An Analysis of Current and Historic Conditions in Odell Lake in Support of a TMDL Nutrient Loading Assessment

A Report Prepared for
RTI International
Research Triangle Park, NC

By

J.M. Eilers[1]
B.J. Eilers[1]
Katrina Moser[2]
Ann St. Amand[3]

Through

MaxDepth Aquatics, Inc.
Bend, OR
And
Carollo Engineers
Walnut Creek, CA

June 2005
Revised February 2006

[1]MaxDepth Aquatics, Inc., 1972 NE 3rd St., #10, Bend, OR 97701
[2]University of Utah, Department of Geography, Salt Lake City, UT
[3]PhycoTech, Inc., St. Joseph, MI

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This 2004 study of Odell Lake, Oregon, assesses water quality problems in the lake, including exceedances of water quality standards for pH and major blooms of *Anabaena* in recent years. To determine the cause of these problems, the study (1) evaluates historical changes in the lake through analysis of lake sediments and fisheries data, (2) uses hydroacoustics to describe the current status of the fisheries, (3) monitors water quality to characterize current conditions and (4) uses these lines of evidence to determine the reasons for the ongoing decline of water quality in the lake. The paleolimnological analyses show that sediment accumulation rates in Odell Lake have increased in response to more productive (eutrophic) conditions in recent decades, and that large, intense blooms of *Anabaena* in Odell Lake are a relatively new phenomenon. Odell Lake has experienced a four-fold increase in the rate of sediment and nutrient accumulation in the 20th century, with a 2.5-fold increase in the deposition of carbon, a 3.5-fold increase in nitrogen, and a five-fold increase in phosphorus deposition to the sediments. The analysis of titanium in the sediments shows that concentrations are very low compared to concentrations in the tributaries, which indicates that over 95 percent of the sediment accumulation in the deep areas of Odell Lake is derived from in-lake sources. Historically, diatoms show an increase of planktonic taxa commonly associated with eutrophic conditions combined with a concomitant reduction in mesotrophic planktonic taxa and a reduction of attached taxa. *Anabaena* akinetes identified in the sediments show relatively low deposition prior to the 1950's when deposition rates of the resting cells began to increase logarithmically. With respect to the fisheries in Odell Lake, the hydroacoustic analysis indicated that over 150 metric tons of fish were present in July 2004, and that based on size distribution and behavioral analysis a substantial portion of the fish currently present in Odell Lake are kokanee. These landlocked sockeye salmon were introduced into the lake through stockings from as early as 1932, but most intensively from 1950 through the early 1980s. The nutrient recycling associated with these fisheries was estimated based on measured biomass and estimated excretion rates, and compared to estimates of nutrient loading from the watershed and summer homes and resorts. These estimates indicate that planktivorous fish contribute about 38 percent of the phosphorus load and about 75 percent of the nitrogen load to the lake, and that this contribution is delivered at a higher rate in the warmer months. Because of this seasonal variation, average annual estimates of fisheries nutrient load underestimate the effective nutrient load during the summer and the degree to which this load impacts water quality in the lake. During the summer, kokanee tend to remain below the thermocline during the day, but ascend into the metalimnion during the night to feed on the zooplankton. This provides a re-supply of nutrients and contributes to more eutrophic conditions in the photic zone during the summer. Because the timing of water quality changes in Odell Lake observed in the sediments is coincident with reconstructed changes in the introduced fisheries, we believe that the water quality changes in Odell Lake are primarily attributed to fisheries management activities, notably the introduction of kokanee into the lake.

INTRODUCTION

1. Lake and Watershed Description

Odell Lake is a moderately large, deep lake located in the southwestern portion of the Deschutes River Basin (Figure 1). The lake is located at an elevation of 1459m (4787 ft) in the Oregon Cascades Range, adjacent to Willamette Pass. The lake is relatively deep and is oriented NW to SE (Figure 2; Table 1). Odell Lake was formed as a glacial trough during the recent ice-age (circa 11,000 YBP). Consequently, the lake has a regular shape which results in a relatively equal distribution of lake volume versus depth (Figure 3). The receding ice left a terminal moraine at the east end, thus impounding water in the newly created lake. The topographic watershed divide for the lake is oriented north and south of the lake and includes several substantial peaks (Figure 4). A pseudo-three dimensional view of the lake and watershed illustrate the location of the lake and the nature of the landscape (Figures 5 and 6). The peaks are all of volcanic origin and the watershed in underlain by fractured basaltic andesite (Sherrod 1991). The areas immediately below the peaks are covered with glacial deposits (Sherrod 1991). Tephra deposits from the eruption of Mt. Mazama, 66 km to the south, covered the watershed with over 100 cm of ash (Hoblitt et al. 1987). A stratigraphic analysis of the material on the east shore of Odell Lake showed that below the shallow organic duff and silt-loam, was a 100 to 110 cm-thick layer of Mazama tephra (Jaehnig et al. 1994). Underneath the ash layer (assumed to be circa 6900 YBP [Bacon 1983]), were lacustrine sediments, indicating that Odell Lake extended higher up the shore than the current shoreline.

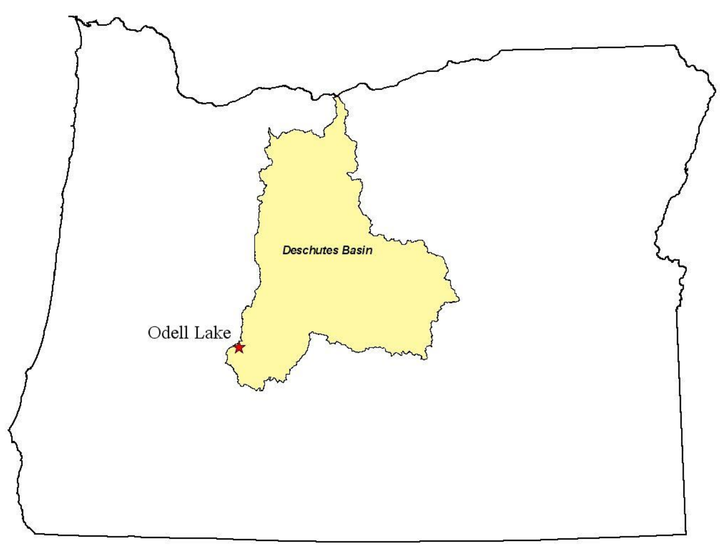

Figure 1. Location of Odell Lake in the Deschutes Basin, Oregon.

Three major tributaries and a number of intermittent streams flow into Odell Lake and surface water discharges through the outlet at Odell Creek on the east end. Odell Creek flows into Davis Lake. Discharge from Davis Lake occurs underground through a lava flow before entering Crane Prairie Reservoir. The area near the lake receives 79 cm precipitation annually on the east end of the lake, although the higher elevation portions of the watershed receive substantially greater precipitation. Most precipitation occurs as snow; snowmelt runoff forms a major component of the hydrologic input to Odell Lake.

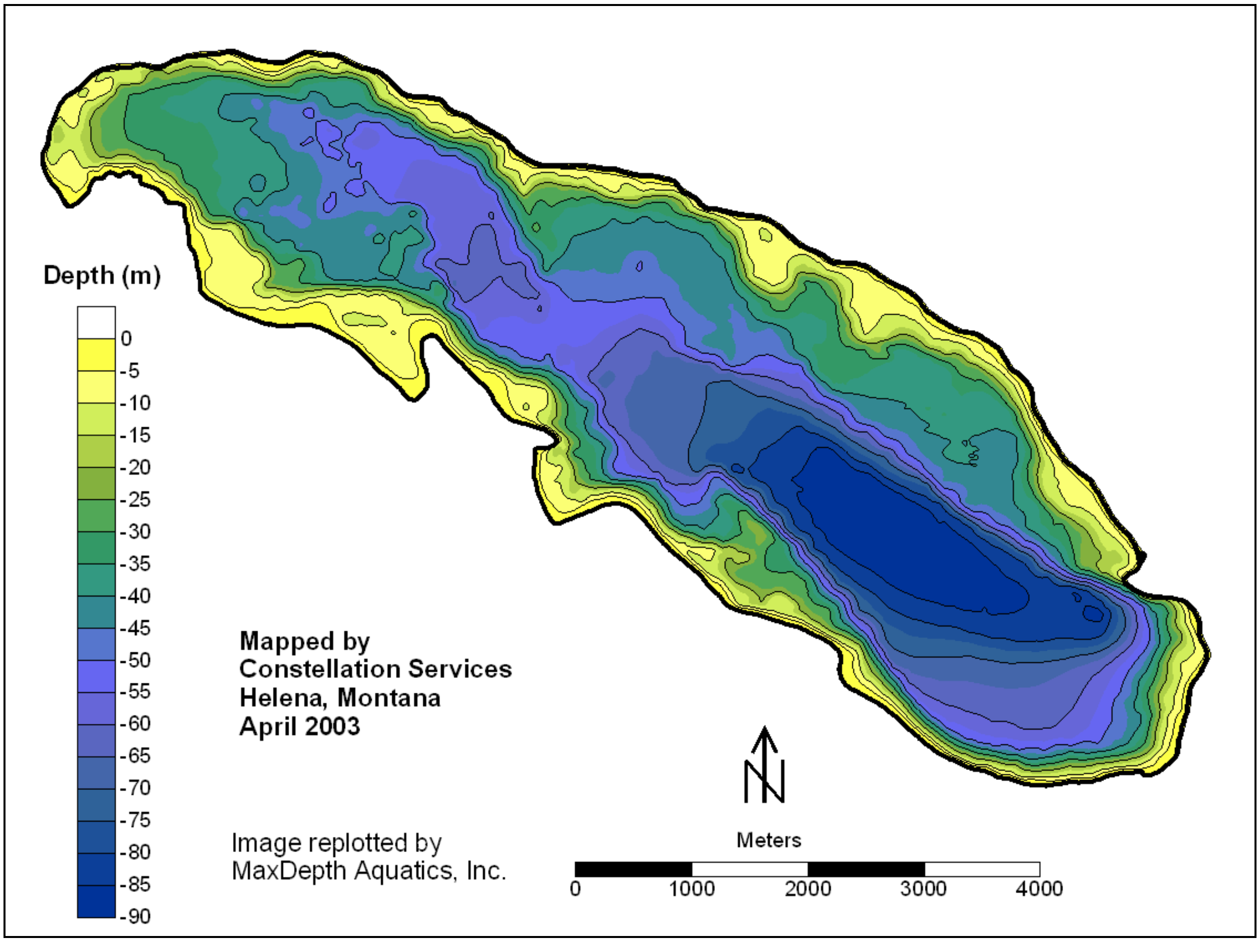

Figure 2. Bathymetric map of Odell Lake regenerated from a grid file provided by Constellation Services. Contours are in meters.

Table 1. Morphometry of Odell Lake (after Constellation Services)

Parameter	Metric	English
Lake Area	13.83 km^2	3418 ac
Maximum Depth	88.7 m	291 ft
Average Depth	42.04 m	137.9 ft
Volume	5.844×10^8 m^3	471,342 ac-ft
Shoreline Length	20.8 km	12.93 mi
Watershed Area[a]	92 km^2	37 mi^2
Hydraulic Residence Time[a]	8 yrs	8 yrs
Elevation	1459.1 m	4787 ft

[a] After Johnson et al. (1985); our estimate of residence time is 6.7 yrs.

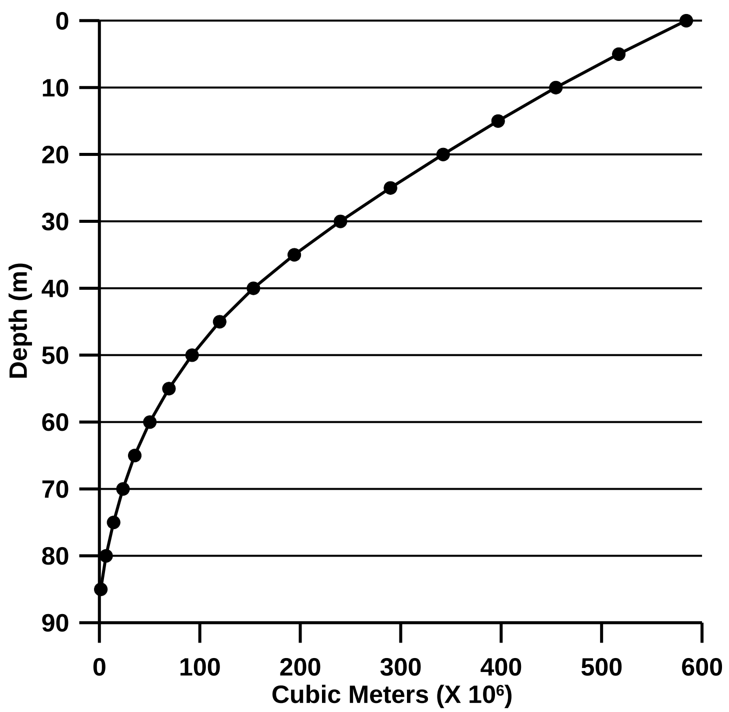

Figure 3. Volume of Odell Lake plotted against depth.

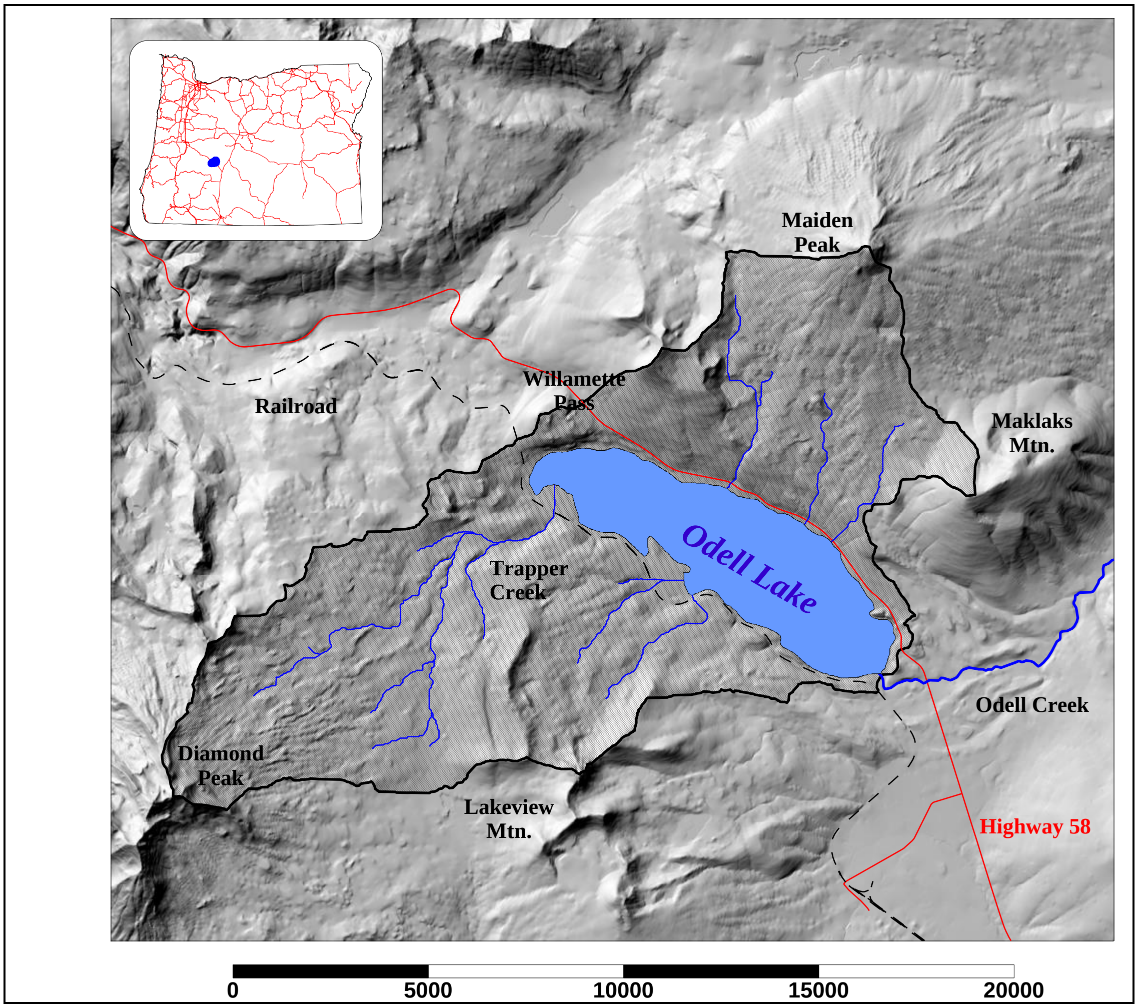

Figure 4. Odell Lake watershed showing the major tributaries and outlet. The scale bar is in meters.

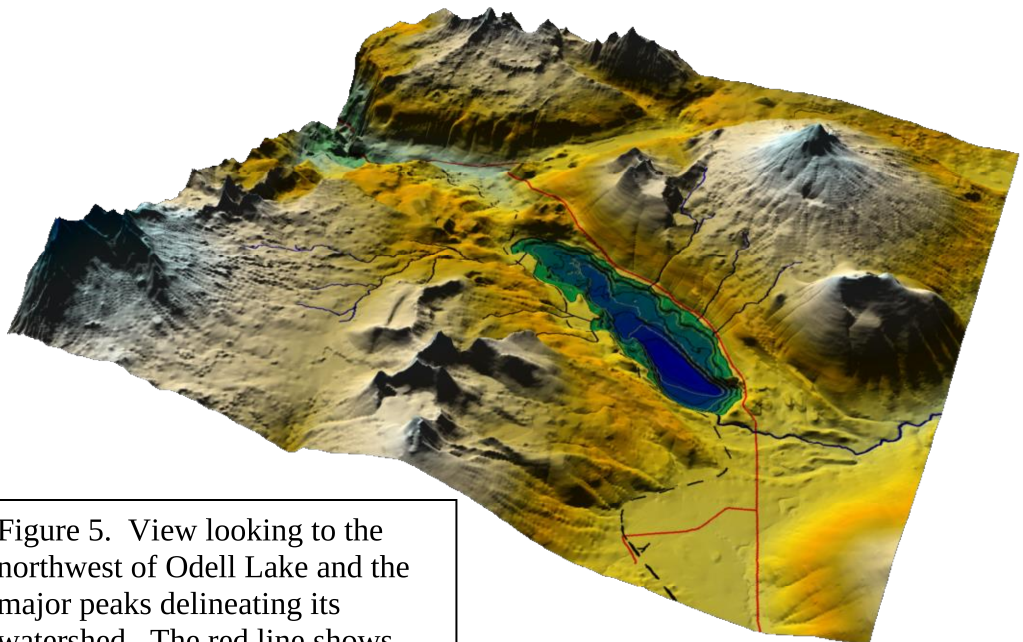

Figure 5. View looking to the northwest of Odell Lake and the major peaks delineating its watershed. The red line shows Highway 58.

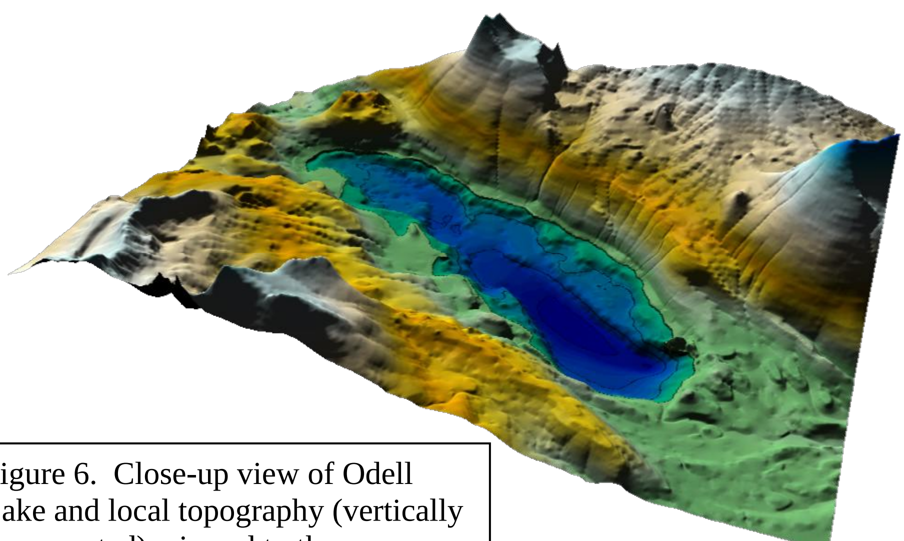

Figure 6. Close-up view of Odell Lake and local topography (vertically exaggerated), viewed to the northwest.

2. Anthropogenic Factors in the Watershed

Odell Lake is wholly contained in the Deschutes National Forest and most of the southern portion of the watershed is located in the Diamond Peak Wilderness. Several Forest Service campgrounds are located on the lakeshore. Two major transportation features pass through the watershed: Highway 58 on the north shore and a rail line near the south shore. The Forest Service has issued 66 long-term leases for private summer homes/residences, most of which are located on the western and northern shoreline (Figure 7). In addition, two resorts operate under special use permits on the lakeshore. Public access to Odell Lake is afforded at several boat ramps. A small portion of the Willamette Pass Ski Area is located at the extreme northeast portion of the Odell Lake watershed. A chronology of major anthropogenic activities in the watershed is presented in Table 2.

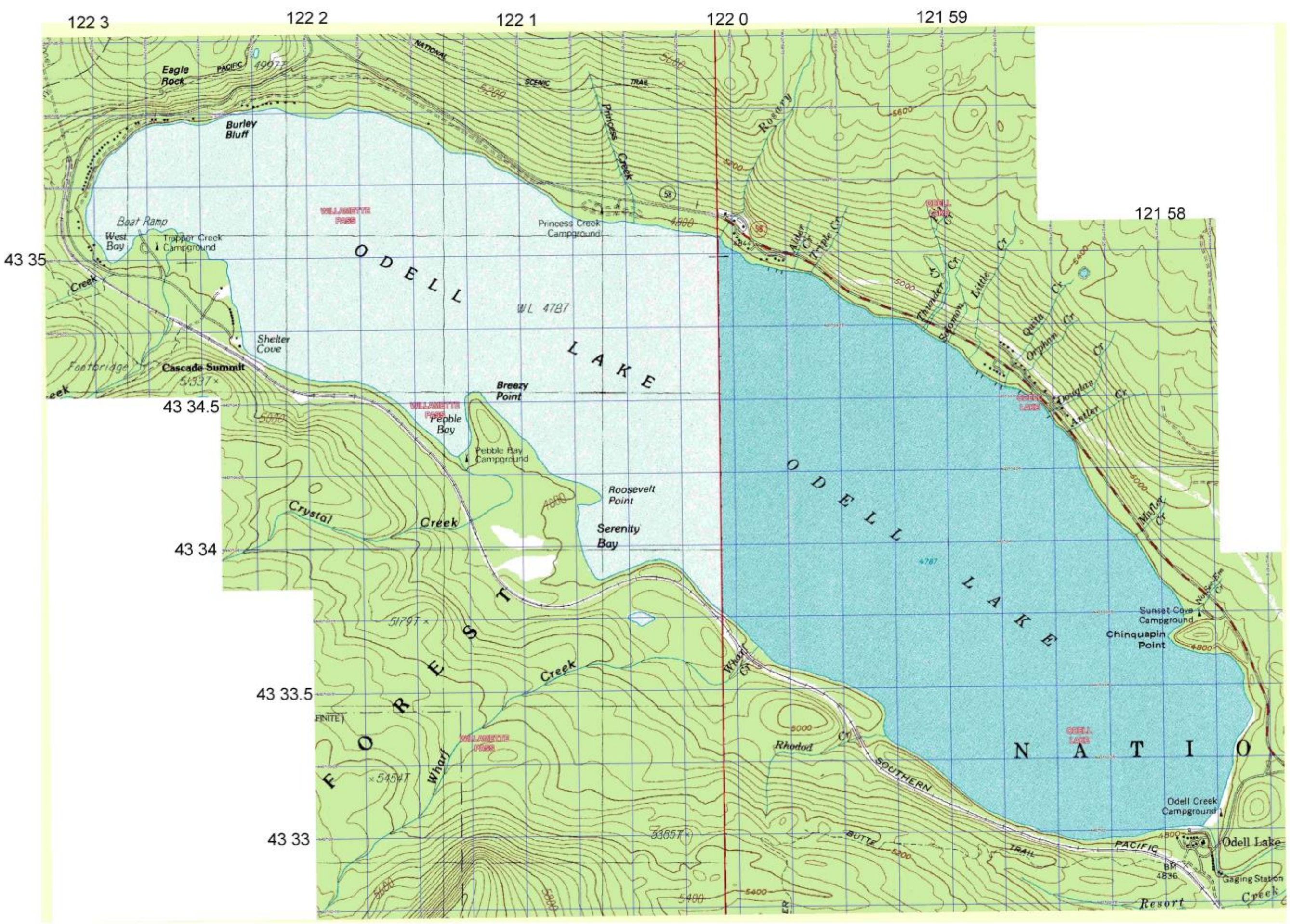

Figure 7. Joined USGS topographic maps (1:24,000) created by combining Willamette Pass and Odell Lake quadrangle maps.

Table 2. Major anthropogenic activities in the Odell Lake watershed.

Year	Action	Note
Pre-1850	Native tribes present	Archeological remains show usage of the lake, extent unknown; possible effects on forest fire frequency.
1880s - ?	Sheep and cattle grazing	Summer usage only; Davis Lake downstream named after cattle rancher.
1908	Deschutes National Forest designated	Forest created from national forest reserves set aside in 1893. Fire suppression highly successful.
1911	Military Road completed to east end of lake	Travel from east end of lake to west end by ferry.
1913-14	Fish hatchery constructed on Odell Creek (downstream of Odell Lake)	Raised rainbow trout for stocking in area lakes. See Table 3 for details of this and other fish stocking.
1923-25	Construction of Central Pacific Railroad on south shore	Required construction of two sawmills and housing for workers.
1923-1966	Construction of two resorts and 66 cabins	One resort was operating prior to 1919. Permits for private cabins halted in 1966. Cabins are on septic systems or pit toilets.
1937-1960s	Construction of five Forest Service campgrounds	Waste treatment converted from septic systems to vaulted toilets from 1965-69.
1939	Willamette Pass Ski Area developed	Only the eastern-most runs are within the Odell Lake watershed.
1940	Construction of Hwy 58 on north shore	
1957	Diamond Peak Wilderness designated	Occupies southern portion of the watershed.

3. Odell Lake Fisheries

Odell Lake has been an important recreational feature in the Cascades, largely because of the fishing opportunities. Odell Lake has indigenous populations of bull trout (*Salvelinus confluentus*), rainbow trout (*Salmo gairdneri*), and mountain whitefish (*Prosopium williamsoni*). Additional fish species have been introduced into Odell Lake during the 20th century, primarily through intentional stockings by the Oregon Department of Fish & Wildlife (ODFW, formerly known as the Oregon Game Commission). These stockings have included hatchery introductions of rainbow trout, lake trout (*Salveliunus namaycush*), Atlantic salmon (*Salmo salar*), kokanee (*Oncorhynchus nerka*), eastern brook trout (*Salvelinus fontinalis*) and Arctic grayling (*Thymallus acticus*). The stockings of Atlantic salmon and the Arctic grayling were unsuccessful, but the other species remain present in the lake. An illegal introduction of tui chub (*Gila bicolor*) also occurred and this species remains present (Table 3).

Table 3. Fish species indigenous (bold) and introduced into Odell Lake.

Fish Species	First Introduced	Present	Notes
Bull Trout	**Native**	**Yes**	**Population threatened**
Rainbow Trout	**Native**	**Yes**	**Genetic status of native RT unknown**
Whitefish	**Native**	**Yes**	
Lake Trout[a]	1902?, 1905? 1917	Yes	Stocked from 1951-1965
Rainbow Trout[b]	1913?, 1925	Yes	Stocked from 1926-1935, 1939, 1946, 1949-1962, 1977
Brook Trout	1915	Yes	Stocked from 1927-1935; small stocking in 1977
Arctic Grayling	1925	No	Stocked once, failed
Kokanee[c]	1932?, 1950	Yes	Stocked 1950-1971, 1981-1983
Tui Chub[d]	Prior to 1940	Yes	Illegally introduced
Atlantic Salmon[e]	1967	No	Stocked 1967-1971

[a] Possible introductions in 1902 and 1905 poorly documented. Stocking was reported in the *Bend Bulletin* (July 26, 1917).

[b] A variety of different sources were used for brood stock throughout the years. The first stocking may have occurred in 1913 with the construction and operation of a fish hatchery built on Odell Creek.

[c] Sockeye salmon (21,000) were planted in Odell Lake in 1932, but records do not indicate if the fish were anadromous or landlocked (kokanee) stock. However, observations circa 1940 (Newcomb 1941) reported kokanee common in Odell Lake. Also, kokanee were observed spawning in Crystal Creek in 1947 (OSGC 1947) prior to the primary stocking period starting in 1950.

[d] Newcomb (1941) mentions that tui chub were common, but no documentation of their first appearance has been located.

[e] Coho salmon were stocked in Davis Lake from 1965-71 and would have had access to Odell Lake through Odell Creek (ODFW, Draft Upper Deschutes Fish Management Plan)

4. Previous Studies of Odell Lake

There have been a number of limnological investigations of Odell Lake, starting first with Newcomb (1941) and leading up to this study (Table 4). The survey by Newcomb (1941) was part of a brief survey of a number of lakes in the region conducted in relation to fisheries management. The first intensive limnological analysis of Odell Lake was not initiated until the 1970's with primary production studies by Larson (1970,1972) and paleolimnological work by Meyerhoff (1976). Less intensive studies include the work of Miller et al. (1974), Johnson et al. (1985), and Sweet (1990). The most intensive and long-term work on Odell Lake was conducted by ODFW beginning with work by Averett (1968) and extending through much of the 1970s (Lewis 1970-1975, Lindsay and Lewis 1975, 1978). The work by ODFW focused on the fisheries, but included routine water quality and zooplankton sampling that provide insight into conditions in the lake. The first assessment by Newcomb (1941) concluded that Odell Lake was oligotrophic based on evaluations of the zooplankton and transparency of the water. Subsequent studies of the lake conducted in the 1970's concluded that Odell Lake was primarily mesotrophic. The apparent change in trophic condition from oligotrophic to mesotrophic was attributed to increasing use of the lake, particularly the proliferation of cabins along the lakeshore made possible through the special use permit program of the Forest Service (Larson 1970, 1972; Meyerhoff et al. 1978; and Johnson et al. 1985). Sweet (1990) reviewed available water quality data for Odell Lake and concluded that water quality had improved from the 1960's, probably in response to reduced nutrient loading associated with a decision by the Forest Service to replace the septic systems at the campgrounds with holding tanks.

Table 4. Previous studies of Odell Lake. Peer-reviewed references are shown in italics.

Author/Date	Period of Study	Focus of Study	Major Findings
Newcomb (1941)	1940, 1941	WQ, plankton, benthos sampling	Lake is **oligotrophic**; transparency of 12.2 -12.8 m
Jennings & Lindland (1964)	1953-63	Fisheries	Lake is oligotrophic; tui chub abundant; "inexhaustible supply of fish"
OSGC (1965)	1960-64	Kokanee angler surveys	84% of anglers fishing for kokanee; length-frequency data
Averett (1966)	1965	Kokanee fisheries	Two distinct groups of kokanee present
Averett & Espinosa (1968)	1965	Kokanee fisheries	Two distinct groups of kokanee present; many kokanee spawning on groundwater discharge sites along shore
Larson (1970)	1968-69	Primary production	**Primary and secondary production is high**; attributed to high human use
Lewis (1970, 1971, **1972**[a], 1973, 1974, 1975)	1969-1974	Kokanee fisheries	Population estimates, vertical distribution (based on hydroacoustics), and diet preferences for kokanee
Larson (1972)	1968-69	Primary production	Classified Odell on the **high end of the trophic scale** based on ^{14}C primary production and zooplankton density
McHugh (1972, 1979)	1968	General limnology	"**lake is still in good condition**, but subject to increasingly heavy use"; remove septic systems
Lindsay and Lewis (1975, **1978**[b])	1972-76	Kokanee fisheries and limnology	Density of *Cyclops bicuspidatus* associated with kokanee abundance; reasons for recent (1977) increases in kokanee production unknown. Phosphorus budget presented.
Miller et al. (1974)	1971	Algal productivity	Algal assay indicates **moderate productivity**; limiting nutrient(s) unclear
Meyerhoff et al. (1978)	1975	Paleolimnology	Diatoms indicate **increased productivity over pre-development**; eutrophication attributed to watershed activities; water quality improving after 1968
Johnson et al. (1985)	3 samples from 1982	Limnology	Lake is **mesotrophic**, attributed to lakeshore development
Sweet (1990)	1988-1989	Phytoplankton	Also compiled other unpublished data; **Odell is mesotrophic to eutrophic**, although improved over conditions in the 1960's
Houslett (2002)	2001	Limnology	Odell is becoming **more eutrophic; *Anabaena* blooms**

[a] Only the report from 1972 has been located

[b] Only the 1978 report has been located

Recently, water quality sampling conducted by the Forest Service has shown the presence of high densities of cyanobacteria in Odell Lake attributed largely to species of *Anabaena* (Houslett 2002; DNF 2004). This water quality sampling conducted by the Deschutes National Forest from 2001 through 2004 has shown high summer values of pH, presumably caused by high primary production. The pH values, some as high as 9.8, exceed the State's water quality criteria of 8.5 by a considerable margin. Consequently, Odell Lake was listed on the Oregon Section 303(d) list as not meeting water quality standards. Water bodies on the 303(d) list are required by EPA to be evaluated for the purpose of developing an assessment of the factors causing the water quality exceedences and developing corrective action. This activity, know as determining the Total Maximum Daily Load [of pollutants], is referred to as the TMDL process. The purpose of the study described in this report is to assess the current water quality conditions in Odell Lake, investigate the possible changes in water quality, and to evaluate possible mechanisms associated with perceived changes in the lake.

During the summer of 2004, the Deschutes National Forest (DNF) continued their sampling of the phytoplankton in Odell Lake. These data were made available to us for the purpose of assessing current conditions. In addition, the Oregon Department of Environmental Quality (DEQ) collected water quality data including nutrient chemistry, water quality profiles, deployment of thermister arrays, and collection of zooplankton samples. Lastly, ODFW continued their assessment of the fisheries in Odell Lake and its major tributaries (ODFW 2005). These efforts were combined with the field activities of MaxDepth Aquatics which consisted of a reconstruction of changes in the lake based on data derived from the lake sediments, hydroacoustic analysis of the fisheries in Odell Lake, and analysis of the lake and watershed hydrology.

This report describes the methods used in this study, the results of the investigation, and interpretation of the data. This report, the water quality model, and the supporting data will be delivered to the USEPA and DEQ for preparation of the TMDL for Odell Lake.

METHODS

The study methods include activities associated with water quality sampling, paleolimnology, and hydroacoustics. The majority of the water quality sampling conducted during the project period was conducted by DEQ staff. DEQ sampled Odell Lake on June 16, July 21, August 24, and September 8. Generally these sampling events took place over two days and the dates shown above represent the first day of sampling. The water quality-related sampling by DEQ took place at three stations oriented along the major axis of the lake (Figure 8). At each of these sites DEQ staff would collect the water quality samples, phytoplankton samples, zooplankton samples, and would measured the profile attributes to a depth of 30 m. *In situ* measurements of temperature, pH, dissolved oxygen (DO), and specific conductance were conducted using a YSI 610 XLM multi-parameter probe calibrated according to manufacturer's recommendations. Water quality samples were analyzed for nutrients, major ions (except sulfate), and metals. Phytoplankton samples were measured for chlorophyll *a* and separate aliquots were preserved with Lugol's solution and were sent to Aquatic Analysts for phytoplankton community composition. Zooplankton samples consisted of vertical tows with a 64 micron mesh net equipped with a 20 cm opening, a 30 cm reduction collar and a modified Wisconsin bucket. All zooplankton tows were collected from 0-25 m. These samples were preserved with ethanol and sent to ZP Taxonomic for characterization of zooplankton community composition.

DEQ staff placed four multi-parameter sondes in Odell Lake. One sonde was placed at each of the three buoys at a depth of 1 m. The fourth sonde was placed at the east site at a depth of 15 m. The cables holding the multi-parameter sondes at the lake center and the 1 m-depth at the east site were cut during the study period and all data from these units were lost. DEQ placed three thermister arrays in the lake, one in the center and one near each end of the lake by lowering a weighted cable and buoyed with a surface float (Figure 8). The thermisters were placed at various intervals and were programmed to record temperature at 1-hr intervals.

In addition to the three primary lake monitoring sites, DEQ also sampled the major tributaries, Trapper, Crystal, and Rosary Creeks, and the outlet, Odell Creek. The sampling protocol at the stream sites followed the same as that used for the lake sites, except that plankton and deeper samples were not collected at the streams. Stream discharge was also measured at the time of sampling.

Samples collected for analysis of nutrients in 2004 were shipped to both the DEQ laboratory and to the Forest Service CCAL laboratory in Corvallis, OR. Samples collected in 2006 were shipped to CCAL for analysis of nutrients. CCAL methods are described on their websites (www.fsl.orst.edu/ccal/). Samples for analysis of major ions were shipped to the Forest Service laboratory in Fort Collins, CO (Forest and Range Experiment Station). Samples were placed in Nalgene HPDE bottles rinsed with the sample water and placed in a cooler. Samples were then frozen prior to shipment to the respective laboratories.

Throughout the study period, staff from the Deschutes National Forest (DNF) collected phytoplankton samples and measured Secchi disk transparency. These samples were collected on a weekly basis in 2004. The samples were collected from the open water and at various embayments around the lake. The phytoplankton samples were preserved in Lugol's solution and shipped to Aquatic Analysts for analysis of community composition and cell counts for *Anabaena* taxa. Selected samples were shipped to the laboratory at Ball State University for analysis of cyanobacterial toxins.

MaxDepth installed a weather station on the east end of Odell Lake at the Odell Lake Resort dock (Figure 8). The station was raised 1 m above the rail for the dock. The instruments were approximately 2.5 m above the lake surface. The station was set to record data at 15 min-intervals. Instrumentation included wind speed, wind direction, solar radiation, air temperature, and relative humidity.

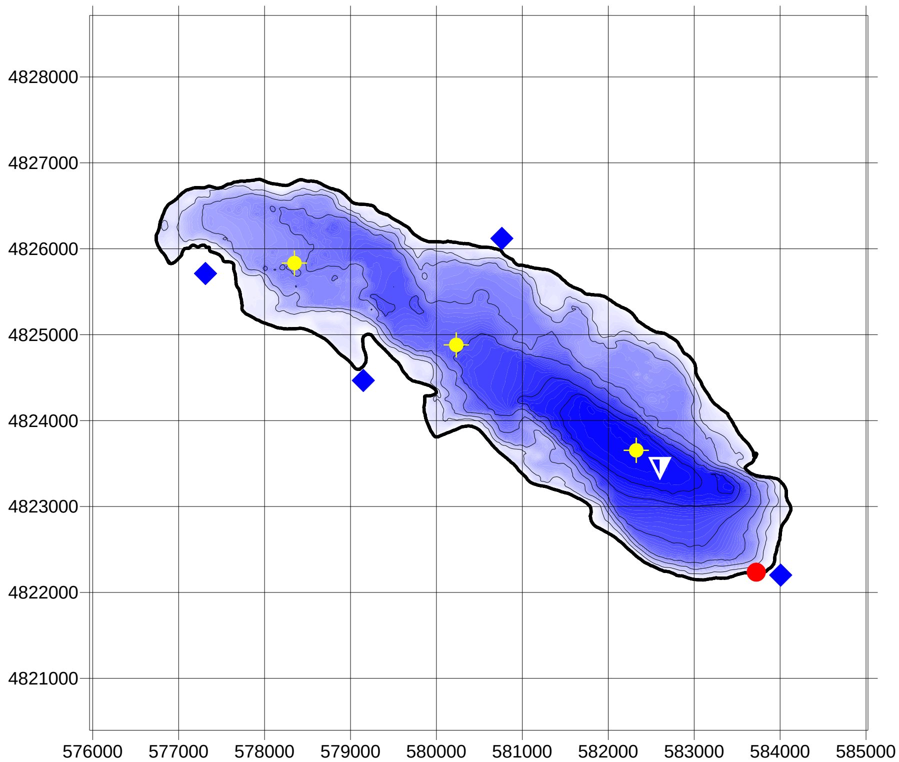

Figure 8. Locations of the lake monitoring stations sampled by DEQ in 2004 (yellow). The stream sites sampled are shown in blue. The sediment coring site is shown as the white triangle and the weather monitoring station is shown in red. UTM coordinates are shown on the axes. The NOAA weather station, Odell Lake East (#356252) also is located near the east end of the lake at an elevation of 4800 ft.

The paleolimnological portion of the study was conducted by collecting multiple sediment cores from the east end of the lake on July 19, 2004. The east end of the lake was chosen for sediment coring because it was on the down-wind side of the lake and would presumably receive higher rates of sediment accumulation than the west end of the lake. A greater accumulation of sediment makes it possible to provide greater resolution on the sediment dating. In addition, this is also relatively close to the site used by

Meyerhoff (1977) to collect his primary sediment core for Odell Lake. The sediment cores were collected with a UWITEC pneumatic corer with an inside core diameter of 84 mm. The cores were inspected immediately upon retrieval and only the sixth core collected at a depth of 83 m (272 ft) was judged to be sufficiently undisturbed to qualify as a suitable sediment sample (Figures 9 and 10). The core was moved to the lakeshore where it was sectioned into 1-cm intervals. The sediment samples were placed into WhirlPac® bags and stored in a cooler for transport to the laboratory.

The lake sediments were analyzed sequentially to make optimum use of additional information for selecting intervals for subsequent analyses. The order of analysis consisted of moisture content, ^{210}Pb dating, sediment chemistry, diatoms, cyanobacterial akinetes, and chironomids. The laboratories involved and the general description of the analyses is summarized in Table 5. Detailed methodology for the sediment analyses is presented in the project QAPP (Quality Assurance Project Plan, on file with EPA).

Figure 9. View of sediment core from Odell Lake.

Figure 10. View of sediment core looking onto the surface of the sediment after draining the overlying water.

Table 5. Summary of sediment analyses for the Odell Lake paleolimnological analyses.

Analysis	Laboratory	Number of Intervals	Description
Moisture	OSU Soils Lab	50	Wet and dry weights
^{210}Pb Dating	MyCore Scientific	20	Alpha counts, CRS modeling
Chemistry	OSU Soils	20	C, N, P, Ti
Diatoms	Univ. Utah	21	Microscopy
Akinetes	PhycoTech	20	Cyanobacteria to species group
Chironomids	3rd Rock Consultants	13	Microscopy

The hydroacoustic analysis of Odell Lake was originally planned to collect information on fisheries and to develop an updated bathymetric map of the lake. However, a new bathymetric map was developed independently by Constellation Services in 2003 and released in 2004; this map was judged to be adequate for the purposes of this project. A hydroacoustic analysis of the fisheries was conducted on July 22 and 23, 2004 on Odell Lake. A survey course was developed in concert with ODFW staff to provide adequate coverage of the potential fish habitats, while minimizing spatial autocorrelation associated with survey courses that were too close to one another (Figure 11). Survey transects were conducted during the day and night to provide information on behavioral patterns in fish distribution.

The hydroacoustic data on the fisheries were collected using a BioSonics DT-X digital echosounder equipped with a 200 KHz split-beam transducer. Vessel speed was maintained at about 9.5 kph with a sampling density of 4 pings per second and a threshold of – 65 db with a pulse length of 0.4 ms. Data were stored onboard in a Panasonic Toughbook computer. Positional data were obtained from a Trimble Ag132 WAAS DGPS with a nominal accuracy of about 1 m. Fisheries data were processed with BioSonics Visual Analyzer software. The hydroacoustics data collects information on target strength of fish in the water column. Fish length data were derived application of Loves (1971) equation. Weights of fish were developed from length-weight data previously collected by ODFW on fish in Odell Lake (Table 6). ODFW staff collected supplemental information on the fisheries in Odell Lake during 2004. These data included near-shore trap nets and creel surveys. These data are being reported separately by ODFW. The procedures used to collect all data gathered by MaxDepth and DEQ are described in the QAAP on file with the funding organization.

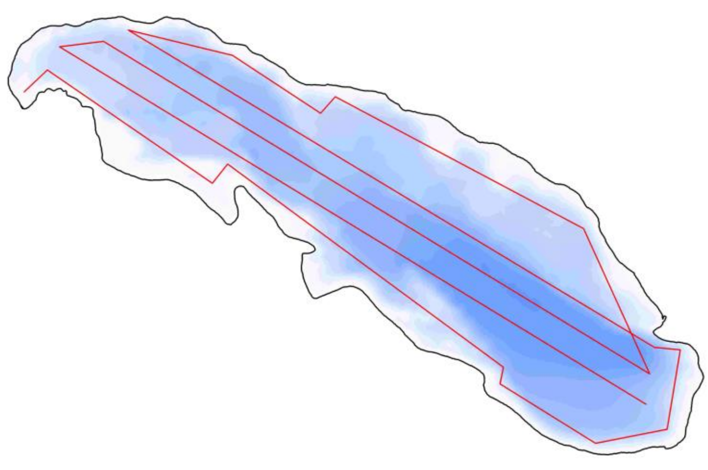

Figure 11. Survey tracks used to conduct the hydroacoustic analysis of the fisheries in Odell Lake, July 22-23, 2004.

Table 6. Equations used to compute fish length from target strength by target strength class.

Target Strength →	-55 -> -40	-39 -> -36	-35 -> -33	-32 -> -25
Starting dB	-55	-39	-35	-32
Ending dB	-39.05	-35.05	-32.05	-24.5
Starting Length (cm) (love 71)	2.99	20.55	33.28	47.78
Ending Length (cm) (love 71)	20.42	33.08	47.49	117.00
Starting Weight (g)	0.218	65.7	358	822
Ending Weight (g)	69.8	380	742	12383
Fish Model	Chinook Salmon	Group I Kokanee	Group II Kokanee	Lake Trout
Equation	w(g) = 0.00819 (l(cm))^3	w(g) = 302.75 + 2.513 ((l(cm)*10)-299.8)	w(g) = 350.85 + 2.7045((l(cm)*10)-330.1)	w(g) = 0.007537 * (l(cm))^3
Source	www.fisheries.org	Fisheries Research report #3 - 1966	Fisheries Research report #3 - 1966	www.fisheries.org

Love (1971) - original form: TS = (19.1 * log(*l*)) - (0.9 * log(*f*)) – 62, where TS is fish target strength (dB), *l* is fish length (cm), *f* is transducer frequency in kHz (201 in our case)

Love (1971) - solved for fish length: *l* = 10^ ((TS + 62 + 0.9 * log(*f*))/19.1)

A hydrodynamic model was used to assist with characterizing water movement and thermal properties in Odell Lake. The CE-QUAL-W2 model was chosen to represent the hydrodynamic properties of Odell Lake. This model is a laterally averaged grid-based model (Cole and Wells 2001). It was set up using a uniform grid with cells 2 m in depth and 200 m in width using the bathymetric data collected by Constellation Services (Figure 2). The spatial segmentation used to represent the reaction cells in the lake is shown in Figure 12. Key coefficients used in the model application are shown in Table 7.

Table 7. Key coefficients used to calibrate the CE-QUAL-W2 model for Odell Lake.

Coefficient	Unit	Value
Water Extinction Coefficient	m^{-1}	0.45
Wind Sheltering Coefficient		0.1 – 0.8 (spatially variable)
Light Extinction Coefficient	m^{-1}	0.15 -0.83 (temporally variable; calculated from Secchi disk data)
Solar Radiation Factor		1.25 (25% increase to account for diffuse solar radiation)
Others		Set to default

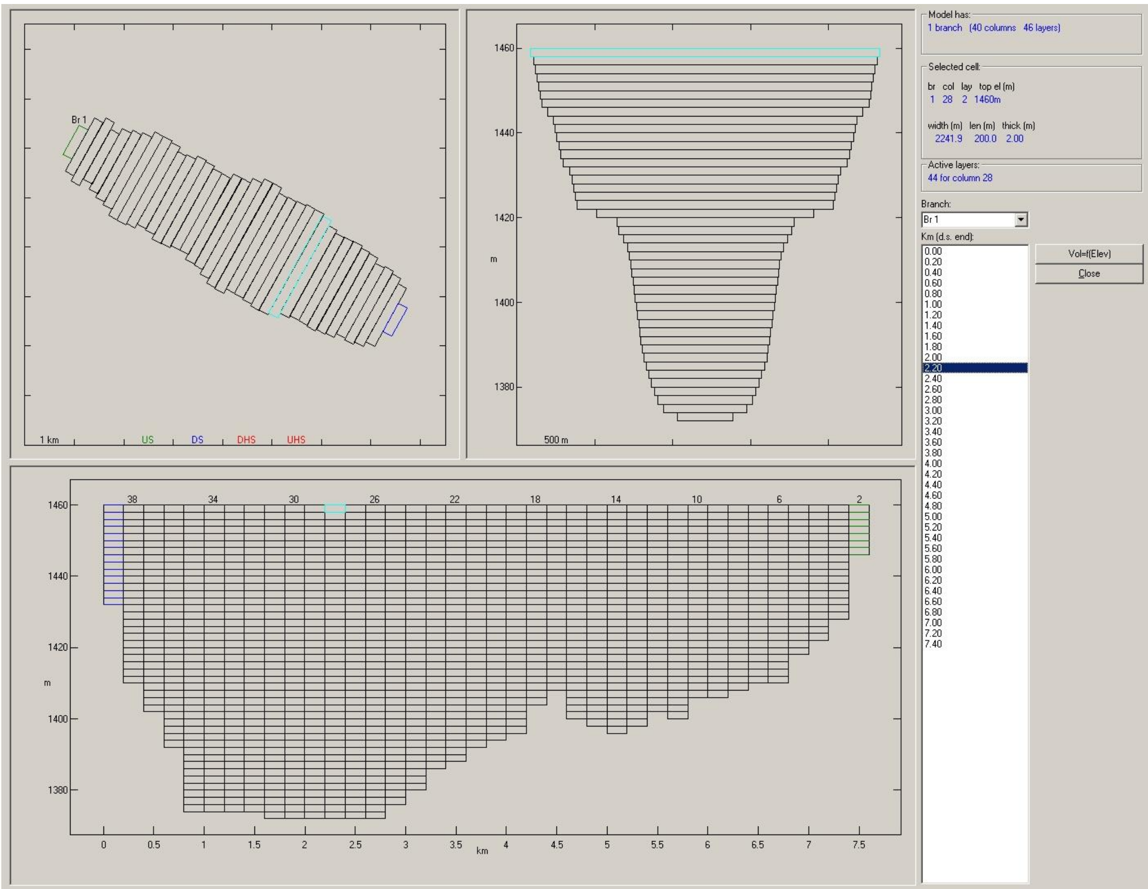

Figure 12. Segmentation used for the CE-QUAL-W2 application to Odell Lake, showing surficial segmentation (upper left), a cross-section (upper right) through the segment shaded in the upper left , and an sagittal section through the lake (bottom). The three displays of the segmentation are linked to one another through the shaded cells, where the green cells represents the boundary of the west end of the lake, the blue cells represent the east end of the lake, and the aqua cells displays the selected surface cell over the deepest portion of the lake.

The model was calibrated by first achieving a water balance that reproduced the water elevation in Odell Lake. Precipitation for the lake was derived from the NOAA Odell East climate station. Precipitation was increased in the higher elevations of the watershed to simulate increased precipitation associated with orographic effects. Wind, temperature, and solar radiation data for the calibration period were obtained from the weather station installed on the east end of the lake for the study period. The model parameters shown in Table 7 were adjusted until satisfactory agreement with lake temperature, derived from the three sets of thermister arrays in the lake, was met.

RESULTS

1. Hydrology/Meteorology

a. Long-term climate data

Annual precipitation during Water Year (WY) 2004 shown in Figure 13 was nearly identical to the 23 year average measured at the closest NOAA weather station (Figure 8). The preceding water year was drier than normal. The daily maximum temperatures measured in 2004 were considerably warmer than the 23-yr average daily maximum temperatures, particularly from March through July (Figure 14).

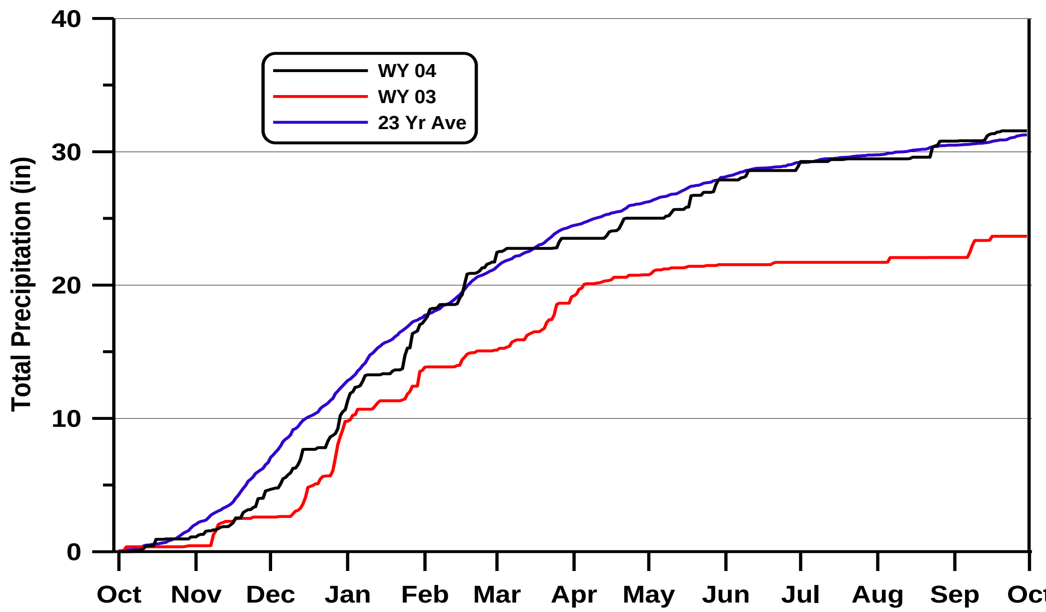

Figure 13. Cumulative precipitation for WY03 and WY04 compared to the 23-yr average for the site (Odell East [356252]).

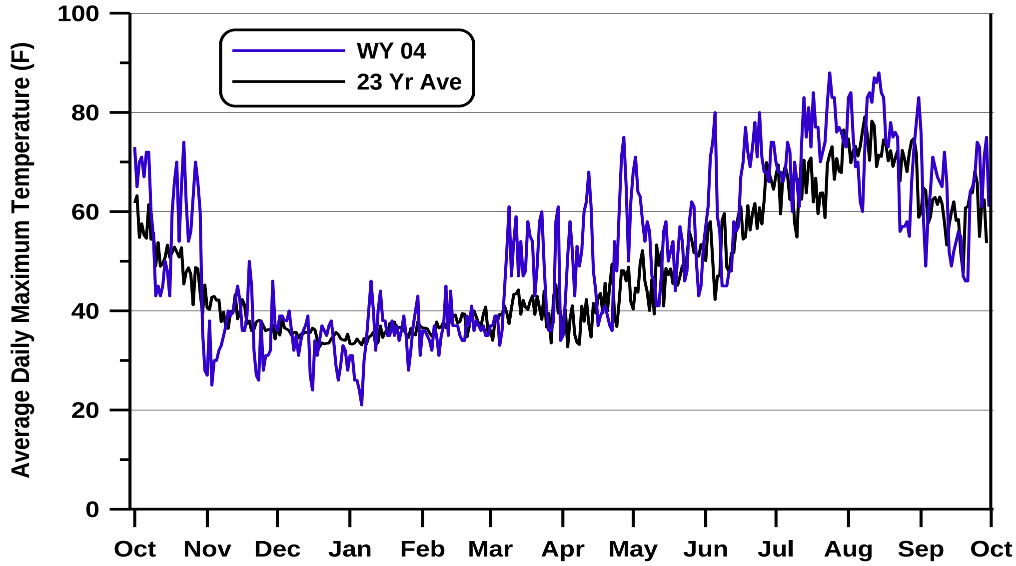

Figure 14. Air temperature at the Odell East station in WY04 compared to the 23-yr average for the site.

d. Surface Discharge

Stream discharge was measured at Trapper Creek, the largest tributary to Odell Lake and on the outlet stream, Odell Creek. Although the DNF was not successful in collecting continuous discharge data at Trapper Creek in 2004, DEQ staff measured instantaneous discharge at their stream sampling sites during each visit. Model estimates of stream discharge were based on these limited discharge data.

c. Evaporation

Odell Lake was the site of a weather station for standard climatological data as well as an evaporation pan collection site from 1948 to 1966. The seasonal average evaporation measured in the Class A land pan was 46.13 cm, which when corrected for land versus lake evaporation (using a coefficient of 0.70; cf Linsley et al. 1975) would yield a seasonal (May-October) average of 32.3 cm.

d. Groundwater

Groundwater discharge to Odell Lake has not been quantified; however, fisheries biologists have documented (Averett and Espinoza 1968; Lewis 1972) that groundwater discharge occurs at a minimum of eight sites along the shoreline. Groundwater inflow areas serve as major sites for spawning of kokanee in Odell Lake, with the area near Shelter Cove serving as the most important site (Lewis 1972). Regional groundwater flow paths for the Odell Lake watershed illustrate that flow paths would be expected to flow towards the lake, but the level of detail of their analysis does not permit us to quantify these flows based on these data (Gannett and Lite 2004).

e. Hydraulic residence time

Johnson et al. (1985) estimated that the hydraulic residence time for Odell Lake was eight years. This value appears to have been based on an estimated watershed-wide annual precipitation for the topographic watershed area (92 km^2) divided by the lake volume (584.3 hm^3). Watershed divides are notoriously poor indicators of the direction of local flow paths in the central Cascade Range and it is not possible to verify the estimate of hydraulic retention time with the available data.

f. Short-term climate data

A DEQ weather station was installed at the east end of Odell Lake on the dock at Odell Lake Resort and operated from July 7 to September 27. The wind usually comes from the WNW at about 290º to 325º through Willamette Pass (Figure 15). The major axis of the lake lies at about 300º which means that there is a considerable fetch available to generate waves of a meter or more almost on a daily basis. Other short-term weather data that was collected in 2004 include wind speed (Figure 16), air temperature (Figure 17), and solar radiation (Figure 18).

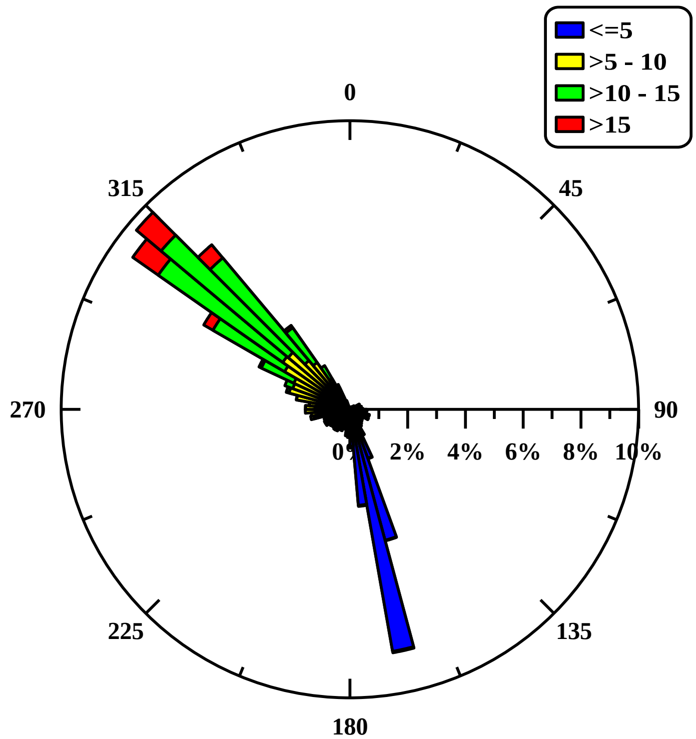

Figure 15. Wind rose chart for the weather station installed near the Odell Creek outlet on Odell Lake, summer 2004. Units for wind velocity are in miles per hour averaged over a 15-min integration period.

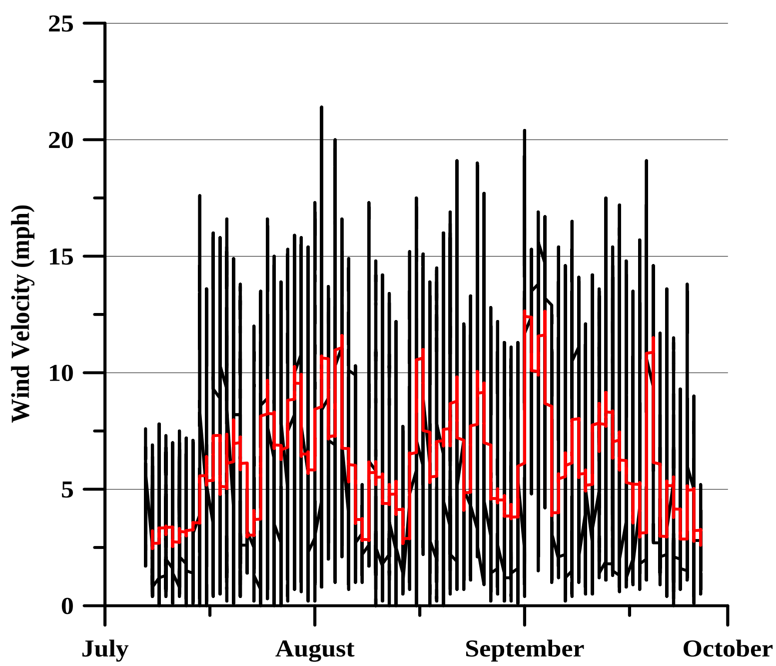

Figure 16. Wind velocity at Odell Lake, summer 2004. Theses data represent the average over 15-min periods. The red line is the moving average.

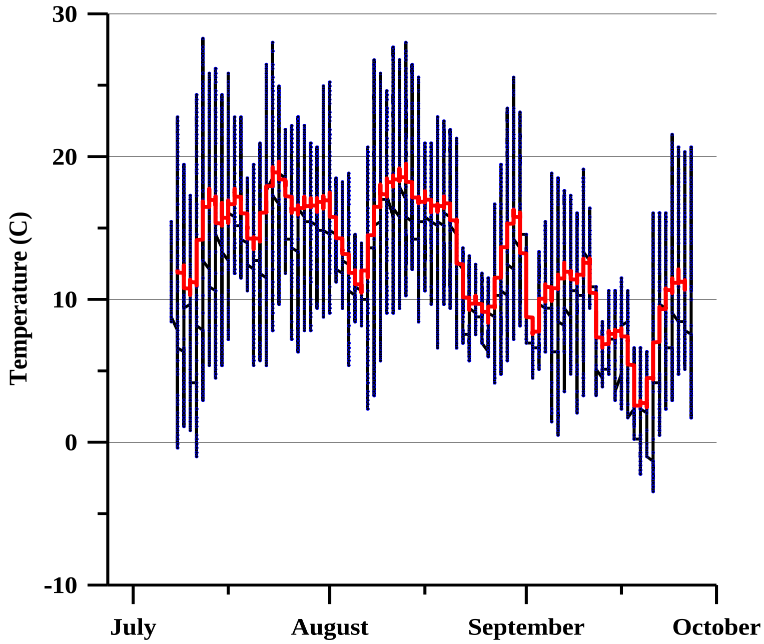

Figure 17. Air temperature at Odell Lake, summer 2004. The red line is the moving average temperature.

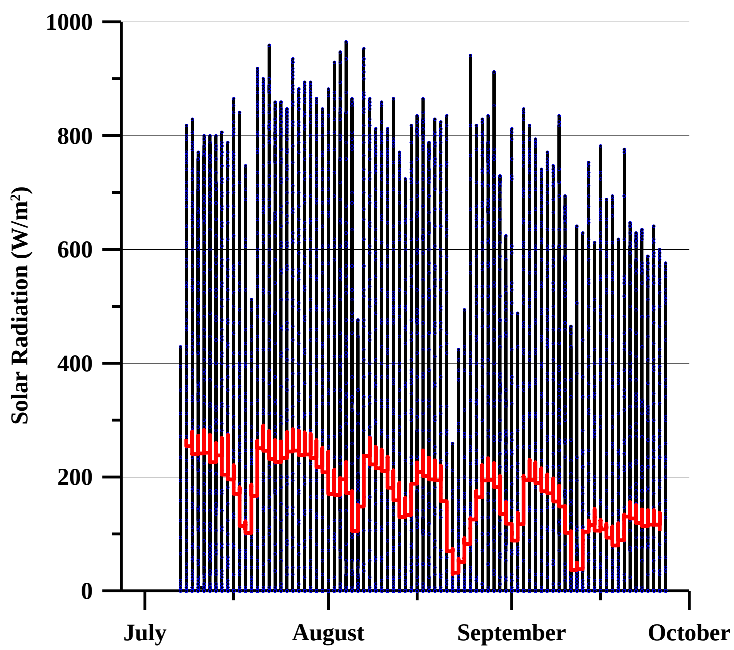

Figure 18. Solar radiation measured at Odell Lake, summer 2004. The moving average is shown as a red line.

2. Water Quality

a. Temperature

Lake temperature varied considerably depending on the depth and position within the lake (Figures 19-22). The lowest variability was observed at the mid-lake station and the greatest variation was observed at the west station. The diurnal variation was less than 1 °C at both deep sites (80 m at the east site and 67 m at the center station). Variability at the surface was next lowest and generally ranged about 2 ºC per day at all three sites. Variation was greatest between 10 m to 25 m where the seiche effect caused fluctuations of 8 °C per day [an internal seiche is defined as the successive oscillation of the metalimnion (Wetzel 2001)]. The greatest temperature fluctuations occurred on the west end of the lake at all depths. This was likely caused by the effects of the NW winds that drove water to the east end of the lake. The release of the accumulated "excess" water on the east end during the calmer periods resulted in a surge of water to the west end of the lake, resulting in a "rocking" motion in the metalimnion. The west end exhibited greater variation in temperature because this end was shallower and the seiche was subject to greater mixing as the seiche reflected off the lake bottom. The seiche is significant

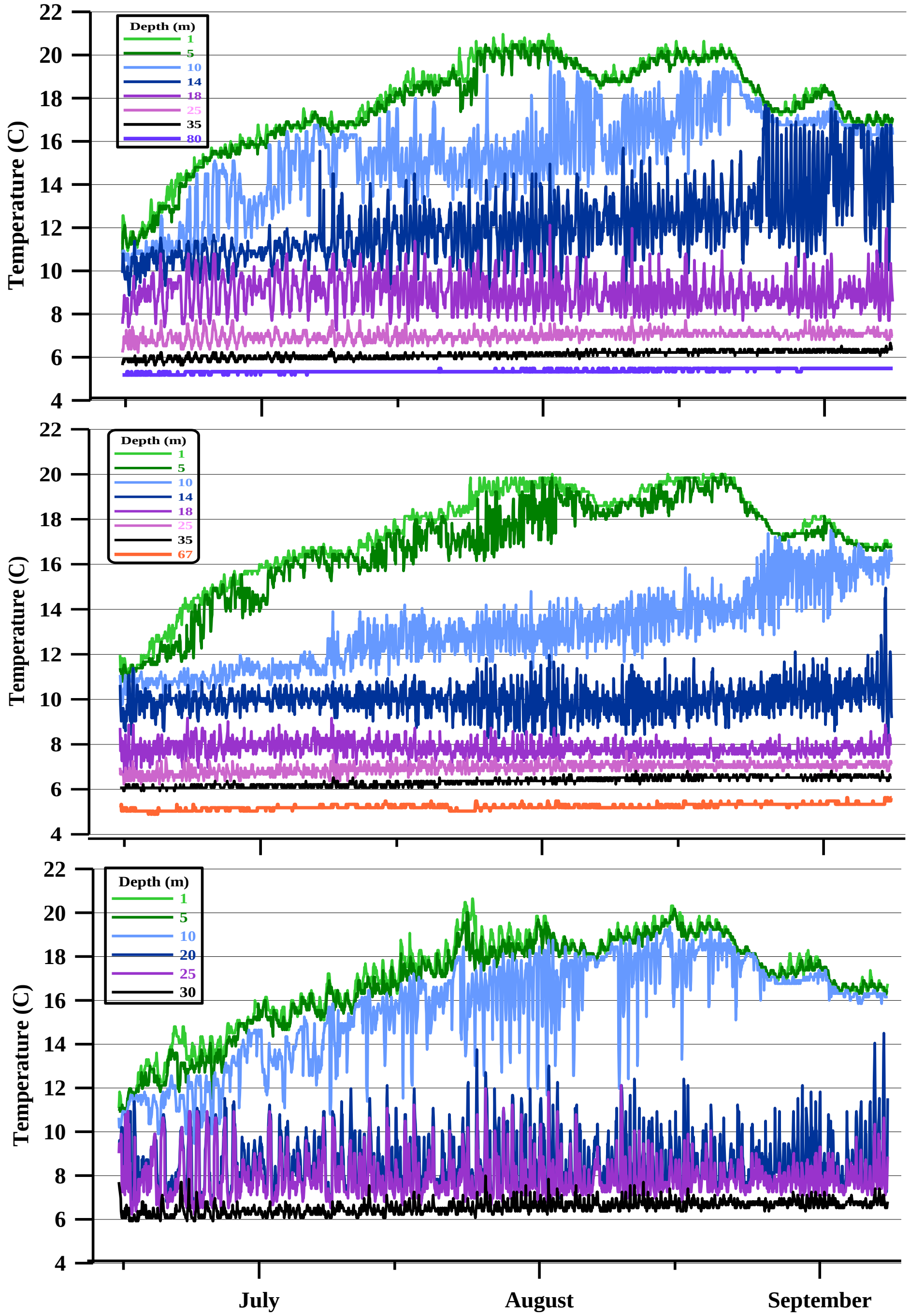

Figure 19. Temperature data from the thermister strings on the east end (top), middle (center), and west end (bottom) of Odell Lake, 2004. Thermisters were present at additional depths not shown above for sake of clarity.

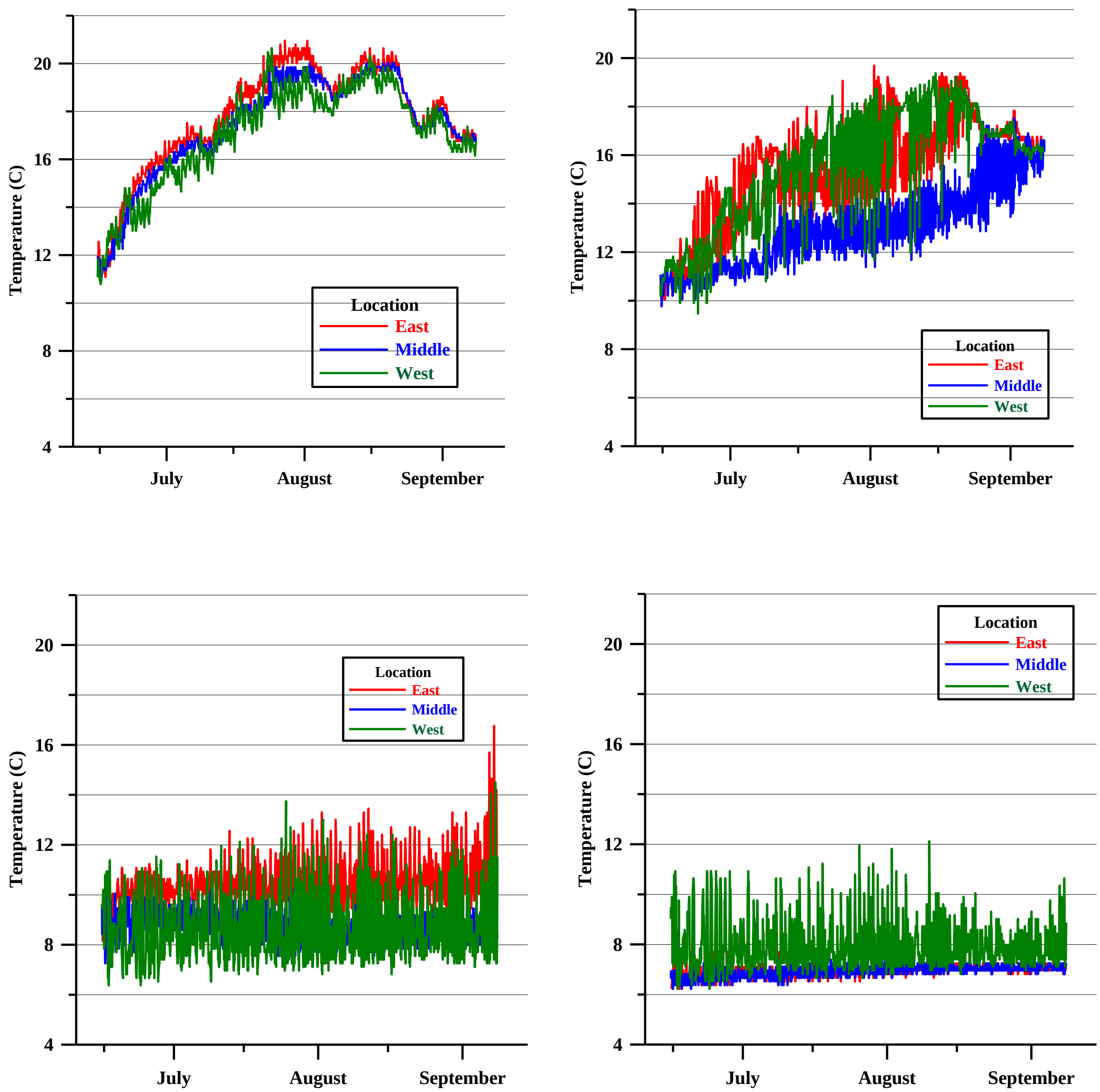

Figure 20. Temperature measurements for the three DEQ locations in Odell Lake during summer 2004. The depths of the thermisters are 1 m (upper left), 10 m (upper right), 16 m for the east and middle stations and 20 m for the west station (lower left), and 25 m (lower right).

because the mixing promotes circulation and increased re-supply of nutrients into the photic zone. The seiche may also play a role in the behavior of fish populations that are sensitive to changes in temperature and to the zooplankton that some of the fish species prey upon. Lakes without internal seiches are recognized by comparatively stable temperature values in and near the metalimnion.

The range in temperature variations at some depths are striking. For example, the temperature variation at a depth of 25 m measured on July 28, 2004 at the west site was 8 ºC compared to 2 ºC at the center site (Figure 21).

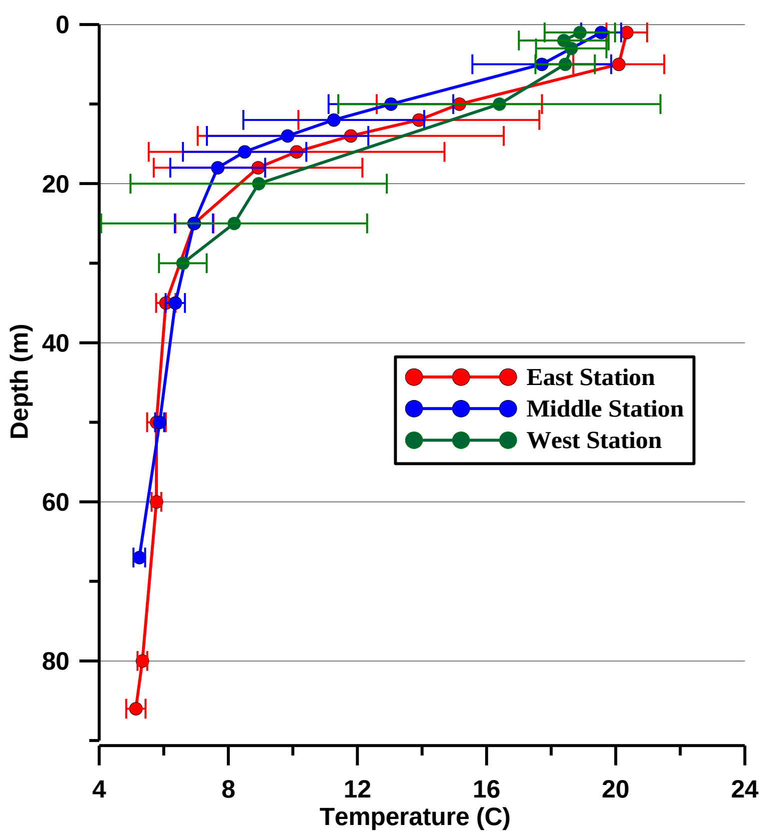

Figure 21. Temperature profiles in Odell Lake at the three DEQ sampling stations for July 28, 2004. The plot shows the average and range of temperatures measured hourly with the thermister arrays.

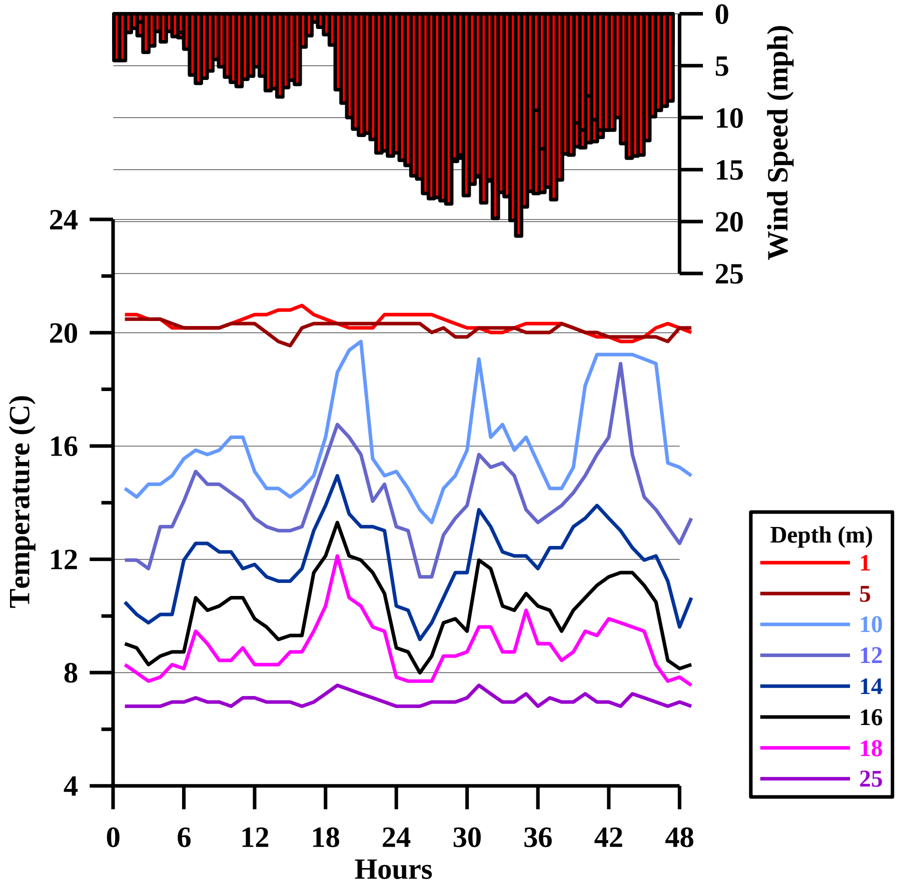

Figure 22. Fluctuations in water temperature at the east end of Odell Lake for July 28-29, 2004 measured with the thermister array. Wind velocity measurements at the east end of the lake are shown on top.

The temperature cross-sections in the CE-QUAL-W2 output (Figure 23) illustrate several important features regarding the dynamics of Odell Lake. First is that the wind drives the warmer surface waters to the east end of the lake and strips the warmer water from the west end of the lake. This creates an imbalance in the lake, resulting in the generation of an internal wave that has a periodicity of about 12 hrs. The greatest fluctuations in temperature occur at the west end of the lake where the returning seiche reflects off the shallower bottom waters. The movement of the internal wave results in two-fold changes in the thickness of the thermocline depending on the position within the lake and the time of day. Analysis of the current vectors shows that the internal wave causes movement of water throughout the lake, even at great depth. The rapid movement of water at both ends of the lake indicates that there is considerable mixing of waters at the interface of the metalimnion in both directions.

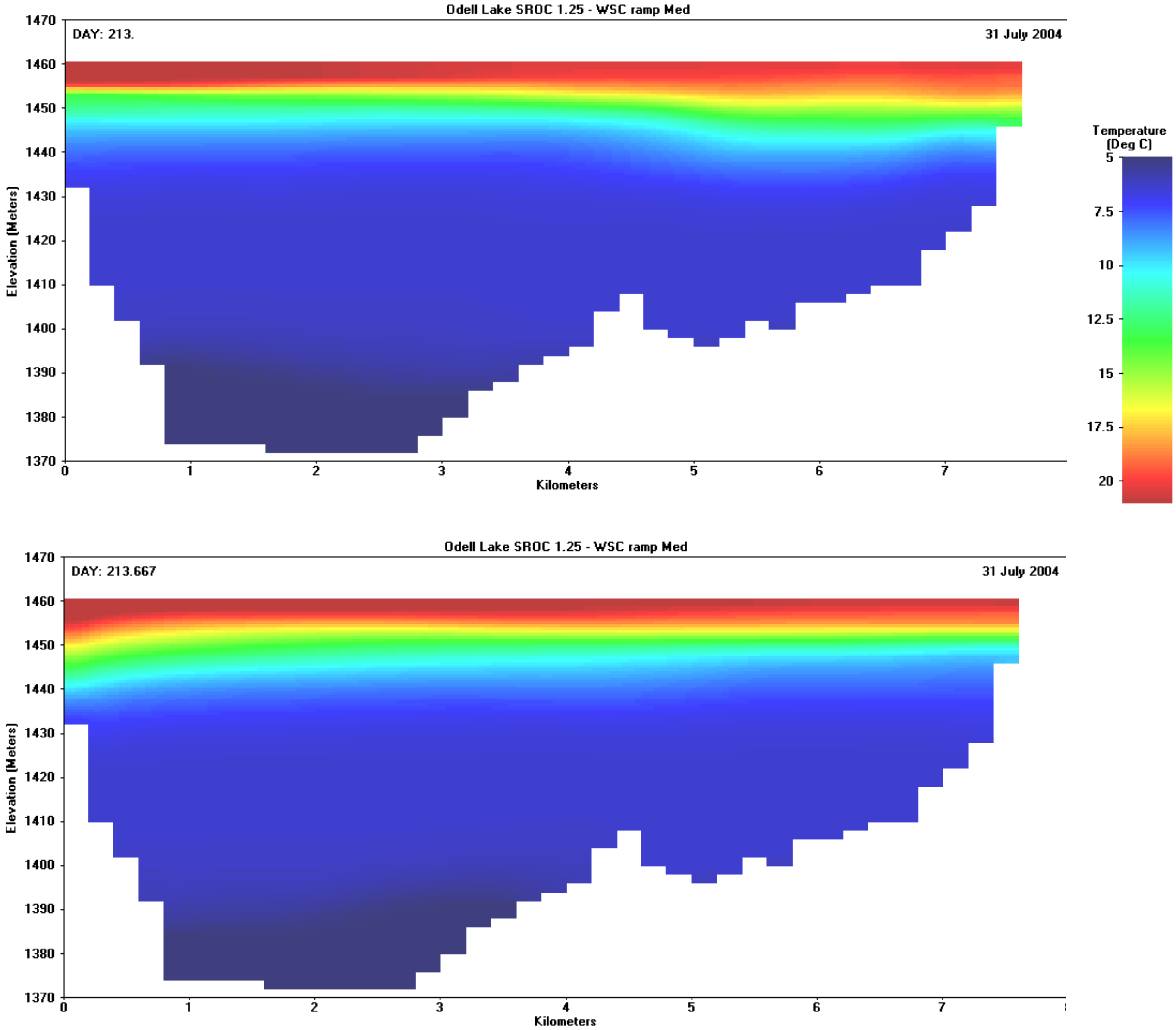

Figure 23. CE-QUAL-W2 model output for Odell Lake for July 16, 2004. The top image represents the temperature (°C) at midnight. The bottom image represents the simulated temperature at 1600 hr. The east end of the lake is shown on the left. The Y axis shows the lake elevation in meters. The horizontal scale is in kilometers.

b. *In Situ* Water Quality

Specific conductance in Odell Lake remained between 33 and 38 µS/cm at all sites and depths except for values reported above 40 µS/cm in the surface waters during July (Figure 24). The surface specific conductance increased over 25 percent between June and July at the east site and increased over 20 percent at the other two sites. No significant change was observed at depth. The large increase in specific conductance would require either a substantial input (tons) of major ions or a remarkable response from evaporation. The fact that specific conductance returned to the previous levels in August rules out evaporation as a possible cause. The data from these events met all quality assurance reviews, yet we are unable to explain the July surface values for specific conductance.

Concentrations of dissolved oxygen (DO) were at or near saturation in the surface samples of Odell Lake (Figures 25 and 26). Mid-depth samples displayed slightly lower DO concentrations compared to the surface samples, although these too were near saturation levels. The DO values in the bottom waters continued to decline throughout the study period at the middle and west stations, but the DO at the east station remained stable in the bottom waters.

The pH values measured in the surface waters exceeded water quality criteria (pH 8.5) from July through early September (Figure 27). The maximum surface pH measured during the lake visits reached 10 in July, but had declined to 8.5-9.0 in early September. pH in the mid-depth and bottom samples were stable between 7 and 8. Overall, the west station exhibited slightly lower pH values than the other two sites.

Two of the four multi-parameter sondes deployed in Odell Lake were recovered (East @ 15 m and West @ 1m). The sondes from the two remaining surface stations were cut from their cables and were never recovered. Because of the vandalism, the two sondes still present were withdrawn from the lake prior to the planned removal date in September. The results from the west surface site show temperature fluctuations of about 3.5 ºC during the month-long deployment (Figure 28). Conductivity showed a substantial spike on July 24 and declined for two weeks, eventually stabilizing between 34 to 36 µS/cm. pH values remained above the water quality criterion of 8.5 during the entire deployment period . Dissolved oxygen concentrations also declined from a maximum value at the beginning of the deployment to a minimum in the first week of August. The sonde deployed at the east station at 15 m commonly exhibited short-term temperature fluctuations exceeding 6 ºC (Figure 29). In contrast, the conductivity values at this depth were highly stable. pH values generally fluctuated between 7.5-8.5, and dissolved oxygen concentrations declined from a high of 10 mg/L at the beginning of the deployment to a minimum of 7 mg/L in the first week of August.

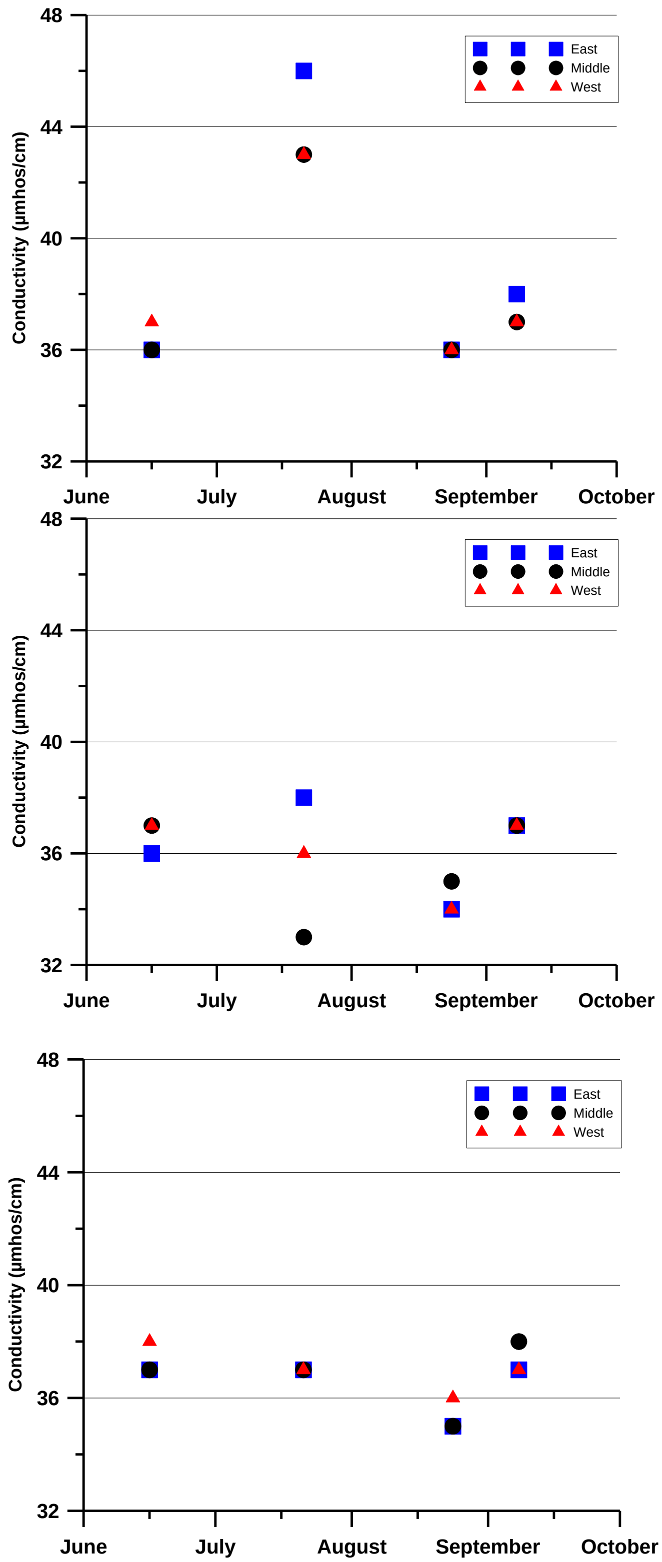

Figure 24. Conductivity measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

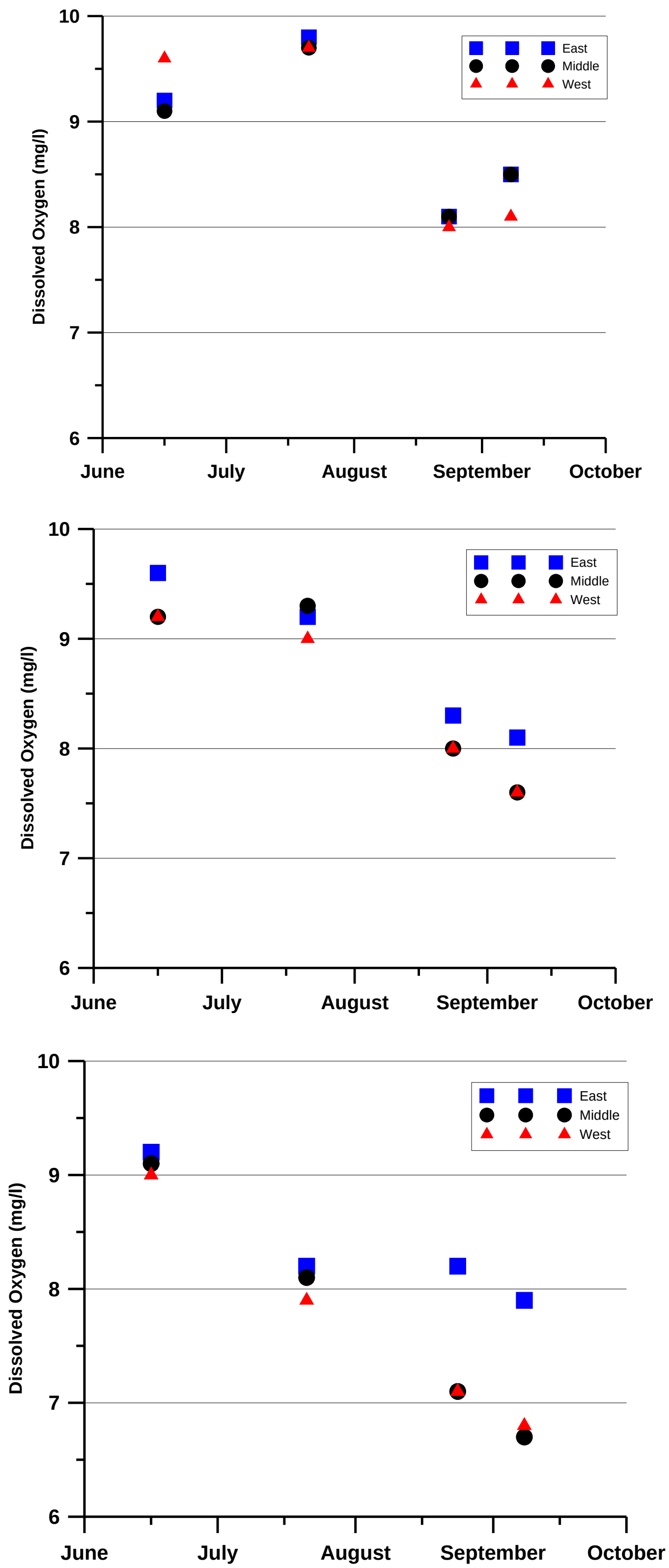

Figure 25. Dissolved oxygen measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

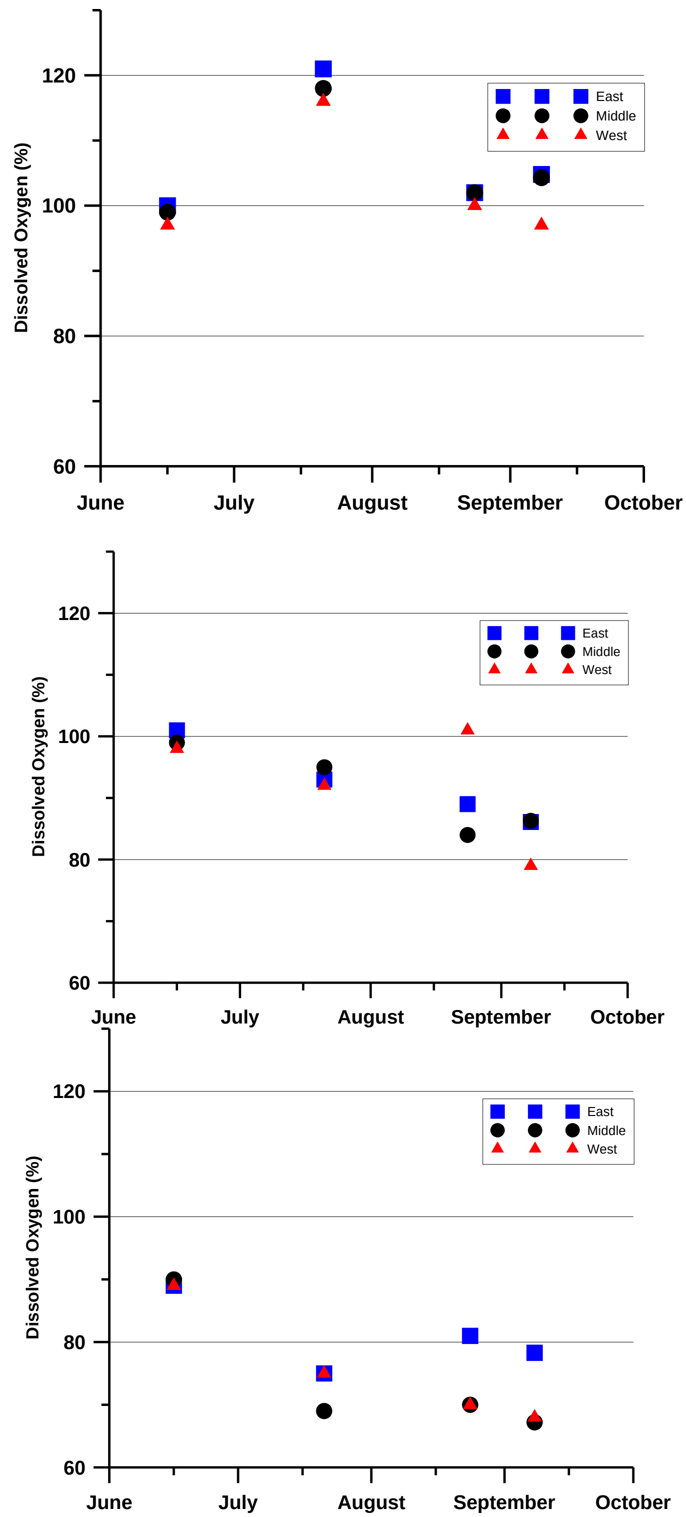

Figure 26. Dissolved oxygen (percent saturation) measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

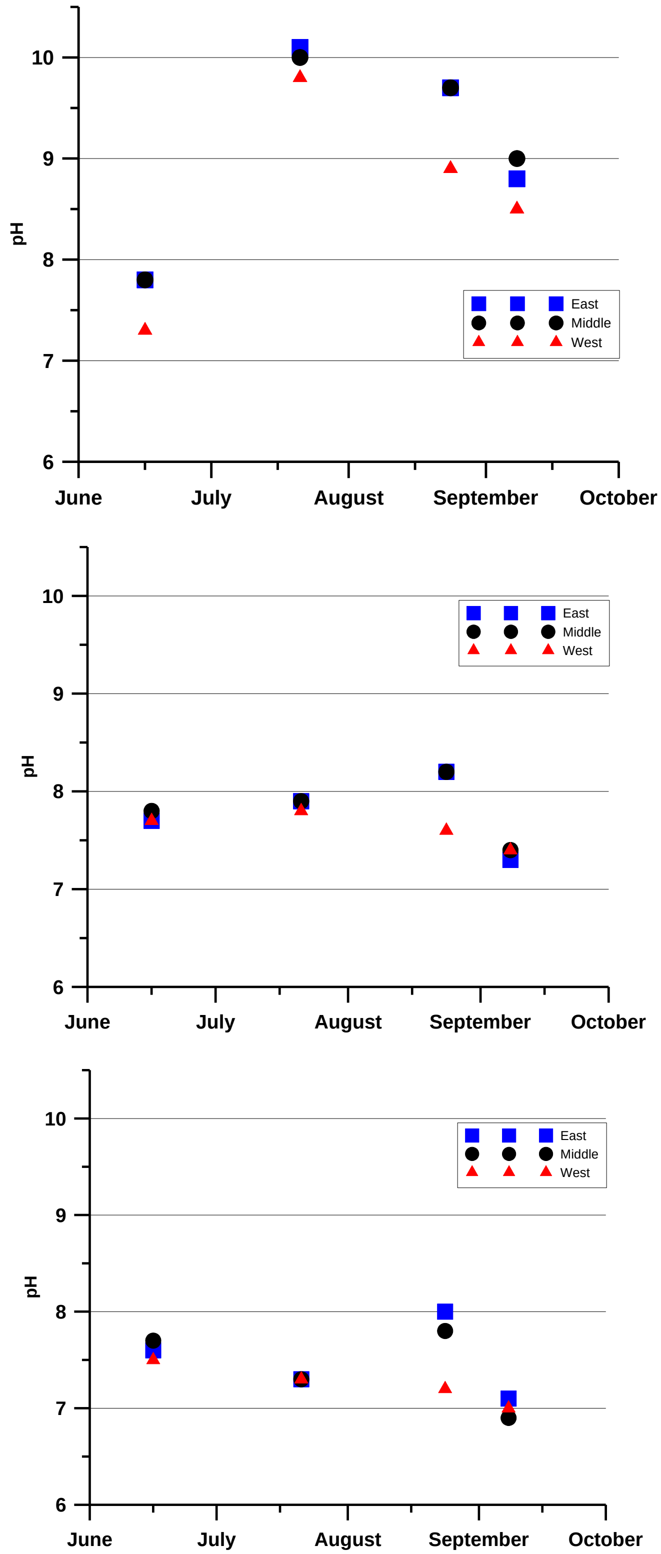

Figure 27. pH measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

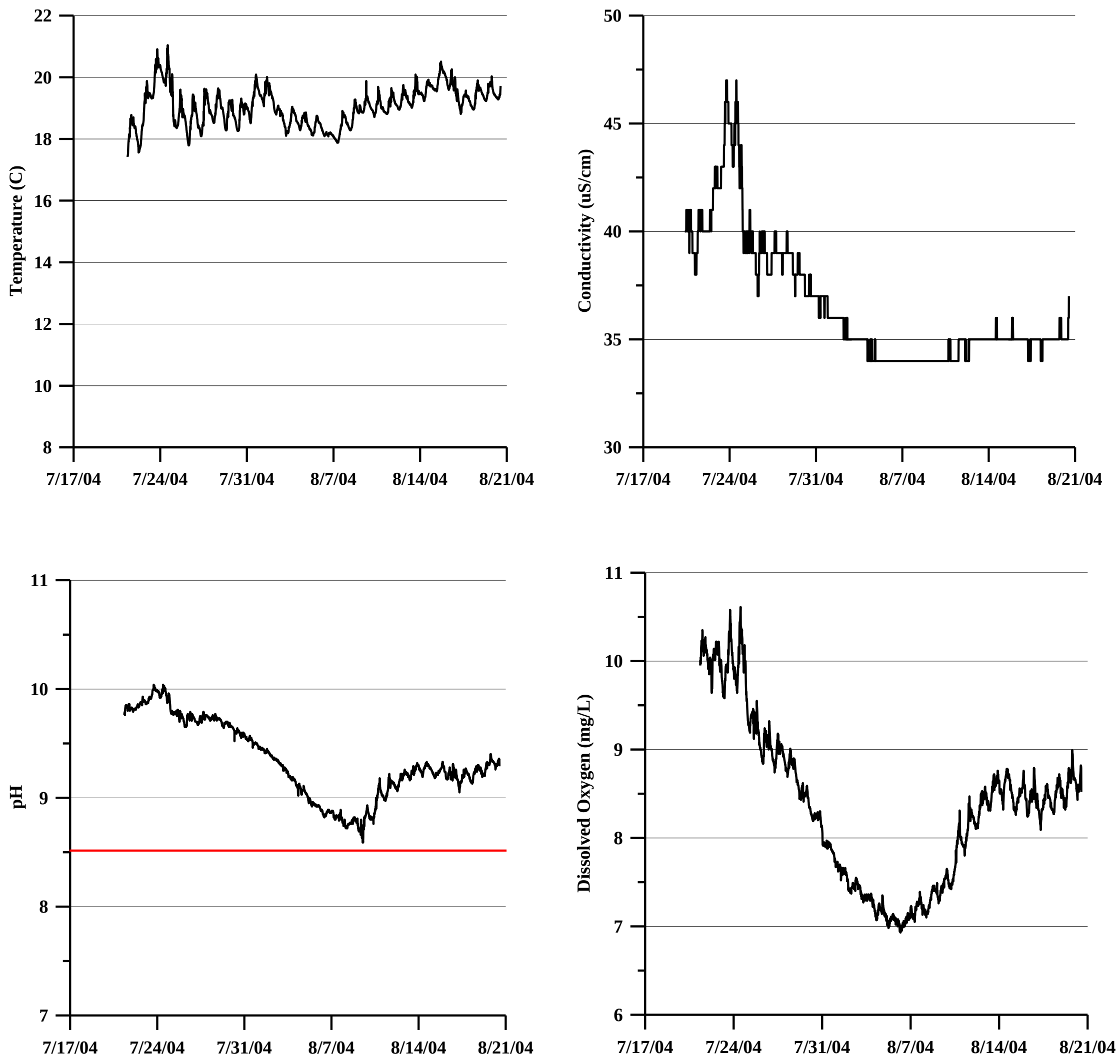

Figure 28. Temperature, conductivity, pH, and dissolved oxygen measured every 15 minutes at the west station, depth 1 m. The red line for pH represents the water quality criterion for Odell Lake.

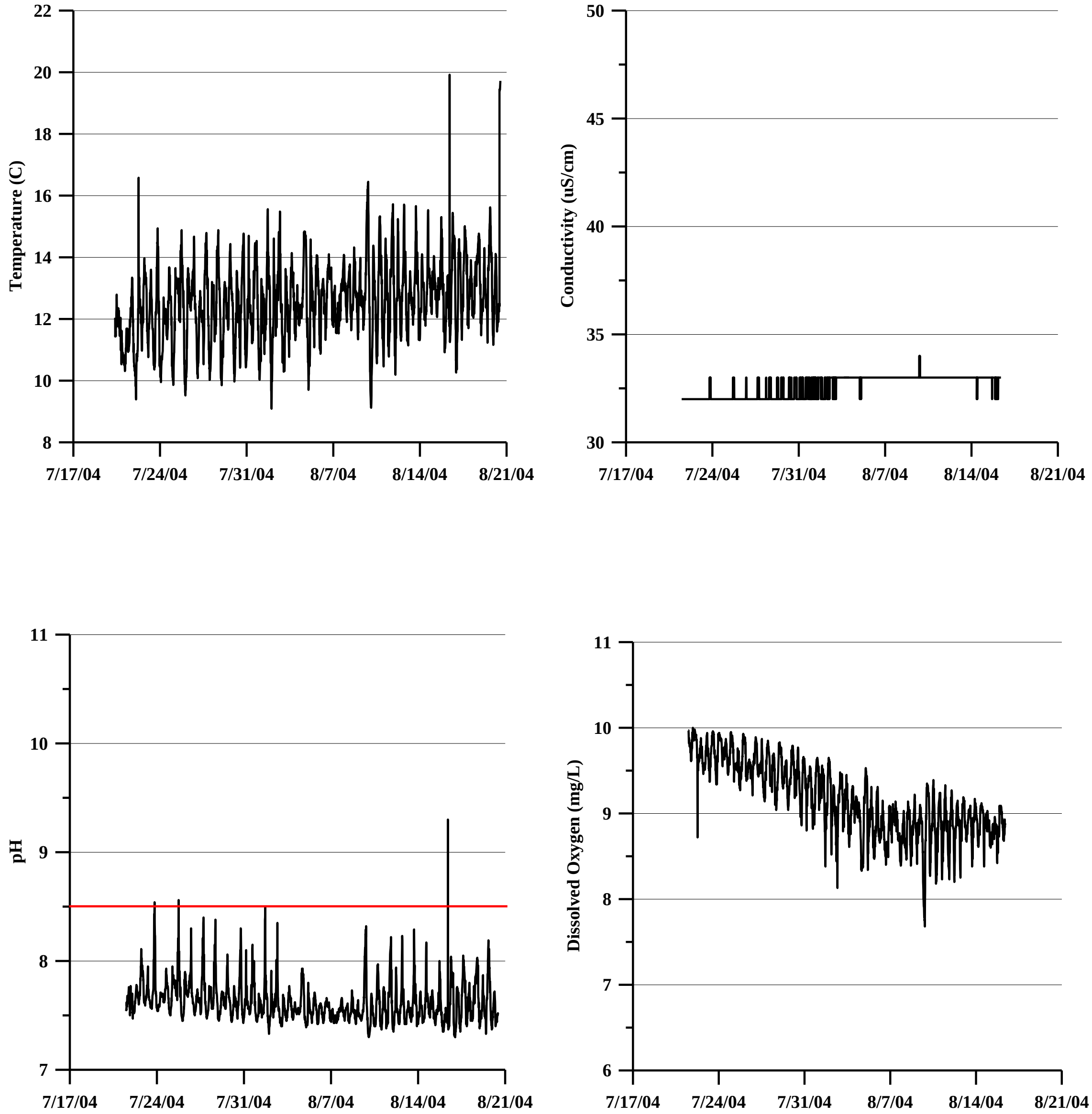

Figure 29. Temperature, conductivity, pH, and dissolved oxygen at the east station at a depth of 15 m. The red line for pH represents the water quality criterion for Odell Lake. The spikes in temperature and pH in August represent a brief removal of the sonde to check its operation.

Secchi disk transparency ranged from 1 m to 11.5 m in Odell Lake in 2004 (Figure 30). The low transparency in mid-July corresponds to the high densities of Anabaena measured in the lake. During the cyanobacteria bloom the range of measurements was less than 1.5 m, whereas during other periods the range was considerably greater. It is remarkable how quickly the *Anabaena* bloom developed and it is also striking how quickly it dissipated in August.

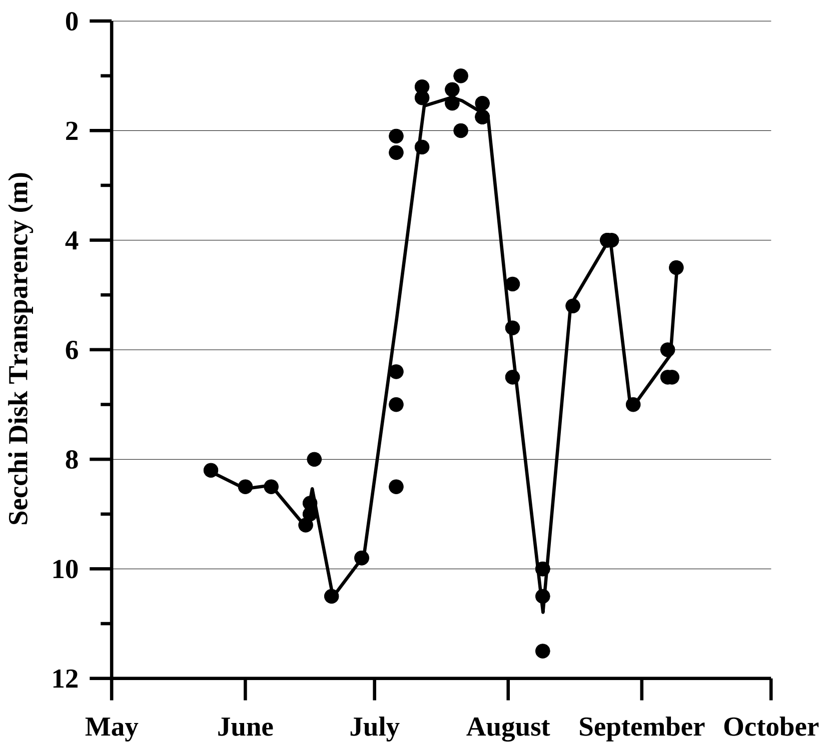

Figure 30. Secchi disk transparency measured in Odell Lake in 2004. These measurements represent measurements by both DEQ and DNF staff.

c. Analytical Chemistry

Chlorophyll *a* concentrations reached a peak of 50 µg/L in July at the east site (Figure 31). Maximum chlorophyll values between 25- 75 ug/L are often associated with eutrophic lakes (OECD 1982). Chlorophyll levels declined rapidly from east to west on the July date, whereas concentrations remained similar among sites during the other sample dates. Chlorophyll declined rapidly with depth, although two samples exceeded 10 µg/L at mid-depth.

Concentrations of total phosphorus (TP) ranged from 0.05 mg/L in some of the deep-water samples to values ranging between 0.01 and 0.03 mg/L in the mid-depth and surface waters (Figure 32). The OECD (1982) classified lakes with annual mean TP values of 0.010 to 0.035 mg/L as mesotrophic. The relatively low precision of these TP measurements makes it difficult to confidently assess vertical and spatial differences in TP among sites.

Ortho-phosphate (PO_4) concentrations were at about 0.015 mg/L in the surface and mid-depth samples in June (Figure 33). These concentrations declined to detection limits first in the surface waters in July and then in the mid-depth samples in August. In contrast, concentrations of PO_4 in the deeper waters increased from 0.02 mg/L in June to 0.028 mg/L in September. There were no systematic differences in PO_4 concentrations among the sites.

Concentrations of total Kjeldahl nitrogen (TKN) remained low (< 0.2 mg/L) in the mid-depth and deeper waters, but increased at the surface station in July (Figure 34). The increase in July was greatest at the east site, less so at the middle station, and no change was observed at the west station. Again, the lack of precision in the TKN measurements makes it difficult to confidently assess spatial and temporal patterns in TKN.

Concentrations of nitrate (NO_3) remained near detection limits in the surface waters (Figure 35). Two observations significantly above the detection limit were observed in the mid-depth samples, the greatest increase measured in the west station in September. The greatest increase in nitrate occurred in the deep samples where concentrations increased slightly from June to July and then dramatically from July to September. The increase in nitrate in the waters below a depth of 30 m represents an increase in mass of over 32 metric tons of nitrogen.

Ammonia (NH_3) concentrations appear to remain low and stable in the surface waters (Figure 36). In the mid-depth samples, the east and middle stations appear to increase from June to July, decrease in August and increase slightly in September. However, the NH_3 at the west site declines rapidly from June to July and then declines gradually from July to September. In the bottom water, NH_3 increases from June to July, declines from July and August, and shows a slight increase in September. The exception again is the west site, where NH_3 declines from August to September. The total N concentrations (TKN + NO_3 – NH_3) were low and fit within the range observed in oligotrophic lakes (OECD 1982).

Concentrations of dissolved silica show a peak in the surface waters in July, decrease slightly in the mid-depths, and continuously increase through the study period in the hypolimnion (Figure 37). The increase in silica in the surface waters in July are unusual in that silica concentrations usually decline during the growing season as silica is utilized by diatoms for construction of the frustules (external structure) enclosing the cytoplasm. The most apparent spatial difference in silica among the study sites are the lower concentrations of silica measured at the east site. Concentrations of dissolved silica are low, although much of the silica in Odell Lake may be present as total silica in the frustules of the diatoms. The silica dynamics in Odell Lake are difficult to decipher with these few samples; for example, the depletion of silica in the surface waters of Odell Lake could have taken place prior to collection of the first samples in June.

Calcium is one of four major base cations that occur in roughly the following proportions in Odell Lake (Ca = Na > Mg > K). The major cations follow similar patterns in concentrations and only the results for calcium are shown here. Calcium concentrations generally increase in Odell Lake at all depths and sites throughout the study period (Figure 38). The one exception is at the west site in which calcium concentrations decrease in the surface waters from June to July and shows some slight aberration in the mid-depths in September.

Biochemical oxygen demand (BOD_5) remained less than 1 mg/L in the mid-depths and bottom waters throughout the study (Figure 39). However, in the surface waters BOD showed a major increase in July. BOD_5 concentrations were much greater at the east station and decreased westward in the lake. The west-to-east increase in BOD_5 resulted in concentrations up to 7.0 mg/L being exported downstream in Odell Creek.

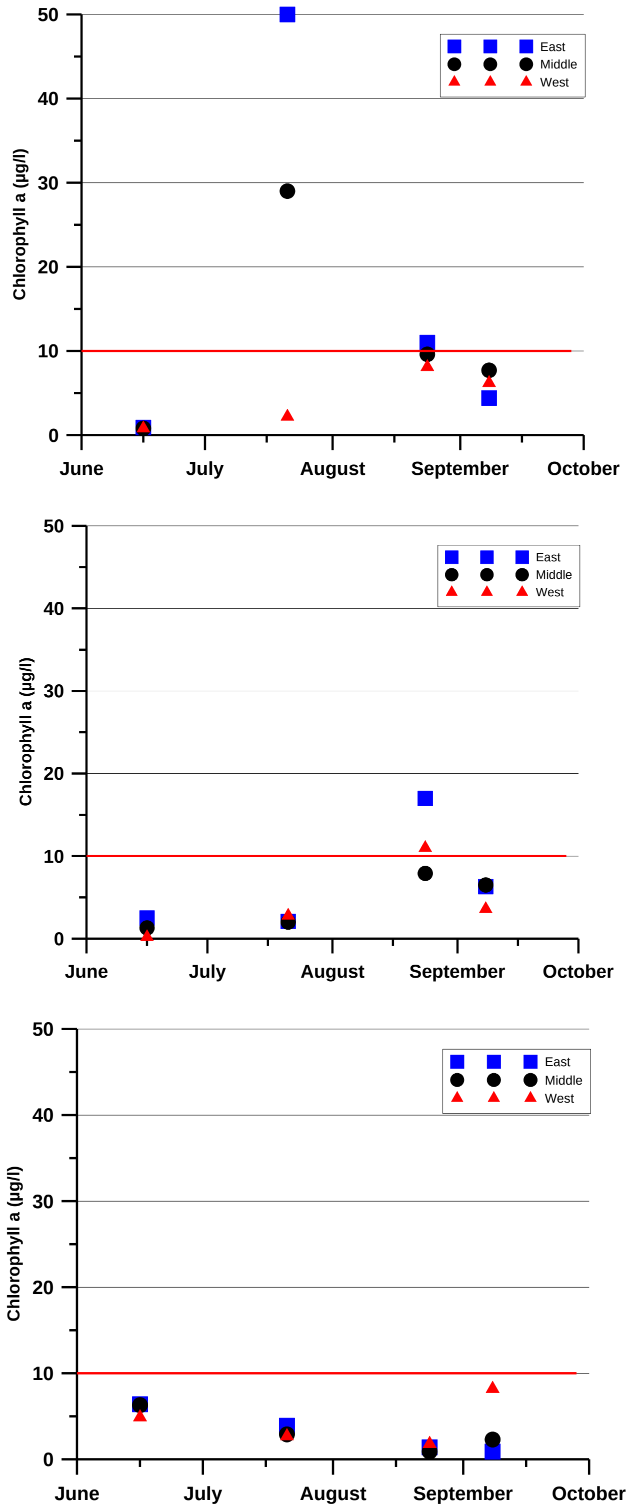

Figure 31. Chlorophyll *a* measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

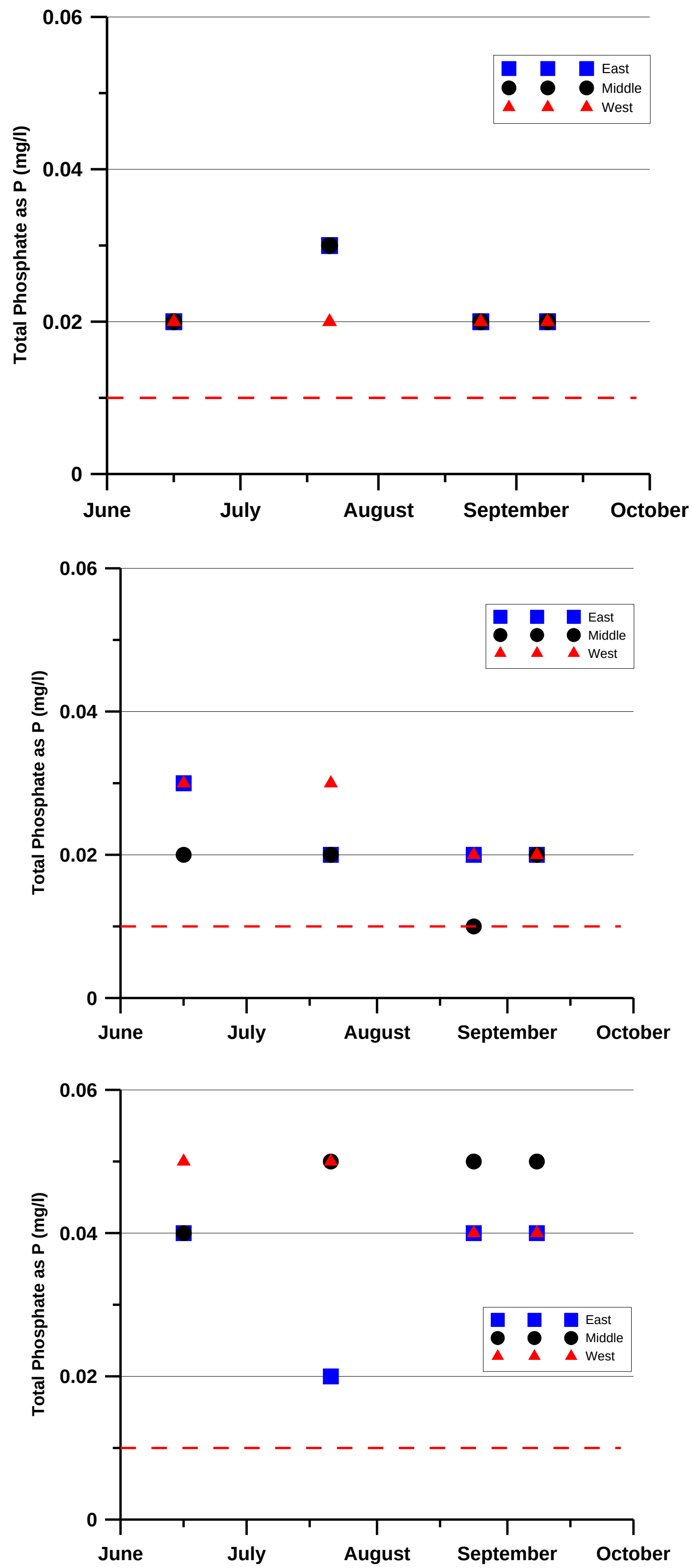

Figure 32. Total phosphorus measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

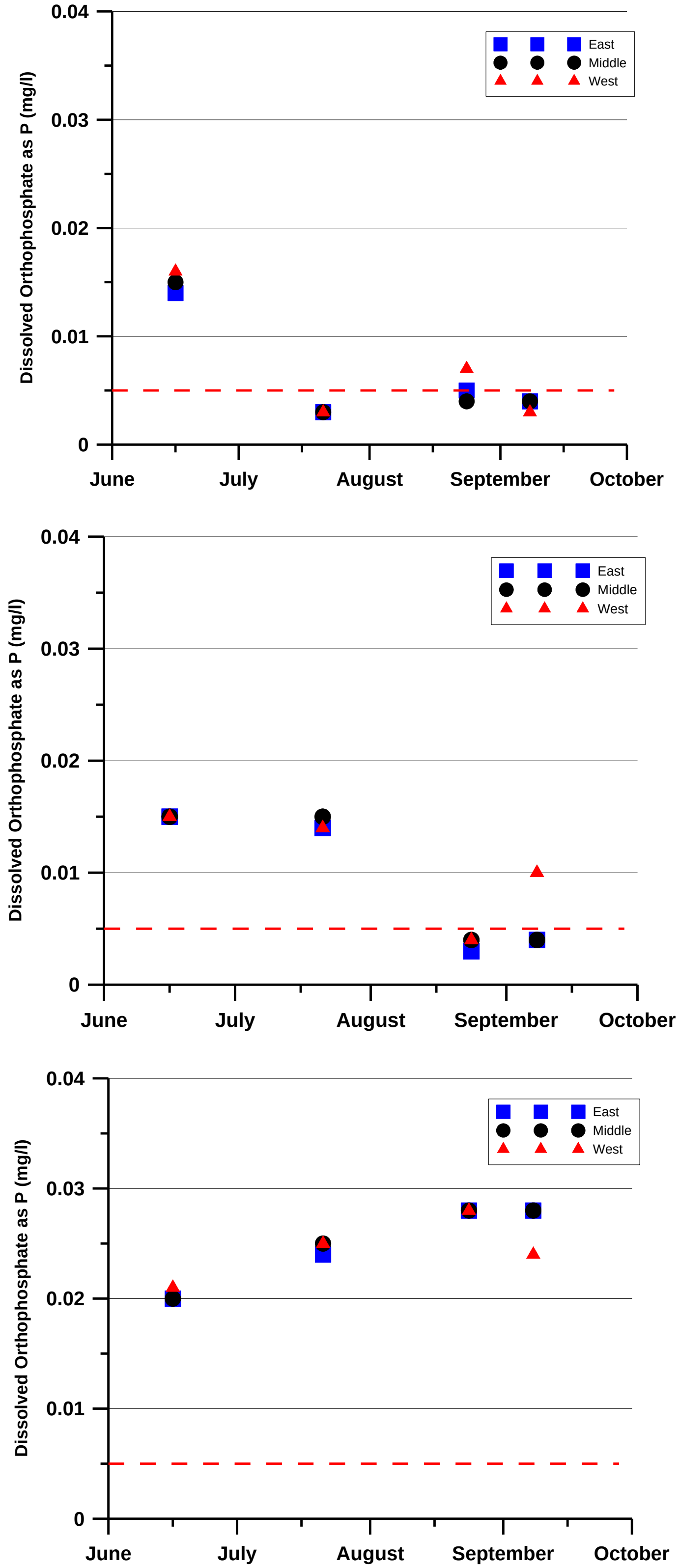

Figure 33. Phosphorus (PO_4) measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

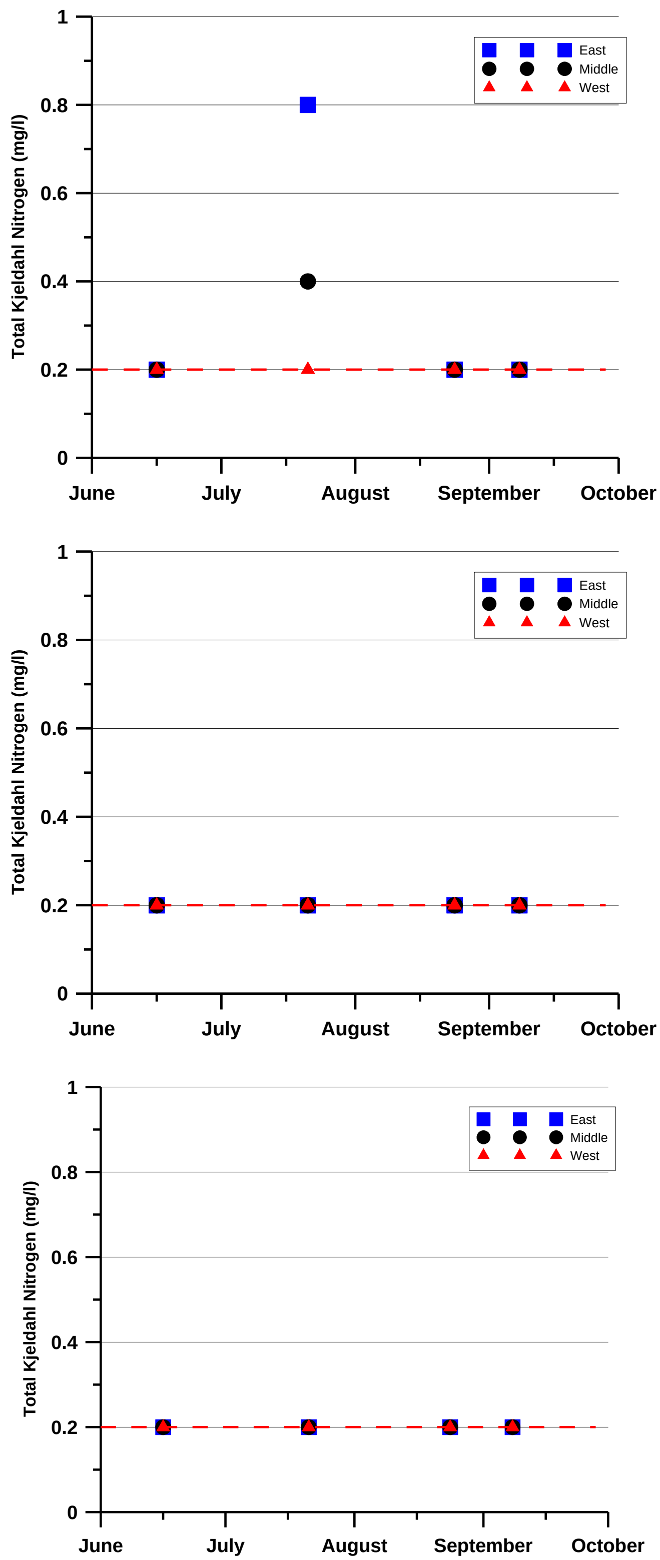

Figure 34. Total Kjeldahl nitrogen measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

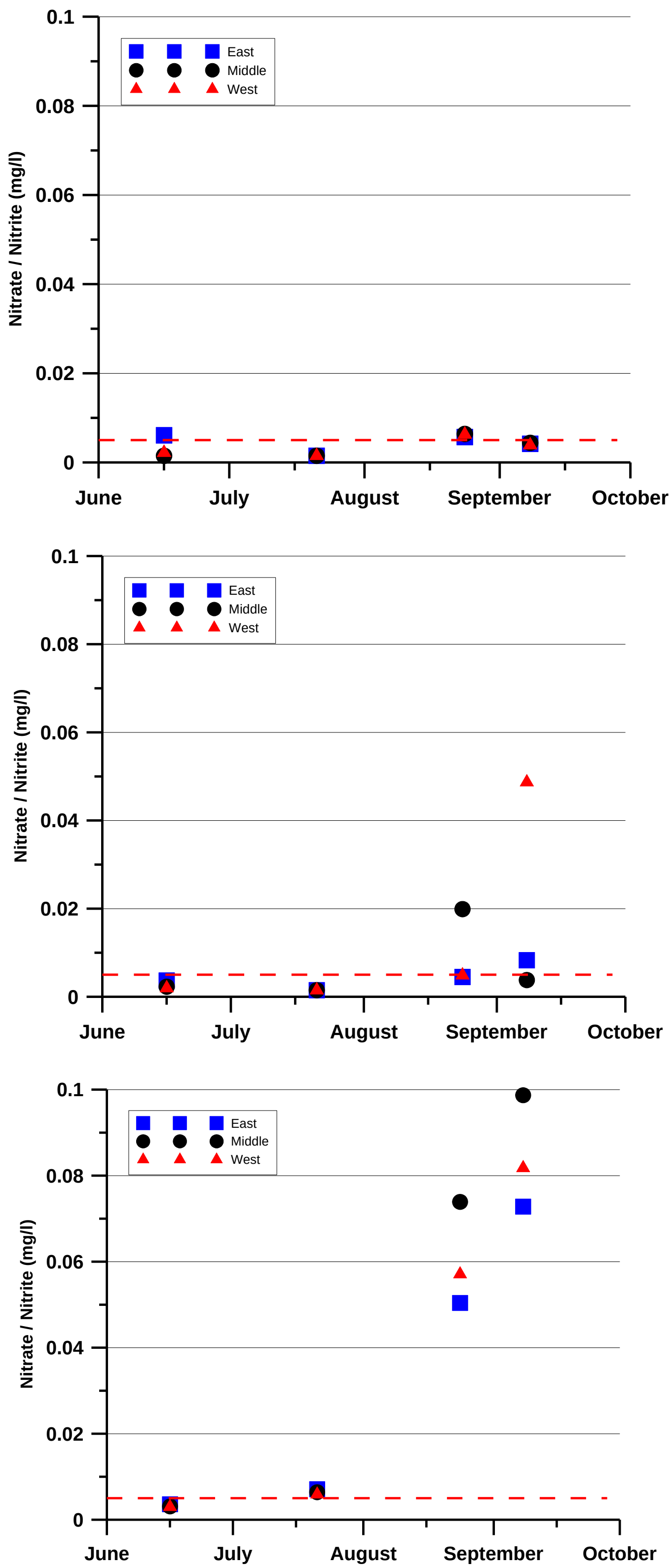

Figure 35. Nitrate-N measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

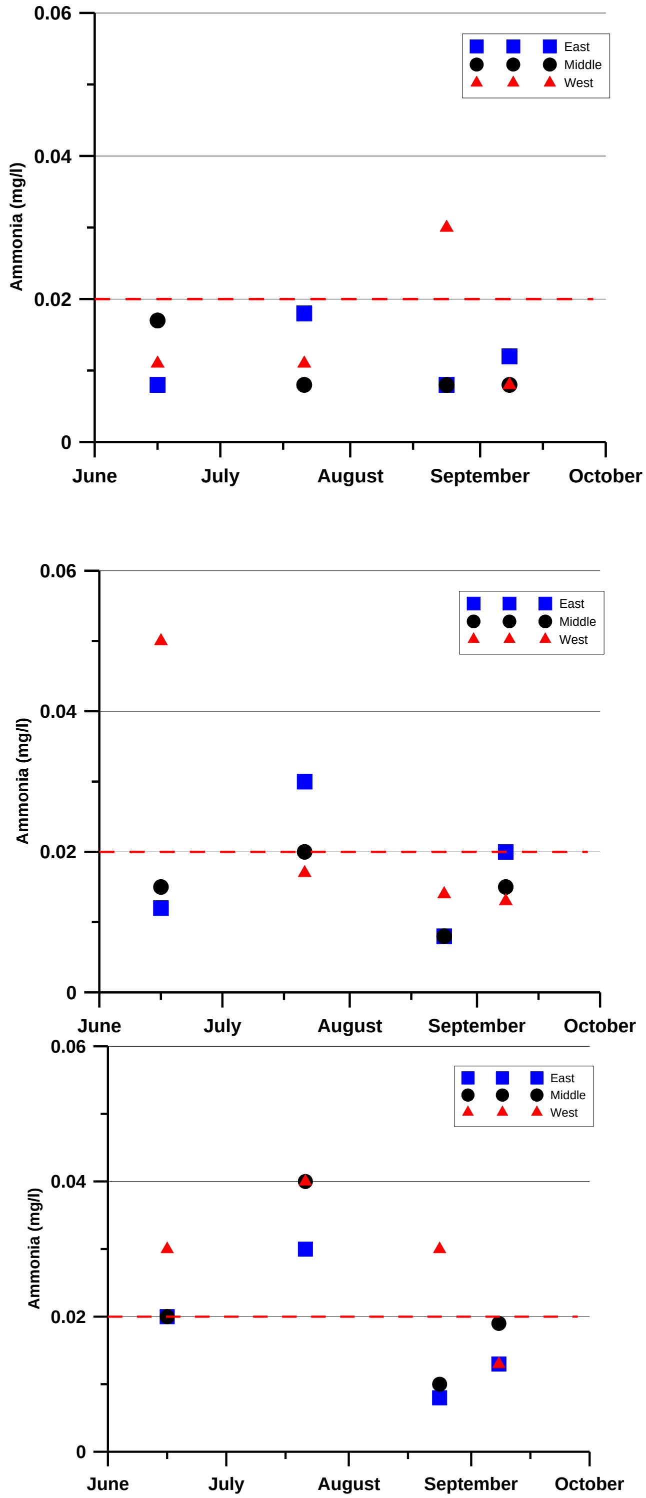

Figure 36. Ammonia-N measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

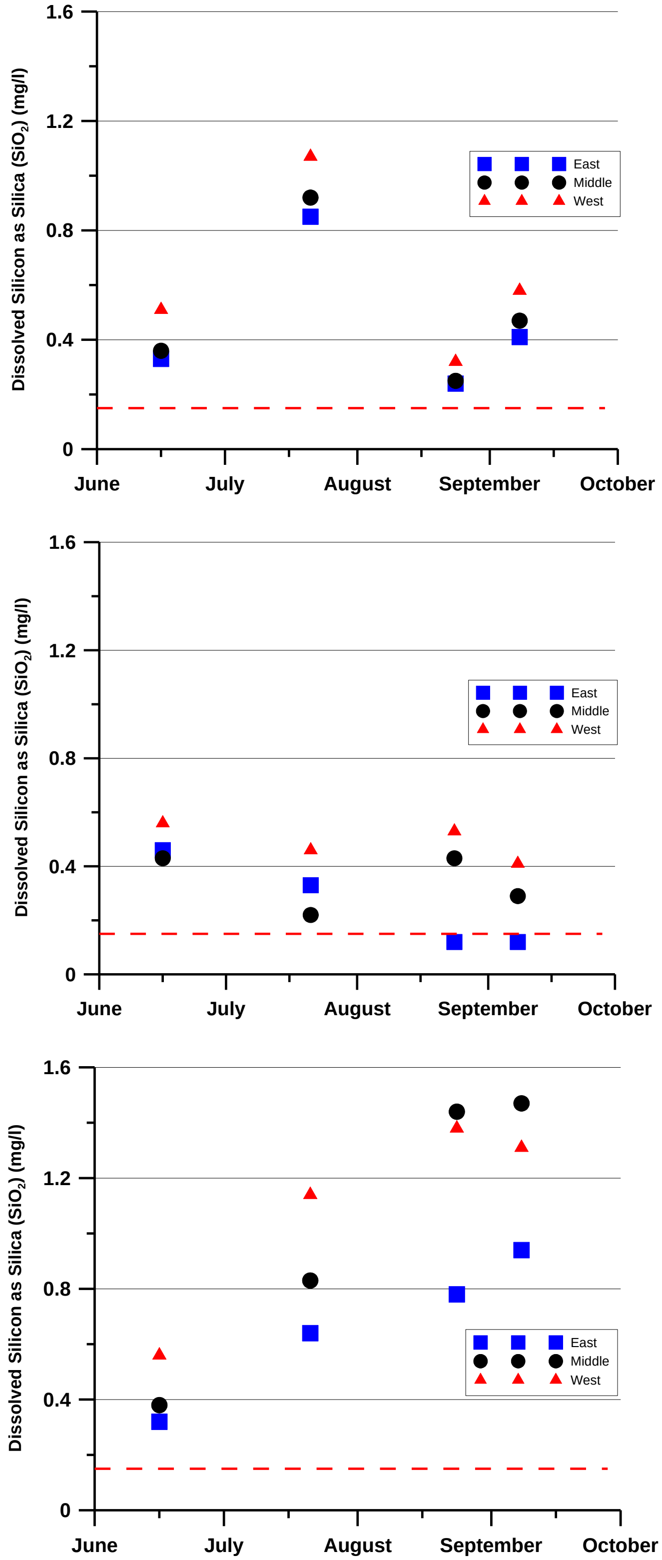

Figure 37. Dissolved silica (as SiO_2) measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

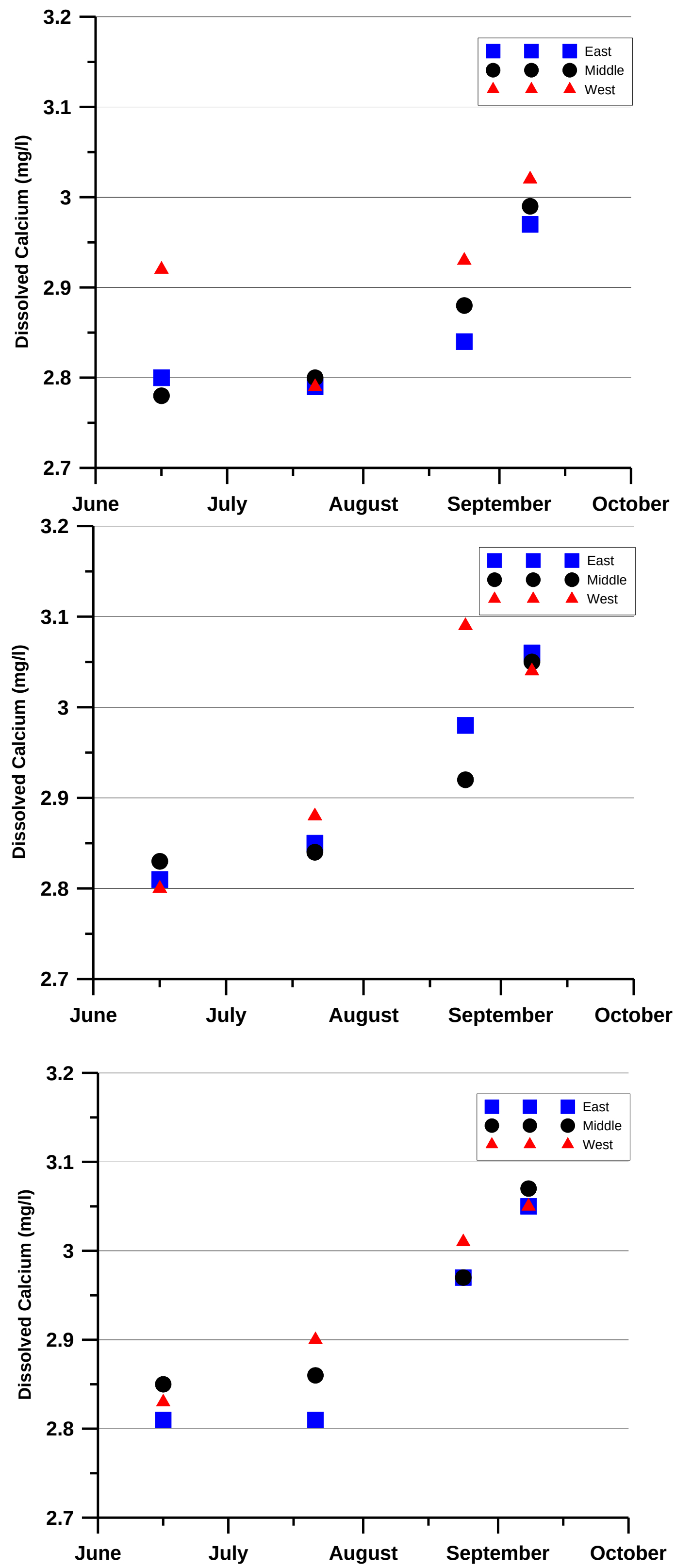

Figure 38. Dissolved calcium measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

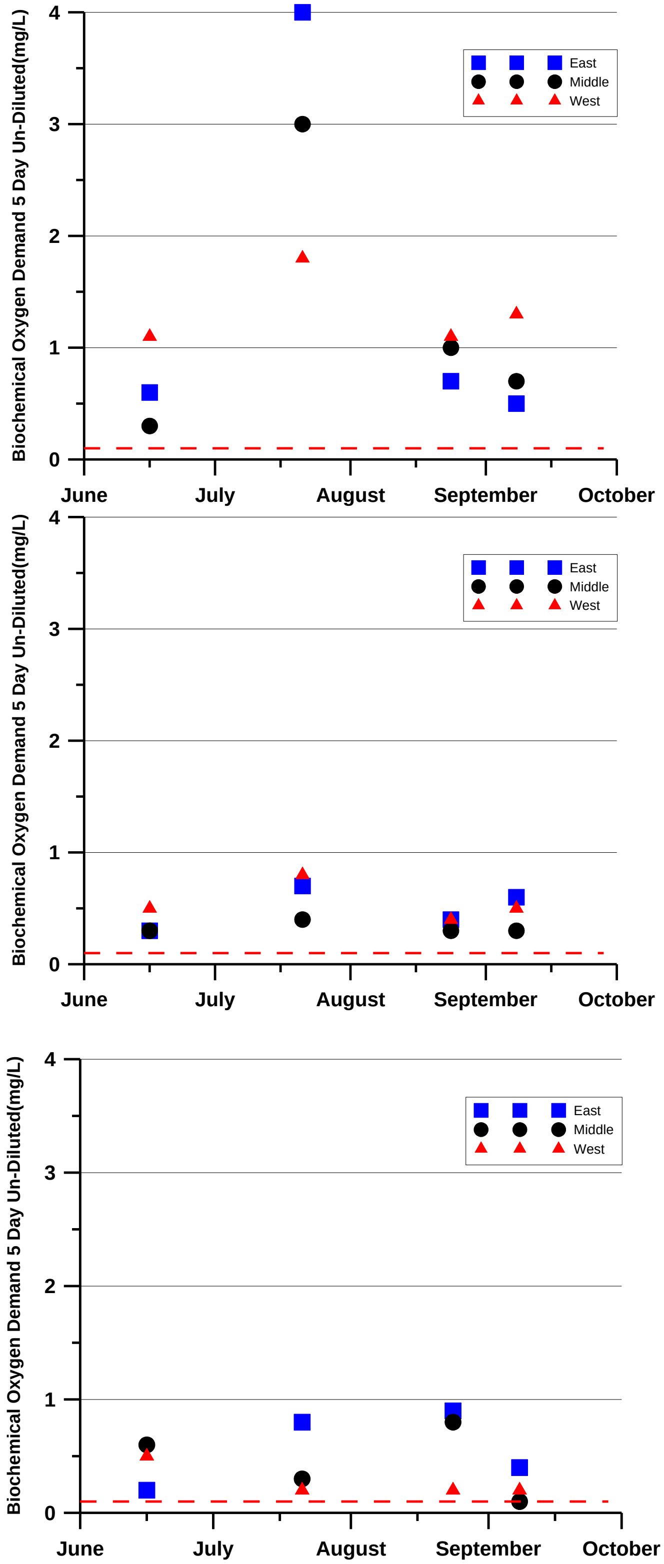

Figure 39. Biochemical oxygen demand (5-day) measured at the surface (top), middle, and bottom (bottom) waters in Odell Lake, 2004 by DEQ.

Several streams were also sampled during the Odell Lake study. These included three tributaries to Odell Lake and the outlet, Odell Creek. The tributaries were depleted in organic and inorganic nitrogen. Almost all of the tributary samples were at or below the MRL for TKN, nitrate and ammonia. Streams were relatively well buffered and contained high concentrations of base cations and alkalinity. The phosphorus concentrations in the tributaries were high, although it is likely phosphorus concentrations were lower in prior to June because of expected dilution from snowmelt runoff (Figure 40). Silica concentrations were high in the tributaries, which is a common weathering product in these volcanic landscapes (Figure 41). Almost all of the silica delivered to Odell Lake is utilized by the diatoms and chrysophytes as indicated by the extremely low concentrations of silica in Odell Creek.

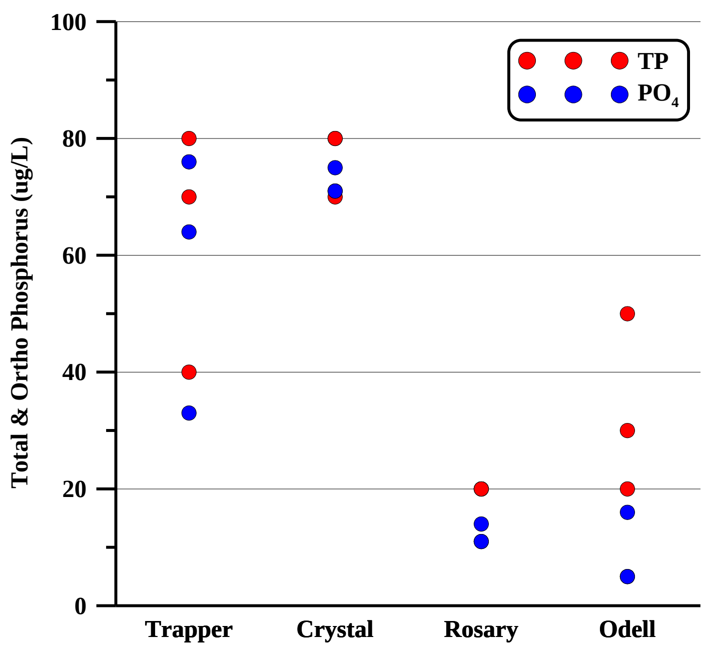

Figure 40. Concentrations of total phosphorus and ortho-phosphorus in the streams sampled during the study.

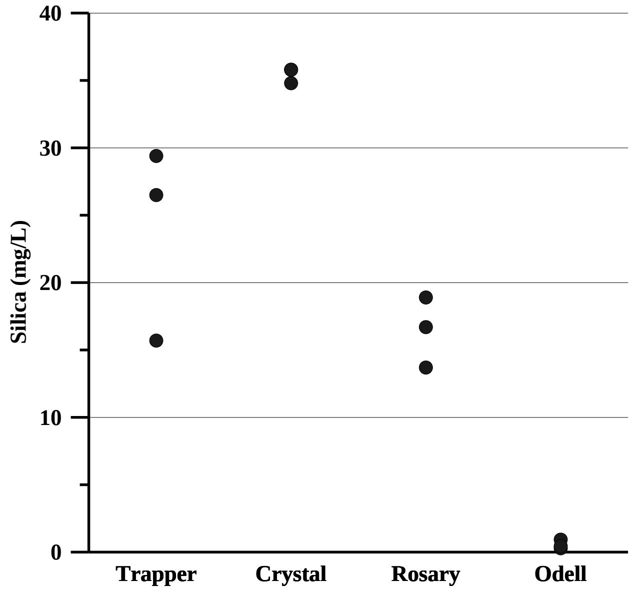

Figure 41. Concentrations of silica in the streams sampled during the study.

d. Phytoplankton

Phytoplankton community composition was comprised of several dominant groups including cyanobacteria, diatoms, and cryptophytes depending on the month. *Tabellaria flocculosa* was dominant in June, but the dominant episode was the bloom of *Anabaena flos-aquae* in July (Figure 42). In late August, the community composition was dominated by diatoms once again, although the dominant taxon switched to *Synedra*. In September the dominant group switched again, this time to the cryptophytes, especially *Cryptomon*as.

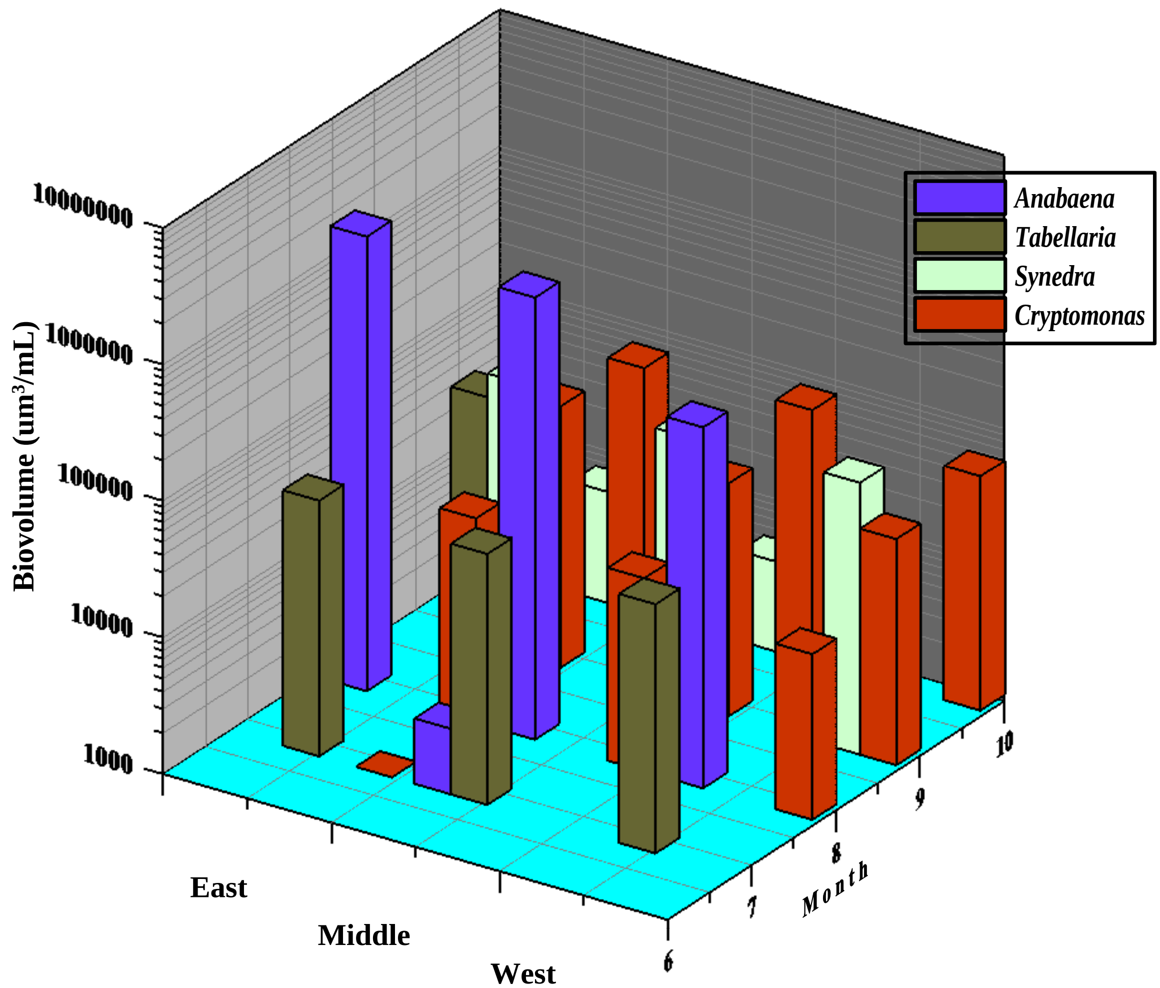

Figure 42. Plot of dominant phytoplankton taxa in the surface waters showing biovolume by site and month based on samples collected by DEQ.

The four site visits collected by DEQ provide a coarse view of the gross changes in phytoplankton community composition during the study period of 2004. A higher resolution view of the changes in phytoplankton was made possible by additional phytoplankton sampling conducted by the Deschutes National Forest during 2004. In particular, the *Anabaena* population can be examined in greater detail. Figure 43 shows the increase in *Anabaena* cell counts from May to the peak densities observed in mid- to late July. The cell counts increased exponentially from mid -June to mid-July, remained high for a week to 10 days, and decreased rapidly to September. The rapid cell division which leads to exponential population increases makes it extremely difficult to forecast cyanobacteria problems in lakes. The maximum *Anabaena* density of 335,000 cells/mL was measured at Serenity Bay on July 19, 2004. This sample showed no measurable anatoxin-a, but the microcystin concentration was 5.8 µg/L (DNF 2005).

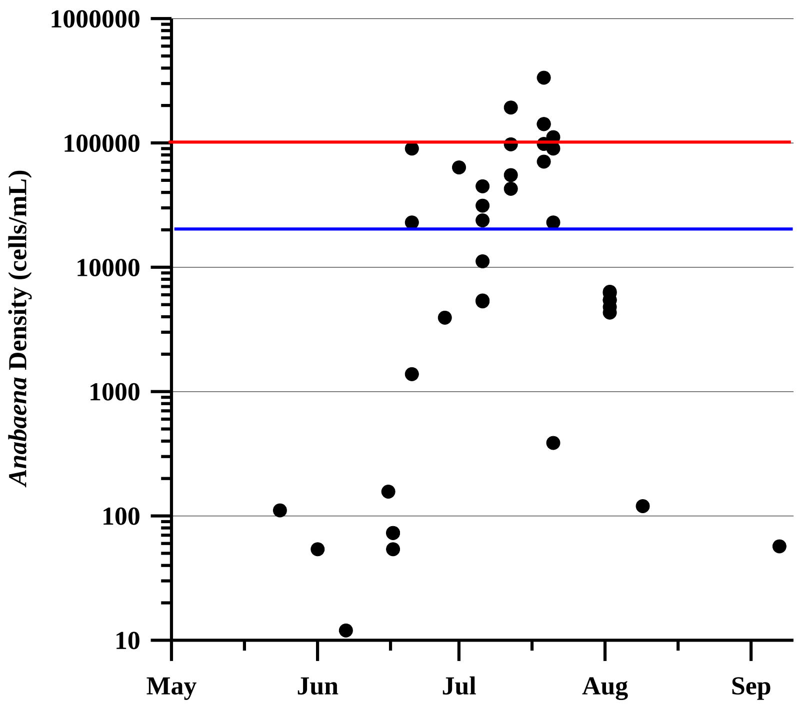

Figure 43. Cell counts of *Anabaena flos-aquae* reported in 2004 for Odell Lake (all sites). The blue line shows the WHO guidelines for a warning level and the red line indicates WHO recommended cell counts for non-contact (WHO 2003). Data supplied by both DEQ and DNF.

e. Zooplankton

The large zooplankton populations have long supported an abundant fishery in Odell Lake. The three dominant groups of zooplankton show, with the exception of the sample collected on the east end of Odell Lake in June, that rotifers were a relatively minor component of the zooplankton community (Figure 44). There was a weak trend for a greater density of copepods on the west end of the lake compared to the other sites. Copepods were most abundant in the July and August samples and cladocerans were most abundant in the September samples from the east and center sites. The two major taxa that would be expected to provide the greatest source of edible zooplankton for fish, the cladocerans *Daphnia pulicaria and, D. rosea*, showed no obvious spatial or seasonal trends based on these few samples (Figure 45). *Cyclops bicuspidatus,* a copepod, was considered by Lindsay and Lewis (1987) as a major food source for kokanee in Odell Lake and is included in Figure 45 for comparison with the dominant cladocerans. However, more recent analyses suggest that *C. bicuspidatus* is not a key component of the diet of salmonids (Allen Vogel, pers. comm., 2005).

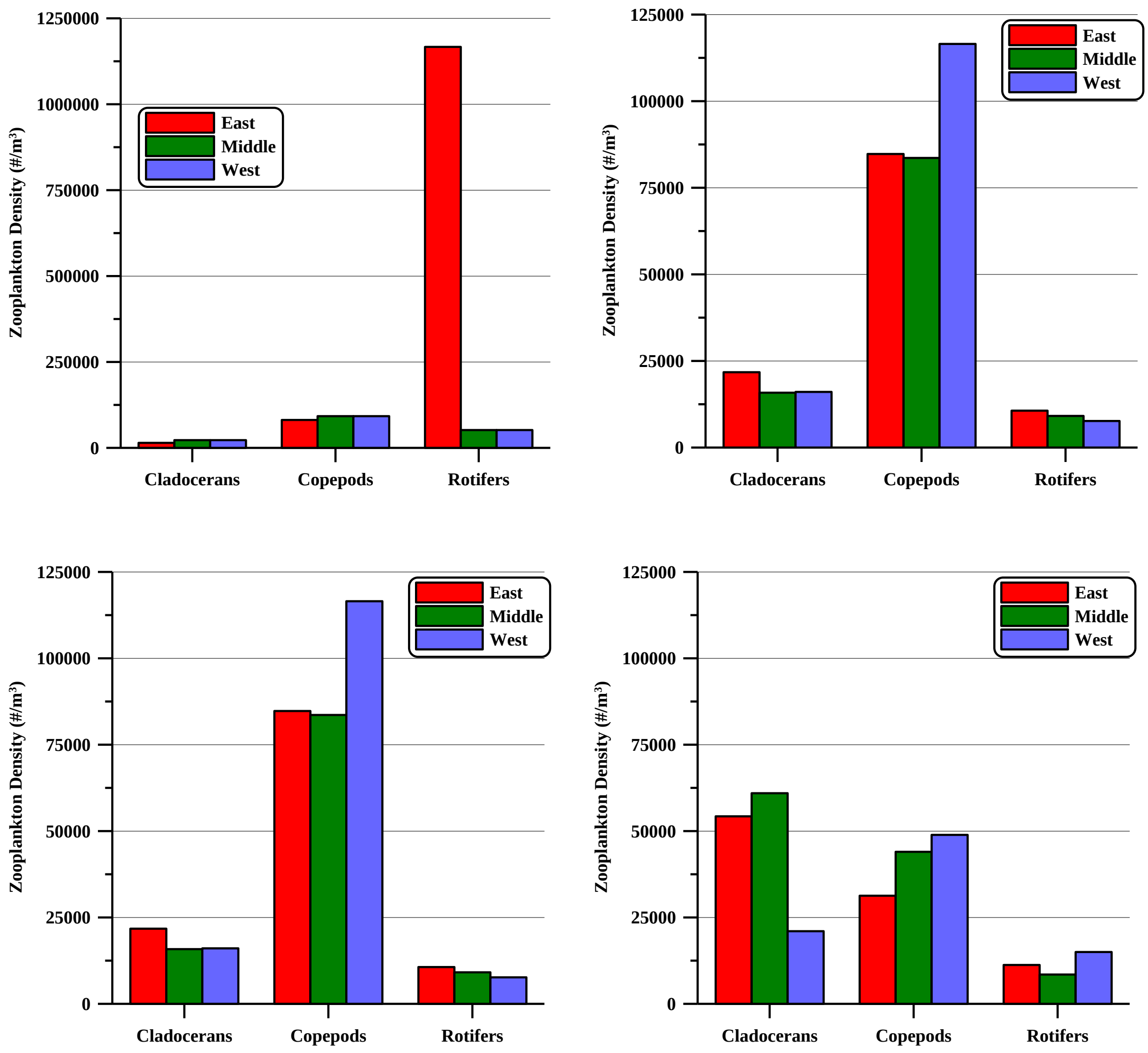

Figure 44. Major groups of zooplankton based on vertical net tows (25 m) in June (upper left), July (upper right), August (lower left), and September (lower right) shown by lake station.

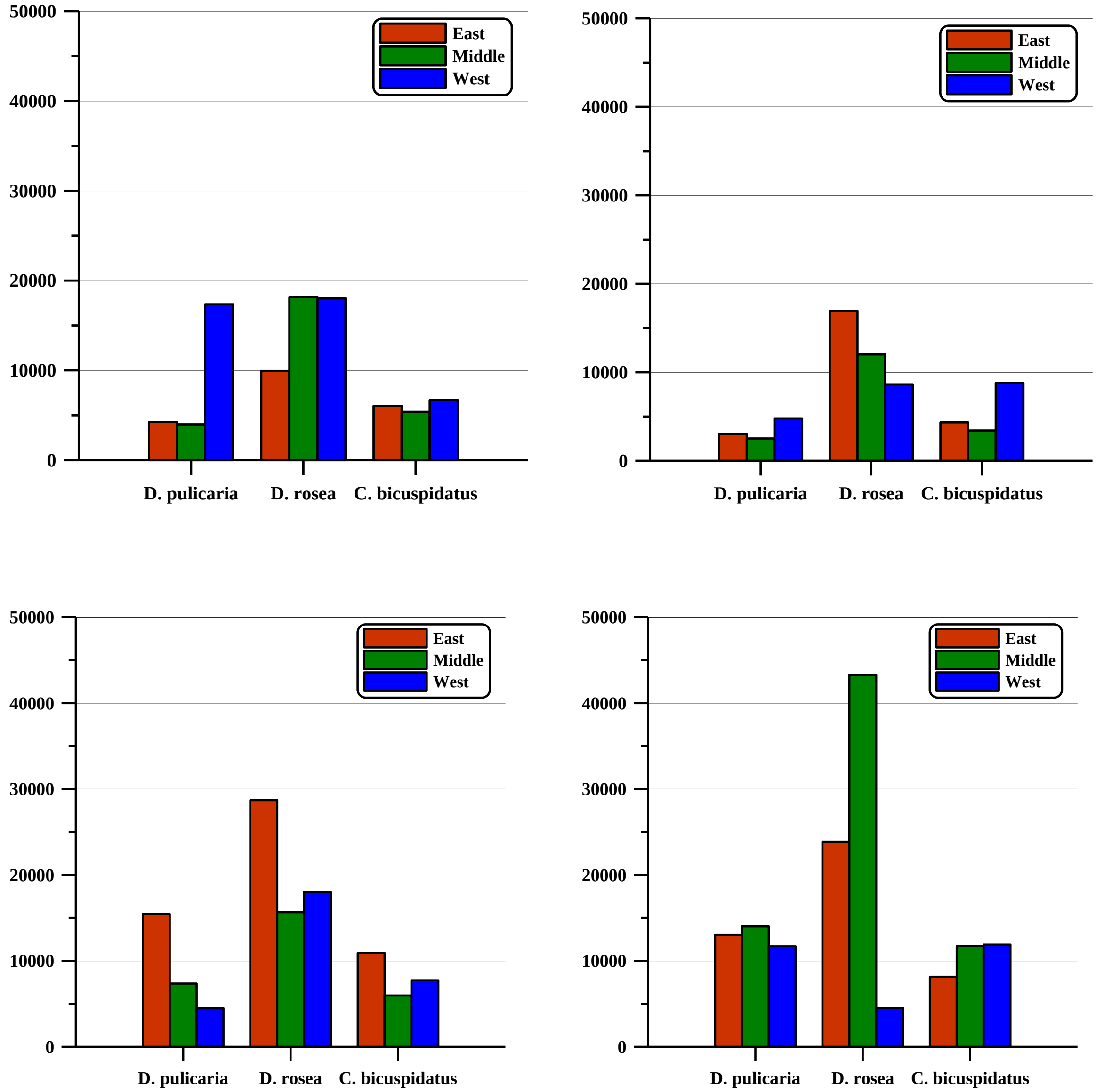

Figure 45. Dominant taxa of zooplankton based on vertical net tows (25 m) in June (upper left), July (upper right), August (lower left), and September (lower right) shown by lake station.

3. Paleolimnology

a. Moisture/physical description

The sediment core retained for analysis was 62 cm in total length and exhibited distinct gradation in color (Figure 46). The upper 16 cm was dark green. This transitioned into a green with tints of brown. The major transition in color occurred between 30 and 40 cm where the green cast disappeared from the sediment and was replaced entirely by a light brown which continued to the base of the core. No chironomid tubes or larvae were visible in the core. A pine needle was found at 47 cm and a piece of charred bark was collected at 58 cm. No other visible features of the sediment were identified. Moisture content in the sediment declined from a high of 97 percent water in the top interval to 84 percent at 50 cm, the bottom-most interval analyzed (Figure 47).

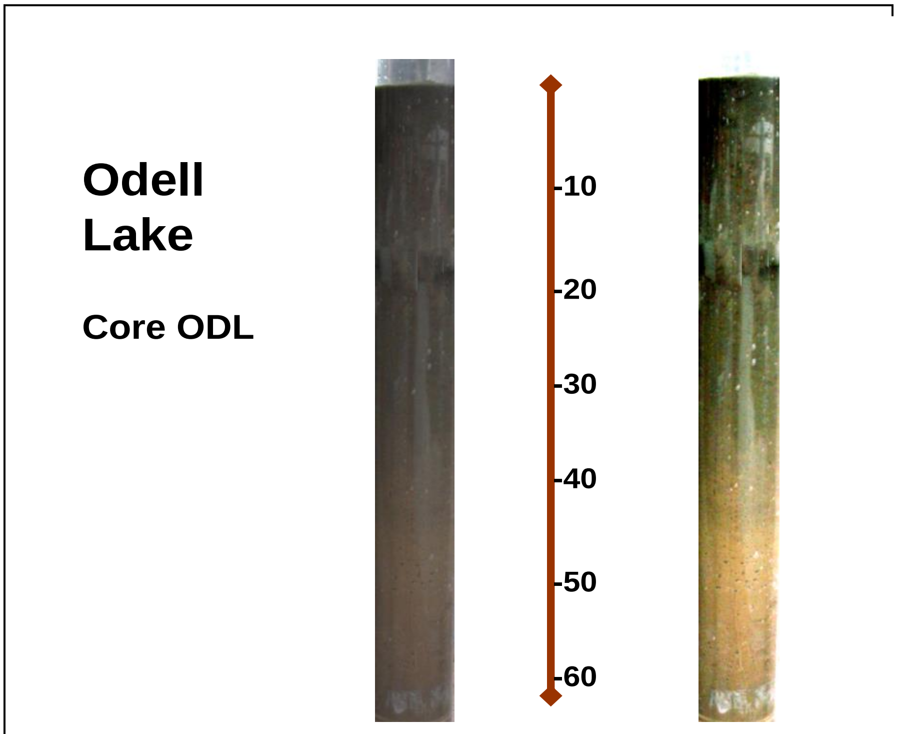

Figure 46. Core ODL from Odell Lake. The photograph of the core under natural light is shown on the left. A digitally enhanced version of the same image is shown on the right. The vertical scale is in centimeters.

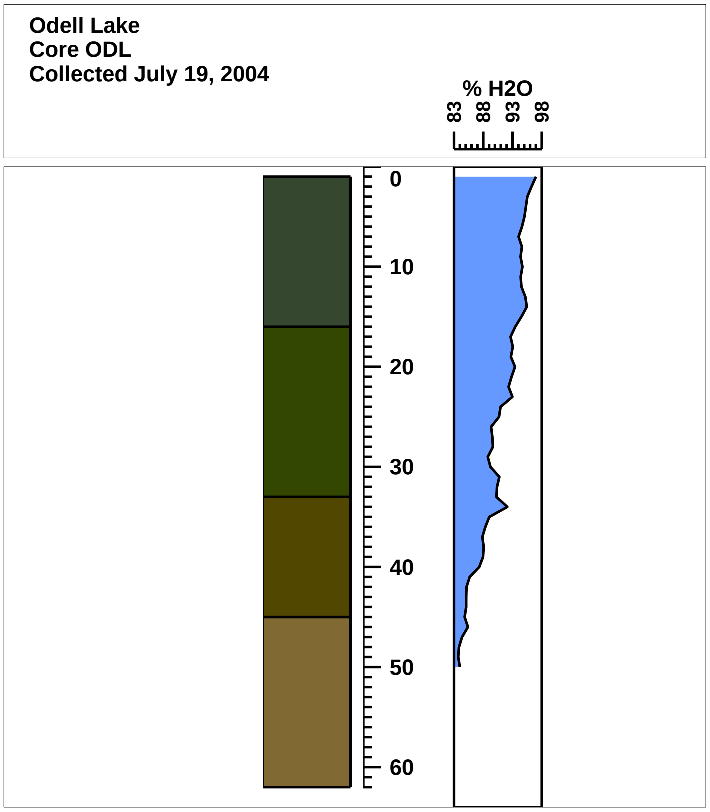

Figure 47. Sediment core visible zonation and percent moisture for core ODL from Odell Lake.

b. ^{210}Pb-dating

The age of the sediments was determined with ^{210}Pb dating and the constant rate of supply (CRS) model (Applebee and Oldfield 1978). The mass of the ^{210}Pb in the sediment declines steadily through the sediments reaching background levels near 40 cm (Figure 48). Overall activity in the core was low, but the consistent measurements yielded estimates of sediment age with high precision (Figure 49). The sediment accumulation rate (SAR) calculated from the change in mass over time yielded a linear increase in SAR from ~1880 to circa 1920 and an increase in the slope of SAR from ~1925 to ~ 1950. From 1950 to present the SAR has continued to increase, but with modest fluctuations in the annual rate of increase (Figures 50 and 51). The spike in SAR in the top of the core is difficult to reliably interpret since this is only one interval. Overall, the data indicate that SAR has increased four to five fold over pre-settlement rates. For this region, we consider pre-settlement to represent the period before 1850.

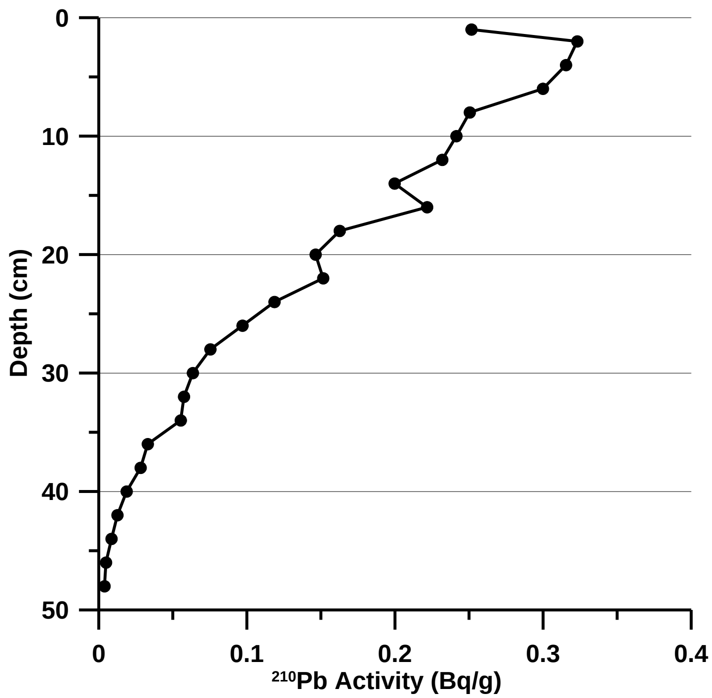

Figure 48. ^{210}Pb activity in the sediment of core ODL from Odell Lake.

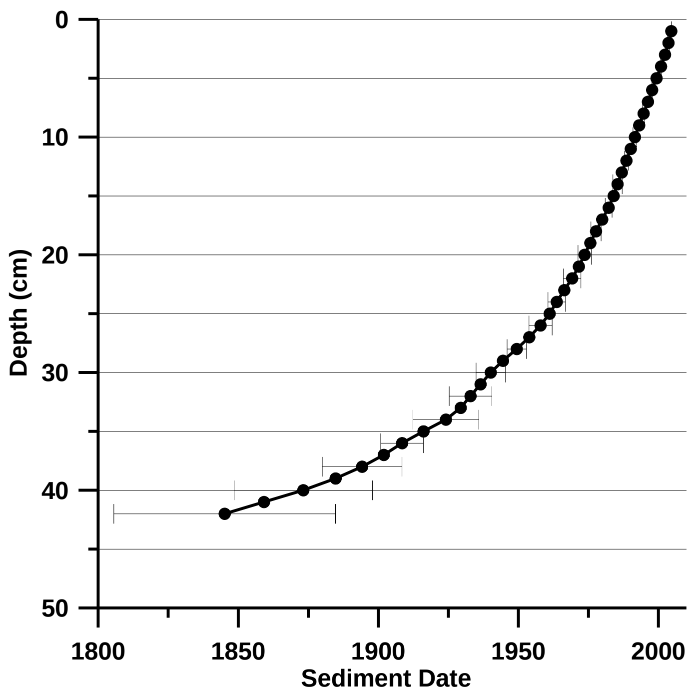

Figure 49. Age of sediment in Odell Lake and the uncertainty in sediment date shown as horizontal

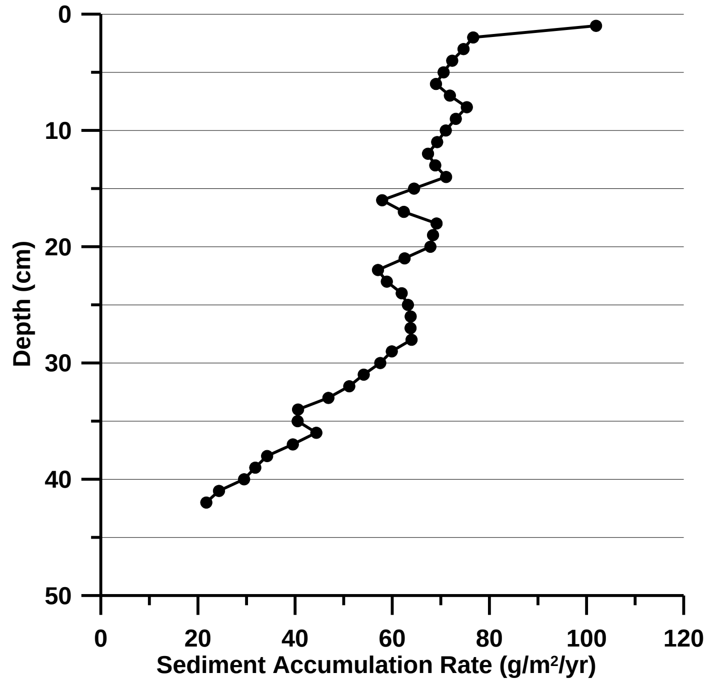

Figure 50. Sediment accumulation rate for Odell Lake plotted against depth in sediment.

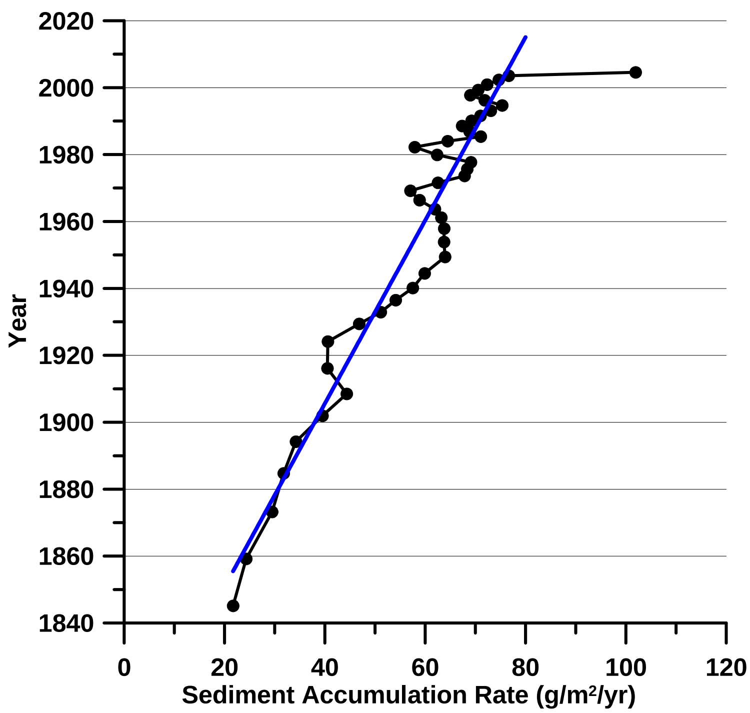

Figure 51. Sediment accumulation rate in Odell Lake plotted against age of sediments.

c. Chemistry

The sediment data show a substantial increase in concentration of carbon, nitrogen, and phosphorus starting at about 22 cm and extending up to the surface (Figures 52). Carbon shows a 2.5 fold increase and nitrogen shows a 3.5 fold increase in concentration above pre-settlement values, whereas phosphorus shows an increase of over 5 fold above base levels. The increase in carbon and nitrogen are monotonic, whereas the increases in phosphorus appear erratic. Maximum sediment concentrations of phosphorus occur at 12 to 15 cm in depth, corresponding to the early 1980s. Unlike sediment nutrients, the concentration of titanium shows an apparent decrease from pre-settlement conditions. However, this trend in titanium is weak and highly variable.

The mass ratio of C:N shows a decline over the period of record indicating that the proportional increases in nitrogen exceed the increase in carbon (Figure 53). The pre-settlement range for the C:N was from 8.2 to 9.2, whereas the ratio for the post-development phase is now below 7. The N:P ratio has been more variable than the C:N ratio as indicated by the minimum pre-development values near 4 and a maximum pre-development value of 14. However, the post-development ratio of N:P has declined from about 13 to near 2 and has remained below the pre-development ratio minimum of 4 throughout the entire modern period.

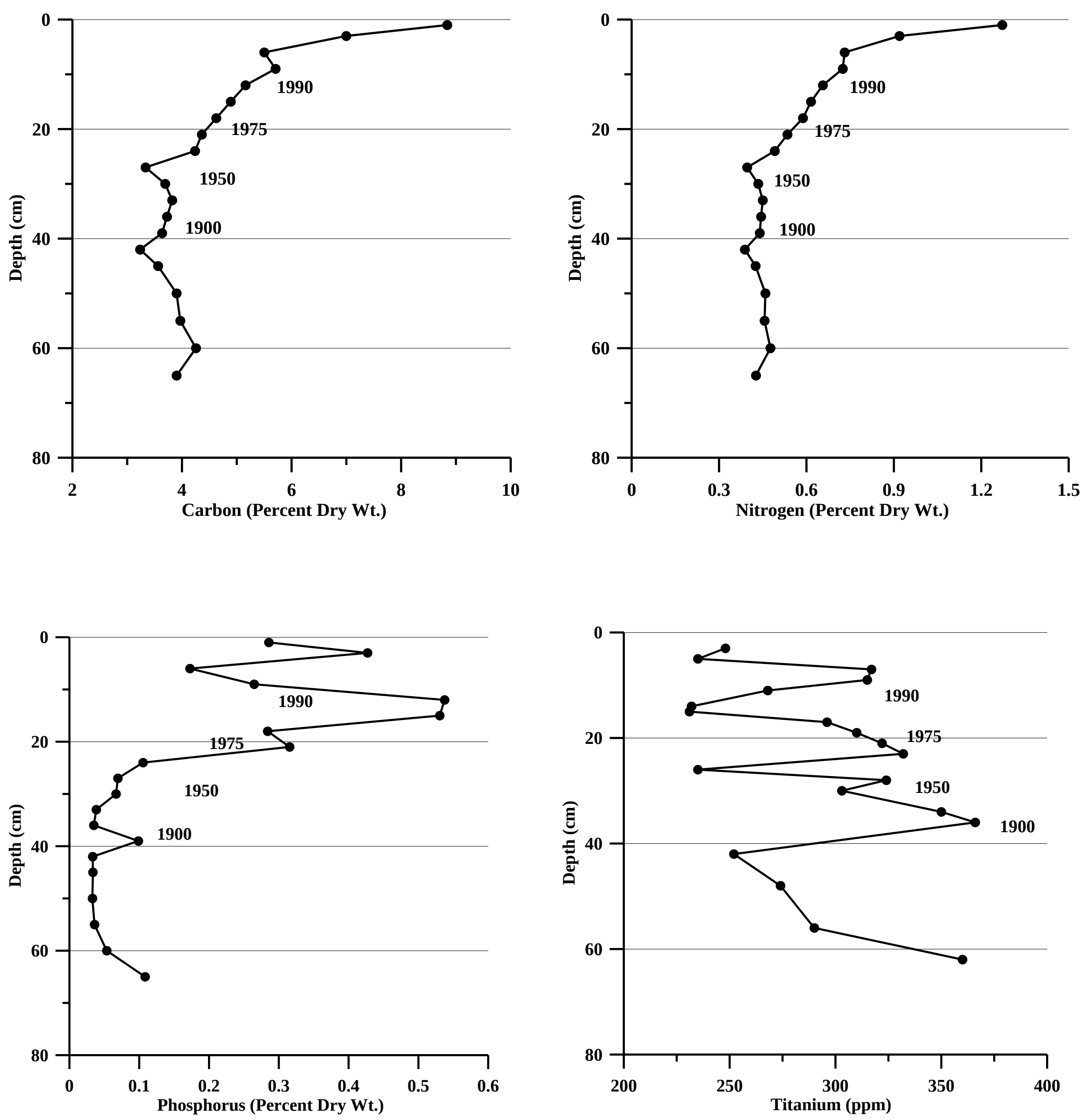

Figure 52. Concentrations of carbon, nitrogen, and phosphorus (percent dry wt) and titanium (ppm dry wt) in the sediment of Odell Lake. Selected dates are shown for reference.

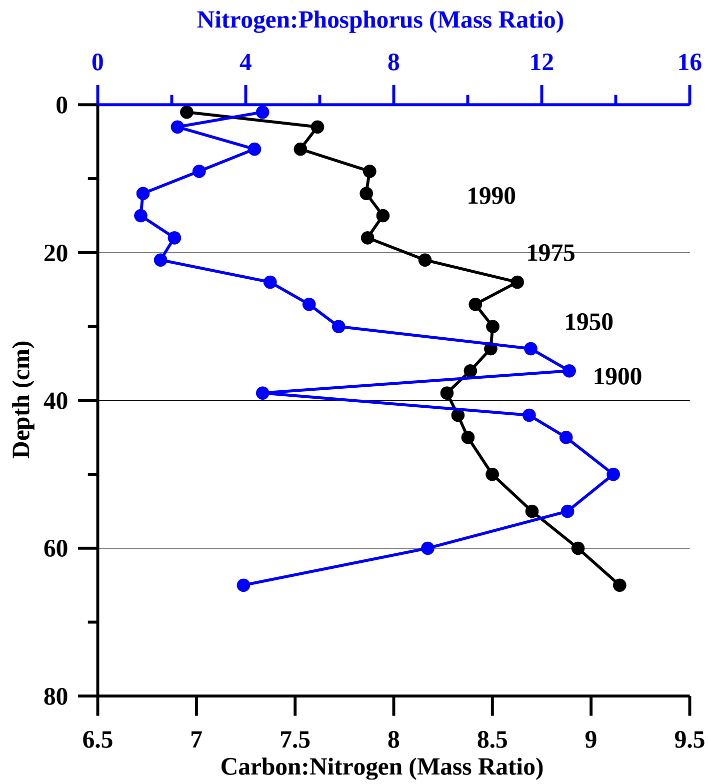

Figure 53. Mass ratios of carbon to nitrogen (black) and nitrogen to phosphorus (blue) in Odell Lake sediments.

d. Biota

Three components of biota were measured in the lake sediments: diatoms, cyanobacteria akinetes, and chironomids. The diatoms were measured in the sediments at 21 intervals to establish changes in the planktonic and attached diatoms formerly inhabiting the lake. Diatoms are commonly used to assess changes in water quality because of their abundance in lakes, their taxonomic richness, and the specificity of various taxa to different water quality issues. In addition, they are usually well preserved in sediments and can often be identified to species. The results show a marked increase in the proportion of eutrophic planktonic diatoms and reduction of non-planktonic and mesotrophic taxa (Figure 54). Although some mesotrophic planktonic species such as *Stephanodiscus medius* have declined in relative abundance, the majority of taxa associated with eutrophic waters have increased. In particular, *Asterionella formosa* has shown substantial increases in the upper sediments. *Tabellaria flocculosa* shows an increase in the upper zone, but in the most recent sediments it has declined considerably. Taxa more typically associated with oligotrophic waters such as various species of *Aulacoseira* (*distans* and *subarctica*) have nearly disappeared from Odell Lake. Two species often associated with eutrophic lakes, *Fragilaria crotonensis* and *S. hantzschii*, make notable increases in the upper sediments. The attached forms (non-planktonic) of diatoms have also declined in the upper sediments, which can often signal a decrease in transparency. There appear to be two areas in the sediment that correspond to the most notable changes in diatom taxa occurring at about 43 cm (pre-1845) and 24 cm (~ 1964). The ratio of diatoms to cysts (chrysophyte cells) shows a dramatic increase in the top zone. This may reflect either a decrease in chrysophytes or an increase in diatoms. In either case, it may be another indicator of increased eutrophication.

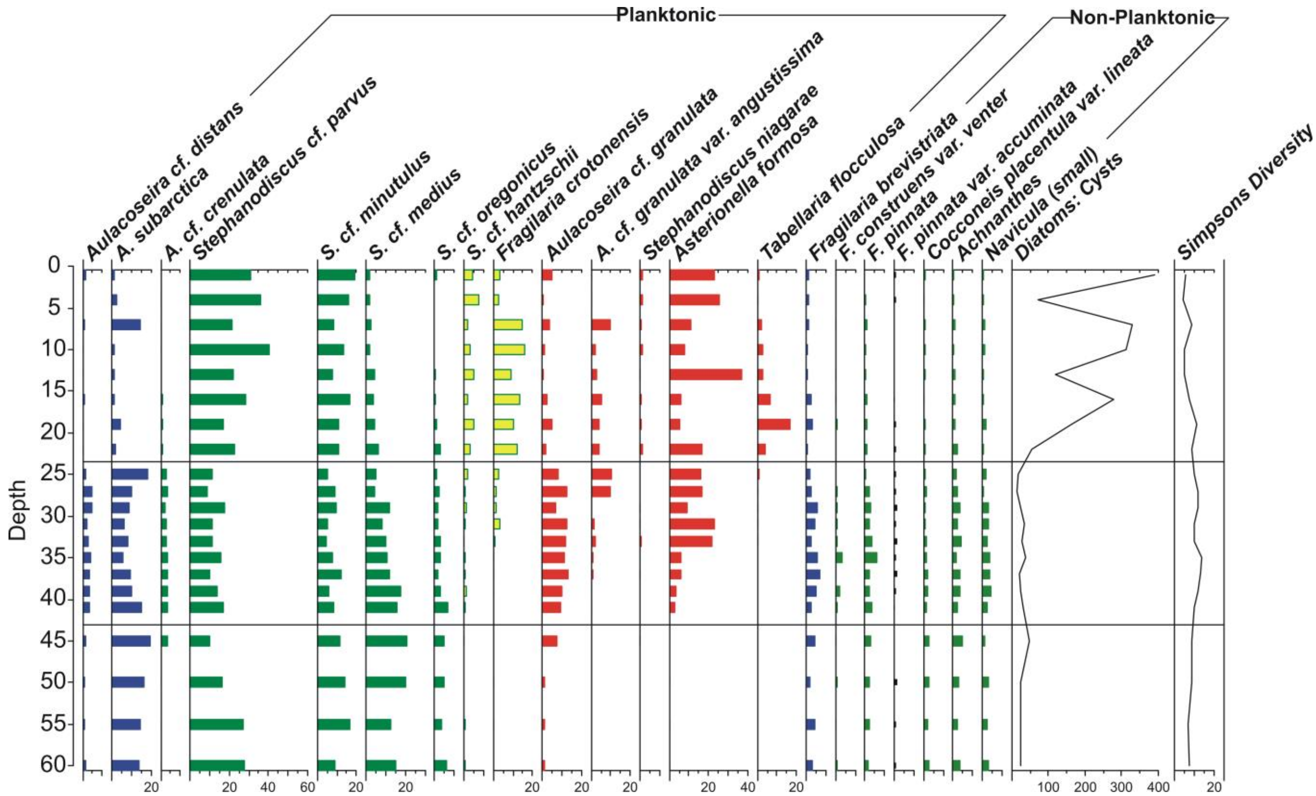

Figure 54. Stratigraphic record of the relative abundance of dominant diatom taxa in the sediment of Odell Lake. The taxa are coded by general trophic assignments and grouped by habitat preferences. The relative abundance of the taxa is shown as a percent on the X axis. Taxa shaded in blue generally prefer waters with low concentrations of phosphorus (TP < 10 µg/L), those shaded in green are associated with waters with intermediate concentrations of phosphorus, and those shaded in red generally prefer high concentrations of phosphorus (TP > 20 µg/L). The taxa shaded in yellow have been classified from laboratory experiments as intermediate in TP requirements, but the field observations usually show these taxa associated with eutrophic waters. The three zones were delineated subjectively and correspond to sediment dates of pre-1845 (+/- 40 yrs) and 1964 (+/- 3 yrs).

The next biological group examined in the sediments was the cyanobacterial akinetes. These are resting cells produced by some species of cyanobacteria and they may remain preserved for hundreds of years or more. The assumption with the use of akinetes is that they were produced at a rate proportional to the abundance of the cyanobacterial colonies. The cyanobacteria akinetes showed several taxa of *Anabaena* present throughout the sediments of Odell Lake. The data indicate that *Anabaena* has been present even during pre-settlement conditions. However, the pre-settlement deposition rates of cyanobacteria akinetes were relatively low. When the concentrations of akinetes are adjusted for sediment accumulation rates, it is apparent that there has been a major increase of cyanobacteria in Odell Lake around 1961 (+/- 3.5 yrs) and peaking in 1992 (+/- 1 yr) (Figure 55). Two other secondary peaks occurred in 1982 and 2001.

The most abundant species of akinetes identified was *A. lemmermannii*. *A. flos-aquae* akinetes were not identified in the sediment. This conflicts with the phytoplankton data collected in 2001 and 2004 in which the dominant *Anabaena* taxon identified by Aquatic Analysts was *A. flos-aquae*. This difference in taxonomy may not have a great deal of ecological significance since both species are N-fixing and both taxa are capable of producing both anatoxin and microcystin (Chorus 2001).

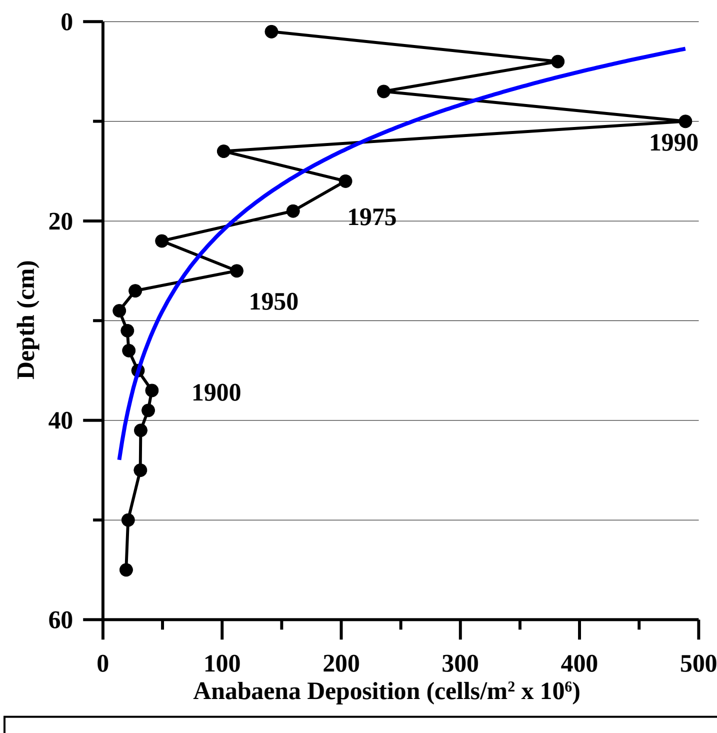

Figure 55. Deposition rate of *Anabaena* akinetes in Odell Lake. The curve is a log-fit to the observed data. Selected dates are shown for reference.

The last group of biological indicators examined in the sediments was chironomid remains. The chironomid fossil head capsules have the potential to provide information on changes in both water quality and predation by fish. The raw density of head capsules in the sediment declines from the base of the core to the surface (Figure 56). However, when these densities are adjusted by increases in sediment accumulation rate, there has been no significant change in gross chironomid density. It appears that there has been a decline in the number of taxa present and an increase in the proportion of individuals that are collectors/filter feeders. Since the absolute numbers of individuals present in the core appear to be unchanged, then a proportional change in habitat preferences would also correspond to an increase in the absolute number of collectors/filter feeders. There appears to be no significant change in the pollution tolerance of the taxa present in Odell Lake.

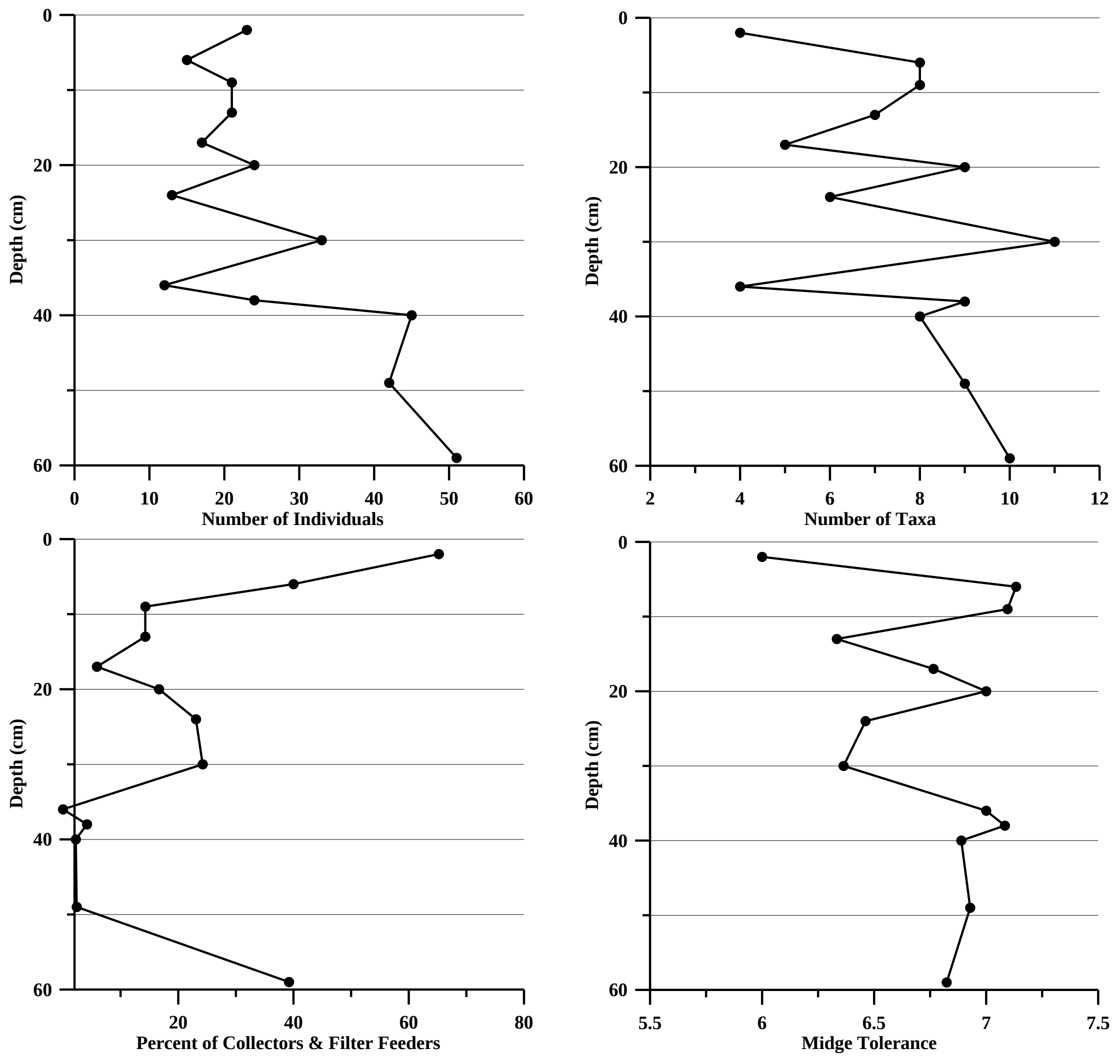

Figure 56. Changes in number of individuals, number of taxa, relative abundance of collectors/filter feeders, and tolerance of taxa to organic pollution. The taxon tolerance was based on Barbour et al. (1999) for taxa in the Pacific Northwest using a scale of 0 to 10, where higher values represent taxa more tolerant to pollution.

4. Fisheries

Odell Lake is an excellent lake for conducting hydroacoustic surveys because it is deep and has few macrophytes present. The great depth allows a large portion of the water column to be surveyed and it also minimizes problems associated with boat avoidance by fish often observed in shallow waters. Additionally, the species of fish believed to be most abundant (kokanee and lake trout; Lindsay and Lewis 1978) are commonly found in the pelagic zone. The small areas of the lake with macrophytes provide fish with limited opportunity to avoid being counted. Fish abundance and distribution in Odell Lake was assessed using hydroacoustic techniques on July 22-23, 2004. Two separate hydroacoustic surveys were conducted during the day and night. The daytime runs were useful in determining the vertical distribution of fish and identifying the aggregation of some fish into schools. Because of the difficulty in target separation of schools, we estimated the biomass of the fish in schools as the difference between the day and night runs and allocated their biomass in the depth classes where the schools were observed. However, the total fish biomass estimates were derived from the night runs.

Much of the water column in Odell Lake during the day was relatively free of fish targets. Large targets were located on or immediately above the lake bottom during the day and many of the fish (< 40 cm) were aggregated into large schools oriented vertically (Figure 57). These schools were typically arrayed at depths of 20 m to 30 m and were about 4 to 8 m in height. At nighttime, the fish would disperse and rise into the thermocline, presumably to feed on the zooplankton (Figure 58). The vertical movement of the smaller fish was followed by the large piscivorous fish (lake trout and bull trout) that rose off the lake bottom and approached or entered the thermocline. The transition from the daytime school-dominated structure to the nighttime dispersed structure was documented during the evening of July 23, 2004 in which schools of fish dispersed and rose into the thermocline (Figure 59). The nature of the prey was evaluated by conducting a separate hydroacoustic run at a lower decibel threshold to detect the presence of larger zooplankton. The results indicate high densities of larger zooplankton that would most likely serve as a prey base for kokanee and whitefish (Figure 60).

The vertical distribution of fish biomass shows a movement of a substantial mass of fish into the metalimnion during the night (Figure 61). In contrast, fewer single-fish targets were observed during the day (Figure 62). We assume that part of the difference between the fish biomass estimates made during the day and those at night reflect the large number of fish that were schooled during the day. In addition, the few large targets were more inclined to be observed close to the lake bottom, which makes it difficult to separate the fish target from the lake bottom.

The fish size distribution in Odell Lake was distinctly bimodal, with peaks in target strength at -53 dB and -37 dB (Figure 63), corresponding to estimated lengths of 4 cm and 27 cm (Figure 64), respectively. The two peaks in size classes may reflect strong kokanee year classes in kokanee Year 1+ and Year 3+ individuals. The number of adult bull trout present in the lake based on spawning surveys in Trapper Creek is less than 100 (Ted Wise, ODFW, personal communication, 2005), consequently we assume that most of the fish greater than 40 cm in Odell Lake are lake trout. The numbers of fish targets observed on the two night runs are displayed in Figures 65 and 66, showing the number of targets as a function of strength of target and depth class. Again, the data show the concentration of targets in the 10-30 m depth zone. The analysis of the spatial distribution of fish targets indicates that larger fish are distributed throughout the lake, although there appeared to be a tendency for more large fish at the west end of the lake (Figure 67). Additional hydroacoustic analyses would be required to better determine habitat utilization of the lake by the fisheries.

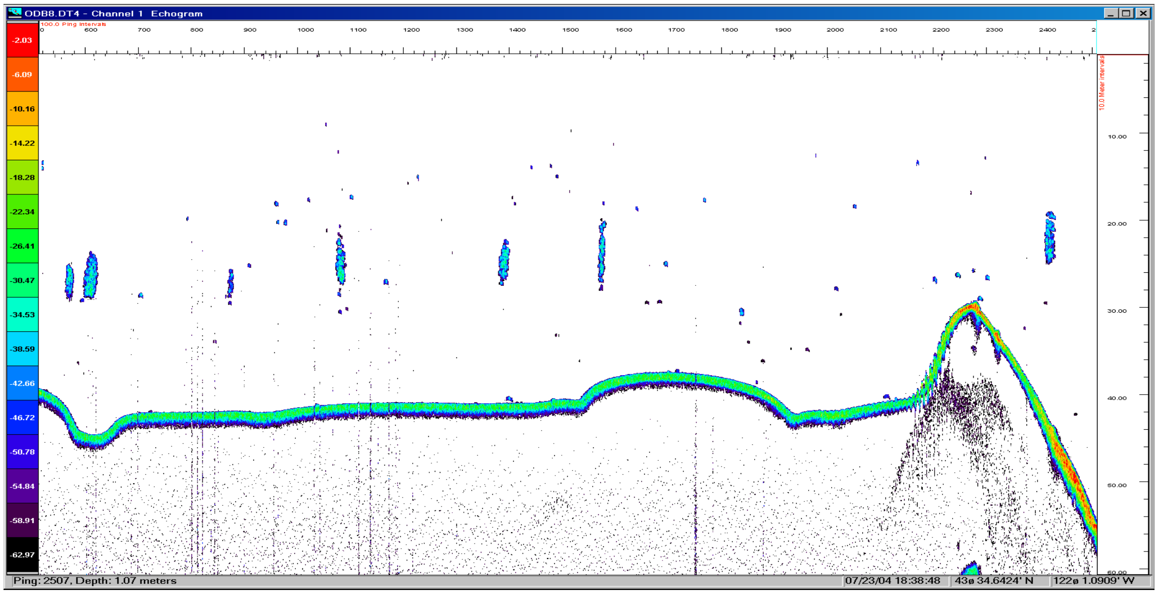

Figure 57. Echogram at the west end of Odell Lake, July 23, 2004 at 1838 hr. Depth scale on the right axis is in meters. The lake bottom is the green-blue line extending horizontally. The left axis displays the intensity of the return echo where red is a very hard surface and blue is a soft target.

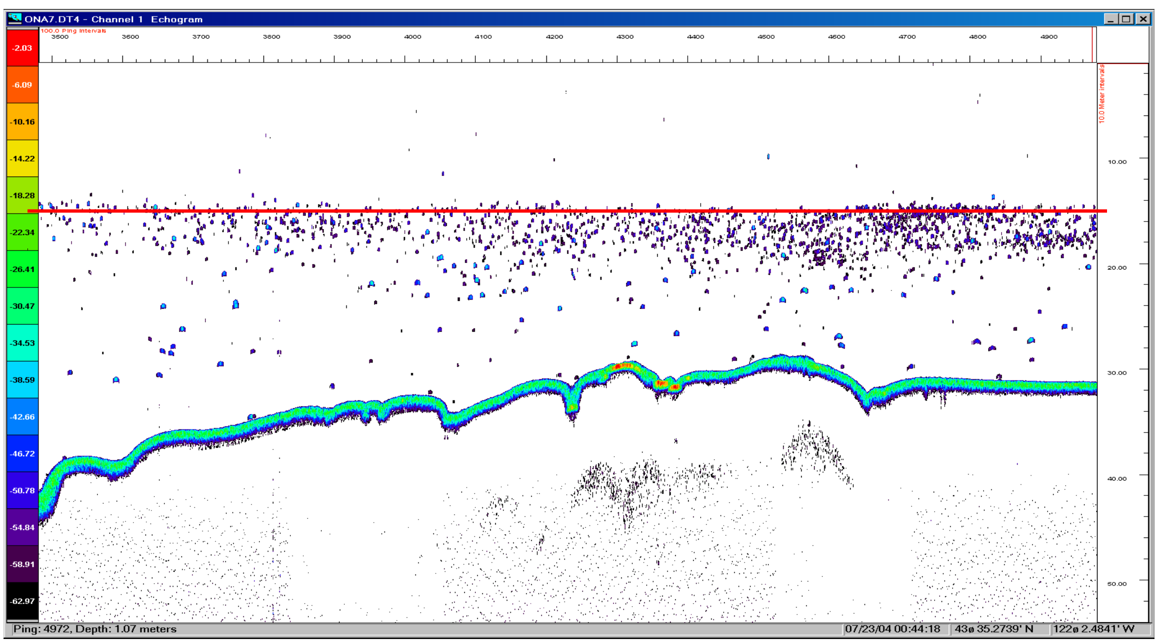

Figure 58. Echogram of Odell Lake, July 23, 2004 at 0044 hr. The small targets are most likely kokanee and the larger targets are most likely lake trout. The red horizontal line marks the 15 m depth.

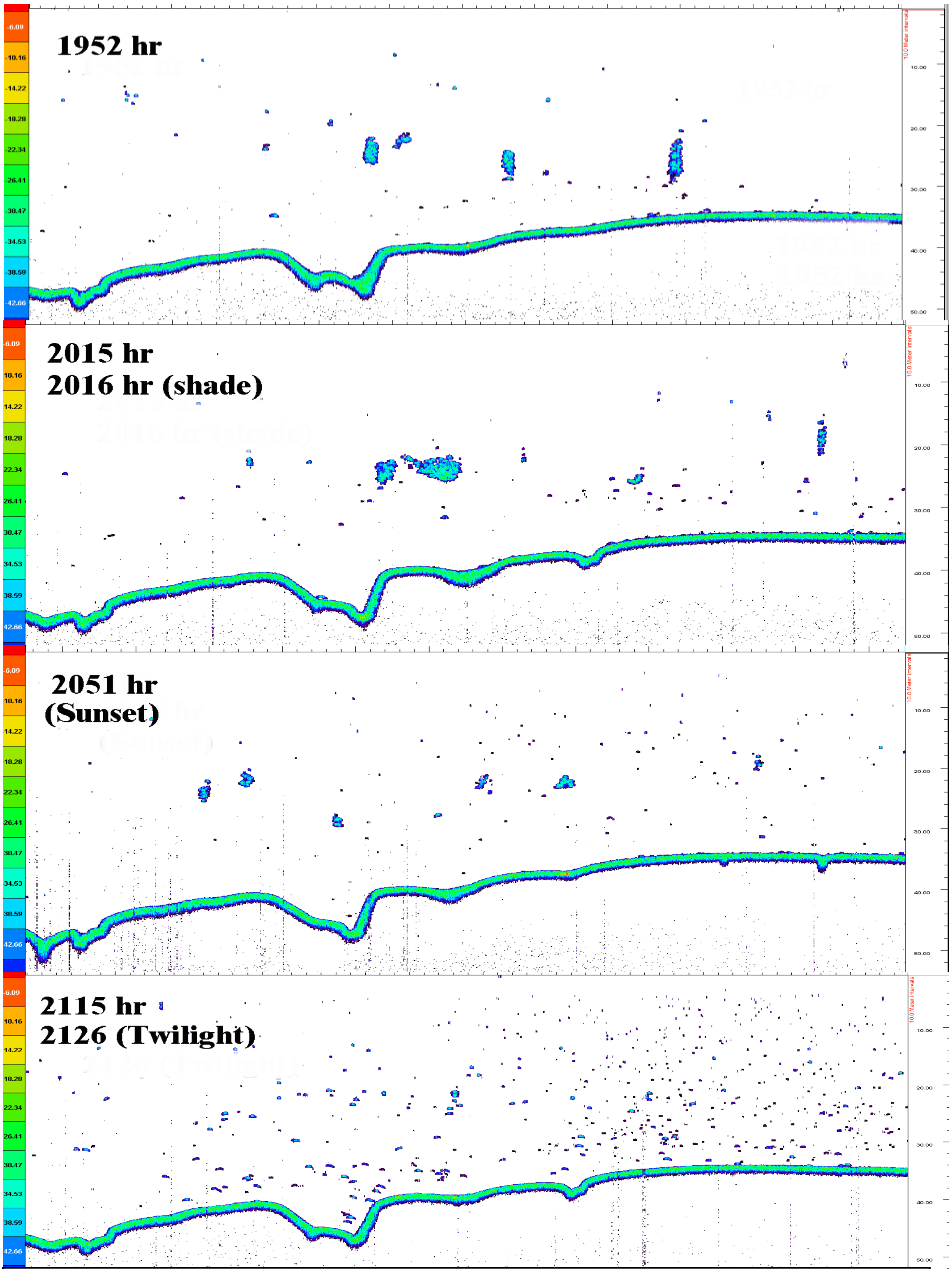

Figure 59. Fish aggregation and vertical distribution as illustrated during repeated transects from 1932 hr to 2118 hr during the transition from light to dark. The top time represents the time of the echogram and the bottom time or description provides information regarding the status of the sun light.

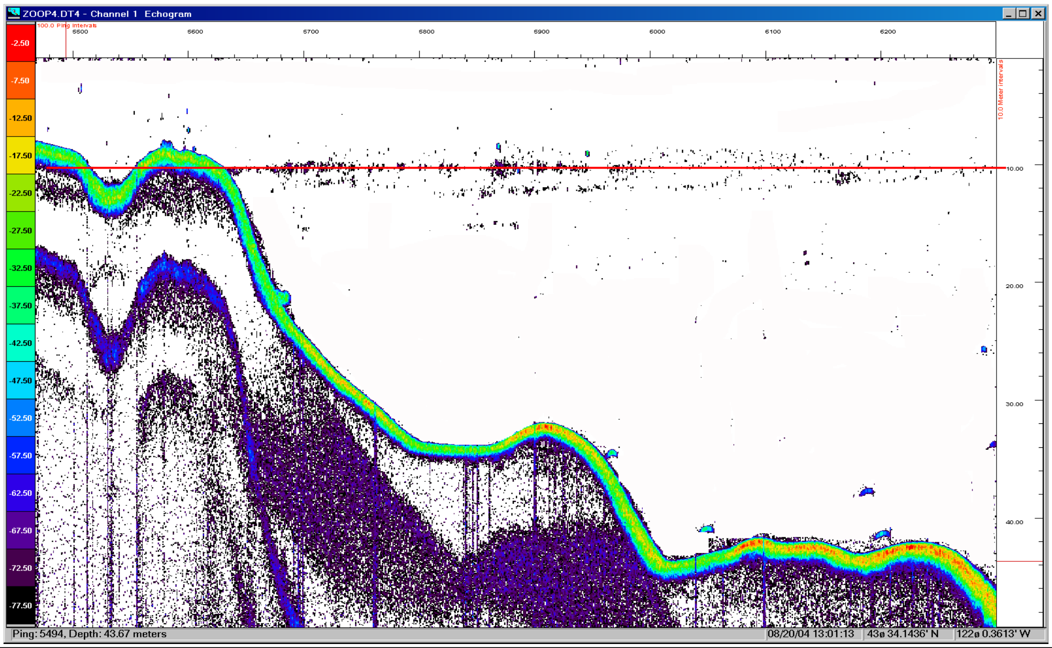

Figure 60. Echogram of zooplankton (generated using a threshold of - 80 dB) during the daytime on the north end of Odell Lake, August 20, 2004, 1300 hr. The horizontal red line represents 10 m. Spurious signals were edited from the echogram.

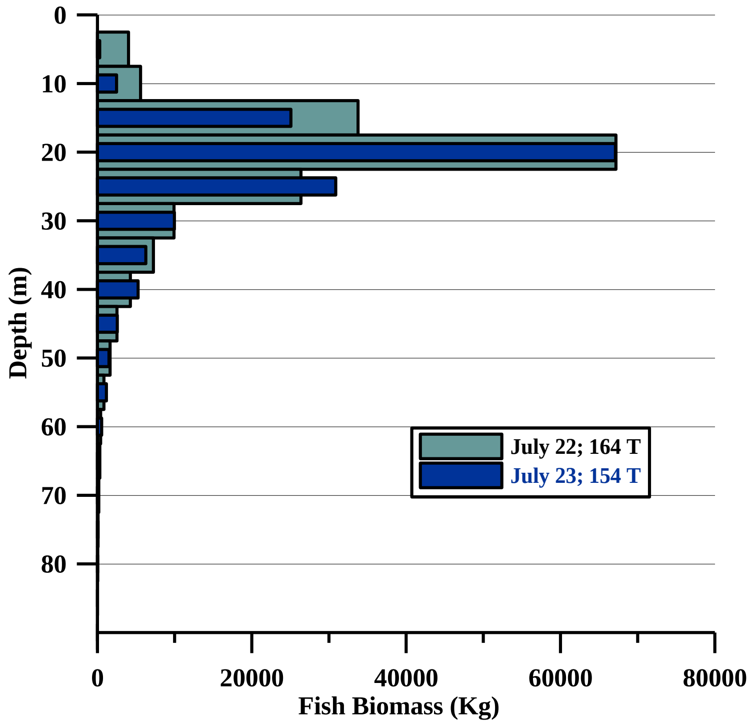

Figure 61. Fish biomass versus depth class measured on the nights of July 22 and 23, 2004. Total fish biomass for each run is shown in the legend.

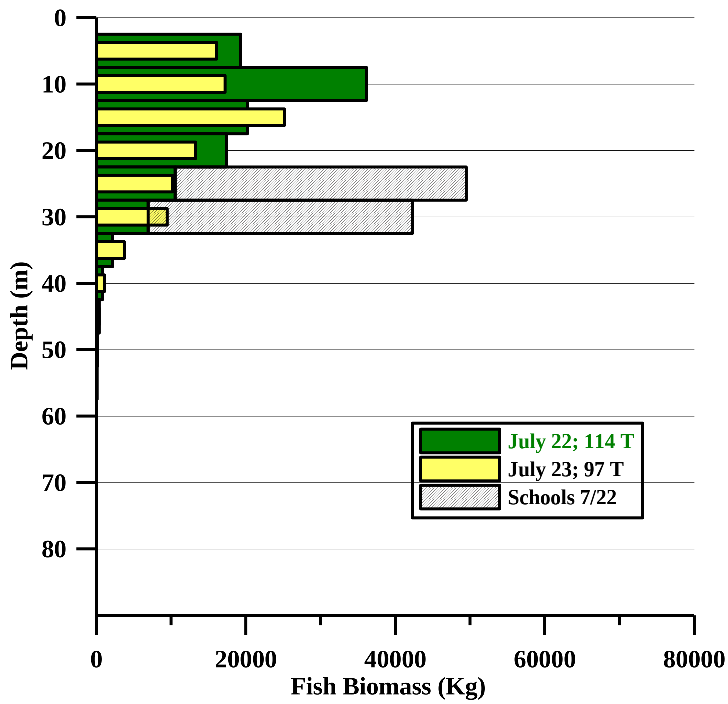

Figure 62. Fish biomass based on daytime runs (July 22 & 23). The estimate of schooled fish is derived from the measurement of fish biomass at night.

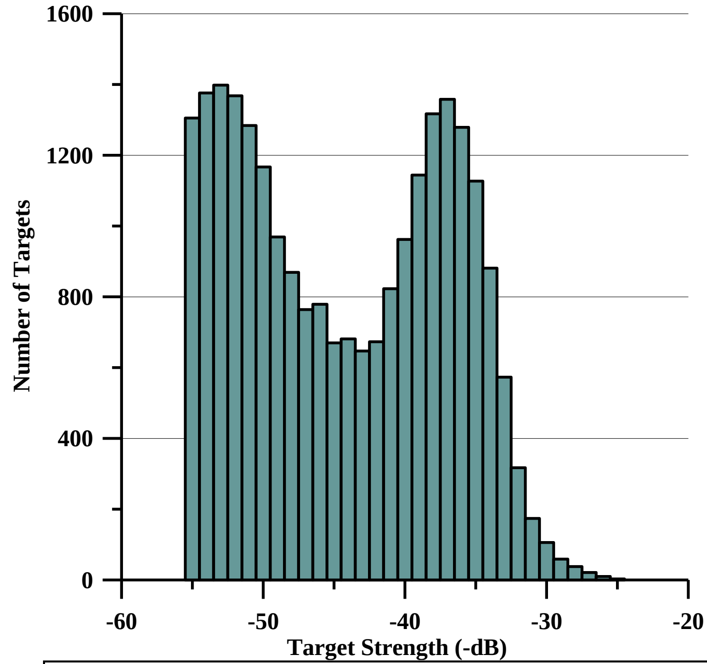

Figure 63. Number of fish targets by target strength based on the July 22 night time survey.

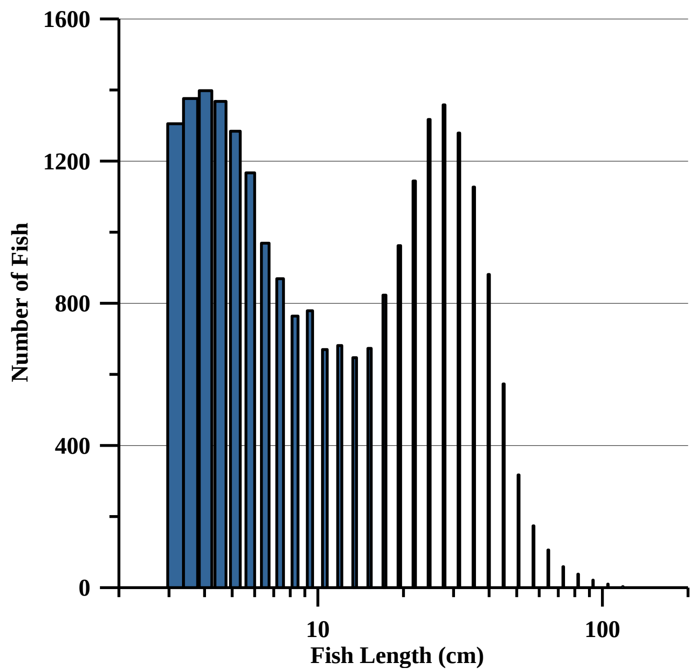

Figure 64. Number of fish by estimated fish length, based on Love's equation. Width of bar varies because of the log-scale and does not signify any data attributes.

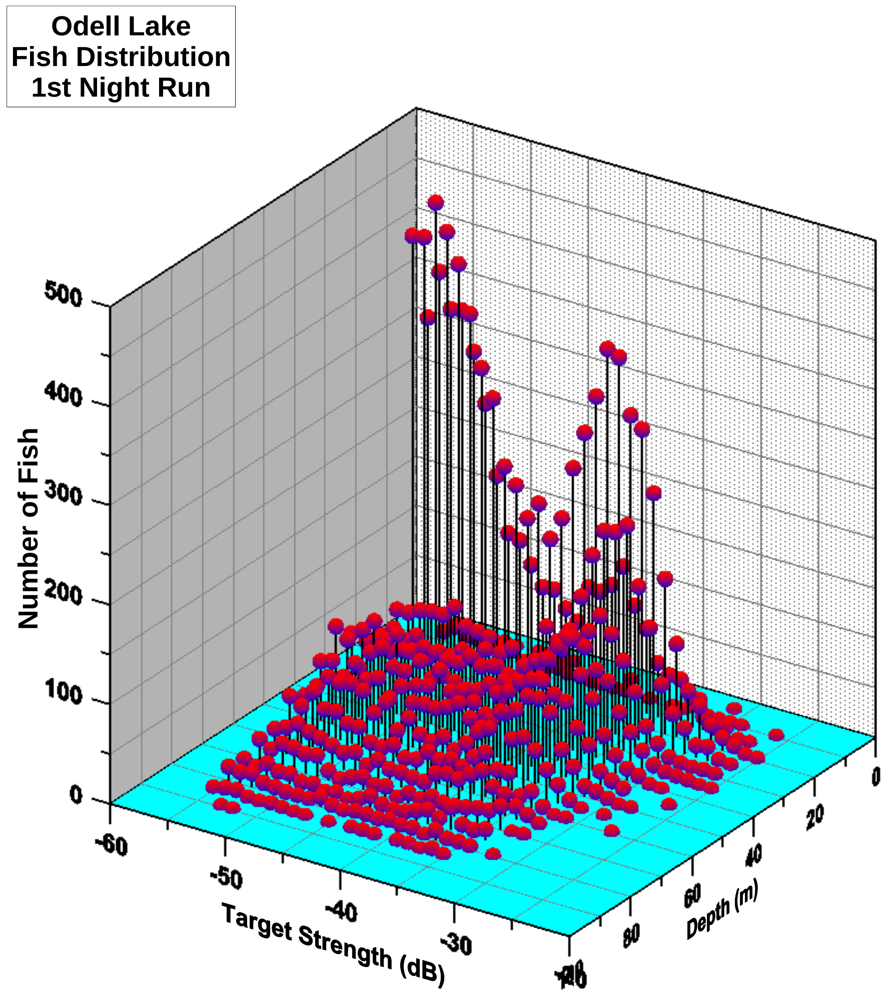

Figure 65. Distribution of fish targets arrayed by target strength and depth for the night run of July 22, 2004. Abundance is displayed on a linear scale.

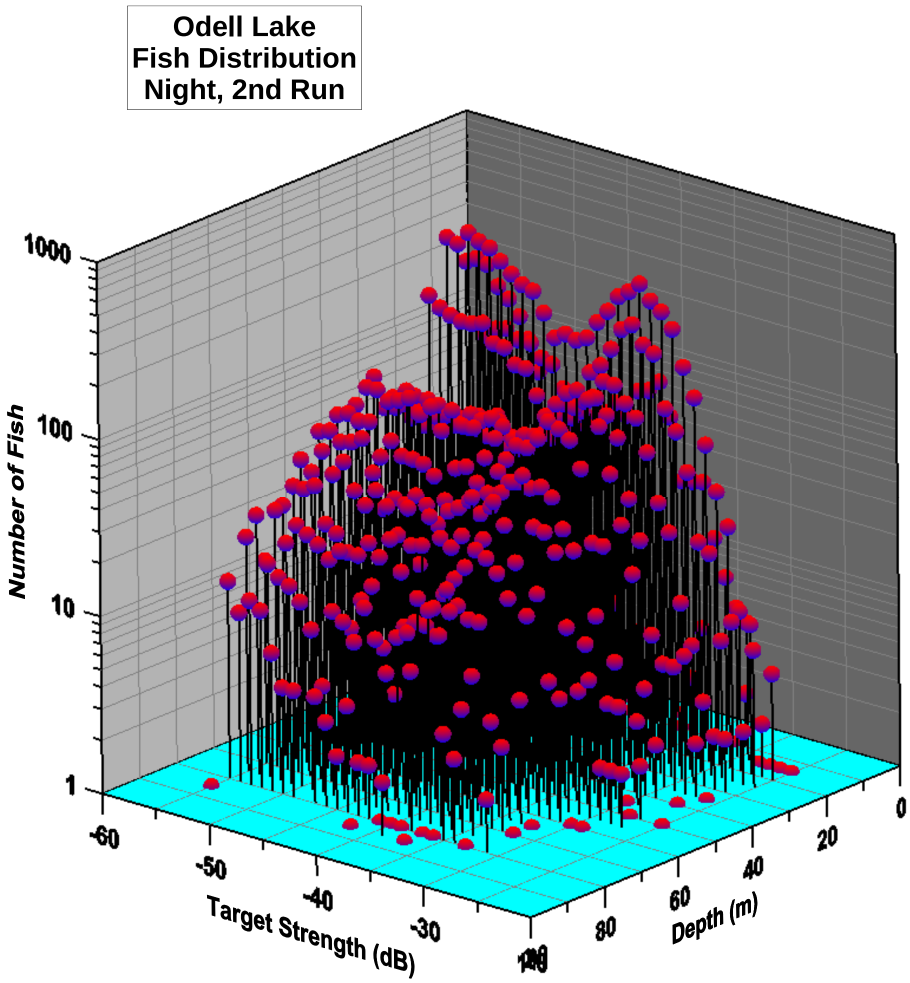

Figure 66. Distribution of fish targets arrayed by target strength and depth for the night run of July 23, 2004. The abundance axis is displayed on a logarithmic scale.

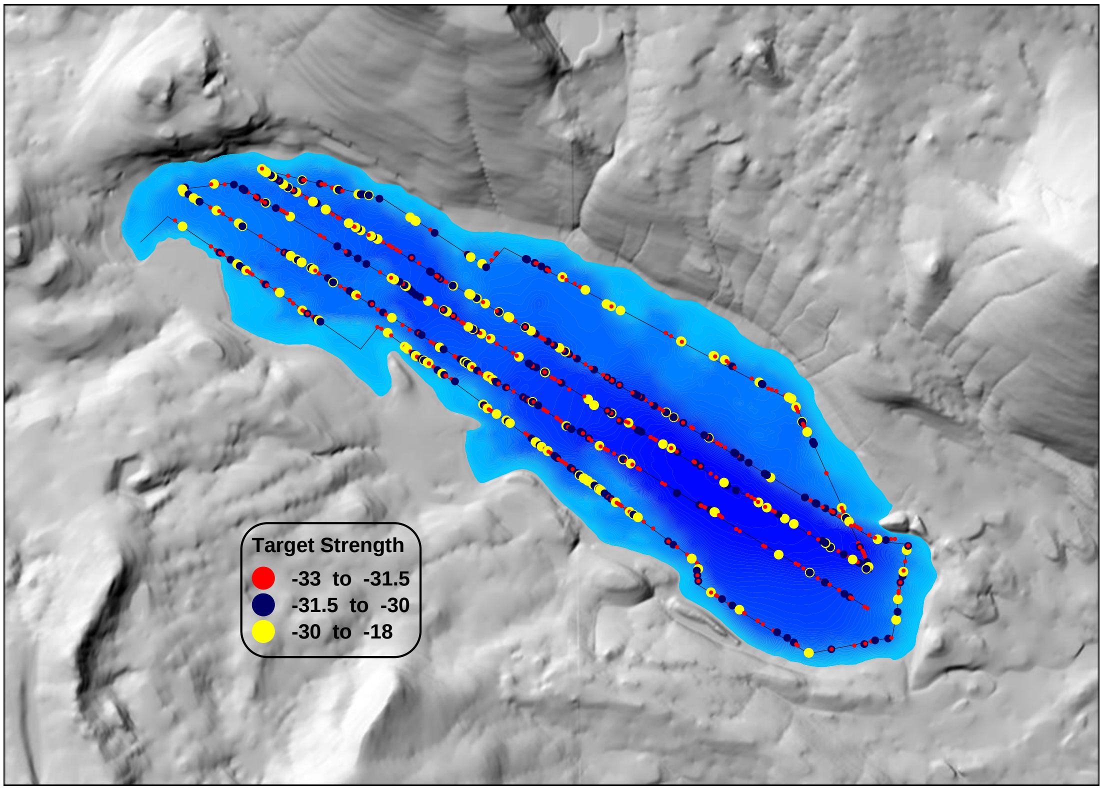

Figure 67. Spatial distribution of the larger fish classed by target strength (dB) from the first night run.

DISCUSSION

1. Water Quality

The water quality in Odell Lake shows evidence of high primary production. The biovolume of the dominant phytoplankton taxa are comprised of cyanobacteria (*Anabaena flos-aquae*) diatoms (*Fragilaria crotonensis, Synedra radians, Tabellaria fenestrata*), and cryptophytes (*Cryptomonas erosa*). These species are typically associated with eutrophic waters and generally require high availability of phosphorus. Because of the high phytoplankton biomass Odell Lake experienced high pH values, approaching or exceeding pH 10 during 2004. Cell counts of *Anabaena* reached 111,000 cells/mL on July 21 at the east station and achieved 335,000 cells/mL at Serenity Bay on July 19, 2004 (the latter data collected by the DNF). Transparency in Odell Lake was measured at 1 m in mid-July and averaged 4 m during 2004. This compares with transparency values exceeding 12 m in 1940 and 1941 measured by Newcomb and co-workers. The measurements reported by Newcomb were collected in September 1940 and June 1941. However, one transparency value of 11.5 m was measured in Odell Lake in 2004 following the collapse of the *Anabaena* bloom. Transparency appears to have declined steadily from 1941, although there are no recorded observations of transparency between 1941 and 1968 to help determine the form of the decline (Figure 68). One of the more interesting aspects regarding the apparent reduction in transparency is that as late as 1971, the highest transparencies occurred in the summer (Figure 69). The lower transparencies reported by Lewis (1972) were in the spring and fall, which may have been associated with higher densities of diatoms. The high transparency in the summer of 1971 indicates low primary production and low availability of nutrients in the photic zone. In contrast, the shape of the transparency curve in 2004 is opposite that observed in 1971 and is directly related to high densities of *Anabaena* and other phytoplankton taxa (Figure 70). Although Secchi disk transparency in 2004 was directly related to phytoplankton biovolume, Lindsay and Lewis (1978) found no statistical relationship between Secchi disk values and phytoplankton biomass from 1969 to 1976. The only significant relationship they observed was between Secchi disk transparency and the density of the copepod, *Cyclops bicuspidatus*.

Concentrations of chlorophyll *a* reached a peak value of 50 µg/L in July at the east site. In contrast, the chlorophyll concentration measured on the same day at the west end was 3 µg/L. The concentration at the center station was intermediate between these two extremes. Because the east site is still almost 2 km from the east end of the lake, had chlorophyll been measured at the east shore of the lake, the concentrations may have been considerably greater than 50 µg/L. It is surprising then that the concentration of chlorophyll at the outlet, Odell Creek, during the July sampling event was only 34 µg/L.

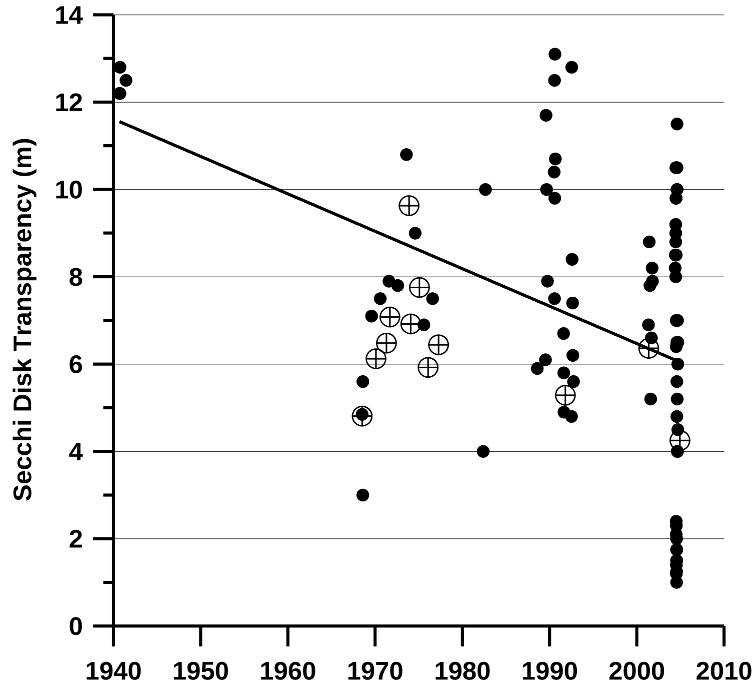

Figure 68. Secchi disk transparency in Odell Lake measured since 1940. Disk symbols represent means of seasonal (usually June-Sept) measurements. The linear fit explains only 17 percent of the variance.

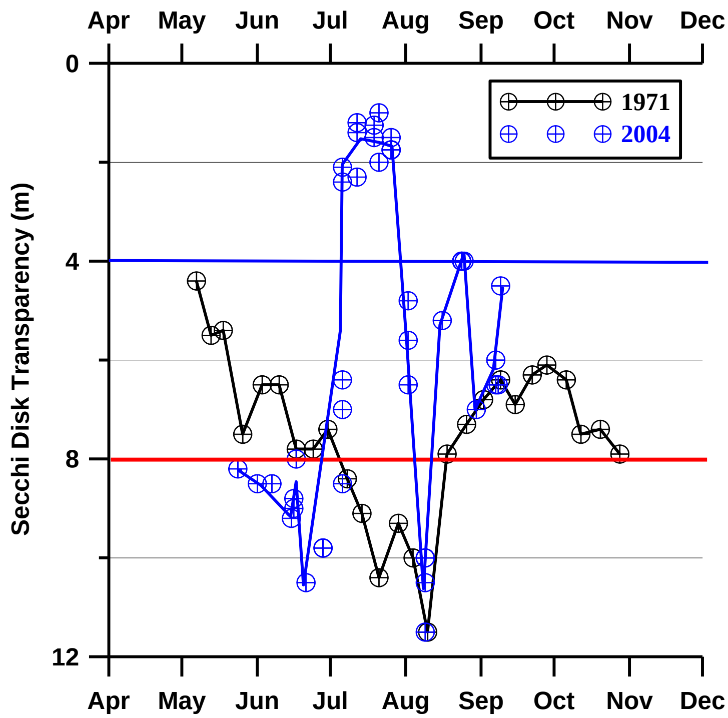

Figure 69. Secchi disk transparency reported by Lewis (1972) for 1971 and data collected in 2004 by DEQ. The red line is the average transparency for 1971 and the blue line is the average for 2004.

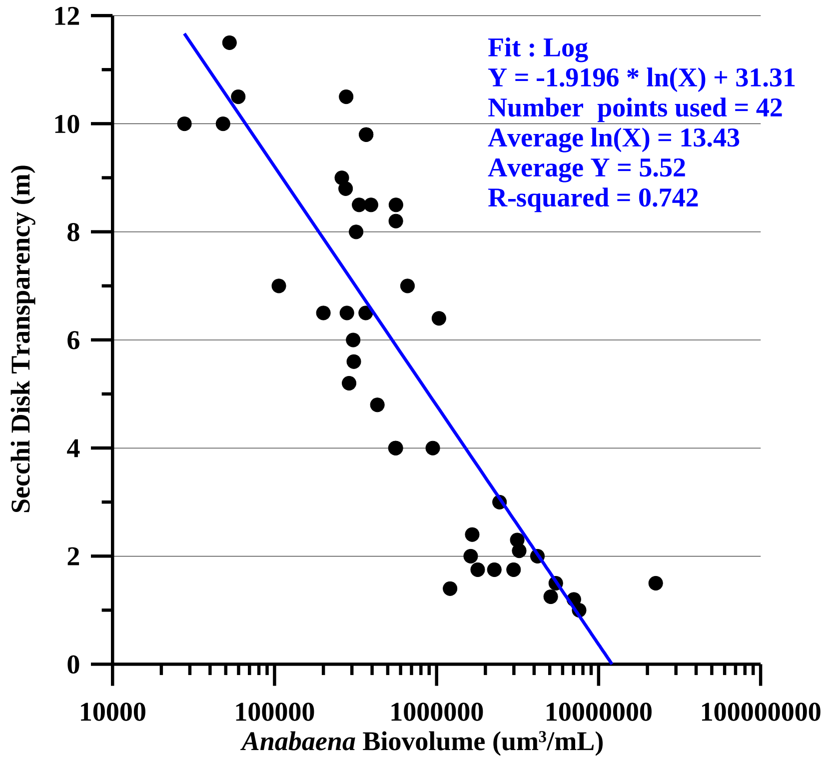

Figure 70. Secchi disk transparency versus phytoplankton biovolume for surface samples in Odell Lake, summer 2004. Data from DEQ and the DNF.

The pH values in the surface waters of Odell Lake were very high. The continuous monitoring probe near the surface on the west end of the lake never dropped below pH 8.5 during the entire deployment period. Even the sonde deployed at the east end of the lake at a depth of 15 m showed several values exceeding pH 8.5. pH values peaked with the phytoplankton populations, but still exhibited surprisingly high pH after the *Anabaena* bloom had "crashed".

Conductivity, which is usually fairly stable in a large lake such as Odell Lake displayed a 25 percent increase in the July measurements. This same pattern was observed in the conductivity measurements collected continuously on the west site. Since conductivity is measuring the sum of the ionic charges in the water, we should be able to observe a comparable shift in one of the major ions. However, when we examine calcium and other ions, we observed no substantial change during July. We are unable to resolve this anomaly at this time.

Dissolved oxygen measurements showed supersaturated conditions in the surface waters of Odell Lake during the *Anabaena* bloom in July, but most of the surface DO measurements were close to saturation. The bottom waters showed a continuous decrease in DO concentrations throughout the study period. This likely reflects an oxygen demand on the system created by dead and decaying plankton settling through the water column. An oligotrophic lake will generally show oxygen levels near saturation through the water column. Eutrophic to hypereutrophic lakes often experience complete depletion of DO in the hypolimnion. In Odell Lake, we observe an intermediate condition. The large hypolimnion in Odell Lake has a large capacity to lose oxygen to decomposition reactions without totally exhausting the available supply. In addition, the high degree of turbulence in Odell Lake acts to replenish some oxygen to deeper waters. For example, the east end of Odell Lake shows a stabilization of DO concentrations, presumably through mixing of surface waters with deeper waters. The BOD concentrations are generally low in Odell Lake, with the exception of the spectacular increase in BOD in July. The large load of BOD caused by the phytoplankton bloom in July probably contributes to the depletion of dissolved oxygen observed later in the summer.

The nutrient situation is difficult to unravel in Odell Lake because many of the observations are at or near the method reporting limits (MRL). Even samples reported above the MRL can be difficult to interpret because the precision of the analyses makes it difficult to identify patterns in the data. This problem is particularly difficult to resolve for the measurements of total phosphorus, total Kjeldahl nitrogen, and ammonia. The results show the depletion of the PO_4 in the epilimnion in July, likely caused by the uptake of PO_4 to support the phytoplankton bloom. PO_4 remained low in the epilimnion for August and September which may explain why a major bloom was unable to develop later in the summer. This suggests that measurement of PO_4 may be useful to gage the potential for a major bloom to occur in Odell Lake. Obviously, additional data are needed to confirm the validity of this approach.

The nitrogen species were generally low in Odell Lake. The peak in TKN in July, showing decreasing values to the west end of the lake, is consistent with other results that indicate that much of the organic matter was being pushed to the east end of the lake. Concentrations of nitrate were low in the surface waters, but showed substantial increases in the bottom waters after July. Again, NH_3 concentrations were low and no meaningful interpretation seems possible.

Silica concentrations can be important in lakes because of the importance of silica to diatoms for constructing the frustules. Only dissolved SiO_2 was measured in Odell Lake and it is possible that much of the silica in the lake is contained in the planktonic diatoms. Silica concentrations show a comparatively large increase in July during the cyanobacteria bloom. This increase may have been caused by the collapse of the diatom population as it was temporarily out-competed by the cyanobacteria. Once the cyanobacteria bloom "crashed", the diatoms had an opportunity to proliferate and use much of the available silica. If the dissolved silica concentrations reported here represent most of the available silica, then silica may be a limiting nutrient for the diatoms in Odell Lake.

Reported concentrations of alkalinity were either 16 or 17 mg/L and thus show no temporal or spatial patterns. Total organic carbon measurements were generally low, although they follow the peak BOD observations seen in July.

2. Paleolimnological Analyses

a. Sediment Accumulation Rate

Titanium is a metal derived from erosional inputs from the watershed. It has no biological source and it does not interact in any biological reactions. Thus, its presence is an unequivocal signal of watershed erosion. The concentrations of Ti measured in the sediments ranged from 370 ppm at the base of the core to about 240 ppm at the top of the core (Figure 71). Samples of stream sediment collected by the USGS (Sherrod et al. 1983) in the Diamond Peak Wilderness showed an average titanium concentration of 0.711 percent (7,110 ppm). The one sample from Trapper Creek had a Ti concentration of 1 percent. The concentration of Ti in the sediment is less than 5 percent of the concentrations measured in the stream sediment. This small ratio of lake sediment-to-stream sediment concentrations indicates that the vast majority of material in the lake sediments is derived from autochthonous (in-lake) sources. Consequently, the increase in sediment accumulation rate (SAR) observed in the deep portion of Odell Lake reflects an increase in lake production. Erosional inputs play a very small component of SAR measured in the deep basin (deltaic deposits at the mouths of the major tributaries play a very small role in the overall sediment accumulation in Odell Lake). Nevertheless, short-term activities, most of which appear to be associated with large precipitation events, show a close association with peaks in the lake sediment concentrations of titanium.

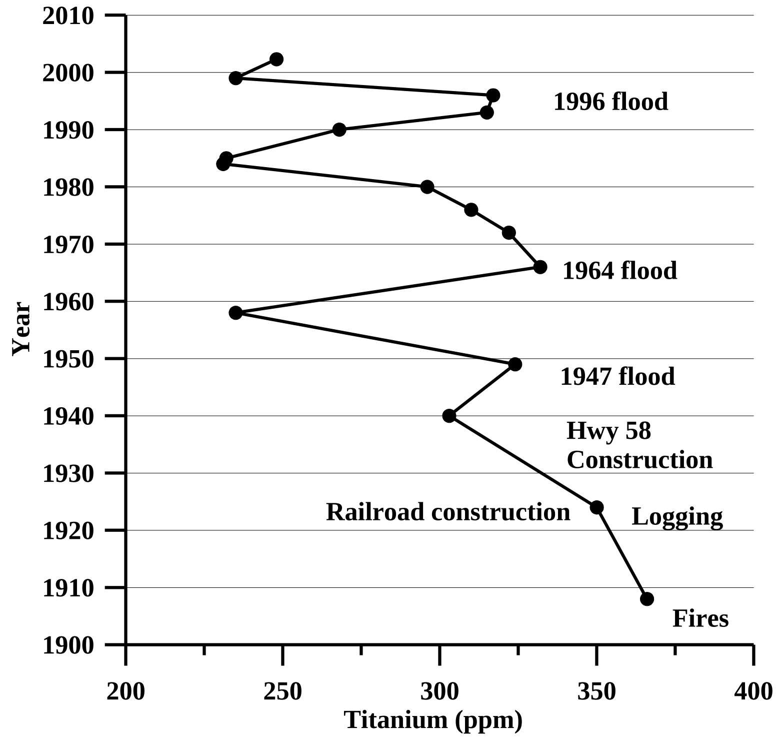

Figure 71. Concentrations of titanium in the sediments of Odell Lake plotted against age of sediments. Possible erosional events and activities are also displayed.

b. Sediment Nutrient Chemistry

Carbon, nitrogen, and phosphorus all show substantial increases in concentration and deposition rates in the sediments. Carbon shows the lowest rate of increase (2.5 fold), whereas phosphorus shows the greatest increase (5-fold). The higher rate of nutrient deposition to the sediments suggests that nutrients that were formerly exported from Odell Lake are now incorporated into biomass and retained in the lake. Some of these nutrients become available to further stimulate phytoplankton growth in the lake. The variation in retention of nutrients may reflect the volatility of carbon and nitrogen which are both subject to diagenesis that can result in release of carbon dioxide and ammonia to the atmosphere. In contrast, phosphorus is not volatile and is more likely to be retained in the lake. The increases in concentrations of carbon, nitrogen and phosphorus all begin at about 22 cm depth, corresponding to a date of 1966 (+/- 3 yrs).

Meyerhoff (1977) measured nitrogen and phosphorus concentrations in the sediment core he collected from Odell Lake circa 1975. The results show that N and P both exhibit consistent increases starting at about 6 cm depth in the sediment (Figure 72). Our data display an increase in C, N, and P starting at about 22 cm depth. There appears to be reasonable agreement in the timing of the nutrient increases between our data and that of Meyerhoff's when one accounts for compaction of sediments that would have occurred over the last 30 years.

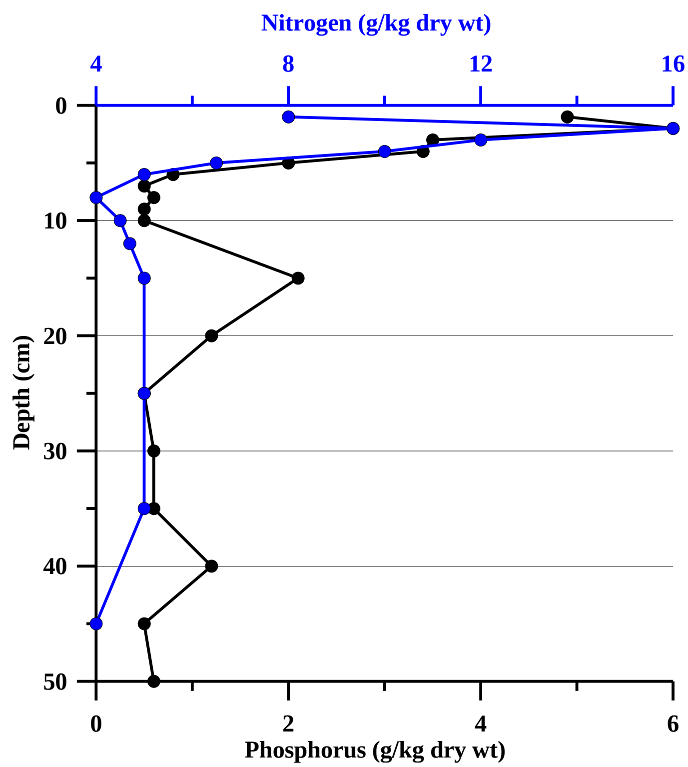

Figure 72. Concentrations of nitrogen and phosphorus for the sediments from the deep core in Odell Lake reported by Meyerhoff (1977).

c. Diatoms

The changes in diatom community composition suggests substantial changes in water quality. The first change, which occurred in the 1800's, involved an increase in planktonic pinnate diatoms typically associated with mesotrophic to eutrophic conditions, particularly *Aulacoseira granulata* and *Asterionella formosa*. However, other species strongly associated with high quality waters such as *Aulacoseira subarctica* remained abundant. In addition there was no change in the attached (non-planktonic) taxa that grow on the substrate. High transparency favors growth of attached diatoms since they can extend into the deeper areas of the lake. Their lack of change during this period suggests that there was probably little change in the overall transparency of the lake in the 1800s. The ratio of diatoms to cysts remained constant through this period, suggesting that there was no major increase in overall abundance of planktonic diatoms or at least no change in the ratio of diatoms to chrysophyte cysts. Since this change apparently occurred prior to significant European settlement in the area, it is unclear what may have caused this change. The effects of forest fires are usually short-lived in lakes. Once vegetative cover returns, nitrogen exports from the watershed decrease rapidly and phosphorus inputs from erosion quickly stabilize.

The greatest change in the diatom community composition occurred circa 1966 (+/- 3 yrs) as planktonic diatoms with preferences for high nutrient concentrations increased and low-nutrient species dramatically decreased. During this period, *Fragilaria crotonensis* became common and *Tabellaria flocculosa* appeared. *Aulacoseira distans* virtually disappeared and *A. subarctica* declined sharply. The non-planktonic diatoms, as a group, showed a large decline during this period and the ratio of diatoms to cysts increased by an order of magnitude. Thus, both the qualitative and quantitative changes in the diatom community show that in the 1960's Odell Lake became mesotrophic to eutrophic. However, the diatom community composition at the base of the core indicates that Odell Lake would not be classified as a typical oligotrophic lake. There were a number of taxa present that would indicate the lake was reasonably productive and would more likely be considered intermediate between oligotrophic and mesotrophic.

Meyerhoff analyzed the sediments in Odell Lake for diatom remains, but the stratigraphic data are only reported as dominant genera, which makes it difficult to assess changes in community composition (Figure 73). Meyerhoff however does report major changes in the relative abundance of *Melosira* (*Aulacoseira*) and *Stephanodiscus* at 10 cm.

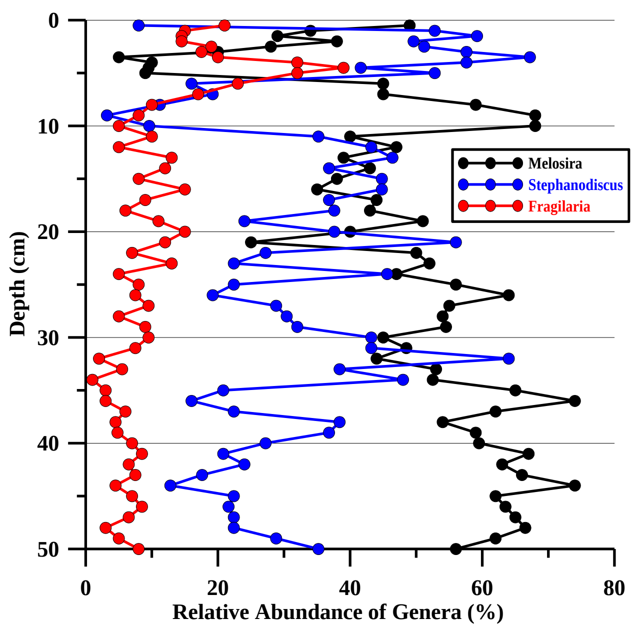

Figure 73. The relative abundance of the three most common genera in Odell Lake sediments reported by Meyerhoff (1977). Note that the genus *Melosira* is now reported as *Aulacoseira*.

d. Akinetes

The density of cyanobacterial akinetes showed only a modest increase in the sediments of Odell Lake. However, when the density of akinetes is adjusted for the increase in the sediment accumulation rate, the deposition rate of akinetes to the sediment shows a logarithmic increase (Figure 74). These akinetes were identified as *Anabaena spp*, which is the genus associated with the blooms currently present in the lake. The deposition rate of the akinetes first shows an increase at 25 cm corresponding to 1961 (+/- 3.5 yrs) and reaches a peak at 10 cm (1992 +/- 1 yr). Thus, the date of the first increase in *Anabaena* akinete deposition is not significantly ($P < 0.05$) different than the date that the diatoms showed a major change in composition. *Anabaena* was present in Odell Lake prior to European settlement, but the deposition rate of akinetes to the sediments is now about an order of magnitude greater than pre-development conditions.

The pattern of phosphorus concentrations in Odell Lake sediments is similar to the akinete deposition, which may reflect a causal relationship (Figure 74). The increase in abundance of cyanobacteria akinetes in Odell Lake appears to slightly precede the changes in the sediment phosphorus concentrations which could be caused by the die-back of cyanobacteria and diatom populations and settling of the decaying organic matter into the sediments.

Anecdotal information based on conversations with several long-term residents (identified in the Acknowledgements) indicated conflicting recollections of past conditions in Odell Lake. Some residents and long-time fishermen indicated that "algal blooms" have been present in the lake for a considerable part of the 20th century. Others recollect that prior to the 1960's the lake was much clearer. We believe that both of these sets of recollections are consistent with the records in the lake sediments. The akinete data show that *Anabaena* has been present in the lake for at least hundreds of years. It would be possible for small (low density) blooms of *Anabaena* to briefly develop and disappear rapidly. Those present would see these fleeting episodes, yet those who only visited the lake occasionally would be more likely to see the lake in its "clear" condition.

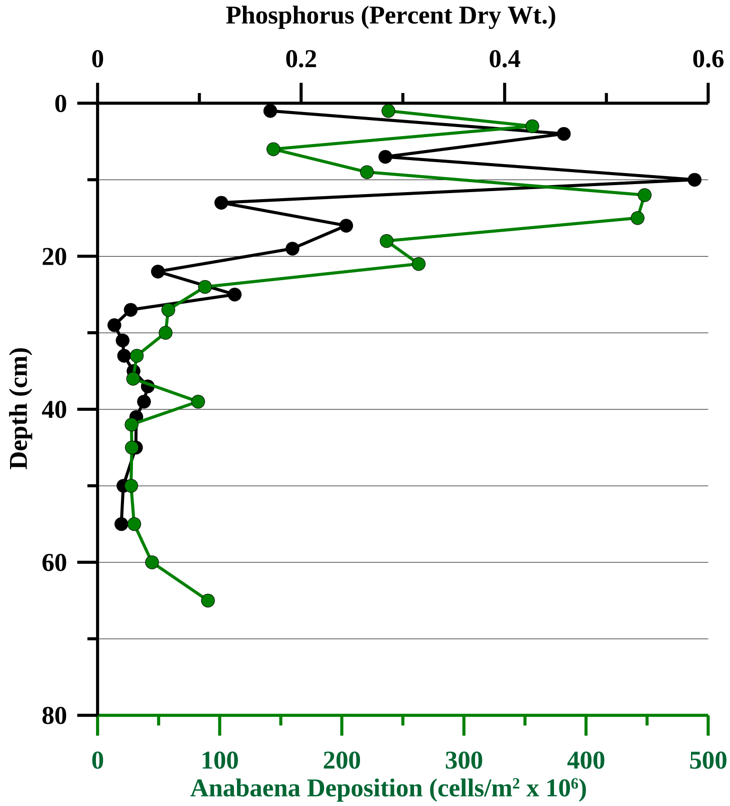

Figure 74. *Anabaena* akinete deposition rates and sediment phosphorus concentrations versus depth in Odell Lake.

Meyerhoff (1977) did not measure cyanobacteria akinetes, but he did examine sedimentary chlorophyll degradation products (SCDP) to assess possible changes in phytoplankton production. The results show a sharp increase in SCDP starting at about 7 cm and extending to the surface (Figure 75). Meyerhoff did not measure isotopic tracers to estimate age of the sediments. However, if we add the additional sediment we measured from 2004 to 1975 (19 cm) to the 7 cm depth in Meyerhoff's core, it would place the date of this increase in SCDP at circa 1958. Assuming there was additional compaction of the overlying sediments, the actual date is probably more recent and may correspond to sometime in the 1960s. These results suggest that primary production increased dramatically at this point, although the interpretation of SCDP can be problematic in some lakes because of digenesis in the sediments leading to incomplete preservation of the algal pigments.

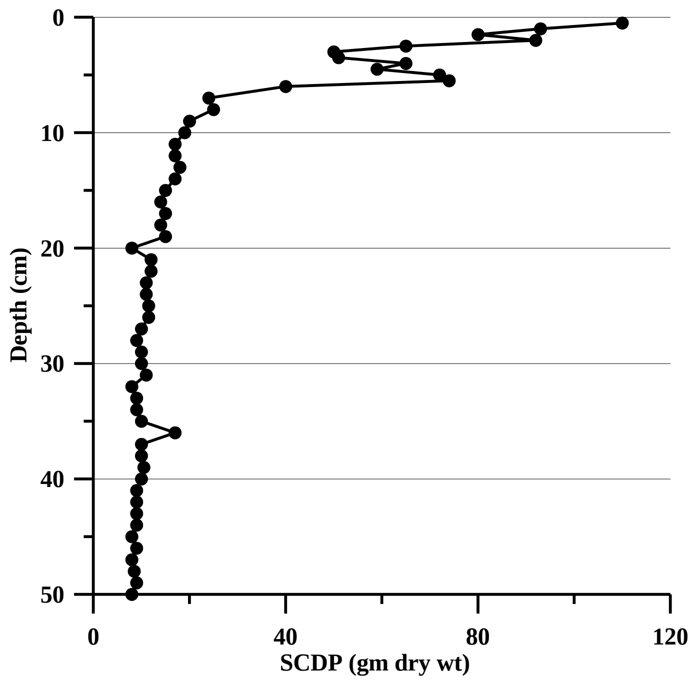

Figure 75. Changes in sedimentary chlorophyll degradation products (SCDP) measured in the sediment of Odell Lake by Meyerhoff (1977).

e. Chironomids

The patterns in deposition of fossil chironomid head capsules suggest that the number of taxa may have declined from pre-settlement times, although the changes are so erratic that the trend is not significant. Similarly, there are a much higher proportion of filter-feeders/collectors in the recent sediments, yet one observation from pre-settlement times also showed a high proportion of these types of chironomids. The pollution tolerance of the fossil chironomids also shows no significant trend over the period of record. Thus whatever changes may have occurred with respect to the chironomids, they have been too subtle to detect.

3. Fisheries

Our hydroacoustic analysis of the fisheries in July 2004 showed that there was over 100 metric tons of fish present. The two nighttime runs showed good precision in the biomass estimates, but obviously these data do not allow us to describe possible changes in fish biomass among years. The daytime runs were also reasonably consistent in the biomass estimates, but the daytime runs measured considerably fewer single targets compared to the night runs. A hydroacoustic run conducted during the evening documented fish schools disaggregating and the vertical movement of fish up into the metalimnion. Lindsay and Lewis (1978) used trawling to sample the fish aggregations during the daytime. They concluded that the large schools of fish they observed with hydroacoustic techniques were kokanee.

The fishery in Odell Lake is comprised of three indigenous salmonids, three introduced salmonids, and the introduced minnow, tui chub. Of the indigenous species, the bull trout population has shown a severe decline from times when bag limits were deemed unnecessary to current conditions in which the spawning population numbers less than 100 individuals. The niche formerly occupied by the bull trout is now occupied by the lake trout, which appear reasonably abundant based on creel surveys. The status of the native whitefish population is unknown, although trap nets set close to shore have yielded numerous whitefish (Ted Wise, ODFW, personal communication 2005). Rainbow trout appear to be reasonably abundant in Odell Lake, although it is unknown to what extent the original genetic stock remains intact following the stocking of other strains of rainbow trout. Brook trout are abundant in the Odell system as evidenced by stream surveys during spawning periods. Two species of introduced fish, the kokanee and the tui chub, are both abundant and are both known to prey heavily on zooplankton. Tui chub prefer shallow, warm water habitat (Wydoski and Whitney 2003) and are caught in near-shore trap net set. The chub were common in the lake when first reported by Newcomb (1941) and it is unknown when they were first introduced. Although the chub are common in the near shore environment, we have no information regarding the extent that they may utilize the pelagic zone in Odell Lake. Previous observations of this species would suggest that extensive use of the pelagic zone by tui chub in the spring and summer is uncommon (Bird 1975). Kokanee, formerly absent from Odell Lake, now appear to be one of be the dominant fish species (based on creel surveys, ODFW unpublished data). Our hydroacoustic analysis of the fish populations identified a large contingent of fish schooled below the thermocline during the day and moving up into the metalimnion during the evening. This is consistent with the data from Lindsay and Lewis (1978) who reported similar behavior based on their hydroacoustic analyses in Odell Lake. Averett (1966) first identified the preference for some kokanee to spawn in areas of groundwater discharge along the shoreline; this analysis was extended by Lindsay and Lewis (1978) who identified eight spawning sites, all associated with groundwater input (Figure 76). The kokanee hatch in the spring and are found in the open water in abundance by late spring. (Lindsay and Lewis 1978).

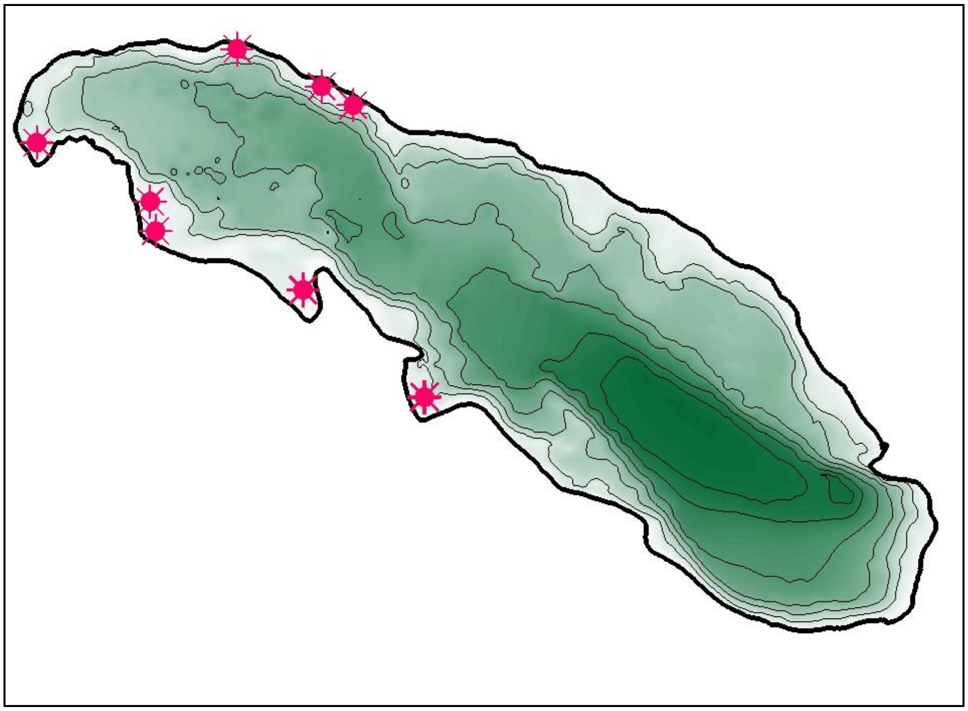

Figure 76. Spawning areas (in red) used by kokanee in Odell Lake in 1974 and 1975 (after Lindsay and Lewis 1978)

Another important feature of kokanee is that population abundance can vary greatly from year to year. Although angler success may not always provide a precise indication of the population size, it can provide insight into the dynamic nature of kokanee abundance (Figure 77). The results suggest that population abundance of kokanee have varied by almost an order of magnitude in Odell Lake. There are two morphologically distinct races of kokanee in Odell Lake, an early race which spawns from mid-September to November and the late race which spawns from mid-October through December (Lindsay and Lewis 1978). Shelter Cove was the site with the greatest fry production in Odell Lake, accounting for an average of 68 percent of the recruitment in 1975 and 1976. Since an average of 82 percent of the spawning population in Shelter Cove was comprised of late spawners, we assume that the late race is the dominant group of kokanee present in Odell Lake. If we assume an average weight of 300 g per fish (Averett and Espinosa 1968), these catches would indicate that the average annual take was 14 metric tons of kokanee during 1964 to 1977. Although we are unsure of the current abundance of kokanee in Odell Lake, these estimates of average catch of kokanee and our estimates of over 150 metric tons of total fish in the lake offer some indication that most of the fish targets we observed were kokanee. Another aspect to consider with the potential effect of nutrient contributions from fish is that the rate of nutrient excretion will be related to the feeding rates of the fish. Since fish feed more actively in the warmer months, their contributions will be more focused during spring, summer and fall.

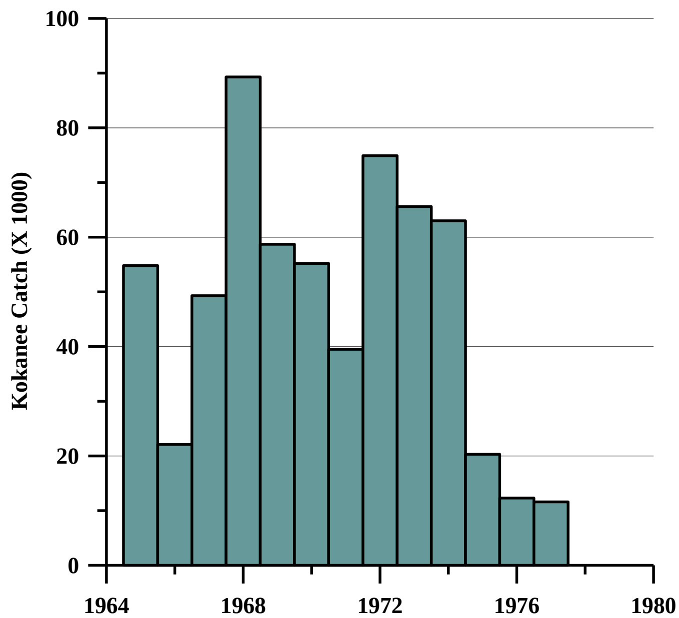

Figure 77. Kokanee angler catch based on creel surveys in Odell Lake (after Lindsay and Lewis 1978).

4. Nutrient Loads

Preliminary nutrient loading estimates were prepared by using the data available from the sampling conducted in 2004. There is considerable uncertainty in the nutrient loading estimates because of the few samples of nutrients collected on the tributaries, the absence of continuous discharge data on the tributaries, the absence of any groundwater chemistry or flux data, the lack of data to characterize precipitation chemistry or watershed variation in precipitation inputs, and the absence of seasonal data throughout a water year. Nevertheless, some ideas on the nature of nutrient budget can be derived from the data collected, supplemented with literature values (Tables 8 -11).

Table 8. Estimated annual loads of total nitrogen for Odell Lake.

Source	Current Low		Current High		Current Mid		Pre-Development	
	Kg/yr	Percent	Kg/yr	Percent	Kg/yr	Percent	Kg/yr	Percent
Streams	1825	14.2	1825	6.0	1825	8.4	1825	35.9
Groundwater	365	2.8	365	1.2	365	1.7	365	7.2
Precipitation	2102	16.4	3679	12.0	2890	13.3	2890	56.9
Homes	110	0.9	450	1.5	280	1.3	0	0.0
Resorts	30	0.2	110	0.4	70	0.3	0	0.0
Fish	8400	65.5	24168	79.0	16284	75.0	0	0.0
Total	12832	100.0	30597	100.0	21714	100.0	5080	100.0

Table 9. Assumptions used to derive estimated annual loads of total nitrogen.

Source	Discharge (m^3/day)	Discharge (m^3/yr)	TN (ug/L)	TN (kg/m^3)		TN Load/yr
Streams	100000	36500000	50	0.00005		1825
Groundwater	40000	14600000	25	0.000025		365
		51100000				
						2190
	Precip (m)	Lake Area (m^2)				
Precip, Low	0.8	13830000	190	0.00019		2102
Pecip, High	1.4	13830000	190	0.00019		3679
Precip, Mid	1.1	13830000	190	0.00019		2890
	Tons (wet)	Tons (dry)	TN (% dry)	Efficiency (% retained)	Recycling factor to Metalimnion	Kg TN/yr
Fish, low	105	21	0.1	0.25	1	8400
Fish, high	159	31.8	0.1	0.25	5	24168

Table 10. Estimated annual loads of total phosphorus for Odell Lake.

Source	Lindsay & Lewis (1978)		Current Low		Current High		Current Mid		Pre-Development Mid	
	Kg/Yr	%	Kg/Yr	%	Kg/yr	%	Kg/yr	%	Kg/Yr	%
Watershed	443	68								
Streams			1825	42.9	1825	35.7	1825	39.0	1825	63.0
Groundwater			876	20.6	876	17.1	876	18.7	876	30.2
Precipitation	83	13	111	2.6	194	3.8	152	3.2	196	6.8
Summer Homes	53	9	11	0.3	45	0.9	28	0.6	0	0.0
Resorts	26	4	3	0.1	11	0.2	7	0.1	0	0.0
Fish			1428	33.6	2162	42.3	1795	38.3	0	0.0
Total	605	94	4254	100.0	5113	100.0	4683	100.0	2897	100.0

Table 11. Assumptions used to derive estimated annual loads of total phosphorus.

Source	Discharge (m^3/day)	Discharge (m^3/yr)	TP (ug/L)	TP (kg/m^3)		TP Load/yr
Streams	100000	36500000	50	0.00005		1825
Groundwater	40000	14600000	60	0.00006		876
		51100000				
						2701
	Precip (m)	Lake Area (m^2)				
Precip, Low	0.8	13830000	10	0.00001		111
Pecip, High	1.4	13830000	10	0.00001		194
Precip, Mid	1.1	13830000	10	0.00001		152
	Tons (wet)	Tons (dry)	TP (% dry)	Efficiency %	Recycling Rate	Kg TP/yr
Fish, low	105	21	1.7	0.25	1	1428
Fish, high	159	31.8	1.7	0.25	5	2162

Fluxes for stream inputs were generated using discharge derived from the CE-QUAL-W2 model water budget for the period of study and extending that to an estimated annual discharge. The concentrations of nutrients in the streams were derived from concentrations measured by DEQ during stream sampling in 2004 of the three largest tributaries (Trapper, Crystal, and Rosary). Fluxes of groundwater into the lake were also derived in a manner similar to that for surface water. Concentrations of phosphorus were assumed to be equal to the highest concentrations measured in any of the stream samples. Concentrations of nitrogen in the groundwater were assumed to be one-half that of the surface water values. The low estimate of precipitation was derived from the Odell East NOAA climatological station and the high estimate was assumed to be twice that, based on the Oregon map of annual precipitation (www.oregonstate.edu/index). Concentrations of phosphorus were derived from literature estimates as summarized in Eilers et al. (2003) for nearby Diamond Lake.

Loading estimates from the summer homes were based on estimates for occupancy multiplied by per capita values commonly used for human wastes (Chapra 1997). Low estimates from these septic sources assumed that 80 percent of the nutrients were removed or bound in the soil prior to reaching the lake. High estimates assumed that only 20 percent of the nutrients were retained in the watershed and 80 percent of the nutrients entered the lake. The septic inputs from the resorts were assumed to be equivalent to one-half of the summer homes, except that the discharge from Odell Lake Resort on the east end of the lake was assumed to be zero because of the expected groundwater flow-paths away from the lake (Gannett and Lite 2004).

Loading estimates from kokanee production are based on assumptions that 75 percent of the fish in Odell Lake are kokanee. Lewis (1972) estimated that over 90 percent of the fish in the pelagic zone, based on gill net sets, were kokanee. The estimates of fish nutrient content were taken from literature values for salmonid content and it was assumed that fish efficiency in converting prey to biomass was 25 percent. The recirculation rate of the nutrients excreted by the fish was assumed to range from a factor of 1.5 to 5. The actual rate of recycling is unknown, although the hydrodynamic modeling shows that there are ample opportunities for mixing in Odell Lake. Figure 78 shows the flow vectors for July 25 (near the time of the hydroacoustic fish surveys in 2004), illustrating strong west-to-east movement of surface waters. The water is driven down on the east shore and circulates below the epilimnion to the west end of the lake. Additional turbulence is created by the west-flowing water colliding with the irregular bottom near Km 4.5.

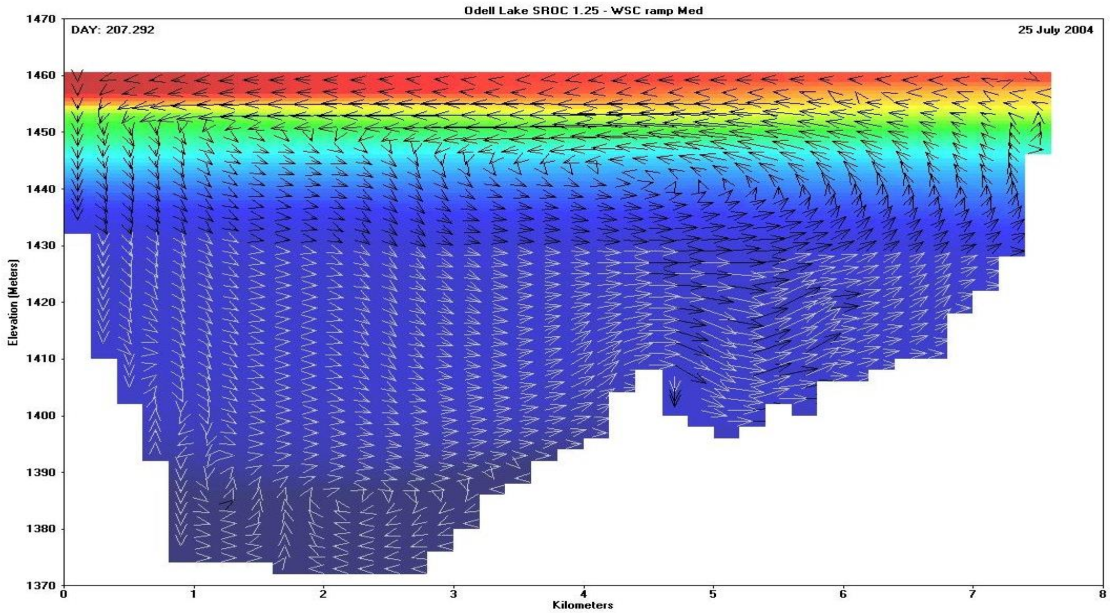

Figure 78. CE-QUAL-W2 model output showing vectors of water movement in Odell Lake on July 25, 2004. The east end of the lake is shown on the left.

The results of the nutrient budget assessment illustrate some important findings (Figures 79 and 80). First, contrary to several previous studies, we conclude that nutrient contributions from summer homes and resorts provide trivial loads of nitrogen and phosphorus to Odell Lake. Natural sources provide slightly over 57 percent of the phosphorus load to Odell Lake. Most of the remaining contribution appears to come from planktivorous fish. However, since the contributions from fish will be distributed more heavily in the spring and summer when the fish are actively feeding, the annual load from the fish underestimates its potential contribution to recycling nutrients into the photic zone. The single largest contribution to the nitrogen load that we calculate is derived from the planktivorous fisheries. However, the nitrogen budget currently does not reflect N-fixation from cyanobacteria. This source could exceed the other sources of nitrogen combined.

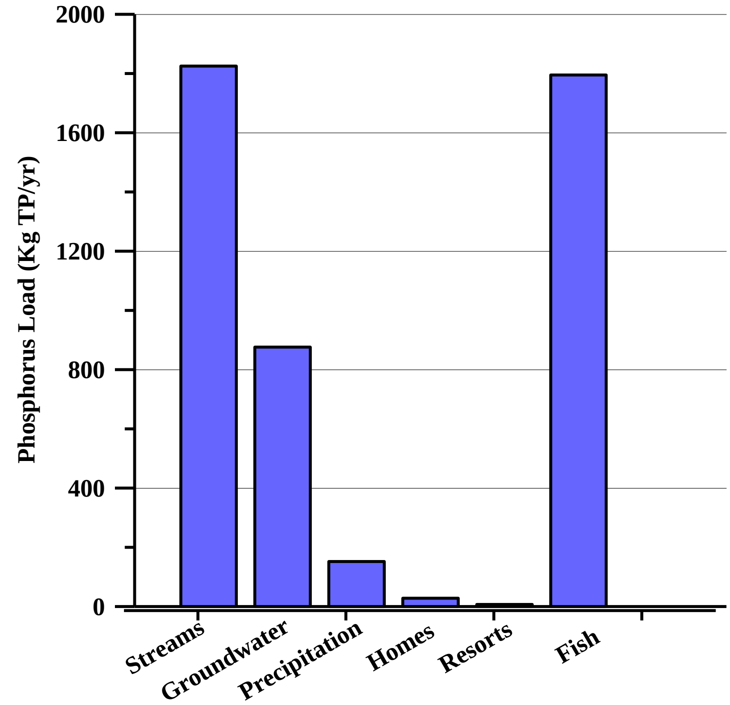

Figure 79. Estimated annual phosphorus inputs into Odell Lake. Shown are the values labeled as mid-range values for the current period.

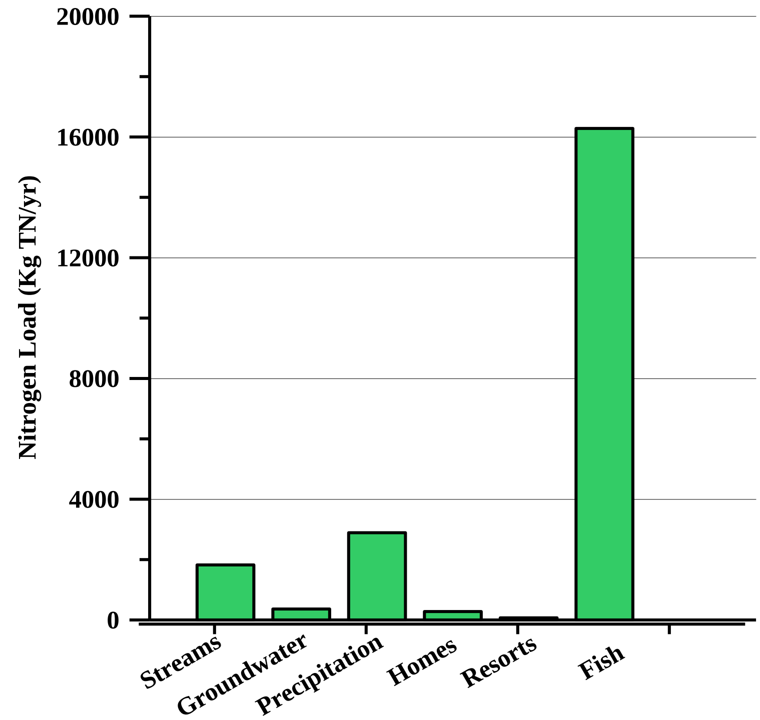

Figure 80. Estimated annual nitrogen inputs into Odell Lake. Shown are the values labeled as mid-range values for the current period.

SUMMARY and CONCLUSIONS

Odell Lake was sampled in 2004 to characterize its current and historical water quality. The current assessment of Odell Lake is that it exceeds water quality criteria for pH and possibly for dissolved oxygen saturation. It also has experienced intense blooms of *Anabaena* since at least 2001. These blooms, and accompanying high densities of diatoms, are indicative of eutrophic conditions. The maximum chlorophyll concentration measured in Odell Lake during 2004 was 50 µg/L, well above levels used to classify lakes as eutrophic. The minimum Secchi disk transparency measured in Odell Lake during 2004 was 1 m, compared to values over 12 m measured in 1940 and 1941. pH values in Odell Lake reached 10.0 and dissolved oxygen saturation exceeded 120 percent. Thus water chemistry and phytoplankton species composition and abundance show that Odell Lake is currently eutrophic and does not meet water quality criteria.

Changes in the Odell Lake were assessed over a 130+ year span by analysis of the lake sediments. The sediment accumulation rate has increased about five-fold over the period of record, largely in a linear manner. Analysis of titanium in the stream sediment compared to the lake sediment shows that over 95 percent of the accumulated material in the deep basin is derived from in-lake sources. Thus, the rate of sediment accumulation in Odell Lake is a direct measure of changes in productivity of the lake. The sediments show an apparent increase in carbon, nitrogen, and phosphorus. The greatest increase is for phosphorus (five-fold) and the lowest increase is for carbon (2.5 fold). The increases in concentrations of nutrients are most pronounced at a depth of 23 cm, corresponding to a modeled date of 1966 (+/- 3 yrs).

Biological evidence in the sediments to assess water quality changes was provided by analysis of fossil diatoms, cyanobacterial akinetes, and fossil chironomid head capsules. The diatoms showed two major changes in community composition, one which appeared to occur in the 1800s (the error of ^{210}Pb dating increases greatly with depth, such that there is considerable uncertainty with dates at the bottom of the core). The greatest change in diatom community composition occurs at a sediment depth of 24 cm, corresponding to a date of 1964 (+/- 3 yrs). At this date, there is a substantial increase in the proportion of diatom taxa associated with eutrophic waters. The non-planktonic species show a conspicuous decline, indicating that lake transparency declined. Cyanobacterial akinetes were present throughout the sediment core. However, the deposition rate of *Anabaena* akinetes increases logarithmically beginning at a depth of 25 cm in the sediment. The chironomids show an apparent decrease in the number of taxa and show an apparent increase in the proportion of filter feeders/collectors, although the relatively small sample size of intervals analyzed for chironomids (n = 13) precludes making any definitive conclusions regarding possible changes in the chironomid community composition.

The temperature monitoring and the hydrodynamic modeling of Odell Lake confirmed the presence of a large internal seiche. The internal wave generated by the strong westerly winds causes the depth of the thermocline to vary by 15 to 20 m in a 24 hr period. The wind drives warmer surface water from the west end to the east end of the lake. The warm water accumulates on the east end until either the wind wanes or the imbalance can no longer be sustained. The returning seiche collides with the west end of the lake, resulting in considerable mixing of waters even below depths of 30 m. The seiche moves with a periodicity of about 12 hrs. The temperature and wind data explain the prevalence of cyanobacteria at the east end of the lake. This end of the lake can be 2 to 3 ºC warmer than the west end. Furthermore, the cyanobacteria often accumulate near the surface and are thus subject to wind-driven effects.

The general nature and distribution of the fisheries were evaluated by use of hydroacoustics. Kokanee were first introduced into Odell Lake in the 1930s, but did not become abundant until a concerted kokanee stocking program was initiated in 1950. Prior to 1953, rainbow trout were the most numerous species present, but these were exceeded by both kokanee and lake trout in 1953 (Jennings and Lindland 1964). Since the 1960s, there has been a very successful sport fishery for kokanee. Mid-water trawls in Odell Lake from May to October, 1971 showed that 91 percent of the catch was kokanee. This contrasts with gill net sampling from 1955-1964 which showed that over 90 percent of the fish caught were tui chub (Jennings and Lindland 1964). The results confirmed that there is a large fish population in Odell Lake with a biomass of about 159 metric tons. A substantial component (about 54 tons) of this fishery is comprised of moderate size fish (median length of about 28 cm) that remain below the thermocline during the day and ascend into the metalimnion in the evening. The behavior, distribution, and size of these fish are consistent with attributes of kokanee that attempt to balance the energetics of prey acquisition with optimal temperature preferences (Lewis 1972).

Our analysis of phosphorus inputs into Odell Lake indicates that anthropogenic watershed sources, such as cabin and resort septic waste systems, comprise a very small percentage of the total inputs into Odell Lake. The wastes generated at the campgrounds have been contained in vaults since 1969 and are no longer a component of the nutrient inputs. Natural watershed inputs from precipitation, surface flows, and groundwater flows are relatively modest and cannot explain the massive blooms of *Anabaena* occurring in the lake. The lake sediments show a substantial enrichment of the lake beginning in the 1960s. Retention of phosphorus in Odell Lake has increased by up to an order of magnitude over pre-development values. Since we cannot identify external sources to account for these increases, we believe that the increases are associated with biological changes in the lake. The most likely mechanism for the increase in phosphorus retention is associated with the increase in the kokanee population. Kokanee now dominate the pelagic niche in Odell Lake and spend most of their life-cycle in the depth range of 5 to 30 m. In Odell Lake, this encompasses the entire metalimnion and the upper part of the hypolimnion. In the 1940s, this depth range would include the entire photic zone (assuming the photic zone is equal to twice the Secchi disk transparency of 12.4 m). The kokanee prey on zooplankton such as *Daphnia* and the efficiency of converting the prey to fish tissue is about 25 percent. The excretion products from the fish are highly labile (largely as NH_3 and PO_4) and can be rapidly assimilated by phytoplankton. Because of the vertical distribution of kokanee in and near the metalimnion and the high rate of mixing occurring in the lake because of the seiche, much of this phosphorus will become available for uptake by phytoplankton. Once the phosphorus is incorporated into the phytoplankton, it can then either be consumed by zooplankton or die and sink to the bottom. However, the very active internal mixing associated with the seiche will create additional opportunities for reacquisition of nutrients by phytoplankton. Thus, the retention of phosphorus in the sediments is a conservative estimate of the degree to which phosphorus availability has been enhanced by kokanee production.

Nitrogen cycling is also being altered in Odell Lake. However, unlike phosphorus which must be derived from external inputs, nitrogen can be added to the lake through nitrogen fixation by cyanobacteria. *Anabaena* has heterocysts that make it possible for the organism to incorporate atmospheric nitrogen into cell tissue in the presence of light, phosphorus, and other required elements. Thus even in conditions where inorganic nitrogen is below detection limit, N-fixing cyanobacteria can thrive. This gives them a competitive advantage over diatoms and cryptophytes which require inorganic N in addition to phosphorus to grow. The nitrate profiles in Odell Lake show a linear increase in the bottom waters after July, despite no increase in surface water concentrations of nitrate. Presumably this is caused by nitrification of the organic nitrogen that enters the hypolimnion from dead and decaying phytoplankton. This increase in nitrate concentration during the growing season represents an increase of over 30 metric tons to the hypolimnion. Much of this nitrate will become available again in the fall when the lake de-stratifies. The rapid availability of nitrate and colder water temperatures would favor a fall bloom of diatoms, although our study period did not extend long enough to verify this.

The estimates of phosphorus and nitrogen inputs into Odell Lake generated here have a number of assumptions that cannot be verified with the current data. However, the results clearly demonstrate that anthropogenic sources associated with septic inputs from summer homes and resorts account for very small percentages of the total inputs. The largest sources of phosphorus entering Odell Lake, based on the assumptions presented above are from natural inputs, surface flows and groundwater discharge. However, the fisheries appear to account for a substantial portion of the total phosphorus load into the lake and since the inputs have been normalized over a year, this tends to under-represent inputs related to internal cycling which will be concentrated from May to September. Thus, inputs of phosphorus from fish excretion when considered during the growing season may be double those presented on an annual basis. The estimates of nitrogen inputs into Odell Lake again show that septic-related inputs are very small. In contrast, the inputs associated with fish excretion may exceed those from natural sources.

The nitrogen budget presented in Figure 80 does not include a component for nitrogen fixation by cyanobacteria, which may exceed all other sources combined. Furthermore, we have not fully evaluated other hypotheses to explain the observed changes in Odell Lake. These alternate hypotheses include changes in the composition of atmospheric deposition and climate change. Our initial review of these alternative hypotheses shows that these changes have not been observed in nearby lakes without a comparable changes in fisheries (Eilers and Raymond 2001) and the composition of the atmospheric deposition in the area has not been significantly altered (Eilers 1991). These and other sources will be considered in greater detail in the subsequent study in which we will attempt to quantitatively represent key biological processes in a dynamic model interfaced with CE-QUAL-W2.

REFERENCES

Averett, R.C. 1966. Studies of the ecology of kokanee in Odell Lake, Oregon. Oregon Game Commission, Research Division. Progress Report, Kokanee Ecology, F-71-R-2. 51 pp.

Averett, R.C. and F.A. Espinosa, Jr. 1968. Site selection and time of spawning by two groups of kokanee in Odell Lake, Oregon. *J. Wildlife Management*. 32:76-81.

Bacon, C.R. 1983. Eruptive history of Mount Mazama and Crater Lake Caldera, Cascade Range, USA. *J. Volcanology & Geothermal Research*. 15:57-117.

Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling. 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish, Second Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Bird, F.H. 1975. Biology of the blue and tui chubs in East and Paulina Lakes, Oregon. MS Thesis. Oregon State University, Corvallis, OR. 165 pp.

Cole, T.M. and S.A. Wells. 2001. CE-QUAL-W2: a two-dimensional, laterally averaged, hydrodynamic and water quality model, Version 3.1. U.S. Army Corps of Engineers. Instruction Report EL-03-1.

Chorus, I. (ed). 2001. Cyanotoxins – Occurrence, Causes, Consequences. Springer, Berlin. 357 pp.

Deschutes National Forest (DNF). 1999. Odell watershed analysis. Crescent Ranger District, Crescent, Oregon. 183 pp.

Deschutes National Forest (DNF). 2005. Blue-Green Algae Sampling Summary. Unpublished report. DNF, Bend, OR 10 pp.

Eilers, J.M. 1991. Are lakes in the Cascade Mountains receiving high ammonium deposition? *Northwest Science*. 65:238-247.

Eilers, J.M. and R. Raymond. 2001. North Umpqua River water quality and paleolimnological analysis. Report to Pacificorp, Portland, OR. JC Headwaters, Inc., Bend, OR

Hoblitt, R.P., C.D. Miller, and W.E. Scott.1987. Volcanic hazards with regard to siting nuclear-power plants in the Pacific Northwest. Open-File Report 87-297. U.S. Geological Survey.

Houslet, B.S. 2002. Summer dynamics of pH and nutrients in Odell Lake, Oregon, 2001. Deschutes National Forest, Crescent Ranger District, Crescent, Oregon. 27 pp.

Jaehnig, M.E.W., J.C. Chatters, R.E. Hughes, T.M. Origer, N.A. Stenholm, S.B. Williams, and Beta Analytic. 1994. The Odell Lake Basin Project: test excavations at the Odell Lake site, 35KL231, Sunset Cove site, 35KL884, and Shelter Cove site, 35KL482, Klamath County, Oregon. Report to the USDA Forest Service, Deschutes National Forest, Crescent, Oregon. 14 pp + appendix.

Jaehnig, M.E.W., J.C.Chatters, R.E. Hughes, T.M. Origer, N.A.Stenholm, S.B. Williams, and Beta Analytic, Inc. 1994. The Odell Lake Basin Project: test excavations at the Odell Lake site, 35KL231, Sunset Cove site, 35KL884, and Shelter Cover site, 35KL482, Klamath County, Oregon. Report to the USDA Forest Service, Crescent, Oregon. 14 pp. + appendices.

Jennings, M. and R. Lindland. 1964. Survey of Odell Lake. Oregon State Game Commission. 20 pp.

Johnson, D.M., R.R. Petersen, D.R. Lycan, J.W. Sweet, M.E. Neuhaus, and A.L. Schaedel. 1985. Atlas of Oregon Lakes. Oregon State University Press, Corvallis, Oregon. 317 pp.

Larson, D.W. 1970. Limnological studies on lakes in the Deschutes National Forest, Oregon – 1. Odell Lake. Oregon Water Resources Research Institute. 4. 34 pp.

Larson, D.W. 1972. Comparative limnology and phytoplankton ecology of four "oligotrophic" lakes in Oregon, U.S.A., with emphasis on lake typology. *Northwest Science*. 46:149-163.

Lewis, S.L. 1970. Life history and ecology of kokanee in Odell Lake. Oregon State Game Commission. Research Division. Kokanee Ecology, Job Progress Report F-71-R-6, Jobs 6 and 10. 49 pp.

Lewis, S.L. 1971. Life history and ecology of kokanee in Odell Lake. Oregon State Game Commission. Research Division. Kokanee Ecology, Job Progress Report F-71-R-7, Jobs 6 and 10. 57 pp.

Lewis, S.L. 1972. Life history and ecology of kokanee in Odell Lake. Oregon State Game Commission. Research Division. Kokanee Ecology, Job Progress Report F-71-R-8, Jobs 6, 10, and 11 . 71pp.

Lewis, S.L. 1973. Life history and ecology of kokanee in Odell Lake. Oregon Wildlife Commission. Research Division. Kokanee Ecology, Job Progress Report F-71-R-9 and 10, Jobs 10 and 11. 33 pp.

Lewis, S.L. 1974. Life history and ecology of kokanee in Odell Lake. Oregon Wildlife Commission. Research Division. Kokanee Ecology, Job Progress Report F-71-R-11, Jobs 10 and 11. 32 pp.

Lewis, S.L. 1975. Evaluation of the kokanee fishery and hatchery releases at Odell Lake, 1964-75. Oregon Department of Fish and Wildlife. Research Division. Kokanee Ecology, Job Final Report F-71-R, Job 6. 26 pp.

Lindsay , R.B. and S.L. Lewis. 1975. Population dynamics of kokanee salmon in Odell Lake. Oregon Department of Fish and Wildlife. Research Division. Kokanee Population Dynamics, Job Progress Report F-71-R-11, Jobs 10 and 11. 38 pp.

Lindsay , R.B. and S.L. Lewis. 1978. Lake and reservoir investigations (Kokanee Ecology). Oregon Department of Fish and Wildlife. Research Division. Kokanee Population Dynamics, Job Progress Report F-71-R, Jobs 10 and 11. 12 pp.

Linsley, R.K., Jr., M.A. Kohler, and J.L.H. Paulhus. 1975. Hydrology for Engineers. McGraw-Hill Book Company. New York. 482 pp.

Love, R.H. 1971. Dorsal aspect target strength of an individual fish. J. Acoust. Soc. Am. 49:816-823.:

McHugh, R.A. 1972. An interim study of some physical, chemical and biological properties of selected Oregon lakes. Oregon Department of Environmental Quality, Portland, OR. 109 pp.

McHugh, R.A. 1979. Some highly eutrophic Oregon lakes, with recommendations for the restoration of the quality. Oregon Department of Environmental Quality, Portland, OR. 25 pp.

Meyerhoff, R.D. 1977. Sediment characteristics and the trophic status of four Oregon lakes. M.S. Thesis. Oregon State University, Corvallis, Oregon. 74 pp.

Meyerhoff, R.D., G.L. Larson, and G.E. Davis. 1978. Sediment characteristics of three mountain lakes with different trophic statuses. *Archiv. Hydrobiol.* 81:397-421.

Miller, W.E., T.E. Maloney, and J. C. Greene. 1974. Algal productivity in 49 lake waters as determined by algal assays. *Water Research.* 8:667-679.

Newcomb, H.R. 1941. A biological investigation of forty lakes of the upper Deschutes River watershed in Oregon. Oregon State Game Commission. Lake Survey Report No. 1. 207 pp.

OECD (Organization for Economic Cooperation and Development). 1982. Eutrophication of waters. Monitoring, Assessment and Control. Final Report. OECD Cooperative Programme on Monitoring of Inland Waters (Eutrophication Control), Environment Directorate, OECD, Paris. 154 pp.

Sherrod, D.R., P.R. Moyle, C.M. Rumsey, and N.S. MacLeod. 1983. Geology and mineral resource potential map of the Diamond Peak Wilderness, Lane and Klamath Counties, Oregon. Open-File Report 83-661. U.S. Geological Survey. Map + 20 pp.

Sherrod, D.R. 1991. Geologic map of a part of the Cascade Range between latitudes 43º-44º. Central Oregon. Misc. Investigations Series, MAP I-1981. U.S. Geological Survey.

Wetzel, R.G. 2001. Limnology, Lake and River Ecosystems. Academic Press, New York. 1066 pp.

WHO (World Health Organization). 2003. Guidelines for safe recreational water environments. ISBN 92 4 154580 1. Paris, France.

Wydoski, R.S. and R.R. Whitney. 2003. Inland Fishes of Washington. American Fisheries Society & University of Washington Press. 322 pp.

ACKNOWLEDGEMENTS

This study was funded by Contract #68-C-02-110, Task Order 2003-47 from the US EPA to RTI International, Research Triangle Park, Raleigh, NC and Carollo Engineering, Inc., Walnut Creek, CA and by subcontract from Carollo Engineers to MaxDepth Aquatics, Inc., Bend OR. Robert Truesdale served as the Task Order Leader for RTI and the project leaders for Carollo Engineers were Steve McDonald and Elisa Garvey. Tracy Chellis served as the EPA Task Order Manager and Helen Rueda served as the EPA Alternate Task Order Manager. The project officer for the Oregon Department of Environmental Quality was Bonnie Lamb. Field studies by DEQ were conducted by Larry Marxer, David Gilbey, and Sarah Miller. Valuable information regarding Odell Lake fisheries was provided by Steven Marx and Ted Wise, Oregon Dept. Fish & Wildlife, Bend. Digital watershed coverages and phytoplankton data on Odell Lake were provided by Paul Powers, Deschutes National Forest, Crescent Ranger District. We thank the Odell Lake Lodge for allowing us to install a weather station on their premises. Several lakeshore residents kindly shared information with us regarding the history of the lake including Steve Stewart, Chris Eames, and Jack Meissner. Dr. Jack Cornett and Janet Larder, MyCore Scientific, Inc. conducted the ^{210}Pb dating for Odell Lake. Nancy Kyle, Crop and Soil Science, Oregon State University, conducted the analytical work on the sediment chemistry. Taxonomists with Third Rock Consultants conducted the analysis of the chironomid head capsules in the sediment. Ian Gunter, MaxDepth Aquatics, Inc. assisted in the field activities for Odell Lake.

Data appendices are included as a CD with the final report.