Prepared in cooperation with the Bureau of Reclamation

Water Quality Conditions in Upper Klamath and Agency Lakes, Oregon, 2005

Scientific Investigations Report 2008–5026

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph of algae bloom on surface of Upper Klamath Lake with Mt. McLoughlin in background. (Photograph taken by Dean Snyder, U.S. Geological Survey, Klamath Falls, Oregon, October 27, 2007.)

Water Quality Conditions in Upper Klamath and Agency Lakes, Oregon, 2005

By Gene R. Hoilman, Mary K. Lindenberg, and Tamara M. Wood

Prepared in cooperation with the Bureau of Reclamation

Scientific Investigations Report 2008–5026

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2008

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Hoilman, G.R., Lindenberg, M.K., and Wood, T.M., 2008, Water quality conditions in Upper Klamath and Agency Lakes, Oregon, 2005: U.S. Geological Survey Scientific Investigations Report 2008–5026, 44 p.

Contents

Abstract 1
Introduction 2
    Purpose and Scope 4
    Description of Study Area 4
Methods 4
    Continuous Water Quality Monitors 4
    Water Sample Collection 6
    Dissolved Oxygen Production and Consumption Experiments 6
    Meteorological Sites 8
    Data Processing 10
Meteorological Conditions 10
Nutrients and Chlorophyll *a* 14
    Bloom Dynamics of *Aphanizomenon flos-aquae* 14
    Spatial Variability in Nutrient and Chlorophyll *a* Concentrations 22
Dissolved Oxygen Production and Consumption Experiments 23
    Dissolved Oxygen Production and Consumption 23
    Depth of Photic Zone 25
Water Quality Conditions 26
    Daily Median Water Quality Conditions 26
    Spatial Variability in Dissolved Oxygen Concentrations 29
        Variability on Monthly to Seasonal Time Scales 29
        Variability on Short Time Scales 32
    Stratification and Wind Speed 32
    Timing of Daily Extremes in Water Quality Conditions 34
Occurrence and Duration of Water Quality Conditions Potentially Harmful to Fish 36
    Dissolved Oxygen Concentration, pH, and Temperature 36
    Ammonia 37
Summary and Conclusions 39
Acknowledgments 40
References Cited 40
Appendix A. Quality Control and Quality Assurance of Water Samples 43

Figures

Figure 1. Photograph showing algal bloom *Aphanizomenon flos-aquae*, disturbed by the wake of the boat, Upper Klamath Lake, Oregon, 2005 2

Figure 2. Map showing location of meteorological sites, continuous water quality monitoring sites, and water quality sampling sites, Upper Klamath and Agency Lakes, Oregon, 2005 3

Figure 3. Schematic diagram of a typical mooring used for placement of continuous water quality monitors in Upper Klamath and Agency Lakes, Oregon 6

Figure 4. Schematic diagram of apparatus for dissolved oxygen production and consumption experiments in Upper Klamath Lake, Oregon, 2005 7

Figure 5. Schematic diagram showing configuration of land-based meteorological measurement sites around Upper Klamath Lake, Oregon, 2005 9

Figure 6. Graphs showing lakewide daily median wind speed, air temperature, relative humidity, and daytime solar radiation for meteorological sites in and around Upper Klamath Lake, Oregon, 2005 11

Figure 7. Map showing water-current velocity predicted by the hydrodynamic model of Upper Klamath Lake, Oregon, under prevailing wind conditions 12

Figure 8. Histograms showing wind speed and direction for all meteorological sites in the vicinity of Upper Klamath Lake, Oregon, 2005 13

Figure 9. Graphs showing weekly measurements of chlorophyll *a* and dissolved nutrient concentration in relation to the duration of a dissolved oxygen concentration of less than 4 milligrams per liter at water samples collected from site MDN, Upper Klamath Lake, Oregon, 2002–05 15

Figure 10. Graphs showing concentrations of chlorophyll *a*, total phosphorus, orthophosphate, ammonia, and nitrite-plus-nitrate in water samples collected from Upper Klamath Lake, Oregon, 2005 16

Figure 11. Graph showing weekly qualitative observations of algal bloom conditions in Agency Lake, Oregon, 2005 18

Figure 12. Graph showing relation of chlorophyll *a* to total phosphorus concentration in water samples collected from Upper Klamath Lake, Oregon, 2005 19

Figure 13. Time-series graph showing ratio of chlorophyll *a* to total phosphorus and ratio of ammonia and nitrite-plus-nitrate (bioavailable nitrogen) to orthophosphate (bioavailable phosphorus) concentrations in water samples collected from Upper Klamath Lake, Oregon, May–October 2005 20

Figure 14. Graphs showing relation of ammonia and orthophosphate concentrations to chlorophyll *a* concentrations in water samples collected from Upper Klamath Lake, Oregon, 2005 21

Figure 15. Graphs showing statistical distribution of ammonia, orthophosphate, total phosphorus, and chlorophyll *a* concentrations measured in water samples collected from Upper Klamath Lake, Oregon, 2005 22

Figure 16. Graphs showing rate of change in dissolved oxygen concentration measured from dissolved oxygen production and consumption experiments at sites in Upper Klamath Lake, Oregon, 2005 24

Figures—Continued

Figure 17. Graphs showing relation of the natural logarithm of chlorophyll *a* concentration to dissolved oxygen production in the upper and lower incubation racks during dissolved oxygen production and consumption experiments in Upper Klamath Lake, Oregon, 2005 25
Figure 18. Graph showing relation of the natural logarithm of chlorophyll *a* concentration to the average depth of the photic zone for all dissolved oxygen production and consumption experiments in Upper Klamath Lake, Oregon, 2005 25
Figure 19. Time-series graphs showing daily median temperature, dissolved oxygen concentration, dissolved oxygen percent saturation, pH, and specific conductance recorded by continuous monitors in Agency Lake, Oregon, 2005 ... 27
Figure 20. Time-series graphs showing lakewide daily median dissolved oxygen concentration, dissolved oxygen percent saturation, temperature, pH, and specific conductance recorded by continuous monitors in Upper Klamath Lake, Oregon, 2005 28
Figure 21. Time-series graphs showing daily dissolved oxygen percent saturation at water quality monitoring sites in Upper Klamath Lake, Oregon, 2005 30
Figure 22. Time-series graphs showing representative hourly vertical variability in pH, dissolved oxygen, and temperature at sites MDN, MDT, and EPT, and hourly median wind speed at site MDN, Upper Klamath Lake, Oregon, 2005 33
Figure 23. Graphs showing daily extreme of dissolved oxygen concentration, pH, and water temperature from a representative shallow (HDB), middepth (BLB), and deep site (EPT) in Upper Klamath Lake, Oregon, 2005 35
Figure 24. Graphs showing lakewide measures of conditions potentially harmful to fish in Upper Klamath Lake, Oregon, 2005: dissolved oxygen concentration less than 4 milligrams per liter, and pH greater than 9.7 37
Figure 25. Graphs showing (*A*) chlorophyll *a* concentration, (*B*) total ammonia concentration, (*C*) un-ionized ammonia concentration, and (*D*) pH in water samples collected at all sites, Upper Klamath Lake, Oregon, 2005 38

Tables

Table 1. Description of continuous water quality monitoring sites used for the 2005 data-collection program, Upper Klamath and Agency Lakes, Oregon 5
Table 2. Depth of incubator racks at each site during dissolved oxygen production and consumption experiments in Upper Klamath Lake, Oregon, 2005 8
Table 3. Description of meteorological sites and parameters measured at each site, Upper Klamath Lake, Oregon, 2005 9
Table 4. Maximum and minimum chlorophyll *a* concentrations and dates relative to *Aphanizomenon flos-aquae* blooms and decline during sampling season, Upper Klamath Lake, Oregon, June–October 2005 17

Conversion Factors, Datums, and Abbreviations

Conversion Factors

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
milliliter (mL)	0.03382	fluid ounce (oz)
liter (L)	1.057	quart (qt)
meter per second (m/s)	3.281	foot per second (ft/s)
milligram per liter per hour [(mg/L)/hr]	1.0	part per million per hour (ppm/hr)
micrometer (µm)	3.937×10^{-5}	inch (in.)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L). One thousand micrograms per liter is equivalent to 1 mg/L. Micrograms per liter is equivalent to “parts per billion.”

Datums

Vertical coordinate information is referenced to the Bureau of Reclamation datum, which is 1.78 feet above National Geodetic Vertical Datum of 1929 (NGVD 29). Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Abbreviations

Abbreviations	Definition
ADAPS	Automated Data Processing System
ADCP	acoustic Doppler current profiler
AFA	*Aphanizomenon flos-aquae*
BOD	biological oxygen demand
LDOE	low dissolved-oxygen event
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
USGS	U.S. Geological Survey

Water Quality Conditions in Upper Klamath and Agency Lakes, Oregon, 2005

By Gene R. Hoilman, Mary K. Lindenberg, and Tamara M. Wood

Abstract

During June–October 2005, water quality data were collected from Upper Klamath and Agency Lakes in Oregon, and meteorological data were collected around and within Upper Klamath Lake. Data recorded at two continuous water quality monitors in Agency Lake showed similar temperature patterns throughout the field season, but data recorded at the northern site showed more day-to-day variability for dissolved oxygen concentration and saturation after late June and more day-to-day variability for pH and specific conductance values after mid-July. Data recorded from the northern and southern parts of Agency Lake showed more comparable day-to-day variability in dissolved oxygen concentrations and pH from September through the end of the monitoring period.

For Upper Klamath Lake, seasonal (late July through early August) lows of dissolved oxygen concentrations and saturation were coincident with a seasonal low of pH values and seasonal highs of ammonia and orthophosphate concentrations, specific conductance values, and water temperatures. Patterns in these parameters, excluding water temperature, were associated with bloom dynamics of the cyanobacterium (blue-green alga) *Aphanizomenon flos-aquae* in Upper Klamath Lake. In Upper Klamath Lake, water temperature in excess of 28 degrees Celsius (a high stress threshold for Upper Klamath Lake suckers) was recorded only once at one site during the field season. Large areas of Upper Klamath Lake had periods of dissolved oxygen concentration of less than 4 milligrams per liter and pH value greater than 9.7, but these conditions were not persistent throughout days at most sites. Dissolved oxygen concentrations in Upper Klamath Lake on time scales of days and months appeared to be influenced, in part, by bathymetry and prevailing current flow patterns. Diel patterns of water column stratification were evident, even at the deepest sites. This diel pattern of stratification was attributable to diel wind speed patterns and the shallow nature of most of Upper Klamath Lake. Timing of the daily extreme values of dissolved oxygen concentration, pH, and water temperature was less distinct with increased water column depth.

Chlorophyll *a* concentrations varied spatially and temporally throughout Upper Klamath Lake. Location greatly affected algal concentrations, in turn affecting nutrient and dissolved oxygen concentrations—some of the highest chlorophyll *a* concentrations were associated with the lowest dissolved oxygen concentrations and the highest un-ionized ammonia concentrations. The occurrence of the low dissolved oxygen and high un-ionized ammonia concentrations coincided with a decline in algae resulting from cell death, as measured by concentrations of chlorophyll *a*.

Dissolved oxygen production rates in experiments were as high as 1.47 milligrams of oxygen per liter per hour, and consumption rates were as much as –0.73 milligrams of oxygen per liter per hour. Dissolved oxygen consumption rates measured in this study were comparable to those measured in a 2002 Upper Klamath Lake study, and a higher rate of dissolved oxygen consumption was recorded in dark bottles positioned higher in the water column. Data, though inconclusive, indicated that a decreasing trend of dissolved oxygen productivity through July could have contributed to the decreasing dissolved oxygen concentrations and percent saturation recorded in Upper Klamath Lake during this time. Phytoplankton self-shading was evident from a general inverse relation between depth of photic zone and chlorophyll *a* concentrations. This shading caused net dissolved oxygen consumption during daylight hours in lower parts of the water column that would otherwise have been in the photic zone.

Meteorological data collected in and around Upper Klamath Lake showed that winds were likely to come from a broad range of westerly directions in the northern one-third of the lake, but tended to come from a narrow range of northwesterly directions over the main body of the lake farther south.

Introduction

Water quality degradation in Upper Klamath Lake has led to critical fishery concerns for the region, including the listing of Lost River and shortnose suckers as endangered in 1988. The algal community of the lake has shifted to a near monoculture of the cyanobacterium (blue-green algae) *Aphanizomenon flos-aquae* (AFA) during summer (Kann, 1997; Perkins and others, 2000), massive blooms of which have been directly related to episodes of poor water quality in Upper Klamath Lake (fig. 1). The growth and decomposition of AFA blooms in the lake frequently cause extreme water quality conditions characterized by high pH values (9–10), widely variable dissolved oxygen conditions (anoxic to supersaturated), and high un-ionized ammonia concentrations (greater than 0.5 mg/L). Large blooms of AFA and the associated water quality concerns also occur in Agency Lake.

Before the U.S. Geological Survey (USGS) began monitoring water quality in Upper Klamath Lake in 2002 in cooperation with the Bureau of Reclamation, continuous datasets of temperature, pH, dissolved oxygen, or specific conductance spanning spring through fall did not exist. The Klamath Tribes have collected biweekly water samples for nutrients and chlorophyll *a* at 10 sites in Upper Klamath and Agency Lakes since 1990. Several studies have used this dataset, which is the longest consistent record of water quality available for Upper Klamath Lake (Wood and others, 1996; Kann and Smith, 1999; Kann and Walker, 2001; Kann and Welch, 2005; Wood and others, 2006; Morace, 2007).

During 2002–04, the USGS water quality monitoring program study area was limited mostly to the northern one-third of Upper Klamath Lake, where the monitoring supported a telemetry tracking study of endangered adult suckers (Wood and others, 2006). Data collected during the 3 years of monitoring showed that the occurrence and severity of poor water quality conditions in Upper Klamath Lake were unpredictable from year to year. During each year, however, seasonal patterns of low dissolved oxygen concentration and high pH coincided with blooms of AFA that occur in the lake. A diel pattern of water column stratification was observed in the lake, but the data did not indicate a strong association between water column stratification and an event of extreme low dissolved oxygen concentration and a consequent fish die-off in 2003.

Water circulation in Upper Klamath Lake is determined by wind speed and direction and the bathymetry of the lake. The lake is mostly shallow (less than 3.5-m depth), with the exception of a narrow trench (greater than 10-m depth) that extends along the western shoreline (fig. 2). Prevailing winds over Upper Klamath Lake are westerly (between about 250 and 315 degrees) over the northern part of the lake and then are constrained by the surrounding topography to northwesterly (between about 315 and 360 degrees) over the southern part of the lake. Velocity measurements of currents made with acoustic Doppler current profilers (ADCPs, Wood and others, 2006) and hydrodynamic modeling with the three-dimensional UnTRIM model (Cheng and others, 2005) have confirmed that circulation is clockwise around the lake during periods of prevailing winds, consisting of a broad and shallow southward flow through most of the lake and a narrow, deep, northward flow through the trench along the western shoreline. The direction of the current in the trench is tightly constrained by the bathymetry to flow to the northwest at about 320 degrees when forced by prevailing winds. Some of the water exiting the trench just west of Bare Island continues clockwise around the island, and the rest turns west around Eagle Point, generating a clockwise circulation within the northern one-third of the lake. This understanding of the wind-driven currents indicates that poor water quality conditions (particularly low dissolved oxygen concentrations) that are observed in the northern part of the lake do not originate locally. Instead, these conditions originate farther south in the lake and are transported to the north along this circulation path through the trench and west of Bare Island (Wood and others, 2006).

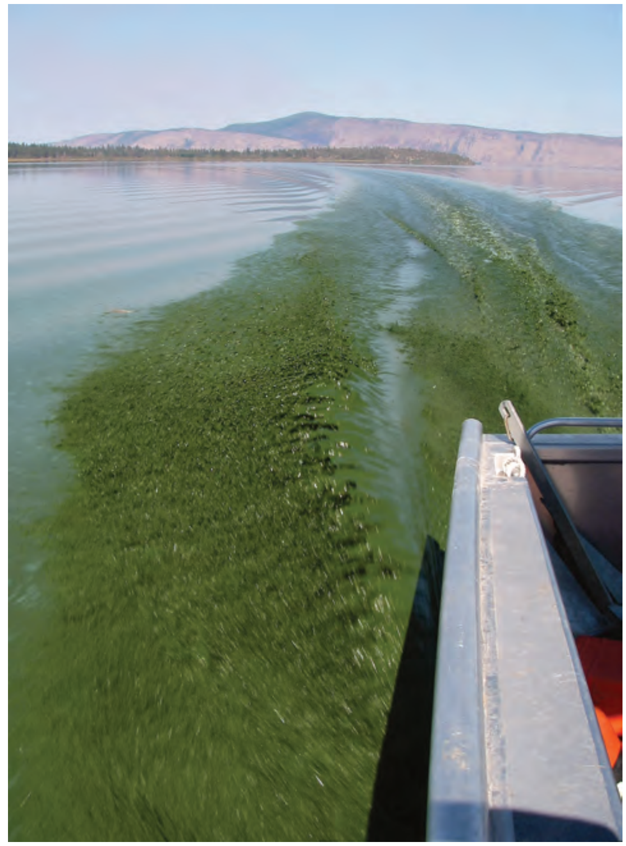
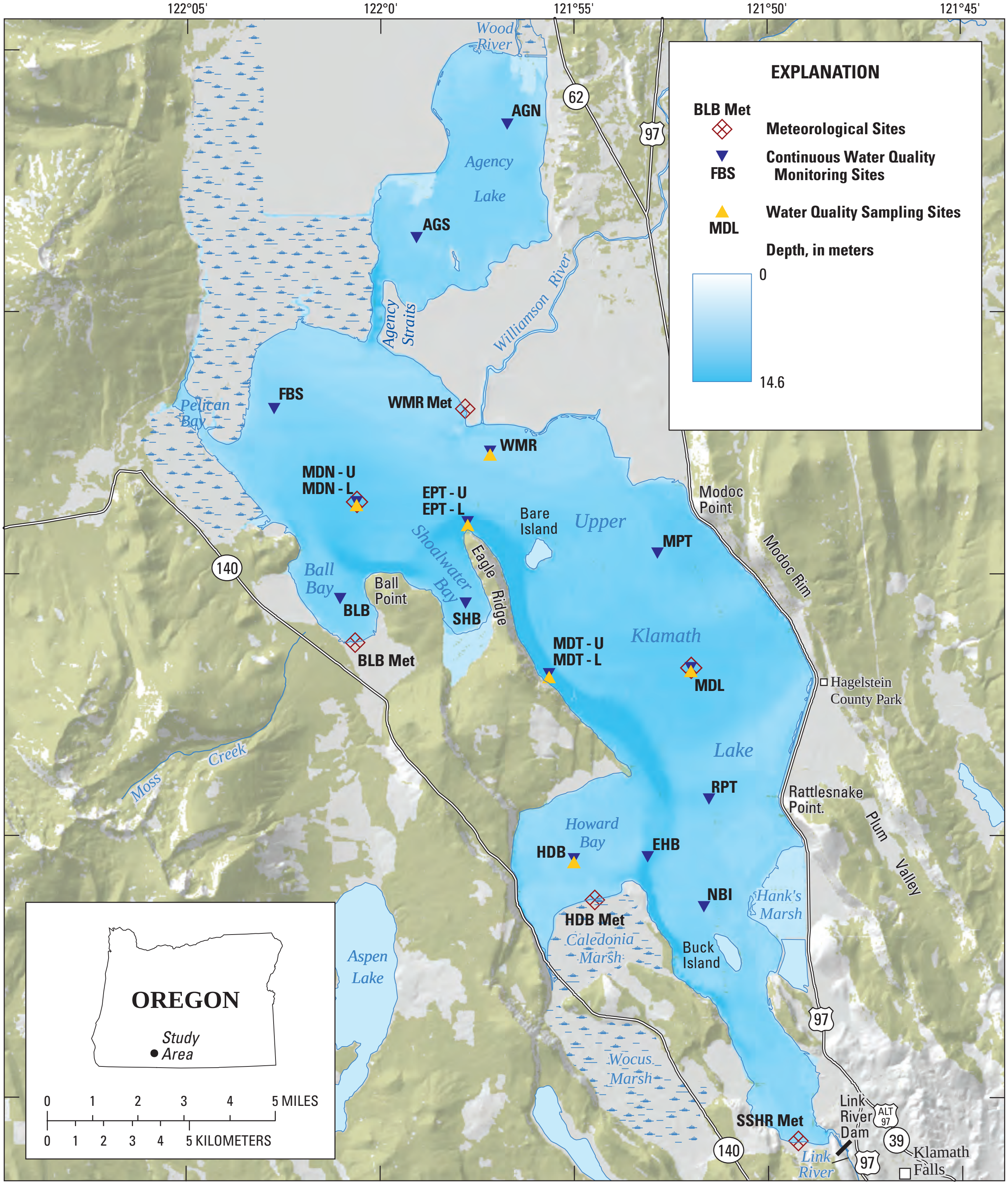


Figure 1. Algal bloom *Aphanizomenon flos-aquae*, disturbed by the wake of the boat, Upper Klamath Lake, Oregon, 2005. (Photograph taken by Mary Lindenberg, U.S. Geological Survey, September 26, 2006.)



Sources:
Bathymetry: Produced by Glen Canyon Environmental Studies in cooperation with U.S. Bureau of Reclamation, Mid-Pacific Region, Klamath Basin Area Office, and the Klamath Tribes.
Digital Raster Graphics and Elevation: Produced by U.S. Geological Survey, various scales.
Projection: UTM, Zone 10

Figure 2. Location of meteorological sites, continuous water quality monitoring sites, and water quality sampling sites, Upper Klamath and Agency Lakes, Oregon, 2005.

In 2005, the existing water quality monitoring program expanded to become lakewide in Upper Klamath Lake and to include Agency Lake. These changes created a program better suited to establishing long-term status and trends of water quality dynamics and monitoring the suitability of water quality for protection of endangered species of fish living within the lakes.

Meteorological sites were established at four locations on land around the lake in addition to the two floating meteorological sites used in previous years, providing greater resolution of wind speed, wind direction, air temperature, and relative humidity. Additionally, collection of solar-radiation data at SSHR began in 2005. The additional wind data were used to improve the hydrodynamic model describing water movement in Upper Klamath Lake. The air temperature, relative humidity, and solar-radiation data were used to calculate heat transfer at the water surface in a heat transport model of Upper Klamath Lake (T.M. Wood, U.S. Geological Survey, unpub. data, 2006; Wood and Cheng, 2006).

Purpose and Scope

This report presents the results of water quality monitoring in Upper Klamath and Agency Lakes during 2005. Meteorological data, including wind speed and direction, air temperature, relative humidity, and solar radiation, are presented and used to describe wind patterns and their influence on circulation in Upper Klamath Lake. Dissolved nutrient concentrations are correlated with chlorophyll *a* concentrations, which serve as a surrogate for algal biomass. Results of dissolved oxygen production and consumption experiments are described. Dissolved oxygen concentration and saturation, water temperature, pH, and specific conductance values of water samples collected from the lakes are presented and used to determine water quality conditions potentially harmful to fish.

Description of Study Area

Upper Klamath Lake (fig. 2) is located in southern Oregon. It is a large, shallow lake with a surface area of 232 km^2 and an average depth of 2.8 m. Most of the lake (about 90 percent) is shallower than 4 m, except for a narrow trench running parallel to Eagle Ridge on the western shore of the lake. This trench contains the deepest waters of the lake, approaching 15 m. Upper Klamath Lake is located in the Klamath Graben structural valley, and much of its 9,415-km^2 drainage basin is composed of volcanically derived soils. The largest single contributor of inflow to the lake is the Williamson River, which contributes, on average, nearly one-half of the lake's incoming water and enters the lake near its northern end. Upper Klamath Lake historically was eutrophic, but over the past several decades has experienced nuisance blooms of AFA during the summer and fall and can now be characterized as hypereutrophic (Eilers and others, 2004). Upper Klamath Lake is a natural water body, but lake-surface elevations have been regulated since 1921, when the Link River Dam was completed at the southern outlet of the lake. The dam was built and currently is operated by the Bureau of Reclamation. The lake is now the principal water source for the Klamath Project, an irrigation system developed to supply water to farms and ranches in and around the Klamath basin (Bureau of Reclamation, 2000).

Agency Lake, just north of Upper Klamath Lake and connected to it by a natural, narrow channel, adds about 38 km^2 of surface area to the Upper Klamath Lake-Agency Lake hydrologic entity (Johnson, 1985). Agency Lake also is shallow, with a maximum depth approaching 3 m and an average depth of 0.9 m. Like Upper Klamath Lake, Agency Lake is hypereutrophic and experiences annual blooms of AFA. Because the channel connecting Upper Klamath Lake and Agency Lake is narrow compared to the two water bodies and the amount of flow through it is small, the two lakes are largely independent in terms of the seasonal cyanobacterial bloom and water quality dynamics.

Methods

Continuous Water Quality Monitors

YSI model 600XLM, 6920, or 6600 continuous multiparameter water quality monitors (sondes) were placed at 13 sites in Upper Klamath Lake and 2 sites in Agency Lake (fig. 2; table 1). At all these locations, sondes were placed vertically at a fixed depth of 1 m from the lake bottom. If the depth at a site was less than 2 m, the sonde was placed horizontally at the midpoint of the water column. A typical sonde mooring is shown in figure 3. The placement depth of 1 m from the bottom was chosen to provide data relevant to the endangered suckers of Upper Klamath Lake, which are bottom feeding fish. To observe water quality conditions near the water surface and provide comparisons to conditions near the lake bottom, a second sonde was placed on the same mooring at a fixed depth 1 m from the surface at three of the deepest locations, MDT, EPT, and MDN (fig. 2). All sondes recorded dissolved oxygen concentration, pH, specific conductance, and temperature at the beginning of every hour.

Sondes were cleaned and field measurements of site depth were made during weekly site visits to ensure proper placement of the instrument in the water column. Separate field measurements of dissolved oxygen concentration, pH, specific conductance, and temperature at the depth of each sonde were made as an additional check of sonde performance. During cleanings, measurements were made to compensate for the effect of biological fouling. Deployments generally lasted 3 weeks; at the end of this time the sonde at the site was replaced with a freshly calibrated instrument. Calibration of the sonde was checked for each parameter in the laboratory after retrieval to account for the effect of calibration drift. Data internally logged during deployment in the field were downloaded from retrieved sondes in the laboratory. These raw data were then loaded into the USGS Automated Data Processing System (ADAPS). Quality of the data was assured by the field information collected at weekly site visits and by processing the time series according to the procedures in Wagner and others (2000). Data corrections resulting from biological fouling and calibration drift were entered into ADAPS, which calculated the corrected values.

Table 1. Description of continuous water quality monitoring sites used for the 2005 data-collection program, Upper Klamath and Agency Lakes, Oregon.

[Sites are shown in order of decreasing depth.]

Site name	Site name abbreviation	USGS site identification No.	Latitude (north)	Longitude (west)	Full-pool measured depth (meters)
Middle of trench (lower)	MDT-L	422305121553800	42° 23' 5.09"	121° 55' 38.2"	15.00
Middle of trench (upper)	MDT-U	422305121553803	42° 23' 5.09"	121° 55' 38.2"	15.00
Eagle Point (lower)	EPT-L	422559121574400	42° 25' 59.2"	121° 57' 44.1"	12.50
Eagle Point (upper)	EPT-U	422559121574403	42° 25' 59.2"	121° 57' 44.1"	12.50
Entrance to Howard Bay	EHB	421935121530600	42° 19' 35.4"	121° 53' 5.9"	5.20
Midlake	MDL	422312121515900	42° 23' 12"	121° 51' 59.1"	4.50
Midnorth (lower)	MDN-L	422622122004000	42° 26' 21.5"	122° 0' 40.0"	4.20
Midnorth (upper)	MDN-U	422622122004003	42° 26' 21.5"	122° 0' 40.0"	4.20
Modoc Point	MPT	422523121525100	42° 25' 23.2"	121° 52' 50.8"	3.70
Ball Bay	BLB	422431122010100	42° 24' 31"	122° 1' 1"	3.50
Rattlesnake Point	RPT	422042121513100	42° 20' 41.6"	121° 51' 31.4"	3.40
Shoalwater Bay	SHB	422444121580400	42° 24' 26.1"	121° 57' 47.1"	3.30
Agency North	AGN	423335121564300	42° 33' 35"	121° 56' 43"	3.00
Fish Banks	FBS	422808122024400	42° 28' 8.8"	122° 2' 43.5"	2.80
North Buck Island	NBI	421838121513900	42° 18' 38"	121° 51' 39"	2.80
Upper Klamath Lake at Williamson River outlet	WMR	422719121571400	42° 27' 19.4"	121° 57' 13.6"	2.50
Agency South	AGS	423124121583400	42° 31' 24.9"	121° 59' 3.4"	2.50
Howard Bay	HDB	421933121550000	42° 19' 33"	121° 55' 0"	2.50

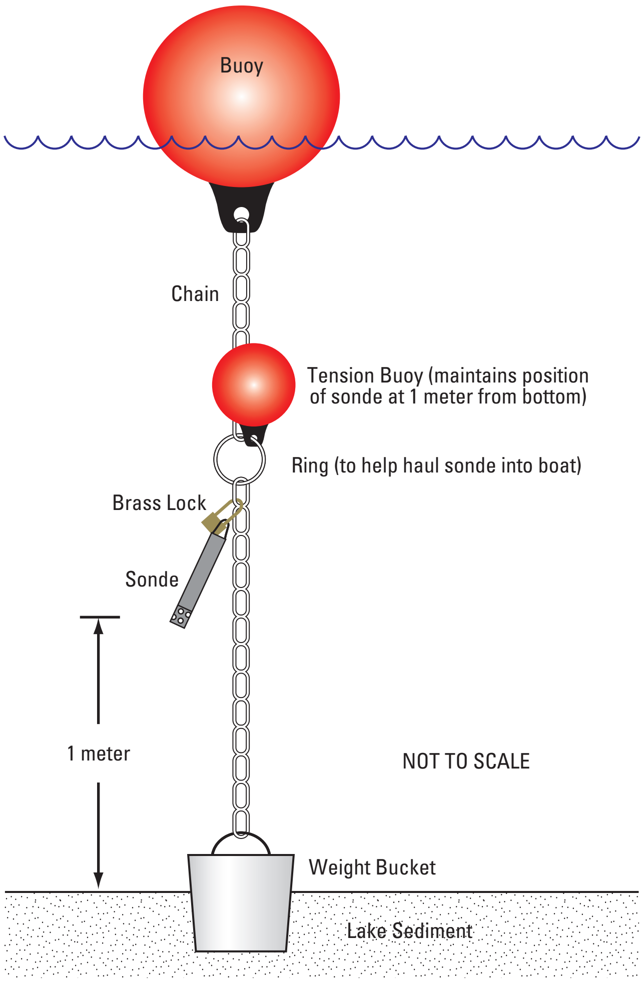


Figure 3. Schematic diagram of a typical mooring used for placement of continuous water quality monitors in Upper Klamath and Agency Lakes, Oregon.

Water Sample Collection

Of the 15 continuous water quality monitoring sites, 6 sites, MDN, WMR, EPT, MDT, HDB, and MDL (fig. 2), were selected for nutrient and chlorophyll *a* analyses. Water samples were collected on a weekly basis according to established protocols (U.S. Geological Survey, variously dated). Samples were analyzed for chlorophyll *a*, total phosphorus, total ammonia (ammonia plus ammonium), orthophosphate, and nitrite-plus-nitrate concentrations. To protect samples from contamination during the collection process, quality control protocols were followed as described in the National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated). Two sampling methods were used relative to the type of constituent measured. Water samples analyzed for dissolved nutrients, including total ammonia, orthophosphate and nitrite-plus-nitrate, were collected from either one or two points in the water column, depending on the depth at the site. At the deep sites MDT and EPT, dissolved nutrient samples were collected from two points in the water column—one-quarter and three-quarters of the total water column depth—to investigate the difference between the upper and lower sections of the water column. At the shallow sites MDN, WMR, HDB, and MDL, dissolved nutrient samples were collected from middepth of the water column. Dissolved nutrient samples were collected by pumping through a hose (lowered to the appropriate depth in the water column) connected to a 0.45-µm capsule filter. Whole (unfiltered) water samples analyzed for total phosphorus and chlorophyll *a* constituted an equal integration over the depth of the water column. To collect depth-integrated samples, a weighted cage holding two 1-L bottles was lowered at a constant rate into the water to 0.5 m from the bottom at sites less than 10.5 m depth and to 10 m from the surface at sites greater than 10.5 m depth. Each bottle had two small ports, one for water to flow in and one for the escape of displaced air. The contents of the bottles from multiple collections of the cage sampler were combined in a churn splitter from which samples were collected for determination of total phosphorus and chlorophyll *a* concentration. Samples to be analyzed for total phosphorus were preserved with 1 mL of 4.5N (4.5 normal) H_2S0_4, and chlorophyll *a* samples were fixed with $MgCO_3$. Samples to be analyzed for dissolved nutrients and total phosphorus were chilled onsite and sent to the National Water Quality Laboratory (NWQL) in Denver, Colorado, for analysis. Finalized data were stored in the USGS National Water Information Systems (NWIS) database. Samples to be analyzed for chlorophyll *a* concentration were chilled onsite and sent to Aquatic Analysts in White Salmon, Washington. Results of the 2005 quality assurance program are discussed in the appendix.

Dissolved Oxygen Production and Consumption Experiments

Experiments were conducted to provide measurements of dissolved oxygen production and consumption rates in Upper Klamath Lake (fig. 4). Biological oxygen demand (BOD) bottles, with a volume of 300 mL and made of type 1 borosilicate glass, were filled with lake water integrated

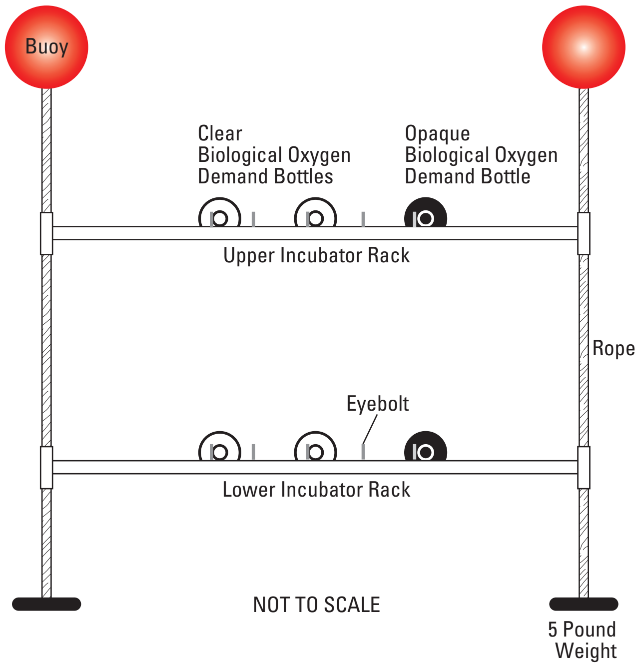


Figure 4. Schematic diagram of apparatus for dissolved oxygen production and consumption experiments in Upper Klamath Lake, Oregon, 2005.

over the entire water column. BOD bottles were filled from the churn splitter with the same collection of lake water as chlorophyll *a* samples. This procedure allowed the chlorophyll *a* data to be used in the analysis of data from the dissolved oxygen production and consumption experiments. After filling, initial dissolved oxygen concentration and temperature were measured in the bottles with a YSI model 52 dissolved oxygen meter. Three bottles were attached to rest horizontally on racks at each of two depths. One bottle out of each group of three was dark (made so by wrapping it and its stopper with black electrical tape). Once attached to the incubator rack, the bottles were lowered into the water.

The experiment apparatus was moored at the site for at least 1 hour and typically retrieved before 3 hours. Dissolved oxygen concentration and temperature were again measured in each bottle, and incubation time was noted. The change in dissolved oxygen concentration was calculated in each bottle, and the incubation time was used to express the rate of dissolved oxygen change in milligrams of oxygen per liter per hour. Most experiments were conducted between the hours of 10:00 a.m. and 3:00 p.m. Logistical constraints did not allow for this experiment to be done at every water sample collection site during every week of sampling, but an attempt was made to collect the dissolved oxygen rate data at each of the six sites throughout the season, if not on a weekly basis (table 2). The upper rack generally was positioned 0.5 m below the water surface. Early in the season experimentation was done with the position of the lower rack before settling on 2 m depth to give sufficient contrast with the upper rack. As the season progressed, the lower rack was raised to 1.5 m, and toward the end of the season the lower rack was raised to 1 m at the shallow sites. Some sites became too shallow toward the end of the field season to incorporate the lower rack into the experiment.

Light intensity was measured in a vertical profile from the water surface to a depth of 2.5 m (or the lake bottom) in 0.5-m increments by using a LiCor LI-193SB underwater spherical quantum sensor. These measurements were used to estimate the depth of the photic zone, defined here as the point at which 99 percent of incident light is absorbed (or, 1 percent of incident light is transmitted), by using Beer's law, which describes the penetration of solar radiation through the water column as an exponential relation (Welch, 1992):

$$I_z = I_0 e^{-\alpha z} \quad (1)$$

where
- z is depth, in meters,
- I_z is radiation at depth z, in micromoles per second per square meter,
- I_o is surface radiation, in micromoles per second per square meter, and
- α is the extinction coefficient.

α was estimated for each set of measurements by fitting equation (1) to the vertical profile of the light meter readings. The depth of the photic zone z_p was then calculated as:

$$z_p = \ln(0.01) / (-\alpha) \quad (2)$$

Measurements were made at each site on each date at the beginning of the incubation period ("early" measurements) and immediately after the incubation period ("late" measurements). The early and late measurements were then combined to provide the average depth of photic zone throughout the duration of each experiment at each site.

Table 2. Depth of incubator racks at each site during dissolved oxygen production and consumption experiments in Upper Klamath Lake, Oregon, 2005.

[Description of sites are shown in table 1; location of sites shown in figure 2. **Abbreviations:** n/a, site became too shallow to incorporate the lower rack into the experiment. –, no data were collected]

Rack location	Depth, in meters below water surface															
	First day of sampling in week															
	June			July				August					September			October
	14	21	28	6	12	19	26	2	9	15	22	29	6	19	26	3
Howard Bay (HDB)																
Upper	0.5	–	–	–	–	–	–	–	–	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lower	1	–	–	–	–	–	–	–	–	1.5	1.5	1	1	n/a	n/a	n/a
Average photic zone	2.35	–	–	–	–	–	–	–	–	0.62	1.42	1.07	1.04	1.08	1.60	2.17
Upper Klamath Lake at Williamson River Outlet (WMR)																
Upper	0.3	–	–	0.5	–	–	–	–	–	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lower	1	–	–	2	–	–	–	–	–	1.5	1	1	1	n/a	n/a	n/a
Average photic zone	2.47	–	–	2.84	–	–	–	–	–	2.01	1.89	1.09	1.55	2.29	2.80	1.8
Midlake (MDL)																
Upper		0.5	0.5	0.5	0.5	–	0.5	–	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lower		2	2	2	2	–	1.5	–	1.5	1.5	1.5	1.5	1.5	1	1	1.5
Average photic zone		2.12	1.87	1.78	2.06	–	3.92	–	2.61	2.71	1.06	2.40	1.87	1.15	1.70	1.88
Midnorth (MDN)																
Upper		0.5	0.5	–	–	0.5	–	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lower		2	2	–	–	2	–	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1	1.5
Average photic zone		1.83	1.69	–	–	2.15	–	4.31	2.76	2.86	1.52	1.61	1.90	1.45	1.51	1.44
Eagle Point (EPT)																
Upper		–	–	–	0.5	–	0.5	–	–	0.5	0.5	0.5	–	0.5	0.5	0.5
Lower		–	–	–	2	–	1.5	–	–	1.5	1.5	1.5	–	1.5	1	1.5
Average photic zone		–	–	–	2.29	–	3.01	–	–	1.90	1.86	1.76	–	1.99	1.52	1.72
Middle of trench (MDT)																
Upper		–	–	–	–	0.5	–	0.5	–	0.5	0.5	0.5	–	0.5	0.5	0.5
Lower		–	–	–	–	2	–	1.5	–	1.5	1.5	1.5	–	1.5	1.5	1.5
Average photic zone		–	–	–	–	0.87	–	1.90	–	0.71	1.07	1.25	–	0.91	1.44	1.42

Meteorological Sites

The location of meteorological measurement sites in the Upper Klamath Lake basin is shown in figure 2 and listed in table 3. Floating meteorological sites have been part of the Upper Klamath Lake monitoring program in previous years. Land-based meteorological sites were a new addition to the monitoring effort in 2005.

A schematic diagram of the typical land-based meteorological site is shown in figure 5. Wind speed and direction data were collected by an RM Young model 05103 wind monitor. Air temperature and relative humidity data were collected by a Campbell Scientific CS500 or HMP35C relative humidity and air temperature sensor. Additionally, solar radiation data were collected only at the WMR MET station by using a Li-Cor LI200SZ pyranometer. Floating sites were configured similarly to the land-based sites, although the mast attached to the buoy provided a height, measured from the surface of the water, of 2 m for wind monitors and 1.5 m for relative humidity and temperature sensors. Relative humidity and temperature data were not collected at the MDN MET, BLB MET, or SSHR MET sites during the 2005 field season. Data collected from all sensors at a site were stored every 15 minutes by a Campbell Scientific CR510, CR10, or CR10X datalogger located at the station. Power was provided by a 12-volt battery at the station charged by a solar power array.

Table 3. Description of meteorological sites and parameters measured at each site, Upper Klamath Lake, Oregon, 2005.

[**USGS site identification No.**: Unique number for each site based on the latitude and longitude of the site. First six digits are the latitude; next eight digits are longitude; and final two digits are a sequence number to uniquely identify each site. **Abbreviations:** USGS, U.S. Geological Survey]

Meteorological site name	Site name abbreviation	USGS site identification No.	Latitude (north)	Longitude (west)	Parameters measured
Ball Bay	BLB MET	422341122003800	42° 23' 40.9"	122° 0' 38.4"	Wind speed/direction
Howard Bay	HDB MET	421846121542800	42° 18' 46.2"	121° 54' 28"	Wind speed/direction, air temperature, relative humidity
Midlake[1]	MDL MET	422312121515900	42° 23' 12"	121° 51' 59.1"	Wind speed/direction, air temperature, relative humidity
Midnorth[1]	MDN MET	422622122004000	42° 26' 21.5"	122° 0' 40"	Wind speed/direction
South Shore	SSHR MET	421402121491400	42° 14' 2.76"	121° 49' 14.38"	Wind speed/direction
Williamson River	WMR MET	422809121574800	42° 28' 9"	121° 57' 48.5"	Wind speed/direction, air temperature, relative humidity, solar radiation

[1]Floating site.

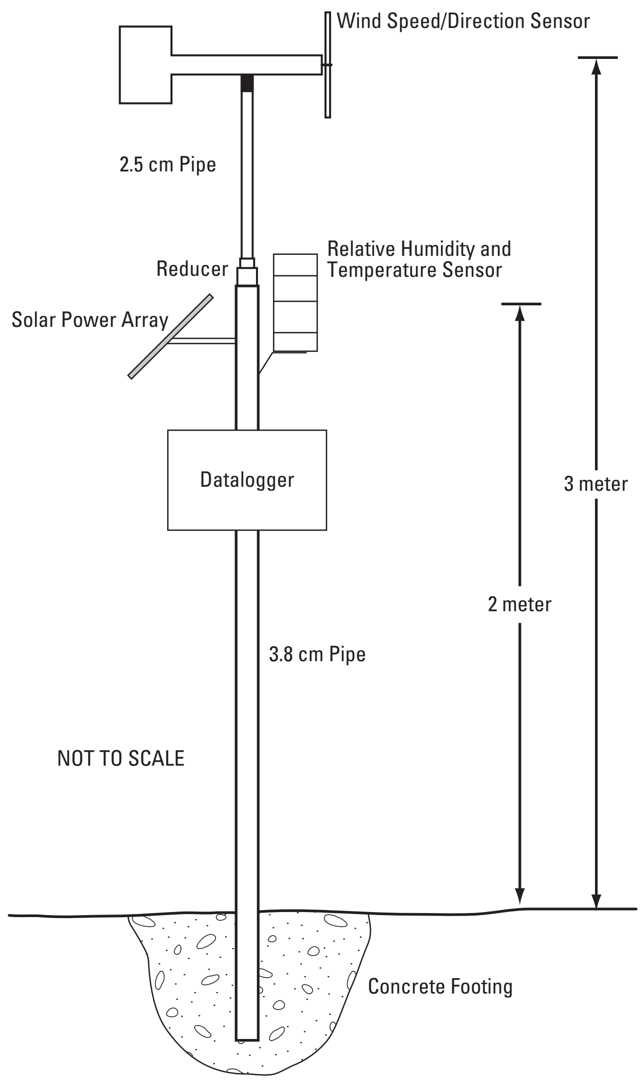


Figure 5. Configuration of land-based meteorological measurement sites around Upper Klamath Lake, Oregon, 2005.

Data were collected during site visits, about every 2 weeks during the field season. During these visits, sensors were checked for proper function by comparison with hand-held instruments and were cleaned and maintained if necessary. Information necessary to correct data that may have been corrupted by fouling or drifts from proper calibration was collected as needed. Raw meteorological data were loaded into ADAPS and processed in the same manner as the water quality data.

Data Processing

Before calculating any statistics, data recorded by continuous water quality monitors were screened using temporal and, when appropriate for the statistic, spatial criteria. In this report, daily statistics are used for continuous water quality monitoring data. For a day's worth of data to be acceptable for computing daily statistics, at least 80 percent of the day's possible measurements were necessary, constituting a "qualifying day" of data. A spatial criterion was applied when data over the entire lake were compiled to compute a statistic, such as lakewide daily median dissolved oxygen concentration. This criterion specified that at least 7 percent of the lake's water quality monitoring sites had to have qualifying daily data to in order to compute the lakewide statistic for a particular day.

For statistics at individual meteorological sites, the temporal criterion ensured that at least 80 percent of the day's possible measurements were available to constitute a qualifying day of data. To compute lakewide meteorological statistics, the SSHR MET site was not included in calculations because this site was not established until August 18, 2005. Different levels of spatial acceptability were applied depending on the parameter because not all parameters were collected at all sites, and there were relatively few meteorological sites around the Upper Klamath Lake basin. Statistics of solar radiation were computed only with data collected during daylight hours. Solar radiation data were collected at only one site, so no spatial criterion was applied to these data. Air temperature and relative humidity data were collected at three sites, so the spatial criterion for these parameters ensured that two of the three sites (67 percent) had daily qualifying data to compute a lakewide daily statistic. Wind speed data were collected at all meteorological sites, so the spatial criterion for wind speed ensured that four of the five sites (80 percent) had daily qualifying data to compute a lakewide daily statistic. Lakewide statistics were not computed for wind direction. Statistics of direction can be potentially misleading or uninformative. For example, a mean wind direction may indicate a direction that was not an actual wind direction during the time the statistic was computed, and because wind direction is a value between 0 and 359, daily minimum and maximum values of direction tend to be 0 and 359, respectively.

Meteorological Conditions

The graphs of lakewide daily median meteorological conditions (fig. 6) provide information about the general behavior of these environmental parameters in the vicinity of the lake throughout the field season. Daily median wind speed generally was constant throughout the study. Some particularly windy periods occurred in mid-June, late August, and mid-September, when lakewide daily median wind speed exceeded 5 m/s. Air temperature gradually increased from June through July and then gradually decreased from August through October. Relative humidity generally followed the inverse of air temperature patterns. Variability in solar radiation was low through July and August; indicating that conditions during these months were mostly sunny. Greater variability in mid-June and again from September onward indicates more periods of cloudiness during these times. These patterns of air temperature, relative humidity, and solar radiation are typical of the hot, dry summers of the Upper Klamath Lake basin.

Wind speed and direction ultimately determine the circulation of the water in Upper Klamath Lake. This phenomenon has been verified with a hydrodynamic model of the lake (Cheng and others, 2005) and with the placement of acoustic Doppler current profilers in the lake (Wood and others, 2006). The hydrodynamic model describes a general clockwise circulation pattern of water in Upper Klamath Lake under northwesterly winds (fig. 7), which are prevalent during the summer.

Because the wind and the currents are so closely related, the preliminary modeling effort also demonstrated the need to collect spatially accurate wind data, rather than data from a single site. Before meteorological measurements were collected at several sites on and around the lake (fig. 2), little was understood about wind characteristics in the vicinity of the lake.

Wind histograms (fig. 8) provide a summary of wind direction and speed at each site. These histograms show the relative frequency of occurrence of wind in four speed categories from each 5-degree direction category around 360 degrees of direction. The wind speed histogram bars are stacked in each 5-degree direction category, with bars for the strongest winds on top. The histograms display simple counts of direction readings categorized by wind speed; no temporal filters were applied to the data used in these plots.

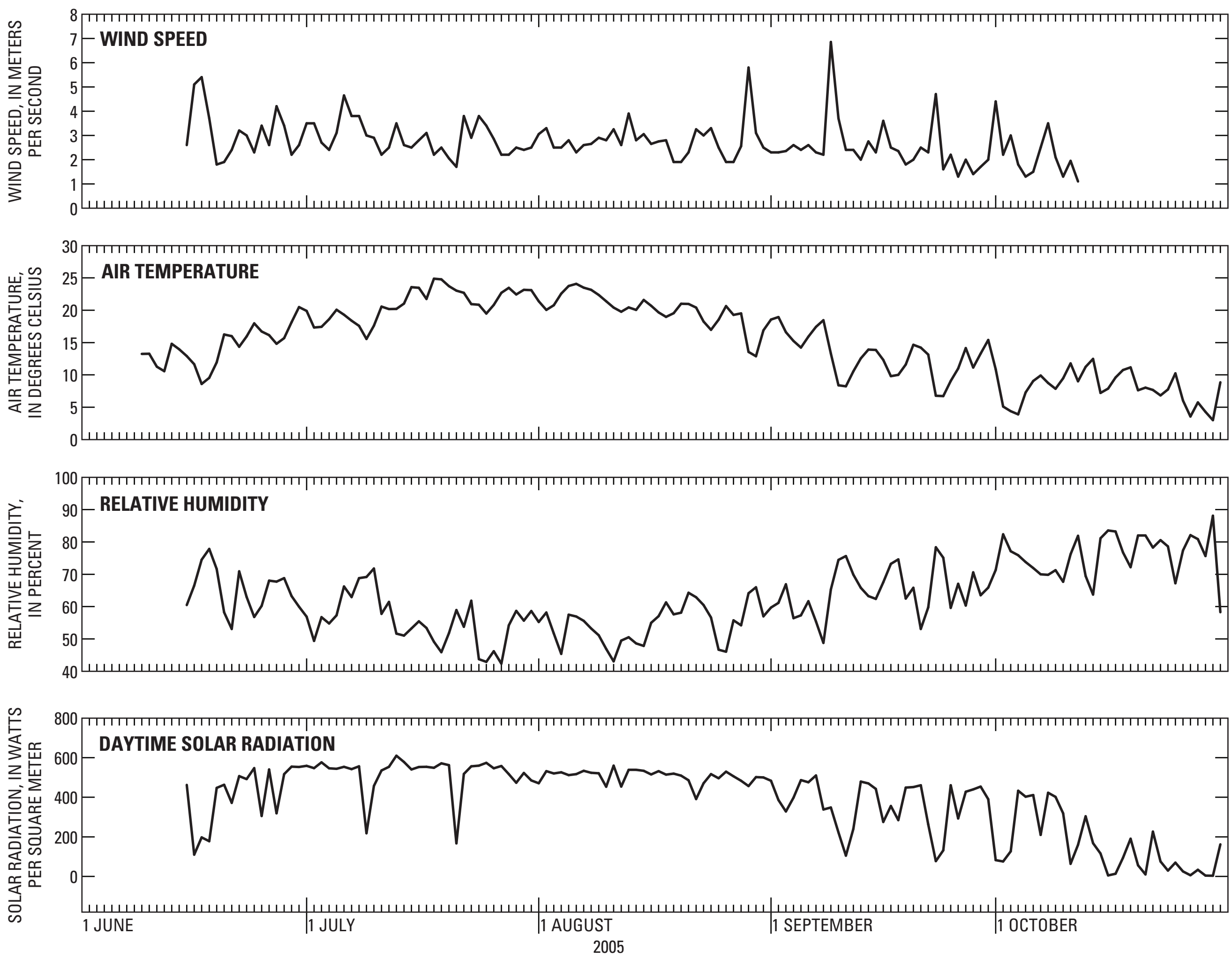


Figure 6. Lakewide daily median wind speed, air temperature, relative humidity, and daytime solar radiation for meteorological sites in and around Upper Klamath Lake, Oregon, 2005.

The histograms reveal that wind characteristics in the northern part of the lake, represented by MDN MET, differed from those in the main body of the lake, represented by MDL MET. In the northern part of the lake, winds were likely to come from the southwest-to-northwest sector, including most winds greater than 5 m/s, which have more potential to drive lake currents. In the main body of the lake, most winds in all speed categories came from a relatively narrow band to the northwest, because the topographic ridges to the east and west funnel the winds into a narrow range of direction over the main body of the lake. This same narrow band of northwesterly winds was observed for most winds greater than 5 m/s at the land-based HDB MET and SSHR MET sites farther south, although winds less than 5 m/s came primarily from the northeast and south at HDB MET and primarily from the south at SSHR MET. This observation indicates that strong winds blowing from the northwest over the main body of the lake typically continue in this direction over the southern part of the lake. At the land-based meteorological sites in the northern part of the lake, the strongest winds typically came from the northwest at BLB MET and from the west at WMR MET, reinforcing the inference drawn from the MDN MET histogram that westerly winds dominate in the northern part of Upper Klamath Lake.

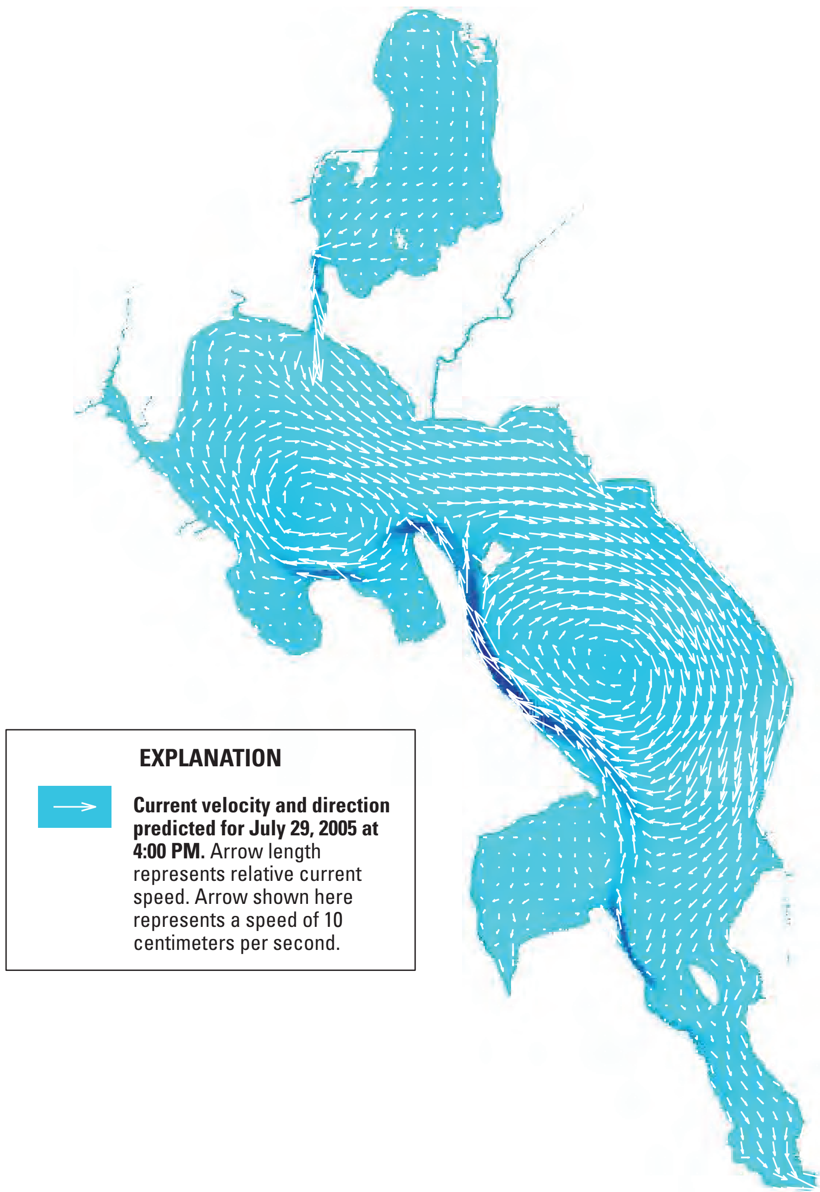


Figure 7. Water-current velocity predicted by the hydrodynamic model of Upper Klamath Lake, Oregon, under prevailing wind conditions.

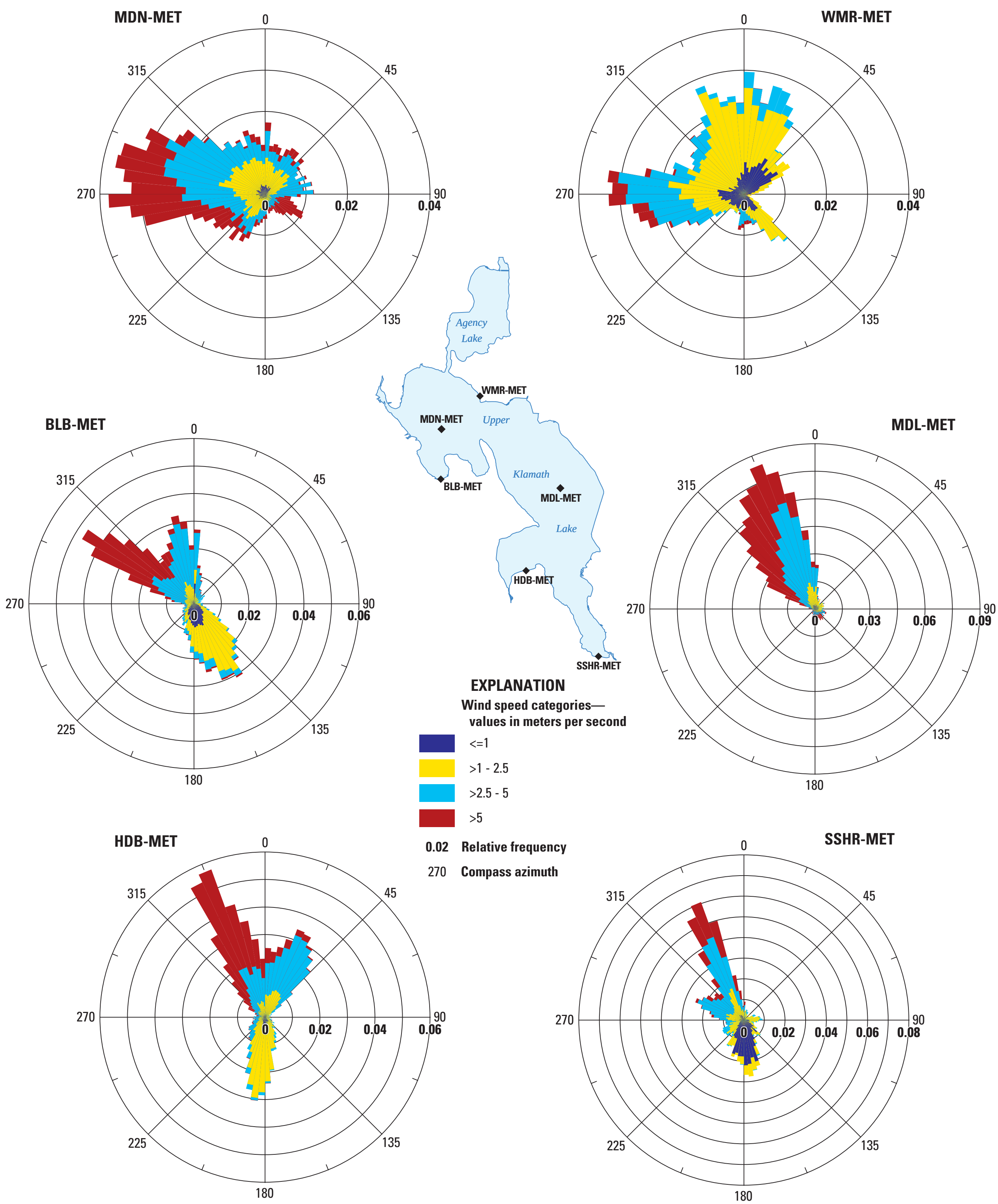


Figure 8. Wind speed and direction for all meteorological sites in the vicinity of Upper Klamath Lake, Oregon, 2005. The histogram bars are stacked in each 5-degree direction category. (The SSHR meteorological site was installed midway through the study and recorded only 38 days of data).

Nutrients and Chlorophyll *a*

Bloom Dynamics of *Aphanizomenon flos-aquae*

Photosynthetic pigments, like chlorophyll *a*, are measured as a surrogate for algal biomass because the cost and time required to collect and analyze chlorophyll *a* is less than that for measurements of algal biomass. In this report, algal biomass will be represented by chlorophyll *a* concentration. Between May and November, 90–100 percent of the total phytoplankton biomass in Upper Klamath Lake consists of AFA (Kann, 1997). The weekly water samples, although collected at only a subset of the sites in the study area, provided valuable context for understanding the data recorded by the continuous water quality monitors.

Trends and fluctuations in water quality parameters commonly were associated with algal trends and fluctuations, as reflected in the chlorophyll *a* data. Maximum concentrations of chlorophyll *a*, coinciding with similar maximum concentrations of dissolved oxygen and pH values, indicated an algal bloom. Week-to-week variation in chlorophyll *a* concentrations indicated that either populations were periodically blooming and declining (as a result of algal cell death) or that there was an inherent patchiness of algal growth and that the patches were moving around the lake. Indicators of cell death are low dissolved oxygen concentration and increased dissolved nutrient concentration. During an event of massive cell death, the magnitude of the increase in dissolved nutrient and decrease in dissolved oxygen concentrations can be variable and is related to the chlorophyll *a* concentrations before the event. Variation in chlorophyll *a* concentration caused by patchiness is not associated with increased nutrient or decreased dissolved oxygen concentration. Many blue-green algae, such as AFA, contain gas vesicles that allow cells to regulate their position in the water column by floating to the surface or sinking to the bottom. The sampling protocols used in this study may be insufficient to detect chlorophyll *a* very near the lake bottom, thereby falsely indicating a lack of chlorophyll *a* at a site. In addition, algae floating to the surface can form mats that are moved around by the wind, possibly resulting in a low chlorophyll *a* concentration at the site of measurement when in fact a bloom is in progress elsewhere in the lake.

A bloom decline is characterized by a sharp reduction in oxygen production through photosynthesis and is manifested as a decrease in dissolved oxygen concentration, generally to values potentially harmful to fish, as oxygen demand in the water column or sediments caused by decomposition of organic material continues. In contrast, periods of growth in the bloom are generally manifested as supersaturated dissolved oxygen concentrations and high pH values, as photosynthesizing algae consume carbon dioxide and produce oxygen.

At site MDN, data were collected from 2002 through 2005, allowing direct interyear comparison. In each year, the algal bloom expanded rapidly to an initial peak sometime between mid-June to mid-July, as measured by a maximum in chlorophyll *a* concentration (fig. 9). Between late July and mid-August in each year, chlorophyll *a* concentrations decreased concurrent with increased dissolved nutrient and decreased dissolved oxygen concentrations, indicating an algal bloom decline associated with large-scale cell death. Dissolved oxygen concentrations of less than 4 mg/L lasting between several hours and several days were measured at site MDN in association with this type of bloom decline from as early as late July to as late as mid-October during 2002–05 (fig. 9). The most severe (longest duration) low dissolved oxygen events occurred mid-season in 2003 and in 2005, and were associated with the largest decreases in chlorophyll *a* from the previous peak and the highest peaks in nutrient concentrations, particularly ammonia (note difference in the vertical scales among the years). The occurrence of a low dissolved oxygen event in October 2003, however, demonstrates that this type of event is not limited to occurring at mid-season, and can occur more than once in a single season.

The variability of chlorophyll *a* concentrations measured in 2005 suggests the occurrence of multiple summer chlorophyll *a* maximums, with concentrations at some sites reaching two or more maximums during the season (fig. 10). The highest chlorophyll *a* concentrations occurred after the mid-season bloom decline at sites HDB, MDL, MDT, and WMR (table 4). Data collected during previous years also indicated late-summer blooms of AFA (Kann, 1997; Wood and others, 2006). Measured reductions in bloom-related chlorophyll *a* concentrations at all sites except HDB in late July 2005 were notable because of the associated low dissolved oxygen events (LDOE) and increased un-ionized ammonia concentrations that were potentially harmful to fish. Chlorophyll *a* concentrations were lowest after the June–July bloom and were measured between July 18 and August 3, 2005, with most of the lowest concentrations in early August (table 4). The decrease in chlorophyll *a* concentrations was measured at site HDB in early August, a week later than the onset of decline at other sites. Howard Bay is largely disconnected from the circulation in the main body of the lake, and as a result the bloom there probably developed its own seasonal dynamics in response to localized nutrient, wind, and circulation patterns within the bay. During the widespread bloom decline, measurements recorded by the continuous water quality monitors showed that dissolved oxygen concentrations decreased to less than 6 mg/L at all sites, less than 4 mg/L at site MDN, and less than 2 mg/L at sites HDB, MDT, and EPT. Dissolved oxygen concentration at sites MDL and WMR did not decrease to such low levels, indicating that oxygen consumption was not as extreme at those two sites.

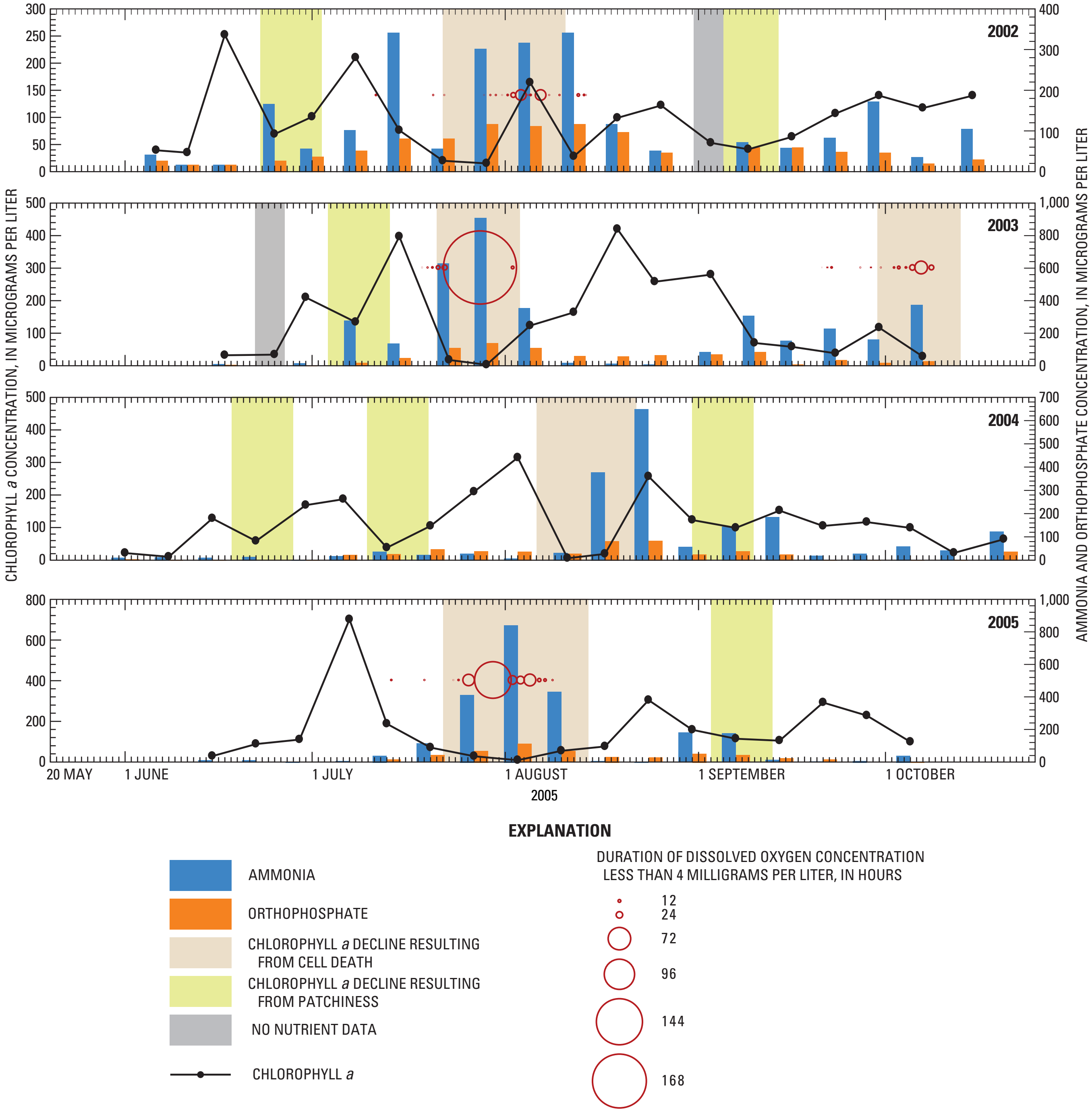


Figure 9. Weekly measurements of chlorophyll *a* and dissolved nutrient concentration in relation to the duration of a dissolved oxygen concentration of less than 4 milligrams per liter at water samples collected from site MDN, Upper Klamath Lake, Oregon, 2002–05. Note the difference in the scale of the chlorophyll *a* and nutrient axes among years.

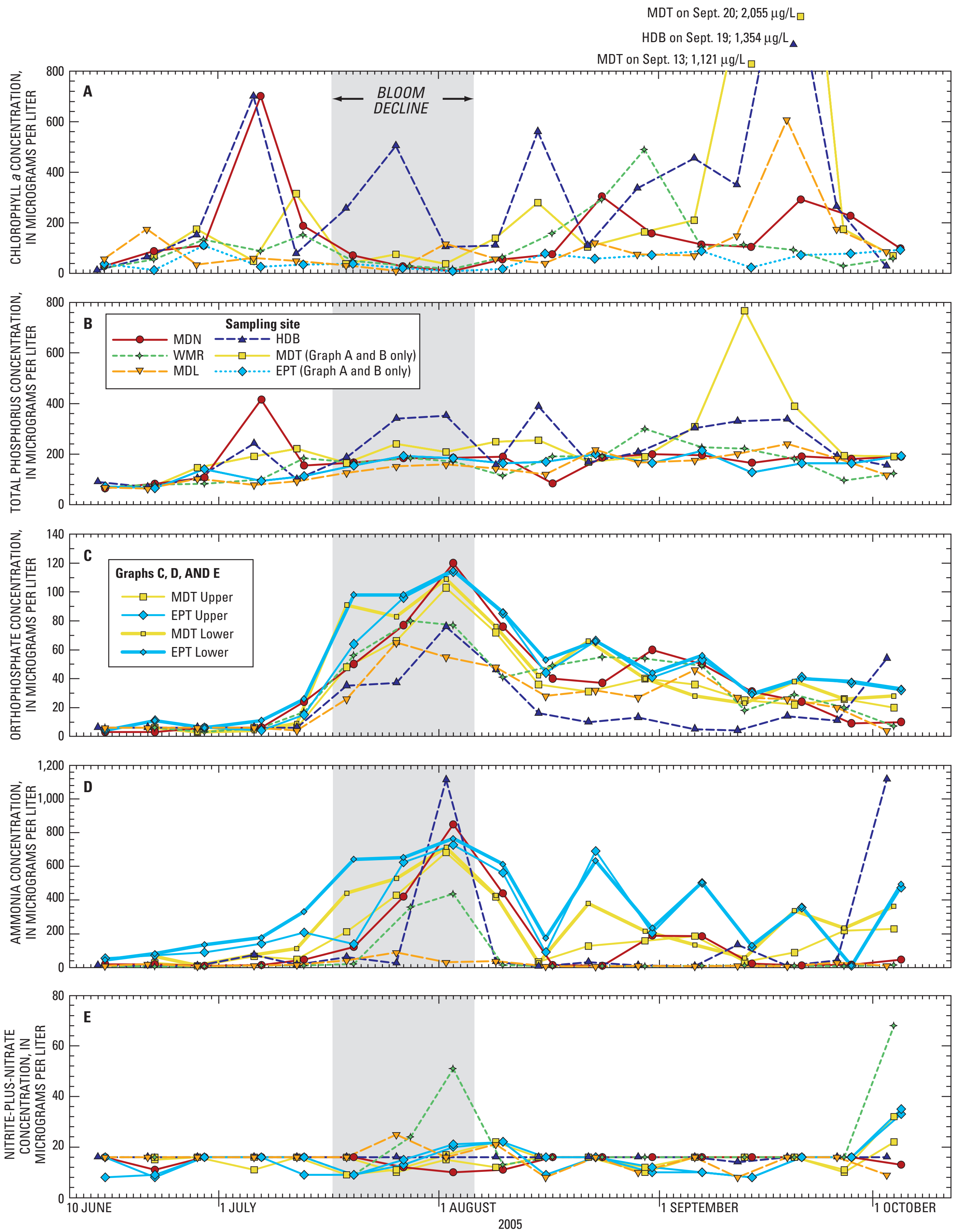


Figure 10. Concentrations of chlorophyll *a*, total phosphorus, orthophosphate, ammonia, and nitrite-plus-nitrate in water samples collected from Upper Klamath Lake, Oregon, 2005.

Table 4. Maximum and minimum chlorophyll *a* concentrations and dates relative to *Aphanizomenon flos-aquae* blooms and decline during sampling season, Upper Klamath Lake, Oregon, June–October 2005.

[NA, not available]

	Chlorophyll *a* concentrations, in micrograms per liter					
Week of	**Howard Bay (HDB)**	**Midlake (MDL)**	**Middle of trench (MDT)**	**Eagle Point (EPT)**	**Upper Klamath Lake at Williamson River outlet (WMR)**	**Midnorth (MDN)**
June 13–17	12	58	NA	38	22	29
June 20–24	64	175	70	13	56	88
June 27–July 1	152	35	175	111	134	110
July 5–8	700	61	49	26	88	701
July 11–15	78	50	315	35	152	188
July 18–22	257	32	38	38	50	71
July 25–29	504	10	76	21	30	28
Aug. 1–5	105	117	38	9	18	9
Aug. 8–12	111	58	140	18	64	55
Aug. 15–19	560	41	280	79	158	76
Aug. 22–26	110	122	105	58	292	304
Aug. 29–Sept. 2	337	76	164	73	490	158
Sept. 6–9	455	71	210	88	105	114
Sept. 12–16	350	149	1,121	24	113	105
Sept. 19–23	1,354	607	2,055	73	93	292
Sept. 26–30	264	175	175	79	29	228
Oct. 3–7	28	86	70	93	58	99
(green)	Maximum concentrations at each site before algae decline resulting from cell death					
(blue)	Minimum concentrations at each site during algae decline resulting from cell death					
(gray)	Sample dates during algae decline resulting from cell death					

Decreases in chlorophyll *a* concentrations after late-season blooms generally were not coupled with low dissolved oxygen concentrations, except at the trench sites MDT and EPT, and to a lesser extent at site HDB in October, as discussed below in the context of the water quality monitors. Dissolved oxygen concentrations at the trench sites probably were affected more by the respiration processes associated with bloom declines than concentrations at the shallow sites because most of the water column was below the photic zone at the deep sites, whereas most of the water column was within the photic zone at the shallow sites. One notable aspect of the sudden decrease in chlorophyll *a* concentrations at the end of July was that it occurred nearly simultaneously at all of the water quality sampling sites. A simultaneous change in chlorophyll *a* concentrations at each site indicates that algal production was affected by factors extending throughout the area, such as temperature or irradiance or a combination of the two.

Although samples were not collected in Agency Lake, qualitative weekly observations of bloom conditions were made at the Agency Lake sites (fig. 11). Trends in these observations closely match trends in chlorophyll *a* data gathered biweekly by the Klamath Tribes at sites AGN and AGS in 2005 (Klamath Tribes, unpub. data, 2005). From mid-June through August, bloom conditions cycled through extremes (between "very light" and "very heavy") on a weekly to biweekly basis at site AGN when bloom conditions at site AGS were observed to be less variable (between "medium" and "heavy"). Bloom conditions above "light" were not observed past mid-August at either site in Agency Lake. This is in contrast to the bloom in Upper Klamath Lake, where the late-season bloom recovered to at least predecline levels at most sites (fig. 11).

Unlike deep lakes in which summertime chlorophyll *a* can often be predicted based on the phosphorus available at spring turnover (Dillon and Rigler, 1974), shallow lakes are not necessarily well-described by simple relations between phosphorus and biomass (Havens and others, 2001). Total phosphorus and chlorophyll *a* in UKL tend to increase simultaneously in spring, as determined within the resolution of weekly or bi-weekly sampling (Kann 1997; Wood and others, 2006). Mass balance studies have confirmed that the source of phosphorus is internal loading from lake sediments (Kann and others, 2001), although the precise mechanism for phosphorus loading is as yet unknown (Jacoby and others, 1982; Barbiero and Kann, 1994; Laenen and LeTourneau, 1996; Fisher and Wood, 2004). Initial results using pore-water profilers suggest that diffusive flux in combination with bioturbation is a possible mechanism for internal phosphorus loading (Kuwabara and others, 2007). Maximums in chlorophyll *a* concentrations in 2005 corresponded loosely with maximums in total phosphorus concentration (fig. 10), and total phosphorus concentrations correlated positively with chlorophyll *a* concentrations (fig. 12). Application of the Spearman Rank Order Correlation test to the data resulted in a correlation coefficient of 0.59 ($p < 0.05$, $n = 101$) for the relation between total phosphorus and chlorophyll *a* concentration in samples from combined sites. Management of the lake's watershed has focused primarily on reducing phosphorus loads to the lake (Walker, 2001), but the evidence for phosphorus limitation seems inconclusive. A ratio of chlorophyll *a* to total phosphorus concentration around 1 or greater indicates that phosphorus was potentially limiting, whereas ratios much less than 1 indicate that phosphorus was not a limiting nutrient (White, 1989; Graham and others,

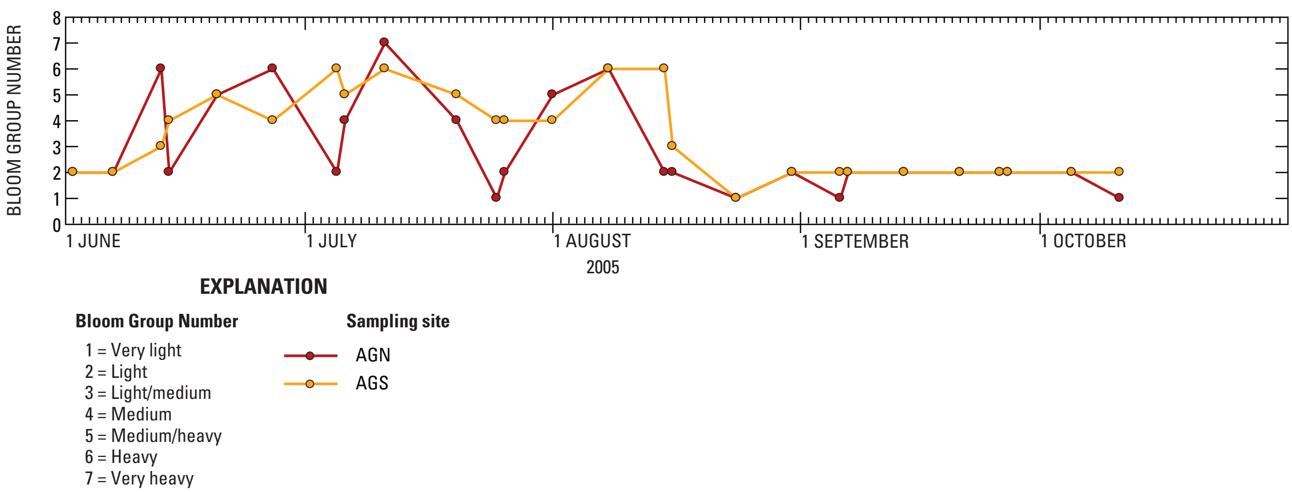


Figure 11. Weekly qualitative observations of algal bloom conditions in Agency Lake, Oregon, 2005.

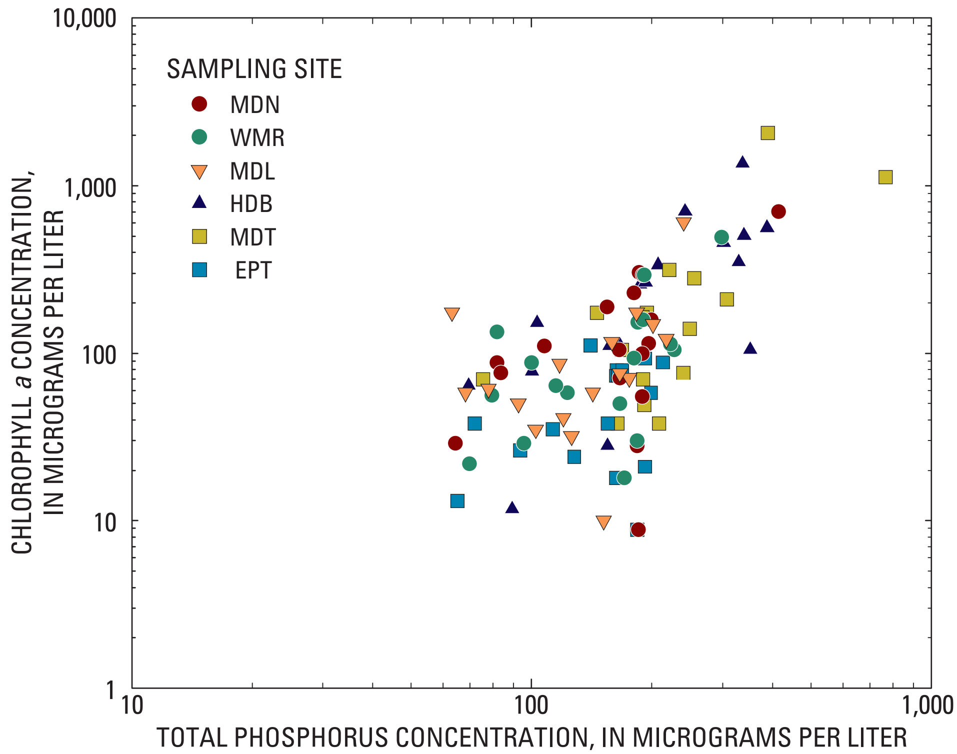


Figure 12. Relation of chlorophyll *a* to total phosphorus concentration in water samples collected from Upper Klamath Lake, Oregon, 2005.

2004). Ratios of chlorophyll *a* to total phosphorus in the 2005 data ranged from 0.05 to 5.28, with 63 percent of samples less than 0.8, indicating that during most of June through October, phosphorus was not potentially limiting (fig. 13). The concentration of bioavailable phosphorus was higher during late-season blooms in comparison to the early-season bloom (fig. 10), and the ratio of bioavailable nitrogen to bioavailable phosphorus decreased between the early season bloom and late-season blooms (fig. 13), both of which suggest that phosphorus limitation was not consistent from June through October. In general, it is necessary to evaluate nitrogen as a potentially limiting nutrient (for example, TN:TP less than 10 indicates potential nitrogen limitation; Forsberg and Ryding, 1980), but because AFA can fix nitrogen, it seems unlikely that nitrogen is limiting. Other potential limiting factors include micronutrients such as iron, or light energy. Kuwabara and others (2007) noted that the trends of phosphorus in UKL were not as expected for a limiting nutrient, whereas the trends in iron were. It seems prudent at this point to leave the question of what is limiting the bloom in UKL open for further research.

Concentrations of the dissolved nutrients orthophosphate and ammonia were slightly negatively correlated with chlorophyll *a* concentrations (fig. 14). Correlations using the Spearman Rank Order Correlation test were –0.21 ($p < 0.05$, $n = 101$) and –0.31 ($p < 0.05$, $n = 101$) for orthophosphate and ammonia, respectively. The greatest maximums of orthophosphate and ammonia coincided with minimums in chlorophyll *a* concentrations at the end of July into early August. Low dissolved oxygen concentrations coincided with the decrease in chlorophyll *a* concentrations and the increase in dissolved nutrient concentrations in late July through early August, indicating that the nutrient maximums resulted from decomposition of senescing cells, which converts organic nutrients to inorganic form while consuming dissolved oxygen. Nitrite-plus-nitrate concentrations were low in comparison to ammonia concentrations, indicating that nitrification is not a rapid or effective process for removal of ammonia from the water column in Upper Klamath Lake.

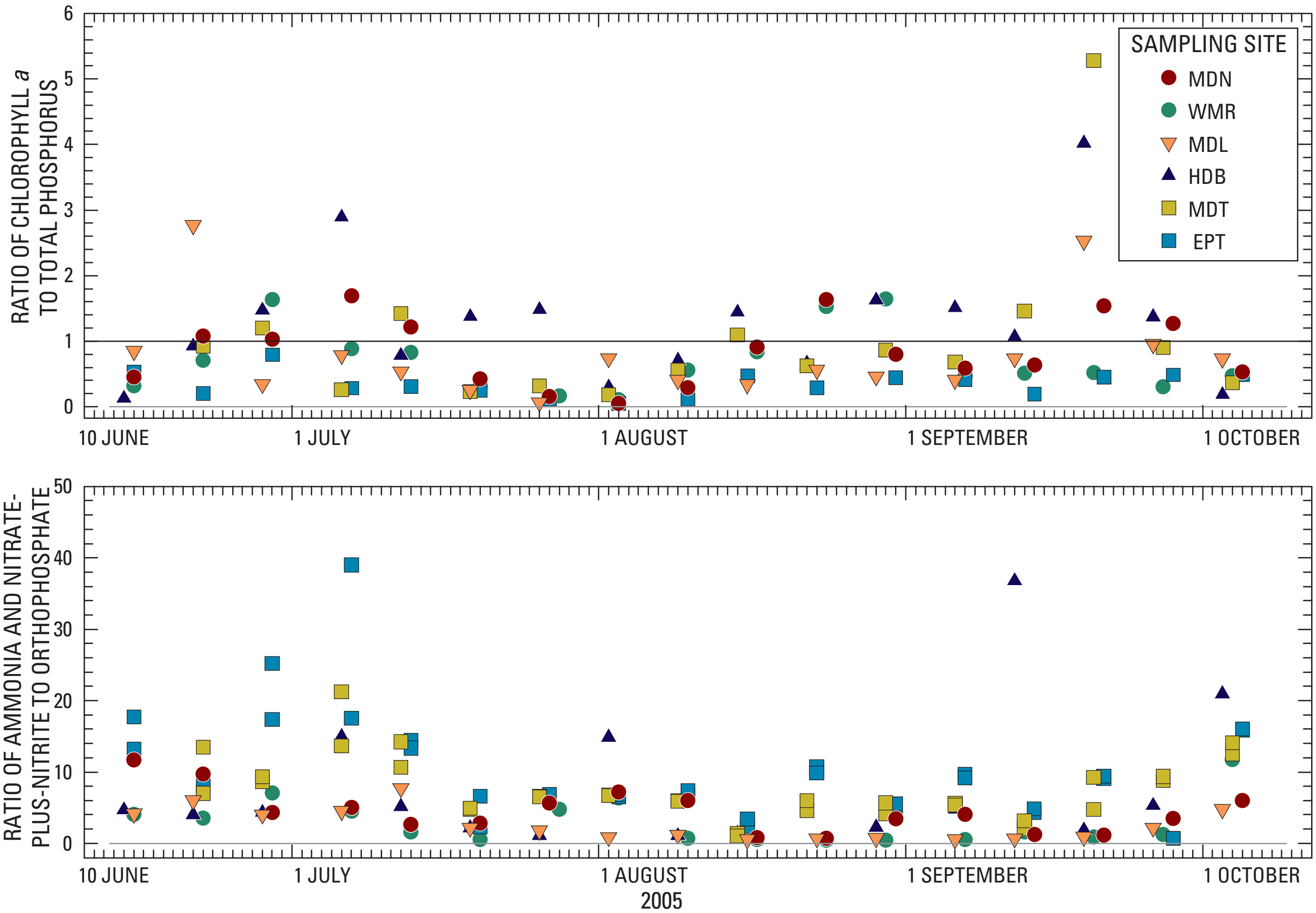


Figure 13. Ratio of chlorophyll *a* to total phosphorus and ratio of ammonia and nitrite-plus-nitrate (bioavailable nitrogen) to orthophosphate (bioavailable phosphorus) concentrations in water samples collected from Upper Klamath Lake, Oregon, May–October 2005.

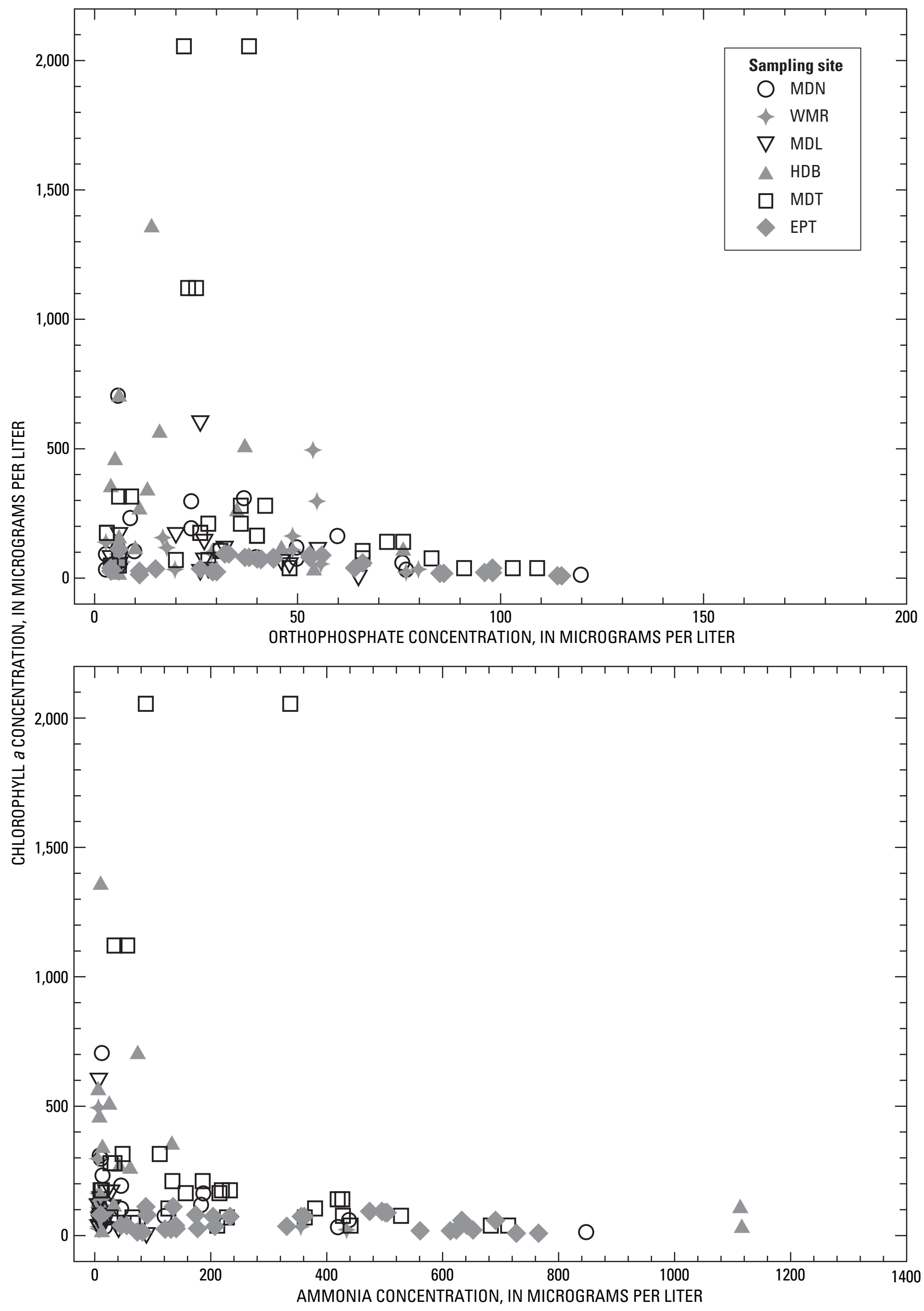


Figure 14. Relation of ammonia and orthophosphate concentrations to chlorophyll *a* concentrations in water samples collected from Upper Klamath Lake, Oregon, 2005.

Spatial Variability in Nutrient and Chlorophyll *a* Concentrations

As with dissolved oxygen concentrations, the bathymetry of the lake appears to influence dissolved nutrient concentrations. Median concentrations of ammonia and orthophosphate were highest at the deep trench sites MDT and EPT (fig. 15), particularly during the period of bloom decline when dissolved nutrient concentrations were the highest of the season. Median concentrations of dissolved nutrients were lowest at shallow sites MDN, WMR, MDL, and HDB, outside of the trench. This contrast indicates a greater degree of mineralization at the deep sites. The oxygen consumption rates obtained from dark bottles (discussed in section, "Dissolved Oxygen Production and Consumption Experiments") do not indicate a large oxygen demand from the water column during the period of bloom decline. Therefore, oxygen consumption and mineralization processes likely occurred primarily at the sediment–water interface. This idea is supported by the downward vertical velocities measured near-bottom in the

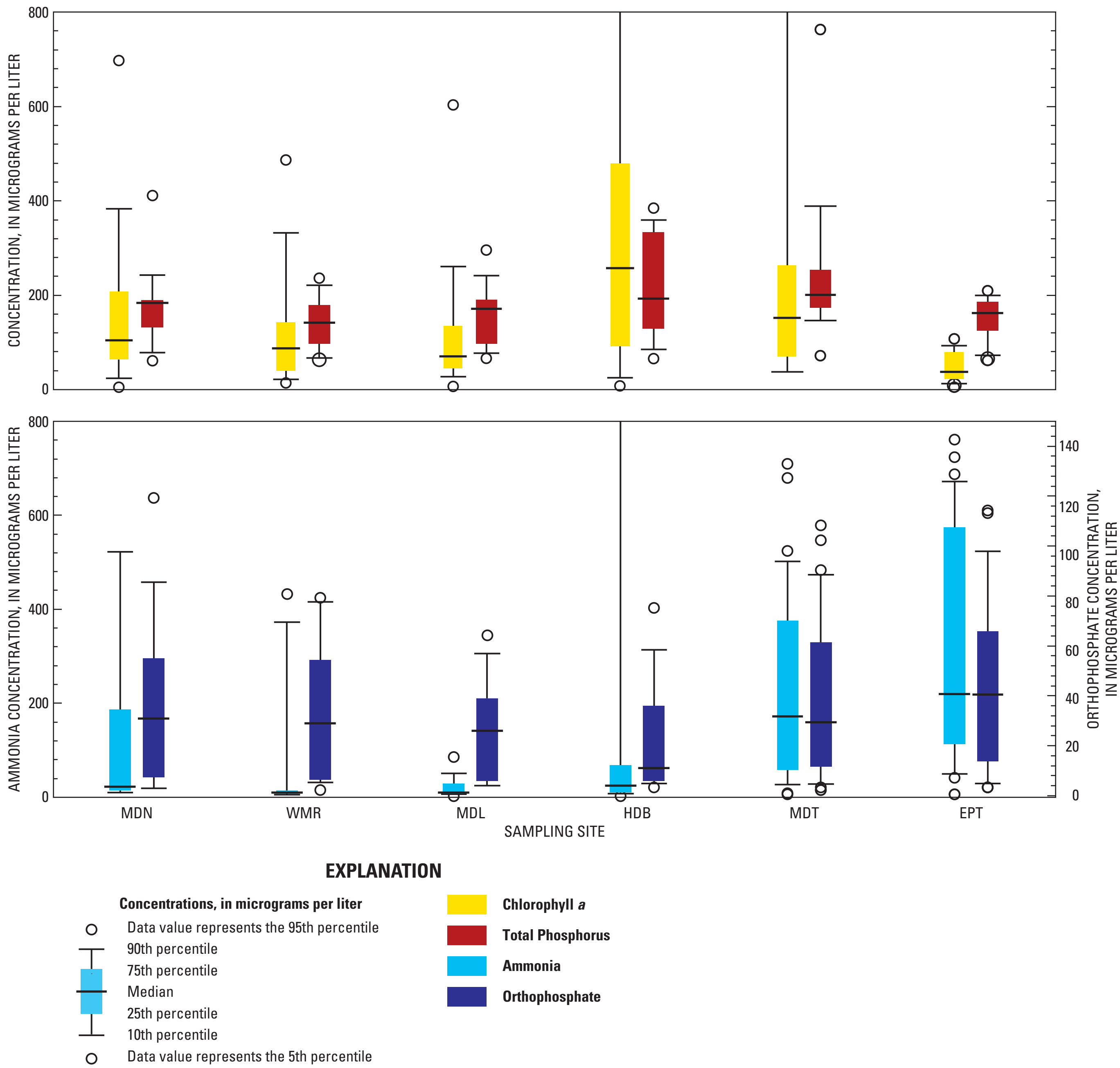


Figure 15. Statistical distribution of ammonia, orthophosphate, total phosphorus, and chlorophyll *a* concentrations measured in water samples collected from Upper Klamath Lake, Oregon, 2005.

trench with ADCPs, in conjunction with sediments containing a large amount of organic matter (Gartner and others, 2007), which together indicate a great deal of settling of organic matter at the deep trench sites.

Chlorophyll *a* and total phosphorus concentrations at sites HDB and MDT were higher than at the other sites (table 4). The high concentration of chlorophyll *a* and total phosphorus at site HDB may be explained by the fact that Howard Bay is largely isolated from the flow regime in the rest of the lake, and the bloom in this bay tends to develop and evolve somewhat independently of the bloom in the rest of the lake. The high chlorophyll *a* concentrations in samples collected at site MDT coincide with observations of the field crews of thick mats of AFA close to the water surface. Additionally, the primary location for companies collecting AFA for commercial production is near site MDT, indicating easy access to high concentrations of AFA near the surface at that site. These observations are consistent with the measurements made with the water quality monitors at MDT that show the water column there has a tendency to stratify more strongly than in the shallow parts of the lake (as discussed in the section on stratification and wind speed), particularly when air temperature is increasing, creating conditions that allow AFA colonies to make use of their buoyancy-regulating mechanism. On the basis of the circulation model, a counterclockwise flow cell forms east of Eagle Ridge and south of Bare Island that may capture large algal mats in a continuous loop (fig. 7). In addition, particle-tracking studies with the model have shown that water can be trapped in the cell for days, particularly when winds are weak (Cheng and others, 2005; Wood and Cheng, 2006). The combination of surface accumulation when conditions are stratified and relatively limited horizontal transport creates ideal conditions for AFA to form very dense blooms at this site.

Dissolved Oxygen Production and Consumption Experiments

Dissolved Oxygen Production and Consumption

The rate of change in dissolved oxygen concentration in light and dark incubation bottles at each level in the water column is shown as time series in figure 16. Rates obtained from the two light bottles were averaged for each rack depth. This was done for dark bottles when there were multiple dark bottles on a rack during an experiment, but only one dark bottle at each depth was used in most of the experiments. Typically, rates from light bottles represented net dissolved oxygen production (positive rates), and rates from dark bottles represented net dissolved oxygen consumption (negative rates). A maximum production rate of 1.47 (mg/L)/hr of oxygen was measured at site HDB on August 15 and a maximum consumption rate of –0.73 (mg/L)/hr of oxygen was measured at site MDN on August 10 (fig. 16). Because the bottles were filled with unaltered lake water, the experiments measured oxygen production and consumption of the entire planktonic community (phytoplankton, zooplankton, and bacteria). Because AFA typically constitutes more than 90 percent of the phytoplankton by weight during the time of year when these experiments were conducted (Kann, 1997; Perkins and others, 2000), dissolved oxygen production was attributable mostly to photosynthesis by AFA. However, the abundance of oxygen consuming components of the planktonic community relative to AFA is less well known, particularly bacterial biomass. Large quantities of the zooplankter *Daphnia plicaria*, a cladoceran that dominates the zooplankton biomass in Upper Klamath Lake (Kann, 1997), were not observed in bottles during experiments. It is expected that AFA is a major contributor to oxygen consumption observed in the experiments, but without knowledge of the bacterial biomass relative to that of AFA it cannot be conclusively stated that AFA dominates dissolved oxygen consumption processes.

The rate of change of dissolved oxygen concentration in dark bottles sometimes was positive (fig. 16), indicating the unlikely occurrence of oxygen production in absence of light. This problem was largely limited to the end of the field season in September and October. Measured positive changes in dark bottles in the raw data were small (median value of 0.08 mg/L), suggesting that the changes were the result of the accuracy limits of the dissolved oxygen probe, which the manufacturer specifies as ±0.2 mg/L.

Excluding the positive rates of change of dissolved oxygen concentration in the dark bottles, consumption rates measured in dark bottles were comparable to the overnight consumption rates measured in Upper Klamath Lake in 2002 by Lieberman and others (2003). Consumption rates ranged from 0 to –0.73 (mg/L)/hr of oxygen in this study, whereas consumption rates in the 2002 study ranged from –0.05 to –0.49 (mg/L)/hr of oxygen. The larger range of consumption rates determined in this study is attributable to annual variability and the fact that experiments in this study were conducted over a period of 6 months, whereas the 2002 study was conducted during 2 consecutive days in late July and 2 consecutive days in mid-September.

Greater consumption rates typically were measured in dark bottles on the upper incubation rack than in those on the lower incubation rack. Final bottle temperatures tended to be higher in the upper rack bottles than in the lower rack bottles, reflecting the difference in the ambient water temperatures. The higher temperatures could explain the generally higher consumption rates in the bottles on the upper rack.

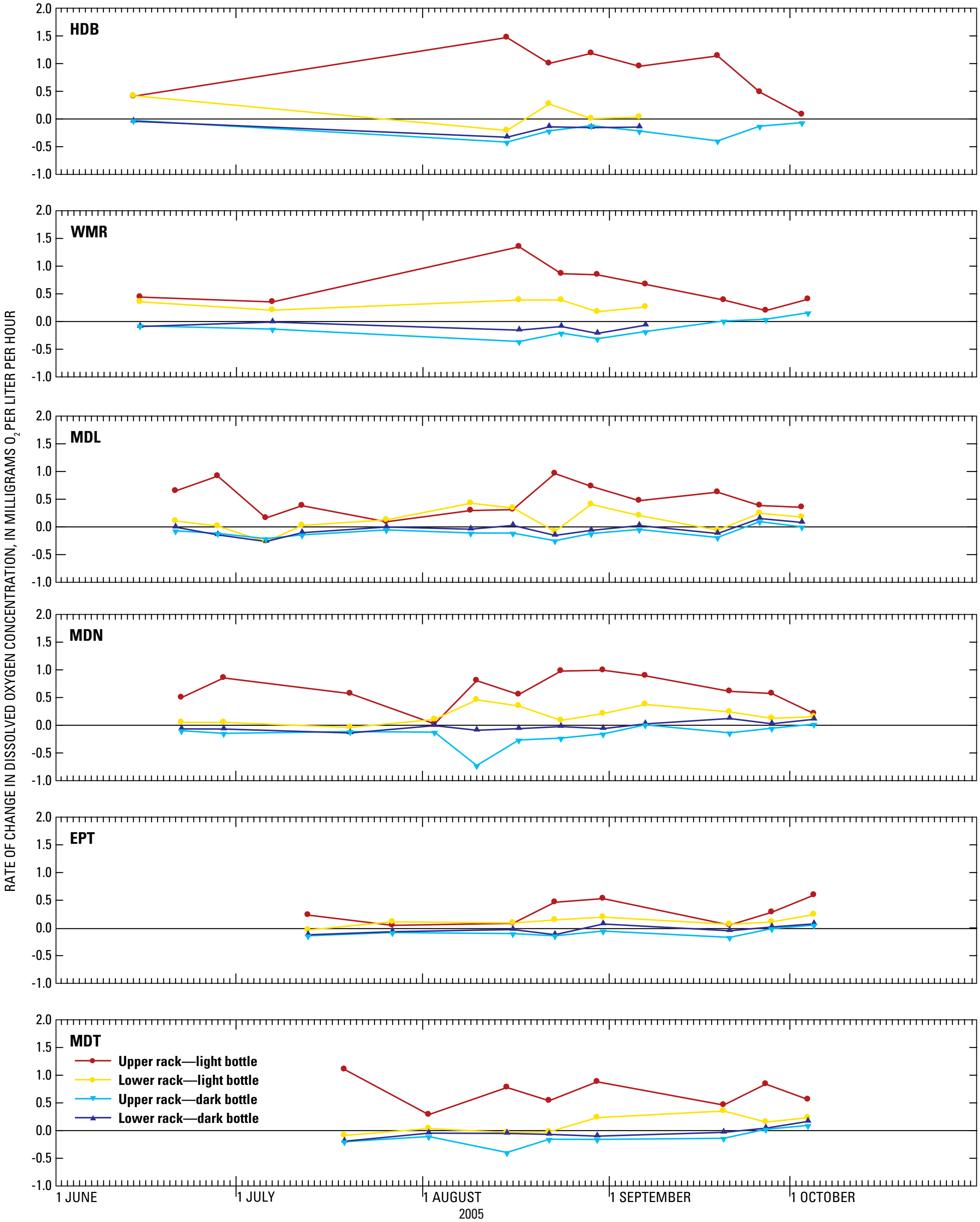


Figure 16. Rate of change in dissolved oxygen concentration measured from dissolved oxygen production and consumption experiments at sites in Upper Klamath Lake, Oregon, 2005.

With the exception of the first experiment at site WMR, upper incubation racks were positioned at 0.5 m below the water surface in the water column during all experiments at all sites (table 2). This placement provided a consistent framework with which to observe patterns in dissolved oxygen production in the upper 0.5 m of the water column. Dissolved oxygen production rates in the upper rack at site MDL were initially high in June, slowed through July, and recovered through August (fig. 16). A similar pattern was observed in the upper rack dissolved oxygen production at site MDN (fig. 16). Experiments were not conducted at sites EPT or MDT during June, but results of experiments done in July and August also show a decrease in upper rack production rates from the mid-July experiment to the late July–early August experiment at both sites, with a subsequent recovery of upper rack dissolved oxygen production rates through August. This pattern of decreasing oxygen production in upper portions of the water column through June and recovery through August is coincident with the patterns in chlorophyll *a* (fig. 10) and the decrease and recovery of dissolved oxygen concentration in the continuous water quality monitors, as discussed in the section, “Daily Median Water Quality Conditions.” When data from all experiments were combined, upper rack production rates also were positively correlated with the natural logarithm of chlorophyll *a* concentrations (fig. 17). The fact that no correlation was observed in data from the lower rack likely results from the effect of algal self-shading, as discussed in the section, “Depth of Photic Zone.”

Because these experiments were not done at all sites during all weeks, a lakewide decrease in dissolved oxygen production rates in late July and early August cannot be confirmed, but the similarities of the production rate, chlorophyll *a*, and time series of dissolved oxygen concentration and percent saturation indicate that reduced AFA dissolved oxygen production contributed to the decreasing dissolved oxygen concentrations observed through July 2005. Because AFA at Agency Lake sites undergoes cycles of large blooms followed by substantial decline similar to the pattern seen in Upper Klamath Lake, decreased oxygen production by AFA also likely contributed to periods of decreasing dissolved oxygen concentrations observed at Agency Lake monitoring sites in July and August.

Depth of Photic Zone

When data from all experiments were combined, an inverse relation was observed between photic zone depth and the natural logarithm of chlorophyll *a* concentrations (fig. 18). This relation reflects the shading effect that blooms of AFA can have on the water column. During some experiments, rates from light bottles on the lower rack were negative. This happened most notably at site HDB during the August 15 experiment and at site MDL during the July 6 experiment, when the average light bottle change in dissolved oxygen concentration on the lower rack was about –0.21 and

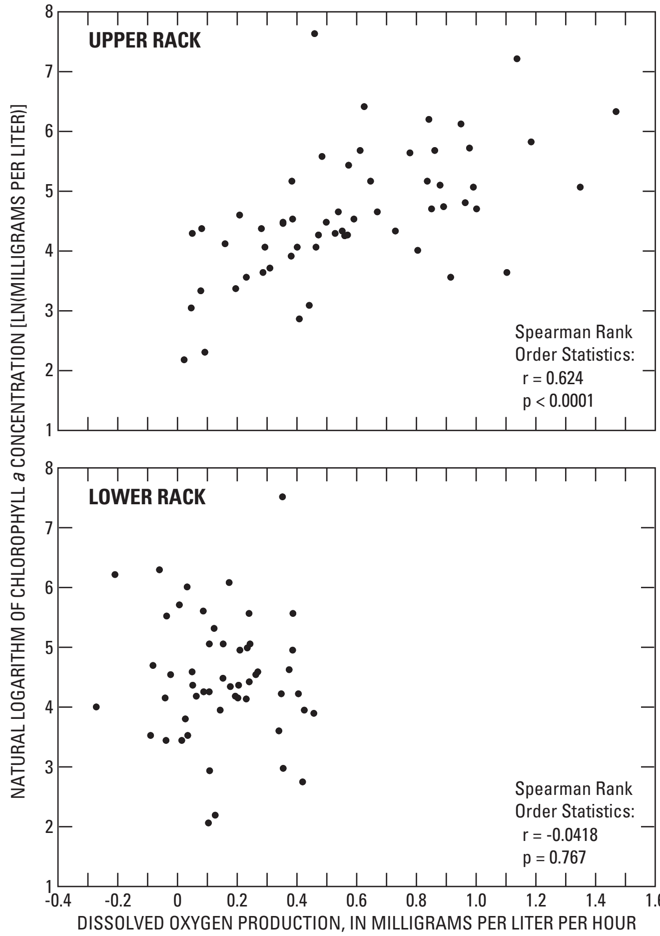


Figure 17. Relation of the natural logarithm of chlorophyll *a* concentration to dissolved oxygen production in the upper and lower incubation racks during dissolved oxygen production and consumption experiments in Upper Klamath Lake, Oregon, 2005.

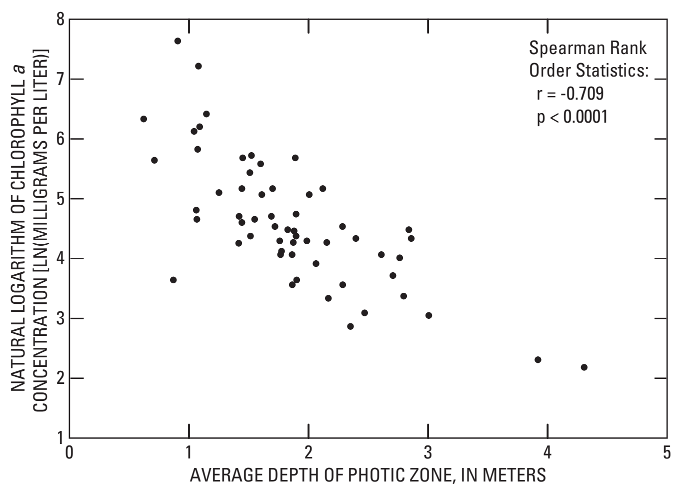


Figure 18. Relation of the natural logarithm of chlorophyll *a* concentration to the average depth of the photic zone for all dissolved oxygen production and consumption experiments in Upper Klamath Lake, Oregon, 2005.

–0.27 (mg/L)/hr of oxygen, respectively (fig. 16). Smaller negative rates were measured in light bottles on the lower incubator racks during several dates at sites MDN, EPT, and MDT. Comparison of the depth of the lower rack with the average depth of the photic zone during the experiments at each site (table 2) shows that these instances of net oxygen consumption in light bottles occurred when the bottles were near or below the photic zone. Furthermore, no correlation existed between oxygen production and chlorophyll *a* concentration in lower incubation racks, whereas a positive correlation was observed in upper incubation racks (fig. 17). These findings indicate that self-shading by AFA during heavy blooms can cause metabolic respiration to exceed photosynthetic production during the daytime in parts of the water column that would otherwise be in the photic zone.

Water Quality Conditions

Daily Median Water Quality Conditions

Time series of daily median water quality conditions at the two sites in Agency Lake are shown in figure 19. Temperature at both sites was similar throughout the field season. Daily median dissolved oxygen concentrations were at and slightly less than 4 mg/L (a high-stress dissolved oxygen concentration threshold for Upper Klamath Lake suckers [Loftus, 2001]) at site AGN during several days in July and for a few days in August. By contrast, comparable daily median dissolved oxygen concentrations occurred for only a short period in mid-August at site AGS. Through June, both sites recorded a steady increase in pH, with daily median pH reaching around 10 for both sites in late June and early July. In mid-July, however, pH varied considerably at site AGN as compared to site AGS. This variability continued until September, after which pH values were relatively stable at both sites. Early season similarity between sites AGN and AGS was evident in dissolved oxygen concentrations as well. Dissolved oxygen concentration varied more at site AGN than at site AGS beginning in late June. Coincident with pH, dissolved oxygen concentrations became more comparable between the two sites from September through the end of the field season. A similar relation between sites AGN and AGS also was observed in specific conductance values, with site AGN generally showing more variability as compared to site AGS from mid-July through the end of the field season.

Data recorded at continuous water quality monitoring sites in Upper Klamath Lake were combined into a single dataset for each parameter to determine lakewide daily medians (fig. 20). Dissolved oxygen and pH values followed a similar trend of increasing and leveling off through June, then decreasing steadily through much of July. Dissolved oxygen concentration reached a minimum in the last half of July that lasted for nearly 2 weeks through the beginning of August, and pH reached a minimum in early August that lasted for only a few days. Both parameters simultaneously recovered relatively rapidly to predecline levels in August and maintained those levels with some fluctuation for the rest of the field season. Temperature gradually increased through mid-July, maintained a plateau from mid-July through mid-August (coinciding with the period of lowest dissolved oxygen and pH values), and gradually decreased for the remainder of the field season. Specific conductance had an early period of relative stability and then began a steady increase from mid-July, peaking coincidentally with the period of minimum dissolved oxygen and pH values. A sharp, short decrease to fairly steady specific conductance values for the remainder of the field season followed.

Water temperatures in Agency and Upper Klamath Lakes (figs. 19 and 20) closely followed patterns in air temperature (fig. 6). Because these lakes are shallow, their small water columns contain a smaller thermal mass, relative to deep lakes, and therefore heat up and cool down more readily along with changes in air temperature. This process is aided by diurnal mixing known to occur in these lakes (Wood and others, 2006).

Dissolved oxygen and pH values have a positive relation through photosynthetic activity and the carbonate buffering system of natural waters (Wetzel, 2001), which is evident in data from both lakes. Dissolved oxygen and pH values in Agency and Upper Klamath Lakes are related to bloom dynamics, but bloom dynamics in the two lakes are largely independent. The bloom patterns observed at sites AGN and AGS (fig. 11) are evident in the dissolved oxygen and pH data collected at those sites (fig. 19). The highly variable pH at site AGN through much of August corresponds to the variability observed in the AFA bloom at that site during this time. Because there was no late-season bloom in Agency Lake, dissolved oxygen concentrations remained largely undersaturated through the last half of August and September. Thus, pH values did not rebound to values seen earlier in the season, as they did during the late-season bloom in Upper Klamath Lake (fig. 20).

In Upper Klamath Lake, the coincidence of the seasonal maximum in lakewide median specific conductance with the seasonal minimums in lakewide median dissolved oxygen and pH values (fig. 20) also is coincident with maximum concentrations of orthophosphate and total ammonia (fig. 10). An inverse correlation also was observed between chlorophyll *a* and both orthophosphate and total ammonia (fig. 14). These observations suggest that the ionic nutrients released by decaying algal cells influence the conductance of the water in Upper Klamath Lake. This situation may have occurred at site AGS in late July, when a sharp decrease in dissolved oxygen and pH values was coincident with a sharp increase in specific conductance (fig. 19). However, a similar

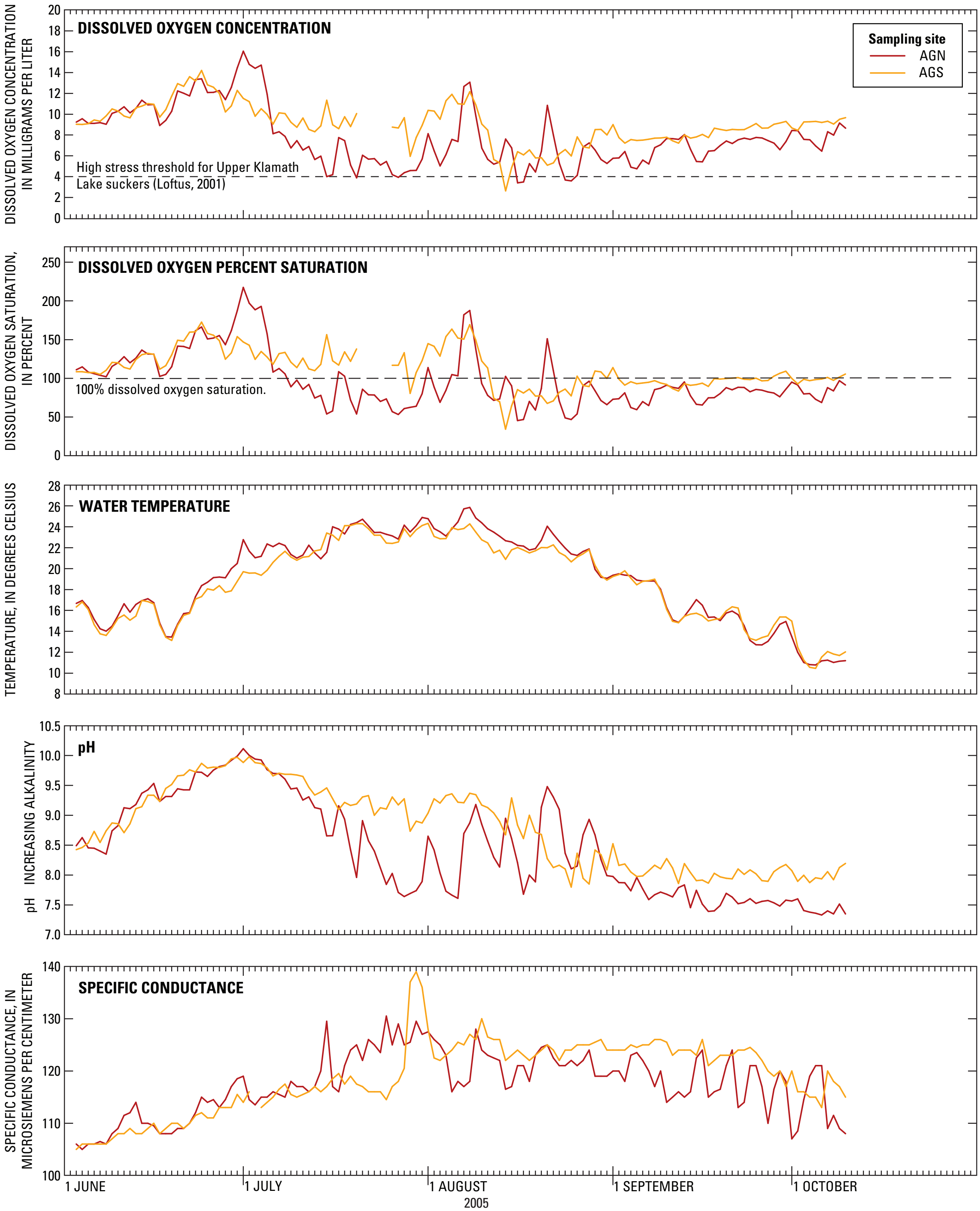


Figure 19. Daily median temperature, dissolved oxygen concentration, dissolved oxygen percent saturation, pH, and specific conductance recorded by continuous monitors in Agency Lake, Oregon, 2005.

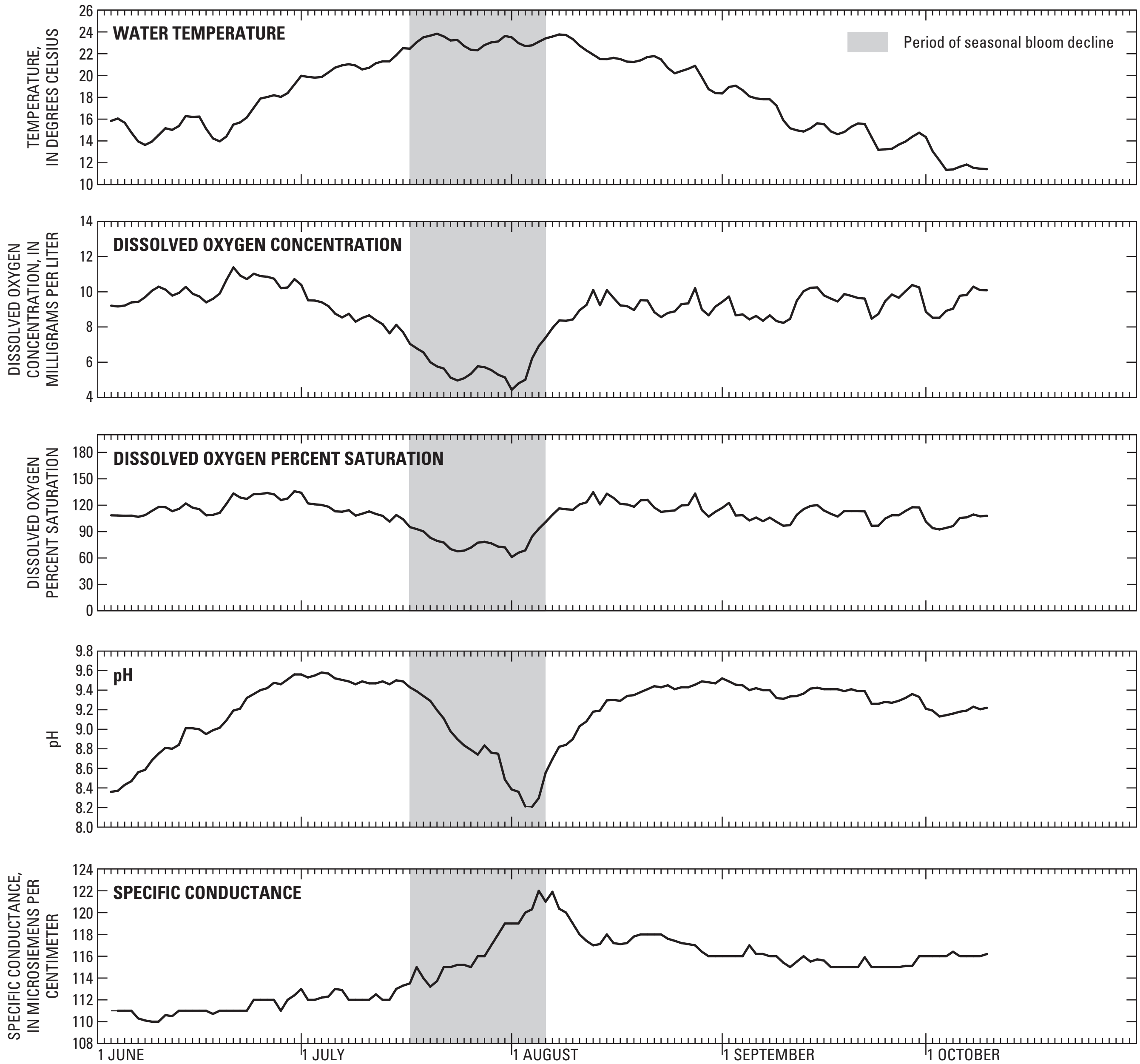


Figure 20. Lakewide daily median dissolved oxygen concentration, dissolved oxygen percent saturation, temperature, pH, and specific conductance recorded by continuous monitors in Upper Klamath Lake, Oregon, 2005.

increase in specific conductance was not recorded at site AGS when dissolved oxygen and pH values quickly decreased with the decline in bloom conditions there in mid-August. Nutrient release and uptake by the variable bloom at site AGN may have contributed to variability in specific conductance, particularly through July and early August. However, the inverse relation of specific conductance with dissolved oxygen and pH values was not as strong during this period at site AGN as in Upper Klamath Lake. The available data indicate that concentrations of other ions were more influential in patterns of specific conductance in Agency Lake. Higher variability in specific conductance at site AGN through the end of the field season could be the result of influent waters from the Wood River and Wood River wetland, to which site AGN is in close proximity relative to site AGS. The specific conductance in the Wood River wetland is dominated by chloride ions (K.D. Carpenter, U.S. Geological Survey, unpub. data, 2008). Similar variability in specific conductance was observed at sites WMR and FBS (sites in the proximity of the Williamson River and west-shore wetlands, respectively) relative to other sites in Upper Klamath Lake.

Spatial Variability in Dissolved Oxygen Concentrations

Periods of very low dissolved oxygen concentrations in Upper Klamath Lake influence endangered sucker movements and have been implicated in die-off events of these species in Upper Klamath Lake (B.J. Adams and others, U.S. Geological Survey, unpub. data, 2005). To study the dynamics of dissolved oxygen in Upper Klamath Lake, time-series graphs of daily median dissolved oxygen percent saturation at each of the water quality monitoring locations (fig. 2) were examined (fig. 21). The graphs are ordered along the primarily clockwise current pattern in Upper Klamath Lake during the summer (fig. 7), beginning with the lower sonde at the middle of trench site (MDT-L). Periods of missing data at site MDT-L resulted from problems positioning the sonde at this site. Data for sites MDL and RPT are not shown but were similar to data from sites MPT and NBI. The graphs indicate that dissolved oxygen dynamics in the lake operated at two time scales in 2005: a long scale (months), and a short scale (days).

Variability on Monthly to Seasonal Time Scales

In the longer time scale, the dissolved oxygen patterns for sites in the north and west, principally sites MDT-L, MDT-U, EPT-L, EPT-U, SHB, BLB, MDN-L, MDN-U, and EHB, (fig. 21) follow a pattern similar to the lakewide median dissolved oxygen percent saturation (fig. 20). This pattern of gradual decline to substantially lower dissolved oxygen concentrations during the mid-season bloom decline and a recovery to predecline concentrations after the bloom recovered was not as strong at the other sites. This distinction was caused in large part by the bathymetry of the lake: sites MDT-L and EPT-L are in the trench portion of Upper Klamath Lake, where much of the water column lies below the photic zone. This characteristic provides more potential for oxygen consuming processes, such as sediment oxygen demand, algal respiration, and bacterial activity, to deplete dissolved oxygen, contributing to the gradual decline in dissolved oxygen concentration observed at these sites. The upper monitors at these deep sites also recorded this gradual seasonal decline in dissolved oxygen concentration because of frequent mixing within the water column, which is described later in this report. At most of the Upper Klamath Lake sites in the east and south, principally sites WMR, MPT, NBI, and HDB, the seasonal decline in dissolved oxygen was largely dampened (fig. 21), reflecting the smaller aphotic zone and lower potential for oxygen consumption in these shallower areas. Sites SHB, MDN-L, and BLB, although of similar depth to sites in the eastern portion of the lake (table 1), recorded a more pronounced seasonal decline in dissolved oxygen. This may be because sites SHB, MDN-L, and BLB receive water from the trench under the dominant flow pattern in the lake (fig. 7). The decline in dissolved oxygen at these sites is not as severe as that in the trench, however, because of the decreased potential for dissolved oxygen consumption in their shallower water columns.

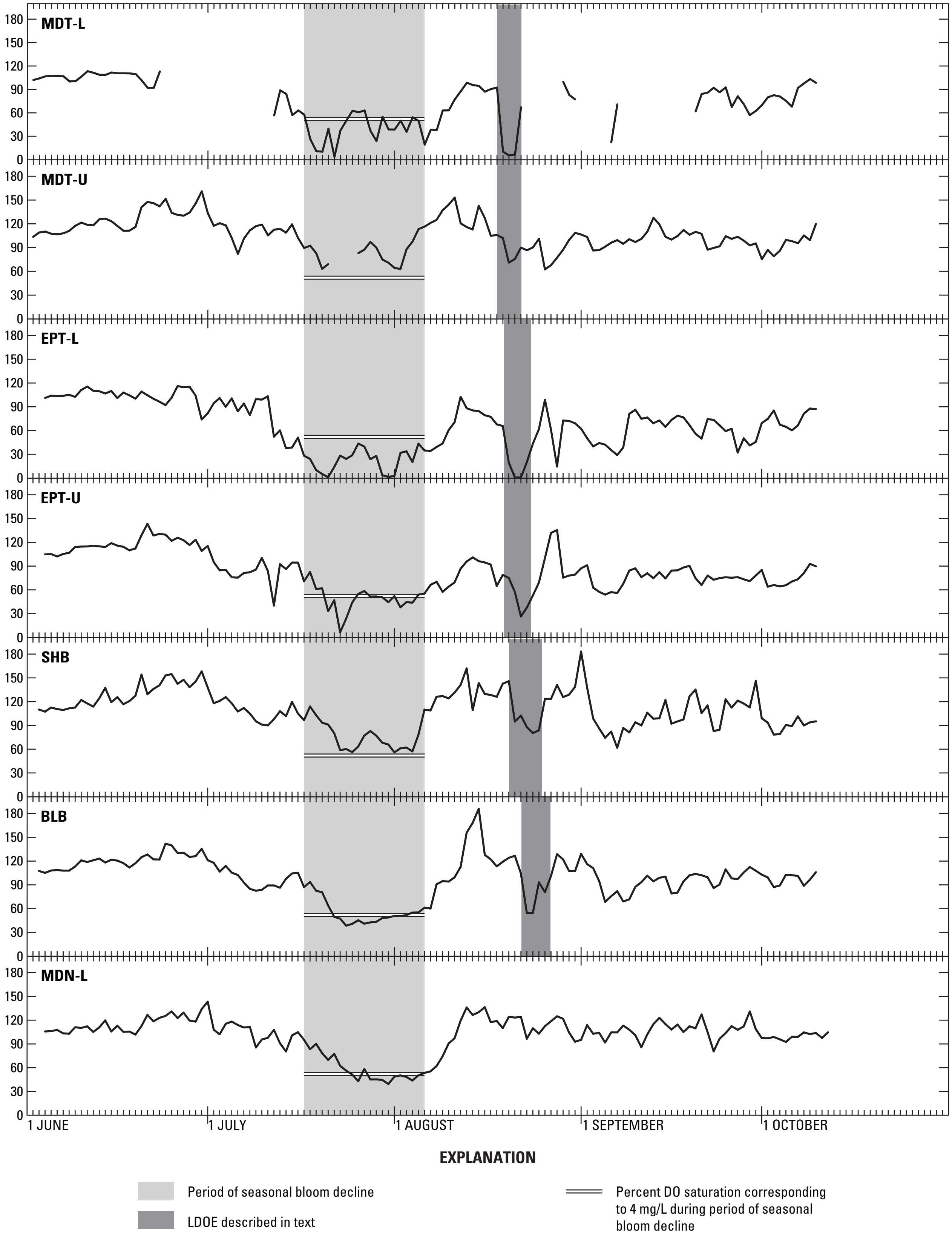


Figure 21. Daily dissolved oxygen percent saturation at water quality monitoring sites in Upper Klamath Lake, Oregon, 2005. Graphs for each site are displayed in order along the predominantly clockwise flow path in Upper Klamath Lake.

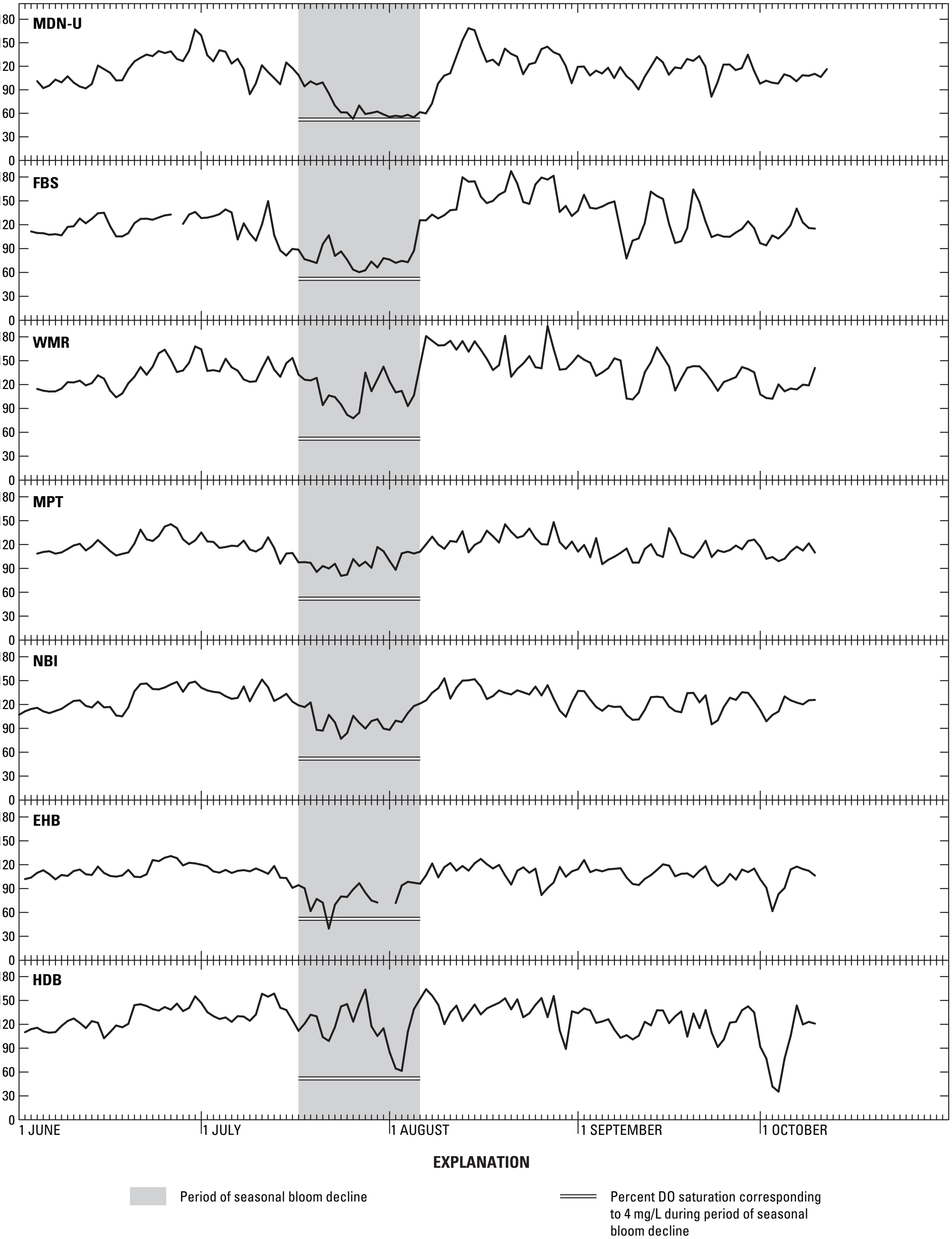


Figure 21.—Continued

Variability on Short Time Scales

Variability occurring on the order of days can be seen in the daily median dissolved oxygen percent saturation graphs in figure 21. Events of extremely low dissolved oxygen percent saturation operating at these shorter time scales may indicate movement through the lake of masses of water that are low in dissolved oxygen, with the conditions observed first at one location and then at subsequent sites as water moves along dominant flow paths in the lake (fig. 7). The condition of the mass of water when it reaches the next station along the flow path provides information about the processes that occurred as the water traveled between monitoring locations.

The darkly shaded sections of the graphs in figure 21 highlight an LDOE that was first observed at site MDT-L. From August 19 through 22, daily median dissolved oxygen saturation declined to nearly 5 percent at site MDT-L. Conditions were not as severe near the top of the water column (at site MDT-U) during this time. From August 20 through August 24, a subsequent LDOE occurred at site EPT-L, with daily median percent saturation of dissolved oxygen reaching almost zero. Low dissolved oxygen concentrations were distributed throughout more of the water column at this site. A subsequent decline in dissolved oxygen concentration occurred at site SHB from August 21 through 25. Percent saturation of dissolved oxygen went from supersaturated before the event (about 140 percent) to just undersaturated (about 80 percent) during the event at site SHB. The LDOE was less severe at SHB, demonstrating mixing of the low-dissolved-oxygen water once it enters the northern part of the lake. A subsequent dip in dissolved oxygen saturation was observed at site BLB from August 23 through 27, but there was no evidence of the LDOE at site MDN around this time, indicating that the LDOE was transported by higher velocities across the mouth of Shoalwater and Ball Bays but largely bypassed MDN, and was probably eroded by mixing before reaching FBS, as there was no evidence of the LDOE at that site. The LDOE likely originated in the trench, because dissolved oxygen saturation at sites immediately south of the trench (sites NBI, EHB, and HDB; fig. 2) did not decrease significantly immediately preceding the August 19 event at site MDT-L (fig. 21).

Stratification and Wind Speed

Stratification of lake waters is caused by density differences between the upper and lower parts of the water column. These density differences are primarily the result of water temperature differences, allowing stratification to be identified by differences in temperature between near-surface waters and near-bottom waters. The three sites (MDN, EPT, and MDT) equipped with a continuous water quality monitor at both 1 m from the surface (the “upper sonde”) and 1 m from the bottom (the “lower sonde”) provided the means to examine the dynamics of water column stratification in Upper Klamath Lake.

Vertical variability in water temperature, dissolved oxygen, and pH was calculated as the upper sonde value minus the lower sonde value for each hourly measurement at each site. Time series of these hourly vertical differences are compared with the hourly median wind speed at site MDN for a representative month of the 2005 field season (fig. 22). The diel (daily) pattern of vertical temperature variability observed in figure 22 is known to be typical of Upper Klamath Lake (Wood and others, 2006). This pattern appears to be driven, in part, by diel variations in wind speed. Typically, wind speeds are low enough to prevent water column mixing during the daylight hours and when skies are clear, maximizing solar heating of the water surface. Vertical temperature differences develop accordingly. During the evening, wind speeds increase, typically providing enough wind shear to induce water column mixing and erode stratification built up during the day. Even the deepest sites (EPT and MDT) undergo this diel buildup and breakdown of temperature vertical variability, although vertical temperature differences at site MDT (the deepest site) are consistently much greater than at site EPT. Diel cycles in the vertical variability of dissolved oxygen and pH also were observed, but vertical differences in these constituents were more likely to persist longer than 24 hours, especially at sites MDT and EPT. This likely results because AFA colonies, having the ability to regulate buoyancy, may congregate near the surface, maintaining vertical variability in dissolved oxygen and pH while temperature becomes more evenly distributed.

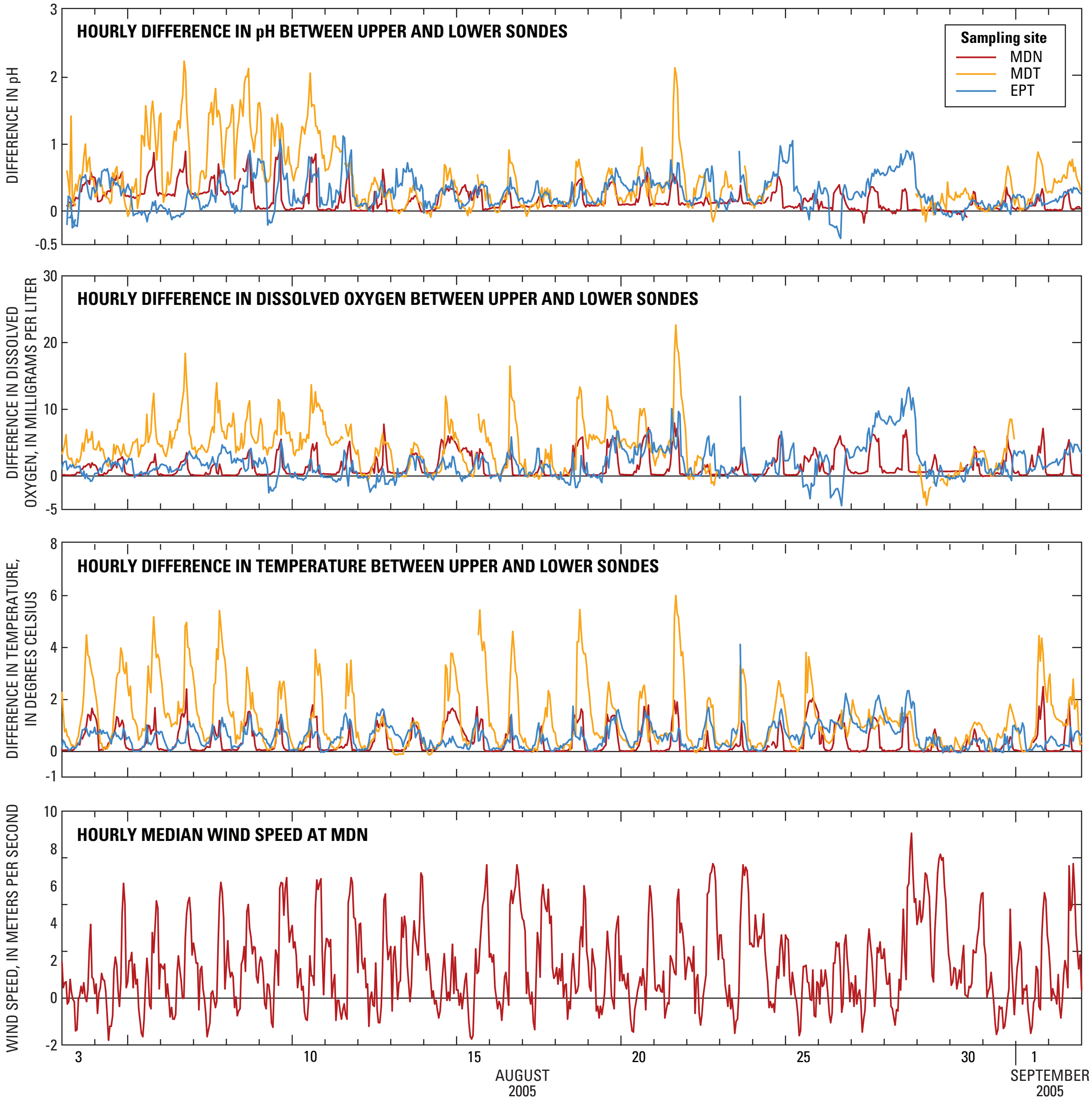


Figure 22. Representative hourly vertical variability in pH, dissolved oxygen, and temperature at sites MDN, MDT, and EPT, and hourly median wind speed at site MDN, Upper Klamath Lake, Oregon, 2005.

Periods of lighter wind result in less wind shear at the lake surface and less energy for mixing, allowing stratification to persist longer than one diel cycle. Stratification persisted, for example, at both trench sites from August 27 to August 29. During this period, the minimum vertical variability in temperature was about 1°C at both sites EPT and MDT. Winds rarely were greater than 5 m/s immediately preceding and during this time period. This period of lighter winds still provided enough energy to induce diel mixing at the shallower MDN site.

Water column stratification affects the dissolved oxygen dynamics. During periods of stratification, the upper water column can become decoupled from the lower water column, allowing oxygen consuming processes such as sediment and water column oxygen demand and algal respiration to deplete the lower part of the water column of oxygen, creating potentially unsuitable conditions for fish. Deeper waters in the trench, although typically undergoing a diel mixing of water, have more resistance to mixing than shallower waters because less of the water column is subject to solar heating, allowing for development of a greater temperature (density) gradient. Accordingly, deeper sites have a smaller proportion of water in the photic zone, which allows oxygen consumption processes to have a greater role in dissolved oxygen dynamics. Therefore, the lowest near-bottom dissolved oxygen concentrations during periods of stratification are likely to occur in the trench. This was observed in 2005 as well as in previous years (Wood and others, 2006). Extended periods of stratification may be an important source of chronic stress to fish, but they have not been identified as the most important cause of the extreme LDOEs that lead directly to fish die-offs (Wood and others, 2006).

Timing of Daily Extremes in Water Quality Conditions

The timing of daily minimum dissolved oxygen concentrations, daily maximum pH, and daily maximum water temperature were related to the total water column depth at the site. To aid in describing these patterns, histograms displaying the timing of the daily extreme parameter value from representative shallow (HDB), mid-depth (BLB), and deep (EPT) sites are shown in figure 23 for each of these water quality parameters. These histograms display the normalized frequency of occurrence of the daily extreme water quality reading as a function of the hour of day. Shallow sites (HDB, AGS, WMR, NBI, and FBS) had an approximate full pool depth of 2.5 to 2.8 m (table 1). Middepth sites (AGN, SHB, RPT, BLB, and MPT) had an approximate full pool depth of 3.0 m to 3.7 m. Deep sites (MDN, MDL, EHB, EPT, and MDT) had an approximate full pool depth of greater than 4.2 m. Patterns in the timing of daily extreme parameter values appeared over a continuum of water column depth, so the categories of shallow, middepth, and deep are not necessarily delineated by fixed depth.

The daily minimum dissolved oxygen concentration at shallow sites tended to occur around 7:00 a.m. The daily maximum in pH and temperature occurred most frequently in the afternoon to early evening between 3:00 and 8:00 p.m. This pattern reflects the strong influence of the diel cycle of photosynthesis and respiration where the sonde is positioned, which is typically within the photic zone at these sites, and is consistent with findings from data collected in previous years (Wood and others, 2006).

At middepth sites, however, the period of day when daily minimum dissolved oxygen concentration occurred became less well defined. At deep sites, there was no distinct period of the day when daily minimum dissolved oxygen concentrations tended to occur. The time of day when daily maximum pH values were likely to occur broadened at middepth sites to include more of the early morning hours and some late morning hours. At the deep sites, no strong tendency for the timing of daily maximum pH to occur in a specific time window was observed. A similar progression from shallow to deep sites was observed for the timing of daily maximum temperature: a strong likelihood for daily maximum temperature to occur in the early evening at shallow sites, a broadening of this time window into the late evening at middepth sites, and the weakest tendency for the daily maximum temperature to occur during a distinct time window at the deep sites.

The tendency of daily extreme parameter values to occur throughout the day at deep sites is caused by the increased tendency for these sites to develop thermal (density) stratification and the position of the sonde in aphotic waters at deeper sites. Below the photic zone, the rate of consumption of dissolved oxygen by metabolic respiration and other oxygen-demanding processes within the water column is greater than the rate of oxygen production by photosynthesis. Near the bottom, sediment oxygen demand also consumes dissolved oxygen from the water. If the water column develops even a small amount of stratification, dissolved oxygen can reach minimum daily concentrations in the lower part of the water column at any time of day, even during daylight hours. This is because dissolved oxygen concentration below the photic zone will decrease until a mixing event erodes the thermal stratification and mixes the lower layer, which is relatively

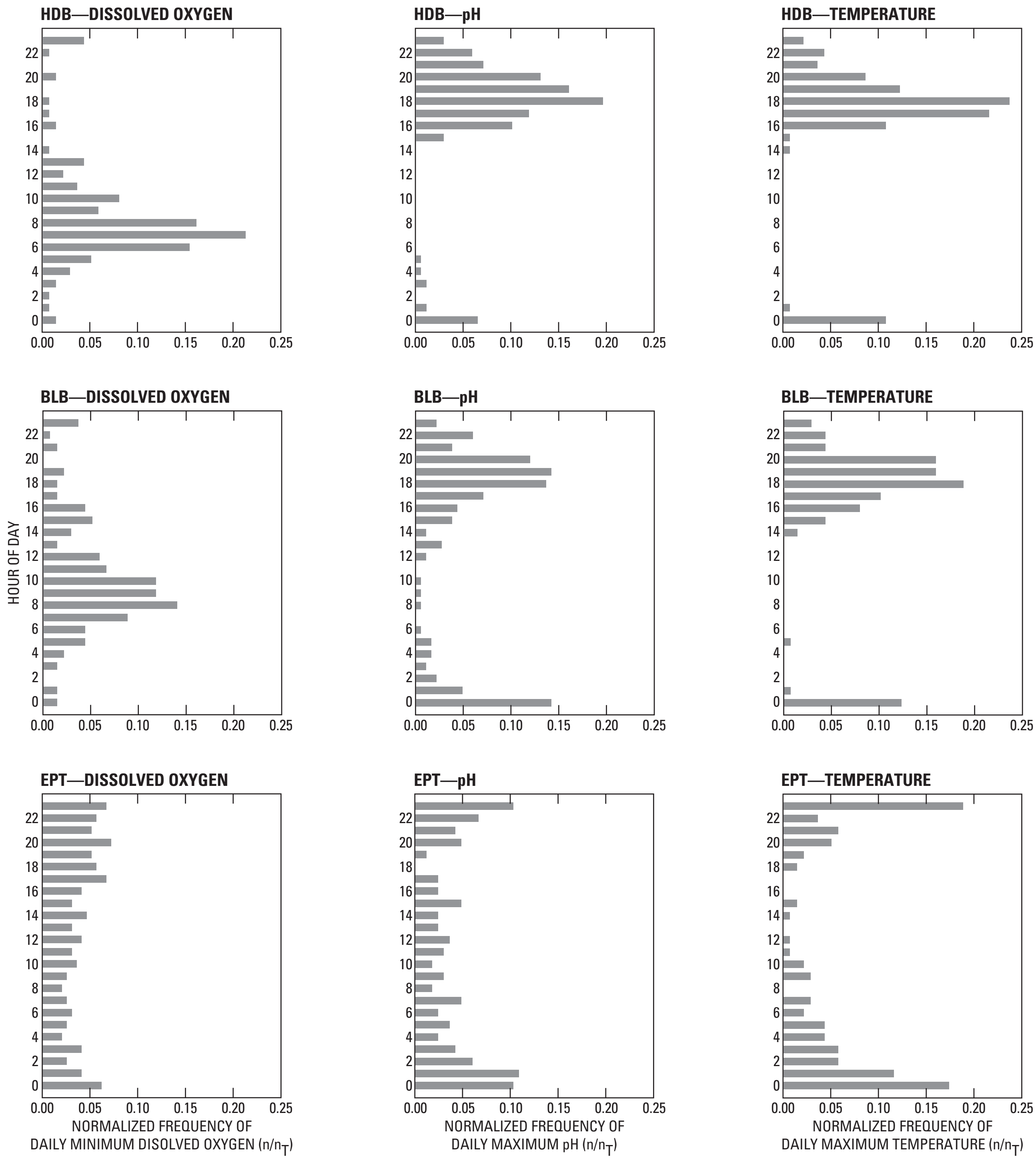


Figure 23. Daily extreme of dissolved oxygen concentration, pH, and water temperature from a representative shallow (HDB), middepth (BLB), and deep site (EPT) in Upper Klamath Lake, Oregon, 2005.

depleted of dissolved oxygen, with the upper layer, which contains a relatively higher concentration after being in the photic zone over the course of the day. At deeper sites, therefore, the minimum dissolved oxygen concentration does not always occur in the early morning just before dawn, but has more potential to occur throughout the day, depending on when the wind picks up and mixes the water column. Water column stratification and sonde position in the water column affects the timing of daily maximum pH and temperature in a similar manner.

These patterns are similar to those seen in previous years (Wood and others, 2006). However, a continuum of characteristics from shallow to deep sites was more apparent in 2005 because of the wider distribution of sites around the lake and the greater range of site depths.

Occurrence and Duration of Water Quality Conditions Potentially Harmful to Fish

Dissolved Oxygen Concentration, pH, and Temperature

In order to identify periods when conditions of dissolved oxygen concentration, pH, and temperature potentially harmful to fish were present in Upper Klamath Lake and the spatial extent of these conditions, hourly data were collected at each site of conditions when dissolved oxygen concentration was less than 4 mg/L, pH was greater than 9.7, or temperature was greater than 28ºC. These values are based on high stress thresholds for Upper Klamath Lake suckers (Loftus, 2001). The percentage of sites at which a potentially harmful condition was recorded at least once in a day was calculated, providing the “one-reading” statistic. Additionally, the numbers of hourly occurrences of these conditions per day were summed over all of the sites to provide a count of “site-hours” per day of these conditions. The counts per day were divided by the total possible site-hours in the day (24 hours multiplied by the number of sites in Upper Klamath Lake), providing a percentage of site-hours in the day during which potentially harmful conditions were recorded, referred to as the “percent of site-hours” statistic.

The “one-reading” statistic provides a measure of the physical presence of that condition in the lake. It also represents the maximum percentage of the lakewide site-hours that would meet the criterion if, at each site where at least one reading met the condition, the condition persisted for an entire 24 hours. The “percent of site-hours” statistic coupled with the “one-reading” statistic, then, provides a measure of the persistence of the condition throughout the day at sites where that condition was recorded. These statistics were graphed as a time series of daily values for dissolved oxygen concentration, pH, and temperature. Graphs of these statistics for dissolved oxygen concentration and pH are shown in figure 24. Only one observation of temperature above 28 ºC was made during the 2005 field season, at the upper sonde at site MDT on August 7 at 7:00 p.m. Because temperature exceeding the criterion was observed only once, a graph of potentially harmful temperature is not shown.

Figure 24 reflects the primary LDOE of 2005, which occurred in late July and early August (fig. 20), and shows that when this event occurred, it was not severe. Most of the 16 Upper Klamath Lake sondes (50–60 percent) recorded a dissolved oxygen concentration of less than 4 mg/L at least once during each day in mid-July through early August, but only 25–35 percent of the site hours recorded these conditions during this period. This pairing of the “one reading” and “site hours” statistics indicates two possible scenarios: either the condition was widespread but marginally persistent throughout the day at all sites recording this condition, or the condition was widespread but persistent at only a few of the sites that logged the condition. Time series of daily median dissolved oxygen percent saturation for each Upper Klamath Lake sonde (fig. 21) indicated that the latter explanation is most likely. (Note that water temperatures were around 21°C throughout Upper Klamath Lake at this time, corresponding to 52 percent dissolved oxygen saturation when dissolved oxygen concentration is 4 mg/L, denoted by the red line on the plots in (figure 21). Sites in and northwest of the trench were the only sites having notably low daily median dissolved oxygen concentration at this time, and only sites in the trench had daily median dissolved oxygen concentration near zero percent saturation. At sites where potentially harmful dissolved oxygen concentrations did not persist throughout the day (sites out of and away from the trench), the previously discussed timing histograms (fig. 23) indicate that when these conditions occurred, they occurred during the early morning hours.

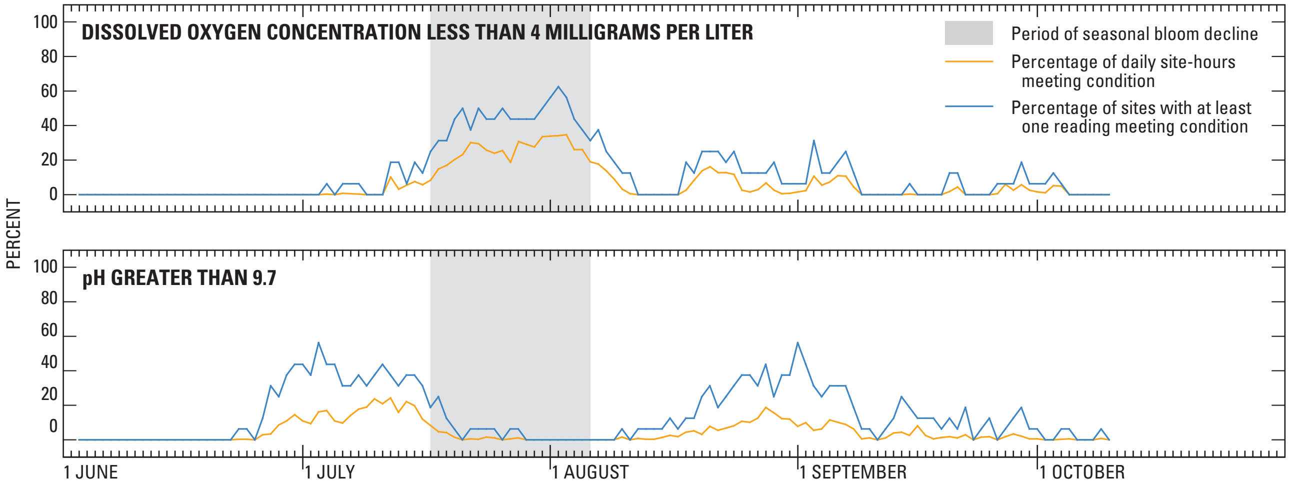


Figure 24. Lakewide measures of conditions potentially harmful to fish in Upper Klamath Lake, Oregon, 2005: dissolved oxygen concentration less than 4 milligrams per liter, and pH greater than 9.7.

Potentially harmful pH values were measured within a large portion of the lake twice during the 2005 field season, from late June through mid-July and again from mid-August through early September. As with the LDOE previously described, conditions resulting from potentially harmful pH values occurred during these times and may have been persistent throughout the day at few sites when this condition was present. Because of the positive relation between dissolved oxygen concentration and pH, and the decreased dissolved oxygen concentrations at sites in and northwest of the trench, sites with persistently high pH were mostly east and south of the trench.

Ammonia

When high ammonia concentrations occur concurrently with high pH and temperature, a significant fraction of the total concentration is present in the un-ionized ammonia form (fig. 25), which is particularly toxic to aquatic life. The dependence on pH is stronger than the dependence on temperature; at 22ºC and a pH of 9, for example, 31 percent of the ammonia will be in un-ionized form, but at 22ºC and a pH of 9.5, the fraction increases to 59 percent (U.S. Environmental Protection Agency, 1998). Because ammonia concentration tended to peak when the bloom declined (with an associated decrease in pH), the maximum concentrations of un-ionized ammonia, which occurred simultaneously with high pH values, often were mismatched in time from maximum concentrations of total ammonia. Mean lethal un-ionized ammonia concentration to larval and juvenile suckers, as determined by Saiki and others (1999), ranged between 480 and 1,290 µg/L. Concentrations of un-ionized ammonia measured in Upper Klamath Lake did not reach the concentrations determined to be lethal to endangered larval and juvenile suckers. Because ammonia was released into the water column concurrently with AFA bloom decline and decreasing pH, the maximum concentrations of un-ionized ammonia, which occurred simultaneously with high pH values at the peak of the bloom, were offset in time from maximum concentrations of total ammonia.

Although un-ionized ammonia concentrations did not reach lethal values, the combination of low dissolved oxygen and high un-ionized ammonia concentrations was stressful to fish, probably making them more susceptible to disease. Lethal concentrations of un-ionized ammonia might occur for short periods of time or in localized areas more susceptible to extremes in temperature and pH, such as shallow water.

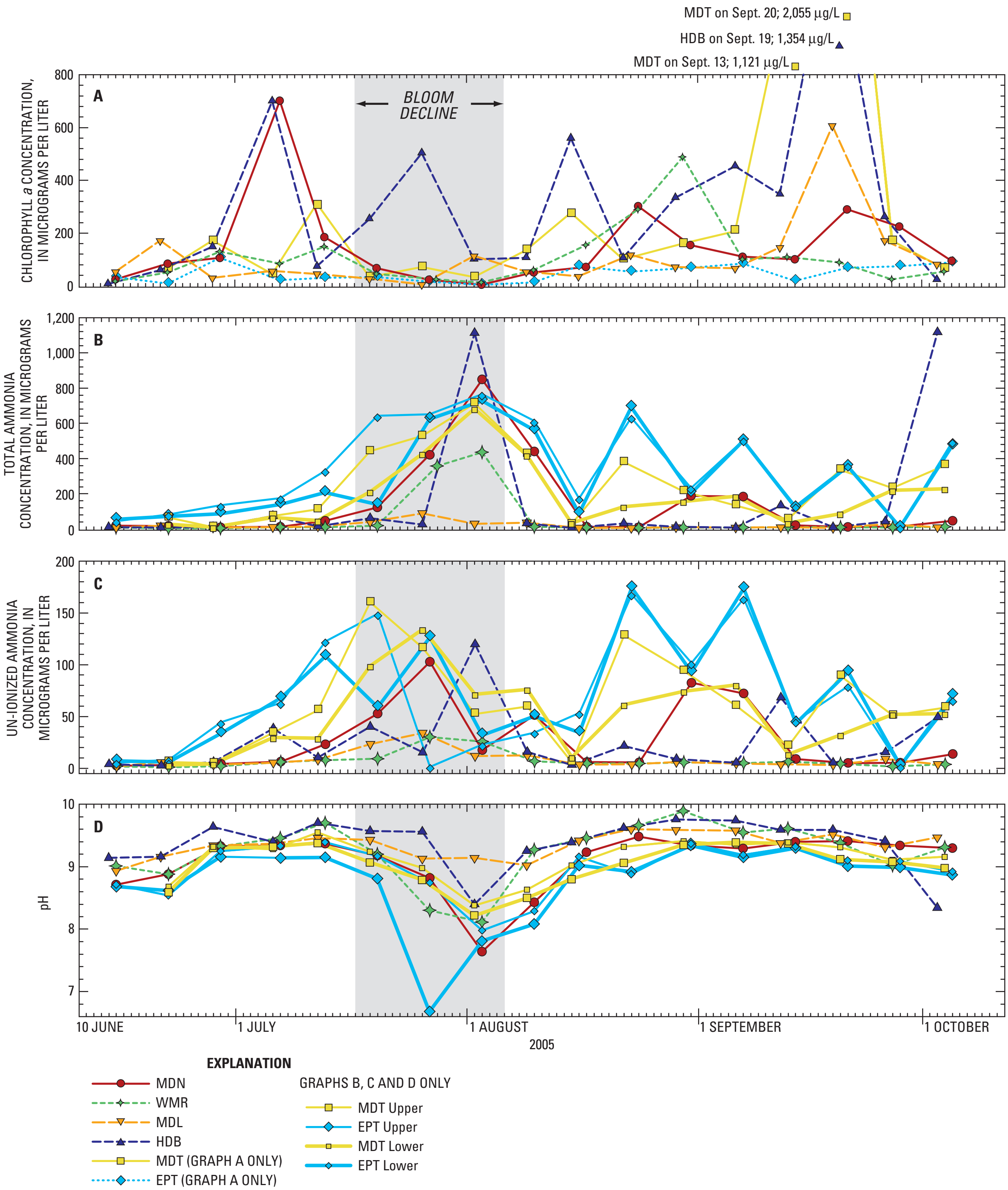


Figure 25. (*A*) chlorophyll *a* concentration, (*B*) total ammonia concentration, (*C*) un-ionized ammonia concentration, and (*D*) pH in water samples collected at all sites, Upper Klamath Lake, Oregon, 2005.

Summary and Conclusions

Water quality degradation in Upper Klamath Lake has led to critical fishery concerns for the region, including the listing of Lost River and shortnose suckers as endangered in 1988. The algal community of the lake has shifted to a near monoculture of the cyanobacterium (blue-green alga) *Aphanizomenon flos-aquae* (AFA) during summer, massive blooms of which have been directly related to episodes of poor water quality in Upper Klamath Lake. The growth and decomposition of AFA blooms in the lake frequently cause extreme water quality conditions characterized by high pH values (9-10), widely variable dissolved oxygen conditions (anoxic to supersaturated), and high un-ionized ammonia concentrations (greater than 0.5 mg/L). Large blooms of AFA and the associated water quality concerns also occur in Agency Lake.

The U.S. Geological Survey (USGS) began monitoring water quality in Upper Klamath Lake in 2002 in cooperation with the Bureau of Reclamation to supplement data collected previously by the Klamath Tribes since 1990. During 2002-04, the USGS water quality monitoring program study area was limited mostly to the northern one-third of Upper Klamath Lake. In 2005, the existing water quality monitoring program expanded to become lakewide in Upper Klamath Lake and to include Agency Lake.

Data from multiparameter continuous water quality monitors, physical water samples, and meteorological sites were collected from Upper Klamath and Agency Lakes, Oregon, in 2005 to assess water quality conditions and processes. The data show that the significant factors controlling water quality processes included AFA dynamics, lake bathymetry, and wind speed.

Diel photosynthesis–respiration processes and the seasonal pattern of changes in AFA biomass (inferred from chlorophyll *a* concentrations) lead to variation in dissolved oxygen, orthophosphate, and ammonia concentrations; pH; and specific conductance values. In previous years, AFA biomass increased markedly, then sharply declined, resulting in low dissolved oxygen concentrations and release of nutrients to the water column. In 2005, chlorophyll *a* concentrations increased in early July and then sharply declined during late July–early August. Daily medians calculated for all sites in Upper Klamath Lake show seasonally increased dissolved oxygen concentrations coinciding with an increase in pH in early July, followed by a decrease in dissolved oxygen concentrations and pH values and an increase in specific conductance values in late July–early August. In addition, orthophosphate and ammonia concentrations increased during the bloom decline in late July–early August. These water quality changes coincide with the AFA bloom in early July and decline in late July–early August. The inverse relation of specific conductance with dissolved oxygen concentration and pH observed from mid-July through early August in Upper Klamath Lake was attributable to the release of ionic nutrients from decaying AFA cells during the bloom decline.

Qualitative observations of the AFA bloom, verified by chlorophyll *a* concentration data provided by the Klamath Tribes, were directly related to patterns observed in dissolved oxygen concentration and pH in Agency Lake. Differences in water quality patterns observed between Upper Klamath Lake and Agency Lake were attributable to differences in bloom dynamics between the two lakes. Variability in specific conductance at sites near rivers and wetlands in Agency Lake and Upper Klamath Lake suggests that these influent waters may locally influence specific conductance.

In dissolved oxygen production and consumption experiments, the maximum observed dissolved oxygen production was 1.47 milligrams per liter per hour of oxygen, and the maximum observed dissolved oxygen consumption was –0.73 milligrams per liter per hour of oxygen. Dissolved oxygen production in the upper water column declined through July and recovered through August. The observed pattern was similar to that of dissolved oxygen concentrations measured by continuous water quality monitors in the lake during this time. In addition to seasonal changes, photosynthesis and respiration processes affect the timing of the daily extreme water quality parameters. At shallow sites, the daily extreme water quality parameter readings occurred during relatively well-defined time intervals linked to diel patterns of sunlight and solar heating. These time intervals became broader and less well defined at deeper sites as a result of the increased potential for water column stratification.

Coupled with AFA dynamics, wind speed and temperature variations also effect diel changes in dissolved oxygen concentrations in Upper Klamath Lake. In response to episodes of low wind speed or to a deep-water-column configuration, the lower portion of the water column can be independent from the upper column and more susceptible to oxygen consuming biological processes that lower dissolved oxygen concentrations.

Bathymetry was the primary factor influencing the magnitude of the seasonal pattern of dissolved oxygen concentration at the deepest and shallowest monitoring locations around Upper Klamath Lake. Wind-driven circulation patterns determined the degree to which the seasonal extremes occurred at sites of similar depth that were either northwest or south and east of the trench under the prevailing clockwise circulation pattern. Because the northern part of the lake (preferred habitat for adult suckers) receives waters from the trench under the dominant circulation pattern, the monitoring sites there tended to record lower seasonal minimums of dissolved oxygen concentration than did the sites in the lake that are south and east of the trench.

These factors also influenced shorter timescale dynamics of dissolved oxygen concentration, as evidenced by a mass of water with a low dissolved oxygen concentration that was first observed in the trench and migrated to subsequent sites along the dominant flow path during a period of 1–2 days. This event illustrates how oxygen-depleted water emerging from the trench is re-oxygenated as it travels through shallower areas in the northern part of the lake.

Monitoring water quality parameters (temperature, dissolved oxygen concentration and saturation, pH, and un-ionized ammonia concentration) allowed identification of the extent and duration of conditions potentially harmful to fish. Although high temperatures may have caused stress to fish and other aquatic species during the 2005 study, water temperatures never exceeded the critical value of 28ºC in Upper Klamath Lake. Periods of dissolved oxygen concentrations potentially harmful to fish were largely confined to the trench and a few sites in the northern part of the lake and were not persistent. On two occasions pH values potentially harmful to fish occurred within a significant portion of Upper Klamath Lake, but the data showed that these values were not persistent. Un-ionized ammonia did not reach concentrations potentially harmful to fish.

The expanded network of continuous water quality monitoring sites, physical water samples, and meteorological sites provided information critical to understanding lakewide water quality dynamics in Upper Klamath Lake. The network provides a greater awareness of water quality conditions in relation to circulation and water column stratification patterns and is central to future water quality modeling efforts. Continued operation of the monitoring sites to collect a long-term data set also would enable the identification of water quality status and trends in Upper Klamath Lake. Future monitoring would be enhanced by the addition of two sites to better quantify conditions surrounding the trench. One of the new sites would best be located between sites MDL and MDT, and the other between sites EPT and MDN, to better quantify the differences in algal dynamics between these sites.

Atmospheric conditions were monitored at meteorological sites over and around Upper Klamath Lake. Patterns of air temperature and relative humidity were consistent with the hot, dry summers typical of the Upper Klamath Lake basin. Wind speed and direction measurements showed significant differences in wind patterns around the lake, particularly between the northern part of the lake and areas to the south. The finer resolution of meteorological conditions in and around Upper Klamath Lake provided by these meteorological sites will improve water quality modeling results and enhance understanding of water quality dynamics in Upper Klamath Lake.

Acknowledgments

The commitment of Rip Shively and Scott Vanderkooi of the USGS Klamath Falls Field Station is gratefully acknowledged for facilitating the water quality field program with the use of boats, trucks, field equipment, and office and laboratory facilities. Ralph Cheng from the USGS National Research Program provided the hydrodynamic modeling results that greatly improved our interpretation of the water quality observations. Many people contributed to the field work of this study, and their efforts are gratefully acknowledged: Jason Cameron from the Bureau of Reclamation in Klamath Falls; Christine Adelsberger, Melissa Berhardt, Pamela Burns, Anna Glass, and Jim Harris from the USGS in Klamath Falls; Amy Brooks, Micelis Doyle, and Matt Johnston from the USGS Oregon Water Science Center. Reviews by John Williams and Annett Sullivan from the USGS Oregon Water Science Center; and Jennifer Graham and Andrew Ziegler from the USGS in Lawrence, Kansas, significantly improved this manuscript.

References Cited

Barbiero, R.P., and Kann, J., 1994. The importance of benthic recruitment to the population development of *Aphanizomenon flos-aquae* and internal loading in a shallow lake: Journal of Plankton Research, v. 16, no. 11, p. 1581–1588.

Bureau of Reclamation, 2000, Klamath Project—Historical operation: Klamath Falls, Oregon, 53 p. plus appendices.

Cheng, R.T., Gartner, J.W., and Wood, T.M., 2005, Modeling and validation of wind-driven circulation in Upper Klamath Lake, Oregon, *in* Walton, Raymond, ed., Proceedings of the 2005 World Water and Environmental Resources Congress, May 15–19, 2005: Anchorage, Alaska, American Society of Civil Engineers, p. 426.

Dillon, P.J., and Rigler, F.H., 1974, The phosphorus-chlorophyll relationships in lakes: Limnology and Oceanography, v. 19, no. 5, p. 767-773.

Eilers, J.M., Kann, J., Cornett, J., Moser, K., and St. Amand, A., 2004, Paleolimnological evidence of change in a shallow, hypereutrophic lake—Upper Klamath Lake, Oregon, USA: Hydrobiologia, v. 520, p. 7–18.

Fisher, L.H., and Wood, T.M., 2004. Effect of water-column pH on sediment-phosphorus release rates in Upper Klamath Lake, Oregon, 2001: U.S. Geological Survey Water-Resources Investigations Report 03-4271, 25 p.

Forsberg, C., and Ryding, S.-O., 1980, Eutrophication parameters and trophic state indices in 30 Swedish waste-receiving lakes: Archiv für Hydrobiologie, v. 89, p. 189–207.

Gartner, J.W., Wellman, R.E., Wood, T.M., and Cheng, R.T., 2007, Water velocity and suspended solids measurements by in-situ instruments in Upper Klamath Lake, Oregon: U.S. Geological Survey Open-File Report 2007-1279, 137 p.

Graham, J.L., Jones. J.R., Jones, S.B., Downing, J.A., and Clevenger, T.E., 2004, Environmental factors influencing microcystin distribution and concentration in the midwestern United States: Water Research, v. 38, p. 4395–4404.

Havens, K.E., Fukushima, T., Xie, P., Iwakuma, T., James, R.T., Takamura, N., Hanazato, T., and Yamamoto, T., 2001, Nutrient dynamics and the eutrophication of shallow lakes Kasumigaura (Japan), Donghu (PR China), and Okeechobee (USA): Environmental Pollution, v. 111, p. 263–272.

Jacoby, J.M., Lynch, D.D., Welch, E., and Perkins, M., 1982, Internal phosphorus loading in a shallow eutrophic lake: Water Research, v. 16, p. 911–919.

Johnson, D.M., 1985, Atlas of Oregon lakes: Corvallis, Oregon State University Press, 317 p.

Kann, Jacob, 1997, Ecology and water quality dynamics of a shallow hypereutrophic lake dominated by cyanobacteria (*Aphanizomenon flos-aquae*): Chapel Hill, University of North Carolina, PhD dissertation, 110 p.

Kann, Jacob, and Smith, V.H., 1999, Estimating the probability of exceeding elevated pH values critical to fish populations in a hypereutrophic lake: Canadian Journal of Fisheries and Aquatic Science, v. 56, p. 2262–2270.

Kann, Jacob, and Walker, W., 2001, Nutrient and hydrological loading to Upper Klamath Lake, Oregon, 1991–1998, prepared for the Klamath Tribes Natural Resources Department and the Bureau of Reclamation: Klamath Falls, Oregon, 48 p. plus appendices.

Kann, Jacob, and Welch, J.B., 2005, Wind control on water quality in shallow, hypereutrophic Upper Klamath Lake, Oregon: Lake and Reservoir Management, v. 21, no. 2, p. 149–158.

Kuwabara, J.S., Lynch, D.D., Topping, B.R., Murphy, F., Carter, J.L., Simon, N.S., Parchaso, F., Wood, T.M., Lindenberg, M.L., Wiese, K., and Avanzino, R.J., 2007, Quantifying the benthic source of nutrients to the water column of Upper Klamath Lake, Oregon: U.S. Geological Survey Open-File Report 2007-1276, 39 p.

Laenen, Antonius, and LeTourneau, A.P., 1996, Upper Klamath Basin nutrient-loading study, estimate of wind-induced resuspension of bed sediment during periods of low lake elevation: U.S. Geological Survey Open-File Report 95–414, 11 p.

Lieberman, D.M., Montano, A., and Holdren, G.C., 2003, Physical, chemical, and biological characteristics of Upper Klamath Lake, Oregon, during summer 2002: Bureau of Reclamation Technical Memorandum No. 8220-03-01.

Loftus, M.E., 2001, Assessment of potential water quality stress to fish, supplement to Effects of water quality and lake level on the biology and habitat of selected fish species in Upper Klamath Lake: Redmond, Wash., R2 Resource Consultants, 38 p., plus appendices.

Morace, J.L., 2007, Relation between selected water-quality variables, climatic factors, and lake level in Upper Klamath and Agency Lakes, Oregon, 1990–2006: U.S. Geological Survey Scientific Investigations Report 2007-5117, 54 p.

Perkins, D., Kann, J., and Scoppettone, G.G., 2000, The role of poor water quality and fish kills in the decline of endangered Lost River and shortnose suckers in Upper Klamath Lake: Klamath Falls, Oregon, U.S. Geological Survey, Biological Resources Division report submitted to Bureau of Reclamation, Klamath Falls Project Office, Contract 4-AA-29-12160, 39 p.

Saiki, M.K., Monda, D.P., and Bellerud, B.L., 1999, Lethal levels of selected water quality variables to larval and juvenile Lost River and shortnose suckers: Environmental Pollution, v. 105, p. 37–44.

U.S. Environmental Protection Agency, 1998, Update of ambient water quality criteria for ammonia: U.S. Environmental Protection Agency Office of Water, EPA 822-R-98-008, 106 p. plus appendices.

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A5m, accessed December 20, 2006, at http://pubs.water.usgs.gov/twri9A

Wagner, R.J., Mattraw, H.C., Ritz, G.F., and Smith, B.A., 2000, Guidelines and standard procedures for continuous water-quality monitors—Site selection, field operation, calibration, record computation, and reporting: U.S. Geological Survey Water-Resources Investigations Report 00–4252, 53 p.

Walker, W.W., 2001, Development of a phosphorus TMDL for Upper Klamath Lake, Oregon: Report prepared for Oregon Department of Environmental Quality, 80 p.

Welch, E.B., 1992, Ecological effects of wastewater, (2d ed.): London, Chapman & Hall, 425 p.

Wetzel, R.G., 2001, Limnology, (3d ed.): San Diego, Academic Press, 1006 p.

White, E., 1989, Utility relationships between lake phosphorus and chlorophyll *a* as predictive tools in eutrophication control studies: New Zealand Journal of Marine and Freshwater Research, v. 23, p. 35–41.

Wood, T.M., and Cheng, R.T., 2006, Use of UnTRIM to investigate dissolved oxygen transport in Upper Klamath Lake, Oregon, *in* Proceedings of the 7th International Conference on Hydroscience and Engineering, September 10–13, 2006: Philadelphia, Drexel University, 12 p.

Wood, T.M., Fuhrer, G.J., and Morace, J.L., 1996, Relation between selected water-quality variables and lake level in Upper Klamath and Agency Lakes, Oregon: U.S. Geological Survey Water-Resources Investigations Report 96-4079, 57 p.

Wood, T.M., Hoilman, G.R., and Lindenberg, M.K., 2006, Water quality conditions in Upper Klamath Lake, Oregon, 2002–04: U.S. Geological Survey Scientific Investigations Report 2006-5209, 52 p.

Appendix A. Quality Control and Quality Assurance of Water Samples

Thirty percent of the samples to be analyzed for dissolved nutrient concentration and 35 percent of the samples to be analyzed for total phosphorus concentration were for quality assurance purposes, which included field blanks (the first sample collected every week) and either a split sample or a method replicate (each type every other week). Field blanks are samples of reagent grade inorganic blank water processed onsite through clean sampling equipment, before an environmental sample is collected. Analysis of blank samples determines if the processes of collection, handling, transport, and analysis cause measurable contamination. Split samples are environmental water samples collected once and divided into two samples that are used to determine the variability in the analytical methods. Replicate samples are environmental samples collected twice in rapid succession from the same location and analyzed to determine both the variability of the system and the variability in the analytical methods.

The results of the quality assurance sampling indicated that precision and accuracy were acceptable and the variability in sampling and processing was lower than seasonal variability (table A1). The field blank concentrations of total phosphorus and orthophosphate were less than the laboratory minimum reporting level. The same was true for the field blank concentration of nitrite-plus-nitrate, except that one outlier sample held some contamination. The field blank samples of ammonia revealed some contamination, although it was minimal compared to the concentrations of the environmental samples. Ammonia concentration in the field blanks was considerably reduced, compared to that in previous years, by the use of capsule filters. Contamination of ammonia blanks in 2003 and 2004 was attributable to atmospheric deposition (Wood and others, 2006). Twice during the season, split samples were sent to two other laboratories in addition to NWQL and Aquatic Analysts. The interlaboratory split samples were analyzed to determine variability in analytical methods between the laboratories. In addition, some of the split samples were collected to examine variability that might be expected as a result of differences in the protocols used by USGS and those used by the Klamath Tribes in the collection of their long-term biweekly dataset. Box plots showing the statistical distribution of the difference between individual split sample concentrations and the median concentration of all of the split samples taken from the same churn splitter indicate that the variance in laboratory processing and analysis is generally low, except in the case of ammonia (fig. A1). The outliers in the distribution of the ammonia splits can all be attributed to the use of a non-USGS protocol and a single non-USGS laboratory. The reason for the high ammonia concentrations in these samples has yet to be determined, but the results do not indicate that the rest of the ammonia samples collected as part of this monitoring program are biased high.

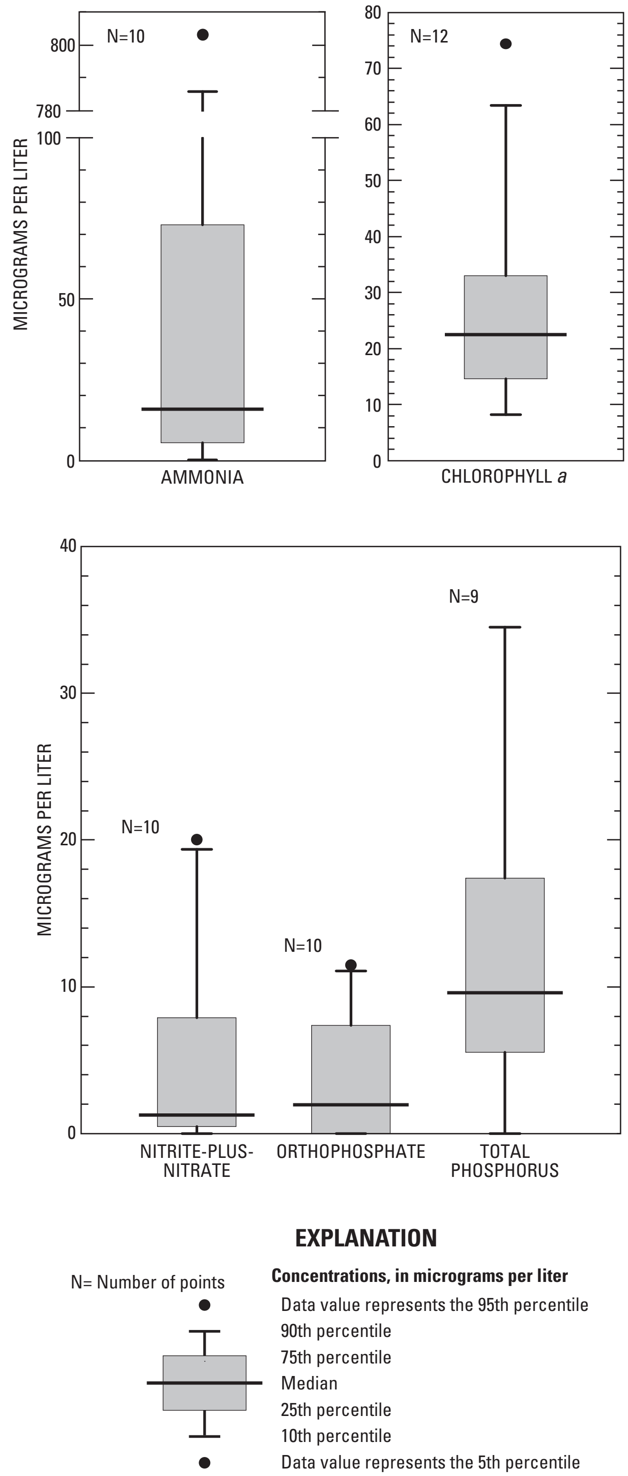


Figure A1. Distribution of differences from the median concentrations among split sample interlaboratory measurements of samples from the water quality data collection program in Upper Klamath and Agency Lakes, Oregon, 2005.

Table A1. Quality-assurance results for water quality data collection program, Upper Klamath and Agency Lakes, Oregon, 2005.

[mg/L, milligram per liter; MRL, minimum reporting level. >, greater than; ≤, less than or equal to]

Blank samples

Analyte	Number of samples		Percentage of blank samples	MRL (mg/L)	Number of blank samples ≤MRL	Value of blank samples >MRL (mg/L)	
	Blank	Total				Maximum	Median
Orthophosphate-P	41	198	21	0.006	41	–	–
Ammonia-N	41	198	21	.010	24	0.043	0.015
Nitrite-plus-nitrate-N	41	198	21	.016	40	.022	–
Total phosphorus	41	170	24	.004	41	–	–
Chlorophyll *a*	3	130	2	–	–	–	–

Split samples

Analyte	Number of samples		Percentage of split samples	Difference between split samples	
	Split	Total		Median (mg/L)	Median (percent)
Orthophosphate-P	6	198	3	0.001	3
Ammonia-N	6	198	3	.002	11
Nitrite-plus-nitrate-N	6	198	3	.000	0
Total phosphorus	5	170	3	.010	8
Chlorophyll *a*	5	130	4	0.035	14

Replicate samples

Analyte	Number of samples		Percentage of replicate samples	Difference between replicate samples	
	Replicate	Total		Median (mg/L)	Median (percent)
Orthophosphate-P	10	198	5	0.001	2
Ammonia-N	10	198	5	.003	13
Nitrite-plus-nitrate-N	10	198	5	.000	0
Total phosphorus	12	170	7	.024	13
Chlorophyll *a*	9	130	7	0.019	9

Manuscript approved for publication, February 20, 2008

Prepared by the USGS Publishing Network,
Bob Crist
Bill Gibbs
Ellen Hardy
Jackie Olson
Bobbie Jo Richey
Sharon Wahlstrom
Cheri Yoesting

For more information concerning the research in this report, contact the
Director, Oregon Water Science Center
U.S. Geological Survey
2130 SW 5th Avenue
Portland, Oregon 97201
http://oregon.usgs.gov/

Hoilman and others—**Water Quality Conditions in Upper Klamath and Agency Lakes, Oregon, 2005**—Scientific Investigations Report 2008–5026