Prepared in cooperation with the Bureau of Reclamation

Water Quality Conditions in Upper Klamath and Agency Lakes, Oregon, 2006

Scientific Investigations Report 2008–5201

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

Cover:
Background: Ice-covered Upper Klamath Lake, Oregon.
(Photograph taken by Mary Lindenberg, U.S. Geological Survey, February 14, 2008.)
Foreground, left: WRW meteorologic station with the Williamson River Delta and Mt. McLoughlin in the background, Upper Klamath Lake, Oregon.
(Photograph taken by Mary Lindenberg, U.S. Geological Survey, April 14, 2008.)
Foreground, right: *Aphanizomenon flos-aquae* bloom in Howard Bay in Upper Klamath Lake, Oregon.
(Photograph taken by Mary Lindenberg, U.S. Geological Survey, September 27, 2006.)

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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

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Conversion Factors, Datums, and Abbreviations and Acronyms

Conversion Factors

Multiply	By	To obtain
micrometer (µm)	3.937×10^{-5}	inch (in)
meter (m)	3.281	foot (ft)
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)/h]	1.0	part per million per hour (ppm/h)
milligram per liter (mg/L)	1.0	part per million (ppm)
microgram per liter (µg/L)	1.0	part per billion (ppb)

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

°F=(1.8×°C)+32.

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 and Acronyms

Abbreviations and Acronyms	Definition
ADAPS	Automated Data Processing System
ADCP	acoustic Doppler current profiler
AFA	*Aphanizomenon flos-aquae*
BOD	biological oxygen demand
H_2SO_4	sulphuric acid
LDOE	low dissolved oxygen event
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
SOD	sediment oxygen demand
USGS	U.S. Geological Survey

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Water Quality Conditions in Upper Klamath and Agency Lakes, Oregon, 2006

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

Abstract

The U.S. Geological Survey Upper Klamath Lake water quality monitoring program gathered information from multiparameter continuous water quality monitors, physical water samples, dissolved oxygen production and consumption experiments, and meteorological stations during the June–October 2006 field season. The 2006 study area included Agency Lake and all of Upper Klamath Lake. Seasonal patterns in water quality were similar to those observed in 2005, the first year of the monitoring program, and were closely related to bloom dynamics of the cyanobacterium (blue-green alga) *Aphanizomenon flos-aquae* (AFA) in the two lakes. High dissolved oxygen and pH conditions in both lakes before the bloom declined in July, which coincided with seasonal high temperatures and resulted in seasonal lows in dissolved oxygen and decreased pH. Dissolved oxygen and pH in Upper Klamath and Agency Lakes increased again after the bloom recovered. Seasonal low dissolved oxygen and decreased pH coincided with seasonal highs in ammonia and orthophosphate concentrations. Seasonal maximum daily average temperatures were higher and minimum dissolved oxygen concentrations were lower in 2006 than in 2005.

Conditions potentially harmful to fish were influenced by seasonal patterns in bloom dynamics and bathymetry. Potentially harmful low dissolved oxygen and high un-ionized ammonia concentrations occurred mostly at the deepest sites in the Upper Klamath Lake during late July, coincident with a bloom decline. Potentially harmful pH conditions occurred mostly at sites outside the deepest parts of the lake in July and September, coincident with a heavy bloom. Instances of possible gas bubble formation, inferred from dissolved oxygen data, were estimated to occur frequently in shallow areas of Upper Klamath and Agency Lakes simultaneously with potentially harmful pH conditions.

Comparison of the data from monitors in nearshore areas and monitors near the surface of the water column in the open waters of Upper Klamath Lake revealed few differences in water quality dynamics. Median daily temperatures were higher in nearshore areas, and dissolved oxygen concentrations were periodically higher as well during periods of high AFA bloom. Differences between the two areas in water quality conditions potentially harmful to fish were not statistically significant ($p < 0.05$).

Chlorophyll *a* concentrations varied temporally and spatially throughout Upper Klamath Lake. Chlorophyll *a* concentrations indicated an algal bloom in late June and early July that was followed by an algae bloom decline in late July and early August and a subsequent recovery in mid-August. Sites in the deepest part of the lake, where some of the highest chlorophyll *a* concentrations were observed, were the same sites where the lowest dissolved oxygen concentrations and the highest un-ionized ammonia concentrations were recorded during the bloom decline, indicating cell senescence. Total phosphorus concentrations limited the initial algal bloom in late June and early July.

The rate of net dissolved oxygen production (that is, production in excess of community respiration) and consumption (due to community respiration) in the lake water column as measured in light and dark bottles, respectively, ranged from 2.79 to –2.14 milligrams of oxygen per liter per hour. Net production rate generally correlated positively with chlorophyll *a* concentration, except episodically at a few sites where high chlorophyll *a* concentrations resulted in self-shading that inhibited photosynthesis. The depth of photic zone was inversely correlated with chlorophyll *a* concentration. Calculations of a 24-hour change in dissolved oxygen concentration indicated that oxygen-consuming processes predominated at the deep trench sites and oxygen-producing processes predominated at the shallow sites. In addition, calculations of the 24-hour change in dissolved

oxygen indicate that oxygen-consuming processes in the water column did not increase during the algal bloom decline in late July; therefore, much of the oxygen consumption probably occurred at the sediment–water interface.

Meteorological data showed that the weather patterns over Upper Klamath and Agency Lakes were typical of summers in the Upper Klamath Lake basin. The prevailing winds were westerly over the northern part of the Upper Klamath Lake and northwesterly directions over the southern two-thirds of the lake. A comparison of air temperature between 2005 and 2006 showed that air temperature peaked earlier and about 2 degrees Celsius higher in 2006 than in 2005.

Introduction

Background and Previous Monitoring Studies

Severe water quality problems in Upper Klamath Lake have led to critical fishery concerns for the region, including the listing of Lost River and shortnose suckers as endangered in 1988 (Stubbs and White, 1993). The lake's algal community has shifted to a near monoculture of *Aphanizomenon flos-aquae* (AFA) during summer (Kann, 1997; Perkins and others, 2000); massive blooms of the alga 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 (as much as 9–10), widely variable dissolved oxygen (anoxic to supersaturated), and high un-ionized ammonia concentrations (>0.5 mg/L). Large AFA blooms and their associated water quality concerns are also present in Agency Lake.

The U.S. Geological Survey (USGS), in cooperation with the Bureau of Reclamation, began monitoring water quality in Upper Klamath Lake in 2002. Before 2002, continuous data sets of temperature, pH, dissolved oxygen, or specific conductance of well-documented quality and spanning several months during the spring through autumn seasons 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. Studies that have used this data set, which is the longest consistent record of the water quality in the Upper Klamath Lake, include Kann (2007) and Morace (2007).

From 2002 through 2004, the USGS continuous water quality monitoring program study area was limited to the northern part of Upper Klamath Lake, where the monitoring supported a telemetry tracking study of endangered adult suckers (Wood and others, 2006). The 3 years of monitoring showed that the occurrence and severity of poor water quality conditions in Upper Klamath Lake was unpredictable from year to year. However, in each year seasonal patterns of low dissolved oxygen and high pH were well described by the dynamics of annual AFA blooms (Hoilman and others, 2008). Seasonally low dissolved oxygen concentrations, for example, tend to occur near the end of July or beginning of August coincident with a collapse of the AFA bloom. A fish die-off in 2003 was associated with a particularly severe low dissolved oxygen event that coincided with a bloom decline at the end of July (Banish and others, 2009).

Circulation patterns in Upper Klamath Lake have been explored with measurements and modeling. Current velocity measurements made with acoustic Doppler current profilers

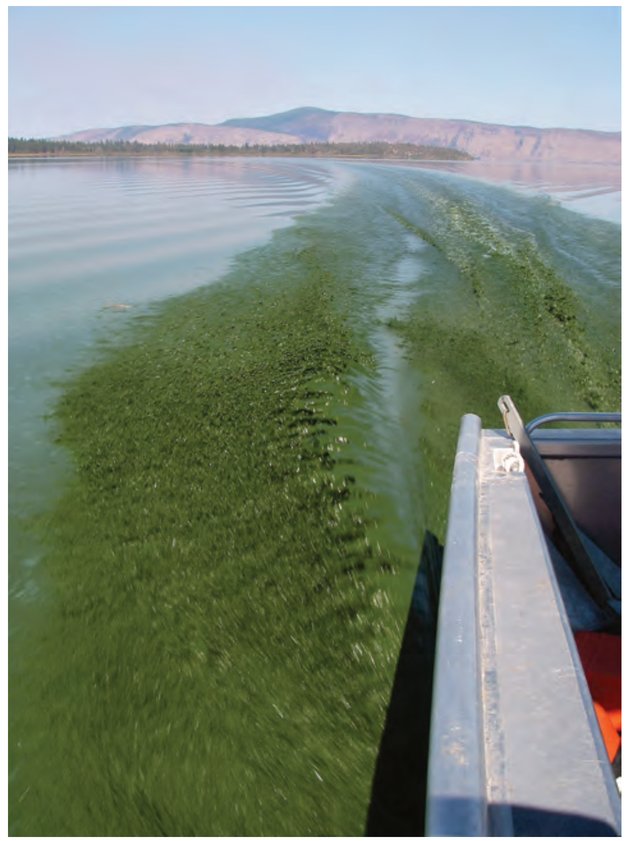


Figure 1. Bloom of the alga *Aphanizomenon flos-aquae*, disturbed by the wake of the boat, Upper Klamath Lake, Oregon, 2006. (Photograph by Mary Lindenberg, U.S. Geological Survey, September 26, 2006.)

(ADCPs; Gartner and others, 2007) and hydrodynamic modeling with the 3-dimensional UnTRIM model (Wood and others, 2008) have confirmed that during periods of prevailing northwesterly winds, circulation is clockwise around the lake, consisting of a broad and shallow southward flow through most of the lake and along the northern and eastern shorelines, and a narrow, deep, northward flow through the trench along the western shoreline. This description of the wind-driven currents indicates that poor water quality conditions, particularly low dissolved oxygen, that are observed in the northern part of the lake do not primarily originate locally. Instead, the circulation pattern could allow transportation of poor water quality conditions originating in the southern part of the lake through the trench west of Bare Island into the northern part of the lake.

In 2005, the USGS water quality monitoring program on Upper Klamath Lake expanded to include most of Upper Klamath Lake as well as sites in Agency Lake. Additional meteorological sites were established around the lake basin to provide greater resolution of meteorological data used in modeling water movement and heat transport in Upper Klamath Lake. Agency Lake was determined to have a seasonal cycle of AFA bloom and decline similar to, but independent from, that of Upper Klamath Lake. Dissolved oxygen production and consumption experiments in Upper Klamath Lake provided evidence that a decreasing trend of dissolved oxygen productivity through July could have contributed to decreasing dissolved oxygen levels observed in continuous monitor data during that time. Evidence of poor water quality conditions flowing northward through the trench along prevailing currents into the northern part of the lake also were observed (Hoilman and others, 2008).

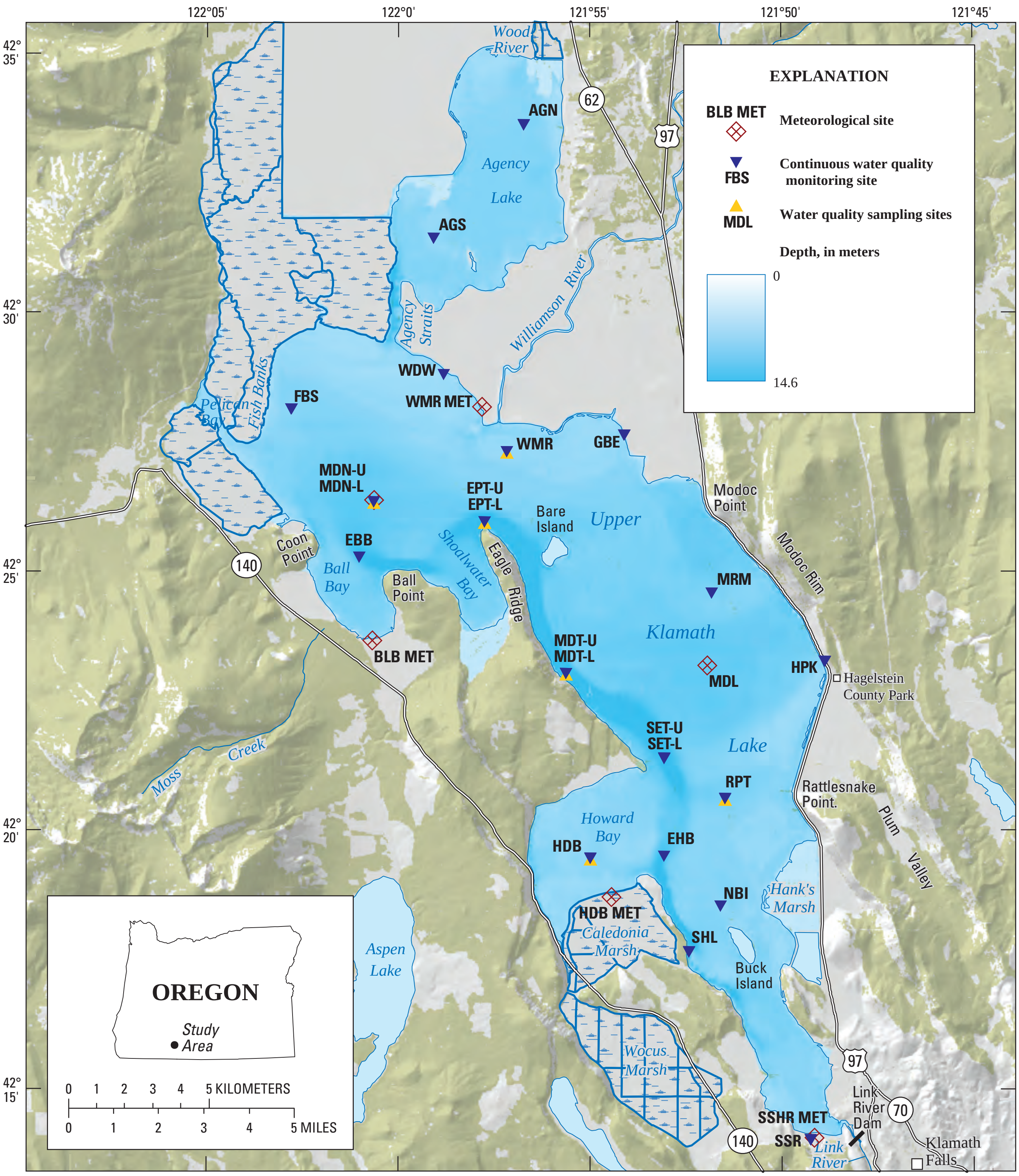
Purpose and Scope

The long-term monitoring effort that began in 2005 was continued in 2006. This report presents the results of the 2006 data-collection program, which includes data from meteorological stations, laboratory analyses of water samples, dissolved oxygen production and consumption experiments, and continuous water quality monitors. To provide continuity, there are many similarities between the presentation of the 2006 data in this report and the presentation of the 2005 data in Hoilman and others (2008). This report also includes comparisons between 2005 and 2006, new analyses that use total nitrogen data, which was not collected in 2005, a more temporally complete data set of dissolved oxygen consumption and production experiments than was collected in 2005, and continuous water quality measurements from nearshore sites to compare to those from open-water sites.

Description of Study Area

Upper Klamath Lake (fig. 2) is in south-central Oregon. The lake is large and shallow 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 lake's western shore. This trench contains water as much as 15 m in depth. Upper Klamath Lake is 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 enters the lake near its northern end and on average contributes about 46 percent of the inflowing water.

Upper Klamath Lake is a natural water body, but lake-surface elevations have been regulated since 1921, when 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 primary water source for the Klamath Project, an irrigation system developed to supply water to farms and ranches in and around the Upper Klamath Basin (Bureau of Reclamation, 2000). Agency Lake, just north of Upper Klamath Lake is connected to Upper Klamath Lake by a narrow natural channel, and adds approximately 38 km^2 of surface area to the Upper Klamath Lake-Agency Lake hydrologic system (Johnson, 1985). Agency Lake is also shallow, with a maximum depth of approximately 3 m and an average depth of 0.9 m. Like Upper Klamath Lake, Agency Lake is hypereutrophic and has annual blooms of AFA. Because the channel connecting Upper Klamath Lake and Agency Lake is narrow compared to the two water bodies and the discharge through it is small, the two lakes are largely independent in terms of the seasonal AFA bloom and water quality dynamics.



Bathymetry produced by Glen Canyon Environmental Studies in cooperation with Bureau of Reclamation, Mid-Pacific Region, Klamath Basin Area Office, and the Klamath Tribes. Digital Raster Graphics and Elevation modified from U.S. Geological Survey, various scales. Base map digital data, U.S. Geological Survey, various sources. Projection: UTM, Zone 10, NAD83 horizontal datum.

Figure 2. Location of meteorological, continuous water quality monitoring, and water quality sampling sites, Upper Klamath and Agency Lakes, Oregon, 2006. (Site descriptions are shown in table 1.)

Methods

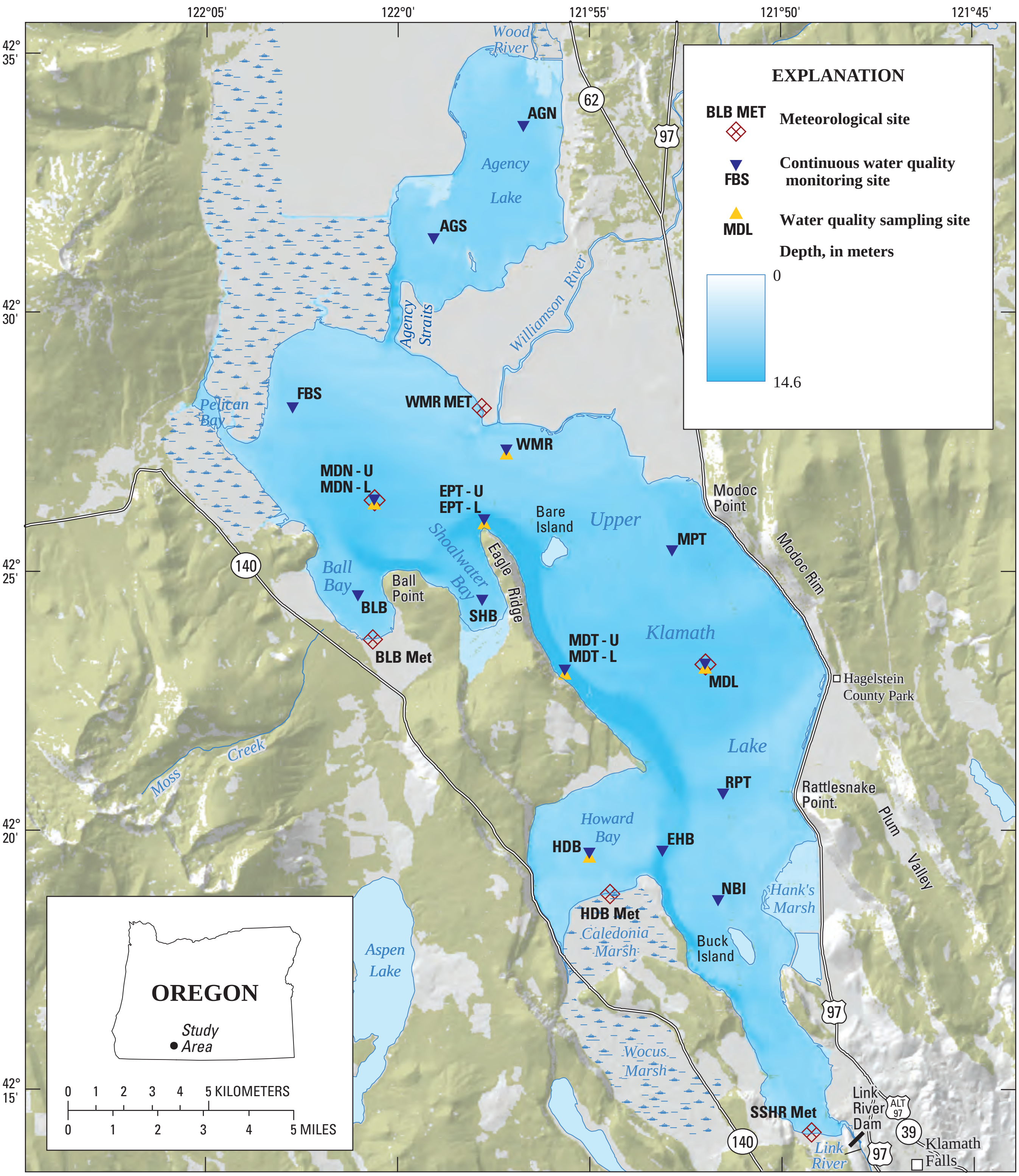
Continuous Water Quality Monitors

YSI model 600XLM or model 6920 continuous water quality monitors (“sondes”) were placed at 2 sites in Agency Lake and 17 sites in Upper Klamath Lake (fig. 2, table 1). In Upper Klamath Lake, 12 monitors were in open-water areas and 5 monitors were in nearshore areas (5–10 m from shore or in reed beds adjacent to the open lake). Nearshore sites were HPK, SHL, SSR, GBE, and WDW. Water quality monitoring locations in open-water areas of Upper Klamath Lake were similar to those in 2005 (fig. 3), but with some changes based on an evolving understanding of the lake system that were made to optimize the data collection effort. For example, several years of monitoring conditions in Shoalwater, Ball, and Howard Bays has established that the bays are largely disconnected from the rest of the lake in terms of the seasonal dynamics of water quality. Although the data are interesting because they quantify extremes in water quality conditions, they add little to the objective of understanding the water quality dynamics in the open-waters of the lake. For this reason, two bay sites (BLB and SHB, fig. 3) were discontinued and two sites were added at the northern and southern extremes of the deep trench on the western side of the lake (sites EBB and SET, fig. 2). In addition, the sites MPT and MDL were determined to be redundant and were replaced by the single site MRM. Meteorological data collection continued at the MDL site.

Table 1. Continuous water quality monitoring and sampling sites, Upper Klamath and Agency Lakes, Oregon, 2006.

[Locations of sites are shown in figure 2. 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)
		Open-Water Sites			
Middle of trench (lower)	MDT-L	422305121553800	42°23'05"	121°55'38"	15.00
Middle of trench (upper)	MDT-U	422305121553803	42°23'05"	121°55'38"	15.00
Eagle Point (lower)	EPT-L	422559121574400	42°25'59"	121°57'44"	12.50
Eagle Point (upper)	EPT-U	422559121574403	42°25'59"	121°57'44"	12.50
Entrance to Ball Bay	EBB	422519122005800	42°25'19"	122°00'58"	7.50
South End of Trench (lower)	SET-L	422128121530600	42°21'28"	121°53'06"	7.00
South End of Trench (upper)	SET-U	422128121530603	42°21'28"	121°53'06"	7.00
Entrance to Howard Bay	EHB	421935121530600	42°19'35"	121°53'06"	5.20
Midlake (meteorological only)	MDL	422312121515900	42°23'12"	121°51'59"	4.50
Midnorth (lower)	MDN-L	422622122004000	42°26'22"	122°00'40"	4.20
Midnorth (upper)	MDN-U	422622122004003	42°26'22"	122°00'40"	4.20
Modoc Rim	MRM	422437121515200	42°24'37"	121°51'52"	3.70
Rattlesnake Point	RPT	422042121513100	42°20'42"	121°51'31"	3.40
Agency North	AGN	423335121564300	42°33'35"	121°56'43"	3.00
Fish Banks	FBS	422808122024400	42°28'08"	122°02'44"	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"	121°57'14"	2.50
Agency South	AGS	423124121583400	42°31'25"	121°59'03"	2.50
Howard Bay	HDB	421933121550000	42°19'33"	121°55'00"	2.20
		Nearshore Sites			
Hagelstein Park	HPK	422319121585700	42°23'19"	121°48'57"	2.60
Skillet Handle	SHL	421746121522800	42°17'46"	121°52'28"	2.50
South Shore	SSR	421410121492000	42°14'10"	121°49'20"	2.50
Goose Bay East	GBE	422749121540700	42°27'39"	121°54'08"	2.40
Williamson Delta West	WDW	422842121584300	42°28'48"	121°58'43"	2.20



Bathymetry produced by Glen Canyon Environmental Studies in cooperation with Bureau of Reclamation, Mid-Pacific Region, Klamath Basin Area Office, and the Klamath Tribes. Digital Raster Graphics and Elevation modified from U.S. Geological Survey, various scales. Base map digital data, U.S. Geological Survey, various sources. Projection: UTM, Zone 10, NAD83 horizontal datum.

Figure 3. Locations of meteorological, continuous water quality monitoring, and water quality sampling sites, Upper Klamath and Agency Lakes, Oregon, 2005.

At most continuous water quality monitoring 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 4. Placing the sonde 1 m from lake bottom provided data relevant to the endangered botton-feeding suckers of Upper Klamath Lake. To monitor 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 the four deepest sites, SET, MDT, EPT, and MDN (fig. 2). All sondes recorded sonde depth, 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 the site sonde were made as an additional check of sonde performance. Deployments generally lasted 3 weeks, and then the sonde at the site was replaced with a newly calibrated instrument. Calibration of each parameter was checked in the laboratory after sonde retrieval to measure calibration drift. The raw data were then uploaded to 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 (2006). Corrections to data due to biological fouling and drift as determined during the post-deployment calibration check were entered into ADAPS, which calculated the corrected values.

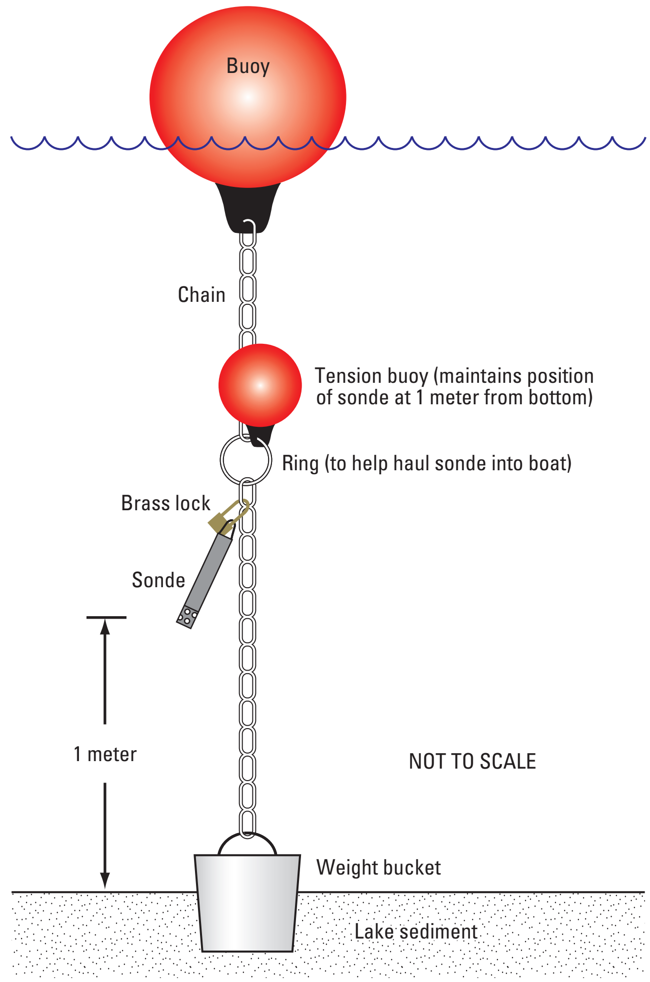


Figure 4. Schematic diagram of a typical mooring used for placement of continuous water quality monitors, Upper Klamath and Agency Lakes, Oregon, 2006.

Water Sample Collection

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 nitrogen, ammonia (includes ammonia plus ammonium), orthophosphate, and nitrite-plus-nitrate concentrations. A subset of the continuous water quality monitoring sites, MDN, WMR, EPT, MDT, HDB, and RPT (fig. 2), were selected for the sampling. Two methods of sampling were used. The choice of method depended on the category of analyte to be measured. Water samples analyzed for total phosphorus, total nitrogen, and chlorophyll *a* were collected using methods designed to achieve 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 (“shallow” sites) and to 10 m from the surface at sites greater than 10.5 m depth (“deep” sites). Each bottle had two ports, one for water to flow in, and one for the escape of displaced air. The contents of bottles from multiple collections at a site were composited, mixed, and then split into separate fractions using a churn splitter.

At the beginning of the sampling season in May, water samples analyzed for dissolved nutrients (ammonia, orthophosphate, and nitrite-plus-nitrate) were collected from a point mid-depth in the water column at sites MDN, WMR, HDB, and RPT, and at two points in the water column (at one-quarter and three-quarters of the total depth) at sites MDT and EPT. Point samples were collected by lowering one end of a hose to the appropriate depth in the water column, then passing the sample through a 0.45 µm capsule filter using a peristaltic pump. After July 1, sites MDN, WMR, and HDB were discontinued to meet logistical and resource constraints.

The sampling protocol at RPT, MDT, and EPT was changed to collection of a sample just below the water surface and another sample 5 m below the water surface (RPT sample was just below water surface only), to support the objectives of a parallel study of AFA buoyancy by Portland State University (J. Rueter, Portland State University, oral commun., 2006).

Dissolved nutrient, total phosphorus, and total nitrogen samples were chilled on site and sent to the National Water Quality Laboratory (NWQL) in Denver, Colorado, for analysis. Total phosphorus and total nitrogen samples were preserved in the field with 1 mL of 4.5 normal (4.5N) H_2SO_4 (Sulfuric Acid). Finalized data were stored in the USGS National Water Information System (NWIS) database. Samples for chlorophyll *a* concentrations were passed through a 0.45 µm glass fiber filter, and the filter membrane was frozen and sent to Portland State University in Portland, Oregon, for analysis. Because samples were processed at Portland State University, the results of the chlorophyll *a* analyses were not stored in the USGS NWIS database. The comparability of Portland State University and NWQL chlorophyll *a* data was established with four interlaboratory splits, two of which were submitted to two laboratories in addition to Portland State University and NWQL. Chlorophyll *a* samples were analyzed according to Arar and Collins (1997).

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). Although all quality assurance protocols were followed to ensure accuracy, there was evidence of minor contamination in ammonia and total nitrogen blank samples; the results are discussed further in appendix A. Less than one-half of blank samples were contaminated, and the magnitude of seasonal differences in environmental samples was greater than the error associated with potential contamination.

Dissolved Oxygen Production and Consumption Experiments

Between mid-June and mid-October, experiments were conducted to obtain direct measurements of gross dissolved oxygen production and consumption rates at six sites—MDN, WMR, RPT, HDB, MDT, and EPT—in Upper Klamath Lake (fig. 5). Biological oxygen demand (BOD) bottles, with a volume of 300 mL and made of type 1 borosilicate glass, were filled with lake water integrated from the entire water column. BOD bottles were filled from the churn splitter with the same collection of lake water as for 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. Immediately after filling the bottles, initial dissolved oxygen concentration and temperature were measured by using a YSI model 52 dissolved oxygen meter. Three bottles were attached to rest horizontally on racks at each of two depths. One bottle in each group of three was dark (made so by wrapping the bottle and stopper with black electrical tape). Once attached to the incubator rack, the bottles were lowered into the water.

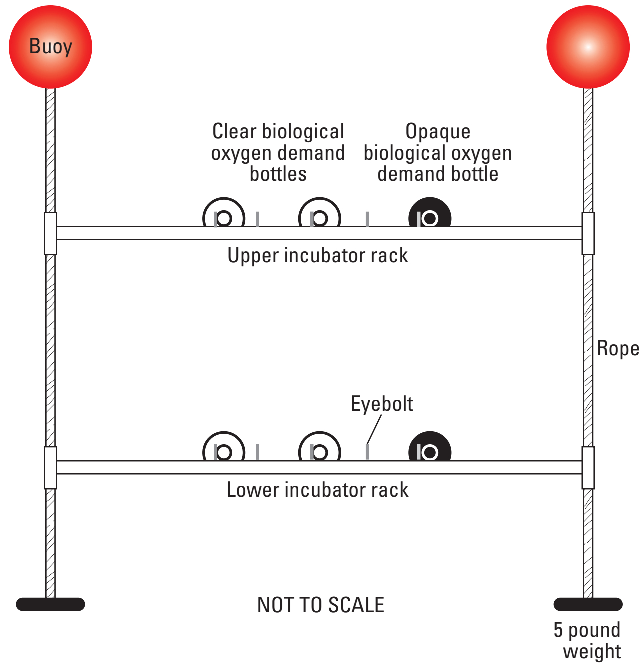


Figure 5. Schematic diagram of the apparatus for *Aphanizomenon flos-aquae* dissolved oxygen production and consumption experiments, Upper Klamath Lake, Oregon, 2006.

The experimental apparatus was moored at the site for at least 45 minutes and typically retrieved before 3 hours had elapsed. Dissolved oxygen concentration and temperature were again measured in each bottle, and incubation time was noted. The change in dissolved oxygen was calculated in each bottle, and the incubation time was used to express the rate of dissolved oxygen change in milligrams per liter per hour [(mg/L)/h]. The upper and lower racks were positioned 0.5 and 1.5 m below water surface, respectively. Toward the end of the season, as the lake level declined, the lower rack was raised to 1 m depth at the shallow sites (table 2). Some sites were 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 2.5 m depth (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

Table 2. Depth of incubator racks during dissolved oxygen production and consumption experiments, Upper Klamath and Agency Lakes, Oregon, 2006.

[Description of sites are shown in table 1; location of sites are 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	
	5	12	19	26	3	10	18	24	31	7	14	21	28	5	12	18	25	2	10
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	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Lower	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Average photic zone	3.89	3.20	3.59	3.50	1.29	1.35	1.21	2.06	2.27	1.81	1.13	1.31	1.71	1.49	1.44	1.29	1.44	1.32	1.52
Upper Klamath Lake at Williamson River Outlet (WMR)																			
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	0.5	0.5	0.5	0.5	0.5	0.5
Lower	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1	1	1	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Average photic zone	3.50	3.57	3.27	2.65	1.76	1.24	1.63	2.71	2.81	2.05	2.48	2.16	1.52	0.83	1.29	1.17	0.95	1.61	3.78
Rattlesnake Point (RPT)																			
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	0.5	0.5	0.5	0.5	0.5	0.5
Lower	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Average photic zone	3.94	3.61	3.40	2.03	2.14	1.59	1.40	1.84	2.44	2.31	2.01	2.21	2.03	1.94	1.49	1.39	1.41	1.40	1.24
Howard Bay (HDB)																			
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	0.5	0.5	0.5	0.5	0.5
Lower	–	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1	1	1	1	n/a	n/a	n/a	n/a	n/a	n/a
Average photic zone	–	3.31	3.22	1.86	0.83	0.42	1.14	0.28	1.16	1.18	0.79	1.03	0.95	0.62	0.60	0.71	1.07	0.87	1.15
Middle of the Trench (MDT)																			
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	0.5	0.5	0.5	0.5	0.5	0.5
Lower	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Average photic zone	3.96	3.04	3.29	1.28	1.32	0.64	0.84	1.01	2.99	1.46	0.48	1.85	1.14	0.52	1.04	0.93	0.40	0.84	1.26
Eagle Point (EPT)																			
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	0.5	0.5	0.5	0.5	0.5	0.5
Lower	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Average photic zone	3.70	3.85	3.41	3.14	1.50	2.29	1.79	2.77	2.81	1.90	1.99	1.44	1.54	1.61	2.01	1.28	1.61	1.92	0.93

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:

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

where

z is depth, in meters,
I_z is radiation at depth, in micromoles per second per square meter,
I_0 is surface radiation, in micromoles per second per square meter, and
α is the extinction coefficient (Welch, 1992).

At each set of measurements, α was estimated 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

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

Measurements of the vertical profile of light intensity were made at each site on each date at the beginning ("early" measurements) and immediately after the incubation period ("late" measurements). These two profiles were combined to provide the average depth of photic zone throughout the duration of each experiment at each site.

An estimate of the potential change in dissolved oxygen over a 24-hour period (ΔDO) was made from the measured oxygen production and consumption rates in the light and dark bottles. The gross production, G, in (mg/L)/h was assumed to have the same exponential dependence with depth as light radiation. Then, in analogy with equation 1, the gross production at any depth in the water column G_z as a function of the gross production at the water surface G_0 is given by

$$G_z = G_0 e^{-\alpha z}. \tag{3}$$

The above equation can be solved for G_0 in terms of the value obtained from the rack at 0.5 m depth

$$G_0 = G_{0.5} e^{0.5\alpha}. \tag{4}$$

The gross production integrated over a water column of depth D, denoted $\bar{G}$, is given by

$$\bar{G} = G_0 \int_0^D e^{-\alpha z}\, dz = \frac{G_0}{10^{-3}\alpha}\left(1 - e^{-\alpha D}\right) \tag{5}$$

where 10^{-3} is a proportionality constant and the units of $\bar{G}$ are (mg/m^2)/h.

Respiration rates (R) were similar in both racks, and were assumed constant throughout the water column for this calculation. Respiration integrated over the water column is given by

$$\bar{R} = \frac{RD}{10^{-3}} \tag{6}$$

where 10^{-3} is a proportionality constant. The units of $\bar{R}$ are (mg/m^2)/h. The final simplification is to assume that the gross production rate is constant at $\bar{G}$ for 12 hours of daylight in every 24 hours and zero for the remaining 12 hours, and that the respiration rate is constant for a full 24 hours. Then the estimated change in dissolved oxygen over a 24-hour period, expressed in terms of a concentration (mg/L), is

$$\begin{aligned}\Delta DO &= (12\bar{G} + 24\bar{R})\frac{10^{-3}}{D} \\ &= \frac{12G_0}{\alpha D}\left(1 - e^{-\alpha D}\right) + 24R.\end{aligned} \tag{7}$$

Meteorological Sites

The locations of meteorological measurement sites in Upper Klamath Lake are shown in figure 2 and listed in table 3. All meteorological sites were in the same locations as the study in 2005.

A diagram of the typical land-based meteorological site is shown in figure 6. 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

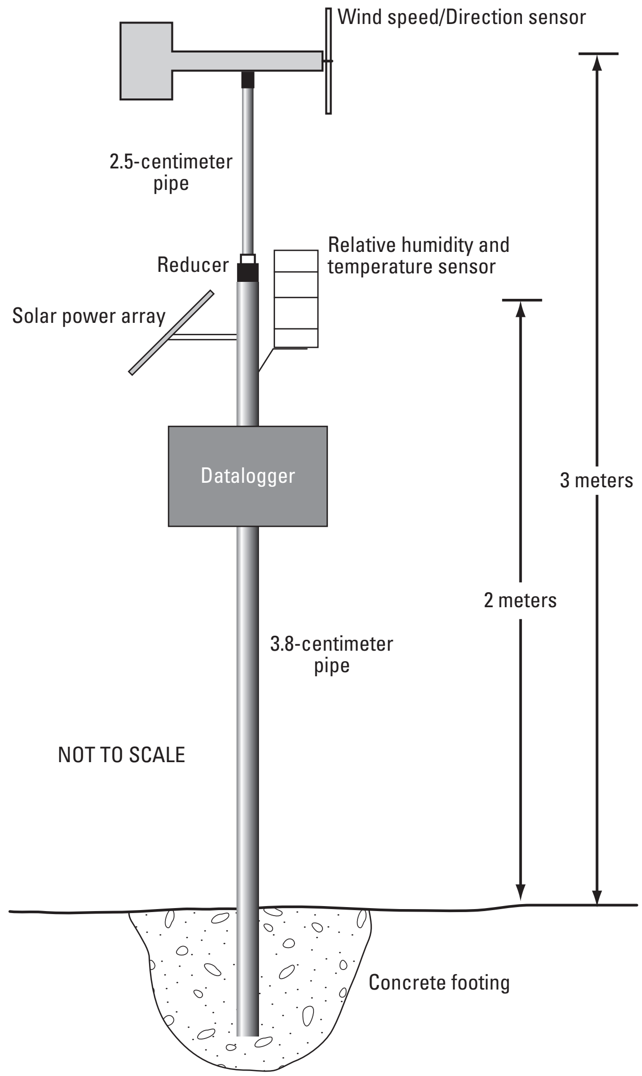


Figure 6. Configuration of land-based meteorological measurement sites around Upper Klamath Lake, Oregon, 2006.

Table 3. Meteorological sites and parameters measured at each site, Upper Klamath Lake, Oregon, 2006.

[Site locations are shown in figure 2. 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
Midnorth[1]	MDN MET	422622122004000	42°26'21.5"	122°00'40"	Wind speed/direction
Williamson River	WMR MET	422809121574800	42°28'09"	121°57'48.5"	Wind speed/direction, air temperature, relative humidity, solar radiation
Ball Bay	BLB MET	422341122003800	42°23'41"	122°00'38"	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
Howard Bay	HDB MET	421846121542800	42°18'46.2"	121°54'28"	Wind speed/direction, air temperature, relative humidity
South Shore	SSHR MET	421402121491400	42°14'02.76"	121°49'14.38"	Wind speed/direction, air temperature, relative humidity, solar radiation

[1]Floating site.

and air temperature sensor. Additionally, solar radiation data were collected at the WMR MET site using a Li-Cor LI200SZ pyranometer and at the SSHR MET site using an Eppley model PSP pyranometer. Floating sites were similar 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 site during the 2006 field season. Data collected from all sensors at a site were stored every 10 minutes by a Campbell Scientific CR510, CR10, or CR10X datalogger at the station. A 12-volt battery at the station charged by a solar power array provided power. Data were collected during site visits approximately 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 as needed. Information necessary to correct data due to drifts from proper calibration was collected as needed. Raw meteorological data also were loaded into ADAPS and processed in the same manner as the water quality monitor data.

Data Processing

Before calculating statistics, data from continuous water quality monitors were screened using temporal and, when appropriate for the statistic, spatial criteria. For this report, daily statistics were used for continuous water quality monitor data. To ensure that data were acceptable to compute daily statistics, at least 80 percent of measurements from one site for one day had to be present, which would constitute a “qualifying day” of data. A spatial criterion was applied when data collected from the entire lake were compiled to compute a statistic, such as lakewide daily median dissolved oxygen. This criterion specified that at least 70 percent of water quality sites in the lake had to have qualifying daily data 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 possible measurements made in one day were present to constitute a qualifying day of data. To compute lakewide meteorological statistics, different levels of spatial acceptability were applied depending on the parameter because not all parameters were collected at all sites, and relatively few meteorological stations were installed around the Upper Klamath Lake basin. Air temperature and relative humidity measurements were collected at five sites, so the spatial criterion for these parameters ensured that daily qualifying data were available at four of the five sites (80 percent) to compute a lakewide daily statistic. Wind speed data were collected at all meteorological sites, so the spatial criterion for wind speed ensured that five of the six sites (83 percent) had daily qualifying data to compute a lakewide daily statistic. Because solar radiation data were collected at only two sites, these data were not screened according to spatial criteria.

Meteorological Data

Daily Lakewide Meteorological Conditions

Lakewide daily average meteorological conditions shown in figure 7 provide information about the general behavior of these environmental parameters throughout the lake during the 2005 and 2006 field season. Time series plots of 2005 data are included to provide an interannual comparison. Daily average wind speed was mostly less than 5 m/s from June through August during both years. However, in 2005 lakewide daily median wind speed exceeded 5 m/s during some days in mid-June and late August. In both years, daily average wind speed beginning in September was more variable. Average air temperature followed similar patterns in both years gradually increasing from June through July and then gradually decreasing from August through October. Average relative humidity largely followed the inverse of air temperature patterns in both years. These patterns of air temperature and relative humidity are typical of the hot, dry summers of the Upper Klamath Lake basin. Average daytime solar radiation was more variable and periodically less intense through much of July and August 2006 relative to 2005, indicating that these months were somewhat cloudier in 2006.

Wind Histograms

Wind speed and direction determine the circulation patterns of the water in Upper Klamath Lake. This phenomenon has been verified with a hydrodynamic model of the lake (Wood and others, 2008) and with the placement of acoustic Doppler current profilers in the lake (Wood and others, 2006). Because the wind and the currents are so tightly coupled, the preliminary modeling effort also determined that spatially accurate wind data from the entire lake is required, rather than data collected from only a single site. Before meteorological measurements were collected at several sites on and around the lake in 2005, little was understood about wind characteristics at different locations on the lake. In 2006, meteorological data were collected at the same sites as 2005 in continued support of the modeling effort (fig. 2).

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. Because the histograms show simple counts of direction readings categorized by wind speed, no temporal filters were applied to the data used in these plots.

Wind characteristics at each site were nearly identical to characteristics shown on the histograms from 2005 (Hoilman and others, 2008). The prevailing westerly winds in the northern one-third of the lake measured at site MDN MET and WMR MET, were funneled by the topography surrounding the main body of the lake into a narrow range in northwesterly winds measured at site MDL MET. This same narrow range of northwesterly winds was observed for most winds greater than 5 m/s at the land-based HDB MET and SSHR MET sites in the southern part of the lake, although winds less than 5 m/s primarily came from the northeast and south at site HDB MET. The range of prevailing northwesterly winds at site SSHR MET is narrower than at site MDL MET, perhaps because the lake basin narrows between the surrounding ridges at the southern end. Overall, data from 2005 and 2006 indicate that the prevailing winds over the northern part of the lake are westerly, and these prevailing winds become northwesterly over the middle and southern part of the lake.

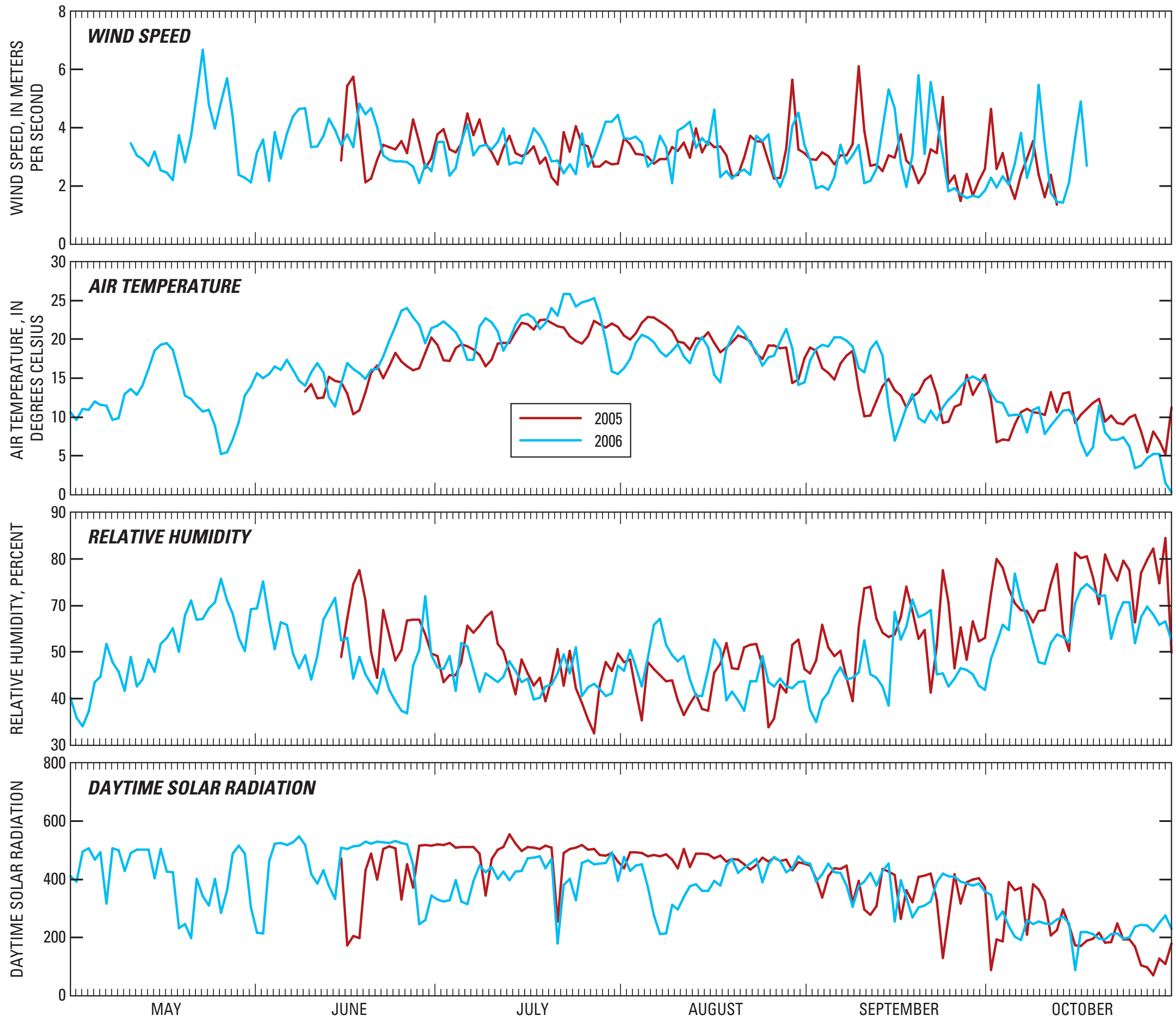


Figure 7. Lakewide daily average wind speed, air temperature, relative humidity, and daytime solar radiation at meteorological sites in and near Upper Klamath Lake, Oregon, 2005 and 2006.

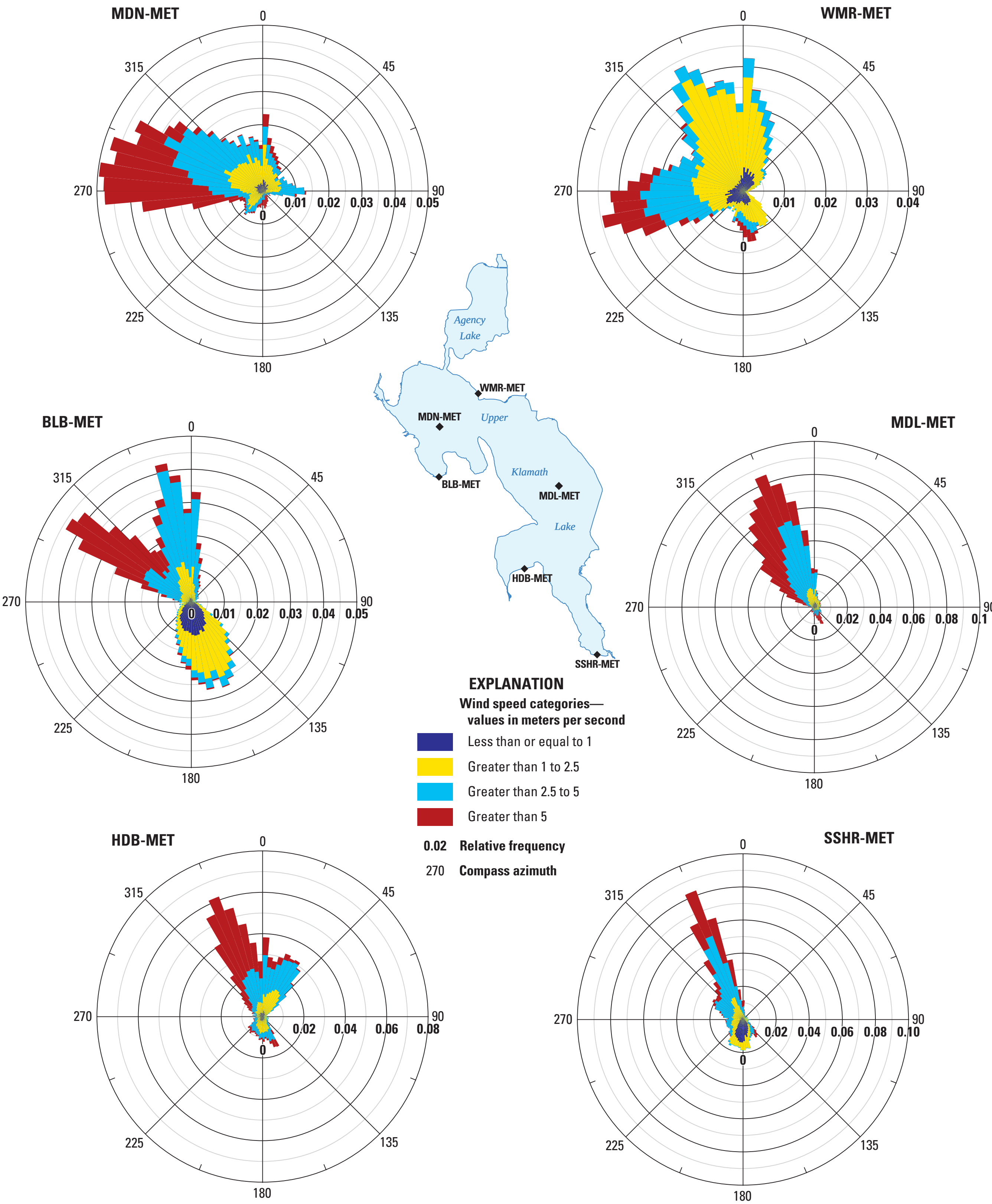


Figure 8. Wind speed and direction for meteorological sites near Upper Klamath Lake, Oregon, 2006. (Histogram bars are stacked in a 5-degree direction category.)

Nutrient and Chlorophyll *a* Water Samples

Aphanizomenon flos-aquae Bloom Dynamics

Photosynthetic pigments, like chlorophyll *a*, are measured as a surrogate for algal biomass (Wetzel, 2001) because the cost and time required to collect and analyze chlorophyll *a* is less than that required to make measurements of algal biomass using gravimetric methods. In this report, algal biomass is represented by chlorophyll *a* concentration. Furthermore, because 90–100 percent of the total phytoplankton biomass in Upper Klamath Lake consists of AFA between May and November (Kann, 1997), chlorophyll *a* represents primarily the biomass of AFA. The weekly water samples, although collected at only a subset of the sites in the study area, provided valuable context for understanding the data from the continuous water quality monitors. Trends and fluctuations in water quality parameters were commonly associated with trends and fluctuations in algal (AFA) biomass, as reflected in the chlorophyll *a* data. Maxima in concentrations of chlorophyll *a* coincided with supersaturated concentrations of dissolved oxygen and the highest pH values, indicating an algal bloom, whereas minima in concentrations of chlorophyll *a* coincided with undersaturated dissolved oxygen concentrations and lower pH values, indicating a bloom decline. A bloom decline is characterized by a sharp reduction in oxygen production through photosynthesis and is manifested as a decrease in dissolved oxygen concentration. These decreases may reach levels potentially harmful to fish when oxygen demand continues in the water column or sediments through the decomposition of organic material. In contrast, periods of growth in the bloom are generally manifested as supersaturated dissolved oxygen concentrations and high pH values, as photosynthesizing algae consume bicarbonate and produce oxygen.

Week-to-week variation in chlorophyll *a* concentrations can indicate either temporal variability (because the population is blooming and declining through time) or spatial variability (because the algal growth is inherently patchy and the patches move around the lake). These two types of variability can be distinguished largely by considering the concurrent dissolved oxygen and nutrient concentrations. Indicators of bloom decline and associated cell senescence are low dissolved oxygen concentration and increased dissolved nutrient concentration; the magnitude of the increase in dissolved nutrients and decrease in dissolved oxygen concentration often is proportional to the chlorophyll *a* concentration before the event. Variation in chlorophyll *a* concentration caused by patchiness, however, is not associated with increased nutrient or decreased dissolved oxygen concentration. Patchiness is an expected characteristic of AFA blooms. AFA cells contain gas vesicles that allow colonies to become positively buoyant; cells also create and consume carbohydrate ballast to regulate their position in the water column. The sampling protocols used in this study may be insufficient to detect chlorophyll *a* near the lake bottom. Additionally, colonies floating to the surface can form mats that are moved around by the wind, resulting in a low chlorophyll *a* concentration at the site of measurement when in fact a bloom is in progress elsewhere in the lake.

At site MDN, chlorophyll *a* data were collected from 2002 through 2006, allowing a direct interyear comparison. In each year, the algal bloom expanded rapidly to peak sometime between mid-June and 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 concurrently with increased dissolved nutrient concentrations and decreased dissolved oxygen concentrations, indicating an algal bloom decline and the associated large-scale cell senescence. (For the purposes of this analysis, dissolved nutrients collected at site EPT are shown for 2006, because they were not measured at site MDN.) 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 late July to mid-October during 2002–06 (fig. 9). The most severe (longest duration) low dissolved oxygen events (LDOE) occurred during the last week in July and first week in August 2003 and 2005, and were associated with the largest declines in chlorophyll *a* and increases in levels of dissolved nutrients, particularly ammonia. The occurrence of a low dissolved oxygen event in October 2003, however, demonstrates that this type of event is not limited to midseason, and can occur more than once in a single season.

Concentrations of chlorophyll *a* at most sites reached two or more peaks during 2006 (fig. 10). The highest chlorophyll *a* concentrations occurred after the midseason bloom decline at sites HDB and MDT (table 4). Data collected during previous years also indicated late-summer blooms of AFA (Kann, 1997; Wood and others, 2006; Hoilman and others, 2008). Throughout the sampling season, chlorophyll *a* concentrations varied between sites, indicating patchiness in the bloom, which was corroborated by the observations of field crews. As the season progressed, the variability between sites increased, indicating that the spatial scale of the patchiness increased. This trend through the season has been observed previously (Hoilman and others, 2008). The chlorophyll *a* concentrations at site HDB had multiple substantial peaks throughout the season, which differed from patterns at the other sites. The bloom in Howard Bay was somewhat isolated from the main body of the lake, and probably developed its own seasonal dynamics in response to localized nutrients, wind, and circulation patterns within the bay (Wood and others, 2008).

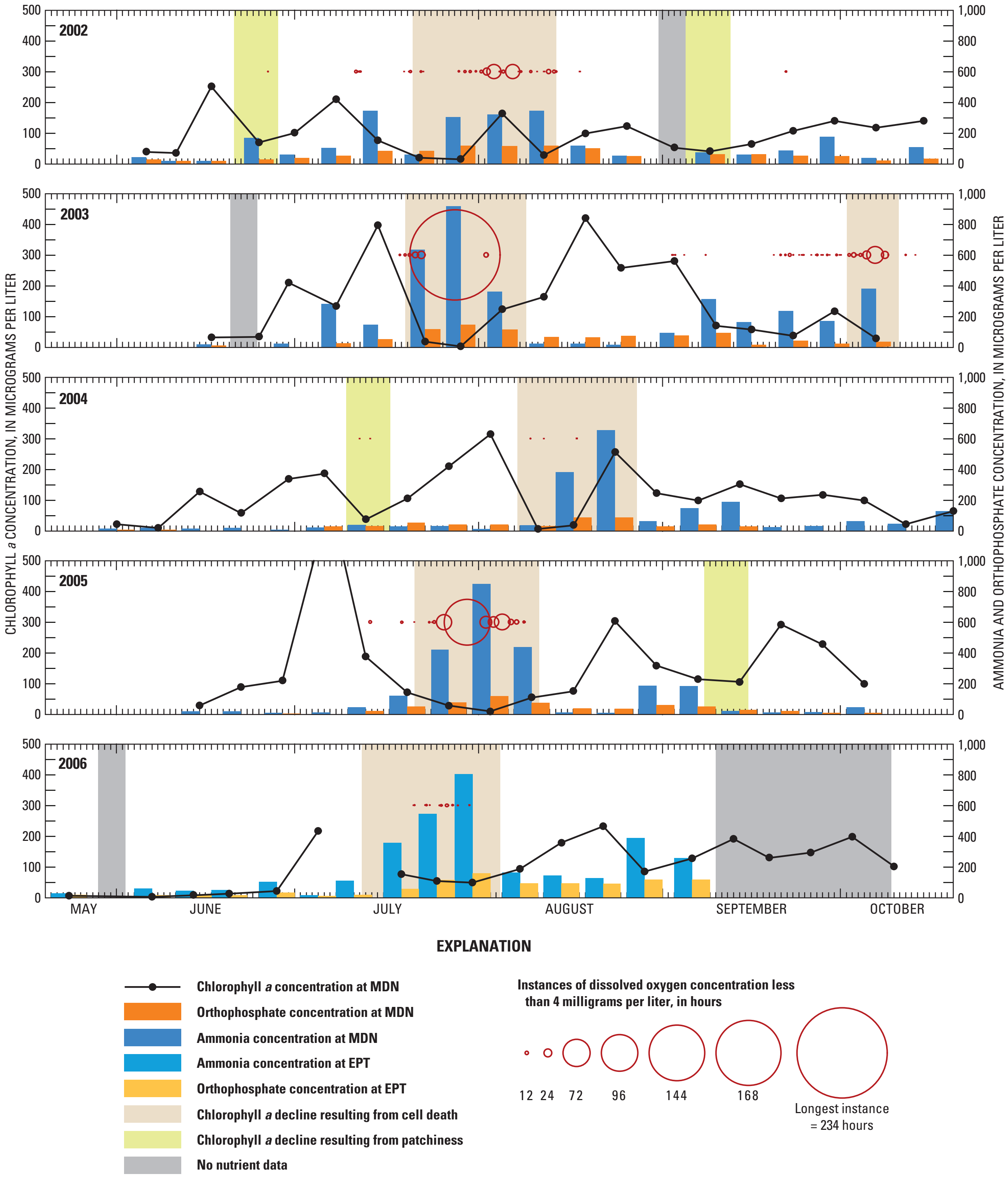


Figure 9. Measurements of chlorophyll *a* and dissolved nutrient concentrations in relation to duration of a dissolved oxygen concentration less than 4 milligrams per liter in water samples collected from site MDN, Upper Klamath Lake, Oregon, 2002–06. (Ammonia and orthophosphate concentrations for 2006 were collected from site EPT, the site nearest to MDN.)

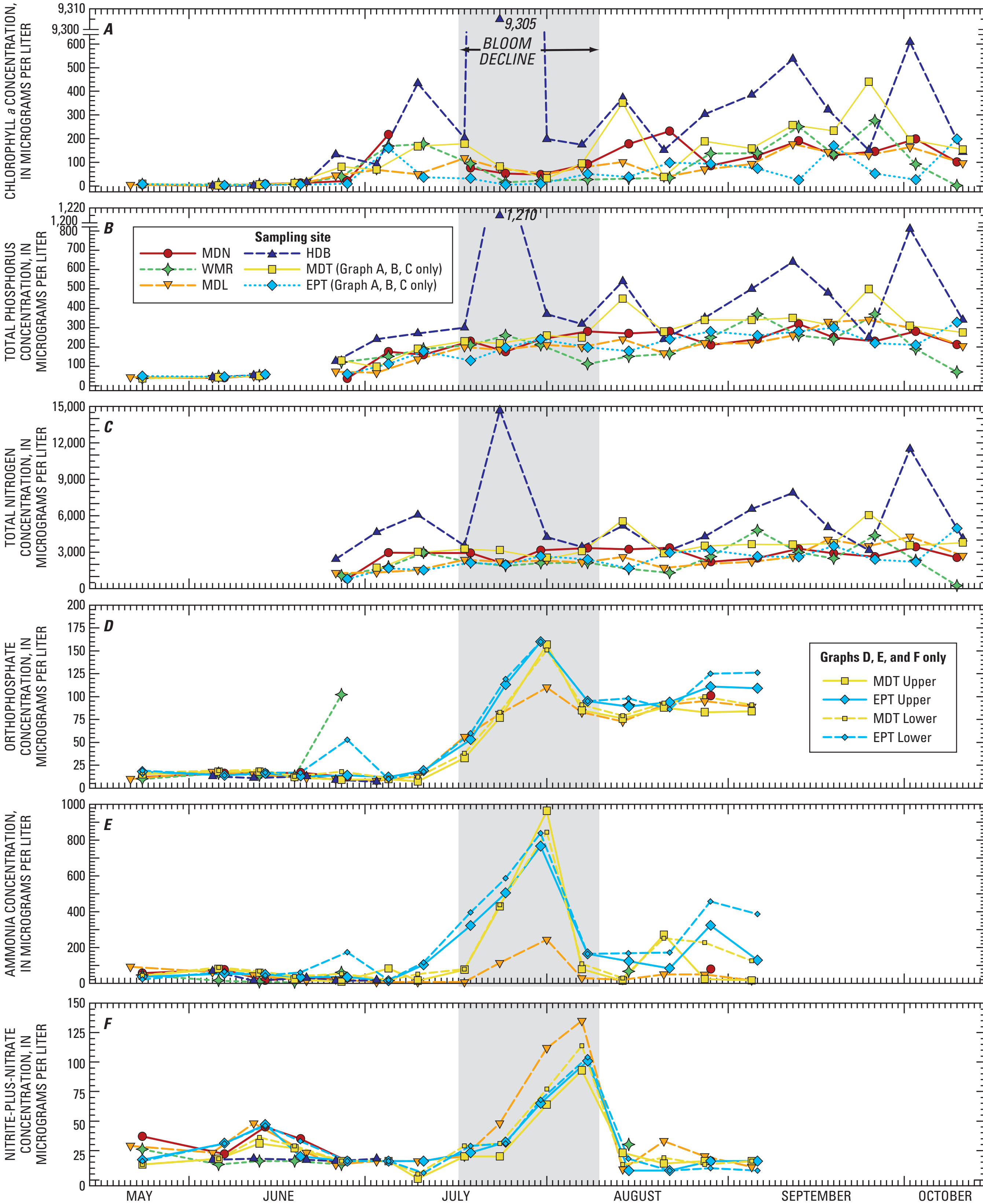


Figure 10. Chlorophyll *a*, total phosphorus, total nitrogen, orthophosphate, ammonia, and nitrite-plus-nitrate concentrations, Upper Klamath Lake, Oregon, May–October 2006. (Site descriptions are shown in table 1.)

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, May–October 2006.

[Site locations are shown in table 2. NA, not available]

Week of	Chlorophyll *a* concentrations, in micrograms per liter					
	Midnorth (MDN)	Upper Klamath Lake at Williamson River outlet (WMR)	Rattlesnake Point (RPT)	Howard Bay (HDB)	Middle of Trench (MDT)	Eagle Point (EPT)
May 22–26	6	6	5	n/a	9	8
May 29–June 2	2	7	2	2	3	3
June 5–9	8	6	4	2	6	6
June 12–16	12	7	15	16	12	6
June 19–23	21	40	45	133	81	10
June 26–30	217	169	69	91	70	160
July 3–7	n/a	178	50	434	168	37
July 10–14	76	94	118	204	179	32
July 17–21	53	16	75	9,305	83	5
July 24–28	48	23	51	198	33	10
July 31–Aug. 4	93	27	79	175	96	51
Aug. 7–11	178	31	101	372	352	38
Aug. 14–18	232	34	37	152	39	98
Aug. 21–25	85	137	70	304	189	94
Aug. 28–Sept. 1	128	139	93	385	159	74
Sept. 4–8	191	250	177	537	258	26
Sept. 11–15	130	133	144	323	234	170
Sept. 18–22	146	276	131	152	441	52
Sept. 25–29	198	92	165	609	196	27
Oct. 2–6	101	2	97	143	154	199
	Maximum concentrations at each site before algae decline resulting from cell death					
	Minimum concentrations at each site during algae decline resulting from cell death					
	Maximum concentrations at each site after algae decline resulting from cell death					
	Sample dates during algae decline resulting from cell death					

Decreases in chlorophyll *a* concentrations that indicate a large decline in the bloom are of interest because previous studies indicate that this phenomenon sometimes coincides with water quality that is harmful to endangered suckers in the lake. For example, a bloom decline has been shown to be the cause of LDOEs and increased un-ionized ammonia concentrations (Wood and others, 2006). In 2006, high chlorophyll *a* concentrations in late June and early to mid-July were followed by low concentrations in late July and early August. Because chlorophyll *a* concentrations decreased simultaneously at most sites indicates that net algal production was reduced by factors extending over a large area; temperature, decreased sunlight, and nutrient limitation are factors that could lead to such rapid lakewide chlorophyll *a* decreases. The lowest chlorophyll *a* concentrations measured after the bloom were between sample collection dates July 25, 2006, and August 1, 2006. During this time, continuous monitors measured dissolved oxygen concentrations less than 4 mg/L at all sites except sites RPT and WMR, less than 2 mg/L at site MDN, and less than 1 mg/L at sites HDB, MDT, and EPT. Dissolved oxygen concentrations at sites RPT and WMR did not decrease to less than 4 mg/L, indicating that the spatial extent of the LDOE did not reach these two sites. Consistent with previous years (Wood and others, 2006, Hoilman and others, 2008), the multiple decreases in chlorophyll *a* concentrations after mid-August in 2006 were not associated with widespread low dissolved oxygen concentrations. Such late-season variability more likely is a result of increased patchiness (decreased spatial scale) of the bloom rather than cell senescence.

Total phosphorus and total nitrogen concentrations were correlated positively with chlorophyll *a* concentrations (fig. 11). Using the Spearman's rank correlation coefficient, the relation between total nitrogen or total phosphorus and chlorophyll *a* samples with data from all sites combined was 0.741 ($p < 0.05$, $n = 99$) and 0.802 ($p < 0.05$, $n = 93$), respectively. Maxima in chlorophyll *a* concentrations in 2006 corresponded with maxima in total phosphorus and total nitrogen concentrations (fig. 11), and total nitrogen and total phosphorus concentrations increased concurrently with chlorophyll *a* concentration at the onset of the initial bloom (fig. 10). Previous studies have shown that total phosphorus and nitrogen concentrations, and chlorophyll *a* concentration in Upper Klamath Lake tend to increase simultaneously in spring, as determined by weekly or biweekly sampling (Kann, 1997, Wood and others, 2006). The increase in total nitrogen concentration has been preceded by an increase in heterocyst formation indicating nitrogen fixation by AFA leading up to the initial bloom (Kann, 1997).

Unlike deep lakes in which summertime chlorophyll *a* often can be predicted based on the phosphorus available at spring turnover (Dillon and Rigler, 1974), the seasonal dynamics of total phosphorus concentration in shallow lakes can be much more complicated, largely because of exchange between the water column and sediments (Havens and others, 2001). Nutrient mass balance studies have confirmed that the source of phosphorus to Upper Klamath Lake in spring and summer is largely internal loading from lake sediments (Kann and Walker, 2001), although the precise mechanism for phosphorus loading is 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 in the lake (Kuwabara and others, 2007). Some phosphorus that is stored in sediments and contributes to current internal loads is the result of increased external loading over the last several decades (Boyd and others, 2002), which is evidenced by a decrease in nitrogen to phosphorus ratios in the upper sediments (Eilers and others, 2004).

Through the combination of internal loading of phosphorus, nitrogen-fixation capability, and buoyancy regulation, blue-green algae such as AFA can dominate other phytoplankton in systems with low nitrogen to phosphorus ratios (less than 29:1 by weight; Smith, 1983). Ratios of total nitrogen to total phosphorus of all samples collected in 2006 were less than 29, which indicate that the appropriate conditions existed to establish AFA dominance over other phytoplankton (fig. 12). Analysis of sediment cores collected in Upper Klamath Lake show increased abundance of AFA and decreased diatoms and green algae in recent decades (Eilers and others, 2004). The changes in abundance of AFA coincide with the decrease in ratios of nitrogen to phosphorus in the upper lake bottom sediments, which is attributable to increases in external loading of phosphorus. The lowest ratios (2.9–10) of total nitrogen to total phosphorus were measured at site WMR (near the mouth of the Williamson River), indicating that total nitrogen to total phosphorus ratios from riverine inflows were lower than the lake water sampled at the other sites.

Potentially phosphorus-limited samples, characterized by chlorophyll *a* to phosphorus ratios greater than 1 (White, 1989; Graham and others, 2004) and total nitrogen to total phosphorus ratios greater than 17 (Forsberg and Ryding, 1980), occurred during the initial bloom in late June and early July (fig. 13). Ratios of total nitrogen to total phosphorus were lower between mid-August and mid-October than the ratios measured in the beginning of the season. Ratios of chlorophyll *a* to total phosphorus also peaked at lower values in September and October than in July (fig. 13). Based on both ratios, late-season blooms were not limited by phosphorus to the same extent as the initial algal bloom in late June and early July. Higher orthophosphate concentrations from mid-August through mid-September than concentrations prior to mid-July also indicate that more phosphorus was available to support bloom growth after the first bloom decline. Understanding the role of phosphorus in eutrophication and excessive algal growth is important from a management perspective (Havens and others, 2001; Schindler, 2006), and reductions in external loads likely will lead to reductions in internal phosphorus loads in Upper Klamath Lake, which in turn will reduce the peaks in the bloom and the severity of bloom declines (Walker, 2001; Boyd and others, 2002). These results indicate that such a strategy would most effectively control the early-season blooms.

Peaks of orthophosphate and ammonia occurred simultaneously with the low chlorophyll *a* concentrations at the end of July (fig. 10). Low dissolved oxygen concentrations coincided with the decline of chlorophyll *a* concentrations and the increase in dissolved nutrient concentrations, suggesting that the nutrient peaks resulted from decomposition of dead algae cells, which converts organic nutrients to inorganic form while consuming dissolved oxygen. Nitrite-plus-nitrate concentrations were low compared with ammonia, which indicates that nitrification is not a rapid or effective process for removal of ammonia from the water column during post-bloom periods of low dissolved oxygen concentrations.

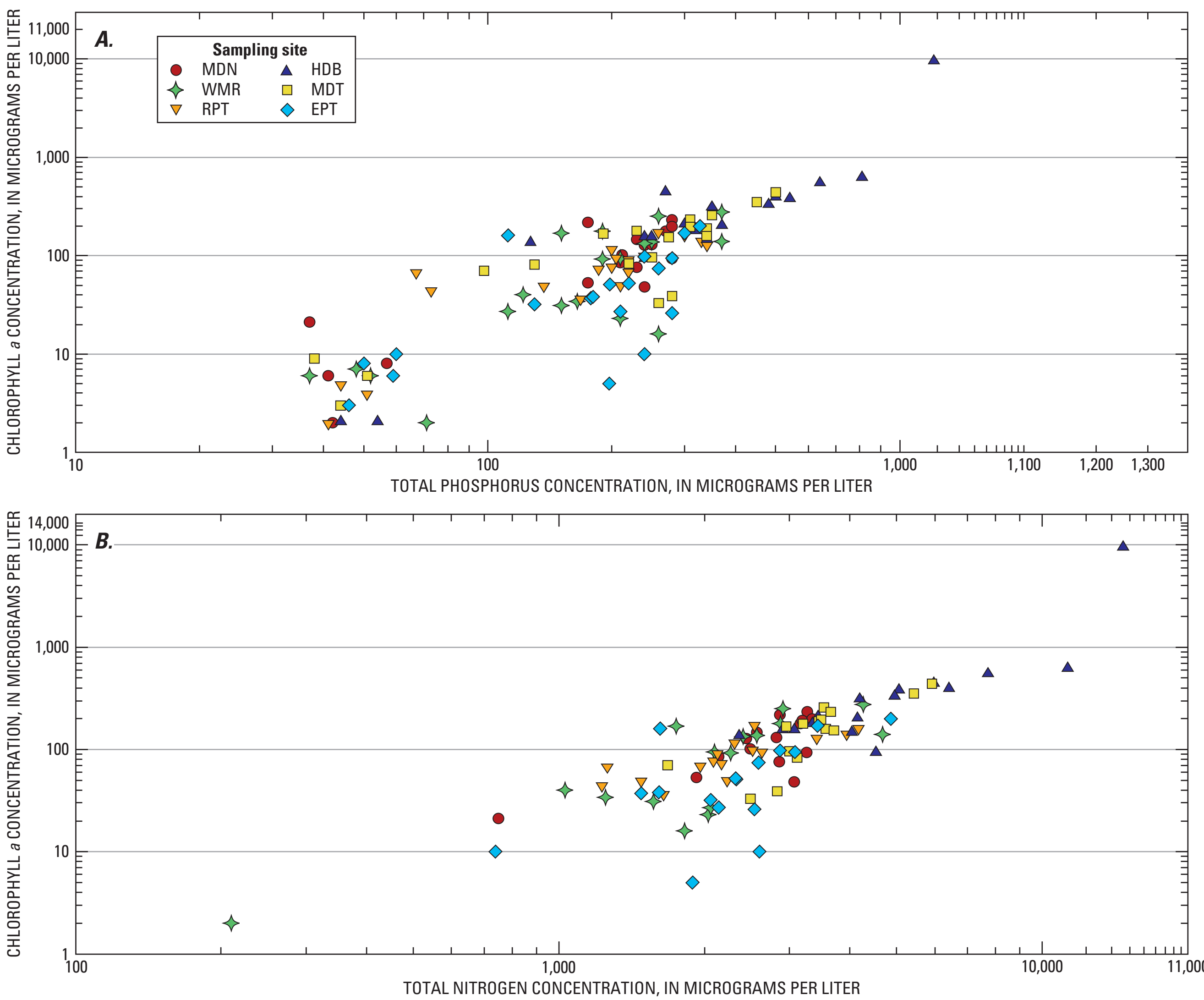


Figure 11. Relation between chlorophyll *a* to (*A*) total phosphorus and (*B*) total nitrogen concentrations in water samples collected from Upper Klamath Lake, Oregon, 2006. (Site descriptions are shown in table 1.)

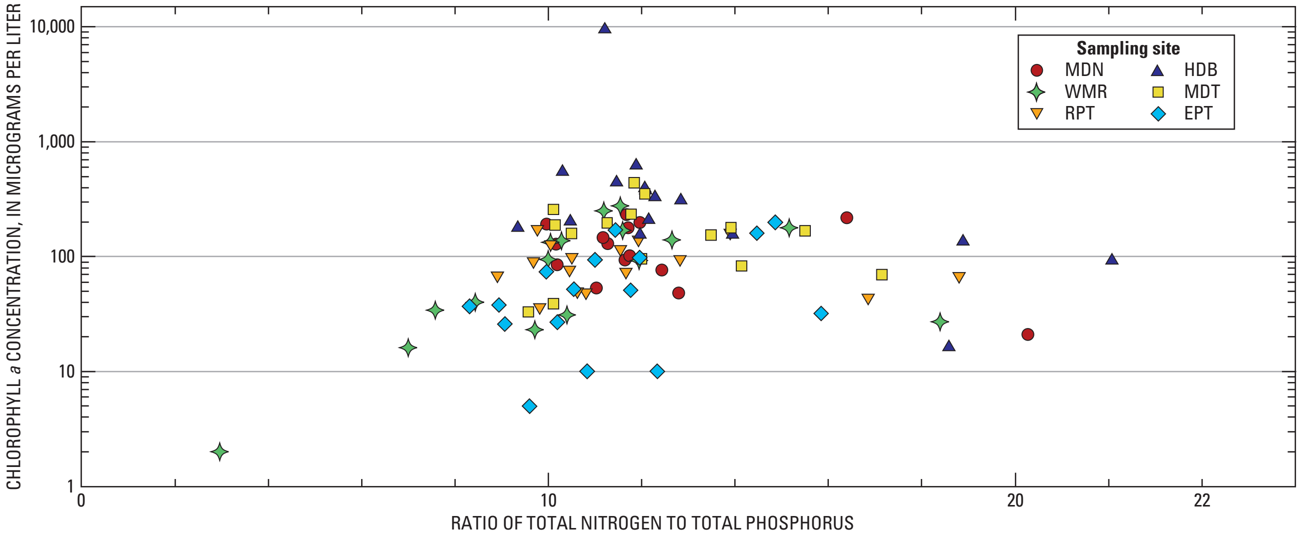


Figure 12. Relation between the ratio of total nitrogen to total phosphorus, and chlorophyll *a* concentrations in water samples collected from Upper Klamath Lake, Oregon, 2006. (Site descriptions are shown in table 1.)

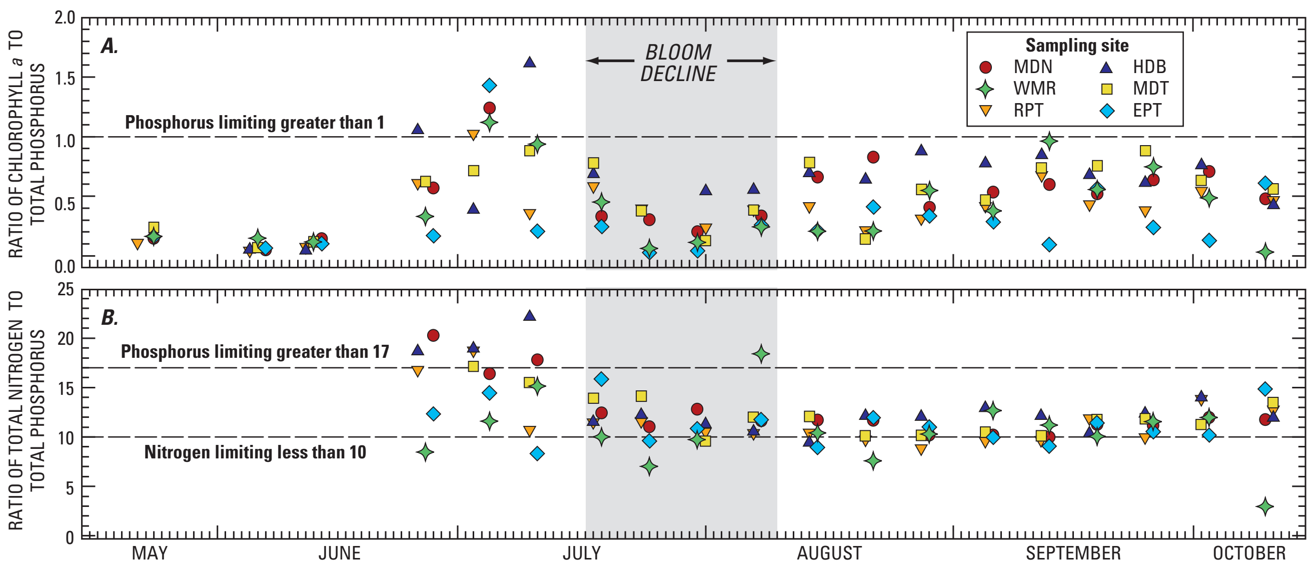


Figure 13. Ratio of chlorophyll *a* to (*A*) total phosphorus concentrations and (*B*) total nitrogen to total phosphorus concentrations in water samples collected from Upper Klamath Lake, Oregon, 2006. (Site descriptions are shown in table 1.)

Spatial Variability in Nutrient and Chlorophyll *a* Concentrations

Lake bathymetry appears to influence dissolved nutrient concentrations. Median concentrations of ammonia and orthophosphate were highest at the deep trench sites MDT and EPT (fig. 14), particularly during the period of bloom decline, when dissolved nutrient concentrations were the highest of the season. Median concentrations of ammonia and orthophosphate were lowest at the shallow site, RPT. The same variation among the sites was seen in 2005 data, indicating a greater degree of mineralization (conversion of organic nitrogen to ammonia) 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 trench with ADCPs in conjunction with sediments containing a large amount of organic matter, which together indicate settling of organic matter at the deep trench sites (Gartner and others, 2007).

Chlorophyll *a*, total nitrogen, and total phosphorus, concentrations were higher at sites HDB and MDT than at the other sites (fig. 14, table 4). The high concentration of chlorophyll *a* and total phosphorus at site HDB may be explained by the relation of the site to the circulation patterns in the open waters of the lake, in which Howard Bay is isolated from the main flow regime.

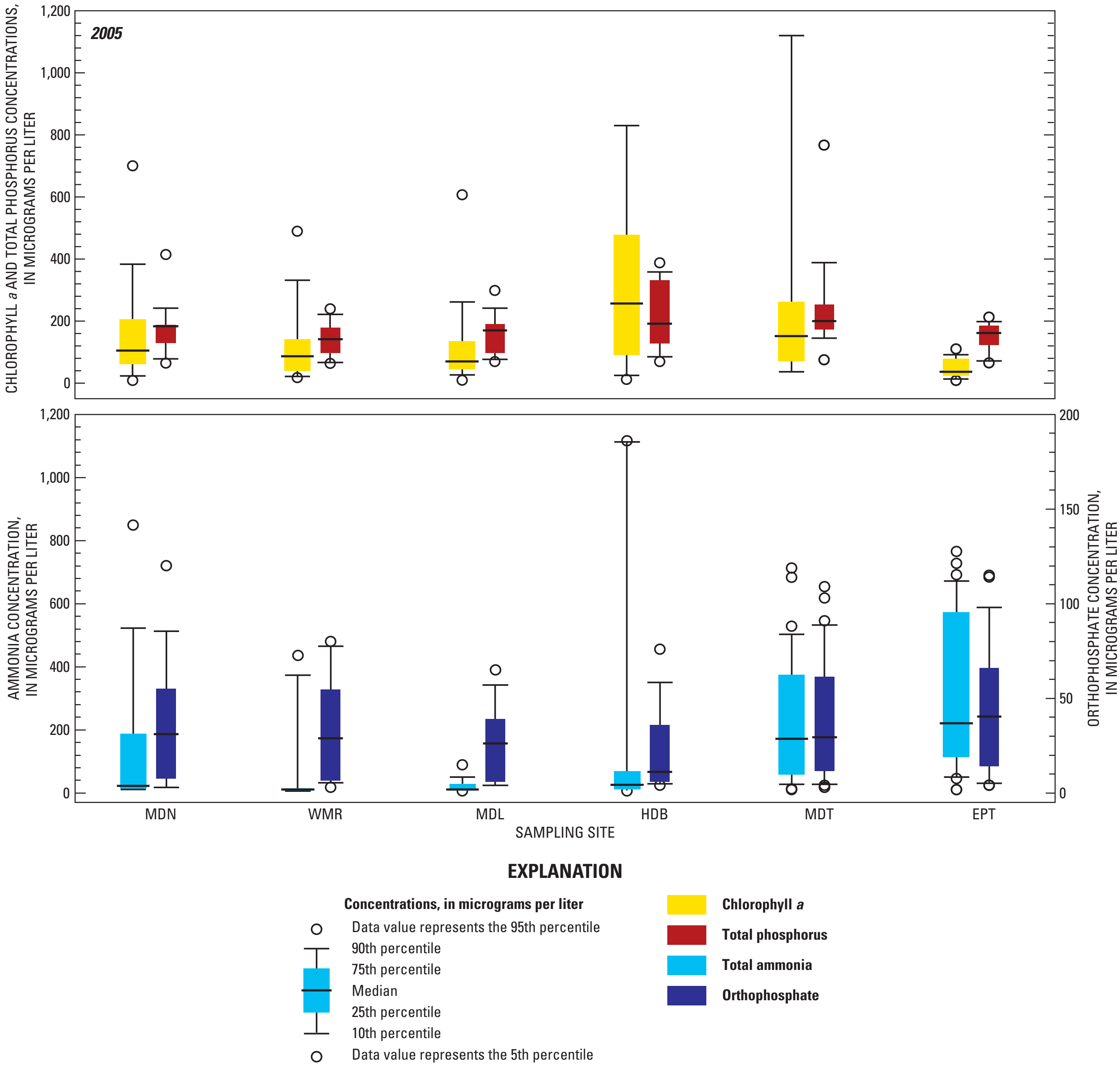


Figure 14. Statistical distribution of chlorophyll *a*, ammonia, orthophosphate, total nitrogen, and total phosphorus concentrations at sites in Upper Klamath Lake, Oregon, 2005 and 2006.

The greater depth of site MDT provides buoyant colonies the opportunity to concentrate at high density near the surface of the water because the water column is more resistant to mixing than at shallow sites. Vertical velocities measured by ADCPs indicated that the movement of the colonies was upward near the surface at MDT (Gartner and others, 2007). The high chlorophyll *a* concentrations in samples collected at site MDT were consistent with observations made by the field crews of thick mats of algae close to the water surface. Additionally, the primary location for companies collecting AFA for commercial production of algal food supplements is near site MDT, indicating that the location provides easy access to the high concentrations of algae near the surface. Furthermore, circulation modeling indicates a clockwise circulation that can capture large algal mats between Eagle Point and Howard Bay (Wood and others, 2008). Particle-tracking studies with the model have shown that water can be trapped in the cell for days.

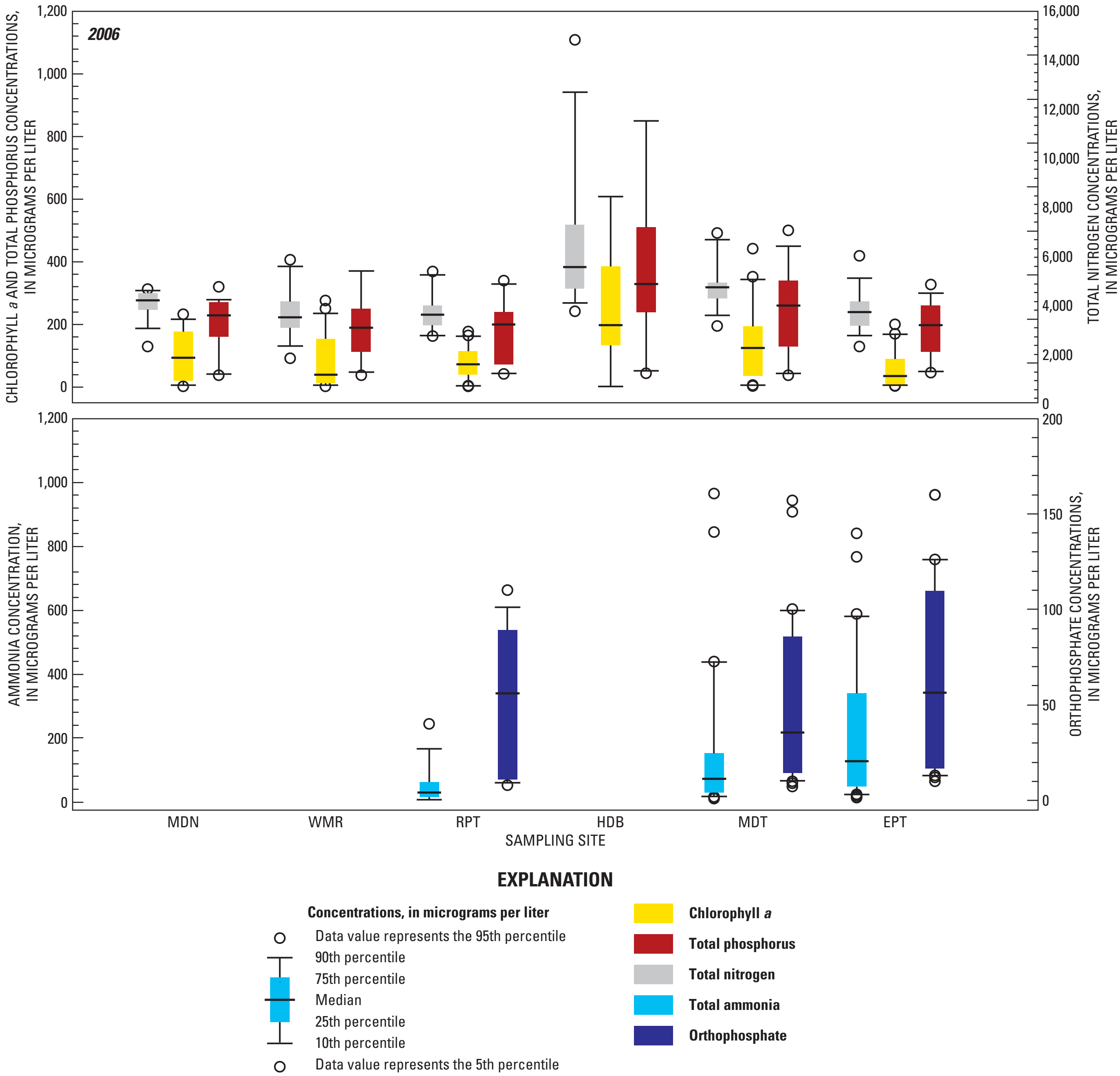


Figure 14. Continued.

Dissolved Oxygen Production and Consumption Experiments

Depth of Photic Zone

A general inverse relation was observed between photic zone depth and chlorophyll *a* concentrations during the light and dark bottle experiments (fig. 15). A Spearman's rank correlation coefficient between chlorophyll *a* concentrations and depth of photic zone resulted in a significant negative correlation for pre- and post-incubation measurements, –0.916 ($p < 0.05$, n=111) and –0.877 ($p < 0.05$, n=110), respectively. The inverse relation between depth of photic zone and chlorophyll *a* was indicative of the effect that blooms of AFA can have on the transmittance of radiation through the water column. The most extensive occurrence of shading by the AFA bloom was at the HDB site on July 24, when high chlorophyll *a* concentrations blocked light to the water column to cause net respiration in light bottles on both racks. Other than this occurrence at site HDB, no other occurrence of a substantial negative production rate was measured from light bottles positioned on the upper rack. During some experiments, production rates from light bottles on the lower rack were negative, indicating that the lower rack was sometimes below the photic zone. The median photic depth of all measurements in 2006 was 1.58 m, 0.08 m deeper than the position of the lower rack in the water column.

Dissolved Oxygen Production and Consumption

The rate of change in dissolved oxygen concentration in light and dark incubation bottles at two levels in the water column are shown as time series in figure 16. Rates obtained from the two light bottles on each rack were averaged to get the net production rate at each depth. Oxygen consumption rates were based on the value from a single dark bottle at each depth. Typically, rates from light bottles were positive, representing net dissolved oxygen production, and rates from dark bottles were negative, representing net dissolved oxygen consumption. The experiments showed that the water column in Upper Klamath Lake was characterized by high rates of both dissolved oxygen production and consumption, with a maximum production rate of 2.79 (mg/L)/h of oxygen recorded at HDB on August 7 and a maximum consumption rate of –2.14 (mg/L)/h of oxygen measured at site HDB on July 24. Outside of site HDB, which was something of an outlier, the maximum consumption rate measured was –0.98 (mg/L)/h of oxygen at site MDN on August 22, and the maximum production rate was 2.77 (mg/L)/h of oxygen at site MDN on July 11. 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 constituted more than 90 percent of the phytoplankton by weight during midsummer (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. AFA likely 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 measured in dark bottles was sometimes positive (fig. 16), suggesting the unlikely occurrence of oxygen production in absence of light. Most positive rates of change in oxygen of dark bottles occurred in the beginning of the sampling season, coincident with low chlorophyll *a* concentrations, when oxygen production due to algae was minimal. The positive change in dissolved oxygen measured in dark bottles was within the precision of the dissolved oxygen meter (± 0.1 mg/L or ± 2 percent of measurement). The minimum and maximum positive change in dissolved oxygen measured in dark bottles was 0.01 and 0.12 mg/L, within the range of error associated with measurements. Another positive rate of change in dissolved oxygen in dark bottles was measured on August 22 at site WMR in the upper and lower racks (0.28 and 0.33 (mg/L)/h of oxygen, respectively). This rate of change was too large to be explained by measurement error of the dissolved oxygen meter. The only plausible explanation for production in a dark bottle would be that light leaked into the bottle.

Excluding the positive oxygen change rates 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 -2.14 (mg/L)/h of oxygen in this study, whereas consumption rates in the 2002 study ranged from -0.05 to -0.49 (mg/L)/h of oxygen. The larger range of consumption rates determined in this study is attributable to annual variability and because experiments in this study spanned 6 months, whereas the 2002 study comprised 2 consecutive days in late July and 2 consecutive days in mid-September.

Rates of oxygen production were determined by the rate of photosynthesis. Rates of net oxygen production were most variable at site HDB and least variable at site EPT. Net production rates measured on the top rack (at 0.5 m depth) generally increased in late June and decreased in late July and early August at most sites. At sites WMR and EPT, oxygen production decreased to rates measured during pre-bloom conditions. The decreased net oxygen production rates at the 0.5 m rack is consistent with a decrease in chlorophyll *a* concentrations measured during the same time. At four sites, MDN, WMR, RPT, and EPT, the net oxygen production rate was correlated positively and significantly with chlorophyll *a* concentration. The Spearman's rank correlation coefficient between oxygen production rates and chlorophyll *a* concentrations at sites MDN, WMR, RPT, and EPT was 0.549, 0.900, 0.672, and 0.852, respectively ($p < 0.05$, n=18, 19, 19, and 19, respectively) (fig. 17). However, there was no significant correlation between the two variables at sites HDB and MDT, possibly because at chlorophyll *a* concentrations greater than about 300 µg/L, self-shading can limit the transmittance of light through the water column. Thick mats of algae have been observed in the areas of sites HDB and MDT (fig. 18). The most extreme case of water column shading was seen at site HDB on July 24, 2006, where high respiration rates were measured in dark and light bottles on both racks, indicating negligible photosynthetic production of oxygen even 0.5 m below the surface.

The potential change in dissolved oxygen over a 24-hour period was calculated from oxygen production and consumption rates measured in light and dark bottles. The relation of chlorophyll *a* concentration to 24-hour change in dissolved oxygen varied among sites (fig. 19). The 24-hour change in dissolved oxygen at sites in the trench, sites MDT and EPT, was negatively correlated with chlorophyll *a* concentration, indicating that as chlorophyll *a* concentrations increased, oxygen consumption increased. Oxygen-consuming processes dominated at the trench sites because most of the water column is below the photic zone. Most of the 24-hour changes in dissolved oxygen calculated for sites MDT and EPT were negative, indicating that oxygen consumption processes predominated in the deeper trench areas. In contrast, 24-hour change in dissolved oxygen was positively correlated and predominantly positive at sites WMR, RPT, and HDB, indicating that oxygen production processes were dominant at the shallow sites.

Site MDN was more variable in the amount of oxygen consumption or production in a 24-hour period, and no significant correlation was determined between chlorophyll *a* concentration and 24-hour change in dissolved oxygen. The water at site MDN is not as shallow as at sites WMR, RPT, and HDB, but not as deep as at sites MDT and EPT; therefore, both oxygen production and consumption processes are equally probable.

During the period of bloom decline, the 24-h change in dissolved oxygen concentrations decreased in magnitude at every site except HDB (fig. 20), indicating that this period was characterized by lower production and lower consumption at those sites. This also was evident in the light and dark bottle incubations (fig. 16). Because this period also was characterized by decreasing dissolved oxygen concentrations (fig. 21), the reduced water-column oxygen demand suggests that much of the oxygen consumption was taking place at the sediment-water interface in the form of sediment oxygen demand (SOD). SOD was measured in Upper Klamath and Agency Lakes in spring (May 18–May 27) and late summer (August 24–September 1) 1999 (Wood, 2001). The potential 24-hour reduction in dissolved oxygen obtained from the measurements at nine sites around Upper Klamath Lake ranged from 0.2 to 0.6 mg/L in spring, and from 0.4 to 1.3 mg/L in late summer (excluding one uncertain value of greater than 3.7 mg/L in Ball Bay). At these rates, processes at the sediment-water interface would be secondary to water-column processes (fig. 20) during most of June through October; during a bloom decline, however, photosynthetic production of oxygen is so diminished that this magnitude of SOD is more important in the oxygen mass balance than during periods of bloom growth.

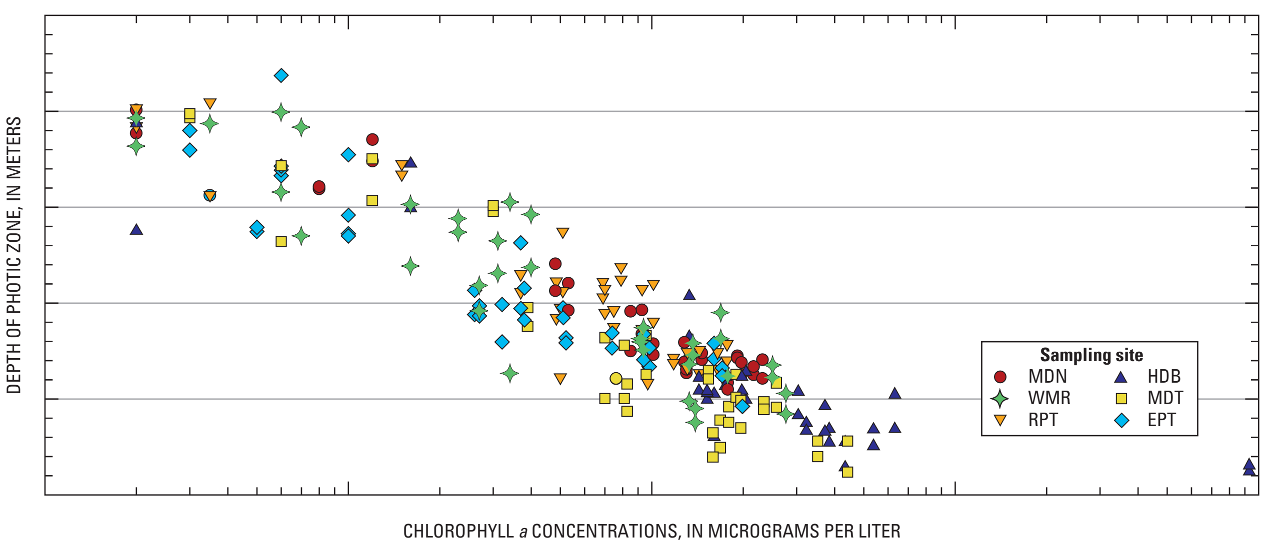


Figure 15. Relation of depth of photic zone to chlorophyll *a* concentration at sites in Upper Klamath Lake, Oregon, 2006. (Site descriptions are shown in table 1.)

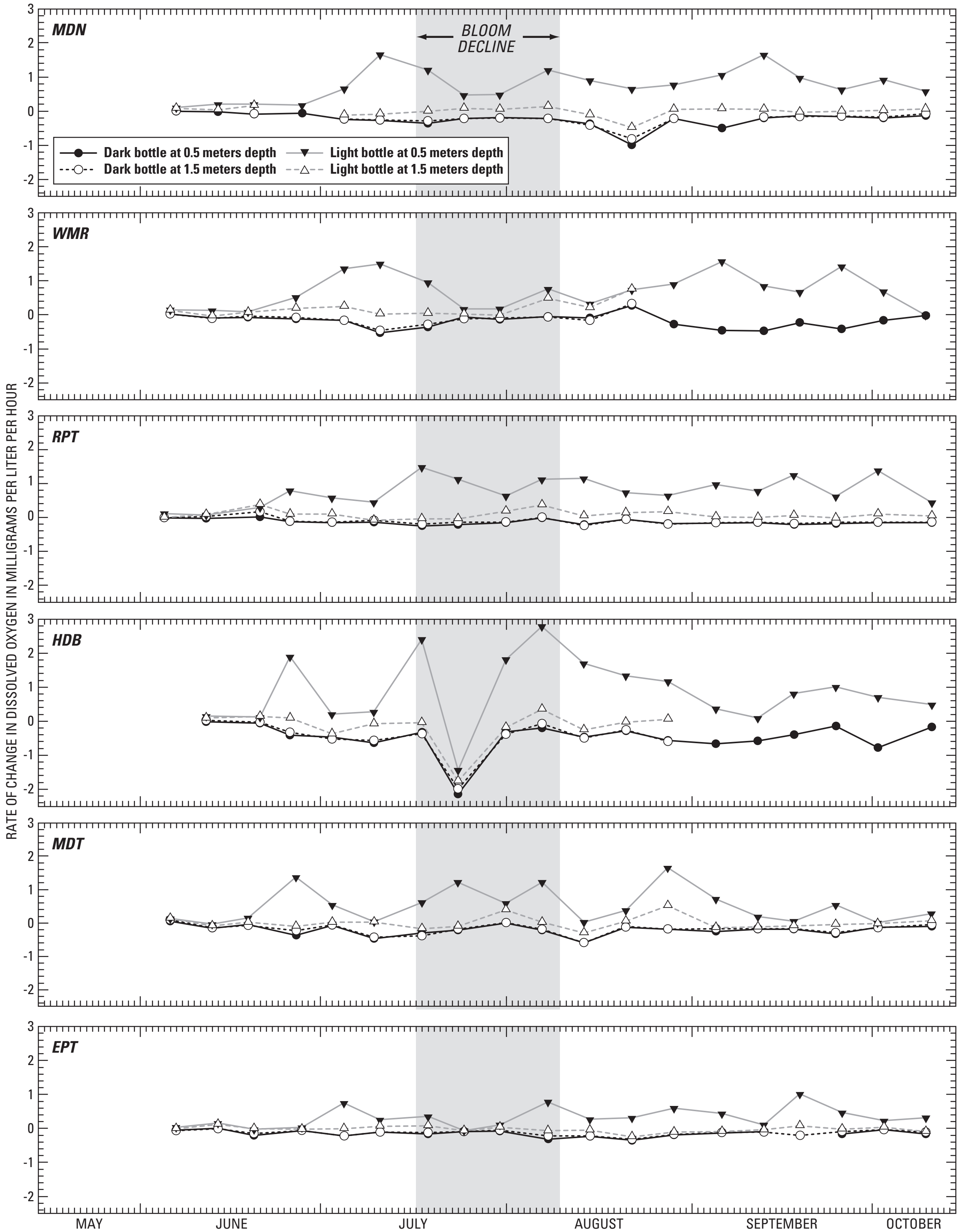


Figure 16. Rate of change in dissolved oxygen concentration measured from light and dark bottle incubation experiments at sites in Upper Klamath Lake, Oregon, 2006. (Site descriptions are shown in table 1.)

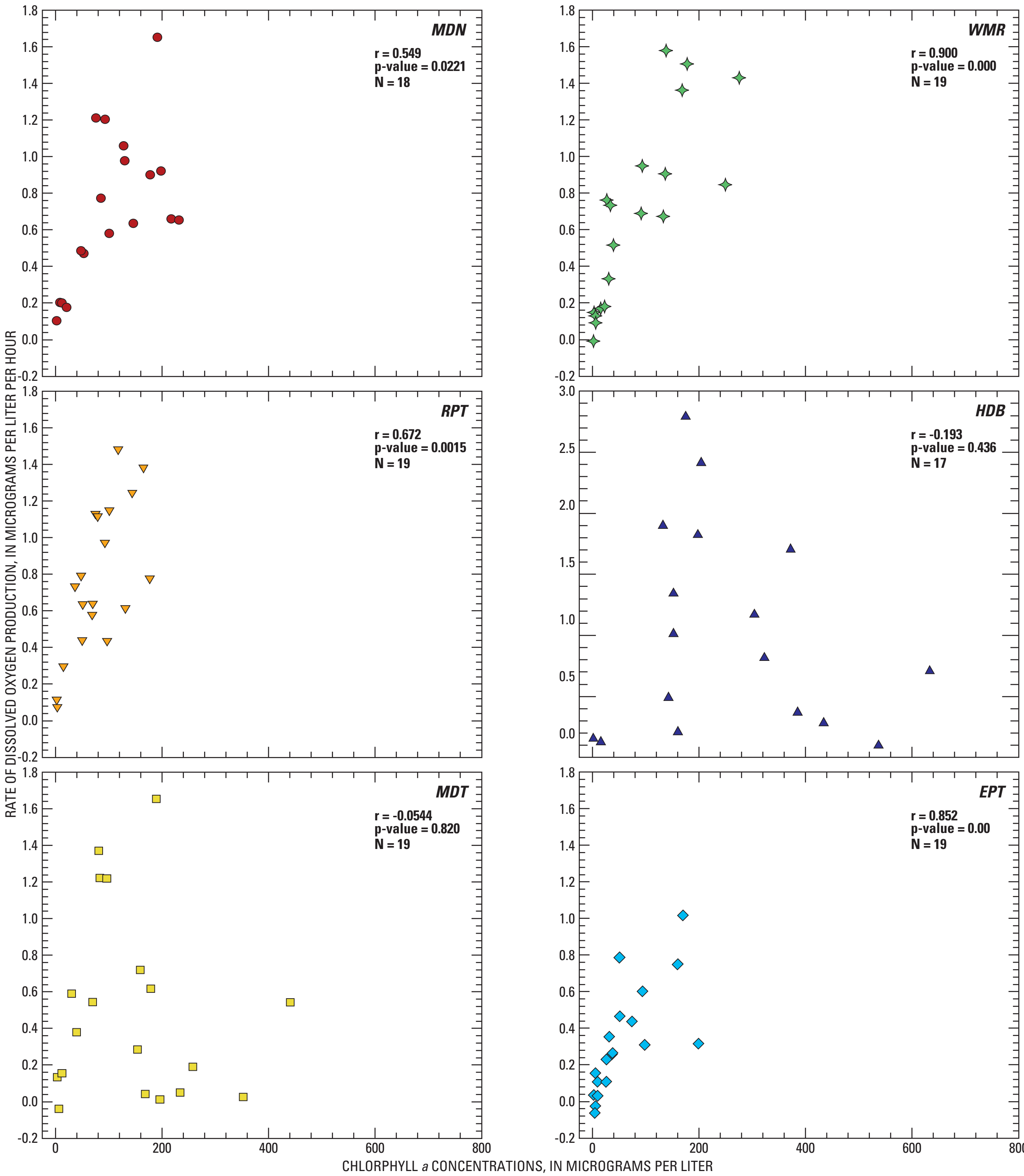


Figure 17. Net rates of dissolved oxygen production and chlorophyll *a* concentrations, Upper Klamath Lake, Oregon, 2006. (Spearman's rank correlation coefficients (r), p-values, and number of measurements are shown for each site. Site descriptions are shown in table 1. Note that y-axis scales vary.)

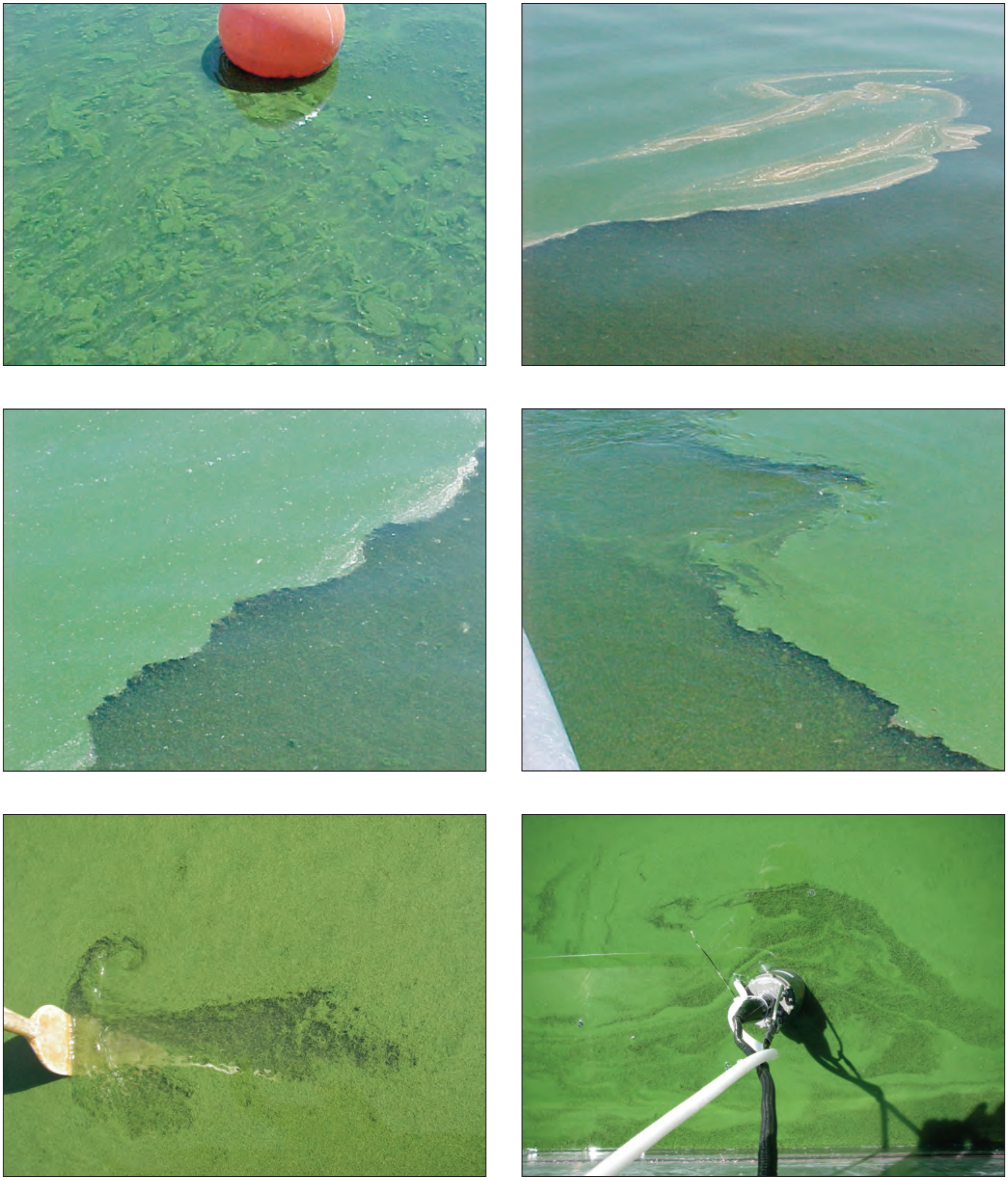


Figure 18. Clumping and mat formation of *Aphanizomenon flos-aquae* (AFA) at the surface showing the potential for self-shading of AFA below the surface, Upper Klamath Lake, Oregon, 2006. (Top left image shows clumping formed a mat of AFA on the surface at site MDT on August 14, 2006. Top right, middle left and middle right images show the defined border of the mat of AFA at site MDT on August 14, 2006. Bottom images show the mat disturbed by a paddle or a water quality monitor at site MDT on September 8, 2007, and July 14, 2007, respectively. [Photographs taken by field personnel, U.S. Geological Survey.])

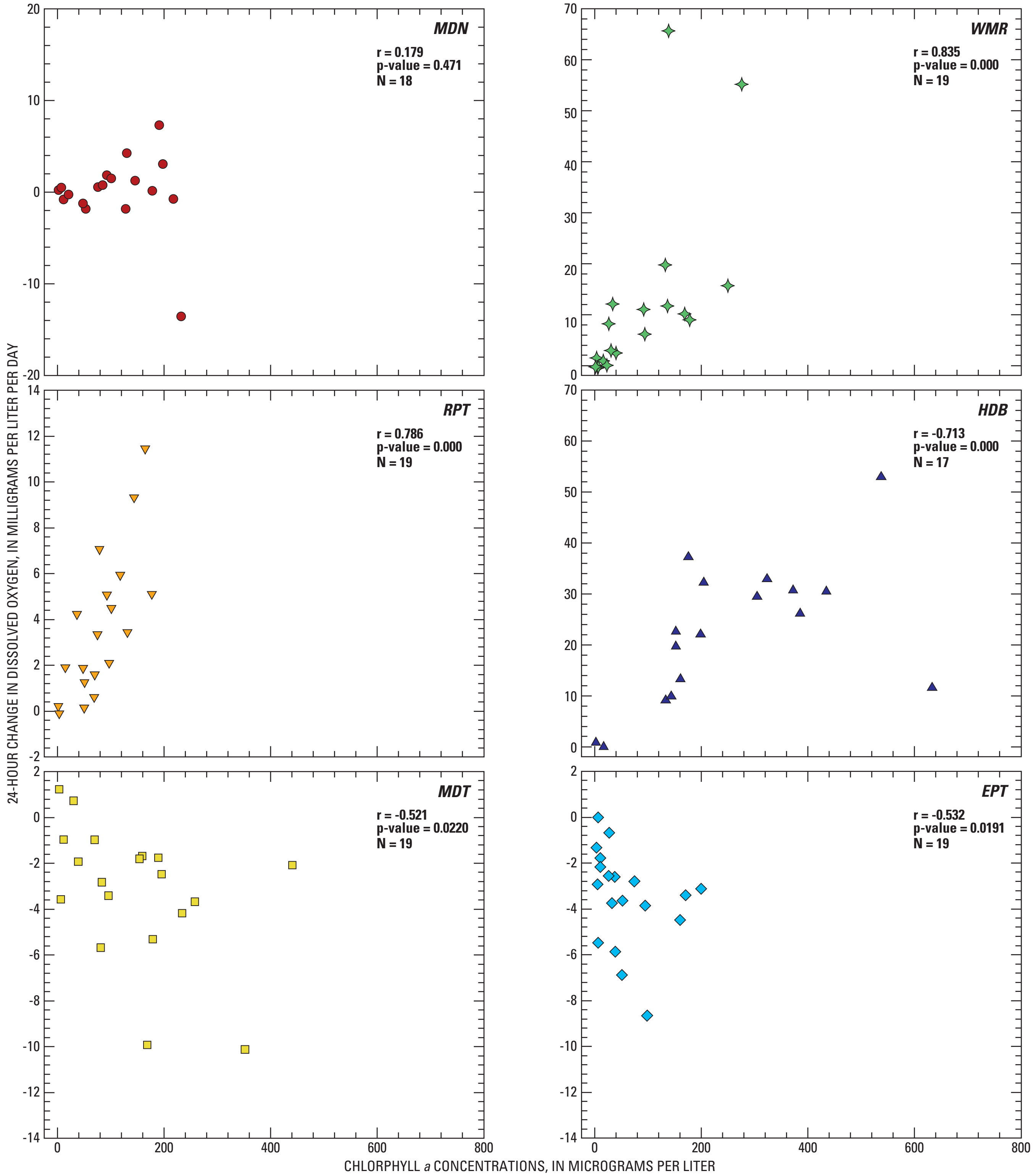


Figure 19. Chlorophyll *a* concentrations and 24-hour change in dissolved oxygen Upper Klamath Lake, Oregon, 2006. (Spearman's rank correlation coefficients (r) and p-values shown for each site. Site descriptions are shown in table 1. Note that y-axis scales vary.)

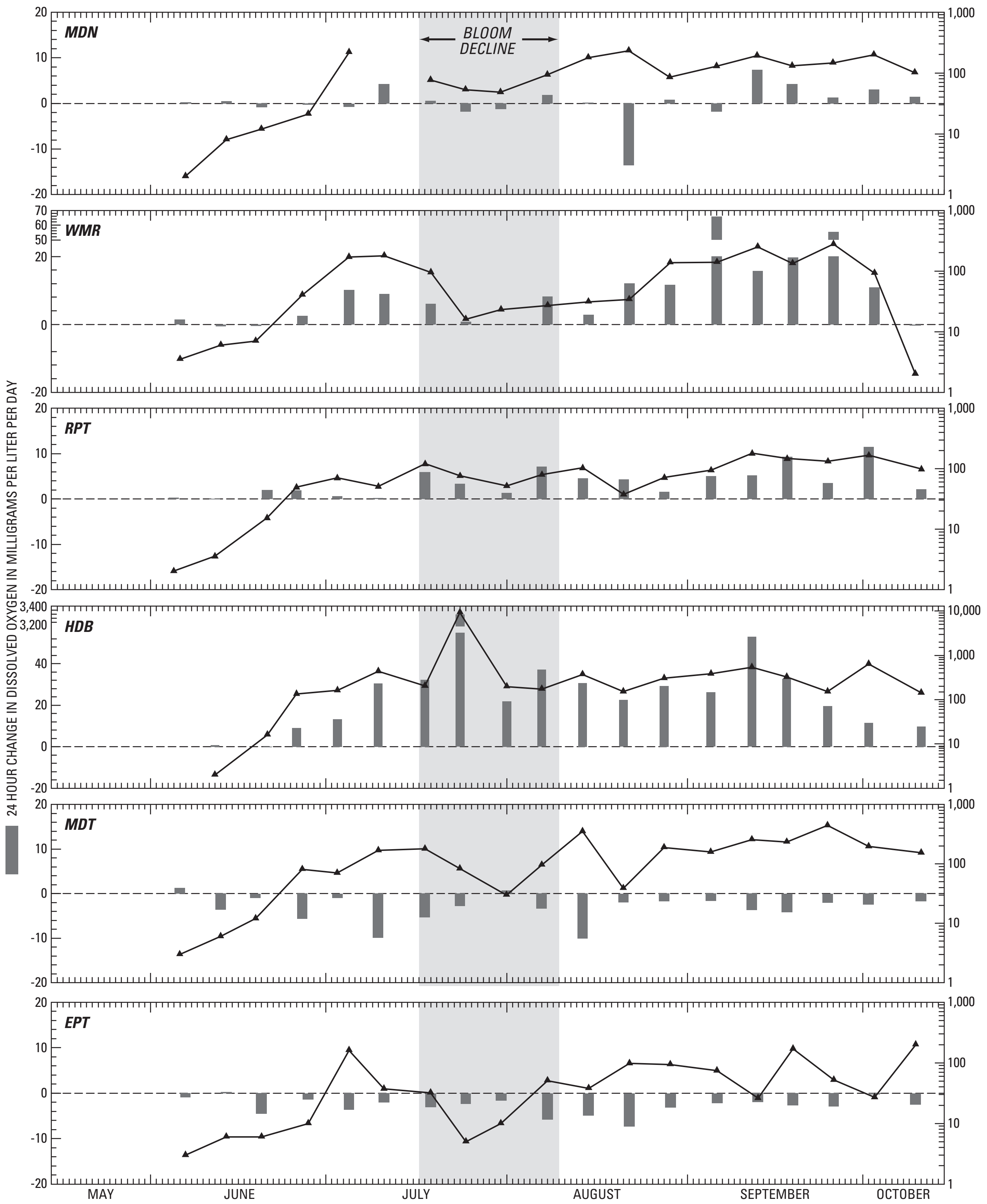


Figure 20. Time series of 24-hour change in dissolved oxygen and chlorophyll *a* concentrations, Upper Klamath Lake, Oregon, 2006. (Site descriptions are shown in table 1. Note that y-axis scales vary.)

Water Quality Monitors

Agency Lake and Upper Klamath Lake Daily Water Quality Conditions

2006 Conditions

Data from all continuous water quality monitoring sites in the open-water areas of Upper Klamath Lake were combined to calculate lakewide daily medians for dissolved oxygen concentration, dissolved oxygen percent saturation, temperature, pH, and specific conductance (fig. 21). Unseasonably warm and sunny conditions in mid-May resulted in an early start to the AFA bloom. This early season bloom was visually confirmed at water quality monitoring sites in Upper Klamath Lake. Also, researchers conducting larval sucker drift sampling at the southern end of the lake noticed large amounts of AFA in their sampling equipment in late May, but relatively small amounts of AFA in early June (Corene Luton, U.S. Geological Survey, oral commun., 2006). Local maximums in daily median dissolved oxygen concentrations and pH coincided with these observations.

After the early season bloom, dissolved oxygen concentrations were constant through June as water temperatures increased, resulting in a slow, steady increase of dissolved oxygen percent saturation. Through June, pH also increased, leveling off in mid-July. Toward late July, dissolved oxygen and pH decreased with the decline of the bloom as water temperatures approached seasonal highs. Seasonal low dissolved oxygen concentrations in Upper Klamath Lake were coincident with seasonal high temperatures but recovered to predecline levels in August as water temperatures cooled. Because the 100 percent saturation concentration of dissolved oxygen decreases as temperature increases, some variation with temperature in the concentration of dissolved oxygen is expected even if the percent saturation remains nearly constant. In Upper Klamath Lake, however, the percent saturation varies with the concentration, and the large magnitude of fluctuations in percent saturation indicates that important sources and sinks of dissolved oxygen are responsible, rather than a simple change in gas solubility with temperature. The seasonal high in temperature and low in dissolved oxygen conditions near the end of July were coincident with a period of low chlorophyll *a* concentrations at most sampling sites in the lake (fig. 10) that marked a temporary decline in bloom conditions. The decreased dissolved oxygen concentrations during this period resulted from increased oxygen demand from cell senescence and a reduction in the photosynthetic production of oxygen. A midseason minimum in lakewide median pH conditions occurred on August 1, 4 days after the seasonal minimum in lakewide dissolved oxygen concentrations. A slight peak in lakewide median specific conductance also was measured at this time, but after a small decrease, specific conductance continued to increase through mid-August before leveling off for the rest of the season.

Time series of daily median water quality conditions at the two sites in Agency Lake are shown in figure 22. Water temperatures in Agency Lake closely paralleled those in Upper Klamath Lake, and the fluctuations in both lakes followed patterns in air temperature (figs. 7, 21, and 22), as expected in these relatively shallow lakes. Dissolved oxygen concentrations and pH peaked in mid-June in Agency Lake, whereas these conditions reached their peak almost a month later in Upper Klamath Lake. Seasonal low dissolved oxygen concentrations occurred in late July at both Agency Lake sites, but this decrease began earlier at site AGN. As in Upper Klamath Lake, seasonal high temperatures in Agency Lake coincided with seasonal low dissolved oxygen concentrations. The timing of these seasonal extremes was almost coincident between the two lakes; however, the lowest daily median dissolved oxygen concentrations (4.60 mg/L at site AGN on July 15 and 4.53 mg/L at site AGS on July 24) corresponded to a percent saturation of 62.83 percent at site AGN and 63.95 percent at site AGS. The lowest lakewide daily median dissolved oxygen concentration (4.21 mg/L on July 28) in Upper Klamath Lake corresponded to a percent saturation of 58.67 percent. Unlike Upper Klamath Lake, daily median pH and dissolved oxygen in Agency Lake did not recover to predecline levels after late July. These differences also were noted in the 2005 data (Hoilman and others, 2008), and are consistent with the lack of a late season AFA bloom in Agency Lake.

Comparison to 2005 Conditions

Time series graphs of Upper Klamath Lake daily median water quality conditions in figure 23 compare water quality conditions in 2006 to those in 2005. Only data from sites monitoring similar areas of the lake between the 2 years—FBS, WMR, MRM (MPT in 2005), RPT, HDB, EHB, and NBI; as well as the upper and lower monitoring sites at MDN, EPT, and MDT—were included in calculating these lakewide daily medians.

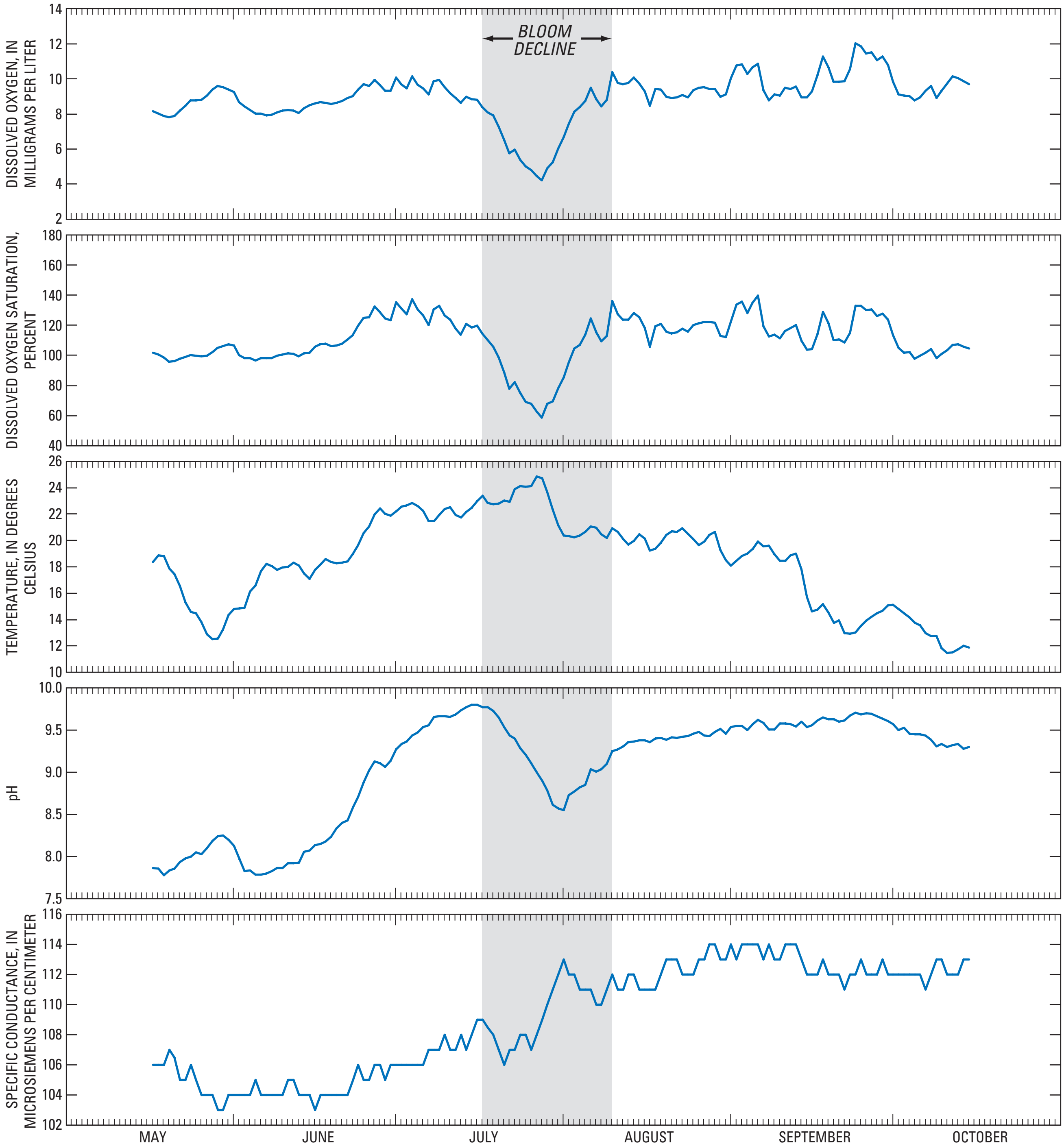


Figure 21. Lakewide daily median dissolved oxygen concentration, dissolved oxygen percent saturation, temperature, pH, and specific conductance, Upper Klamath Lake, Oregon, 2006.

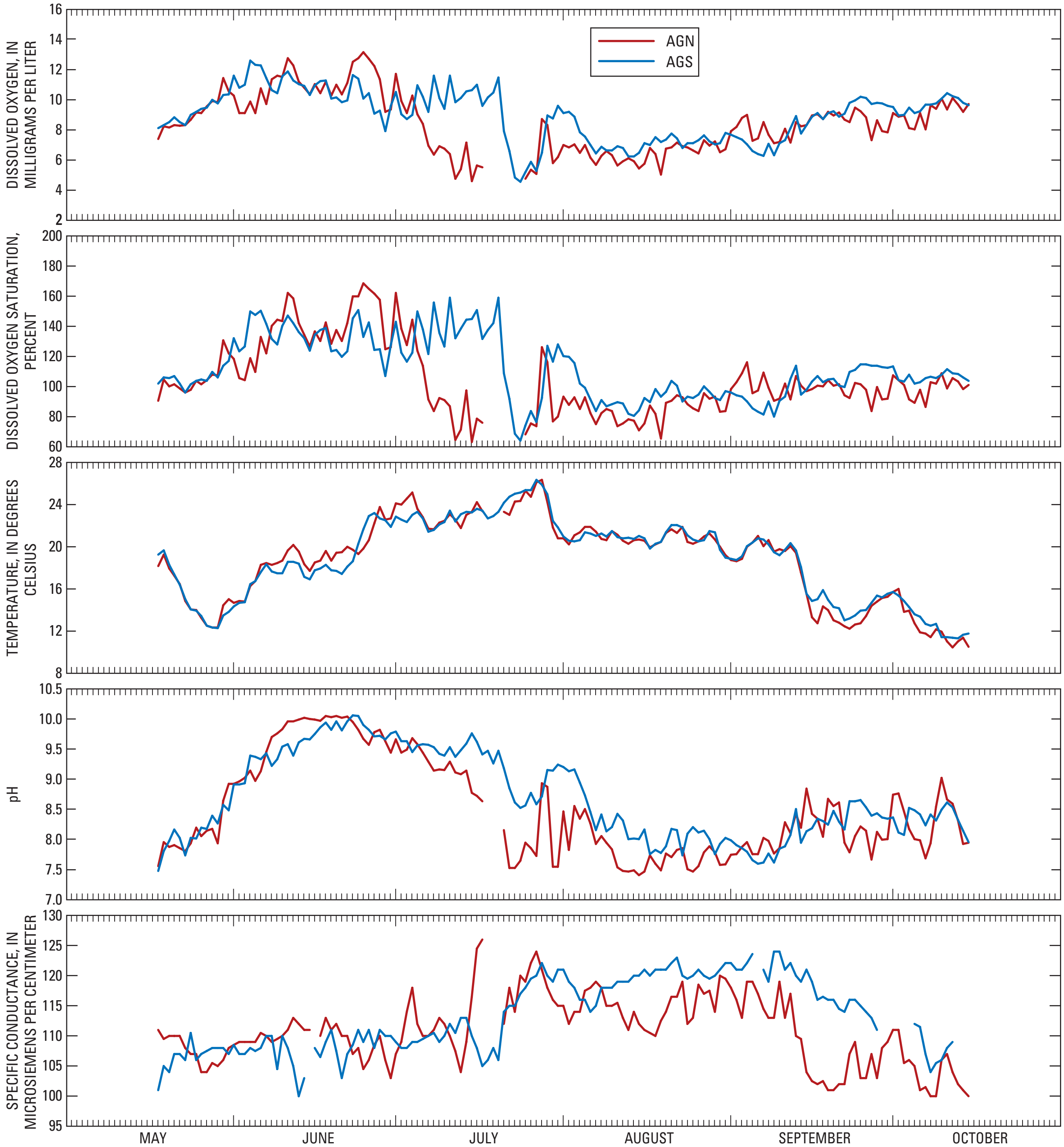


Figure 22. Daily median dissolved oxygen concentration, dissolved oxygen percent saturation, temperature, pH, and specific conductance, Agency Lake, Oregon, 2006.

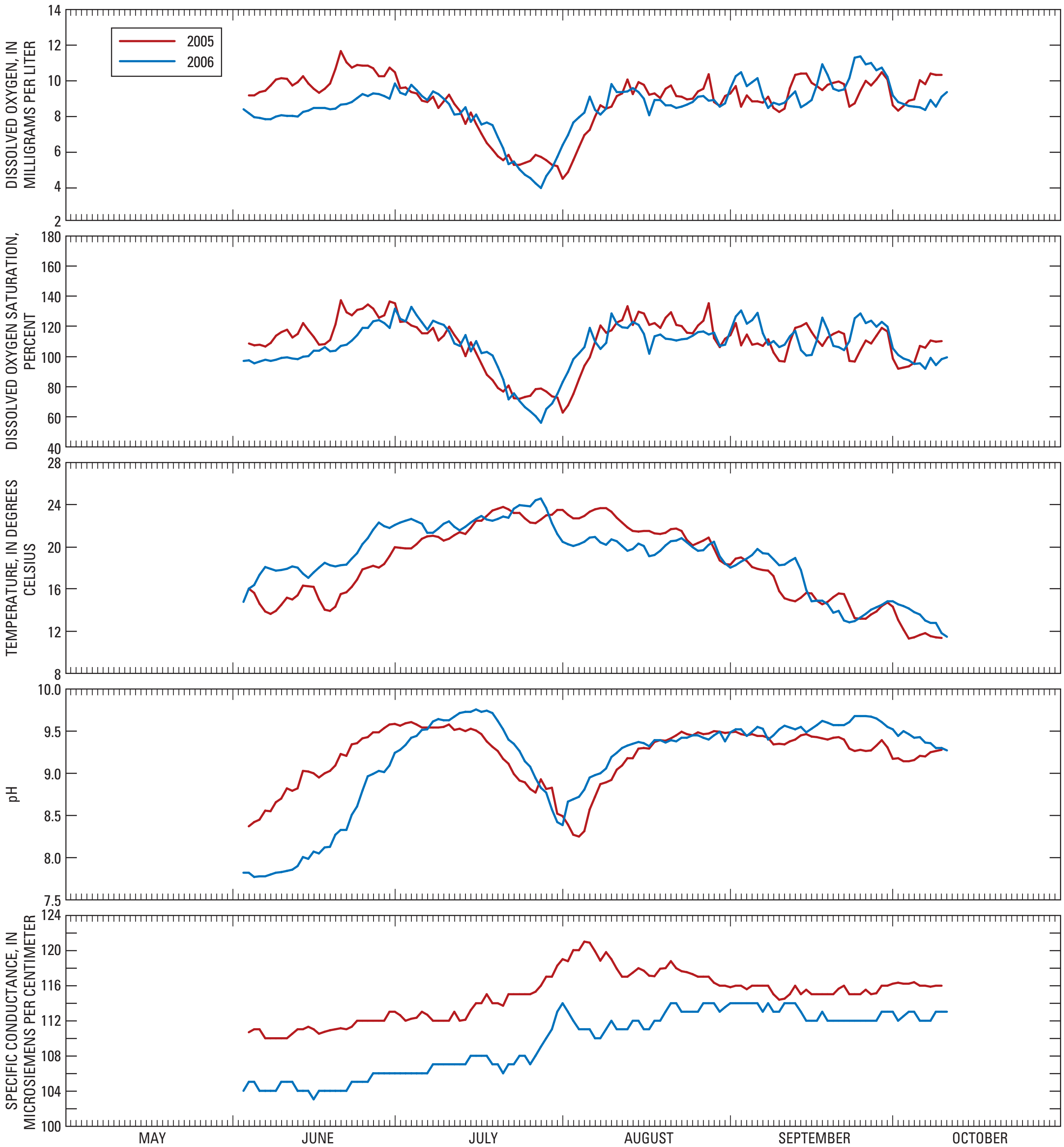


Figure 23. Lakewide daily median dissolved oxygen concentration, dissolved oxygen percent saturation, temperature, pH, and specific conductance in Upper Klamath Lake, Oregon, 2005 and 2006.

Seasonal patterns in lakewide water quality dynamics were similar between the 2 years. The period with the lowest dissolved oxygen concentrations was late July during both years, and these conditions coincided with the highest lakewide average water temperatures during each year. In both years, a midseason minimum in pH occurred 3 to 4 days after the midseason minimum in dissolved oxygen. In 2005, the midseason minimum in pH corresponded with a maximum in specific conductance, although this correspondence between pH and specific conductance was not evident in 2006. Even with these similarities, notable differences in water quality conditions existed between the 2 years. Maximum lakewide temperatures were higher and minimum lakewide dissolved oxygen concentrations were lower in 2006. In addition, lakewide pH was higher before and after the bloom decline in 2006. Specific conductance was lower than in 2005 throughout most of 2006, partly because inflows were higher in spring 2006, and outflows at Link River were higher through June 2006 than during 2005 (Wood and others, 2008). Residence time and therefore concentration through evaporation was less in 2006 than in 2005, at least through the month of June.

In both years, the relation between daily median dissolved oxygen saturation and daily median temperature was different during the period of bloom decline than during the rest of the season (fig. 24). For purposes of this discussion, the period of bloom decline is defined in terms of dissolved oxygen saturation. In 2005 and 2006, the bloom began when the lakewide daily median of dissolved oxygen saturation decreased to less than 100 percent in July and ended when the lakewide daily median of dissolved oxygen saturation increased to greater than 100 percent in August. Spearman's rank correlation coefficient analyses of dissolved oxygen and temperature were done separately for data collected during the bloom decline and the rest of the season for both years. In both years, a significant ($p < 0.0001$) positive relation was noted between dissolved oxygen and temperature outside the period of bloom decline. During the 2005 period of bloom decline, no significant relation was observed and a strong inverse relation ($r = -0.815$) was observed in 2006. The lack of a significant relation in 2005 between temperature and dissolved oxygen during the bloom decline may have been partly due to the relatively narrow range of temperature measured in 2005 (a 2 degree range in 2005 in contrast to a 6 degree range in 2006).

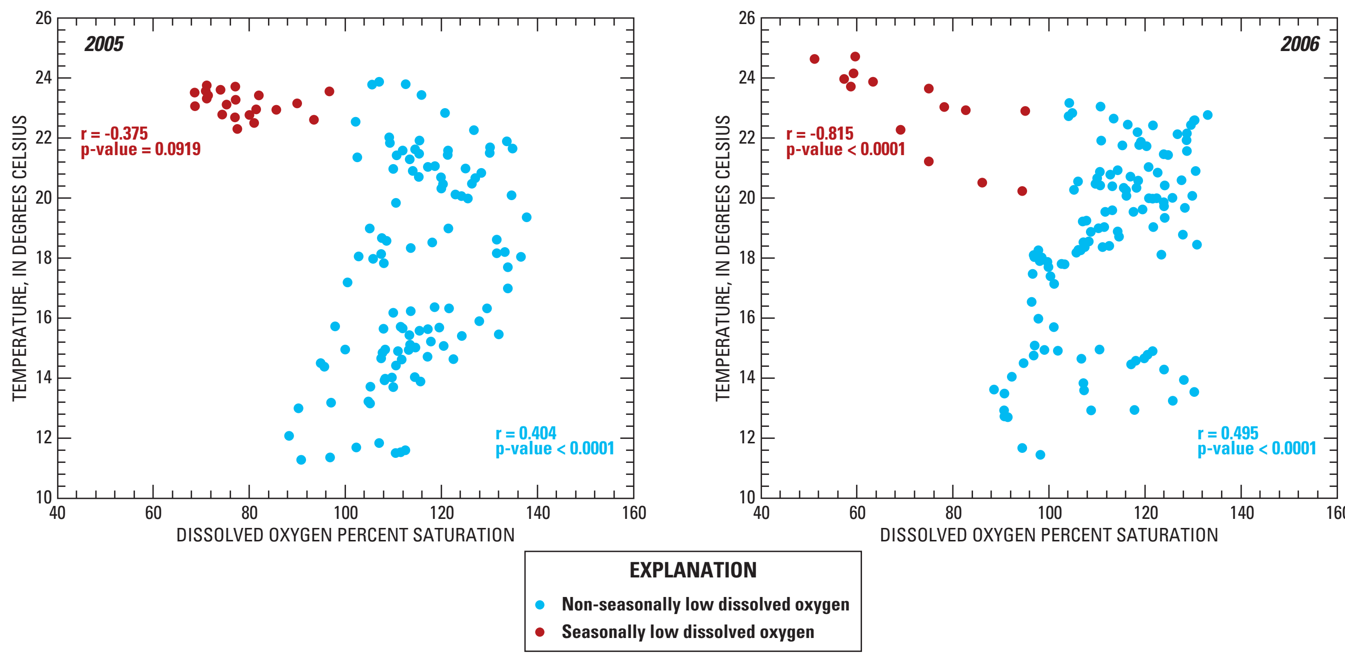


Figure 24. Relation of lakewide daily median dissolved oxygen percent saturation to temperature, Upper Klamath Lake, Oregon, 2005 and 2006. (Correlation coefficients (r) and p-values during the period of bloom decline are shown in red. Correlation coefficients (r) and p-values outside of this period are shown in blue.)

In both years, dissolved oxygen saturation peaked at well over 100 percent saturation (nearly 140 percent in 2005 and about 130 percent in 2006), but the peak occurred at water temperatures well below the seasonal maximum (between about 16 and 22°C in 2005 and between about 18 and 23°C in 2006; fig. 24). In 2006, late season blooms characterized by greater than 130 percent saturation coincided with water temperatures between 13 and 15°C. In contrast, the highest water temperatures of the season in both years coincided with the lowest dissolved oxygen saturation values (about 70 percent in 2005 and about 50 percent in 2006). This relation between dissolved oxygen and temperature was noted in earlier years, particularly 2003 (Wood and others, 2006). In contrast to the observations for Upper Klamath Lake, other studies have shown that the optimum temperature for AFA can be as high as 29°C (Tsujimura and others, 2001). The fact that the highest temperatures are associated with bloom declines in Upper Klamath Lake is an indication that the effect of temperature on metabolic processes is secondary to other undetermined factors that precipitate a bloom decline.

Nearshore Water Quality Monitors

Prior to 2006, some water quality monitoring was done in the nearshore areas of the lake in support of juvenile sucker sampling, but no long-term records were obtained for an entire season that could be compared to the records from monitors in open-water. The five nearshore continuous water quality monitoring sites operated in 2006 (fig. 2) provided continuous records of water quality and were maintained identically to the open-water sites. This continuous monitoring of nearshore sites enables a comparison of water quality variables and their dynamics between the open-water and nearshore areas of Upper Klamath Lake. Nearshore site selection was largely based on consideration of areas known to be occupied by juvenile suckers.

The comparisons generally showed some differences between open-water and nearshore water quality dynamics, but these differences were largely due to the influence that data from monitors positioned in the lower part of the water column at deep sites had on the composite data set from open-water monitors. When data from the monitors positioned at the deep sites were removed, differences were not as great between open-water and nearshore areas. This is not surprising, given the differences in water quality dynamics between deep waters and shallow waters in Upper Klamath Lake (Wood and others, 2006; Hoilman and others, 2008). Because most of Upper Klamath Lake consists of shallow waters outside of the trench, comparisons of these areas of the open-water were made to nearshore water quality dynamics. These comparisons provided the most relevant answers to questions of similarity between open-water and nearshore areas of Upper Klamath Lake.

Water quality data for the nearshore monitors were combined in the same manner as open-water data to create graphs of daily median water quality conditions (fig. 25). Daily median temperature was higher in nearshore areas for most of the field season, whereas pH was generally lower or the same as open-water conditions. Seasonal patterns of, and relations between, dissolved oxygen, temperature, and pH in the open-water also were observed in nearshore water quality dynamics. Spearman's rank correlation coefficients (table 5) supported these observations.

Table 5. Spearman's rank correlation coefficients between daily average values of water quality conditions in nearshore and open-water areas of Upper Klamath Lake, Oregon, 2006.

[Data do not include sites in the trench. All coefficient values are significant ($p < 0.0001$). Abbreviations: ºC, degrees Celsius; µS/cm, microsiemens per centimeter]

Parameter	*rho*
Dissolved oxygen (percent saturation)	0.875
Temperature, in ºC	0.989
pH	0.885
Specific conductance, in µS/cm	0.798

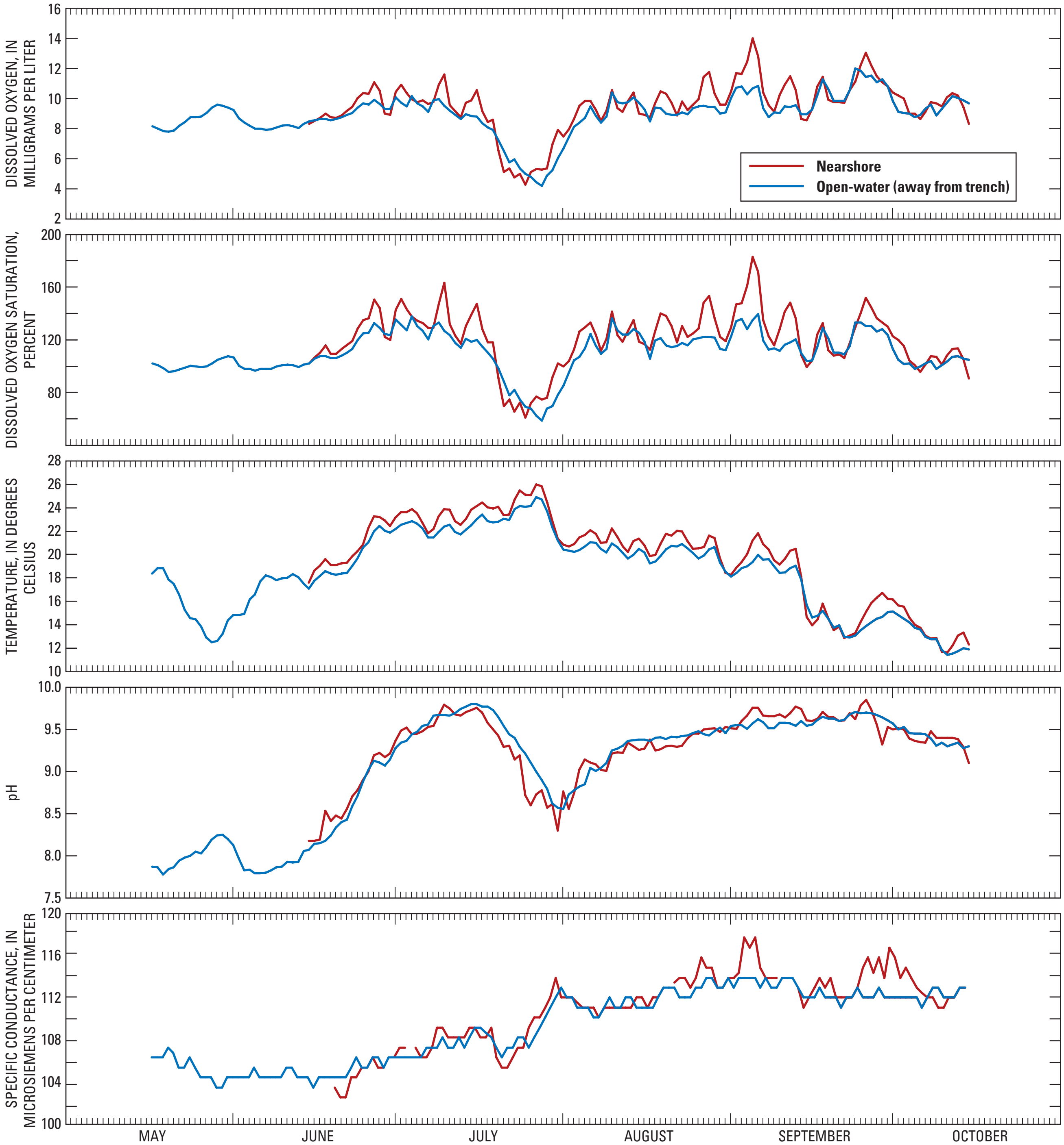


Figure 25. Time series of daily median water quality conditions in nearshore and open-water areas away from the trench, Upper Klamath Lake, Oregon, 2006.

Occurrence and Duration of Water Quality Conditions Potentially Harmful to Fish

Through their studies in Upper Klamath Lake, fish biologists have formed the hypothesis that poor water quality may not be the sole factor causing fish kills in Upper Klamath Lake, it is a compounding factor in which fish are stressed to the point that diseases may gain a foothold in the population. Perkins and others (2000), suggested that even though infection may be the clinical cause of death, poor water quality should be considered as the primary cause of death. With this hypothesis in mind, different potentially stressful water quality scenarios were investigated to gain a broader understanding of the different ways water quality conditions may cause harm to fish in the study area.

Potentially Harmful Water Quality Conditions in Open-Water Areas

To identify potentially harmful low dissolved oxygen and high pH conditions in the study area, the hours when dissolved oxygen concentration was less than 4 mg/L, temperature was greater than 28 ºC, or pH was greater than 9.7 were enumerated at each site. These values were based on high stress thresholds for Upper Klamath Lake suckers (Loftus, 2001). Instances meeting a higher tier of potentially harmful conditions (dissolved oxygen concentration less than 2 mg/L and pH greater than 10; no higher tier for temperature) also were investigated. These higher tiers for dissolved oxygen concentration and pH were based on 96-hour median lethal values for Lost River juvenile suckers (Saiki and others, 1999). Together, these two tiers of dissolved oxygen, pH, and temperature conditions indicated when conditions may have been severe enough to cause stress and when conditions were potentially lethal.

Time series graphs ("bubble plots") of these conditions are shown in figure 26 for representative near-bottom monitors (positioned 1 m from the lake bottom) in deep and shallow areas, as well as surface monitors (positioned above deep monitors at 1 m below the surface), in the open-waters of Upper Klamath Lake. Graphs for the two Agency Lake sites are shown in figure 27. Each instance when conditions exceeded the criterion appears as a "bubble" on the graph, centered on the midpoint of the time span of the event. The duration of the event is represented by the size of the bubble. Temperatures exceeded 28ºC only at the MDT-Upper site for 2 hours or less on 4 individual days in late July, so a plot of potentially harmful temperature conditions for open-water sites is not shown.

Occurrences of potentially harmful pH and dissolved oxygen conditions were markedly different between deep sites and shallow sites in Upper Klamath Lake. Potentially harmful pH conditions were more likely to occur in shallower water, whereas potentially harmful low dissolved oxygen concentrations were more likely to occur in deeper water (fig. 26). Monitors at the shallow sites commonly recorded periods of pH greater than 9.7 over multiple days before the AFA bloom decline in late July and for much of the season thereafter. The process of photosynthesis elevated the pH at these sites by consuming carbon dioxide (CO_2) and reducing the concentration of carbonic acid in the water (Wetzel, 2001). However, few potentially harmful dissolved oxygen concentrations were recorded at these sites at any time during the field season, 2006. Conditions at the relatively shallow Agency Lake sites followed this trend, with more frequent occurrences of pH greater than 10 (fig. 27). However, potentially harmful pH conditions were not present in Agency Lake after the bloom recovered in late July, corresponding to the lack of a vigorous bloom later in the season.

The near-bottom monitors at the deep sites recorded instances of low dissolved oxygen concentrations exceeding the less than 2 and 4 mg/L criteria of potentially harmful conditions over multiple days during the period of seasonally low lakewide median dissolved oxygen. Occurrences of potentially harmful low dissolved oxygen continued at these sites even after lakewide average dissolved oxygen had recovered from seasonal lows in the rest of the lake (fig. 26). These post-recovery episodes of potentially harmful low dissolved oxygen most frequently met the less than 4 mg/L criterion and were more numerous at sites EPT and EBB. A plausible explanation, as demonstrated with the light and dark bottle incubation experiments, is that there was a net consumption of oxygen at the deep sites in the trench, resulting in greater oxygen depletion and increased frequency of potentially harmful low dissolved oxygen at sites EPT and EBB than shallow sites (Wood and others, 2006). Potentially harmful pH conditions were rare during the field season at near-bottom and near-surface monitors at the deep sites.

The differences in patterns of potentially harmful pH and dissolved oxygen conditions between deep and shallow water are a result of the depth of light penetration. At deep sites, the near-bottom monitor is constantly in the aphotic zone, where photosynthetic activity, and therefore photosynthetically elevated pH, does not occur. The lack of photosynthesis in deep water results in decreased dissolved oxygen production and greater potential for metabolic processes to cause a net consumption of oxygen.

The near-surface monitors at the deep sites recorded more occurrences of potentially harmful dissolved oxygen concentration, and fewer occurrences of potentially harmful pH conditions than the monitors at the shallow sites, even though, at 1 m from the water surface, these monitors were usually closer to the water surface than the monitors at the shallow sites (fig. 26). The water column, even at the deepest sites, typically mixes daily (Hoilman and others, 2008). This mixing has the effect of moderating pH conditions and decreasing dissolved oxygen concentrations near the surface.

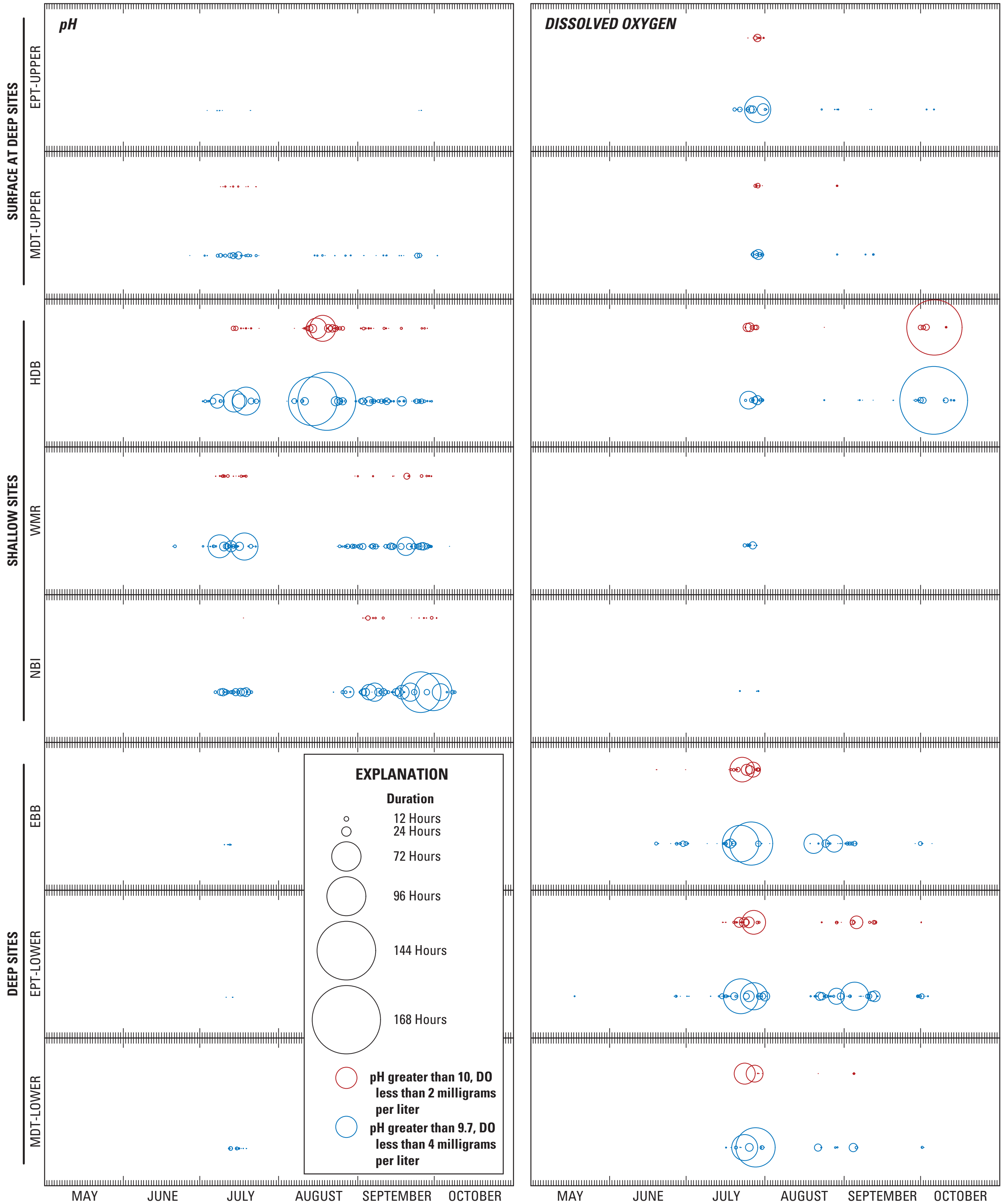


Figure 26. Potentially harmful pH and dissolved oxygen conditions at representative surface, shallow, and deep sites in open-water areas of Upper Klamath Lake, Oregon, 2006. (Data are shown in order of increasing site depth. Site descriptions are shown in table 1.)

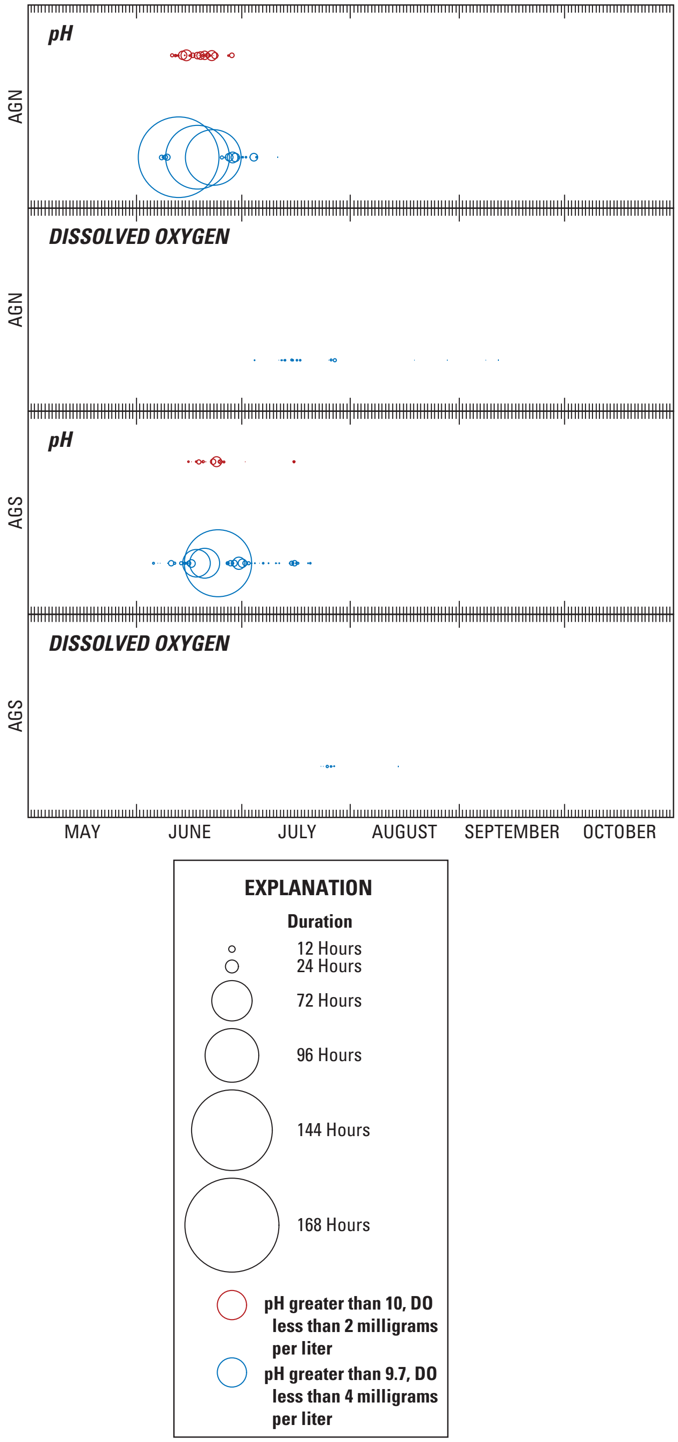


Figure 27. Potentially harmful pH and dissolved oxygen conditions in Agency Lake, Oregon, 2006. (Site descriptions are shown in table 1.)

In addition to low dissolved oxygen concentrations during episodes of bloom decline, high concentrations of un-ionized ammonia were present in trench areas (fig. 28). When high ammonia concentrations occur coincident with high pH and high temperatures, a significant fraction of the concentration is present in the un-ionized form, which is particularly toxic to aquatic life. The percentage of un-ionized ammonia relative to ammonia concentrations throughout the sampling period ranged from 0 to 87 percent. 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 a temperature of 22ºC and a pH of 9.5, the fraction jumps to 59 percent (U.S. Environmental Protection Agency, 1998). Mean un-ionized ammonia concentrations lethal to suckers (Saiki and others [1999]) ranged between 480 and 1,290 µg/L. Concentrations of un-ionized ammonia measured in the Upper Klamath Lake did not reach lethal concentrations. Ammonia was released into the water column concurrent with AFA bloom decline and the peaks of un-ionized ammonia, which occurred simultaneously with high pH values, were offset in time from ammonia peaks because as ammonia was released into the water column, pH values were decreasing.

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

Unlike other shallow sites in Upper Klamath Lake, instances of potentially harmful dissolved oxygen concentrations were measured at site HDB (fig. 26). However, water quality dynamics at HDB are known to be somewhat disconnected from the rest of the lake (Hoilman and others, 2008). In early October at site HDB, dissolved oxygen remained less than 2 mg/L for more than 5 consecutive days. During this time, several dead fish (mostly fathead minnows and chubs) were observed in Howard Bay. This event, which was not observed anywhere else in Upper Klamath Lake, demonstrates that the water quality dynamics in Howard Bay are somewhat disconnected from the rest of the lake. The dissolved oxygen plots for HDB (fig. 16), together with the results of dissolved oxygen production and consumption experiments there, give insight into metabolic processes behind the LDOEs that occurred at HDB. The smaller LDOE in late July (fig. 26) coincided with net oxygen consumption measured in light bottles throughout the water column (fig. 16), indicating that oxygen consuming processes in the water column played a part in this LDOE. Water column oxygen demand was not as strong during the larger LDOE at site HDB in early October, when dark bottle oxygen rates decreased only slightly and light bottle oxygen rates (at 0.5 m depth) showed net oxygen production. This indicates that SOD processes, which can influence water column dissolved oxygen concentration, but operate separately from water column processes, probably caused the early October LDOE at site HDB. SOD can be significant in Upper Klamath Lake, especially when large mats of AFA sink to the bottom and decompose. This process was thought to be the cause of an exceptionally large SOD measured in Ball Bay in 1999 (Wood, 2001), and it is likely that the same process occurred at site HDB in the current study.

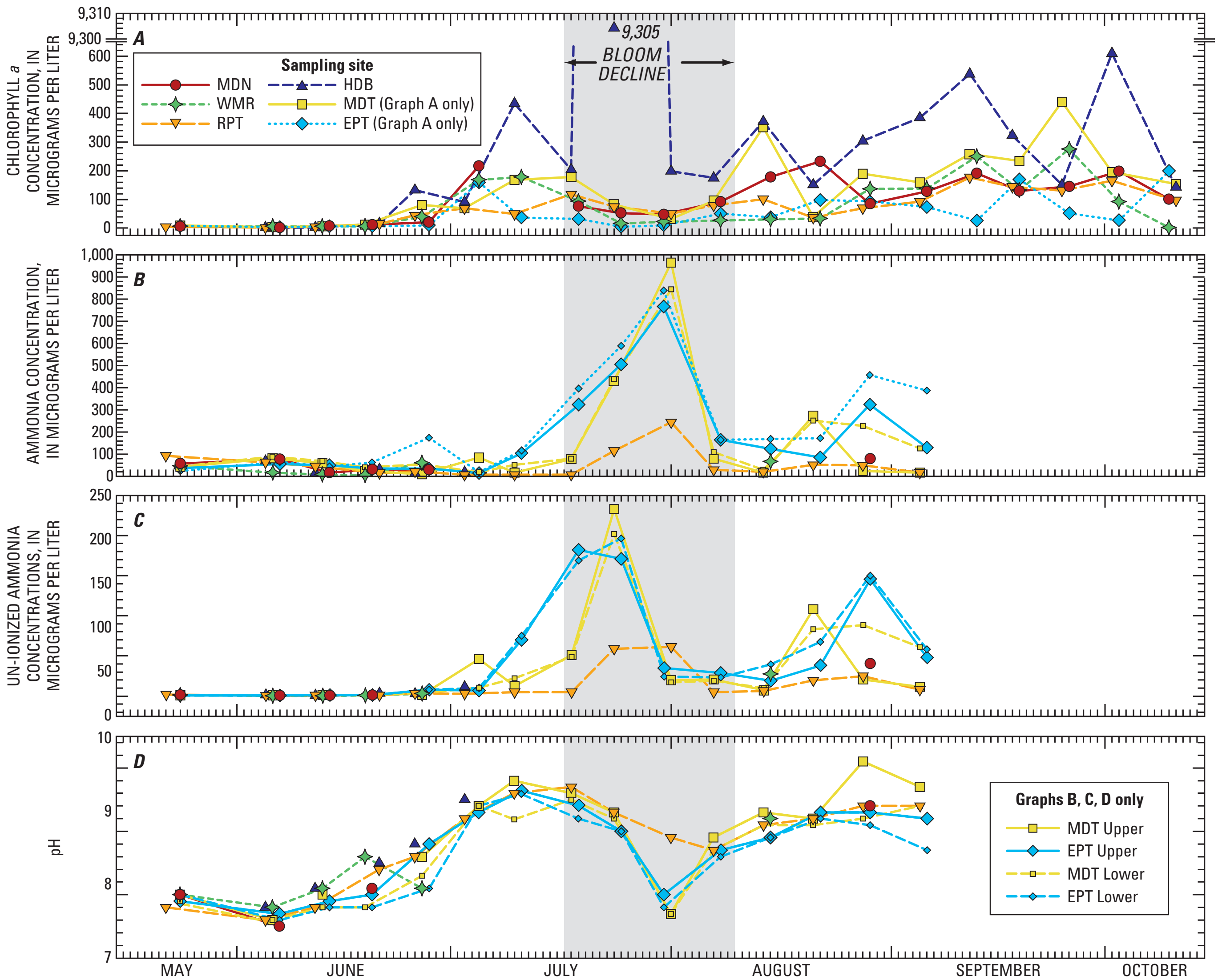


Figure 28. Chlorophyll *a*, ammonia, un-ionized ammonia concentrations, and pH, Upper Klamath Lake, Oregon, 2006. (Site descriptions are shown in table 1.)

Supersaturated Dissolved Oxygen

When the combined pressure of dissolved gases in the water column is greater than the combined local barometric and hydrostatic pressures, it is possible for gas bubbles to form in the tissues of fish. This condition, called gas bubble disease, can cause direct mortality to fish through bubbles in gill tissue or chambers of the heart that restrict oxygen uptake and (or) blood flow in the fish. Sublethal effects caused by the disease, such as lesions and blindness, can make fish more susceptible to mortality (Weitkamp and Katz, 1980). Gas supersaturation typically is associated with physical processes that drive atmospheric gases into solution, such as water crashing into a deep pool after flowing over the spillway of a dam. However, supersaturation caused solely by oxygen production through photosynthesis also has been known to cause gas bubble disease (Weitkamp and Katz, 1980). Gas bubble disease is probably not a major cause of mortality in fishes of Upper Klamath Lake, but it may be another source of stress that could act synergistically with other factors to cause harm (Scott Foote, U.S. Fish and Wildlife Service, oral commun., 2006).

Photosynthetic production created supersaturated dissolved oxygen conditions during much of 2006 in Upper Klamath Lake (fig. 21). However, supersaturation of dissolved oxygen alone may not always provide the necessary conditions to produce the disease. Waters must be supersaturated with respect to total atmospheric gases to produce gas bubble disease. Additionally, gases must be supersaturated enough to come out of solution to form bubbles. The hydrostatic pressure of the depth of the water column helps keep dissolved gases in solution. Equations given by Colt (1984) take these factors into account and were adapted to estimate when total dissolved gases may come out of solution given the percent saturation of dissolved oxygen at the depth where measurements were made (fig. 29). These instances were defined by times when the total dissolved gas pressure (P_d) was equal to or greater than the atmospheric and hydrostatic pressures combined (P_{a+h}). Nitrogen gas was assumed to be fully saturated throughout the water column for all calculations.

Sites with full pool depths deeper than 4 m (table 1) did not have occurrences of potential gas bubble formation, so data for these sites are not shown. The graphs in figure 29 are ordered according to increasing site depth. The shallowest sites, all with full-pool depths of 2.8 m or less, had the most potential for bubble formation, reflecting the lessened hydrostatic pressure relative to the deeper sites, where the greater pressure kept gases dissolved. At SET-U, a site in deep water where the monitor was placed 1 m from the water surface, the nearly daily mixing with water lower in oxygen from large aphotic zones below made instances of possible bubble formation less frequent and of shorter duration than at shallow sites where conditions were monitored at a similar depth (such as sites FBS and NBI). When lakewide average dissolved oxygen concentrations were high (fig. 23) the shallow areas of Upper Klamath Lake were likely to have conditions that could potentially lead to bubble formation, often lasting for several days at a time. These occurrences were most frequent in August and September, when potential for dissolved oxygen production was still high and the depth of the water column was decreasing.

As previously mentioned, potentially harmful low dissolved oxygen conditions occurred in deeper waters of Upper Klamath Lake during August and September. This coincidence with increased instances of possible gas bubble formation in shallow water could further limit available refuge for fish from potentially harmful water quality conditions: shallow waters tend to have more dissolved oxygen, but in concentrations that could potentially lead to gas bubble disease. Gas bubble disease is unlikely to occur in deep waters, but these areas also are more likely to have potentially harmful low dissolved oxygen concentrations.

Same-Day Occurrences of Potentially Harmful pH and Dissolved Oxygen Conditions

Because of the direct correlation between dissolved oxygen concentration and pH, potentially harmful dissolved oxygen and pH conditions are unlikely to occur simultaneously. Previous research has shown that, in shallow waters of Upper Klamath and Agency lakes, daily minimum dissolved oxygen concentrations tend to occur early in the morning, and maximum pH conditions are most likely to occur during the late afternoon. In areas of deeper water, the timing of these daily extremes becomes less definite due to diel stratification of the water column (Wood and others, 2006; Hoilman and others, 2008). Data from 2006 are consistent with these findings. Although potentially harmful pH and dissolved oxygen did not occur simultaneously at any time during 2006, instances of these events taking place closely in time (the same day) did occur at some locations in Upper Klamath and Agency lakes (table 6). The occurrence of these potentially harmful dissolved oxygen and pH conditions in close succession may present additional harm to fish beyond what is experienced by either of these conditions alone (Power, 1997). However, because only 25 events were recorded during May through October, these conditions probably were not a significant threat to fish during 2006.

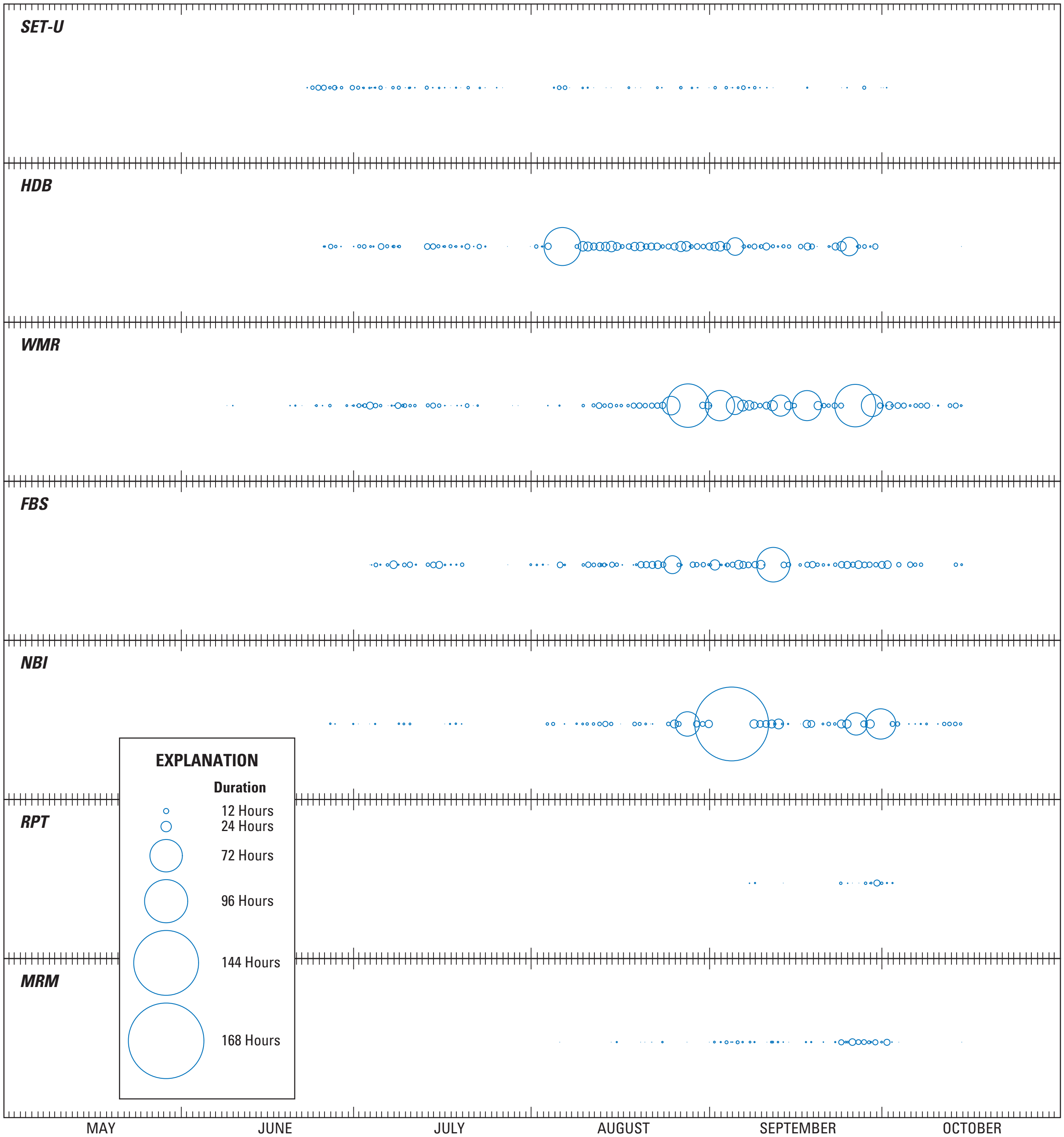


Figure 29. Possible occurrences gas bubble formation, Upper Klamath Lake, Oregon, 2006. (Data are shown in order of increasing site depth. Site descriptions are shown in table 1.)

Table 6. Potentially harmful high pH and low dissolved oxygen conditions occurring during the same day, Upper Klamath and Agency Lakes, Oregon, 2006.

[Site locations are shown in figure 2]

Site name	Site name abbreviation	Date	Minimum dissolved oxygen	Maximum pH	Time between readings (hours)
Agency North	AGN	07-04-06	3.12	9.92	14
Entrance Ball Bay	EBB	07-13-06	3.84	9.71	6
Entrance to Howard Bay	EHB	09-08-06	2.63	9.71	12
		10-04-06	1.88	9.78	4
		10-09-06	1.62	9.83	10
Eagle Point (upper)	EPT-U	07-20-06	2.95	9.73	15
Fish Banks	FBS	08-27-06	3.76	10.03	8
Howard Bay	HDB	08-24-06	1.06	10.09	5
		09-06-06	3.08	10.03	5
		09-07-06	2.16	9.99	10
		09-08-06	2.94	9.90	12
		09-12-06	2.80	10.01	5
		09-28-06	3.89	9.89	14
		09-29-06	2.00	9.88	12
Midnorth (upper)	MDN-U	08-28-06	2.67	9.86	11
Middle of trench (lower)	MDT-L	07-16-06	2.47	9.79	18
		07-18-06	3.83	9.81	18
South end of trench (lower)	SET-L	09-07-06	1.86	9.72	1
South end of trench (upper)	SET-U	07-20-06	1.79	10.06	8
		07-22-06	2.63	9.76	14
		09-04-06	3.93	9.84	20
		09-09-06	3.34	9.79	17
		09-11-06	0	9.74	4
		09-28-06	2.81	9.76	19

Because photosynthetic production of dissolved oxygen also increases pH, gas bubble formation and potentially harmful pH could occur simultaneously. Water quality data indicated that these potentially harmful conditions may occur often and be widespread in Upper Klamath and Agency lakes (table 7). These conditions were not estimated to occur simultaneously at only the two deepest sites outside of the trench areas (MDN-Lower and EHB). Because almost 90 percent of the lake is less than 4 m deep, most of the lake is represented by the sites shown in table 7. The instances of possible gas bubble formation were inferred only from prevailing conditions, however. Without direct monitoring of total dissolved gases, the potential harm posed to fish by gas bubble formation and its interrelations with other aspects of water quality in these lakes cannot be known conclusively.

Table 7. Numbers of days having simultaneous occurrences of potentially harmful high pH and possible gas bubble formation at individual sites, Upper Klamath and Agency Lakes, Oregon, 2006.

Lake basin	Site name	Site name abbreviation	Number of days
	$(P_d - P_{(a-h)}) \geq 0$ and pH>9.7		
Agency Lake	Agency South	AGS	31
	Agency North	AGN	13
Upper Klamath Lake	Midnorth (upper)	MDN-U	31
	Middle of trench (upper)	MDT-U	35
	South End of trench (upper)	SET-U	34
	Eagle Point (upper)	EPT-U	4
	Howard Bay	HDB	70
	Upper Klamath Lake at Williamson River outlet	WMR	59
	Fish Banks	FBS	63
	North Buck Island	NBI	46
	Rattlesnake Point	RPT	12
	Modoc Rim	MRM	28
	$(P_d - P_{(a-h)}) \geq 0$ and pH>10		
Agency Lake	Agency South	AGS	9
	Agency North	AGN	4
Upper Klamath Lake	Midnorth (upper)	MDN-U	3
	Middle of trench (upper)	MDT-U	9
	South end of trench (upper)	SET-U	7
	Howard Bay	HDB	40
	Upper Klamath Lake at Williamson River outlet	WMR	21
	Fish Banks	FBS	13
	North Buck Island	NBI	14
	Modoc Rim	MRM	8

Potentially Harmful Water Quality Conditions in Nearshore Areas

Graphs of low dissolved oxygen and high pH conditions potentially harmful to fish in nearshore areas (fig. 30) appear similar to those for open-water sites away from the trench (fig. 26). Few instances of dissolved oxygen concentrations met either criterion of potential harm (less than 2 or 4 mg/L) or relatively numerous instances of potentially harmful pH conditions. Occurrences of possible gas bubble formation were correspondingly numerous (fig. 31), owing to the high potential for dissolved oxygen production (and associated elevated pH) in the shallow waters of Upper Klamath Lake.

Among the nearshore sites, no clear relation of occurrences of potentially harmful pH or possible bubble formation with site depth was noted. Because these sites are similar in depth (table 1), local factors seem more likely to influence the occurrence of these conditions. For instance, occurrences of potentially harmful pH and possible gas bubble formation often were long lasting at site SSR. This likely is due to the action of prevailing northerly winds concentrating AFA along the southern shore of the lake, increasing the potential for photosynthetic oxygen production and its associated increase in pH. Temperatures exceeded 28°C at the three shallowest nearshore sites (fig. 32). Occurrences of potentially harmful temperature conditions were few and of short duration relative to potentially harmful dissolved oxygen and pH conditions, and were less likely to cause harm to fish.

Mann-Whitney rank-sum tests were conducted to provide a quantitative measure of the similarity (or difference) between nearshore and open-water occurrences of potentially harmful water quality conditions. This nonparametric test for a difference in the distribution of two variables was used because it does not require the data sets to be normally distributed. The duration of individual events at all sites, listed separately for nearshore and open-water areas, was compared, as was the total number of hours meeting the criterion at each site for nearshore and open-water areas. A quantitative comparison of potentially harmful temperature conditions was not obtained because temperature greater than 28°C in the open-water areas were few, and occurred at only one site, making the data unsuitable for the Mann-Whitney rank-sum test. As with the comparison of daily median water quality conditions between the two areas, data from the deep monitors at sites EBB, EPT, MDT, and SET were removed from the open-water group in the analysis. All p-values mentioned are two sided.

The comparisons indicated no statistically significant ($p < 0.05$) difference in the duration of events of potentially harmful dissolved oxygen conditions or in the total number of hours these conditions existed at sites in nearshore and open-water areas. The duration of events of pH conditions greater than 10 and the duration of events of possible gas bubble formation were determined to be significantly greater in nearshore areas ($p = 0.006$ and $p = 0.002$, respectively). No differences, however, were noted in the total hours potentially harmful pH conditions or possible gas bubble formation existed at sites between the two groups. The differences observed can be explained by the buildup of AFA at the nearshore SSR site discussed earlier, causing high pH conditions and potential gas bubble formation for considerable lengths of time. When data from this outlier were removed, no significant differences were found in any of the comparisons. The results of these comparisons indicate that potentially harmful dissolved oxygen and pH conditions occur with similar patterns near shore and in open-waters, but that areas where wind tends to cause algae to accumulate are especially prone to possible gas bubble formation and high pH.

Note that the similarities between Upper Klamath Lake nearshore areas and open-water areas away from the trench were observed during a single season when severely low dissolved oxygen was largely confined to the deep trench areas of the lake. In other years, low dissolved oxygen has been more widespread in shallower waters of the lake (Wood and others, 2006). The similarities observed between open-water and nearshore areas in 2006 might not be observed during a year when low dissolved oxygen is more widespread.

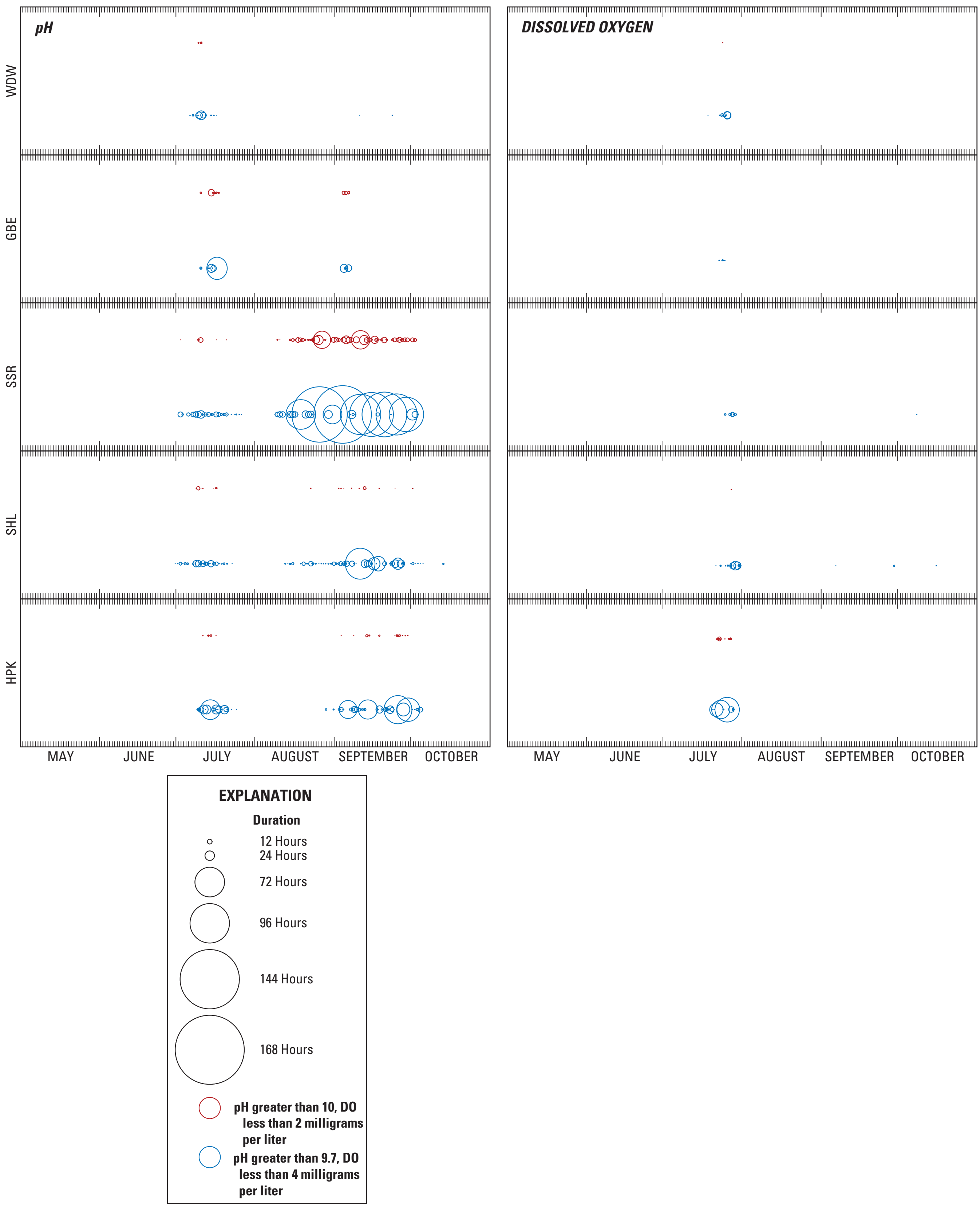


Figure 30. Dissolved oxygen and pH conditions potentially harmful to fish in nearshore areas, Upper Klamath Lake, Oregon, 2006. (Data are shown in order of increasing site depth. Site descriptions are shown in table 1.)

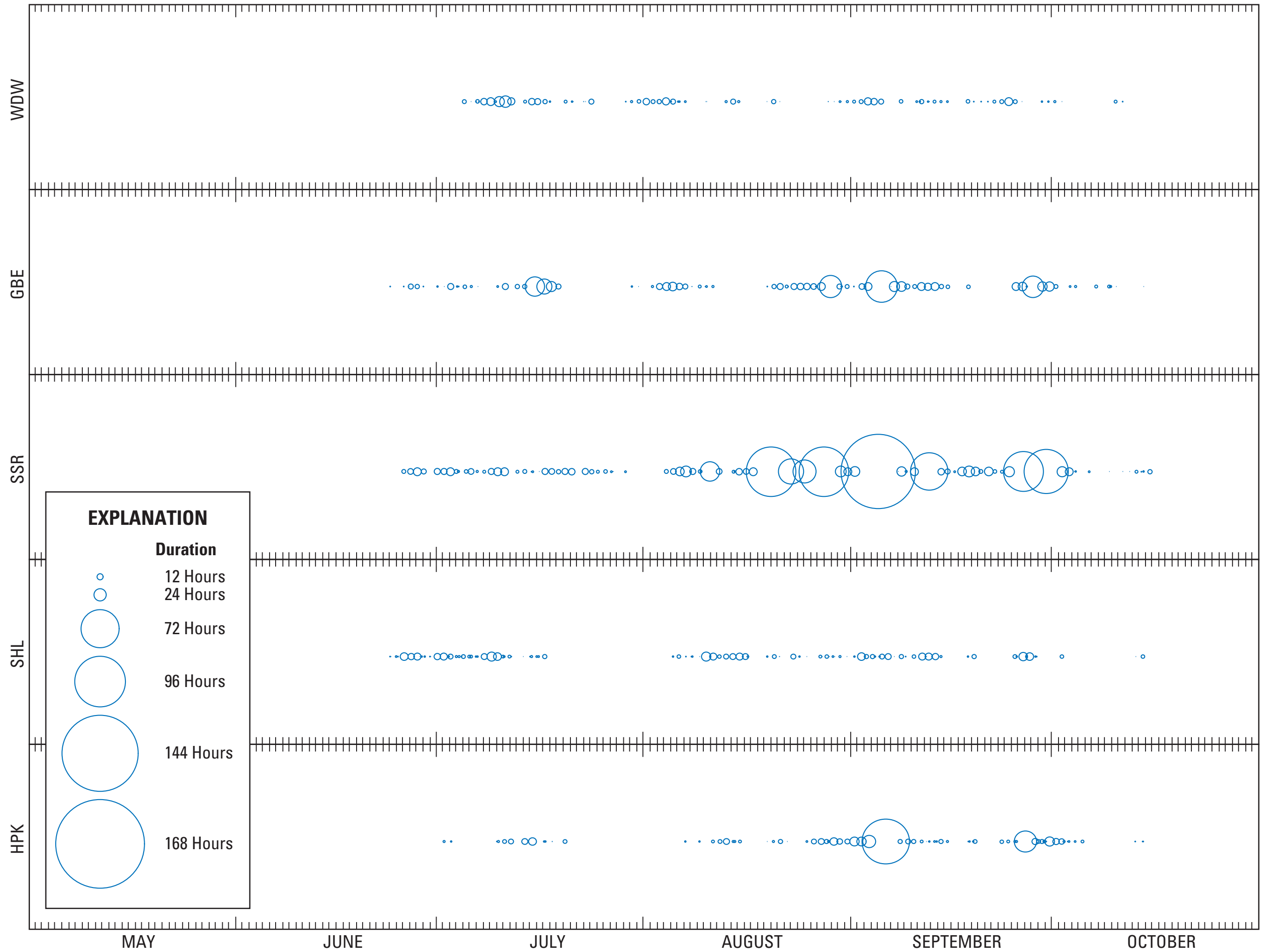


Figure 31. Possible gas bubble formation in nearshore areas, Upper Klamath Lake, Oregon, 2006. (Data are shown in order of increasing site depth. Site descriptions are shown in table 1.)

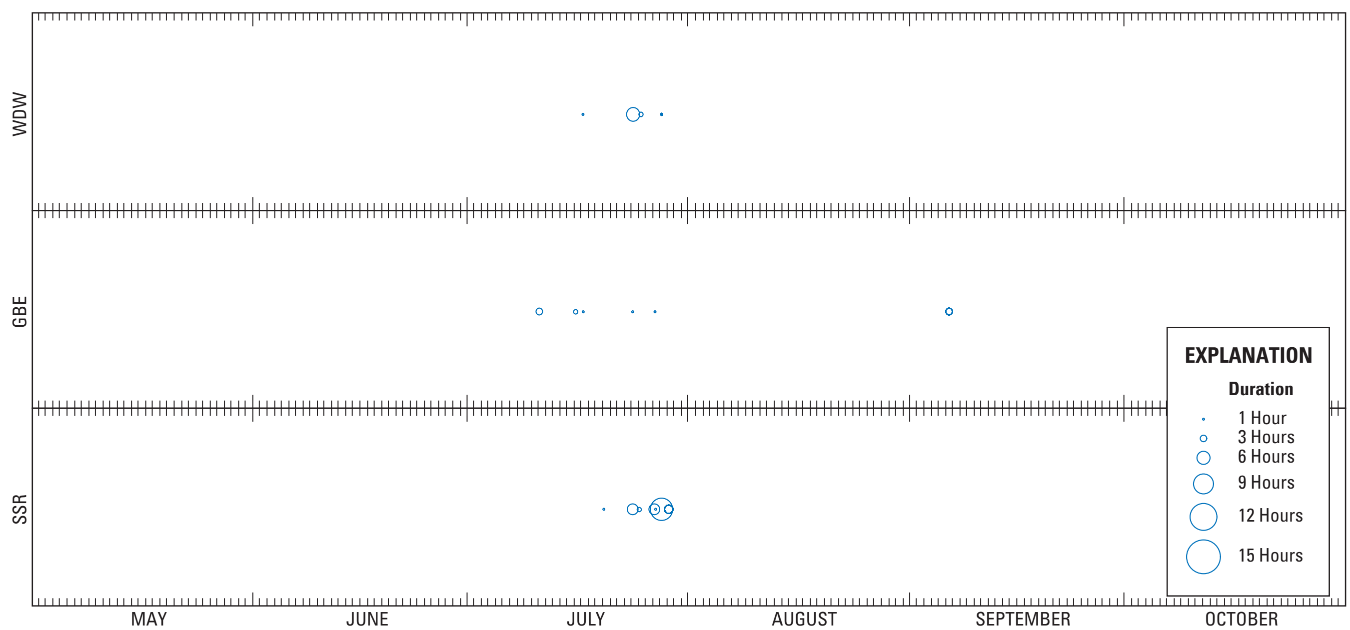


Figure 32. Temperature conditions in nearshore areas potentially harmful to fish, Upper Klamath Lake, Oregon, 2006. (Data are shown in order of increasing site depth. Site descriptions are shown in table 1.)

Summary and Conclusions

Data from multiparameter continuous water quality monitors, physical water samples, and meteorological stations were collected from Upper Klamath and Agency Lakes, Oregon, in 2006 to assess water quality conditions and processes. The data show that the factors controlling water quality processes included *Aphanizomenon flos-aquae* (AFA) dynamics, temperature, bathymetry, and circulation patterns. These factors induced extremes in pH and dissolved oxygen concentrations that were potentially harmful to fish. Water quality processes that were potentially harmful to fish were temporally coincident but spatially different, thereby reducing refuge from potentially harmful waters.

Diurnal photosynthesis–respiration processes and the seasonal pattern of changes in AFA biomass lead to variation in dissolved oxygen, orthophosphate, and ammonia concentrations, pH, and specific conductance values. In previous years, AFA biomass, measured as chlorophyll *a* concentrations, increased markedly, inducing increased pH, then decreased, resulting in low dissolved oxygen concentrations. In 2006, chlorophyll *a* concentrations increased in early July and then decreased in late July–early August before recovering in mid-August. Daily lakewide medians for Upper Klamath Lake showed a seasonal pattern of dissolved oxygen and pH that followed patterns in AFA bloom, decline, and recovery, similar to previous years. Dissolved oxygen concentrations and pH increased in early July, followed by a decrease in dissolved oxygen and pH values in late July when the AFA bloom declined. Additionally, orthophosphate and ammonia concentrations increased during the bloom decline in late July–early August. The bloom recovery period in mid-August resulted in an increase in dissolved oxygen concentrations and pH, and a decrease in ammonia and, to a lesser extent, orthophosphate concentrations. Dissolved oxygen and pH generally were high before and after the bloom decline in Upper Klamath Lake, whereas these conditions occurred only before the bloom decline in Agency Lake. As in 2005, differences in water quality dynamics between the two lakes were attributable to differences in bloom dynamics.

In Upper Klamath Lake, the seasonal maximum in lakewide daily median temperature coincided with the seasonal minimum in lakewide daily median dissolved oxygen. A strong inverse relation between temperature and dissolved oxygen percent saturation was observed in the 2006 data during the time of bloom decline and recovery, although it is unclear whether temperature itself was the cause of the decline. In both 2005 and 2006, the seasonal minimum dissolved oxygen coincided with the season maximum temperature, but seasonal maximum temperatures were higher and seasonal minimum dissolved oxygen was lower in 2006 than in 2005. In Agency Lake, more variability was noted in the relation between dissolved oxygen and temperature, but the seasonal maximum in lakewide daily median temperature coincided with some of the lowest dissolved oxygen concentration values of the 2006 season. Dissolved oxygen concentrations recovered rapidly from seasonal lows in both lakes concurrently with a decrease in temperatures from the seasonal maximum in late July 2006.

Bathymetry influenced overall patterns of water quality conditions as well as the spatial distribution and severity of water quality conditions potentially harmful to fish. Results of dissolved oxygen production and consumption experiments showed that depth of the photic zone was inversely proportional to chlorophyll *a* concentrations. In the trench, much of the water column lies below the photic zone, where oxygen-consuming processes dominate. As a result of algal decay during bloom decline, dissolved nutrient concentrations such as ammonia were greatest at the trench sites. Calculations of 24-hour change in dissolved oxygen indicate that the deep trench areas were characterized by oxygen consumption and shallow areas of the lake were characterized by oxygen production. Waters in the trench area also were more likely to have potentially harmful low dissolved oxygen concentrations. These conditions continued to occur in trench areas well after dissolved oxygen concentrations had recovered in most of Upper Klamath Lake, lasting sometimes for multiple consecutive days.

In contrast, potentially harmful pH conditions occurred for much of July, August, and September 2006 in the shallow waters outside of the trench in Upper Klamath Lake. These conditions also were prevalent in Agency Lake, but only during June and mid-July. Calculations indicated that gas bubble formation, which may lead to gas bubble disease in fish, may occur in the shallow waters of Upper Klamath and Agency lakes. Because dissolved oxygen production and pH are directly correlated, bubble formation and potentially harmful pH conditions may occur simultaneously over much of both lakes. Potentially harmful low dissolved oxygen and high pH occurred during the same day in Upper Klamath and Agency Lakes, but these same-day occurrences were not frequent or widespread. Water temperature potentially harmful to fish (28°C) was exceeded at the three shallowest nearshore sites.

Circulation patterns were an additional influence on water quality and conditions potentially harmful to fish. Occurrences of potentially harmful pH and possible gas bubble formation were particularly common and long lasting at site SSR. Prevailing northerly winds concentrated AFA along the southern shore of the lake, increasing the potential for photosynthetic oxygen production and its associated increase in pH. The most instances of low dissolved oxygen concentrations potentially harmful to fish were deep in the water column at sites in the trench area on the western shoreline of the lake. These conditions typically were measured at near-bottom sites at the northern end of the trench. Under prevailing wind and current patterns, water flows from south to north through the trench, so water at the northern end of the trench has spent the most time in the areas of the lake where oxygen-consuming processes dominate photosynthetic production. Seasonal patterns in meteorological conditions were similar to those observed in 2005, suggesting similar circulation patterns between these years.

The network of continuous water quality monitoring stations, physical water samples, and meteorological stations provides information critical to understanding lakewide water quality dynamics in Upper Klamath and Agency Lakes. The network provides water quality data at a high temporal resolution that can be related to bloom conditions, weather, bathymetry, and currents. This network is central to future water quality modeling efforts. Continued operation of the monitoring stations to collect a long-term data set also will enable the identification of water quality status and trends in Upper Klamath Lake. Future monitoring would be enhanced by the addition of sites to better quantify conditions that describe the dynamic between Howard Bay and the trench. Other monitoring efforts could include analysis of total dissolved gases and relations between temperature and algal health.

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Appendix A. Quality Control and Quality-Assurance of Water Samples

Overall, 36 percent of dissolved nutrient samples, 33 percent of total phosphorus samples, 32 percent of total nitrogen samples, and 58 percent of chlorophyll *a* samples were collected for quality-assurance purposes. These samples 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 deionized 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 variability of the system and 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 less than seasonal variability (table A1). Most field blank concentrations of orthophosphate and total phosphorus were less than the NWQL's minimum reporting level. The median value of the blank samples greater than the minimum reporting level was 0.013 mg/L for orthophosphate and 0.006 mg/L for total phosphorus. Almost one-half of the field blank samples had concentrations of ammonia and total nitrogen greater than laboratory minimum reporting level. These concentrations, however, were minimal compared to the concentrations of the environmental samples. The number of nitrite-plus-nitrate blank samples measured that were greater than laboratory minimum reporting level was less than ammonia and total nitrogen, indicating that the contamination to total nitrogen was the ammonia-nitrogen species. Contamination of ammonia blanks in 2003 and 2004 was attributable to atmospheric deposition (Wood and others, 2006). This contamination subsequently has been reduced, but has not been eliminated by the use of capsule filters. Twice during the season, split samples of all constituents were sent to two other laboratories in addition to NWQL and Portland State University (table A2). Additionally, two interlaboratory split samples were sent to Portland State University and NWQL, for four interlaboratory chlorophyll *a* split samples between the two laboratories. The interlaboratory split samples were analyzed to determine variability in analytical methods between the laboratories. Some split samples also were collected to examine variability that might be expected due to different protocols used by USGS and the Klamath Tribes in the collection of their long-term biweekly data set. The coefficient of variation for each constituent measured on each sampling date ranges from 4 to 36 percent, where the greatest percentages of variance from the mean were in chlorophyll *a* and nitrite-plus-nitrate concentrations. Mean and standard deviations of split sample concentrations all of the split samples taken from the same churn splitter indicate that the variance in interlaboratory processing and analysis is generally low.

An extraordinary chlorophyll *a* concentration was measured at site HDB on July 24. The value of that sample, 9,305 µg/L, was the greatest ever measured for this project. As a result, the validity of this high value has been in question. The method used to determine chlorophyll *a* concentrations requires that values are diluted to fall within the upper limit for this method, 250 µg/L. The sample was diluted twice in order to reduce concentrations to fall within the upper limit, which allows for greater error in the process. While the error associated with this chlorophyll *a* value probably is higher than that associated with the rest of the 2006 chlorophyll *a* data, other data collected at the same site on the same day corroborate a high value. Total phosphorus and total nitrogen concentrations reached 1,210 and 14,700 µg/L, respectively at site HDB on June 24. Total phosphorus and total nitrogen concentrations measured at site HDB on June 24 were greater than any other measured that sampling season. These high values indicate that increased total nutrients was due to higher concentrations of algal cells required to take up the nutrients concentrations, thereby validating a greater concentration of chlorophyll *a* than measured at all other sites at any point in the field season. Additionally, results from dissolved oxygen production and consumption experiments show that on June 24 at site HDB, light and dark bottles on both racks measured net respiration rates that were greater than measurements from any other dark bottles measured during the sampling period. The depth of photic zone measured during June 24 at site HDB was less than 0.5 m, indicating a high concentration of AFA colonies near the surface of the water. The depth of the photic zone was shallower than the placement of the upper rack in the water column. The high respiration rates at site HDB on June 24 were measured from bottles that had a high algal concentration (the water was taken from the same churn splitter as the sample analyzed for chlorophyll *a* at that site) and the bottles were incubated on a rack that was below the photic zone. Therefore, the other measurements and samples collected on that day—total nutrient concentration, light penetration, and oxygen production and consumption—are all consistent with a high chlorophyll *a* measurement at site HDB on June 24.

Table A1. Quality-assurance results for the water quality collection program in Upper Klamath and Agency Lakes, Oregon, 2006.

[mg/L, milligram per liter; MRL, minimum reporting level]

Blank samples							
Analyte	Number of samples		Percentage of blank samples	MRL (mg/L)	Number of blank samples greater than MRL	Value of blank samples greater than MRL (mg/L)	
	Blank	Total				Median	Maximum
Orthophosphate-P	61	211	29	0.006	1	0.013	0.013
Ammonia-N	61	211	29	0.01	23	0.02	0.04
Nitrite plus nitrate-N	61	211	29	0.016	7	0.031	0.052
Total nitrogen	44	190	23	0.06	8	0.115	0.3
Total phosphorus	52	207	25	0.004	17	0.006	0.011
Chlorophyll *a*	61	130	47	0.004	0	–	–

Split samples					
Analyte	Number of samples		Percentage of split samples	Difference between split samples	
	Split	Total		Median (mg/L)	Median (percent)
Orthophosphate-P	8	211	4	0.001	2.22
Ammonia-N	8	211	4	0.003	12.44
Nitrite plus nitrate-N	8	211	4	0.001	0.45
Total nitrogen	7	190	4	0.160	6.64
Total phosphorus	9	207	4	0.010	4.26
Chlorophyll *a*	8	148	5	0.006	11.38

Replicate samples					
Analyte	Number of samples		Percentage of replicate samples	Difference between replicate samples	
	Replicate	Total		Median (mg/L)	Median (percent)
Orthophosphate-P	6	211	3	0.001	0.51
Ammonia-N	6	211	3	0.002	5.13
Nitrite plus nitrate-N	6	211	3	0.001	1.05
Total nitrogen	9	190	5	0.200	4.73
Total phosphorus	8	207	4	0.016	5.41
Chlorophyll *a*	9	148	6	0.021	15.38

Table A2. Distribution of differences from the median concentrations among split sample interlaboratory measurements of samples from the water quality collection program in Upper Klamath and Agency Lakes, Oregon, 2006.

Analyte	Concentrations, in micrograms per liter					
	August 15, 2006			August 29, 2006		
	Mean	Standard deviation	Coefficient of variation	Mean	Standard deviation	Coefficient of variation
Orthophosphate-P	80.40	8.44	11	97.80	13.86	14
Ammonia-N	66.20	7.36	11	72.80	9.58	13
Nitrite plus nitrate-N	25.40	5.08	20	11.80	2.49	21
Total nitrogen	1,597.50	97.08	6	2,395.00	216.72	9
Total phosphorus	159.50	8.10	5	219.75	8.18	4
Chlorophyll *a*	27.78	9.88	36	86.33	14.28	17

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