,628.0	ND	ND	1,506.6
Orzinski	ND	533.4	719.7	569.9	ND	ND	607.7

Table 11.–Monthly and seasonal averages of zooplankton abundance (number/m^2) from Kodiak Island and Alaska Peninsula lakes, 2011.

	Month						Seasonal
Lake	May	June	July	August	September	October	average
Akalura	35,563	109,873	71,975	393,312	157,643	ND	153,673
Frazer	423,965	380,573	200,823	210,589	469,745	293,259	386,513
Karluk	537,420	629,512	589,084	646,426	829,883	413,217	691,454
Red	2,025,478	1,503,185	789,809	1,500,000	1,901,274	ND	1,544,188
Uganik	253,981	349,522	259,554	166,136	134,820	ND	232,803
Upper Station	1,471,338	810,111	1,157,113	713,376	537,420	ND	935,324
Bear	ND	1,157,743	586,890	670,860	ND	ND	805,164
Orzinski	ND	7,962	ND	5,042	ND	ND	6,502

Table 12.–Monthly and seasonal averages of zooplankton biomasses (mg/m^2) from Kodiak Island and Alaska Peninsula lakes, 2011.

	Month						Seasonal weighted
Lake	May	June	July	August	September	October	average
Akalura	44	133	101	367	285	ND	185
Frazer	401	899	571	196	534	341	490
Karluk	734	1,096	1,386	1,505	1,417	1,543	1,280
Red	1,833	2,974	1,880	2,331	3,686	ND	2,541
Uganik	379	436	383	311	267	ND	355
Upper Station	1,512	1,356	2,693	1,944	1,541	ND	1,809
Bear	ND	2,048	1,399	1,229	ND	ND	1,558
Orzinski	ND	18	ND	16	ND	ND	17

Table 13.–Seasonal averages of zooplankton lengths (mm) from Kodiak Island and Alaska Peninsula lakes, 2011.

	Lake							
Taxon	Akalura	Frazer	Karluk	Red	Uganik	Upper Station	Bear	Orzinski
Copepods:								
Epischura	0.84	0.94	-	1.01	-	1.14	-	0.63
Ovig. *Epischura*	1.30	-	-	-	-	1.66	-	-
Eurytemora	0.88	-	-	-	-	-	-	0.79
Ovig. *Eurytemora*	1.10	-	-	-	-	-	-	-
Diaptomus	0.61	1.05	0.95	0.98	1.14	0.92	0.65	-
Ovig. *Diaptomus*	-	-	1.23	1.28	-	-	-	-
Cyclops	0.55	0.76	0.68	0.70	0.67	0.79	0.80	0.64
Ovig. *Cyclops*	1.21	1.15	1.14	1.17	1.10	1.20	1.06	-
Harpaticus	0.53	0.57	0.57	-	-	-	-	-
Cladocerans:								
Bosmina	0.31	0.33	0.41	0.34	-	0.35	0.19	-
Ovig. *Bosmina*	0.57	0.43	0.56	0.50	0.41	0.52	0.50	-
Daphnia longiremis	1.29	0.53	0.66	0.66	0.62	0.62	-	-
Ovig. *Daphnia longirem*	-	0.71	0.87	0.88	0.98	0.94	-	-
Holopedium	-	0.54	-	-	-	0.62	-	-
Ovig. *Holopedium*	-	-	-	-	-	0.94	-	-
Chydorinae	-	0.31	-	0.25	-	-	-	-

Table 14.–Red Lake AUV and traditionally collected temperature data, by depth, month, and region, 2011.

			May		June		July		August		September	
Region	Depth (m)		AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional
Upper												
	Surface	°C	ND	4.30	7.39	7.40	11.33	10.90	13.13	12.90	11.51	11.60
		SD	ND	-	0.12	-	0.02	-	0.26	-	0.03	-
	1-m	°C	ND	4.10	7.08	7.20	11.22	10.90	ND	12.90	11.52	11.60
		SD	ND	-	-	-	-	-	ND	-	0.02	-
	5-m	°C	ND	4.00	ND	7.20	11.18	10.80	ND	12.90	ND	11.40
		SD	ND	-	ND	-	-	-	ND	-	ND	-
Middle												
	Surface	°C	ND	ND	7.16	ND	11.37	ND	13.34	ND	11.49	ND
		SD	ND	ND	0.02	ND	0.00	ND	0.18	ND	0.09	ND
	1-m	°C	ND	ND	ND	ND	ND	ND	ND	ND	11.45	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	0.09	ND
	5-m	°C	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lower												
	Surface	°C	ND	ND	7.73	ND	11.12	ND	12.98	ND	11.41	ND
		SD	ND	ND	0.06	ND	0.04	ND	0.09	ND	0.11	ND
	1-m	°C	ND	ND	7.76	ND	11.11	ND	ND	ND	11.35	ND
		SD	ND	ND	0.07	ND	0.02	ND	ND	ND	0.03	ND
	5-m	°C	ND	ND	7.62	ND	ND	ND	ND	ND	ND	ND
		SD	ND	ND	0.08	ND	ND	ND	ND	ND	ND	ND

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

Table 15.–Red Lake AUV and traditionally collected dissolved oxygen data, by depth, month, and region, 2011.

			May		June		July		August		September	
Region	Depth (m)		AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional
Upper												
	Surface	mg/L	ND	13.60	12.48	12.69	11.25	11.58	10.36	10.54	10.38	10.71
		SD	ND	-	0.02	-	0.01	-	0.04	-	0.02	-
	1-m	mg/L	ND	14.10	12.48	12.88	11.13	11.65	ND	10.54	10.32	10.70
		SD	ND	-	-	-	-	-	ND	-	0.05	-
	5-m	mg/L	ND	14.10	ND	12.86	10.99	11.63	ND	10.48	ND	10.64
		SD	ND	-	ND	-	-	-	ND	-	ND	-
Middle												
	Surface	mg/L	ND	ND	12.50	ND	11.26	ND	10.35	ND	10.33	ND
		SD	ND	ND	0.02	ND	0.00	ND	0.02	ND	0.05	ND
	1-m	mg/L	ND	ND	ND	ND	ND	ND	ND	ND	10.32	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	0.05	ND
	5-m	mg/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lower												
	Surface	mg/L	ND	ND	12.42	ND	11.16	ND	10.33	ND	10.19	ND
		SD	ND	ND	0.03	ND	0.03	ND	0.03	ND	0.08	ND
	1-m	mg/L	ND	ND	12.41	ND	11.16	ND	ND	ND	10.29	ND
		SD	ND	ND	0.03	ND	0.01	ND	ND	ND	0.03	ND
	5-m	mg/L	ND	ND	12.44	ND	ND	ND	ND	ND	ND	ND
		SD	ND	ND	0.03	ND	ND	ND	ND	ND	ND	ND

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

Table 16.–Red Lake AUV collected turbidity data, by depth, month, and region, 2011.

Region	Depth (m)		July	August	September
Upper					
	Surface	NTU	1.43	2.49	126.90
		SD	0.67	20.63	167.64
	1-m	NTU	ND	ND	177.58
		SD	ND	ND	176.65
	5-m	NTU	ND	ND	ND
		SD	ND	ND	ND
Middle					
	Surface	NTU	1.50	1.50	373.44
		SD	0.85	1.13	139.36
	1-m	NTU	ND	ND	384.24
		SD	ND	ND	143.83
	5-m	NTU	ND	ND	ND
		SD	ND	ND	ND
Lower					
	Surface	NTU	323.07	1.51	269.49
		SD	177.44	0.75	135.52
	1-m	NTU	470.17	ND	437.73
		SD	130.24	ND	51.95
	5-m	NTU	ND	ND	ND
		SD	ND	ND	ND

Note: Turbidity was measured in nephelometric turbidity units (NTU). Turbidity sensor was disabled during June missions.

Table 17.–Uganik Lake AUV and traditionally collected temperature data, by depth, month, and region, 2011.

			May		June		July		August		Sept	
Region	Depth (m)		AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional
Upper												
	Surface	°C	ND	ND	7.13	ND	ND	ND	ND	ND	9.12	ND
		SD	ND	ND	0.73	ND	ND	ND	ND	ND	0.17	ND
	1-m	°C	ND	ND	7.43	ND	ND	ND	ND	ND	8.91	ND
		SD	ND	ND	0.36	ND	ND	ND	ND	ND	0.29	ND
	5-m	°C	ND	ND	ND	ND	ND	ND	ND	ND	8.16	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	0.04	ND
Middle												
	Surface	°C	ND	6.30	7.93	8.70	ND	10.20	ND	9.80	8.63	8.50
		SD	ND	-	0.73	-	ND	-	ND	-	0.15	-
	1-m	°C	ND	5.40	7.49	8.40	ND	9.00	ND	9.80	8.55	8.40
		SD	ND	-	0.26	-	ND	-	ND	-	0.18	-
	5-m	°C	ND	5.20	7.15	7.50	ND	7.90	ND	9.60	8.16	8.20
		SD	ND	-	0.19	-	ND	-	ND	-	0.04	-
Lower												
	Surface	°C	ND	ND	8.01	ND	ND	ND	ND	ND	8.42	ND
		SD	ND	ND	0.32	ND	ND	ND	ND	ND	0.15	ND
	1-m	°C	ND	ND	7.72	ND	ND	ND	ND	ND	8.45	ND
		SD	ND	ND	0.26	ND	ND	ND	ND	ND	0.21	ND
	5-m	°C	ND	ND	7.47	ND	ND	ND	ND	ND	8.21	ND
		SD	ND	ND	0.28	ND	ND	ND	ND	ND	0.13	ND

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

Table 18.–Uganik Lake AUV and traditionally collected dissolved oxygen data, by depth, month, and region, 2011.

			May		June		July		August		Sept	
Region	Depth (m)		AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional
Upper												
	Surface	mg/L	ND	ND	11.98	ND	ND	ND	ND	ND	10.94	ND
		SD	ND	ND	0.03	ND	ND	ND	ND	ND	0.02	ND
	1-m	mg/L	ND	ND	11.98	ND	ND	ND	ND	ND	10.85	ND
		SD	ND	ND	0.18	ND	ND	ND	ND	ND	0.09	ND
	5-m	mg/L	ND	ND	ND	ND	ND	ND	ND	ND	10.89	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	0.10	ND
Middle												
	Surface	mg/L	ND	12.40	11.93	12.05	ND	11.63	ND	11.88	10.88	11.29
		SD	ND	-	0.14	-	ND	-	ND	-	0.04	-
	1-m	mg/L	ND	12.50	11.98	12.18	ND	11.93	ND	11.86	10.82	11.31
		SD	ND	-	0.09	-	ND	-	ND	-	0.05	-
	5-m	mg/L	ND	12.40	11.90	12.28	ND	12.02	ND	11.80	10.85	11.17
		SD	ND	-	0.11	-	ND	-	ND	-	0.06	-
Lower												
	Surface	mg/L	ND	ND	11.90	ND	ND	ND	ND	ND	10.87	ND
		SD	ND	ND	0.14	ND	ND	ND	ND	ND	0.03	ND
	1-m	mg/L	ND	ND	11.91	ND	ND	ND	ND	ND	10.83	ND
		SD	ND	ND	0.09	ND	ND	ND	ND	ND	0.05	ND
	5-m	mg/L	ND	ND	11.84	ND	ND	ND	ND	ND	10.83	ND
		SD	ND	ND	0.10	ND	ND	ND	ND	ND	0.05	ND

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

Table 19.–Uganik Lake AUV collected turbidity data, by depth, month, and region, 2011.

Region	Depth (m)		June	September
Upper				
	Surface	NTU	ND	5.79
		SD	ND	1.58
	1-m	NTU	ND	5.19
		SD	ND	1.32
	5-m	NTU	ND	10.30
		SD	ND	1.10
Middle				
	Surface	NTU	ND	8.82
		SD	ND	15.22
	1-m	NTU	ND	7.47
		SD	ND	2.33
	5-m	NTU	ND	9.79
		SD	ND	2.44
Lower				
	Surface	NTU	ND	13.45
		SD	ND	27.60
	1-m	NTU	ND	8.84
		SD	ND	2.81
	5-m	NTU	ND	10.57
		SD	ND	2.66

Note: Turbidity was measured in nephelometric turbidity units (NTU). Turbidity sensor was disabled during June missions.

Table 20.–Red Lake AUV and traditionally collected chlorophyll data, by depth, month, and region, 2011.

			May		June		July		August		September	
Region	Depth (m)		AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional
Upper												
	Surface	µg/L	ND	ND	3.86	ND	1.73	ND	1.83	ND	56.12	ND
		SD	ND	ND	12.56	ND	1.15	ND	4.07	ND	61.37	ND
	1-m	µg/L	ND	1.28	3.60	1.60	3.00	0.96	ND	0.64	71.22	0.48
		SD	ND	-	-	-	-	-	ND	-	52.41	-
	5-m	µg/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Middle												
	Surface	µg/L	ND	ND	4.81	ND	1.25	ND	1.59	ND	154.47	ND
		SD	ND	ND	12.32	ND	1.63	ND	1.13	ND	51.49	ND
	1-m	µg/L	ND	ND	ND	ND	ND	ND	ND	ND	154.48	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	53.53	ND
	5-m	µg/L	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lower												
	Surface	µg/L	ND	ND	1.88	ND	92.92	ND	1.60	ND	132.71	ND
		SD	ND	ND	3.94	ND	36.32	ND	1.13	ND	61.38	ND
	1-m	µg/L	ND	ND	1.44	ND	129.99	ND	ND	ND	191.28	ND
		SD	ND	ND	1.45	ND	15.69	ND	ND	ND	18.91	ND
	5-m	µg/L	ND	ND	0.40	ND	ND	ND	ND	ND	ND	ND
		SD	ND	ND	0.52	ND	ND	ND	ND	ND	ND	ND

Note: Traditionally collected data values are from a sample size of one precluding SD calculation. All AUV values are averages by region, depth, and month.

Table 21.–Red Lake AUV and traditionally collected pH data, by depth, month, and region, 2011.

			May		June		July		August		September	
Region	Depth (m)		AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional
Upper												
	Surface	pH	ND	ND	8.16	ND	8.02	ND	7.98	ND	7.85	ND
		SD	ND	ND	0.02	ND	0.02	ND	0.03	ND	0.02	ND
	1-m	pH	ND	7.39	8.13	7.54	7.69	7.55	ND	7.88	7.82	7.61
		SD	ND	-	-	-	-	-	ND	-	0.01	-
	5-m	pH	ND	ND	ND	ND	7.65	ND	ND	ND	ND	ND
		SD	ND	ND	ND	ND	-	ND	ND	ND	ND	ND
Middle												
	Surface	pH	ND	ND	8.14	ND	8.04	ND	7.98	ND	7.81	ND
		SD	ND	ND	0.01	ND	0.00	ND	0.02	ND	0.02	ND
	1-m	pH	ND	ND	ND	ND	ND	ND	ND	ND	7.80	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	0.01	ND
	5-m	pH	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lower												
	Surface	pH	ND	ND	8.02	ND	8.12	ND	7.99	ND	7.75	ND
		SD	ND	ND	0.10	ND	0.06	ND	0.10	ND	0.12	ND
	1-m	pH	ND	ND	8.03	ND	8.11	ND	ND	ND	7.76	ND
		SD	ND	ND	0.02	ND	0.01	ND	ND	ND	0.01	ND
	5-m	pH	ND	ND	8.04	ND	ND	ND	ND	ND	ND	ND
		SD	ND	ND	0.01	ND	ND	ND	ND	ND	ND	ND

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

Table 22.–Uganik Lake AUV and traditionally collected chlorophyll data, by depth, month, and region, 2011.

			May		June		July		August		Sept	
Region	Depth (m)		AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional
Upper												
	Surface	µg/L	ND	ND	2.71	ND	ND	ND	ND	ND	1.58	ND
		SD	ND	ND	13.82	ND	ND	ND	ND	ND	1.11	ND
	1-m	µg/L	ND	ND	1.60	ND	ND	ND	ND	ND	1.33	ND
		SD	ND	ND	-	ND	ND	ND	ND	ND	0.73	ND
	5-m	µg/L	ND	ND	ND	ND	ND	ND	ND	ND	1.48	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	0.62	ND
Middle												
	Surface	µg/L	ND	ND	1.76	ND	ND	ND	ND	ND	1.58	ND
		SD	ND	ND	10.05	ND	ND	ND	ND	ND	1.08	ND
	1-m	µg/L	ND	0.92	0.75	0.16	ND	0.64	ND	0.64	1.74	0.64
		SD	ND	-	0.62	-	ND	-	ND	-	1.07	-
	5-m	µg/L	ND	ND	2.13	ND	ND	ND	ND	ND	1.59	ND
		SD	ND	ND	0.94	ND	ND	ND	ND	ND	1.36	ND
Lower												
	Surface	µg/L	ND	ND	5.08	ND	ND	ND	ND	ND	1.99	ND
		SD	ND	ND	20.64	ND	ND	ND	ND	ND	6.47	ND
	1-m	µg/L	ND	ND	1.19	ND	ND	ND	ND	ND	1.60	ND
		SD	ND	ND	0.62	ND	ND	ND	ND	ND	1.26	ND
	5-m	µg/L	ND	ND	0.93	ND	ND	ND	ND	ND	1.53	ND
		SD	ND	ND	1.40	ND	ND	ND	ND	ND	1.33	ND

Note: Traditionally collected data values are from a sample size of one precluding SD calculation. All AUV values are averages by region, depth, and month.

Table 23.–Uganik Lake AUV and traditionally collected pH data, by depth, month, and region, 2011.

			May		June		July		August		Sept	
Region	Depth (m)		AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional	AUV	Traditional
Upper												
	Surface	pH	ND	ND	7.35	ND	ND	ND	ND	ND	7.48	ND
		SD	ND	ND	0.01	ND	ND	ND	ND	ND	0.01	ND
	1-m	pH	ND	ND	7.29	ND	ND	ND	ND	ND	7.44	ND
		SD	ND	ND	0.01	ND	ND	ND	ND	ND	0.02	ND
	5-m	pH	ND	ND	ND	ND	ND	ND	ND	ND	7.44	ND
		SD	ND	ND	ND	ND	ND	ND	ND	ND	0.02	ND
Middle												
	Surface	pH	ND	ND	7.34	ND	ND	ND	ND	ND	7.44	ND
		SD	ND	ND	0.01	ND	ND	ND	ND	ND	0.03	ND
	1-m	pH	ND	7.23	7.30	7.57	ND	7.31	ND	7.11	7.41	7.43
		SD	ND	-	0.02	-	ND	-	ND	-	0.03	-
	5-m	pH	ND	ND	7.33	ND	ND	ND	ND	ND	7.41	ND
		SD	ND	ND	0.03	ND	ND	ND	ND	ND	0.02	ND
Lower												
	Surface	pH	ND	ND	7.39	ND	ND	ND	ND	ND	7.41	ND
		SD	ND	ND	0.10	ND	ND	ND	ND	ND	0.03	ND
	1-m	pH	ND	ND	7.34	ND	ND	ND	ND	ND	7.39	ND
		SD	ND	ND	0.02	ND	ND	ND	ND	ND	0.02	ND
	5-m	pH	ND	ND	7.34	ND	ND	ND	ND	ND	7.39	ND
		SD	ND	ND	0.03	ND	ND	ND	ND	ND	0.02	ND

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

Table 24.–Comparison of AUV and original bathymetry statistics for Red and Uganik lakes.

Lake	Bathymetry statistic	Map version	
		Original	AUV
Red			
	Area (m^2)	8,400,000	7,496,100
	Volume (m^3)	207,700,000	178,105,100
	Maximum depth (m)	45.0	46.5
	Average depth (m)	24.7	27.3
Uganik			
	Area (m^2)	800,000	3,471,552
	Volume (m^3)	13,000,000	116,262,018
	Maximum depth (m)	79.0	76.1
	Average depth (m)	17.2	45.2

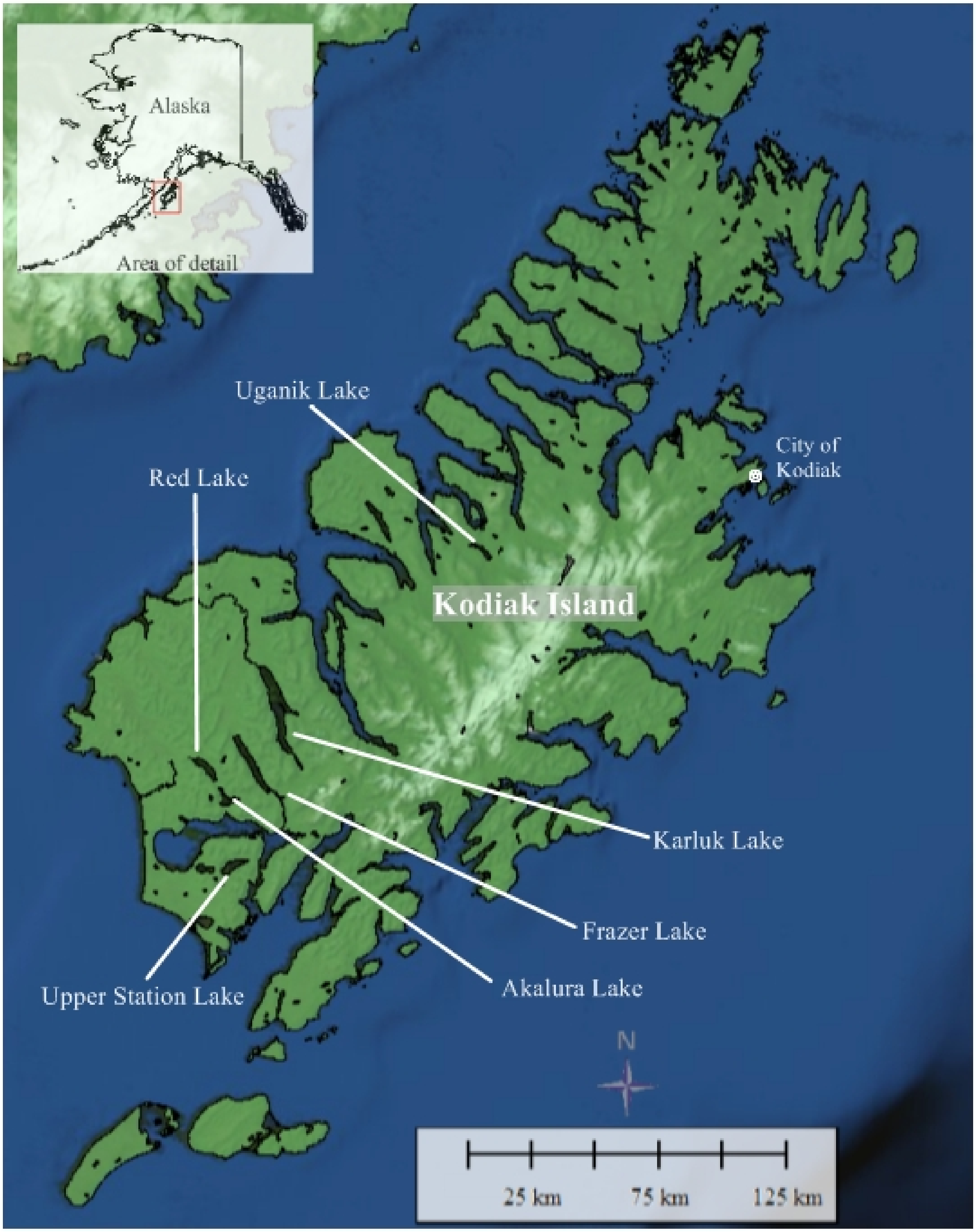


Figure 1.–Map of lakes sampled on Kodiak Island, Alaska in 2011.

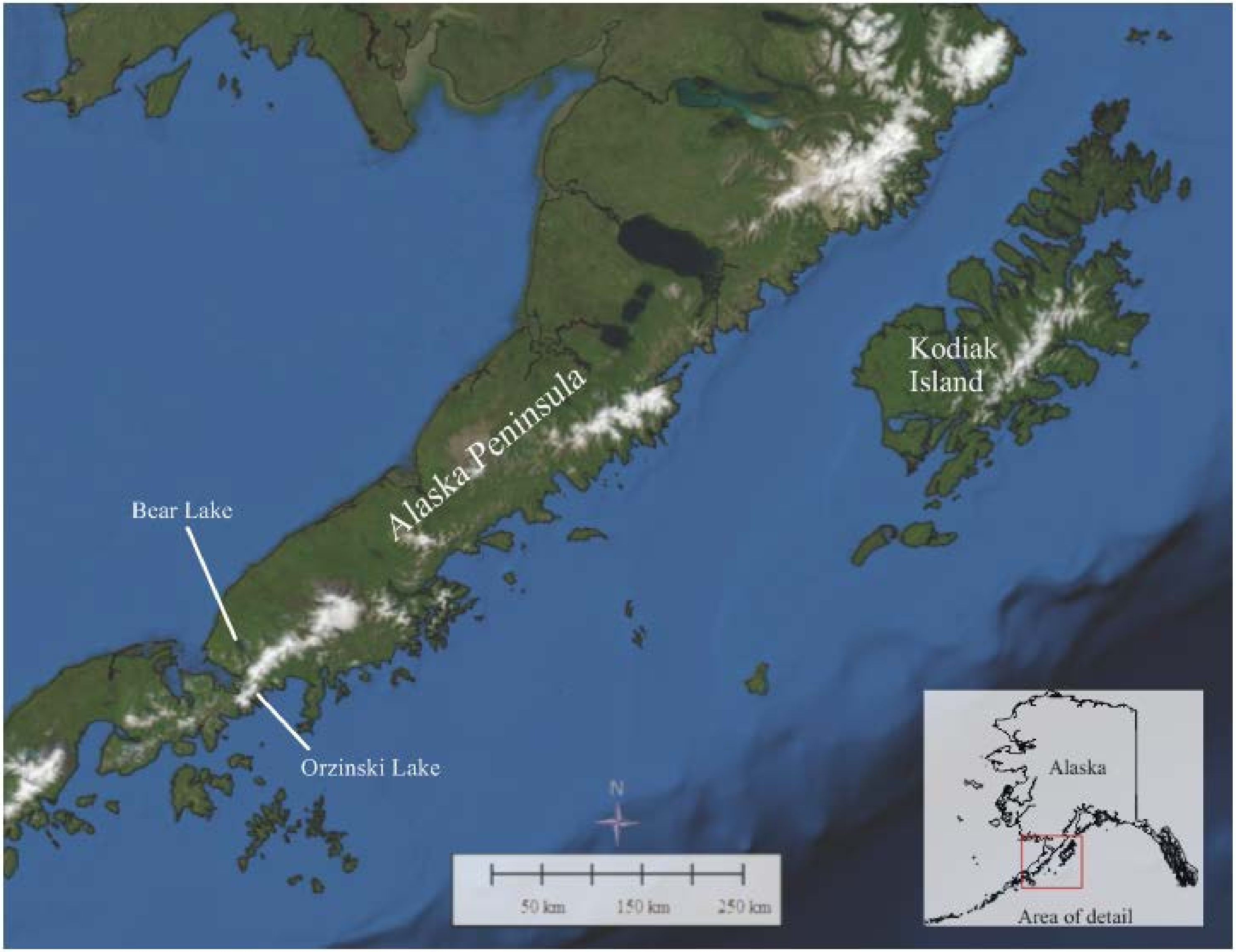


Figure 2.–Maps of lakes sampled on the Alaska Peninsula during 2011.

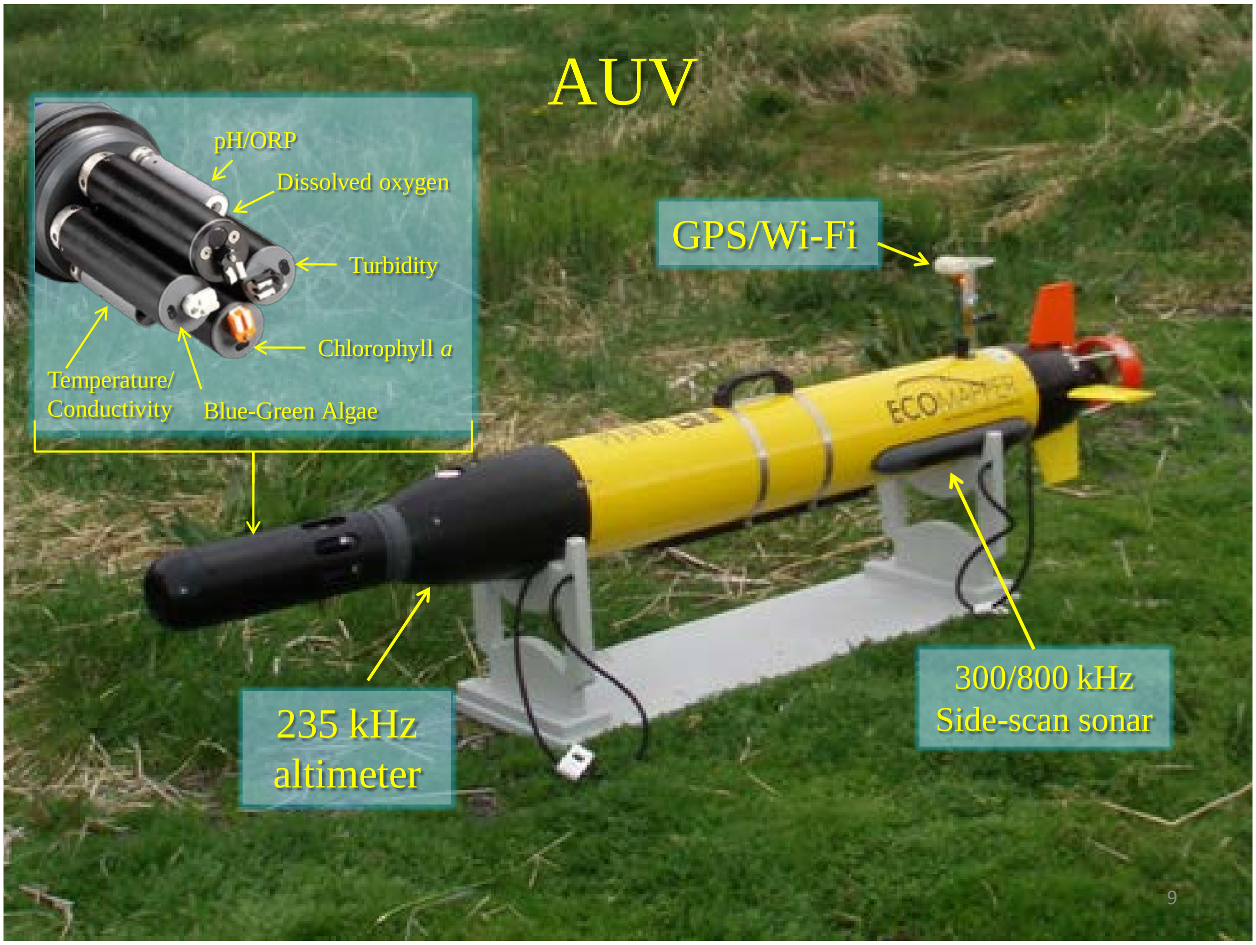


Figure 3.–The AUV and its features.

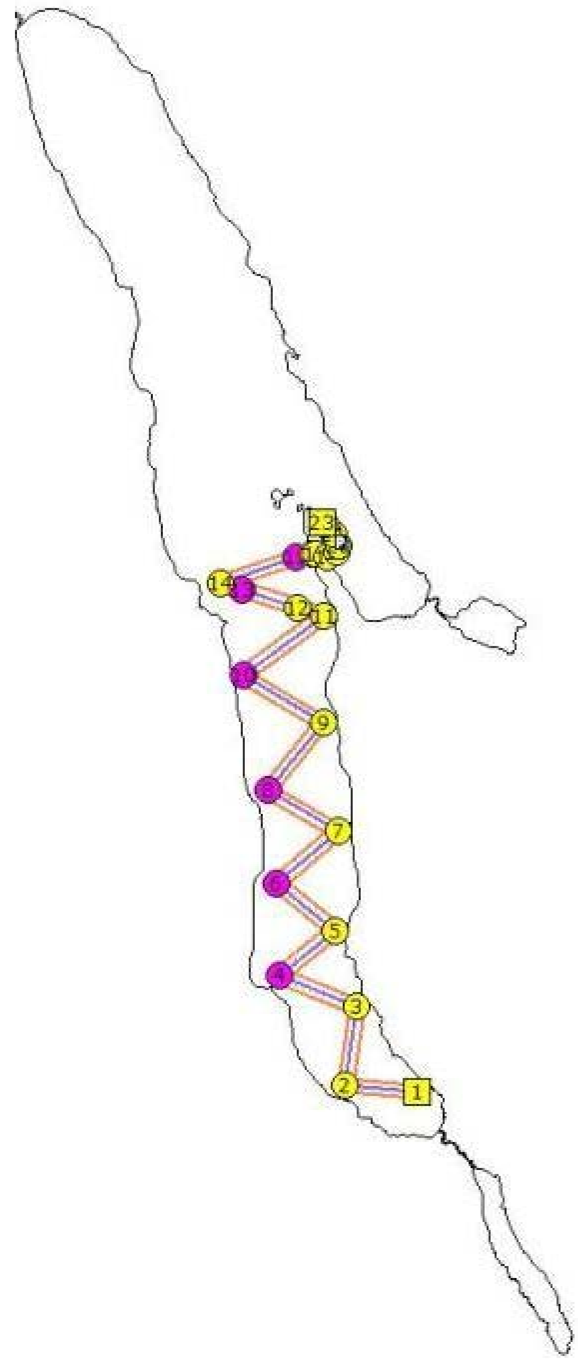
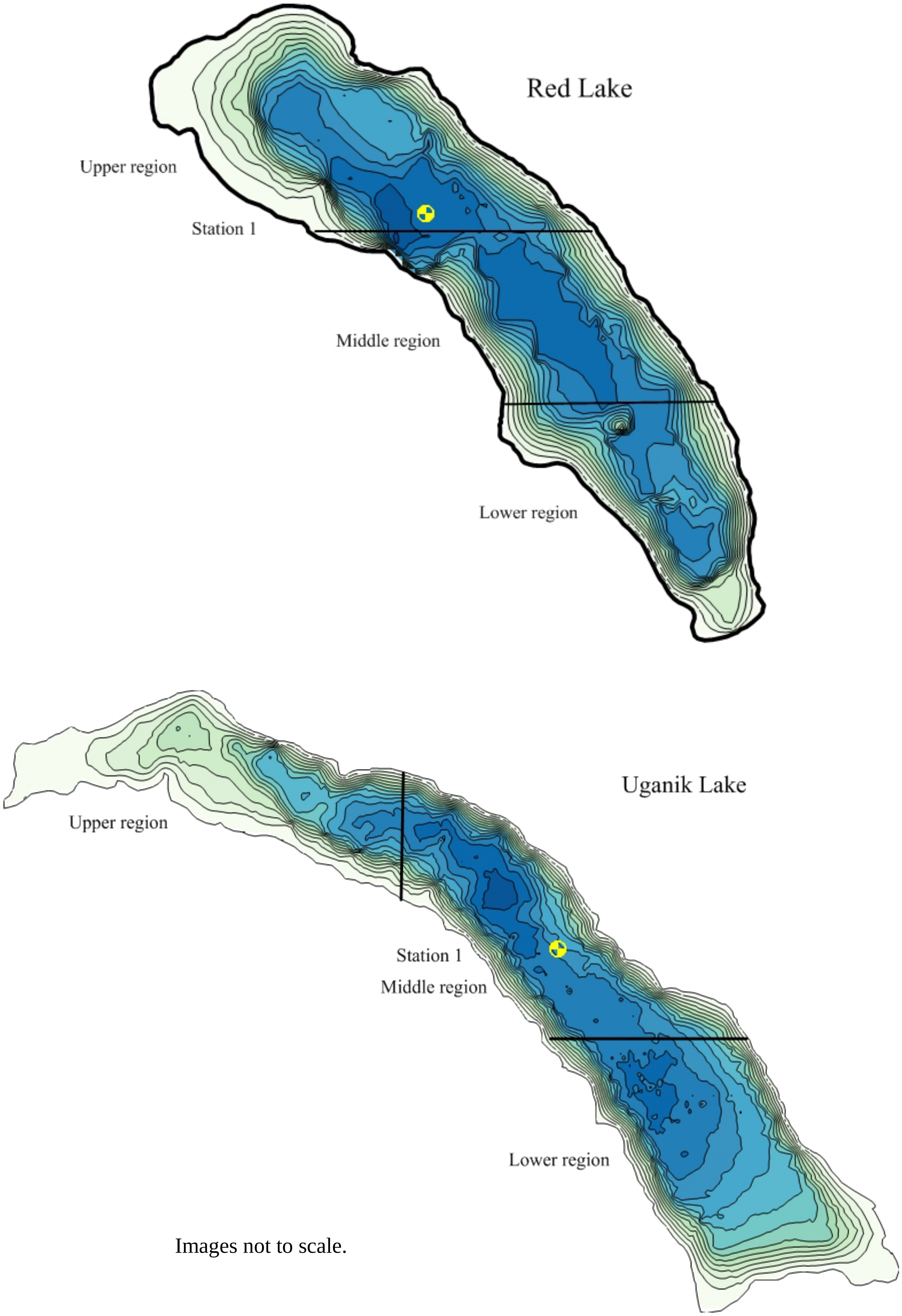


Figure 4.–Example of an AUV mission plotted in Karluk Lake using VectorMap software.



Images not to scale.

Figure 5.–AUV sampling regions and locations of traditional sampling stations for Red (top) and Uganik (bottom) lakes, 2011.

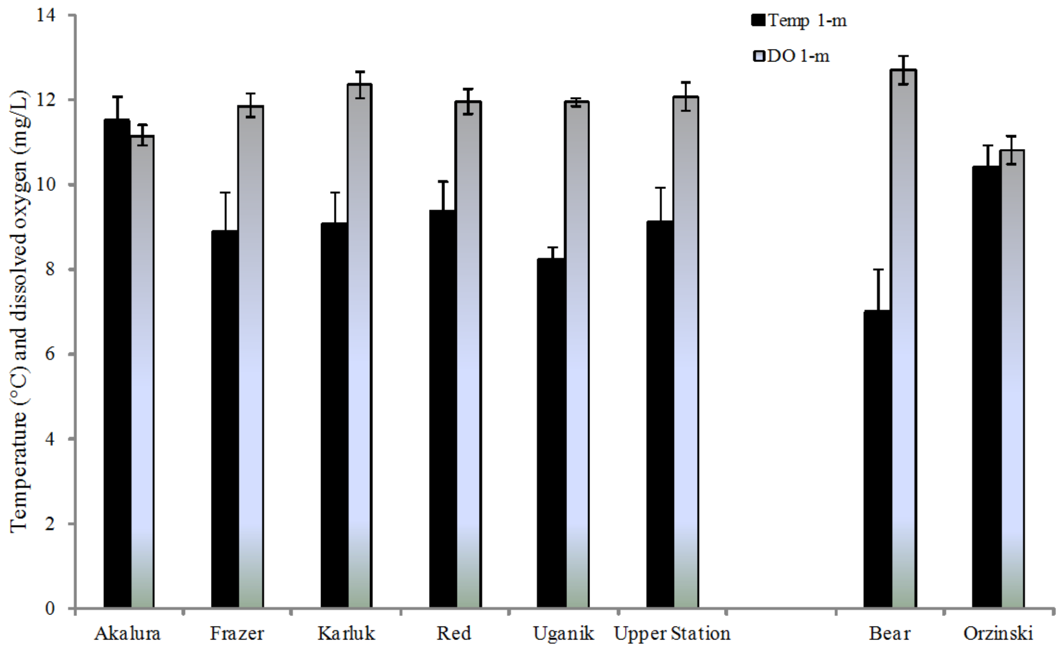


Figure 6.–Seasonal average 1 m temperature and dissolved oxygen measurements from all sampled lakes, 2011. Standard error bars are shown for each measurement.

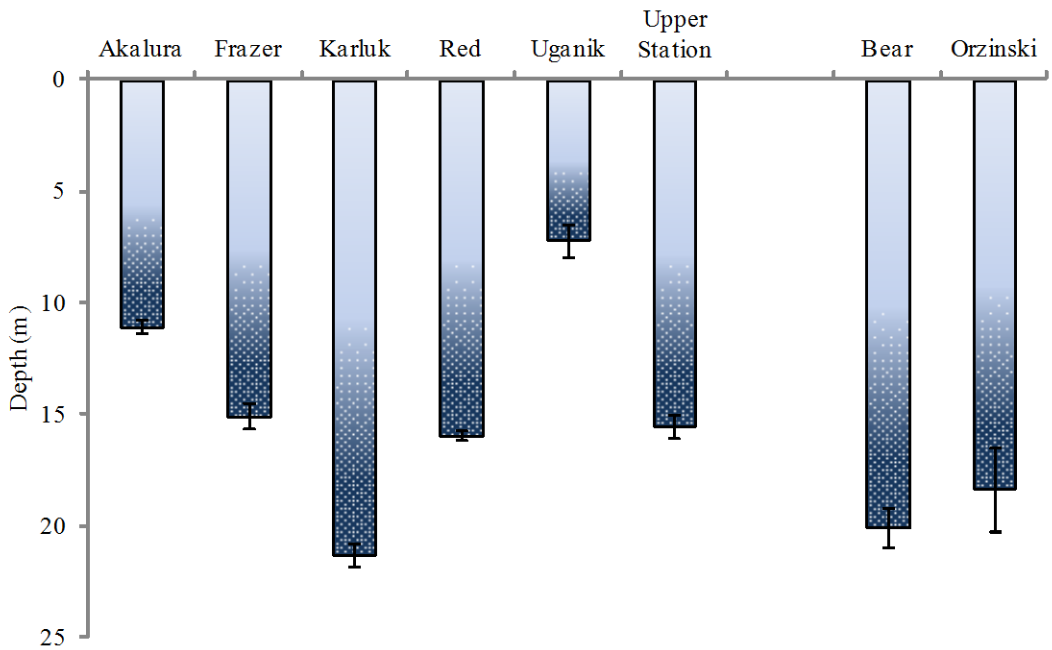


Figure 7.–Seasonal average euphotic zone depth (EZD) for all lakes sampled, 2011. Standard error bars are shown for each measurement.

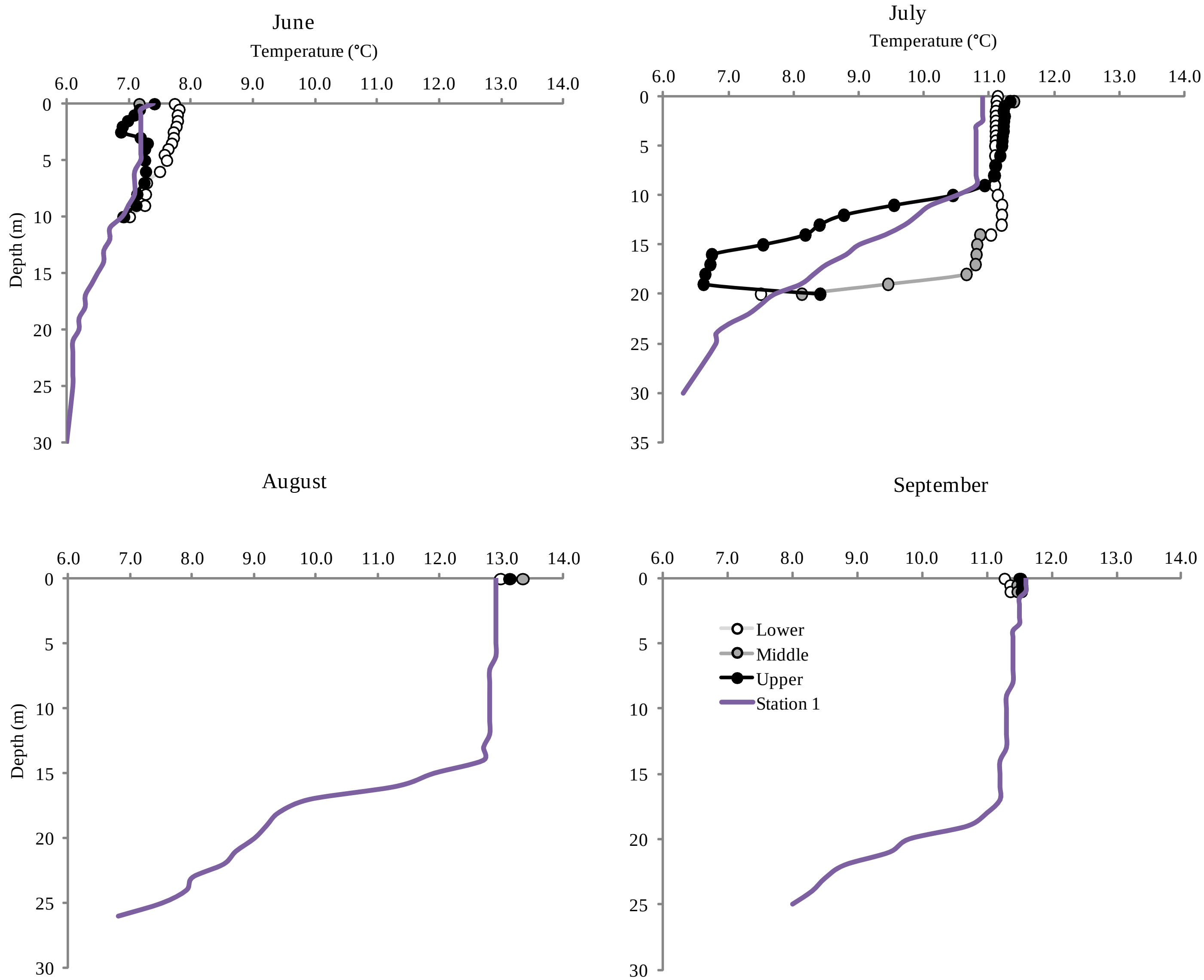


Figure 8.–Red Lake AUV (Lower, Middle, Upper) temperature depth profiles by month compared to traditionally collected (Station 1) data, 2011.

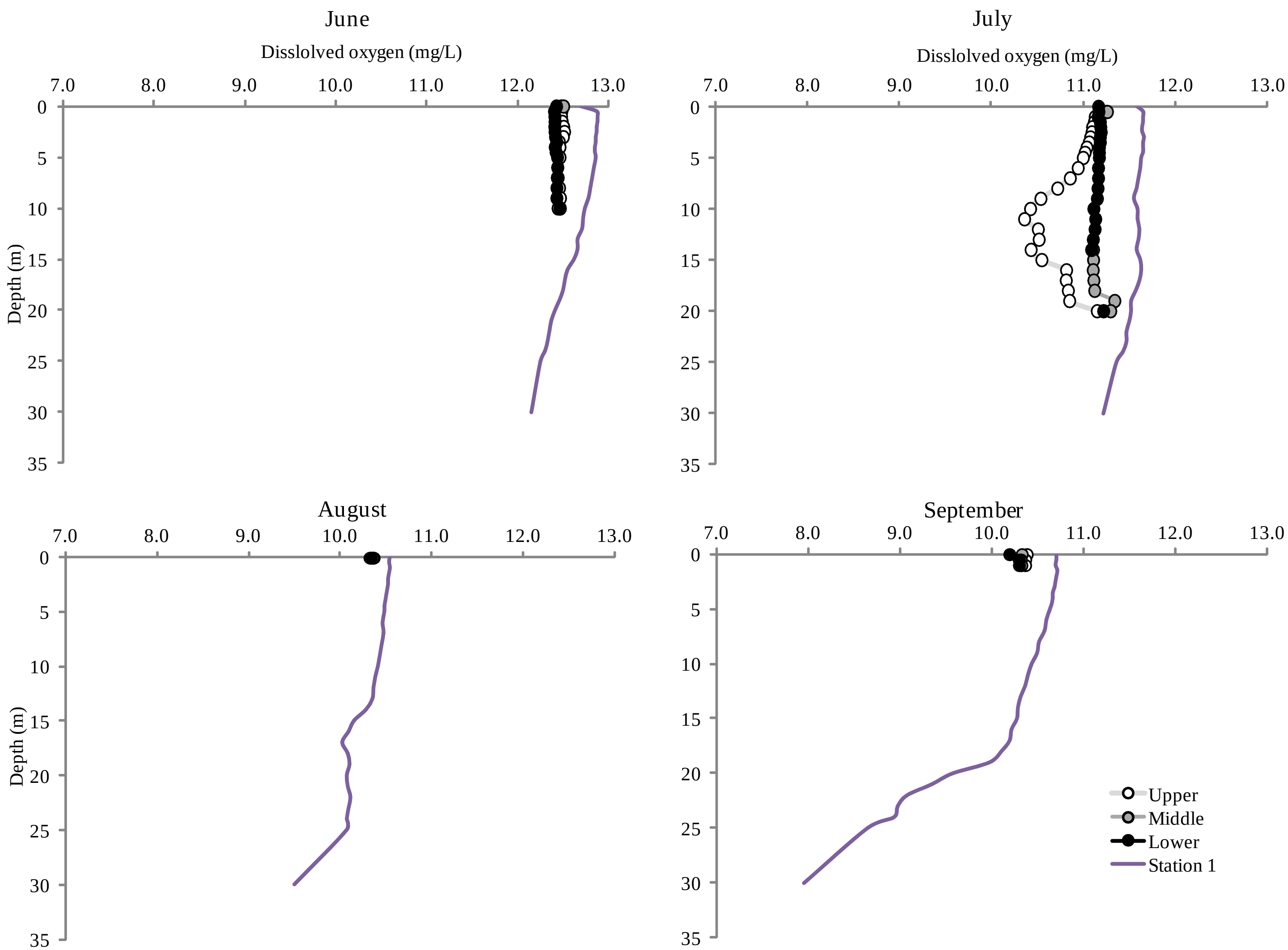


Figure 9.–Red Lake AUV (Lower, Middle, Upper) dissolved oxygen depth profiles by month compared to traditionally collected (Station 1) data, 2011.

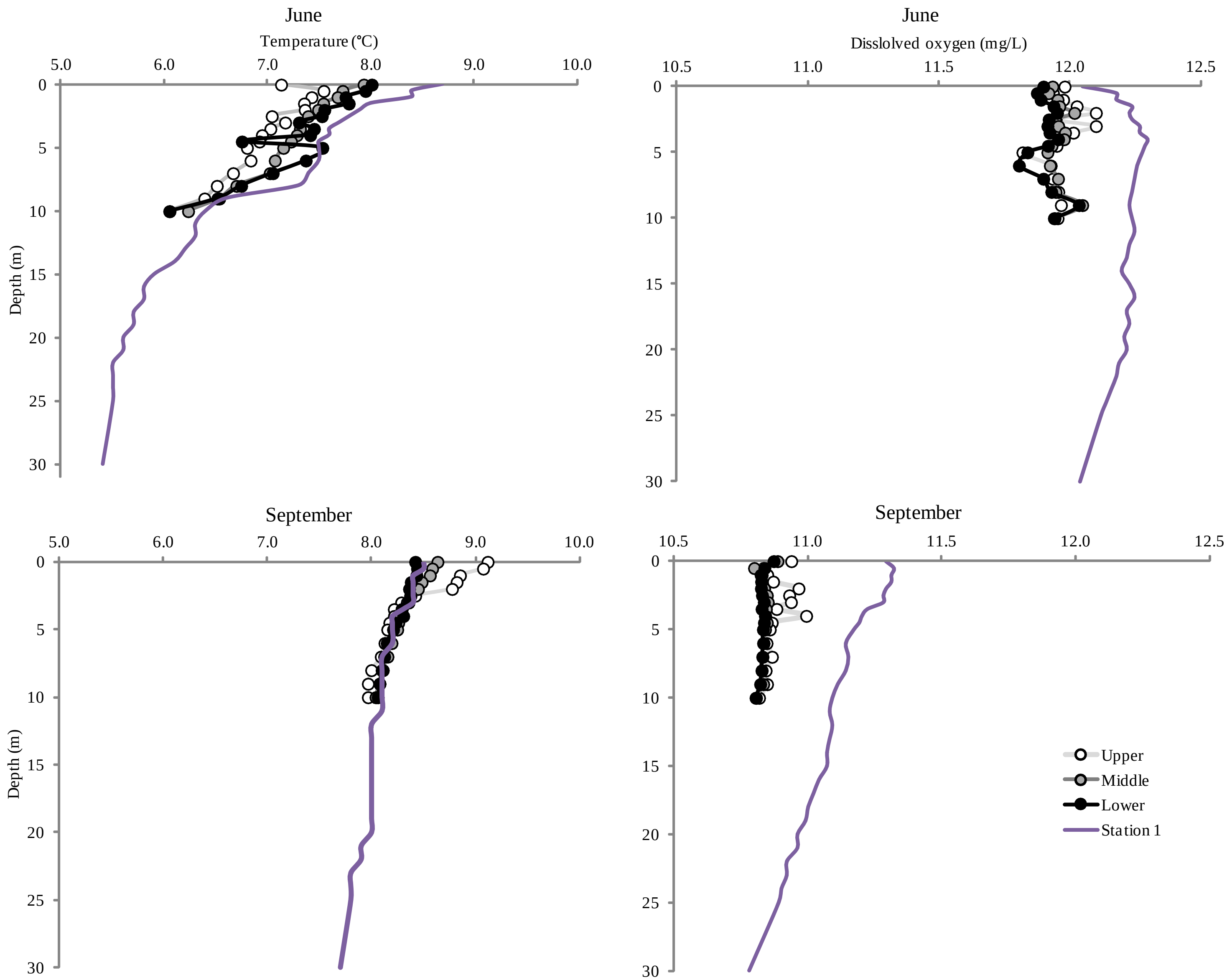


Figure 10.–Uganik Lake AUV (Upper, Middle, Lower) temperature (left panels) and dissolved oxygen (right panels) depth profiles compared to traditionally collected (Station 1) data for June and September, 2011.

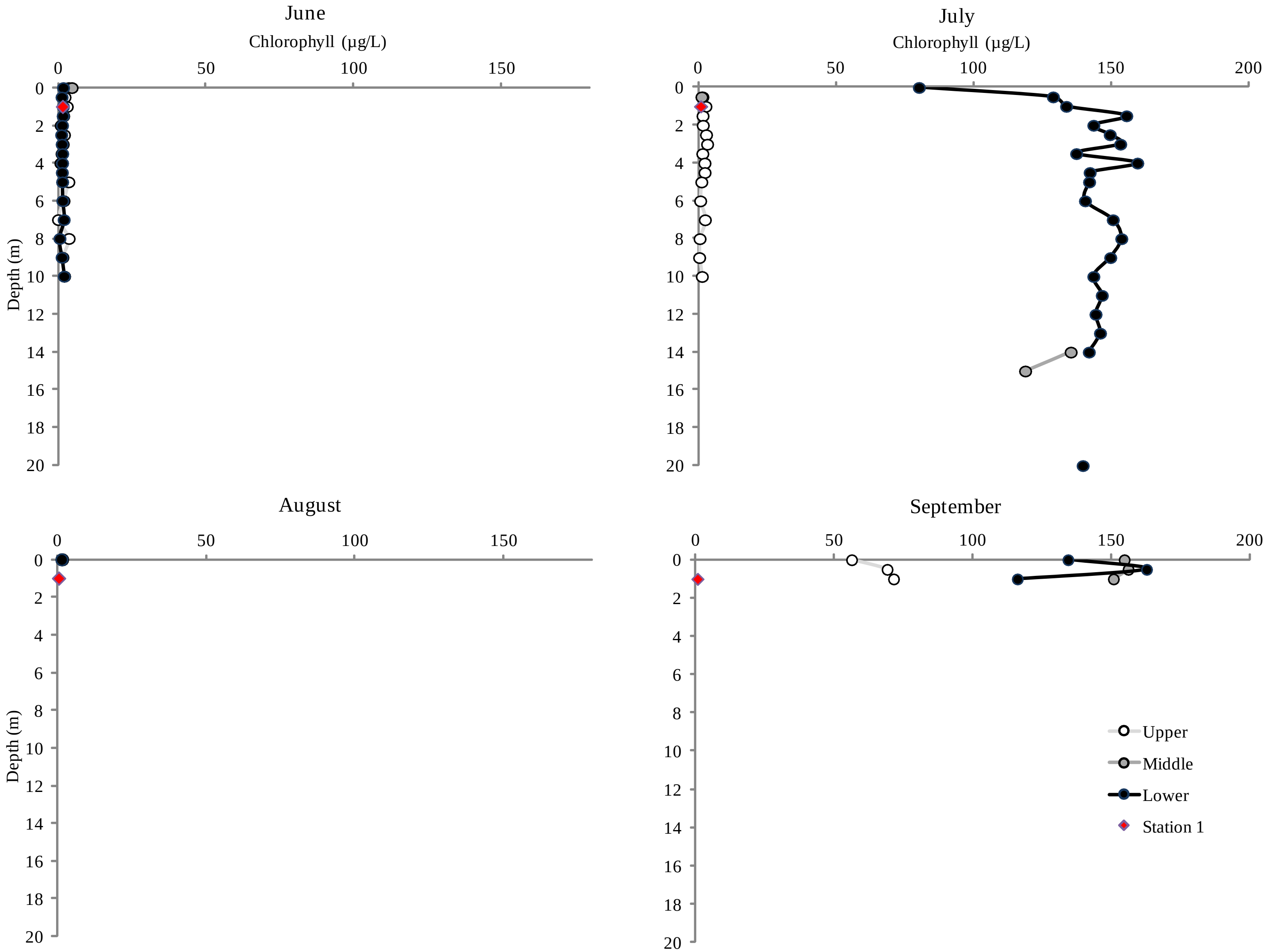


Figure 11.–Red Lake AUV (Upper, Middle, Lower) chlorophyll concentration depth profiles by month compared to traditionally collected (Station 1) data, 2011.

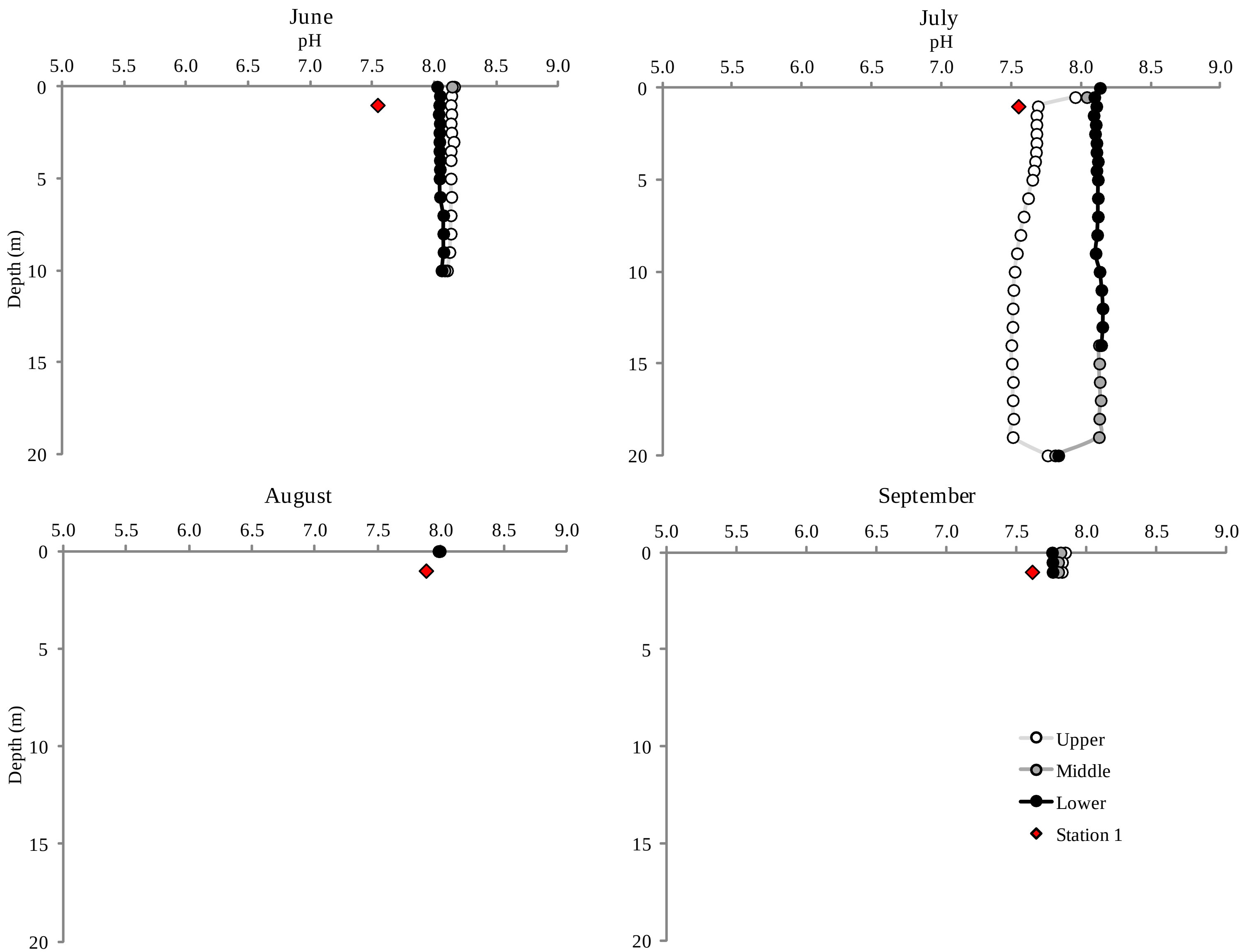


Figure 12.–Red Lake AUV (Upper, Middle, Lower) pH depth profiles by month compared to traditionally collected (Station 1) data, 2011.

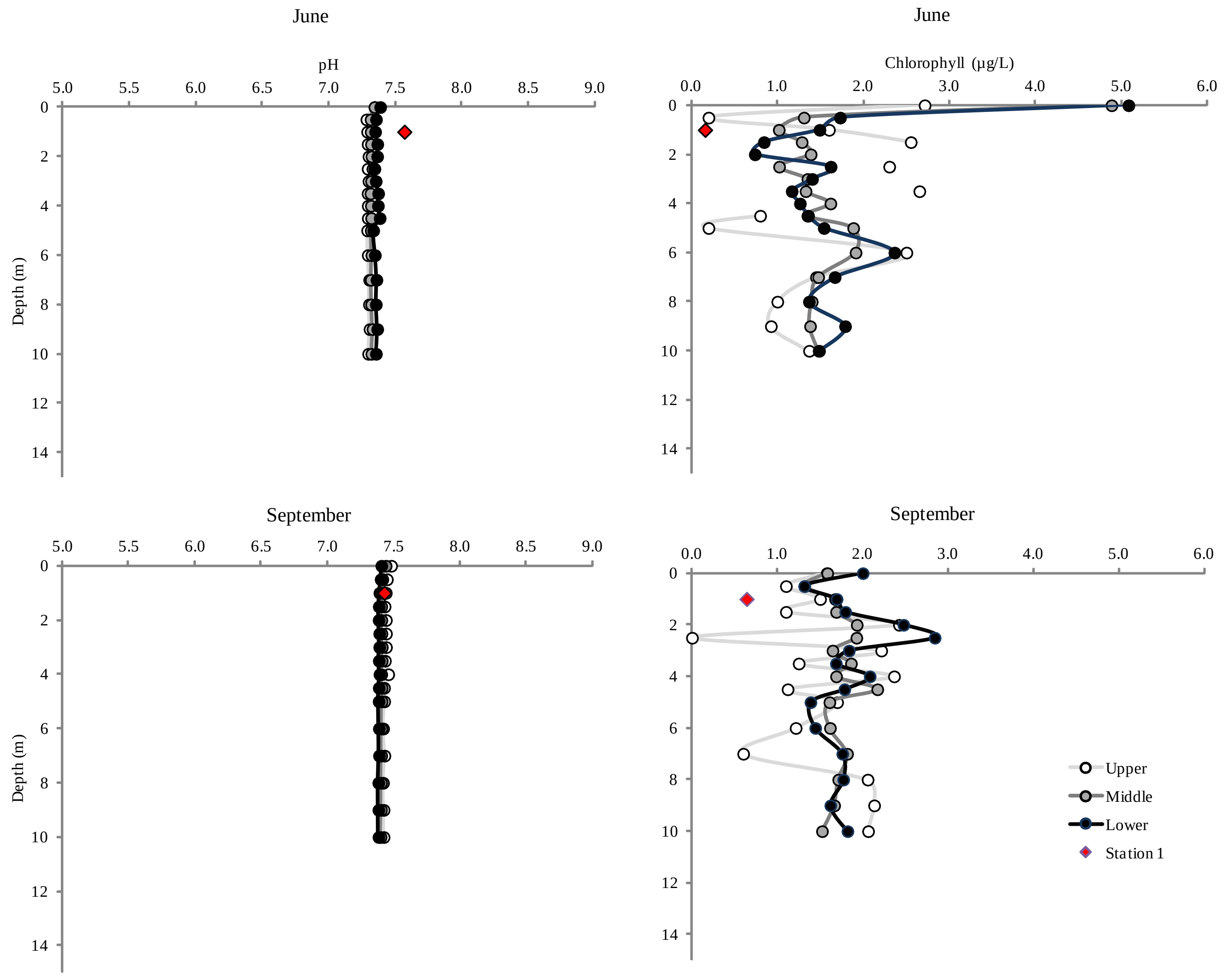


Figure 13.–Uganik Lake AUV (Upper, Middle, Lower) pH (left panels) and chlorophyll (right panels) depth profiles by month compared to traditionally collected (Station 1) data for June and September, 2011.

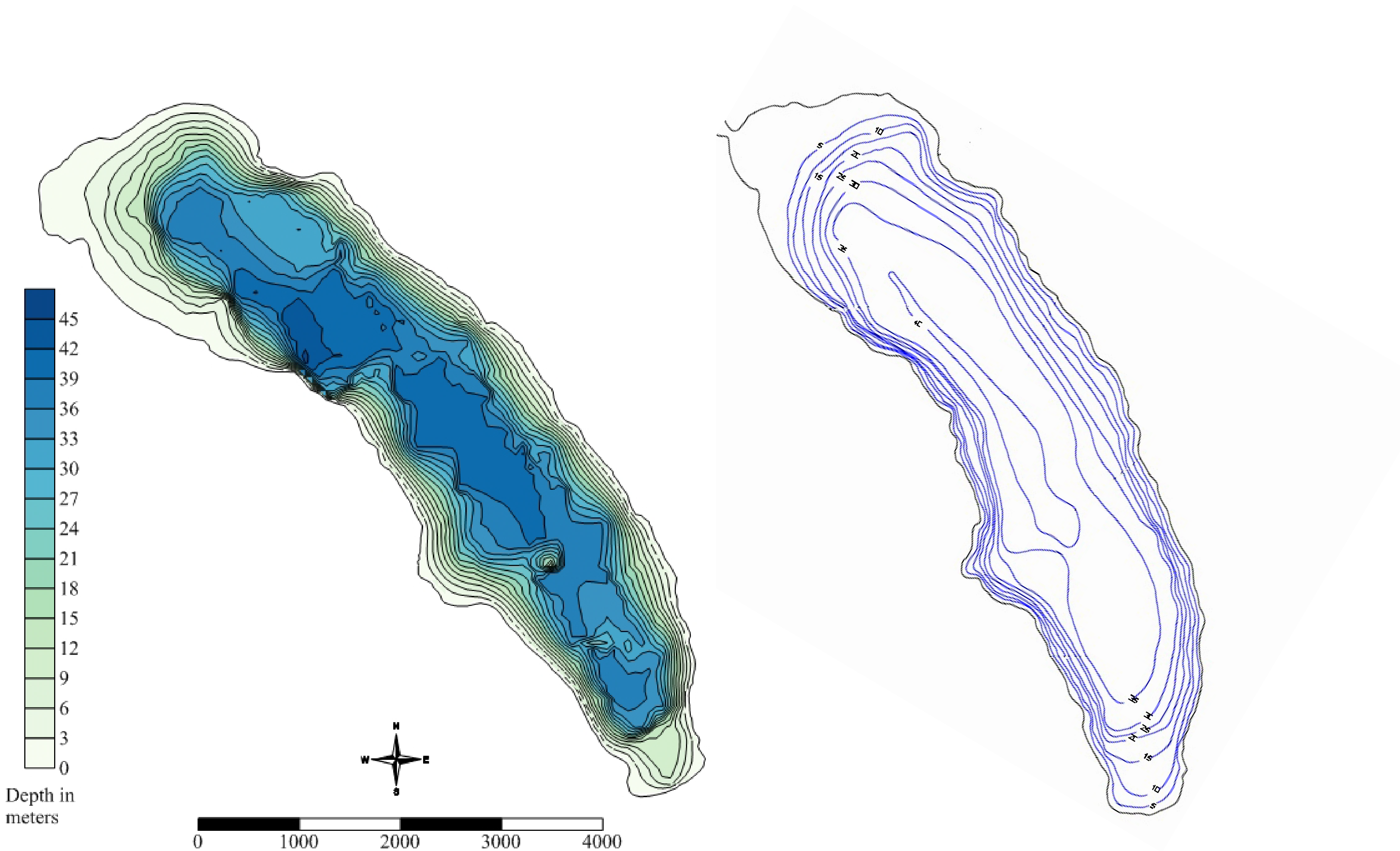


Figure 14.–Red Lake bathymetric maps comparing AUV-based (left) and original (right) maps.

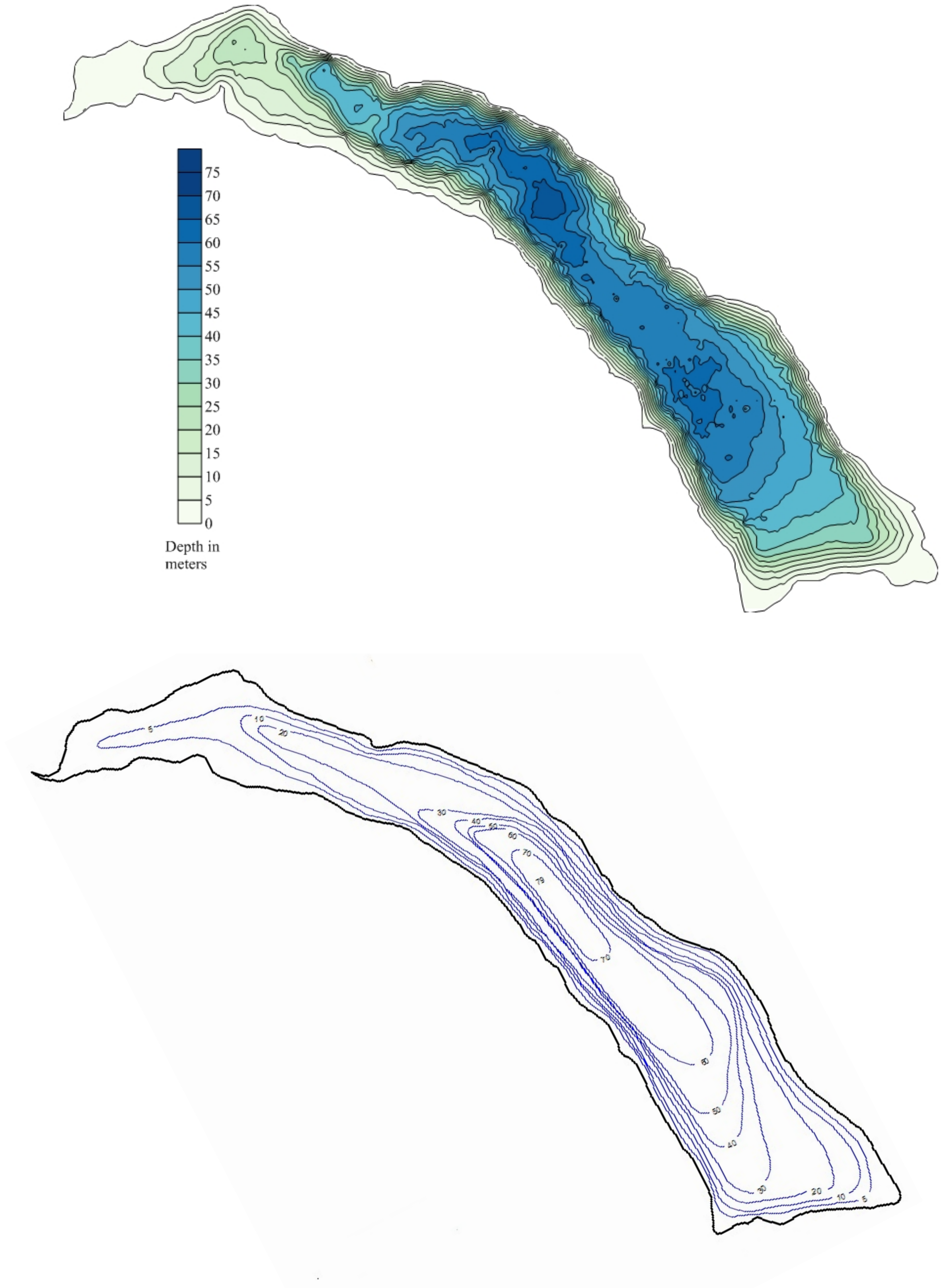


Figure 15.–Uganik Lake bathymetric maps comparing AUV-based (top) and original (bottom) maps.

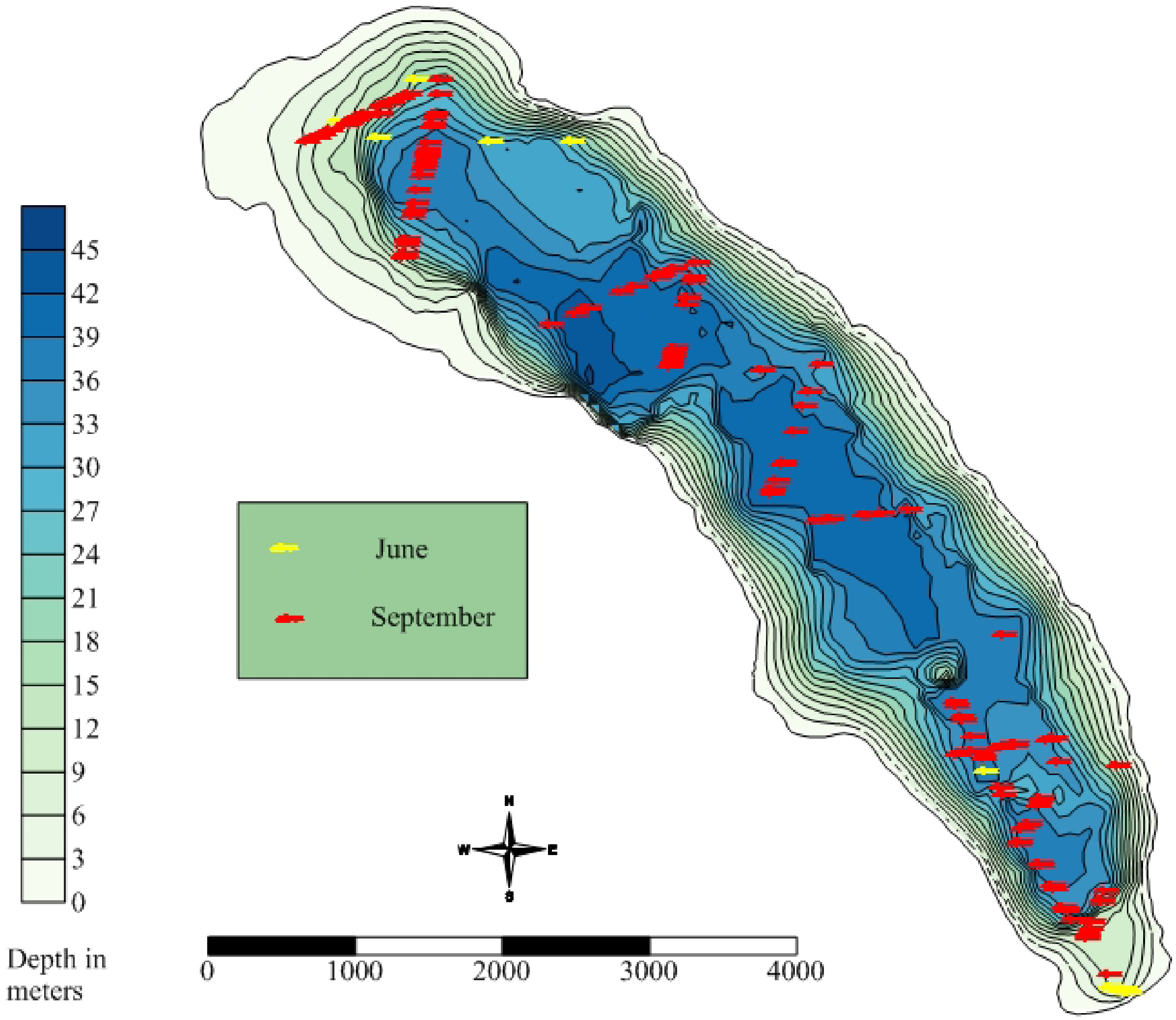


Figure 16.–Map of fish presence by month in Red Lake, 2011.

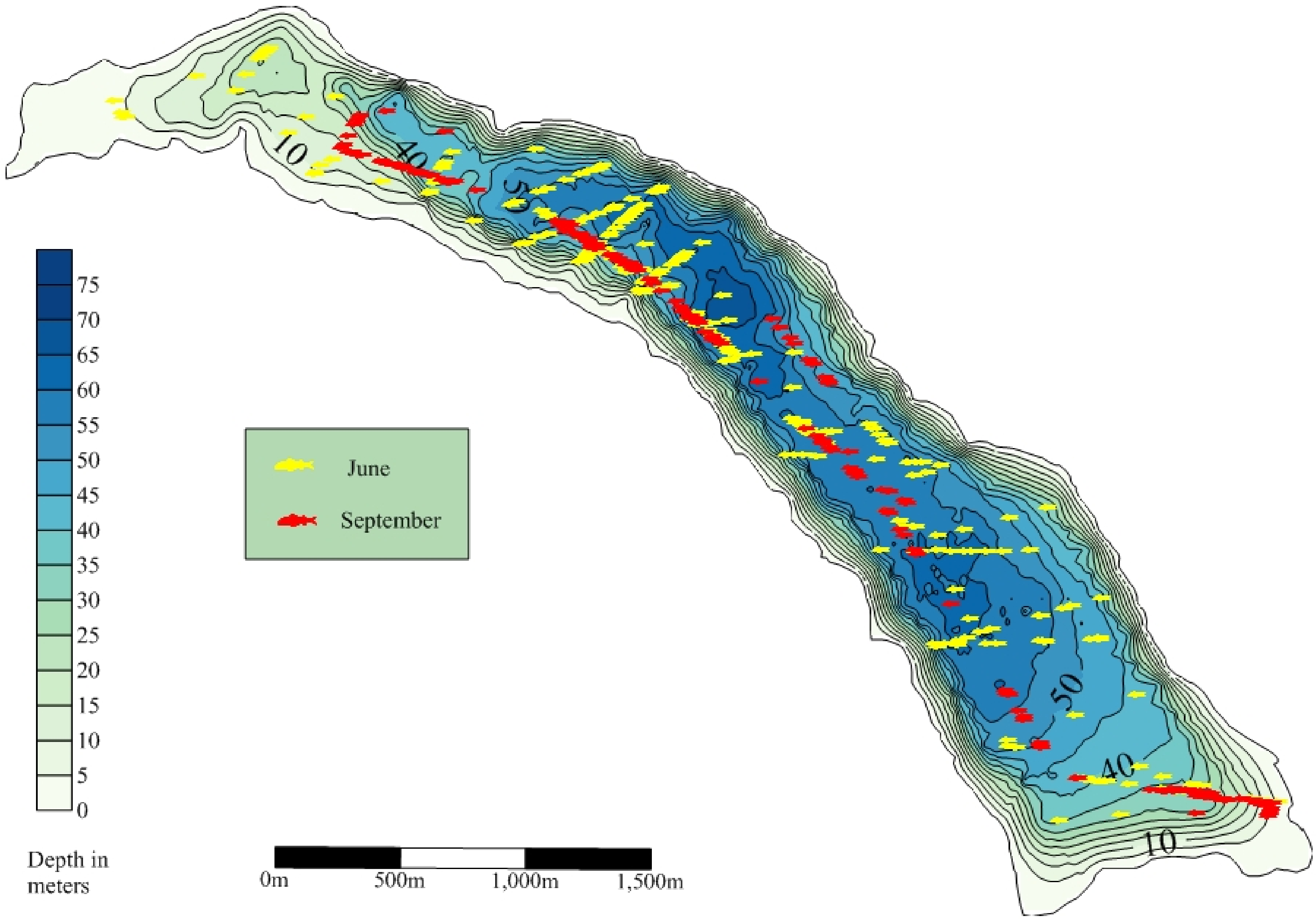


Figure 17.–Map of fish presence by month in Uganik Lake, 2011.

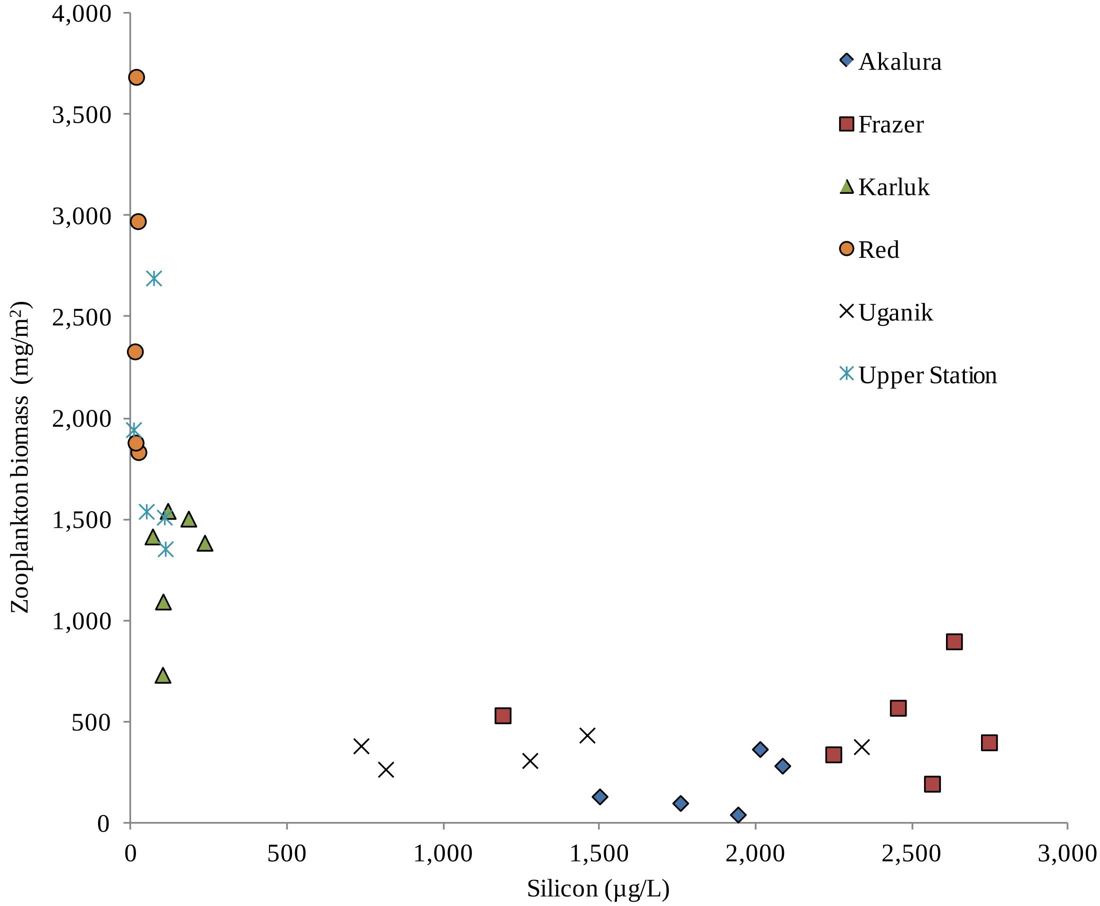
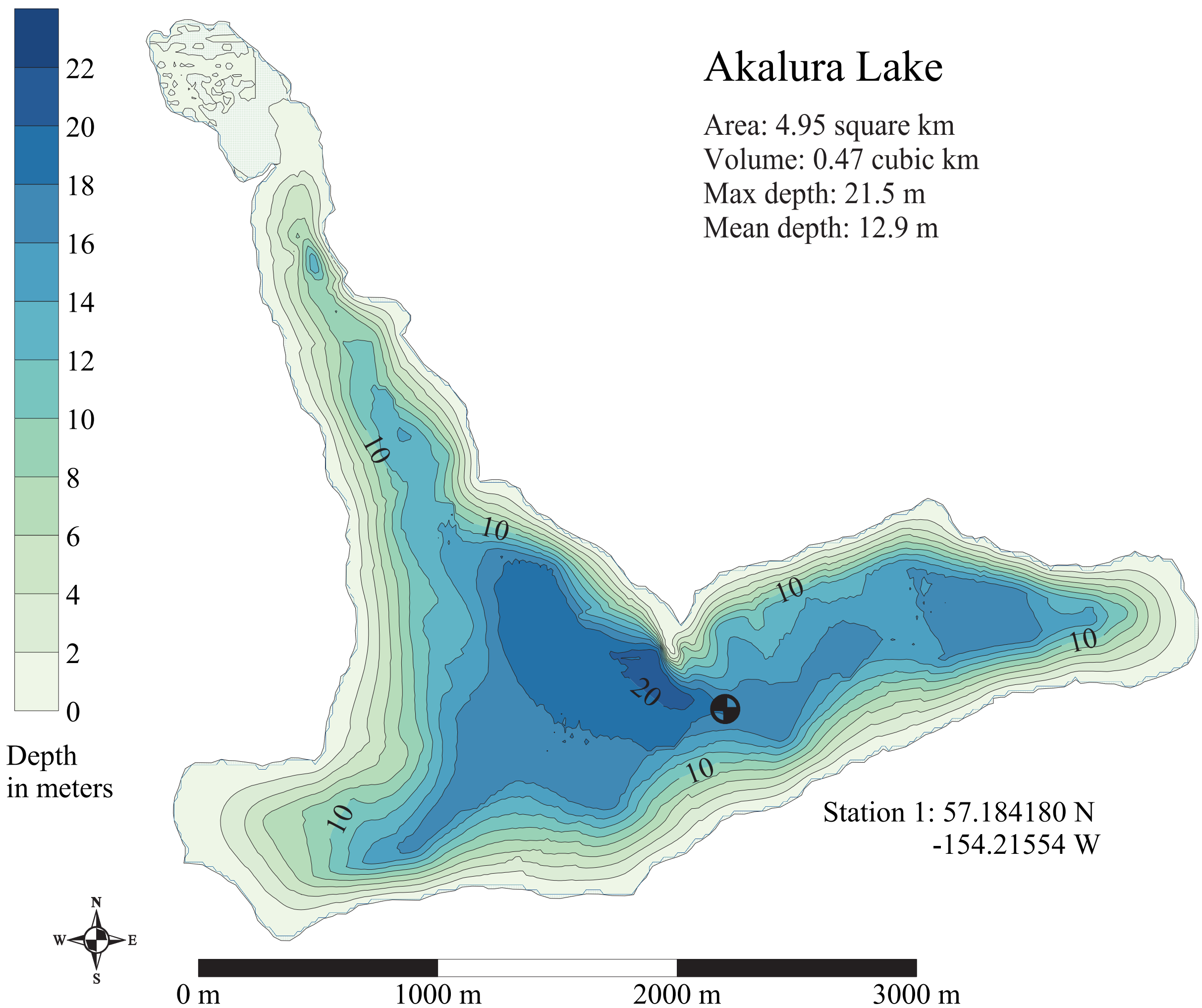


Figure 18.–Relationship between silicon and zooplankton biomass for Kodiak lakes, 2011.

APPENDIX A. AKALURA LAKE

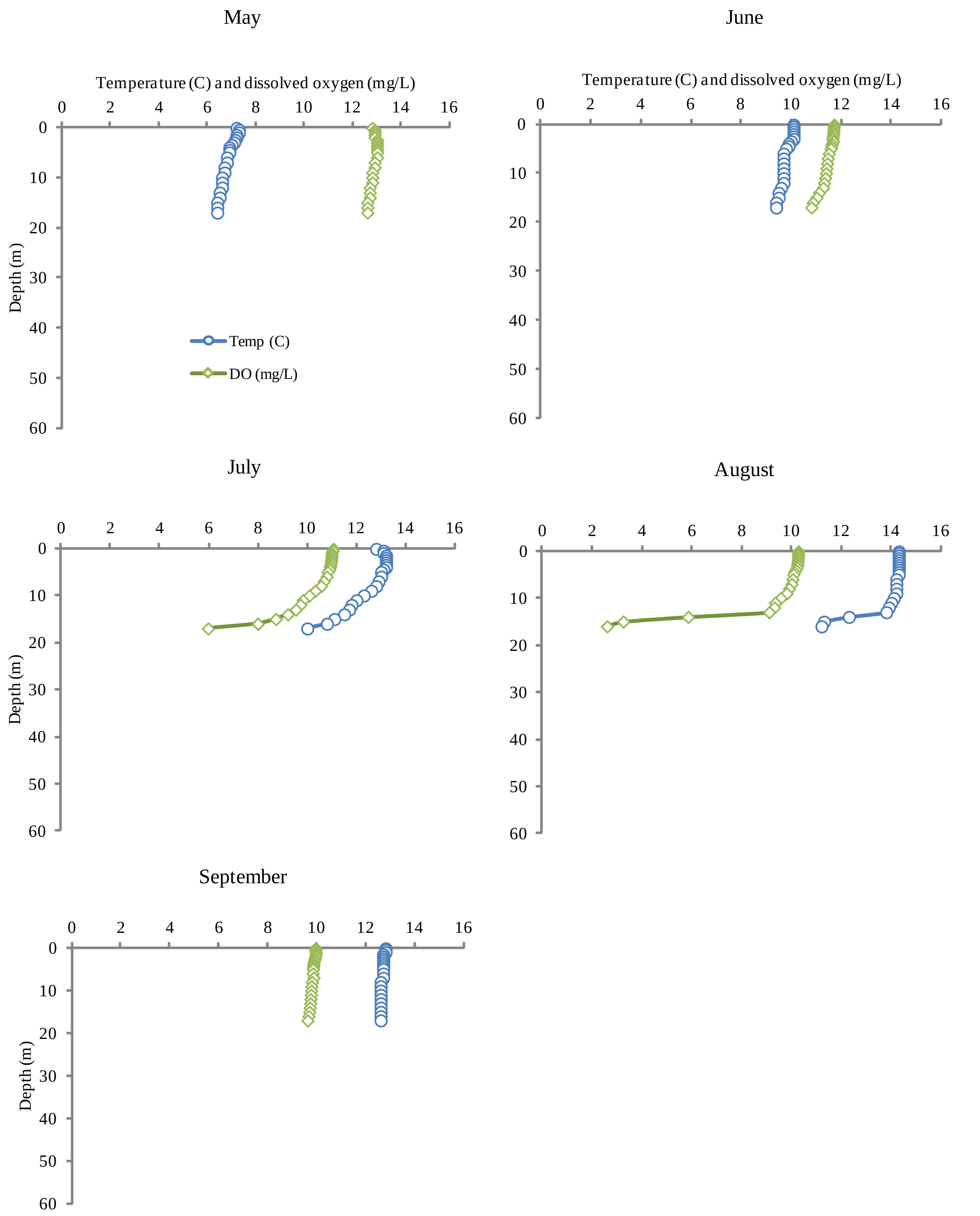
Appendix A1.–Map of Akalura Lake showing the limnological sampling station.



Appendix A2.–Monthly and seasonal averages of 1 m temperature and dissolved oxygen, euphotic zone depth (EZD), and Secchi measurements from Akalura Lake, 2011.

	May	June	July	August	September	Seasonal average
1-m Temperature (°C)	7.3	10.1	13.1	14.3	12.8	11.5
1-m Dissolved oxygen (mg/L)	12.9	11.7	11.0	10.3	10.0	11.2
EZD (m)	10.1	10.0	12.3	13.4	9.6	11.1
Secchi depth (m)	2.8	4.3	4.3	5.8	4.3	4.3

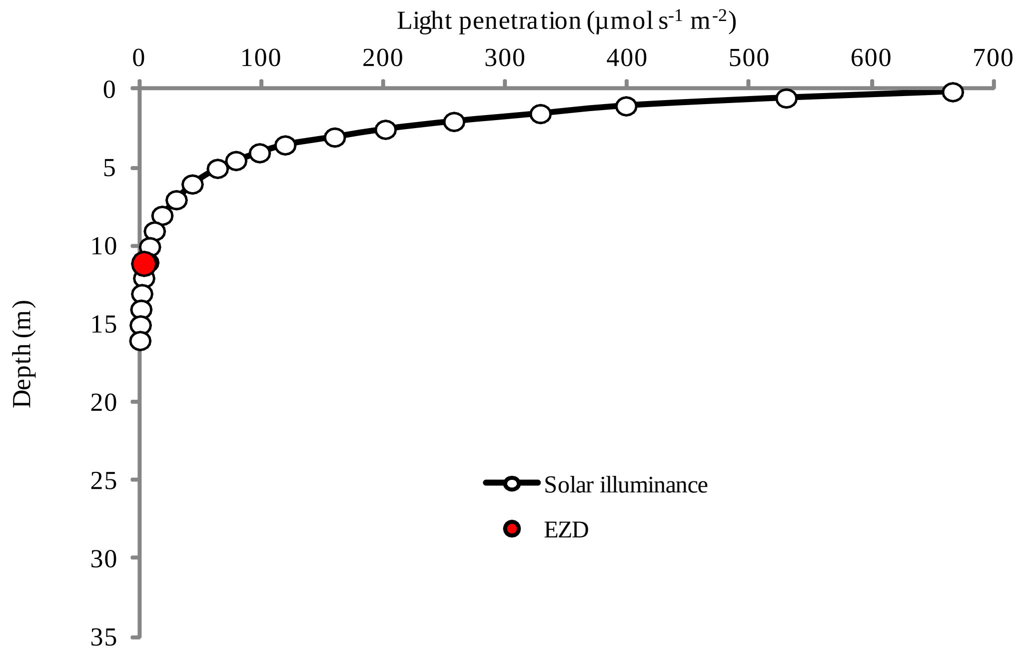
Appendix A3.–Temperature and dissolved oxygen depth profiles by month for Akalura Lake, 2011.



Appendix A4.–Akalura Lake solar illuminance (μmol s^{-1} m^{-2}) profiles by month, 2011.

	Date					
Depth (m)	13-May	16-Jun	18-Jul	26-Aug	15-Sep	Average
0.1	1,265.0	527.0	284.0	280.0	976.0	666.4
0.5	990.0	373.0	242.0	163.0	882.0	530.0
1	828.0	231.0	166.0	113.0	656.0	398.8
1.5	663.0	172.0	129.0	121.0	558.0	328.6
2	508.0	138.0	105.0	109.0	429.0	257.8
2.5	410.0	117.0	75.9	88.7	316.6	201.6
3	336.0	95.0	66.0	70.8	232.4	160.0
3.5	239.0	79.1	56.1	56.3	167.1	119.5
4	203.0	64.3	48.2	47.1	130.2	98.6
4.5	156.0	52.3	43.6	40.3	104.1	79.3
5	122.0	42.1	37.3	33.8	85.3	64.1
6	78.0	28.6	26.7	24.3	59.6	43.4
7	51.0	19.0	19.9	19.2	42.6	30.3
8	33.0	13.1	14.1	12.7	20.6	18.7
9	20.7	8.9	9.9	9.4	13.6	12.5
10	13.4	6.2	6.7	8.2	8.3	8.6
11	9.5	4.2	4.8	11.8	5.6	7.2
12		2.9	3.4	5.2	3.6	3.8
13		2.0	2.3	2.4	1.9	2.2
14		1.4	1.5			1.5
15		0.9	1.0			1.0
16			0.6			0.6
17						
18						
19						
20						
21						
22						
23						
24						
25						
26						
27						
28						
29						
30						

Appendix A5.–Average monthly solar illuminance profile for Akalura Lake, 2011.



Appendix A6.–Akalura Lake seasonal water quality properties, nutrients and photosynthetic pigments, 2011.

Sample type	May	June	July	August	September	Seasonal average	SE
pH	7.16	7.51	7.48	7.66	7.50	7.46	0.04
Alkalinity (mg/L $CaCO_3$)	15.5	15.5	16.0	17.5	16.0	16.1	0.16
Total phosphorous (µg/L P)	10.9	10.0	9.7	11.5	11.6	10.7	0.17
Total filterable phosphorous (µg/L P)	4.1	2.4	3.2	4.0	3.9	3.5	0.14
Filterable reactive phosphorous (µg/L P)	5.6	1.0	1.0	1.4	1.3	2.1	0.40
Total Kjeldahl nitrogen (µg/L N)	184.0	191.0	193.0	102.0	217.0	177.4	8.79
Ammonia (µg/L N)	8.9	1.5	1.6	2.4	12.6	5.4	1.01
Nitrate + nitrite (µg/L N)	0.6	0.2	2.1	2.0	8.4	2.7	0.66
Organic silicon (µg/L)	1,942.0	1,499.1	1,757.5	2,012.4	2,084.2	1,859.0	47.01
Chlorophyll *a* (µg/L)	1.60	0.80	1.28	2.31	2.49	1.70	0.14
Phaeophytin *a* (µg/L)	0.87	0.43	0.51	0.55	0.75	0.62	0.04

Appendix A7.–Seasonal zooplankton abundance (number/m^2) in Akalura Lake, 2011.

Taxon	Date 13-May	16-Jun	18-Jul	26-Aug	15-Sep	Seasonal average
Copepods:						
Epischura	-	20,701	5,732	30,255	39,278	19,193
Ovig. *Epischura*	-	-	-	2,389	-	478
Eurytemora	6,900	28,662	3,185	24,682	11,677	15,021
Ovig. Eurytemora	-	-	-	796	531	265
Cyclops	9,554	3,185	22,293	11,943	6,369	10,669
Ovig. *Cyclops*	-	-	1,274	-	-	255
Harpaticus	-	-	637	1,592	1,062	658
Nauplii	16,985	50,159	5,732	9,554	12,739	19,034
Total copepods:	33,439	102,707	38,854	81,210	71,656	65,573
Cladocerans:						
Bosmina	1,592	3,185	15,924	136,943	37,155	38,960
Ovig. *Bosmina*	-	2,389	1,274	93,153	28,662	25,096
Daphnia longiremis	-	-	637	-	531	234
Ovig. *Daphnia longiremis*	-	-	637	-	-	127
Holopedium	-	-	-	-	-	-
Immature cladocerans	531	1,592	14,650	82,006	19,639	23,684
Total cladocerans:	2,123	7,166	33,121	312,102	85,987	88,100
Total copepods + cladocerans	35,563	109,873	71,975	393,312	157,643	153,673

Appendix A8.–Akalura Lake seasonal weighted zooplankton biomass (mg/m^2) for 2011.

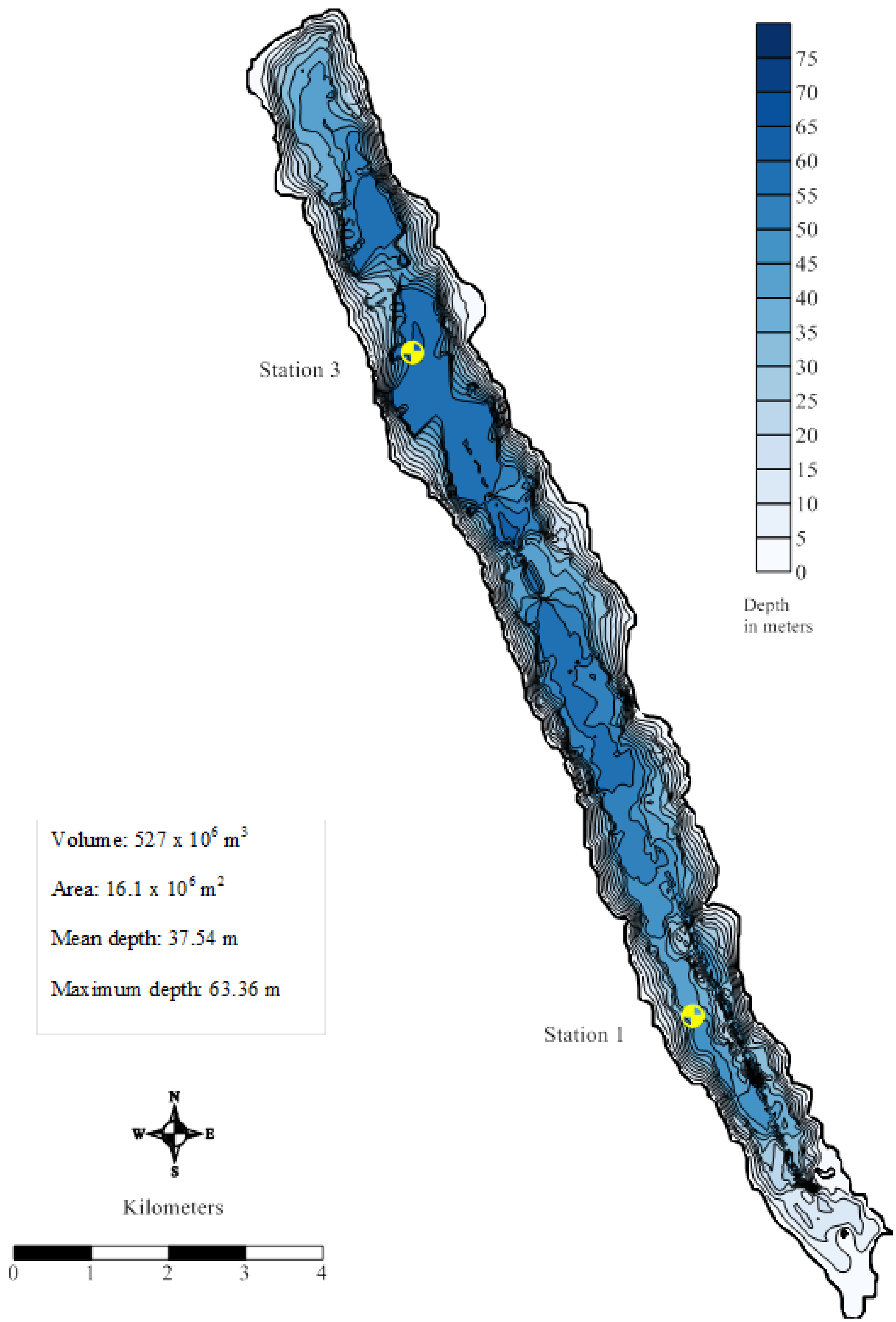
Taxon	Date					Seasonal weighted average
	13-May	16-Jun	18-Jul	26-Aug	15-Sep	
Copepods:						
Epischura	-	19	33	51	167	54
Ovig. *Epischura*	-	-	-	23	-	5
Eurytemora	32	107	18	112	57	65
Ovig. *Eurytemora*	-	-	-	5	4	2
Cyclops	11	3	25	16	4	12
Ovig. *Cyclops*	-	-	7	-	-	1
Harpaticus	-	-	-	2	1	-
Total copepods:	43	128	83	208	233	139
Cladocerans:						
Bosmina	1	2	10	78	24	23
Ovig. *Bosmina*	-	3	1	81	27	23
Daphnia longiremis	-	-	2	-	1	1
Ovig. *Daphnia longiremis*	-	-	5	-	-	1
Holopedium	-	-	-	-	-	-
Chydorinae	-	-	-	-	-	-
Total cladocerans:	1	5	18	159	52	47
Total copepods + cladocerans	44	133	101	367	285	185

Appendix A9.–Akalura Lake seasonal zooplankton lengths (mm), 2011.

Taxon	Date					Seasonal average length
	13-May	16-Jun	18-Jul	26-Aug	15-Sep	
Copepods:						
Epischura	-	0.57	1.09	0.71	0.98	0.84
Ovig. *Epischura*	-	-	-	1.30	-	1.30
Eurytemora	0.87	0.76	0.99	0.86	0.90	0.88
Ovig. *Eurytemora*	-	-	-	1.08	1.12	1.10
Cyclops	0.58	0.50	0.58	0.62	0.47	0.55
Ovig. *Cyclops*	-	-	1.21	-	-	1.21
Harpaticus	-	-	-	0.55	0.50	0.53
Cladocerans:						
Bosmina	-	0.37	0.31	0.25	0.32	0.31
Ovig. *Bosmina*	-	-	0.80	0.31	0.61	0.57
Daphnia longiremis	-	-	1.29	-	-	1.29
Ovig. *Daphnia longiremis*	-	-	-	-	-	-
Holopedium	-	-	-	-	-	-
Chydorinae	-	-	-	-	-	-

APPENDIX B. FRAZER LAKE

Appendix B1.–Map of Frazer Lake showing the limnological sampling station.

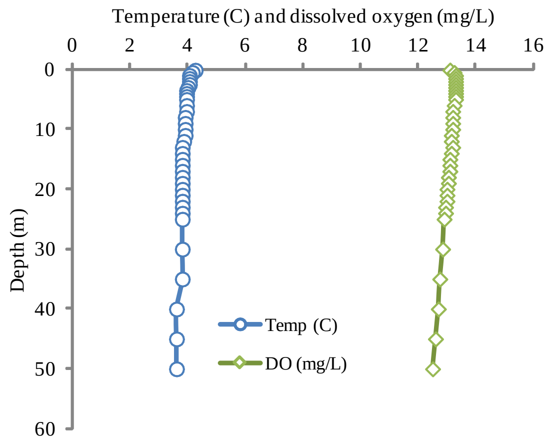


Appendix B2.–Monthly and seasonal averages of 1 m temperature and dissolved oxygen, euphotic zone depth (EZD), and Secchi measurements from Frazer Lake, 2011.

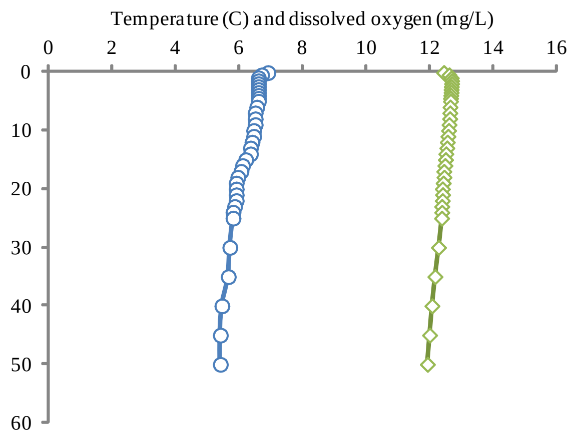
Sample type	May	June	July	August	September	October	Seasonal average
Station 1							
1-m Temperature (°C)	4.3	6.3	10.4	13.2	10.2	8.8	8.9
1-m Dissolved oxygen (mg/L)	13.3	12.7	11.9	11.1	11.0	11.3	11.9
EZD (m)	15.0	15.8	12.8	19.8	15.5	13.6	15.4
Secchi depth (m)	7.3	5.3	5.8	7.0	8.0	4.8	6.3
Station 3							
1-m Temperature (°C)	3.8	6.9	10.0	12.9	10.7	9.0	8.9
1-m Dissolved oxygen (mg/L)	13.3	12.7	11.9	11.3	11.0	11.0	11.9
EZD (m)	15.7	15.9	11.8	15.2	16.6	13.8	14.8
Secchi depth (m)	6.8	6.3	5.8	5.5	6.0	4.5	5.8

Appendix B3.–Temperature and dissolved oxygen depth profiles by month for Frazer Lake, 2011.

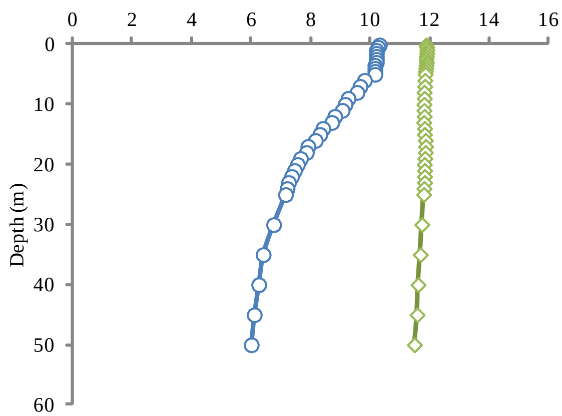
May



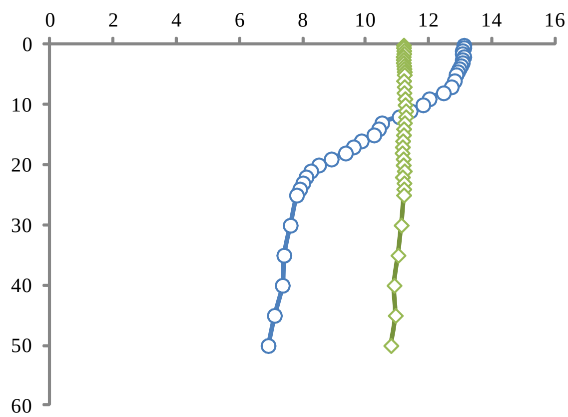
June



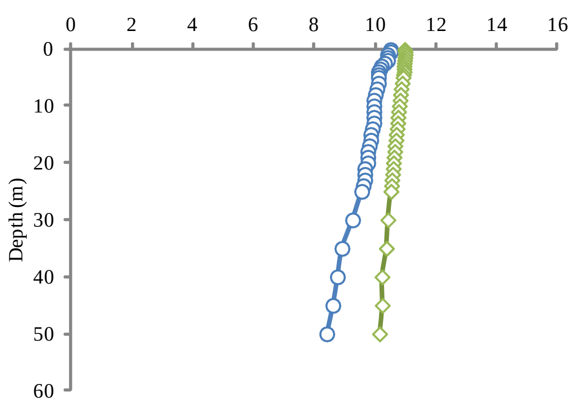
July



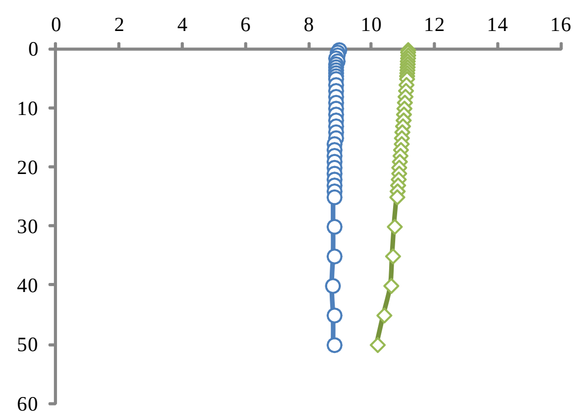
August



September



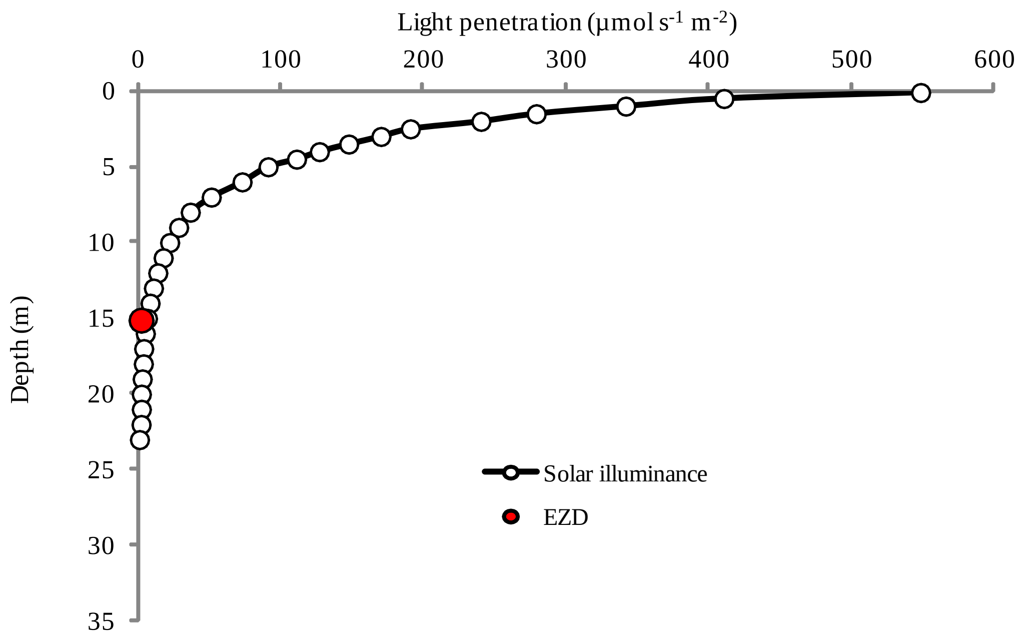
October



Appendix B4.–Frazer Lake solar illuminance (µmol s^{-1} m^{-2}) profiles by month, 2011.

	Date						
Depth (m)	13-May	16-Jun	16-Jul	17-Aug	15-Sep	13-Oct	Average
0.1	1,462.5	506.0	778.0	286.8	237.5	18.1	548.2
0.5	1,114.5	383.5	572.0	182.7	196.5	12.9	410.3
1	997.5	330.5	433.0	128.6	150.5	9.9	341.7
1.5	802.5	275.0	343.0	114.5	129.5	8.8	278.9
2	720.5	218.5	290.5	93.5	111.0	7.3	240.2
2.5	536.0	178.0	233.0	91.8	99.9	5.8	190.7
3	492.5	157.0	195.5	89.2	81.7	5.0	170.1
3.5	433.0	138.5	158.0	80.2	71.5	4.4	147.6
4	367.5	122.0	133.1	71.6	64.1	3.8	127.0
4.5	323.0	106.5	112.0	65.2	56.4	3.1	111.0
5	256.5	87.7	93.3	53.5	51.3	4.3	91.1
6	200.1	67.6	85.0	41.4	41.5	2.1	72.9
7	143.9	52.7	43.3	33.6	33.1	1.5	51.3
8	105.0	39.4	31.3	26.1	16.9	1.1	36.6
9	81.5	31.0	23.8	20.8	13.3	0.8	28.5
10	64.7	23.9	16.6	16.6	11.1	0.6	22.2
11	49.7	18.7	13.5	12.7	10.6	0.4	17.6
12	39.0	14.6	11.0	9.7	8.5	0.3	13.8
13	31.1	11.5	8.4	7.4	6.5	0.2	10.8
14	24.7	9.0	6.5	5.9	4.9	0.1	8.5
15	19.3	7.1	5.1	4.8	3.6	0.1	6.6
16	15.0	5.7	4.1	3.8	2.4	0.0	5.1
17	11.8	4.6	3.1	3.0	1.6	0.0	4.0
18	9.2	3.5	2.5	2.3	1.0		3.7
19	7.4	2.9	2.0	1.9	0.6		2.9
20	6.3	2.3	1.5	1.5	0.2		2.3
21	5.1	1.8	1.1	1.2			2.3
22	5.3	1.5	0.9	1.0			2.2
23		1.1					1.1
24							
25							
26							
27							
28							
29							
30							

Appendix B5.–Average monthly solar illuminance profile for Frazer Lake, 2011.



Appendix B6.–Frazer Lake averaged seasonal water quality properties, nutrients and photosynthetic pigments, 2011.

Depth	Sample type	May	June	July	August	September	October	Seasonal average	SE
1 meter									
	pH	7.35	7.48	7.46	7.72	7.47	7.44	7.49	0.02
	Alkalinity (mg/L $CaCO_3$)	14.6	14.9	15.8	16.3	15.6	14.8	15.3	0.11
	Total phosphorous (µg/L P)	5.0	5.7	5.2	4.2	4.5	5.7	5.03	0.10
	Total filterable phosphorous (µg/L P)	2.2	2.8	2.2	1.7	1.6	2.0	2.05	0.07
	Filterable reactive phosphorous (µg/L P)	0.4	1.0	0.7	0.4	0.5	0.7	0.61	0.04
	Total Kjeldahl nitrogen (µg/L N)	132.3	133.7	115.8	154.9	153.3	180.6	145.1	3.78
	Ammonia (µg/L N)	3.0	3.1	3.8	3.5	9.3	5.7	4.70	0.41
	Nitrate + nitrite (µg/L N)	45.1	39.4	12.7	1.7	20.0	28.0	24.4	2.73
	Organic silicon (µg/L)	2,746.0	2,633.8	2,454.3	2,563.6	1,188.6	2,247.5	2,305.6	95.49
	Chlorophyll *a* (µg/L)	0.95	0.80	1.36	1.12	0.80	2.08	1.18	0.08
	Phaeophytin *a* (µg/L)	0.38	0.32	0.77	0.23	0.43	0.50	0.44	0.03
Hypolimnion									
	pH	7.34	7.42	7.39	7.47	7.25	7.39	7.4	0.01
	Alkalinity (mg/L $CaCO_3$)	14.1	14.8	15.6	16.8	15.8	15.3	15.4	0.15
	Total phosphorous (µg/L P)	4.9	7.3	5.8	4.3	4.2	5.6	5.3	0.19
	Total filterable phosphorous (µg/L P)	7.3	3.7	2.6	2.9	1.7	1.7	3.3	0.35
	Filterable reactive phosphorous (µg/L P)	4.4	0.6	0.5	0.5	0.5	0.4	1.1	0.26
	Total Kjeldahl nitrogen (µg/L N)	116.5	145.0	130.6	118.5	142.5	168.6	137.0	3.25
	Ammonia (µg/L N)	4.1	6.6	13.7	20.1	20.4	4.2	11.5	1.27
	Nitrate + nitrite (µg/L N)	25.2	39.4	40.5	40.0	33.2	30.6	34.8	1.03
	Organic silicon (µg/L)	2,684.1	2,696.4	2,599.3	2,560.0	898.7	2,098.9	2,256.2	116.77
	Chlorophyll *a* (µg/L)	0.80	0.48	0.48	0.40	0.48	1.92	0.76	0.10
	Phaeophytin *a* (µg/L)	0.21	0.31	0.08	0.16	0.20	0.77	0.29	0.04

Appendix B7.–Seasonal zooplankton abundance (number/m^2) in Frazer Lake, 2011.

Taxon	13-May	16-Jun	16-Jul	17-Aug	15-Sep	13-Oct	Seasonal average
Copepods:							
Epischura	-	-	1,354	-	531	-	314
Ovig. *Epischura*	-	-	-	-	-	-	-
Diaptomus	663	-	-	-	2,521	-	531
Ovig. *Diaptomus*	-	-	-	-	-	-	-
Cyclops	359,209	358,081	150,000	15,658	16,720	5,839	150,918
Ovig. *Cyclops*	-	-	9,050	9,421	18,710	6,104	7,214
Harpaticus	-	-	-	1,327	531	-	310
Nauplii	60,244	3,583	1,699	2,919	7,033	43,126	19,767
Total copepods:	420,117	361,664	162,102	29,326	46,046	55,069	179,054
Cladocerans:							
Bosmina	531	4,180	10,483	64,358	84,262	8,625	28,740
Ovig. *Bosmina*	-	1,194	6,024	28,530	70,329	57,723	27,300
Daphnia longiremis	1,062	3,185	4,751	16,454	95,143	94,878	35,912
Ovig. *Daphnia longiremis*	-	-	1,008	7,696	51,884	53,344	18,989
Holopedium	-	-	-	-	1,062	-	177
Chydorinae	-	-	-	-	-	1,725	288
Immature cladocerans	2,256	10,350	16,454	64,225	121,019	21,895	39,367
Total cladocerans:	3,848	18,909	38,721	181,263	423,700	238,190	150,772
Total copepods + cladocerans	423,965	380,573	200,823	210,589	469,745	293,259	329,826

Appendix B8.–Frazer Lake seasonal weighted zooplankton biomass (mg/m^2) for 2011.

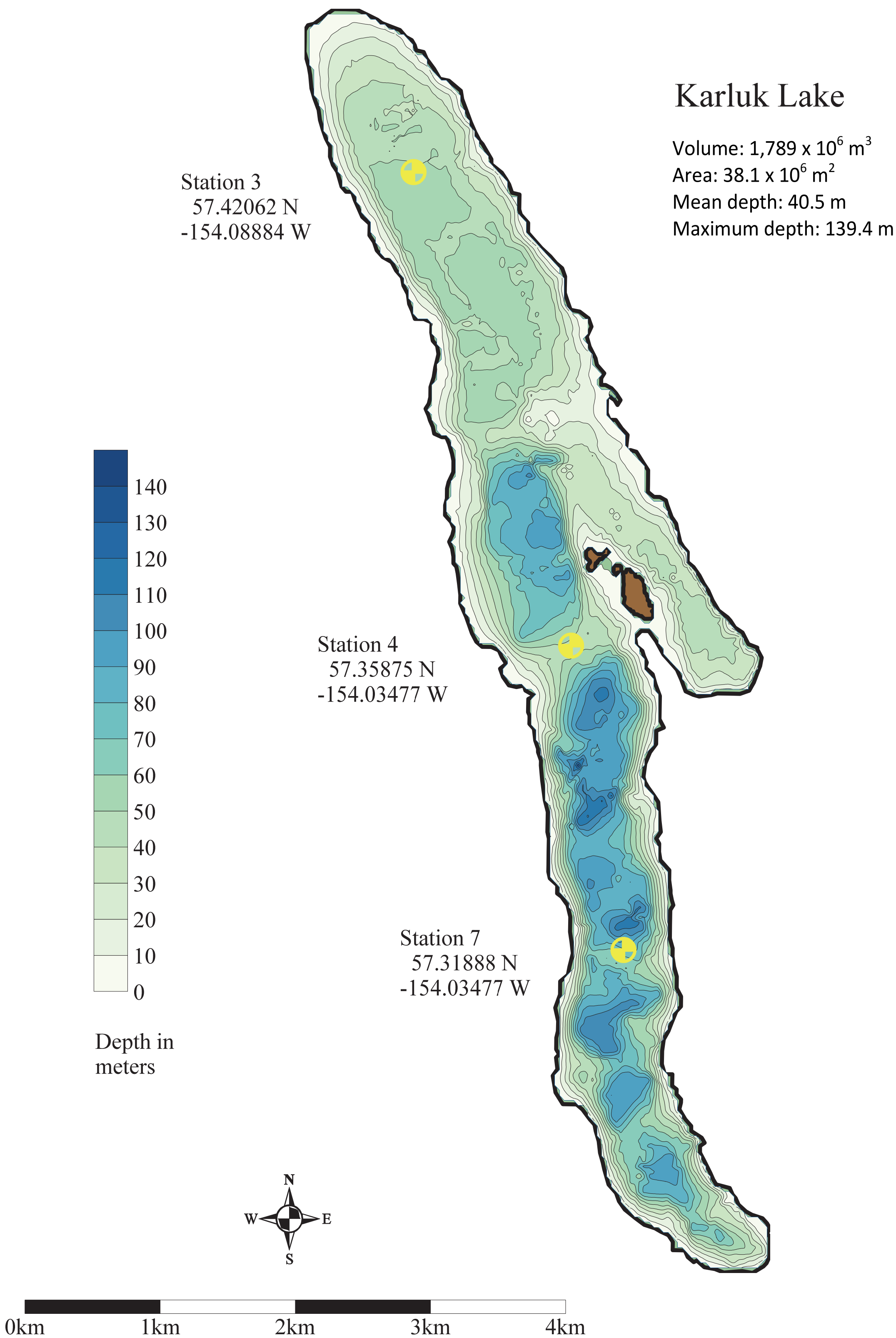
Taxon	Date						Seasonal weighted average
	13-May	16-Jun	16-Jul	17-Aug	15-Sep	13-Oct	
Copepods:							
Epischura	-	-	8	-	1	-	2
Ovig. *Epischura*	-	-	-	-	-	-	-
Diaptomus	4	-	-	-	8	-	2
Ovig. *Diaptomus*	-	-	-	-	-	-	-
Cyclops	394	888	489	29	37	7	308
Ovig. *Cyclops*	-	-	46	42	88	30	34
Harpaticus	-	-	-	1	1	-	-
Total copepods:	398	888	544	73	136	37	346
Cladocerans:							
Bosmina	1	5	8	44	80	7	24
Ovig. *Bosmina*	-	2	12	40	108	104	44
Daphnia longiremis	2	4	5	19	104	94	38
Ovig. *Daphnia longiremis*	-	-	3	18	106	97	37
Holopedium	-	-	-	3	-	-	-
Ovig. *Holopedium*	-	-	-	-	-	-	-
Chydorinae	-	-	-	-	-	1	-
Total cladocerans:	2	11	27	123	398	304	144
Total copepods + cladocerans	401	899	571	196	534	341	490

Appendix B9.–Frazer Lake seasonal zooplankton lengths (mm), 2011.

Taxon	Date						Seasonal average length
	13-May	16-Jun	16-Jul	17-Aug	15-Sep	13-Oct	
Copepods:							
Epischura	-	-	1.10	-	0.77	-	0.94
Ovig. *Epischura*	-	-	-	-	-	-	-
Diaptomus	1.13	-	-	-	0.96	-	1.05
Ovig. *Diaptomus*	-	-	-	-	-	-	-
Cyclops	0.57	0.85	0.96	0.73	0.81	0.64	0.76
Ovig. *Cyclops*	-	-	1.18	1.10	1.13	1.17	1.15
Harpaticus	-	-	-	0.54	0.60	-	0.57
Cladocerans:							
Bosmina	0.41	0.35	0.29	0.28	0.33	0.32	0.33
Ovig. *Bosmina*	-	0.46	0.46	0.39	0.41	0.43	0.43
Daphnia longiremis	0.59	0.54	0.52	0.53	0.51	0.50	0.53
Ovig. *Daphnia longiremis*	-	-	0.75	0.73	0.69	0.66	0.71
Holopedium	-	-	-	-	0.54	-	0.54
Chydorinae	-	-	-	-	-	0.31	0.31

APPENDIX C. KARLUK LAKE

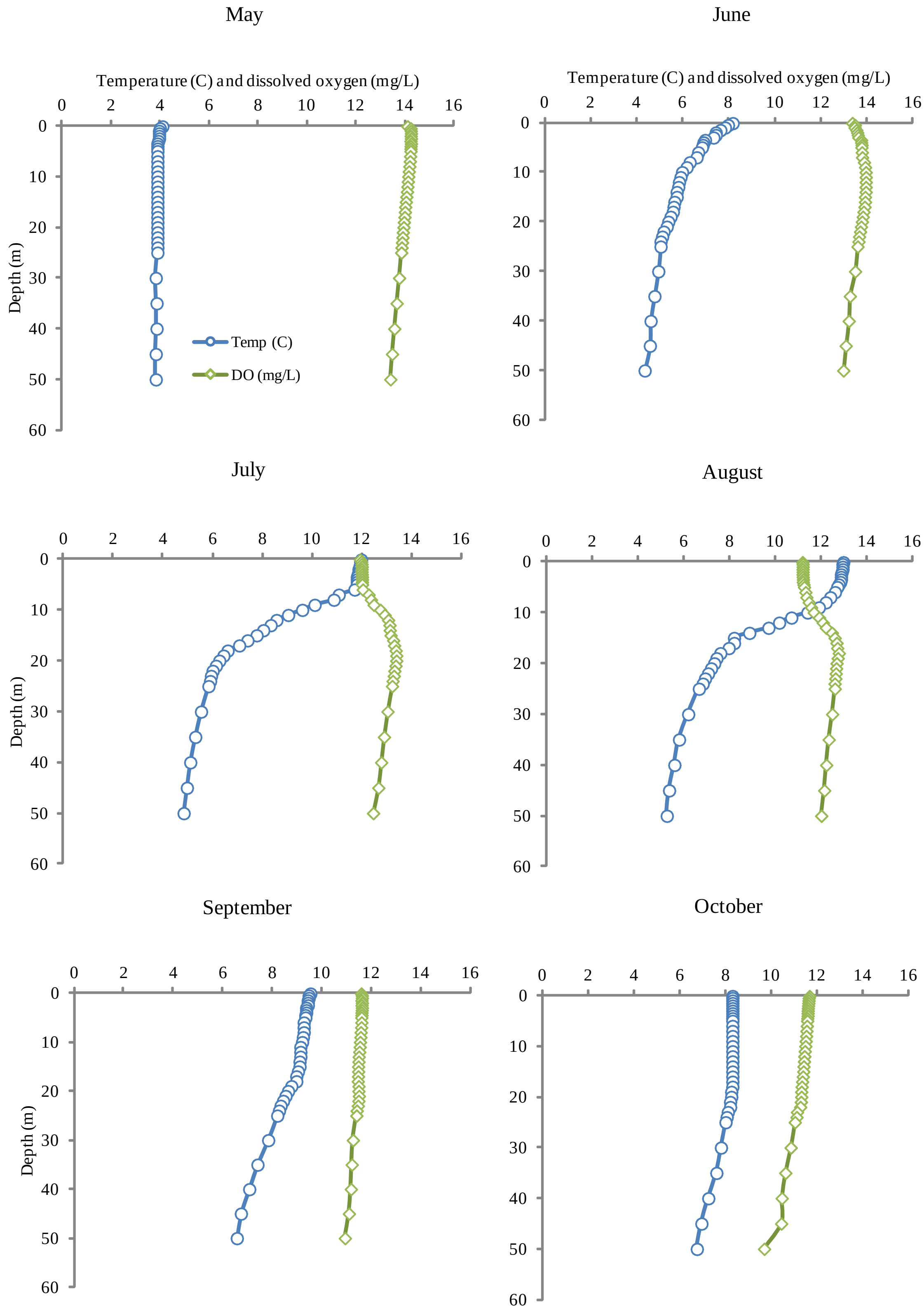
Appendix C1.–Map of Karluk Lake showing the limnological sampling stations.



Appendix C2.–Monthly and seasonal averages of 1 m temperature and dissolved oxygen, euphotic zone depth (EZD), and Secchi measurements from Karluk Lake, 2011.

Sample type	May	June	July	August	September	October	Seasonal average
Station 3							
1-m Temperature (°C)	4.5	8.7	12	12.6	9.8	8.3	9.3
1-m Dissolved oxygen (mg/L)	14.1	13.3	12.0	11.2	11.6	11.6	12.3
EZD (m)	22.3	19.7	23.6	20.1	21.0	23.7	21.7
Secchi depth (m)	9.3	10.0	9.3	10.5	8.0	8.5	9.3
Station 4							
1-m Temperature (°C)	3.8	7.7	12.2	13.0	9.5	8.3	9.1
1-m Dissolved oxygen (mg/L)	14.3	13.4	12.0	11.2	11.7	11.6	12.3
EZD (m)	21.5	19.1	22.7	20.3	22.1	23.3	21.5
Secchi depth (m)	9.8	9.0	ND	10.5	8.8	7.5	9.1
Station 7							
1-m Temperature (°C)	3.6	7.1	11.6	13.2	9.1	ND	8.9
1-m Dissolved oxygen (mg/L)	14.3	13.7	12.0	11.2	11.6	ND	12.6
EZD (m)	24.2	18.5	22.9	21.0	15.8	ND	20.5
Secchi depth (m)	10.8	11.3	ND	11.5	11.0	ND	11.1

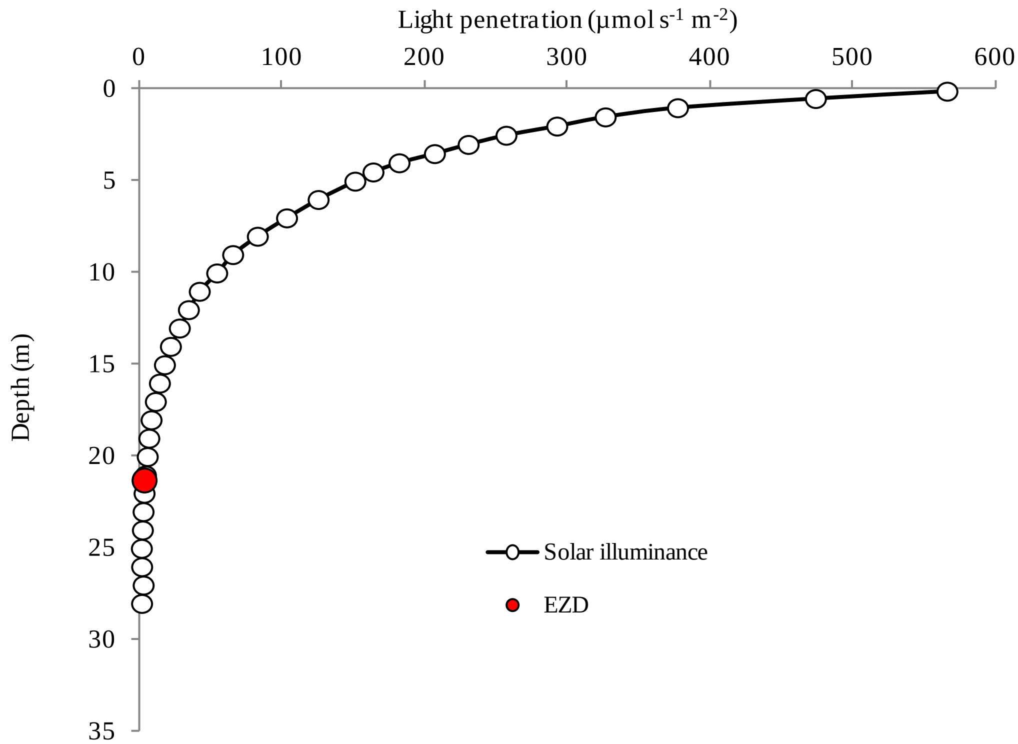
Appendix C3.–Temperature and dissolved oxygen depth profiles by month for Karluk Lake, 2011.



Appendix C4.–Karluk Lake solar illuminance (μmol s^{-1} m^{-2}) profiles by month, 2011.

	Date						
Depth (m)	27-May	20-Jun	21-Jul	10-Aug	14-Sep	13-Oct	Average
0.1	152.6	838.7	301.7	1,077.6	461.0	117.6	566.3
0.5	125.0	738.7	252.6	844.1	410.3	96.8	474.1
1	85.2	617.7	188.9	660.1	335.6	81.1	377.5
1.5	80.8	512.3	168.8	574.4	297.7	69.5	326.8
2	74.7	477.7	153.6	491.4	267.0	59.7	292.9
2.5	66.4	407.5	134.2	449.8	228.3	49.4	257.3
3	61.0	348.5	122.3	413.3	208.6	45.6	230.8
3.5	62.1	304.5	114.3	365.1	189.6	40.1	207.1
4	59.0	271.4	104.6	320.7	155.9	35.9	182.3
4.5	44.6	253.8	92.6	289.4	139.9	33.8	164.1
5	49.9	226.0	85.4	271.9	123.7	32.6	151.4
6	42.7	181.4	73.6	232.4	98.0	28.2	125.6
7	36.7	138.8	64.9	198.3	78.7	23.2	103.5
8	30.2	109.3	54.9	163.2	57.4	19.4	83.0
9	25.1	88.6	44.9	128.5	41.6	16.0	65.7
10	21.1	71.1	37.2	108.1	35.2	13.3	54.5
11	17.1	56.8	30.7	76.9	30.2	10.9	42.3
12	14.0	45.9	26.0	65.1	22.6	9.0	34.7
13	11.4	35.1	21.8	58.0	15.3	7.6	28.3
14	9.4	27.5	17.6	43.8	12.2	6.5	22.1
15	7.7	21.6	14.2	35.8	10.2	5.5	17.9
16	6.3	17.8	11.5	28.1	8.2	4.7	14.4
17	4.2	14.5	9.7	22.4	6.9	3.9	11.5
18	2.9	11.7	7.8	14.6	5.7	3.3	8.5
19	2.7	9.2	6.3	12.2	4.5	2.8	7.0
20	3.7	7.2	5.1	9.8	3.5	2.4	5.9
21	2.9	5.9	4.2	7.4	2.6	2.0	4.6
22	2.4	4.9	3.2	5.7	1.9	1.7	3.6
23	1.9	4.0	2.6	4.5	1.7	1.4	2.9
24		3.1	2.0	3.5	1.3	1.3	2.5
25		2.4	1.6	2.5	0.5		1.7
26				3.7	0.2		2.0
27				3.0			3.0
28				1.9			1.9
29							
30							

Appendix C5.–Average monthly solar illuminance profile for Karluk Lake, 2011.



Appendix C6.–Karluk Lake seasonal water quality properties, nutrients and photosynthetic pigments, 2011.

Depth	Sample type	May	June	July	August	September	October	Seasonal average	SE
1 meter									
	pH	7.79	7.80	7.55	7.99	7.82	7.77	7.79	0.02
	Alkalinity (mg/L $CaCO_3$)	23.2	23.4	22.2	24.1	21.5	22.3	22.8	0.16
	Total phosphorous (µg/L P)	5.8	5.1	4.2	4.4	4.8	5.3	4.9	0.10
	Total filterable phosphorous (µg/L P)	2.4	2.8	2.5	2.4	2.7	2.5	2.5	0.03
	Filterable reactive phosphorous (µg/L P)	0.7	0.4	0.7	1.1	0.8	1.1	0.8	0.04
	Total Kjeldahl nitrogen (µg/L N)	141.0	119.6	174.9	271.5	282.1	178.0	194.5	11.24
	Ammonia (µg/L N)	7.7	5.9	3.2	4.1	6.5	6.5	5.7	0.28
	Nitrate + nitrite (µg/L N)	23.1	23.2	2.4	0.6	10.2	12.4	12.0	1.62
	Organic silicon (µg/L)	100.7	99.7	217.7	159.7	90.8	116.3	130.8	8.19
	Chlorophyll *a* (µg/L)	2.45	0.64	1.07	0.37	0.59	0.80	0.99	0.13
	Phaeophytin *a* (µg/L)	0.76	0.33	0.35	0.15	0.27	0.10	0.33	0.04
Hypolimnion									
	pH	7.82	7.81	7.49	7.57	7.41	7.76	7.64	0.03
	Alkalinity (mg/L $CaCO_3$)	23.0	24.1	22.3	24.3	21.8	21.8	22.9	0.18
	Total phosphorous (µg/L P)	5.5	8.6	4.8	7.4	6.2	4.6	6.2	0.26
	Total filterable phosphorous (µg/L P)	2.3	5.0	2.6	2.9	2.4	2.5	3.0	0.17
	Filterable reactive phosphorous (µg/L P)	0.7	0.4	0.6	1.1	0.8	0.8	0.7	0.04
	Total Kjeldahl nitrogen (µg/L N)	156.2	163.1	257.6	292.9	238.8	154.8	215.4	12.42
	Ammonia (µg/L N)	7.7	9.8	15.8	21.9	16.3	4.8	12.7	1.06
	Nitrate + nitrite (µg/L N)	24.8	26.5	22.9	21.6	18.0	32.4	24.4	0.82
	Organic silicon (µg/L)	122.7	143.4	88.2	57.5	73.0	97.7	97.1	5.28
	Chlorophyll *a* (µg/L)	2.56	2.88	1.81	1.65	1.08	1.20	1.86	0.12
	Phaeophytin *a* (µg/L)	0.50	0.41	0.35	0.59	0.36	0.09	0.38	0.03

Appendix C7.–Seasonal zooplankton abundance (number/m^2) in Karluk Lake, 2011.

Taxon	Date						Seasonal average
	27-May	20-Jun	12-Jul	16-Aug	14-Sep	13-Oct	
Copepods:							
Epischura	-	-	-	-	-	-	-
Ovig. *Epischura*	-	-	-	-	-	-	-
Diaptomus	31,847	72,187	97,222	154,848	188,252	202,229	124,431
Ovig. *Diaptomus*	-	354	-	460	354	-	195
Cyclops	468,772	500,000	393,843	216,525	201,079	212,580	332,133
Ovig. *Cyclops*	885	3,539	18,577	42,109	3,185	8,758	12,842
Harpaticus	-	-	-	-	354	796	192
Nauplii	31,228	34,324	42,374	56,653	80,060	78,822	53,910
Total copepods:	532,732	610,403	552,017	470,594	473,284	473,284	523,703
Cladocerans:							
Bosmina	2,035	5,308	9,731	35,244	35,474	35,032	20,471
Ovig. *Bosmina*	1,504	4,600	4,954	26,999	92,357	83,599	35,669
Daphnia longiremis	354	3,185	6,281	36,553	129,512	171,975	57,977
Ovig. *Daphnia longiremis*	-	1,062	1,592	13,765	54,848	89,968	26,872
Holopedium	-	-	-	-	-	-	-
Ovig. *Holopedium*	-	-	-	-	-	-	-
Immature cladocerans	796	4,954	14,508	63,270	44,409	32,643	26,763
Total cladocerans:	4,689	19,108	37,067	175,832	356,599	413,217	167,752
Total copepods + cladocerans	537,420	629,512	589,084	646,426	829,883	413,217	691,454

Appendix C8.–Karluk Lake seasonal weighted zooplankton biomass (mg/m^2) for 2011.

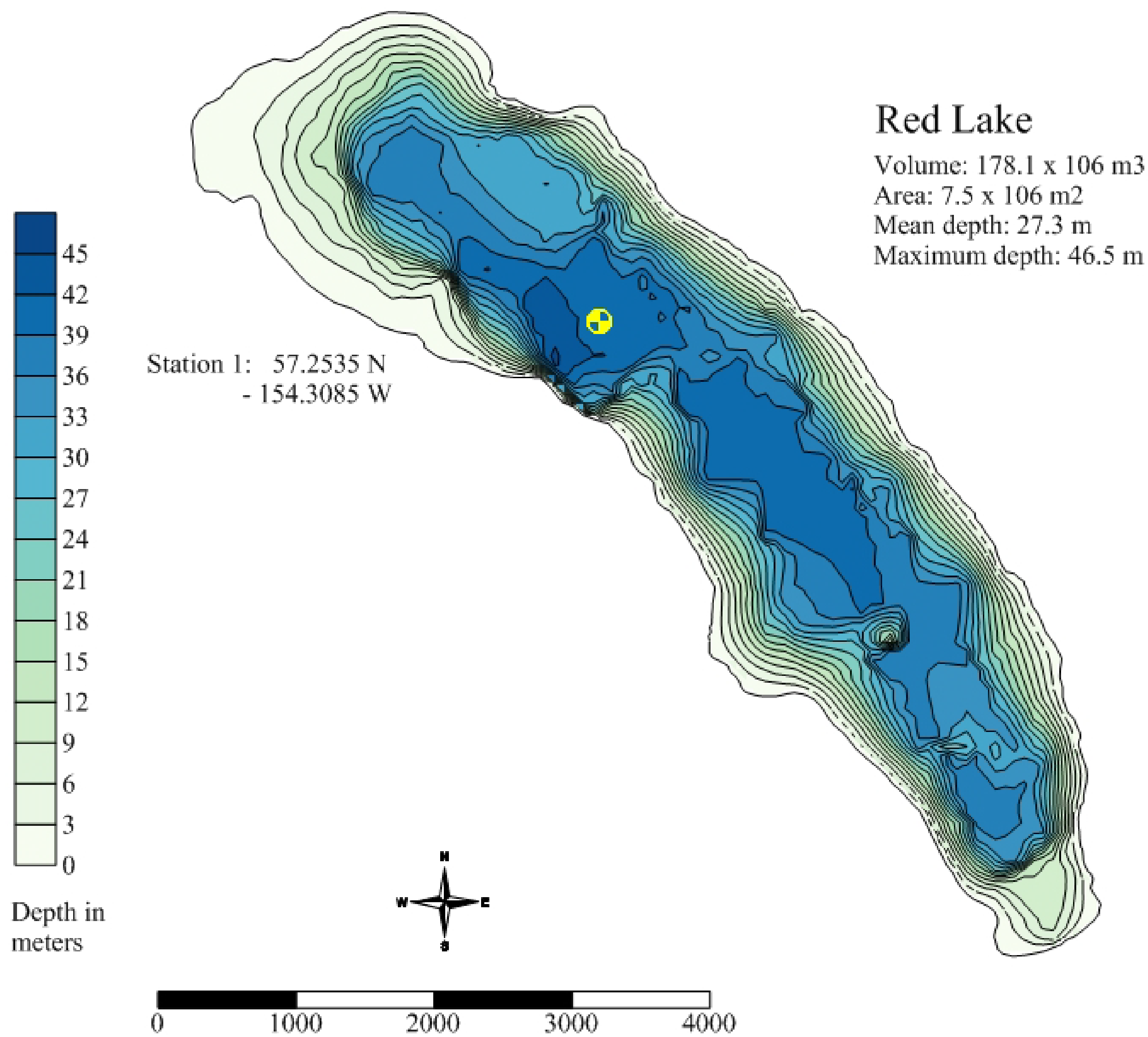
Taxon	Date: 27-May	20-Jun	12-Jul	16-Aug	14-Sep	13-Oct	Seasonal weighted average
Copepods:							
Epischura	-	-	-	-	-	-	-
Ovig. *Epischura*	-	-	-	-	-	-	-
Diaptomus	109	276	498	681	566	521	442
Ovig. *Diaptomus*	-	3	-	4	2	-	2
Cyclops	615	767	748	422	280	303	523
Ovig. *Cyclops*	3	19	94	192	17	41	61
Harpaticus	-	-	-	-	-	1	-
Total copepods:	727	1,065	1,341	1,299	865	866	1,027
Cladocerans:							
Bosmina	2	7	11	39	37	39	23
Ovig. *Bosmina*	4	15	14	63	188	177	77
Daphnia longiremis	-	5	13	53	176	212	76
Ovig. *Daphnia longiremis*	-	5	6	50	150	250	77
Holopedium	-	-	-	-	-	-	-
Ovig. *Holopedium*	-	-	-	-	-	-	-
Chydorinae	-	-	-	-	-	-	-
Total cladocerans:	6	30	45	206	552	677	253
Total copepods + cladocerans	734	1,096	1,386	1,505	1,417	1,543	1,280

Appendix C9.–Karluk Lake seasonal zooplankton lengths (mm), 2011.

Taxon	Date 27-May	20-Jun	12-Jul	16-Aug	14-Sep	13-Oct	Seasonal average length
Copepods:							
Epischura	-	-	-	-	-	-	-
Ovig. *Epischura*	-	-	-	-	-	-	-
Diaptomus	0.92	0.95	1.07	1.01	0.89	0.83	0.95
Ovig. *Diaptomus*	-	-	-	1.23	-	-	1.23
Cyclops	0.63	0.67	0.74	0.74	0.65	0.65	0.68
Ovig. *Cyclops*	1.02	1.19	1.17	1.12	1.19	1.13	1.14
Harpaticus	-	-	-	-	-	0.57	0.57
Cladocerans:							
Bosmina	0.40	0.40	0.43	0.41	0.38	0.42	0.41
Ovig. *Bosmina*	0.55	0.66	0.60	0.51	0.50	0.52	0.56
Daphnia longiremis	-	0.58	0.73	0.71	0.65	0.65	0.66
Ovig. *Daphnia longiremis*	-	0.95	-	0.90	0.82	0.82	0.87
Holopedium	-	-	-	-	-	-	-
Ovig. *Holopedium*	-	-	-	-	-	-	-

APPENDIX D. RED LAKE.

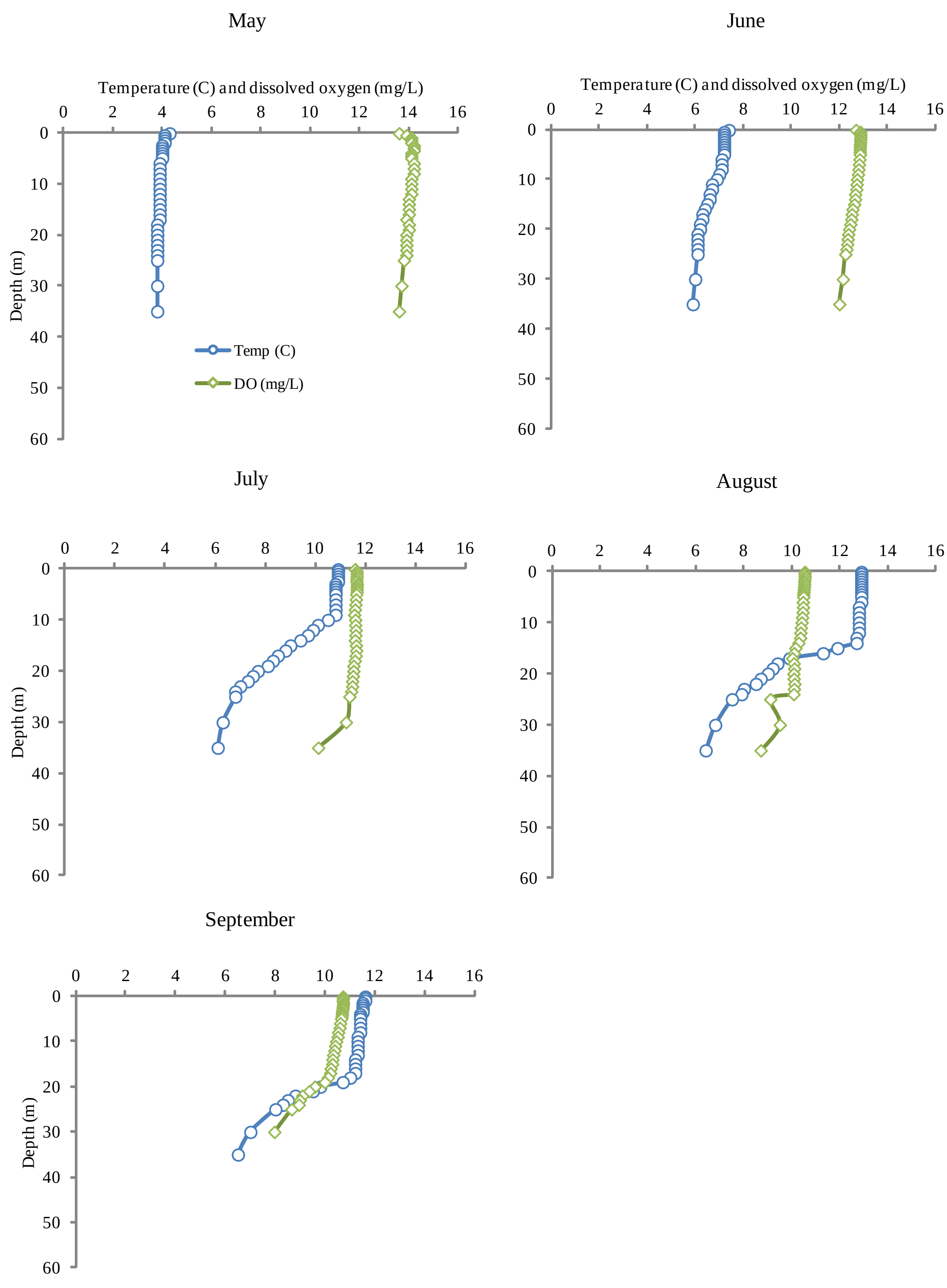
Appendix D1.–Map of Red Lake showing the limnological sampling station.



Appendix D2.–Monthly and seasonal averages of 1 m temperature and dissolved oxygen, euphotic zone depth (EZD), and Secchi measurements from Red Lake, 2011.

Sample type	May	June	July	August	September	Seasonal average
1-m Temperature (°C)	4.1	7.4	10.9	12.9	11.6	9.4
1-m Dissolved oxygen (mg/L)	14.1	12.9	11.7	10.5	10.7	12.0
EZD (m)	14.6	15.0	17.3	17.0	15.8	16.0
Secchi depth (m)	5.8	4.5	5.2	5.5	8.0	5.8

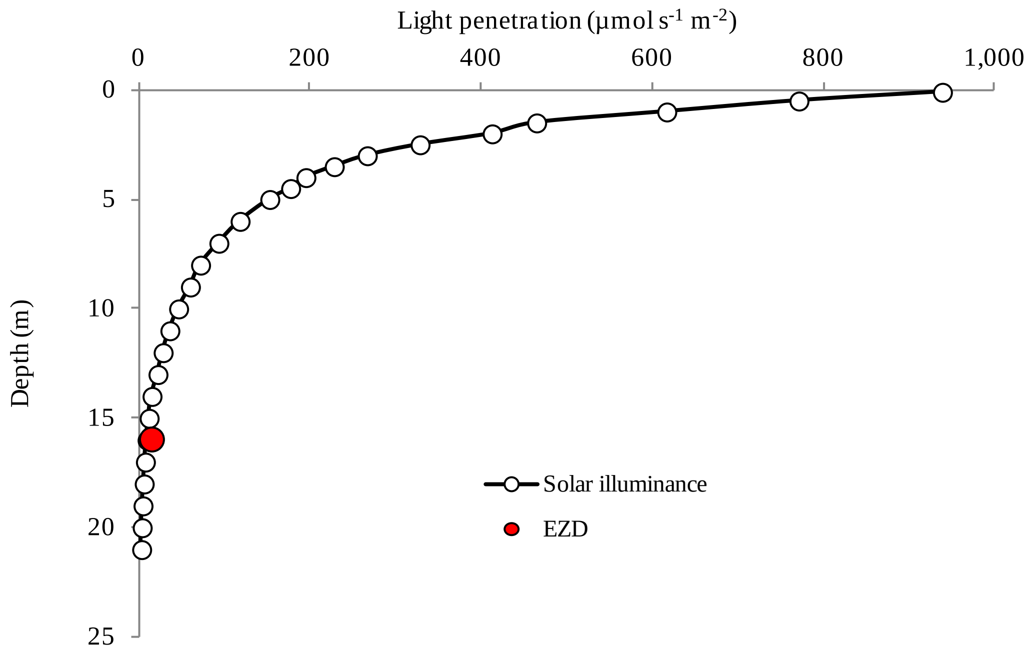
Appendix D3.–Temperature and dissolved oxygen depth profiles by month for Red Lake, 2011.



Appendix D4.–Red Lake solar illuminance (µmol s^{-1} m^{-2}) profiles by month, 2011.

	Date					
Depth (m)	13-May	16-Jun	18-Jul	26-Aug	15-Sep	Average
0.1	1,528.0	812.0	279.0	701.0	1,373.0	938.6
0.5	1,316.0	701.0	240.0	448.0	1,150.0	771.0
1	1,145.0	602.0	149.0	351.0	836.0	616.6
1.5	894.0	426.0	116.0	316.0	571.0	464.6
2	816.0	376.0	106.0	362.0	403.0	412.6
2.5	607.0	308.0	98.3	348.0	281.0	328.5
3	466.0	279.0	89.9	285.0	214.0	266.8
3.5	393.0	226.0	78.1	238.0	206.0	228.2
4	273.0	199.0	71.6	192.0	240.0	195.1
4.5	275.0	166.0	62.3	161.0	222.0	177.3
5	230.0	142.0	54.6	142.0	196.0	152.9
6	171.0	107.0	44.2	107.0	162.0	118.2
7	128.0	82.7	36.6	88.0	132.0	93.5
8	98.1	58.7	28.5	61.0	114.0	72.1
9	78.9	44.4	22.8	57.0	98.0	60.2
10	65.9	34.6	17.3	42.8	71.5	46.4
11	50.0	27.3	13.7	32.9	57.2	36.2
12	37.3	21.6	10.7	24.8	47.3	28.3
13	27.8	16.7	8.5	20.2	38.4	22.3
14	20.8	12.1	6.4	16.1	21.4	15.4
15	16.1	8.8	5.1	12.2	17.8	12.0
16	13.1	6.8	3.9	9.4	14.7	9.6
17	10.2	5.4	3.1	7.3	12.2	7.6
18	8.0	4.0	2.4	5.9	10.9	6.2
19	6.1	3.1	1.8	4.9	8.3	4.8
20	4.5	2.8	1.5	4.2	6.4	3.9
21	3.8	2.3	1.3	3.6	5.2	3.2
22	2.7	1.9	0.8	3.1	4.5	2.6
23		1.4		2.6	3.3	2.4
24		0.8		2.2	2.3	1.8
25				1.9	1.7	1.8
26				1.5		1.5
27				1.2		1.2
28				1.0		1.0
29				0.8		0.8
30						

Appendix D5.–Average monthly solar illuminance profile for Red Lake, 2011.



Appendix D6.–Red Lake averaged seasonal water quality properties, nutrients and photosynthetic pigments, 2011.

Depth	Sample type	May	June	July	August	September	Seasonal average	SE
1 meter								
	pH	7.39	7.54	7.55	7.88	7.61	7.59	0.04
	Alkalinity (mg/L $CaCO_3$)	17.3	17.0	17.0	18.5	17.0	17.4	0.13
	Total phosphorous (µg/L P)	22.4	20.6	18.8	11.2	15.1	17.6	0.90
	Total filterable phosphorous (µg/L P)	1.7	9.0	7.9	6.8	11.1	7.3	0.70
	Filterable reactive phosphorous (µg/L P)	1.0	5.7	3.9	3.1	5.6	3.9	0.39
	Total Kjeldahl nitrogen (µg/L N)	293.3	216.3	172.3	227.9	398.7	261.7	17.59
	Ammonia (µg/L N)	5.4	3.3	4.6	3.1	9.8	5.2	0.54
	Nitrate + nitrite (µg/L N)	47.3	0.7	0.5	0.5	5.1	10.8	4.10
	Organic silicon (µg/L)	180.3	99.7	166.5	114.7	190.3	150.3	8.12
	Chlorophyll *a* (µg/L)	1.28	1.60	0.96	0.64	0.48	0.99	0.09
	Phaeophytin *a* (µg/L)	0.51	0.64	0.61	0.26	0.30	0.46	0.04
30 meters								
	pH	7.51	7.44	7.60	7.49	7.45	7.50	0.01
	Alkalinity (mg/L $CaCO_3$)	17.0	16.5	16.8	18.0	17.0	17.1	0.11
	Total phosphorous (µg/L P)	27.2	23.0	20.5	29.3	47.7	29.5	2.14
	Total filterable phosphorous (µg/L P)	13.8	11.0	14.1	20.9	36.1	19.2	2.03
	Filterable reactive phosphorous (µg/L P)	9.8	7.0	9.8	17.2	28.8	14.5	1.77
	Total Kjeldahl nitrogen (µg/L N)	197.1	159.4	260.2	207.9	291.3	223.2	10.48
	Ammonia (µg/L N)	8.0	10.1	23.3	16.8	3.8	12.4	1.54
	Nitrate + nitrite (µg/L N)	5.6	0.7	3.8	52.6	98.8	32.3	8.58
	Organic silicon (µg/L)	91.1	134.3	65.7	301	526.1	223.6	38.47
	Chlorophyll *a* (µg/L)	1.28	1.60	0.80	0.64	1.28	1.12	0.08
	Phaeophytin *a* (µg/L)	0.51	0.64	0.43	0.26	0.06	0.38	0.05

Appendix D7.–Seasonal zooplankton abundance (number/m^2) in Red Lake, 2011.

Taxon	Date					Seasonal
	13-May	16-Jun	18-Jul	26-Aug	15-Sep	average
Copepods:						
Epischura	-	-	3,185	-	-	637
Ovig. *Epischura*	-	-	-	-	-	-
Diaptomus	90,764	152,866	90,764	229,299	308,121	174,363
Ovig. *Diaptomus*	-		1,592	3,185	-	1,194
Cyclops	1,196,656	1,299,363	458,599	230,892	248,408	686,783
Ovig. *Cyclops*	4,777	-	50,955	31,847	31,051	23,726
Harpaticus	-	-	-	-	-	-
Nauplii	692,675	41,401	58,917	229,299	179,140	240,287
Total copepods:	1,984,873	1,493,631	664,013	724,522	766,720	1,126,990
Cladocerans:						
Bosmina	2,389	-	4,777	238,854	28,662	54,936
Ovig. *Bosmina*	-	-	14,331	42,994	169,586	45,382
Daphnia longiremis	2,389	-	12,739	361,465	556,529	186,624
Ovig. *Daphnia longiremis*	2,389	-	15,924	39,809	257,962	63,217
Chydorinae	-	-	-	1,592	-	318
Immature cladocerans	33,439	9,554	78,025	90,764	121,815	66,720
Total cladocerans:	40,605	9,554	125,796	775,477	1,134,554	417,197
Total copepods + cladocerans	2,025,478	1,503,185	789,809	1,500,000	1,901,274	1,544,188

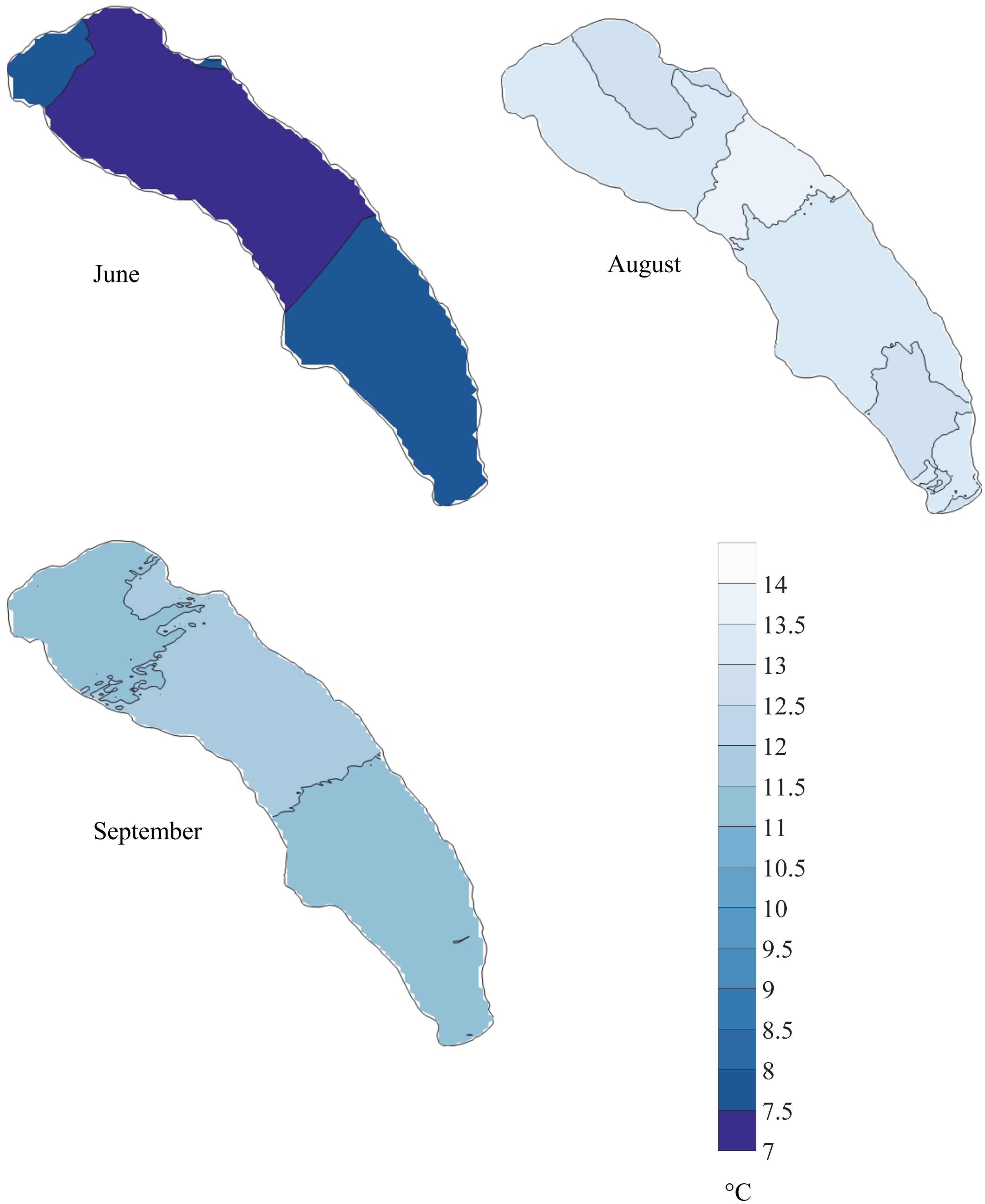
Appendix D8.–Red Lake seasonal weighted zooplankton biomass (mg/m^2) for 2011.

Taxon	13-May	16-Jun	18-Jul	26-Aug	15-Sep	Seasonal weighted average
	Date					
Copepods:						
Epischura	-	-	15	-	-	3
Ovig. *Epischura*	-	-	-	-	-	-
Diaptomus	445	478	507	743	1,144	664
Ovig. *Diaptomus*	-	-	12	31	-	9
Eurytemora	-	-	-	-	-	-
Ovig. *Eurytemora*	-	-	-	-	-	-
Cyclops	1,354	2,496	926	394	431	1,120
Ovig. *Cyclops*	23	-	265	168	148	121
Harpaticus	-	-	-	-	-	-
Total copepods:	1,823	2,974	1,725	1,337	1,724	1,916
Cladocerans:						
Bosmina	2	-	7	266	28	61
Ovig. *Bosmina*	-	-	39	86	376	100
Daphnia longiremis	-	-	36	525	836	279
Ovig. *Daphnia longiremis*	9	-	74	116	722	184
Holopedium	-	-	-	-	-	-
Chydorinae	-	-	-	1	-	-
Total cladocerans:	11	-	156	994	1,962	625
Total copepods + cladocerans	1,833	2,974	1,880	2,331	3,686	2,541

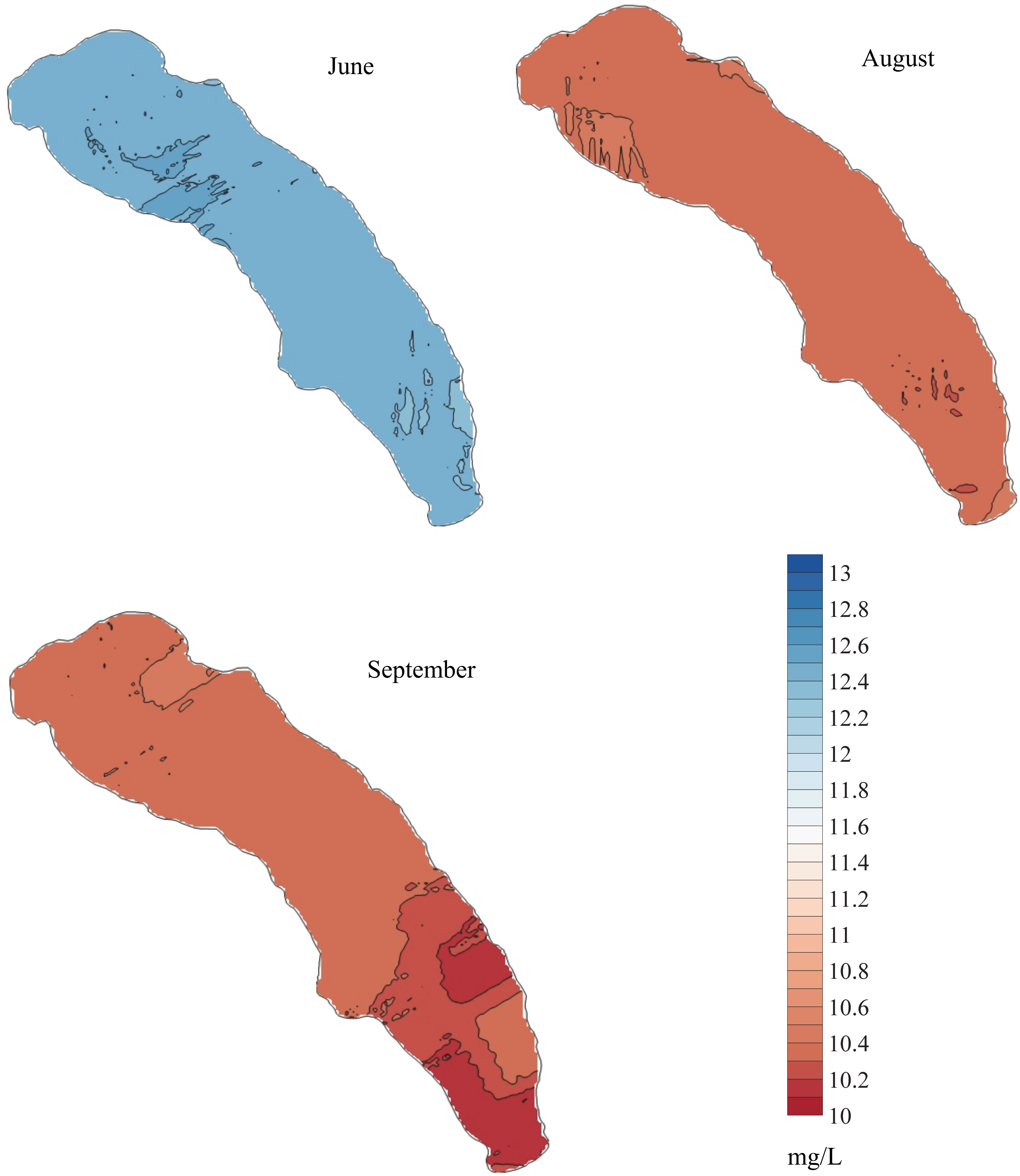
Appendix D9.–Red Lake seasonal zooplankton lengths (mm), 2011.

Taxon	Date					Seasonal average length
	13-May	16-Jun	18-Jul	26-Aug	15-Sep	
Copepods:						
Epischura	-	-	1.01	-	-	1.01
Ovig. *Epischura*	-	-	-	-	-	-
Diaptomus	1.05	0.89	1.10	0.90	0.95	0.98
Ovig. *Diaptomus*	-	-	1.22	1.34	-	1.28
Cyclops	0.58	0.75	0.76	0.71	0.71	0.70
Ovig. *Cyclops*	1.16	-	1.19	1.20	1.14	1.17
Harpaticus	-	-	-	-	-	-
Cladocerans:						
Bosmina	0.29	-	0.39	0.35	0.33	0.34
Ovig. *Bosmina*	-	-	0.54	0.46	0.49	0.50
Daphnia longiremis	-	-	0.80	0.59	0.60	0.66
Ovig. *Daphnia longiremis*	0.90	-	1.00	0.81	0.80	0.88
Chydorinae	-	-	-	0.25	-	0.25

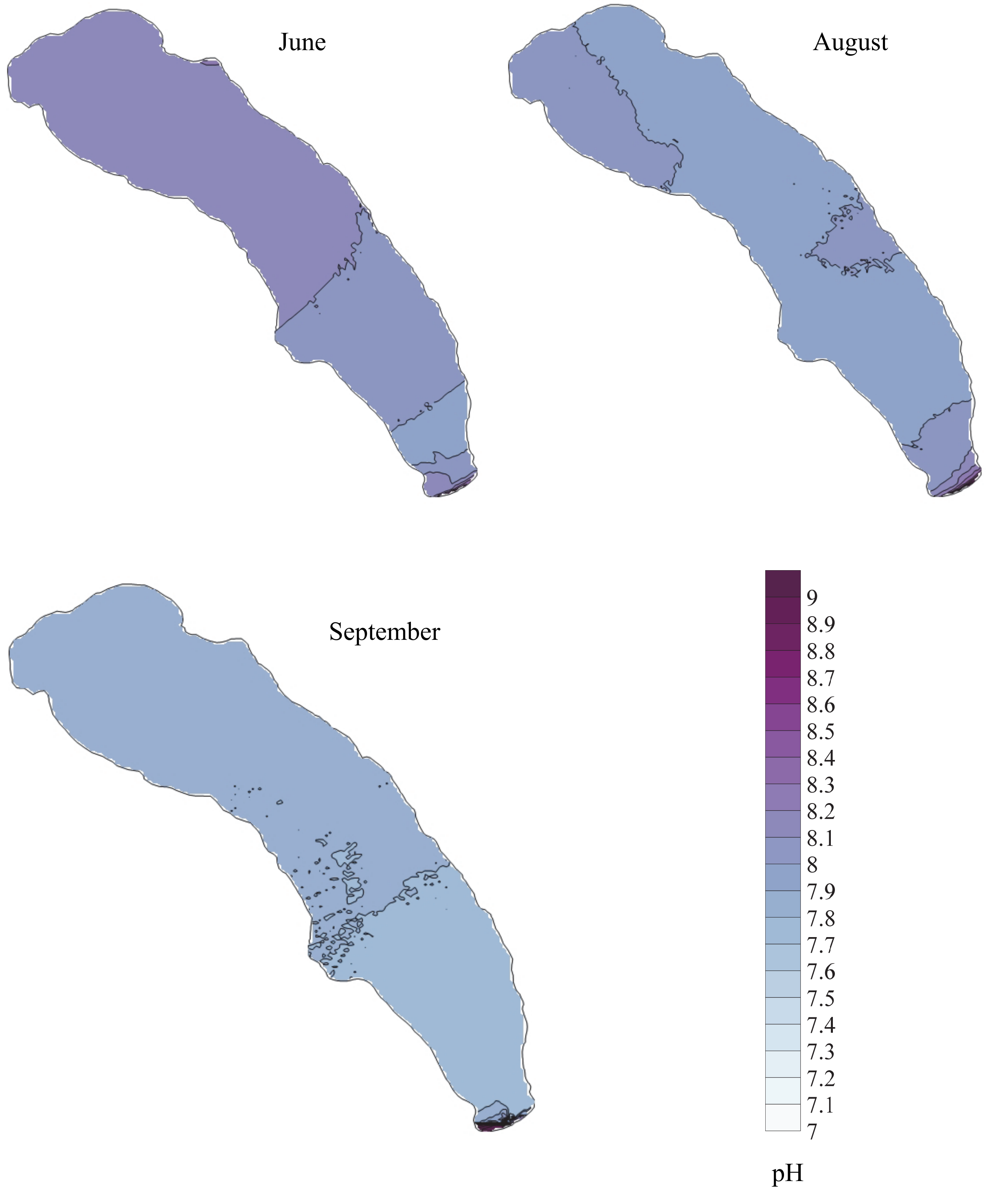
Appendix D10.–Red Lake AUV surface temperatures by month, 2011.



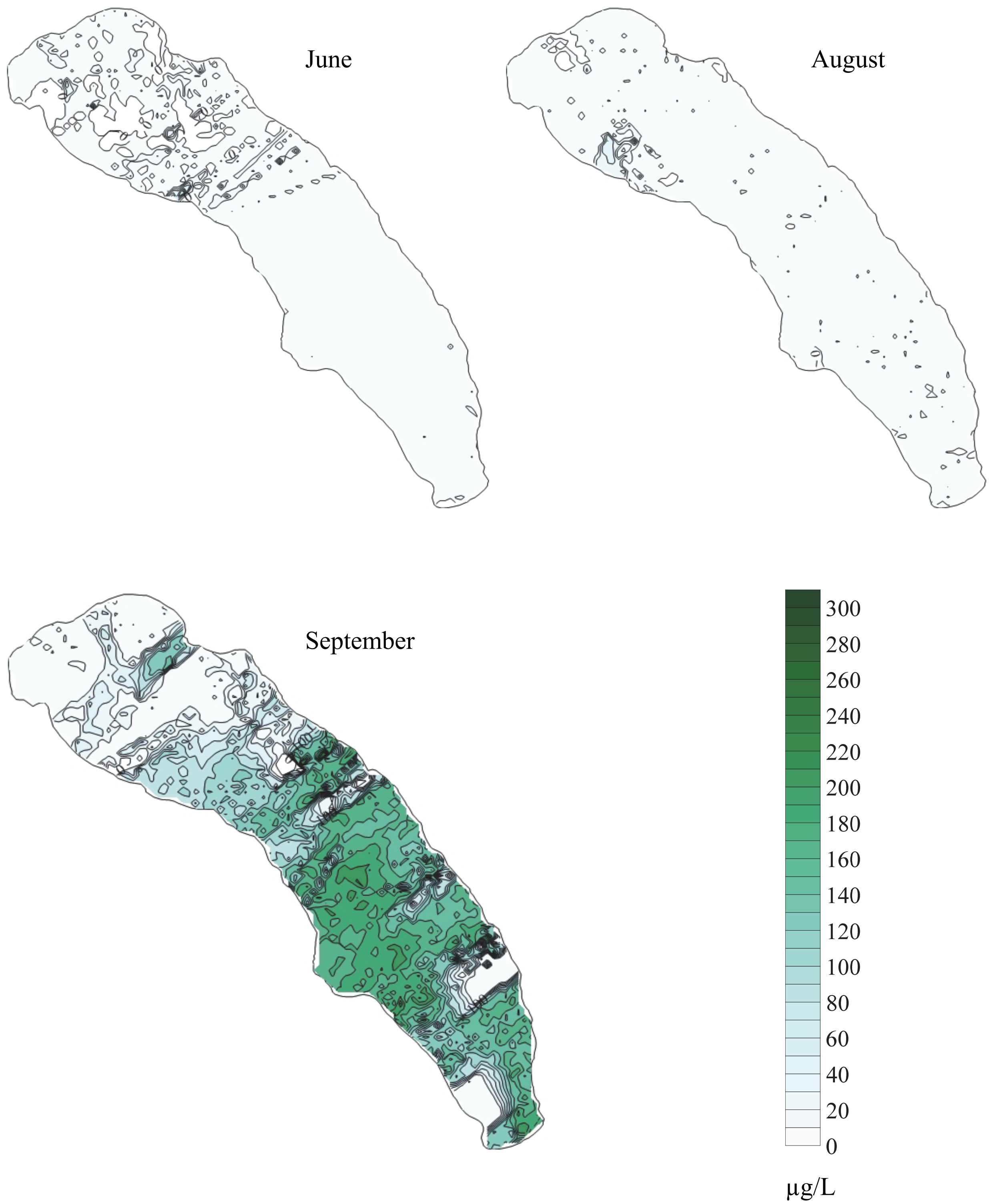
Appendix D11.–Red Lake AUV surface dissolved oxygen concentrations by month, 2011.



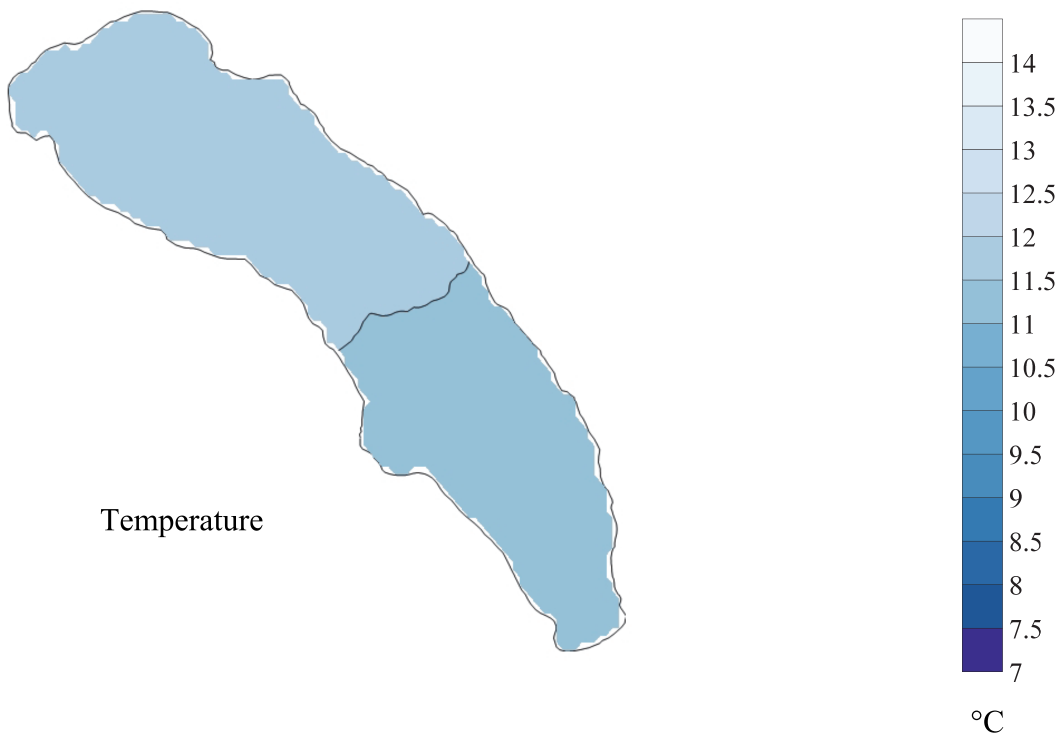
Appendix D12.–Red Lake AUV surface pH by month, 2011.

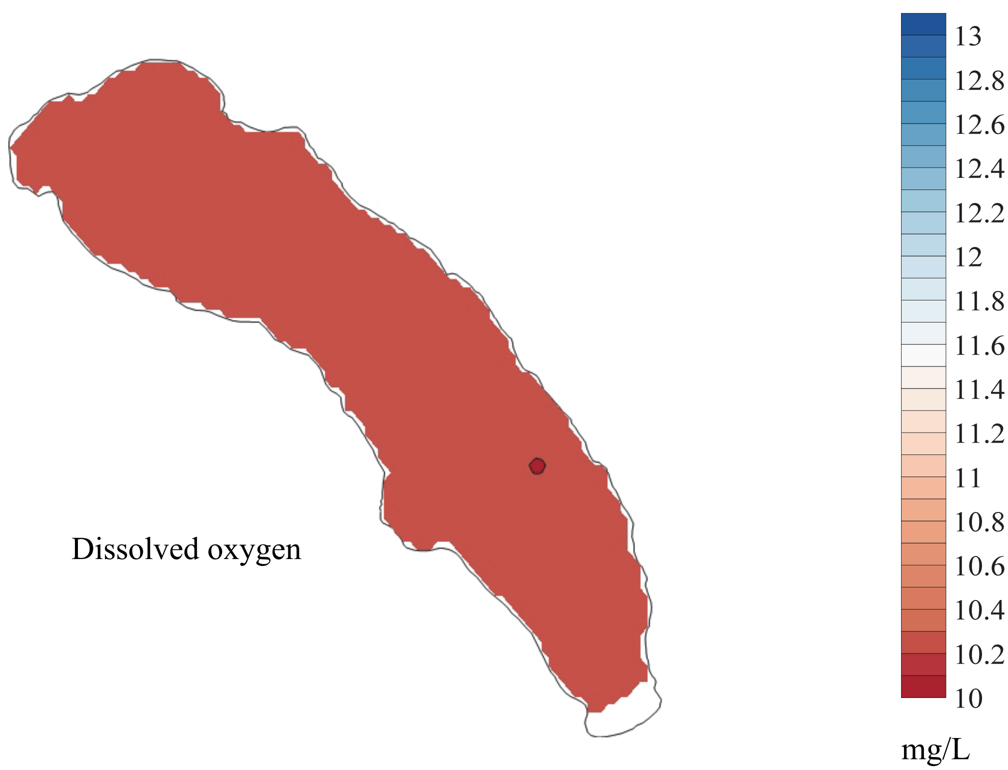


Appendix D13.–Red Lake AUV surface chlorophyll concentrations (µg/L) by month, 2011.

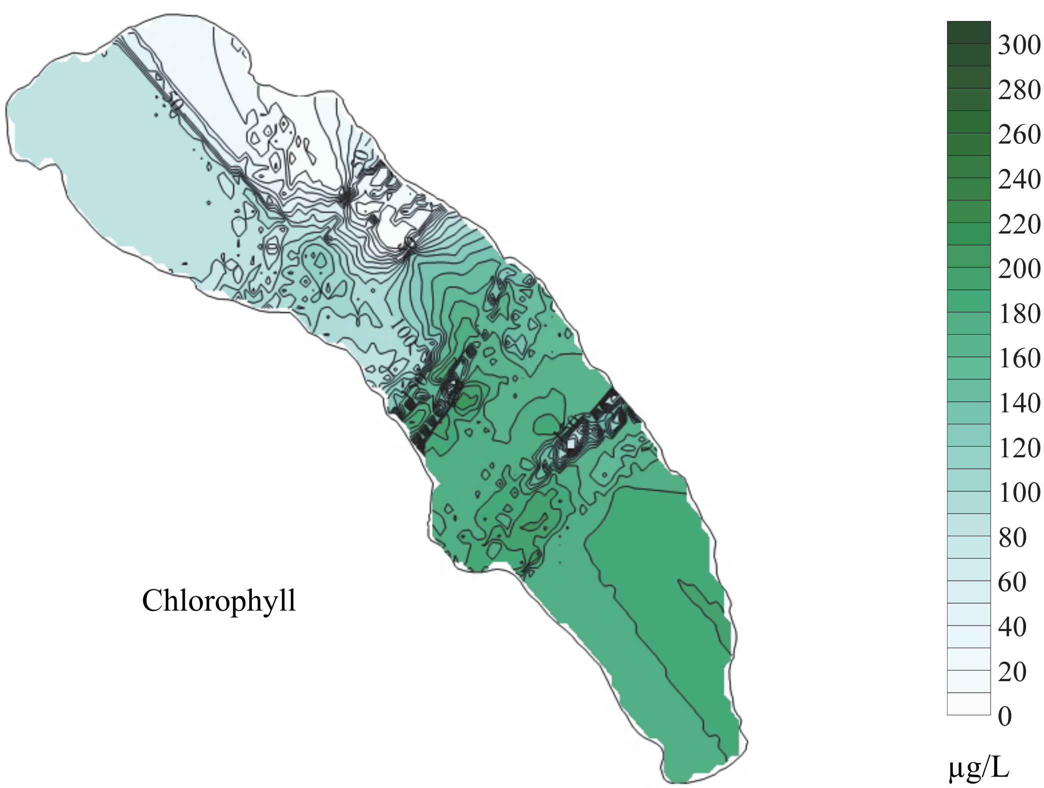


Appendix D14.–Red Lake AUV 1 meter temperature and dissolved oxygen concentration, September 2011.



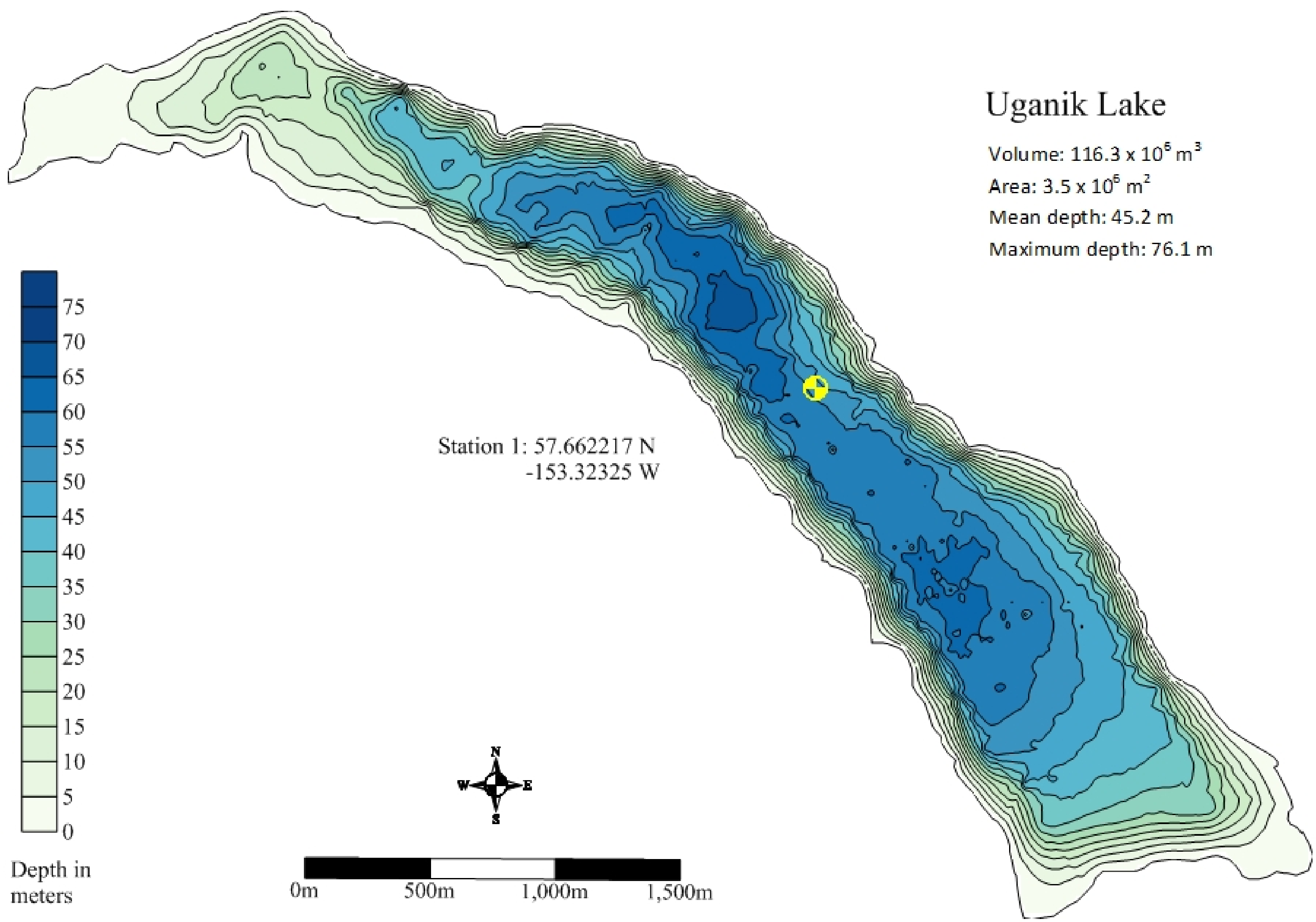


Appendix D15.–Red Lake AUV 1 meter pH and chlorophyll concentration, September 2011.



APPENDIX E. UGANIK LAKE

Appendix E1.–Map of Uganik Lake showing the limnological sampling station.

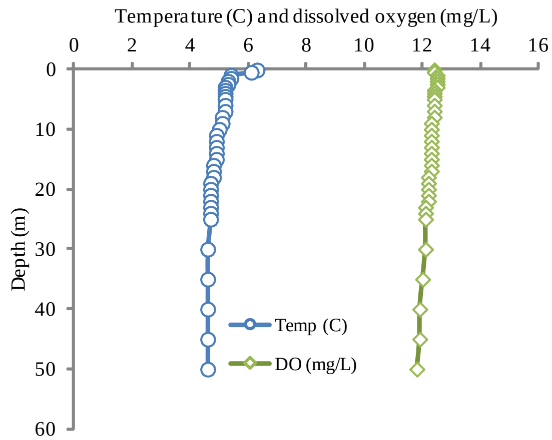


Appendix E2.–Monthly and seasonal averages of 1 m temperature and dissolved oxygen, euphotic zone depth (EZD), and Secchi measurements from Uganik Lake, 2011.

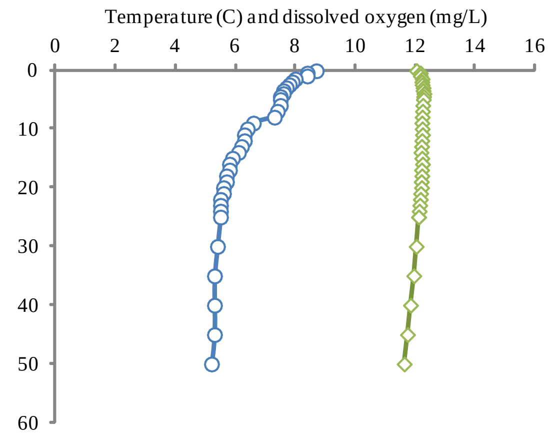
Sample type	May	June	July	August	September	Seasonal average
1-m Temperature (°C)	5.4	8.4	9.0	9.8	8.4	8.2
1-m Dissolved oxygen (mg/L)	12.5	12.2	11.9	11.9	11.3	12.0
EZD (m)	4.8	6.3	6.9	13.6	4.6	7.2
Secchi depth (m)	1.3	1.3	1.8	4.0	0.6	1.8

Appendix E3.–Temperature and dissolved oxygen depth profiles by month for Uganik Lake, 2011.

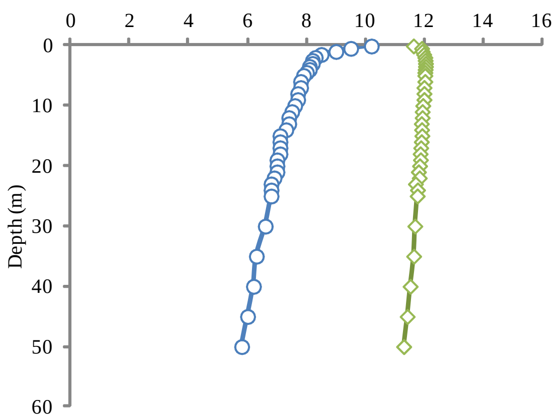
May



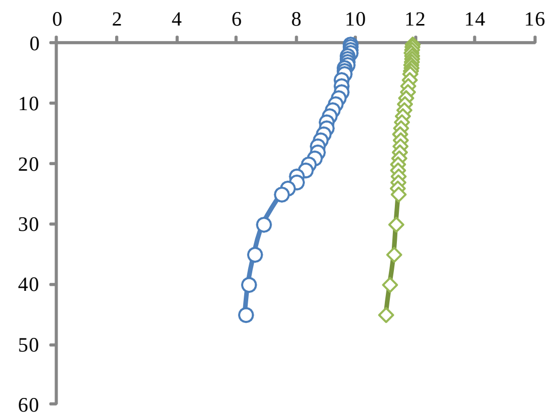
June



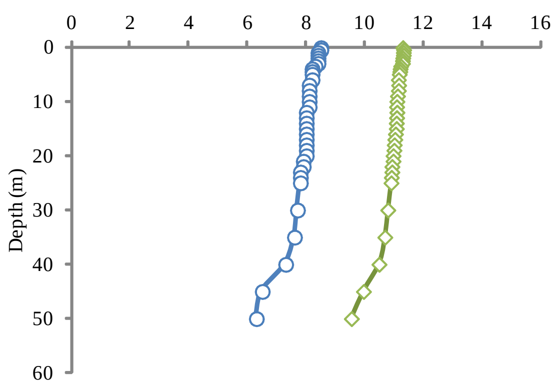
July



August



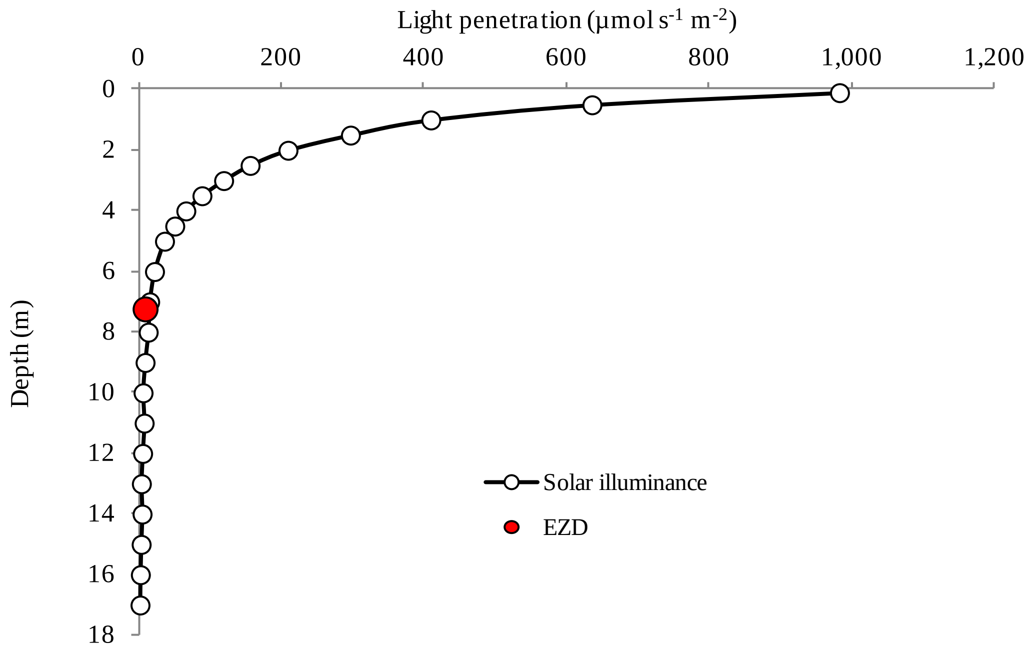
September



Appendix E4.–Uganik Lake solar illuminance (µmol s^{-1} m^{-2}) profiles by month, 2011.

	Date					
Depth (m)	27-May	23-Jun	16-Jul	10-Aug	21-Sep	Average
0.1	1,817.0	804.0	1,394.0	587.0	308.0	982.0
0.5	1,141.0	524.0	986.0	339.0	185.0	635.0
1	595.0	378.0	702.0	267.0	104.0	409.2
1.5	376.0	234.0	516.0	287.0	69.6	296.5
2	234.0	155.0	365.0	246.0	45.0	209.0
2.5	139.0	117.0	260.0	237.0	26.5	155.9
3	88.0	85.0	182.0	222.0	16.9	118.8
3.5	58.8	59.1	129.0	185.0	10.1	88.4
4	37.4	43.2	92.0	151.0	5.5	65.8
4.5	27.7	29.2	62.4	129.0	3.1	50.3
5	17.8	20.3	48.8	91.0	1.7	35.9
6	7.8	10.9	26.3	63.9	0.6	21.9
7	3.5	5.7	14.2	52.2	0.1	15.1
8	1.6	2.9	8.0	39.8		13.1
9	0.7	1.4	4.7	28.0		8.7
10	0.3	0.6	2.6	20.0		5.9
11			1.5	13.3		7.4
12			0.8	9.7		5.3
13			0.4	6.6		3.5
14				4.5		4.5
15				3.2		3.2
16				2.1		2.1
17				1.6		1.6
18				1.1		1.1
19				1.3		1.3
20				0.6		0.6
21				0.5		0.5
22				0.3		0.3
23						
24						
25						
26						
27						
28						
29						
30						

Appendix E5.–Average monthly solar illuminance profile for Uganik Lake, 2011.



Appendix E6.–Uganik Lake averaged seasonal water quality properties, nutrients and photosynthetic pigments, 2011.

Depth	Sample type	May	June	July	August	September	Seasonal average	SE
1 meter								
	pH	7.23	7.57	7.31	7.11	7.43	7.33	0.04
	Alkalinity (mg/L $CaCO_3$)	13.8	16.5	15.5	11.5	11.0	13.7	0.48
	Total phosphorous (µg/L P)	9.8	9.3	7.2	2.8	10.8	8.0	0.64
	Total filterable phosphorous (µg/L P)	1.4	1.8	1.4	1.4	1.3	1.5	0.04
	Filterable reactive phosphorous (µg/L P)	1.2	1.2	1.5	1.3	1.5	1.3	0.03
	Total Kjeldahl nitrogen (µg/L N)	185.8	187.6	154.7	194.8	166.5	177.9	3.33
	Ammonia (µg/L N)	8.8	5.9	4.8	4.0	8.1	6.3	0.41
	Nitrate + nitrite (µg/L N)	338.2	229.2	137.2	91.2	130.2	185.2	19.88
	Organic silicon (µg/L)	2,337.5	1,458.8	735.1	1,275.7	814.0	1,324.2	128.63
	Chlorophyll *a* (µg/L)	0.92	0.16	0.64	0.64	0.64	0.60	0.05
	Phaeophytin *a* (µg/L)	0.37	0.18	0.26	0.48	0.26	0.31	0.02
50 meters								
	pH	7.28	7.58	7.32	7.13	7.48	7.36	0.04
	Alkalinity (mg/L $CaCO_3$)	13.5	17.0	15.0	12.5	11.0	13.8	0.46
	Total phosphorous (µg/L P)	26.5	12.3	5.4	4.1	7.2	11.1	1.83
	Total filterable phosphorous (µg/L P)	1.5	4.7	1.4	1.0	0.9	1.9	0.32
	Filterable reactive phosphorous (µg/L P)	1.3	1.6	1.3	1.5	1.5	1.4	0.03
	Total Kjeldahl nitrogen (µg/L N)	257.2	156.7	151.8	165.8	509.9	248.3	30.50
	Ammonia (µg/L N)	8.4	9.4	9.8	13.5	7.3	9.7	0.47
	Nitrate + nitrite (µg/L N)	318.4	243.6	198.2	205.2	31.8	199.4	21.03
	Organic silicon (µg/L)	2,223.9	1,474.6	1,666.5	862.6	1,587.0	1,562.9	97.29
	Chlorophyll *a* (µg/L)	0.69	0.16	0.10	0.00	0.32	0.25	0.05
	Phaeophytin *a* (µg/L)	0.27	0.06	0.06	0.00	0.13	0.10	0.02

Appendix E7.–Seasonal zooplankton abundance (number/m^2) in Uganik Lake, 2011.

Taxon	Date					Seasonal average
	27-May	23-Jun	16-Jul	10-Aug	21-Sep	
Copepods:						
Epischura	-	-	-	-	-	-
Ovig. *Epischura*	-	-	-	-	-	-
Diaptomus	-	-	1,592	1,592	-	637
Ovig. *Diaptomus*	-	-	-	-	-	-
Cyclops	234,076	336,783	248,938	154,459	113,057	217,463
Ovig. *Cyclops*	-	7,962	4,777	1,062	15,924	5,945
Harpaticus	-	-	-	-	-	-
Nauplii	19,904	4,777	1,592	6,900	5,308	7,696
Total copepods:	253,981	349,522	256,900	164,013	134,289	231,741
Cladocerans:						
Bosmina	-	-	-	-	-	-
Ovig. *Bosmina*	-	-	531	-	531	212
Daphnia longiremis	-	-	1,062	1,062	-	425
Ovig. *Daphnia longiremis*	-	-	1,062	1,062	-	425
Holopedium	-	-	-	-	-	-
Immature cladocerans	-	-	-	-	-	-
Total cladocerans:	-	-	2,654	2,123	531	1,062
Total copepods + cladocerans	253,981	349,522	259,554	166,136	134,820	232,803

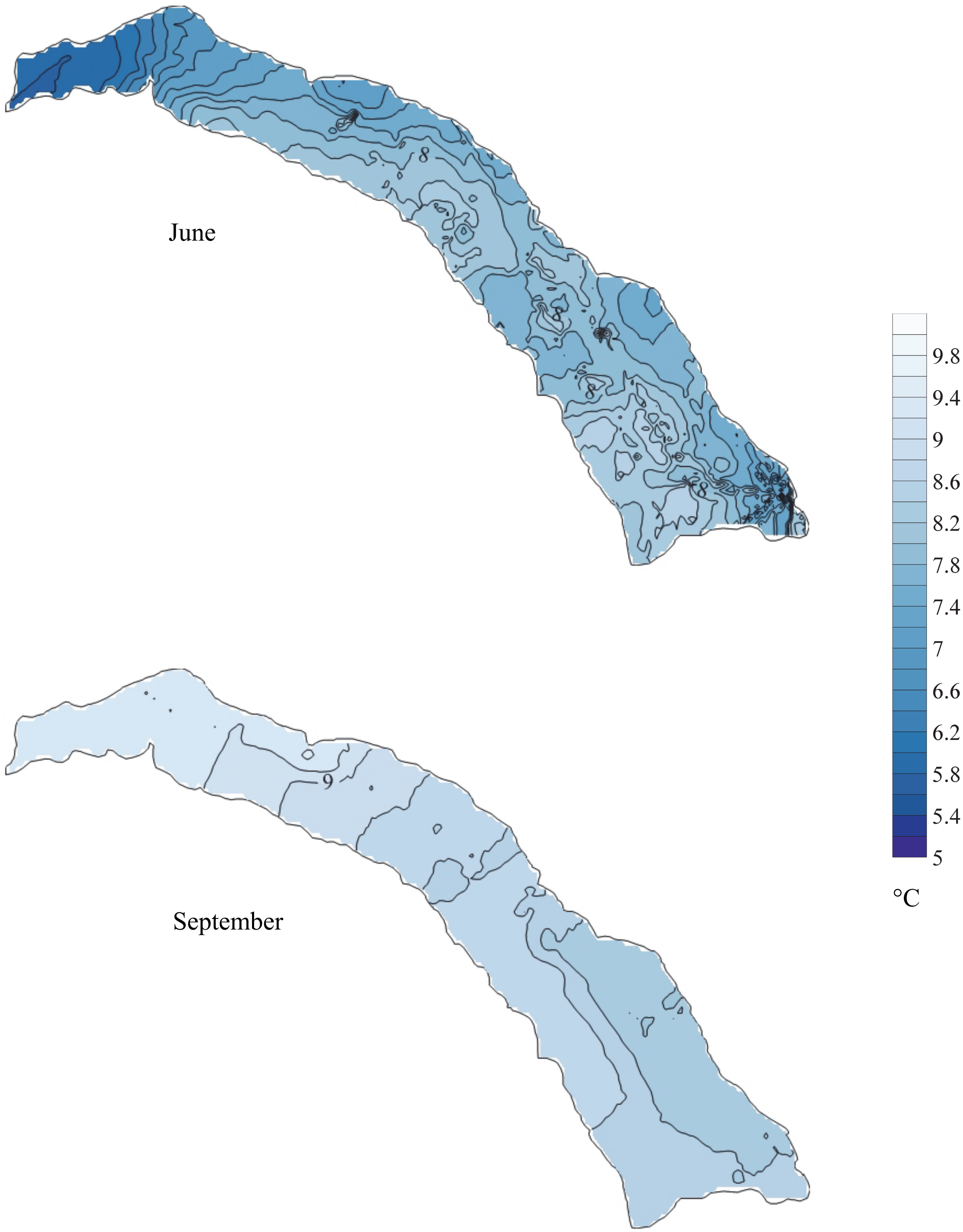
Appendix E8.–Uganik Lake seasonal weighted zooplankton biomass (mg/m^2) for 2011.

Taxon	Date 27-May	23-Jun	16-Jul	10-Aug	21-Sep	Seasonal weighted average
Copepods:						
Epischura	-	-	-	-	-	-
Ovig. *Epischura*	-	-	-	-	-	-
Diaptomus	-	-	7	13	-	4
Ovig. *Diaptomus*	-	-	-	-	-	-
Cyclops	379	400	348	286	194	321
Ovig. *Cyclops*	-	37	21	4	73	27
Harpaticus	-	-	-	-	-	-
Total copepods:	379	436	377	303	266	352
Cladocerans:						
Bosmina	-	-	-	-	-	-
Ovig. *Bosmina*	-	-	1	-	1	-
Daphnia longiremis	-	-	2	2	-	1
Ovig. *Daphnia longiremis*	-	-	4	6	-	2
Holopedium	-	-	-	-	-	-
Chydorinae	-	-	-	-	-	-
Total cladocerans:	-	-	6	7	1	3
Total copepods + cladocerans	379	436	383	311	267	355

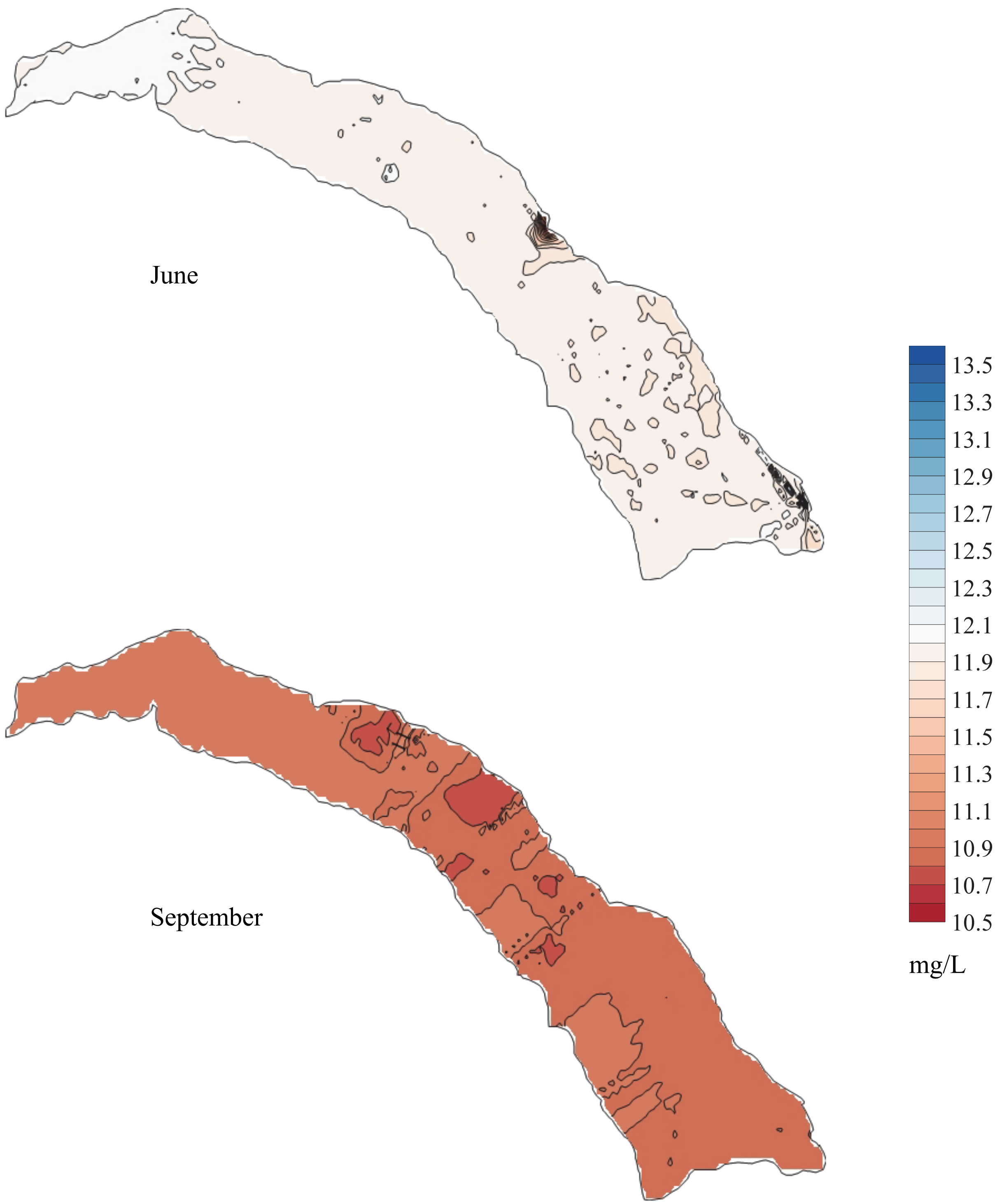
Appendix E9.–Uganik Lake seasonal zooplankton lengths (mm), 2011.

Taxon	Date					Seasonal average length
	27-May	23-Jun	16-Jul	10-Aug	21-Sep	
Copepods:						
Diaptomus	-	-	1.02	1.26	-	1.14
Ovig. *Diaptomus*	-	-	-	-	-	-
Cyclops	0.69	0.60	0.64	0.73	0.71	0.67
Ovig. *Cyclops*	-	1.12	1.11	1.07	1.12	1.10
Harpaticus	-	-	-	-	-	-
Cladocerans:						
Bosmina	-	-	-	-	-	-
Ovig. *Bosmina*	-	-	0.38	-	0.44	0.41
Daphnia longiremis	-	-	0.64	0.60	-	0.62
Ovig. *Daphnia longiremis*	-	-	0.88	1.08	-	0.98
Holopedium	-	-	-	-	-	-
Chydorinae	-	-	-	-	-	-

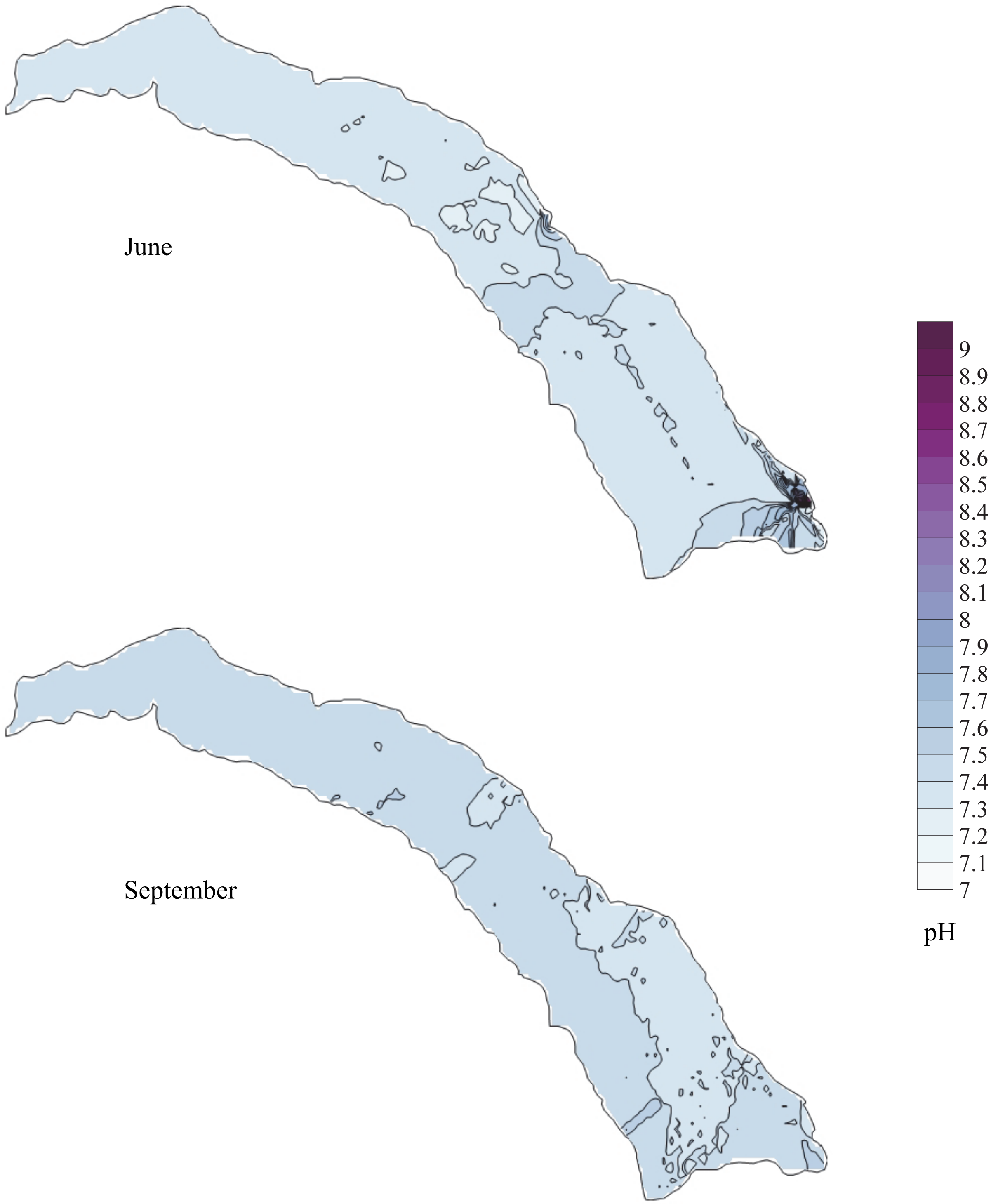
Appendix E10.–Uganik Lake AUV surface temperatures by month, 2011.



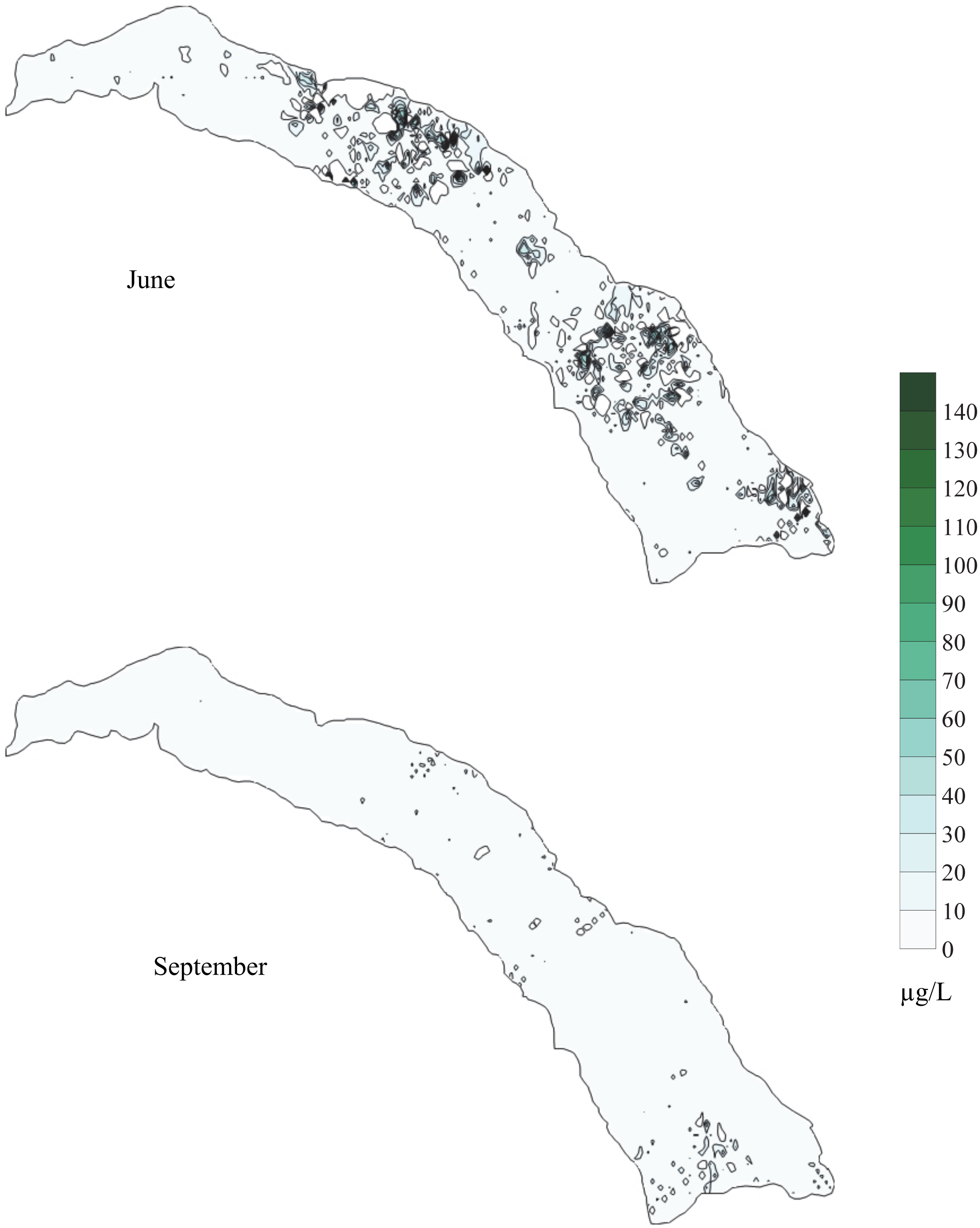
Appendix E11.–Uganik Lake AUV surface dissolved oxygen concentrations by month, 2011.



Appendix E12.–Uganik Lake AUV surface pH by month, 2011.

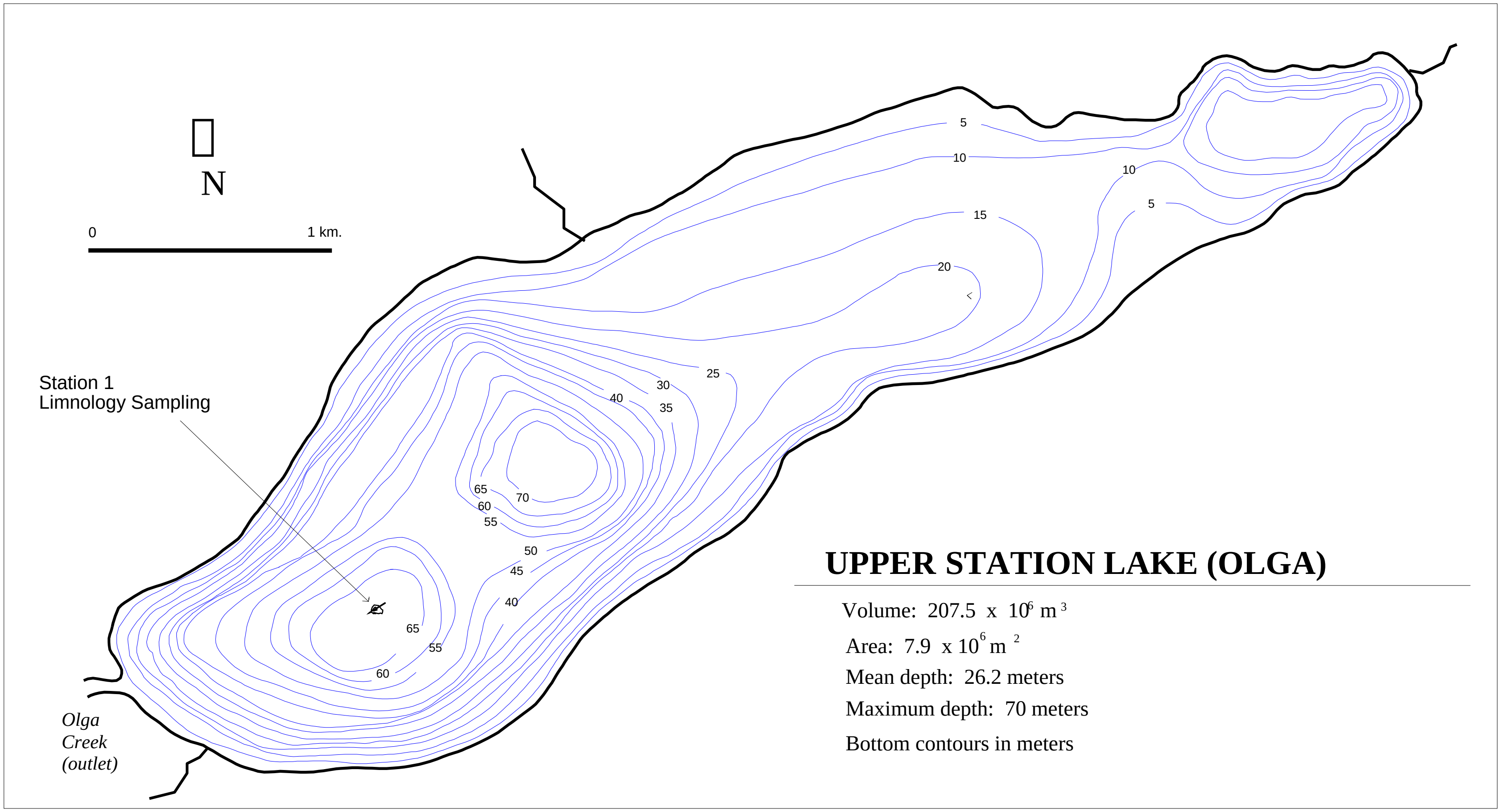


Appendix E13.–Uganik Lake AUV surface chlorophyll concentrations (µg/L) by month, 2011.



APPENDIX F. UPPER STATION LAKE

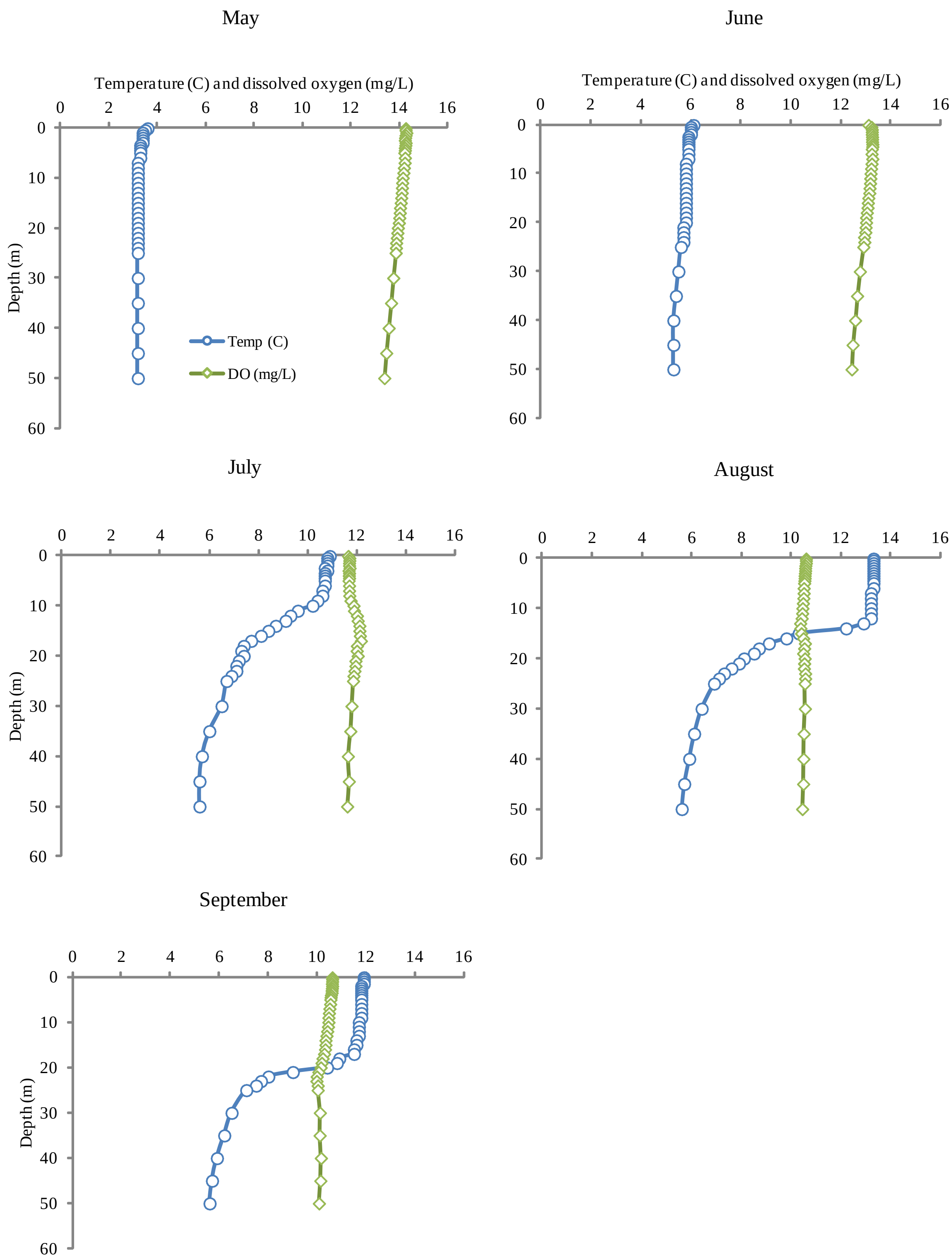
Appendix F1.–Map of Upper Station Lake showing the limnological sampling station.



Appendix F2.–Monthly and seasonal averages of 1 m temperature and dissolved oxygen, euphotic zone depth (EZD), and Secchi measurements from Upper Station Lake, 2011.

Sample type	May	June	July	August	September	Seasonal average
1-m Temperature (°C)	3.4	6.0	10.8	13.3	11.9	9.1
1-m Dissolved oxygen (mg/L)	14.3	13.3	11.7	10.6	10.6	12.1
EZD (m)	12.9	14.0	19.6	16.3	15.0	15.5
Secchi depth (m)	6.3	5.3	5.0	5.5	7.0	5.8

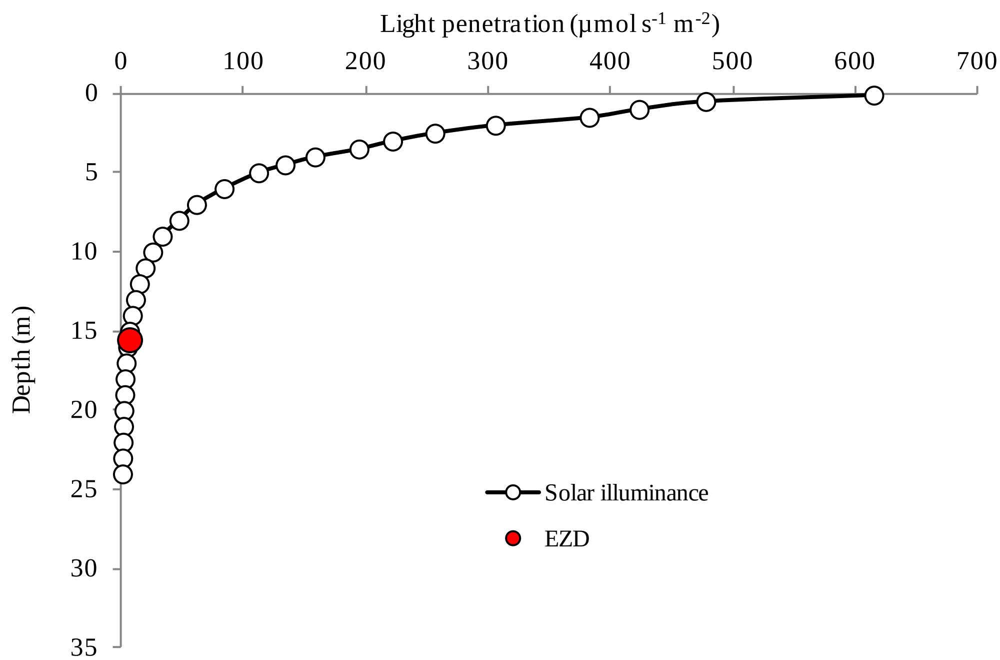
Appendix F3.–Temperature and dissolved oxygen depth profiles by month for Upper Station Lake, 2011.



Appendix F4.–Upper Station Lake solar illuminance (µmol s^{-1} m^{-2}) profiles by month, 2011.

	Date					
Depth (m)	13-May	16-Jun	18-Jul	26-Aug	15-Sep	Average
0.1	1,345.0	668.0	213.0	617.0	231.4	614.9
0.5	967.0	532.0	139.0	565.0	184.4	477.5
1	934.0	427.0	108.0	502.0	144.0	423.0
1.5	779.0	410.0	107.0	496.0	119.0	382.2
2	543.0	330.0	97.0	458.0	99.4	305.5
2.5	476.0	330.0	95.0	292.0	87.0	256.0
3	395.0	319.0	83.0	235.0	75.1	221.4
3.5	296.0	319.0	80.8	207.0	66.9	193.9
4	239.0	231.0	75.0	186.0	58.9	158.0
4.5	237.0	157.0	65.6	155.0	53.0	133.5
5	164.0	127.0	60.7	161.0	46.7	111.9
6	125.0	80.8	48.6	126.0	37.9	83.7
7	97.0	52.9	42.6	91.3	21.7	61.1
8	65.0	48.6	32.3	71.2	16.6	46.7
9	50.0	29.0	26.7	47.1	12.7	33.1
10	38.6	22.9	20.9	33.9	10.2	25.3
11	29.3	16.9	16.2	25.2	8.0	19.1
12	20.0	13.1	12.4	20.6	6.1	14.4
13	15.1	10.9	9.5	16.3	4.4	11.2
14	12.2	7.9	7.6	12.6	3.1	8.7
15	8.3	6.0	5.7	9.6	2.3	6.4
16	6.9	4.2	4.5	7.0	1.5	4.8
17	5.0	3.4	3.5	5.2	0.9	3.6
18	3.9	2.6	2.8	3.8	0.4	2.7
19	2.9	2.0	2.0	2.9		2.5
20		1.5	1.6	2.2		1.8
21			1.2	1.7		1.5
22			0.9	1.3		1.1
23			0.7	0.8		0.8
24			0.6			0.6
25						
26						
27						
28						
29						
30						

Appendix F5.–Average monthly solar illuminance profile for Upper Station Lake, 2011.



Appendix F6.–Upper Station Lake averaged seasonal water quality properties, nutrients and photosynthetic pigments, 2011.

Depth	Sample type	May	June	July	August	September	Seasonal average	SE
1 meter								
	pH	7.10	7.39	7.32	7.58	7.39	7.36	0.03
	Alkalinity (mg/L $CaCO_3$)	10.0	10.0	10.3	9.5	10.5	10.1	0.07
	Total phosphorous (µg/L P)	7.8	8.4	7.2	5.1	5.1	6.7	0.31
	Total filterable phosphorous (µg/L P)	2.1	2.9	2.3	2.3	2.8	2.5	0.07
	Filterable reactive phosphorous (µg/L P)	0.9	1.2	1.3	1.5	1.6	1.3	0.05
	Total Kjeldahl nitrogen (µg/L N)	208.6	219.3	217.5	192.6	218.5	211.3	2.26
	Ammonia (µg/L N)	5.7	10	4.1	3.2	4.6	5.5	0.53
	Nitrate + nitrite (µg/L N)	13.1	5.1	0.5	0.5	0.5	3.9	1.10
	Organic silicon (µg/L)	105.5	108.4	71.0	6.8	47.7	67.9	8.49
	Chlorophyll *a* (µg/L)	2.88	2.24	0.80	1.28	0.96	1.63	0.18
	Phaeophytin *a* (µg/L)	0.70	0.67	0.32	0.96	0.83	0.70	0.05
50 meters								
	pH	7.13	7.28	7.26	6.67	7.17	7.10	0.05
	Alkalinity (mg/L $CaCO_3$)	10.3	9.5	10.5	9.8	10.0	10.0	0.08
	Total phosphorous (µg/L P)	9.0	8.5	7.6	8.4	7.0	8.1	0.16
	Total filterable phosphorous (µg/L P)	2.3	2.8	2.9	2.0	2.4	2.5	0.07
	Filterable reactive phosphorous (µg/L P)	1.0	1.2	1.2	1.2	1.5	1.2	0.04
	Total Kjeldahl nitrogen (µg/L N)	271.8	228.7	274.1	241.1	218.5	246.8	5.03
	Ammonia (µg/L N)	6.3	9.9	21	32.6	11.4	16.2	2.13
	Nitrate + nitrite (µg/L N)	13.6	7.2	9.6	15.7	32.5	15.7	1.99
	Organic silicon (µg/L)	60.9	85.4	68.1	5.0	81.0	60.1	6.46
	Chlorophyll *a* (µg/L)	2.56	2.56	2.24	1.92	2.24	2.30	0.05
	Phaeophytin *a* (µg/L)	0.80	0.58	0.90	0.54	0.22	0.61	0.05

Appendix F7.–Seasonal zooplankton abundance (number/m^2) in Upper Station Lake, 2011.

	Date					Seasonal
Taxon	13-May	16-Jun	18-Jul	26-Aug	15-Sep	average
Copepods:						
Epischura	-	-	14,862	11,146	15,924	8,386
Ovig. *Epischura*	-	-	-	9,554	7,962	3,503
Diaptomus	-	-	-	3,185	-	637
Ovig. *Diaptomus*	-	-	-	-	-	-
Cyclops	1,025,478	720,263	696,391	418,790	207,006	613,585
Ovig. *Cyclops*	19,108	5,892	48,832	14,331	95,541	36,741
Harpaticus	-	-	-	-	-	-
Nauplii	380,042	10,311	4,246	44,586	42,463	96,330
Total copepods:	1,424,628	736,465	764,331	501,592	368,896	759,183
Cladocerans:						
Bosmina	8,493	27,986	76,433	28,662	14,597	31,234
Ovig. *Bosmina*	8,493	19,148	182,590	90,764	71,656	74,530
Daphnia longiremis	-	-	-	19,108	1,327	4,087
Ovig. *Daphnia longiremis*	-	-	-	4,777	-	955
Holopedium	-	-	2,123	6,369	6,635	3,025
Ovig. *Holopedium*	-	-	-	4,777	7,962	
Immature cladocerans	29,724	26,513	131,635	57,325	66,348	62,309
Total cladocerans:	46,709	73,646	392,781	211,783	168,524	176,141
Total copepods + cladocerans	1,471,338	810,111	1,157,113	713,376	537,420	935,324

Appendix F8.–Upper Station Lake seasonal weighted zooplankton biomass (mg/m^2) for 2011.

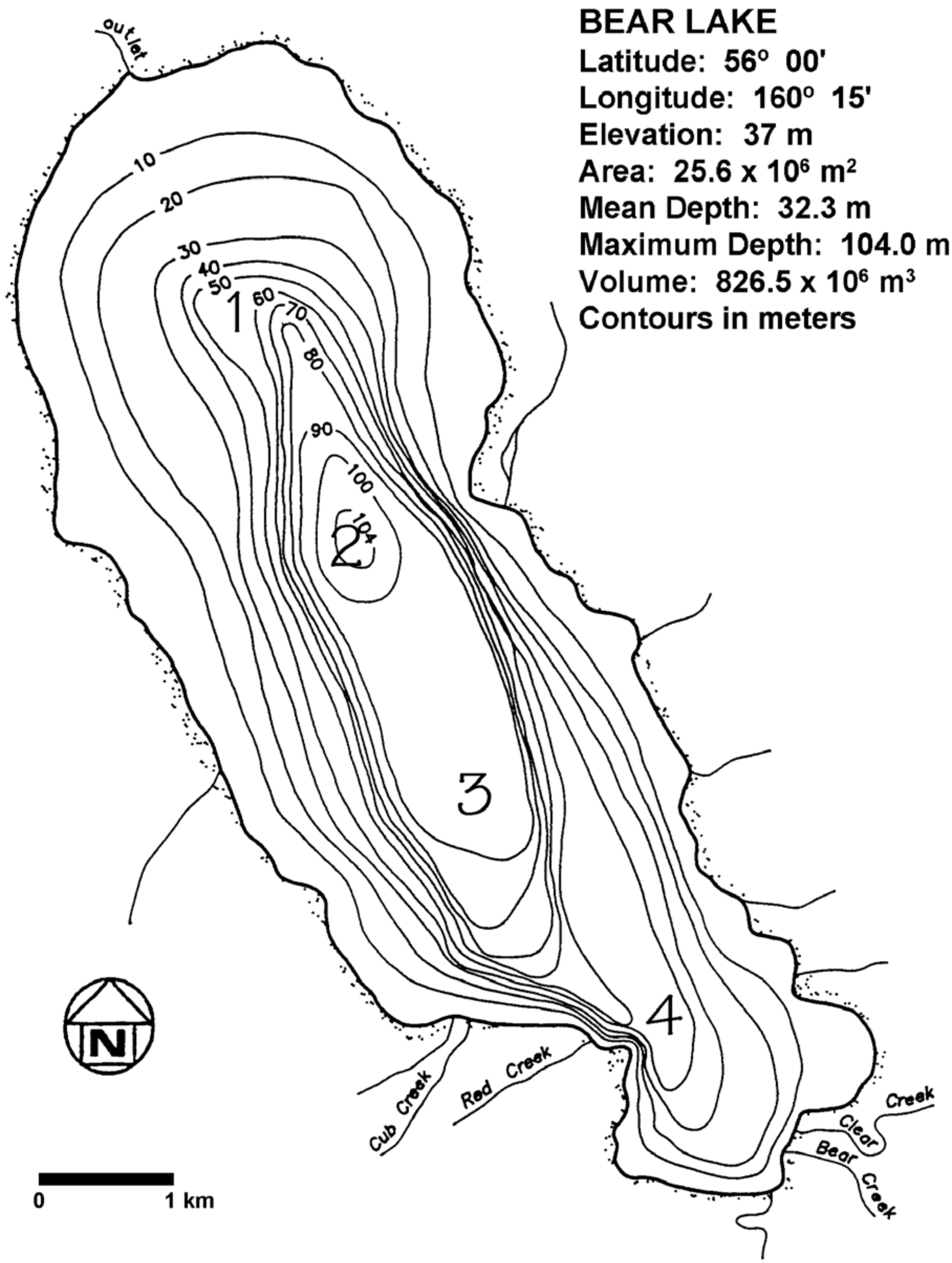
Taxon	Date 13-May	16-Jun	18-Jul	26-Aug	15-Sep	Seasonal weighted average
Copepods:						
Epischura	-	-	61	134	78	55
Ovig. *Epischura*	-	-	-	180	151	66
Diaptomus	-	-	-	11	-	2
Ovig. *Diaptomus*	-	-	-	-	-	-
Cyclops	1,384	1,247	1,842	1,157	499	1,226
Ovig. *Cyclops*	95	32	285	77	492	196
Harpaticus	-	-	-	-	-	-
Total copepods:	1,479	1,279	2,188	1,558	1,220	1,545
Cladocerans:						
Bosmina	11	31	80	36	15	34
Ovig. *Bosmina*	22	47	425	236	198	186
Daphnia longiremis	-	-	-	31	2	7
Ovig. *Daphnia longiremis*	-	-	-	19	-	4
Holopedium	-	-	-	17	30	9
Ovig. *Holopedium*	-	-	-	47	76	25
Total cladocerans:	33	77	505	386	321	264
Total copepods + cladocerans	1,512	1,356	2,693	1,944	1,541	1,809

Appendix F9.–Upper Station Lake seasonal zooplankton lengths (mm), 2011.

Taxon	Date 13-May	16-Jun	18-Jul	26-Aug	15-Sep	Seasonal average length
Copepods:						
Epischura	-	-	0.97	1.41	1.03	1.14
Ovig. *Epischura*	-	-	-	1.66	1.66	1.66
Diaptomus	-	-	-	0.92	-	0.92
Ovig. *Diaptomus*	-	-	-	-	-	-
Cyclops	0.63	0.71	0.87	0.88	0.83	0.79
Ovig. *Cyclops*	1.16	1.21	1.25	1.20	1.18	1.20
Harpaticus	-	-		-	-	-
Cladocerans:						
Bosmina	0.37	0.35	0.34	0.37	0.33	0.35
Ovig. *Bosmina*	0.52	0.51	0.50	0.52	0.54	0.52
Daphnia longiremis	-	-	-	0.61	0.63	0.62
Ovig. *Daphnia longiremis*	-	-	-	0.94	-	0.94
Holopedium	-	-	-	0.56	0.68	0.62
Ovig. *Holopedium*	-	-	-	0.94	0.93	0.94

APPENDIX G. BEAR LAKE

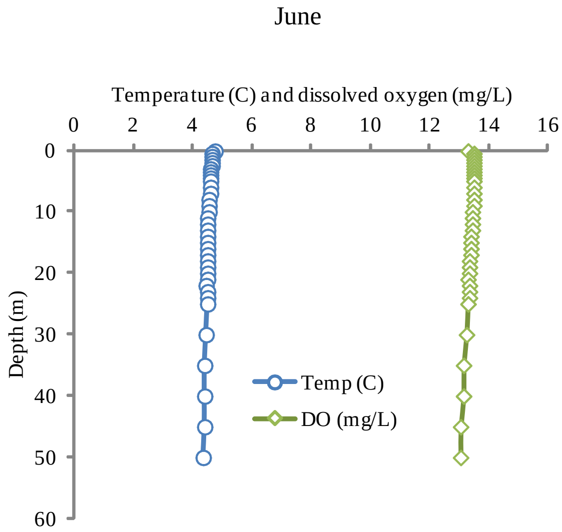
Appendix G1.–Map of Bear Lake showing the limnological sampling station.

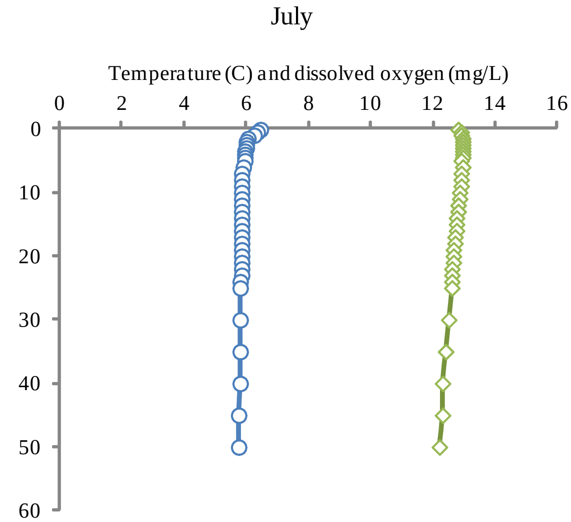


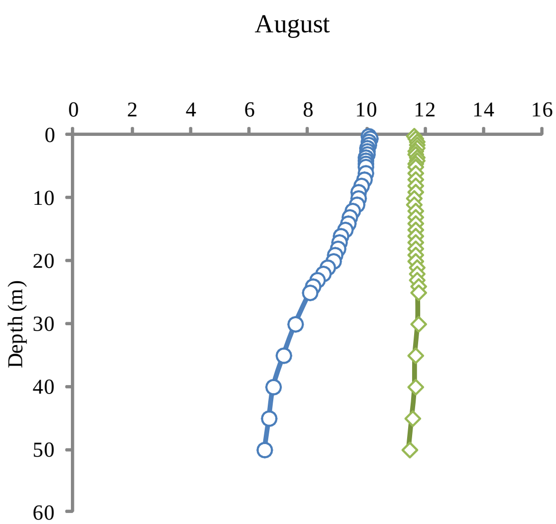
Appendix G2.–Monthly and seasonal averages of 1 m temperature and dissolved oxygen, euphotic zone depth (EZD), and Secchi measurements from Bear Lake, 2011.

Station	Sample type	June	July	August	Seasonal average
Station 2					
	1-m Temperature (°C)	4.7	6.3	10	7.0
	1-m Dissolved oxygen (mg/L)	13.5	13.0	11.7	12.7
	EZD (m)	17.5	19.1	16.9	17.8
	Secchi depth (m)	4.7	6.0	4.8	5.2
Station 4					
	1-m Temperature (°C)	4.6	6.2	10.1	7.0
	1-m Dissolved oxygen (mg/L)	13.5	12.8	11.7	12.7
	EZD (m)	22.4	20.6	18.1	20.4
	Secchi depth (m)	4.7	6.1	5.5	5.4

Appendix G3.–Temperature and dissolved oxygen depth profiles by month for Bear Lake, 2011.



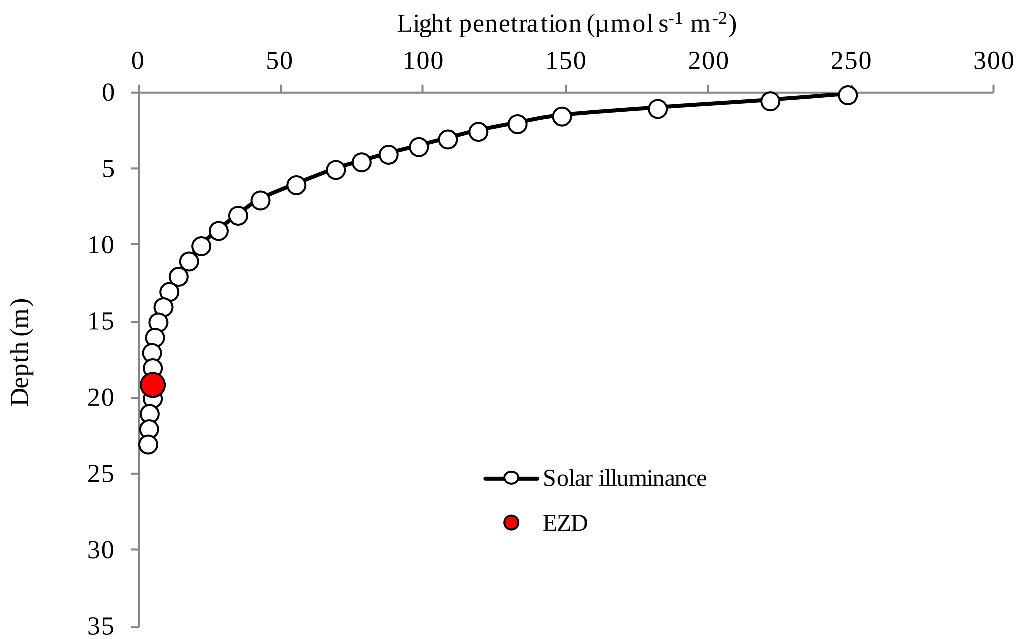




Appendix G4.–Bear Lake solar illuminance (µmol s^{-1} m^{-2}) profiles by month, 2011.

	Date			
Depth (m)	9-Jun	9-Jul	25-Aug	Average
0.1	248.1	165.3	331.8	248.4
0.5	224.5	141.3	297.9	221.2
1	189.0	115.7	240.7	181.8
1.5	161.5	88.6	194.6	148.2
2	144.9	82.7	170.3	132.6
2.5	127.1	76.5	153.2	118.9
3	118.0	71.6	135.0	108.2
3.5	108.8	63.0	122.4	98.0
4	98.6	57.9	105.8	87.4
4.5	86.8	53.2	93.9	78.0
5	78.3	46.9	81.7	69.0
6	64.9	37.2	63.3	55.1
7	50.3	29.6	47.7	42.5
8	41.1	23.8	39.3	34.7
9	32.8	19.3	31.6	27.9
10	26.0	15.3	24.1	21.8
11	21.7	12.2	18.7	17.5
12	17.1	9.7	14.8	13.8
13	13.2	7.1	11.5	10.6
14	10.5	6.1	9.1	8.5
15	8.3	4.9	7.2	6.8
16	7.0	3.9	5.8	5.6
17	5.8	3.2	4.6	4.5
18	7.1	2.5		4.8
19	5.9	2.1		4.0
20	4.8			4.8
21	3.7			3.7
22	3.5			3.5
23	3.2			3.2
24				
25				
26				
27				
28				
29				
30				

Appendix G5.–Average monthly solar illuminance profile for Bear Lake, 2011.



Appendix G6.–Bear Lake averaged seasonal water quality properties, nutrients and photosynthetic pigments, 2011.

Depth	Sample type	June	July	August	Seasonal average	SE
1 meter						
	pH	7.14	7.08	7.15	7.12	0.01
	Alkalinity (mg/L $CaCO_3$)	13.3	14.5	13.0	13.6	0.27
	Total phosphorous (µg/L P)	4.5	2.6	3.3	3.4	0.32
	Total filterable phosphorous (µg/L P)	1.7	2.2	1.3	1.7	0.15
	Filterable reactive phosphorous (µg/L P)	4.2	4.8	4.5	4.5	0.10
	Total Kjeldahl nitrogen (µg/L N)	148.8	147.1	126.3	140.7	4.18
	Ammonia (µg/L N)	5.8	6.8	23.3	11.9	3.27
	Nitrate + nitrite (µg/L N)	78.0	84.2	29.5	63.9	9.99
	Organic silicon (µg/L)	1,184.8	1,707.1	1,628.0	1,506.6	93.85
	Chlorophyll *a* (µg/L)	1.48	0.4	0.96	0.95	0.18
	Phaeophytin *a* (µg/L)	0.05	0.33	0.00	0.13	0.06
Hypolimnion						
	pH	7.09	7.17	7.08	7.11	0.02
	Alkalinity (mg/L $CaCO_3$)	13.3	14.0	11.8	13.0	0.38
	Total phosphorous (µg/L P)	5.2	3.6	3.9	4.2	0.29
	Total filterable phosphorous (µg/L P)	1.7	1.9	1.4	1.6	0.09
	Filterable reactive phosphorous (µg/L P)	5.3	5.7	4.9	5.3	0.13
	Total Kjeldahl nitrogen (µg/L N)	133.1	137.7	141.7	143.0	2.7
	Ammonia (µg/L N)	5.4	9.0	22.2	12.2	2.96
	Nitrate + nitrite (µg/L N)	80.8	71.5	71.0	74.4	1.84
	Organic silicon (µg/L)	1,349.3	1,328.3	1,510.4	1,396.0	33.21
	Chlorophyll *a* (µg/L)	0.96	0.80	0.56	0.77	0.07
	Phaeophytin *a* (µg/L)	0.61	0.24	0.23	0.36	0.07

Appendix G7.–Seasonal zooplankton abundance (number/m^2) in Bear Lake, 2011.

Taxon	Date 9-Jun	9-Jul	25-Aug	Seasonal average
Copepods:				
Epischura	-	-	-	-
Ovig. *Epischura*	-	-	-	-
Diaptomus	1,062	-	-	354
Ovig. *Diaptomus*	-	-	-	-
Cyclops	943,836	412,500	227,946	528,094
Ovig. *Cyclops*	498	40,791	32,537	24,609
Harpaticus	-	-	-	-
Nauplii	91,693	12,420	94,798	66,304
Total copepods:	1,037,089	465,711	355,281	619,360
Cladocerans:				
Bosmina	1,493	-	1,858	1,117
Ovig. *Bosmina*	104,399	86,412	254,140	148,317
Daphnia longiremis	-	-	-	-
Ovig. *Daphnia longiremis*	-	-	-	-
Holopedium	-	-	-	-
Ovig. *Holopedium*	-	-	-	-
Immature cladocerans	14,762	34,766	59,581	36,370
Total cladocerans:	120,654	121,178	315,579	185,804
Total copepods + cladocerans	1,157,743	586,890	670,860	805,164

Appendix G8.–Bear Lake seasonal weighted zooplankton biomass (mg/m^2) for 2011.

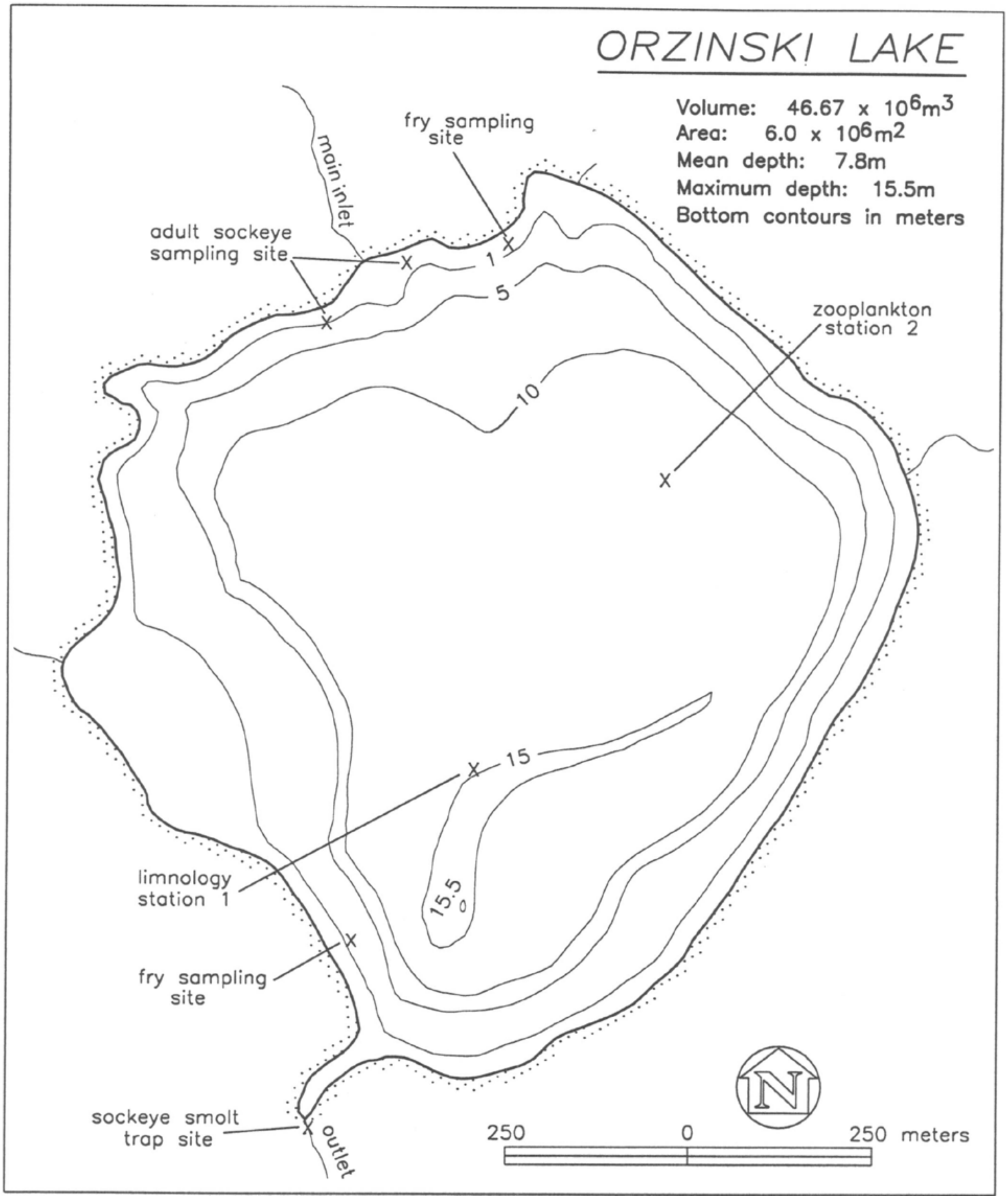
Taxon	Date 9-Jun	9-Jul	25-Aug	Seasonal weighted average
Copepods:				
Epischura	-	-	-	-
Ovig. *Epischura*	-	-	-	-
Diaptomus	9	-	-	3
Ovig. *Diaptomus*	-	-	-	-
Cyclops	1,762	1,016	563	1,114
Ovig. *Cyclops*	4	165	132	100
Harpaticus	-	-	-	-
Total copepods:	1,775	1,181	695	1,217
Cladocerans:				
Bosmina	2	-	2	1
Ovig. *Bosmina*	270	219	532	340
Daphnia longiremis	-	-	-	-
Ovig. *Daphnia longiremis*	-	-	-	-
Holopedium	-	-	-	-
Ovig. *Holopedium*	-	-	-	-
Chydorinae	-	-	-	-
Total cladocerans:	272	219	534	341
Total copepods + cladocerans	2,048	1,399	1,229	1,558

Appendix G9.–Bear Lake seasonal zooplankton lengths (mm), 2011.

Taxon	Date			Seasonal average length
	9-Jun	9-Jul	25-Aug	
Copepods:				
Epischura	-	-	-	-
Ovig. *Epischura*	-	-	-	-
Diaptomus	0.65	-	-	0.65
Ovig. *Diaptomus*	-	-	-	-
Cyclops	0.73	0.82	0.84	0.80
Ovig. *Cyclops*	1.07	1.05	1.06	1.06
Harpaticus	-	-	-	-
Cladocerans:				
Bosmina	0.21	-	0.17	0.19
Ovig. *Bosmina*	0.52	0.51	0.48	0.50
Daphnia longiremis	-	-	-	-
Ovig. *Daphnia longiremis*	-	-	-	-
Holopedium	-	-	-	-
Ovig. *Holopedium*	-	-	-	-

APPENDIX H. ORZINSKI LAKE.

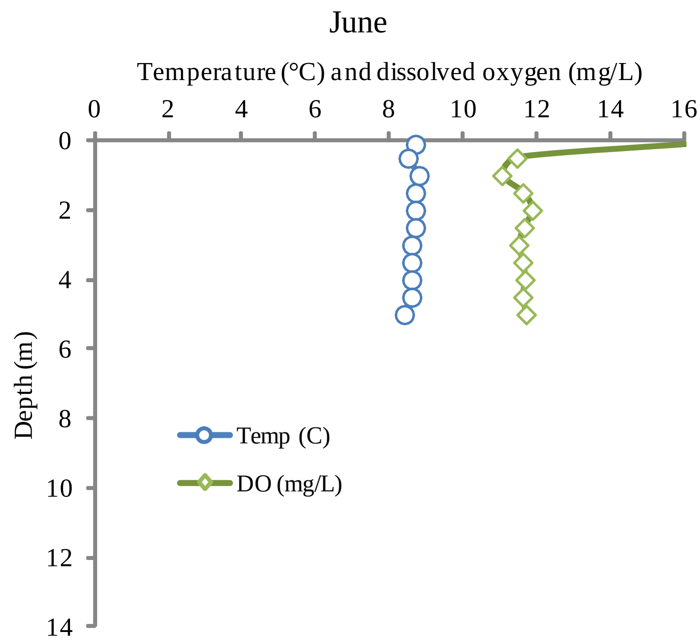
Appendix H1.–Map of Orzinski Lake showing the limnological sampling station.

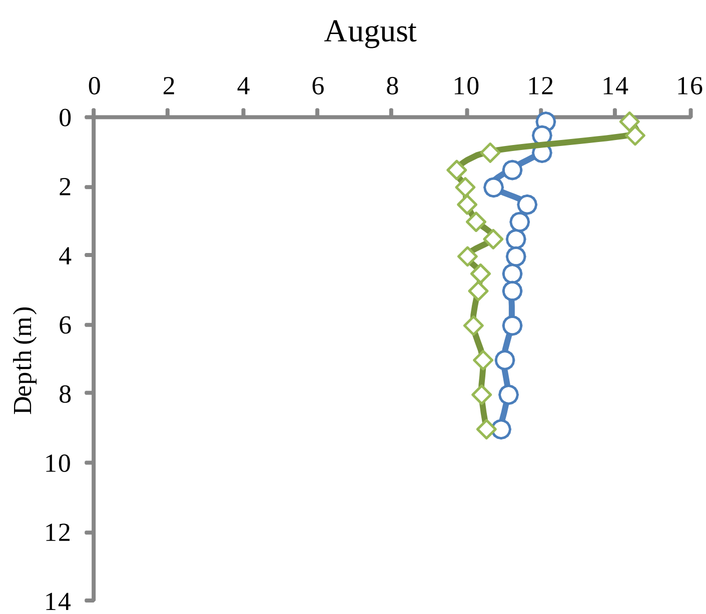


Appendix H2.–Monthly and seasonal averages of 1 m temperature and dissolved oxygen, euphotic zone depth (EZD), and Secchi measurements from Orzinski Lake, 2011.

	June	July	August	Seasonal average
1-m Temperature (°C)	8.8	ND	12.0	10.4
1-m Dissolved oxygen (mg/L)	11.1	ND	10.6	10.9
EZD (m)	16.9	ND	20.0	18.5
Secchi depth (m)	4.5	ND	3.9	4.2

Appendix H3.–Temperature and dissolved oxygen depth profiles by month for Orzinski Lake, 2011.

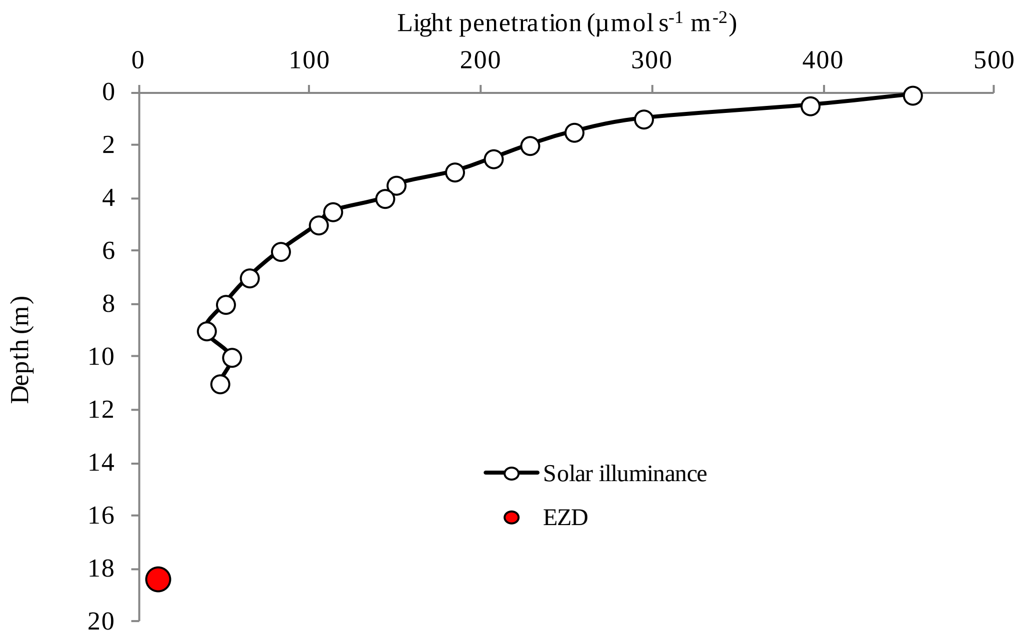




Appendix H4.–Orzinski Lake solar illuminance (μmol s^{-1} m^{-2}) profiles by month, 2011.

	Date		
Depth (m)	30-Jun	1-Aug	Average
0.1	857.2	46.3	451.8
0.5	755.3	28.7	392.0
1	571.3	18.1	294.7
1.5	492.6	15.6	254.1
2	443.4	13.1	228.3
2.5	400.9	13.1	207.0
3	357.4	11.3	184.3
3.5	289.2	11.2	150.2
4	276.1	11.1	143.6
4.5	215.3	11.0	113.2
5	199.0	10.6	104.8
6	155.1	10.3	82.7
7	119.0	10.0	64.5
8	91.6	9.5	50.6
9	69.8	9.0	39.4
10	54.2		54.2
11	47.3		47.3
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			
27			
28			
29			
30			

Appendix H5.–Average monthly solar illuminance profile for Orzinski Lake, 2011.



Appendix H6.–Orzinski Lake averaged seasonal water quality properties, nutrients and photosynthetic pigments, 2011.

Sample type	June	July	August	Seasonal average	SE
pH	ND	ND	ND	-	-
Alkalinity (mg/L $CaCO_3$)	ND	ND	ND	-	-
Total phosphorous (µg/L P)	7.3	7.4	8.8	7.8	0.28
Total filterable phosphorous (µg/L P)	ND	ND	ND	-	-
Filterable reactive phosphorous (µg/L P)	ND	ND	ND	-	-
Total Kjeldahl nitrogen (µg/L N)	ND	ND	ND	-	-
Ammonia (µg/L N)	ND	ND	ND	-	-
Nitrate + nitrite (µg/L N)	ND	ND	ND	-	-
Organic silicon (µg/L)	533.4	719.7	569.9	-	-
Chlorophyll *a* (µg/L)	0.64	0.32	2.56	1.17	0.40
Phaeophytin *a* (µg/L)	0.70	0.35	0.35	0.47	0.07

Appendix H7.–Seasonal zooplankton abundance (number/m^2) in Orzinski Lake, 2011.

Taxon	Date 14-Jul	Date 1-Aug	Seasonal average
Copepods:			
Epischura	2,654	-	1,327
Ovig. *Epischura*	-	-	-
Eurytemora	2,654	4,777	3,716
Ovig. *Eurytemora*	-	-	-
Diaptomus	-	-	-
Ovig. *Diaptomus*	-	-	-
Cyclops	2,123	-	1,062
Ovig. *Cyclops*	-	-	-
Harpaticus	-	-	-
Nauplii	531	265	398
Total copepods:	7,962	5,042	6,502
Cladocerans:			
Bosmina	-	-	-
Ovig. *Bosmina*	-	-	-
Daphnia longiremis	-	-	-
Ovig. *Daphnia longiremis*	-	-	-
Holopedium	-	-	-
Immature cladocerans	-	-	-
Total cladocerans:	-	-	-
Total copepods + cladocerans	7,962	5,042	6,502

Appendix H8.–Orzinski Lake seasonal weighted zooplankton biomass (mg/m^2) for 2011.

Taxon	Date 14-Jul	Date 1-Aug	Seasonal weighted average
Copepods:			
Epischura	3	-	2
Ovig. *Epischura*	-	-	-
Eurytemora	12	16	14
Ovig. *Eurytemora*	-	-	-
Diaptomus	-	-	-
Ovig. *Diaptomus*	-	-	-
Cyclops	3	-	2
Ovig. *Cyclops*	-	-	-
Harpaticus	-	-	-
Total copepods:	18	16	17
Cladocerans:			
Bosmina	-	-	-
Ovig. *Bosmina*	-	-	-
Daphnia longiremis	-	-	-
Ovig. *Daphnia longiremis*	-	-	-
Holopedium	-	-	-
Chydorinae	-	-	-
Total cladocerans:	-	-	-
Total copepods + cladocerans	18	16	17

Appendix H9.–Orzinski Lake seasonal zooplankton lengths (mm), 2011.

Taxon	Date 14-Jul	Date 1-Aug	Seasonal average length
Copepods:			
Epischura	0.63	-	0.63
Ovig. *Epischura*	-	-	-
Eurytemora	0.86	0.71	0.79
Ovig. *Eurytemora*	-	-	-
Diaptomus	-	-	-
Ovig. *Diaptomus*	-	-	-
Cyclops	0.64	-	0.64
Ovig. *Cyclops*	-	-	-
Harpaticus	-	-	-
Cladocerans:			
Bosmina	-	-	-
Ovig. *Bosmina*	-	-	-
Daphnia longiremis	-	-	-
Ovig. *Daphnia longiremis*	-	-	-
Holopedium	-	-	-
Chydorinae	-	-	-