Prepared in cooperation with the Bureau of Reclamation

Relation Between Selected Water-Quality Variables, Climatic Factors, and Lake Levels in Upper Klamath and Agency Lakes, Oregon, 1990-2006

Scientific Investigations Report 2007–5117

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

Cover: Photograph of *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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Conversion Factors, Datums, and Abbreviations and Acronyms

Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	247.1	acre
liter (L)	0.2642	gallon (gal)
meter (m)	3.281	foot (ft)

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

°F=(1.8×°C)+32.

Concentrations of chemical constituents in water are reported either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Lake level, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

Abbreviations	Meaning
AFA	*Aphanizomenon flos-aquae*
AIC_c	Akaike Information Criterion
LC_{50}	median lethal concentration
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

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Abstract

Growth and decomposition of dense blooms of *Aphanizomenon flos-aquae* in Upper Klamath Lake frequently cause extreme water-quality conditions that have led to critical fishery concerns for the region, including the listing of two species of endemic suckers as endangered. The Bureau of Reclamation has asked the U.S. Geological Survey (USGS) to examine water-quality data collected by the Klamath Tribes for relations with lake level. This analysis evaluates a 17-year dataset (1990–2006) and updates a previous USGS analysis of a 5-year dataset (1990–94).

Both univariate hypothesis testing and multivariable analyses evaluated using an information-theoretic approach revealed the same results—no one overarching factor emerged from the data. No single factor could be relegated from consideration either. The lack of statistically significant, strong correlations between water-quality conditions, lake level, and climatic factors does not necessarily show that these factors do not influence water-quality conditions; it is more likely that these conditions work in conjunction with each other to affect water quality. A few different conclusions could be drawn from the larger dataset than from the smaller dataset examined in 1996, but for the most part, the outcome was the same. Using an observational dataset that may not capture all variation in water-quality conditions (samples were collected on a two-week interval) and that has a limited range of conditions for evaluation (confined to the operation of lake) may have confounded the exploration of explanatory factors. In the end, all years experienced some variation in poor water-quality conditions, either in timing of occurrence of the poor conditions or in their duration. The dataset of 17 years simply provided 17 different patterns of lake level, cumulative degree-days, timing of the bloom onset, and poor water-quality conditions, with no overriding causal factor emerging from the variations.

Water-quality conditions were evaluated for their potential to be harmful to the endangered sucker species on the basis of high-stress thresholds—water temperature values greater than 28 degrees Celsius, dissolved-oxygen concentrations less than 4 milligrams per liter, and pH values greater than 9.7. Few water temperatures were greater than 28 degrees Celsius, and dissolved-oxygen concentrations less than 4 milligrams per liter generally were recorded in mid to late summer. In contrast, high pH values were more frequent, occurring earlier in the season and parallel with growth in the algal bloom.

The 10 hypotheses relating water-quality variables, lake level, and climatic factors from the earlier USGS study were tested in this analysis for the larger 1990–2006 dataset. These hypotheses proposed relations between lake level and chlorophyll-*a*, pH, dissolved oxygen, total phosphorus, and water temperature. As in the previous study, no evidence was found in the larger dataset for any of these relations based on a seasonal (May–October) distribution. When analyzing only the June data, the previous 5-year study did find evidence for three hypotheses relating lake level to the onset of the bloom, chlorophyll-*a* concentrations, and the frequency of high pH values in June. These hypotheses were not supported by the 1990–2006 dataset, but the two hypotheses related to cumulative degree-days from the previous study were: chlorophyll-*a* concentrations were lower and onset of the algal bloom was delayed when spring air temperatures were cooler. Other relations between water-quality variables and cumulative degree-days were not significant.

In an attempt to identify interrelations among variables not detected by univariate analysis, multiple regressions were performed between lakewide measures of low dissolved-oxygen concentrations or high pH values in July and August and six physical and biological variables (peak chlorophyll-*a* concentrations, degree-days, water temperature, median October–May discharge in the Williamson River, median monthly wind speed, and median monthly lake level). Model sets were developed for each combination of these factors and evaluated using an information-theoretic approach. For each water-quality measure tested, the models with the lowest Akaike Information Criterion statistics, and therefore the best fit, were the models that considered each variable individually.

The variables with the best fit for dissolved oxygen were water temperature and wind speed, whereas for pH it was water temperature. Akaike weights for the remaining variables were fairly evenly distributed, indicating that there was no clear hierarchy of importance among those variables.

Although water temperature and wind speed appear to be important explanatory variables for the variance observed in different water-quality measures, no overarching variable or combination of variables was revealed. The dynamic nature of these variables and their interactions from year to year, within a season, and between sites around the lake confounds the ability to explain or predict water-quality conditions in Upper Klamath Lake. At present, no single causal factor can be clearly identified.

Introduction

Upper Klamath Lake is a large (232 km^2), relatively shallow lake located in southern Oregon, 25 km north of the Oregon-California border (fig. 1). Most of the lake is less than 4 m deep except for the narrow trench on the western edge of the lake. This trench, which runs parallel to Eagle Ridge, can be as much as 15 m deep. Just north of Upper Klamath Lake and connected by a narrow channel is Agency Lake, a smaller (37 km^2) but equally shallow lake that is distinct from Upper Klamath Lake, both hydrologically and in terms of water quality. The primary contributor of inflow to Upper Klamath Lake is the Williamson River, which enters the lake near its northern end, east of the Agency Lake inflow, and accounts for about 46 percent of the lake's incoming water (Johnson and others, 1985).

Lake surface levels are regulated by the Link River Dam, built at the southern outlet of the lake in 1921 by the Bureau of Reclamation. During construction of the dam, the rock sill that held Upper Klamath Lake was removed and replaced with the Link River Dam. As a result, the minimum possible post-dam lake level is about 1 m lower than the minimum possible pre-dam level. Area demands for water during summer months result in declines in lake level from May to September. At the median May lake level of 4,143 feet above sea level, the volume of water contained in the lake is 1,080 cubic hectometers (875,000 acre-feet). In contrast, the volume of water in the lake at the mean summer lake level of 4,141.3 feet is 765 cubic hectometers (620,000 acre-feet) [Snyder and Morace, 1997]. Water is diverted upstream of the lake for agricultural use and downstream to supply the irrigators of the Klamath Project, an irrigation system developed to supply water to 970 km^2 of farm and ranch land in and around the Upper Klamath basin. To meet the National Marine Fisheries Service flow requirements for Klamath River coho salmon (National Marine Fisheries Service, 2002), water is sent downstream through the Link River. Lastly, evaporation from the lake also results in a loss of water in the lake itself. It is difficult to balance these competing demands for water from the lake.

The lake was historically eutrophic but has become hypereutrophic, in large part due to land-use practices in the basin (U.S. Fish and Wildlife Service, 1993). As a result, the algal assemblage of the lake has shifted to a monoculture of the blue-green alga *Aphanizomenon flos-aquae* (AFA), massive blooms of which have been directly related to episodes of poor water quality in Upper Klamath Lake (poor conditions are defined as those that have the potential to be harmful to the endangered sucker species). The lake has experienced nuisance blooms of AFA during summer and fall for the past 40 years. The growth and decomposition of dense algal blooms frequently cause extreme water-quality conditions characterized by high pH (9–10.5), widely variable dissolved oxygen (anoxic to supersaturated), and high ammonia concentrations (greater than 0.5 mg/L, un-ionized) [Wood and others, 2006]. Severe water-quality problems in Upper Klamath Lake have led to critical fishery concerns for the region (Perkins and others, 2000).

In 1988, the U.S. Fish and Wildlife Service (USFWS) listed two species of suckers endemic to the lake as endangered: the Lost River sucker (*Deltistes luxatus*) and the shortnose sucker (*Chasmistes brevirostris*). Poor water-quality conditions associated with the long and productive blooms of AFA are believed to be the primary threat to adult endangered suckers. According to Ronald Larson (U.S. Fish and Wildlife Service, written commun., 2006), "of all the factors that might affect water quality in the short term, elevations [or lake level] are the only one we have some control over."

Purpose and Scope

In 1996, Wood and others (1996) evaluated water-quality data collected by the Klamath Tribes from Upper Klamath and Agency Lakes for relations between water-quality conditions and lake level. At that time, data were available only for 1990 through 1994. The Tribes have continued to collect data and a comparable dataset is now available for 1990 through 2006. The Bureau of Reclamation asked the U.S. Geological Survey to update the original analysis performed by Wood and others (1996) with this larger dataset. In addition to the univariate approach used in the previous analysis, multivariable analyses will be assessed with this larger dataset and evaluated using an information-theoretic approach. These two approaches to the data analysis offer a chance to explore the data in a purely empirical manner unhampered by preconceived notions and an opportunity to use some of the knowledge developed since the initial analysis to inform a more in-depth evaluation of the data.

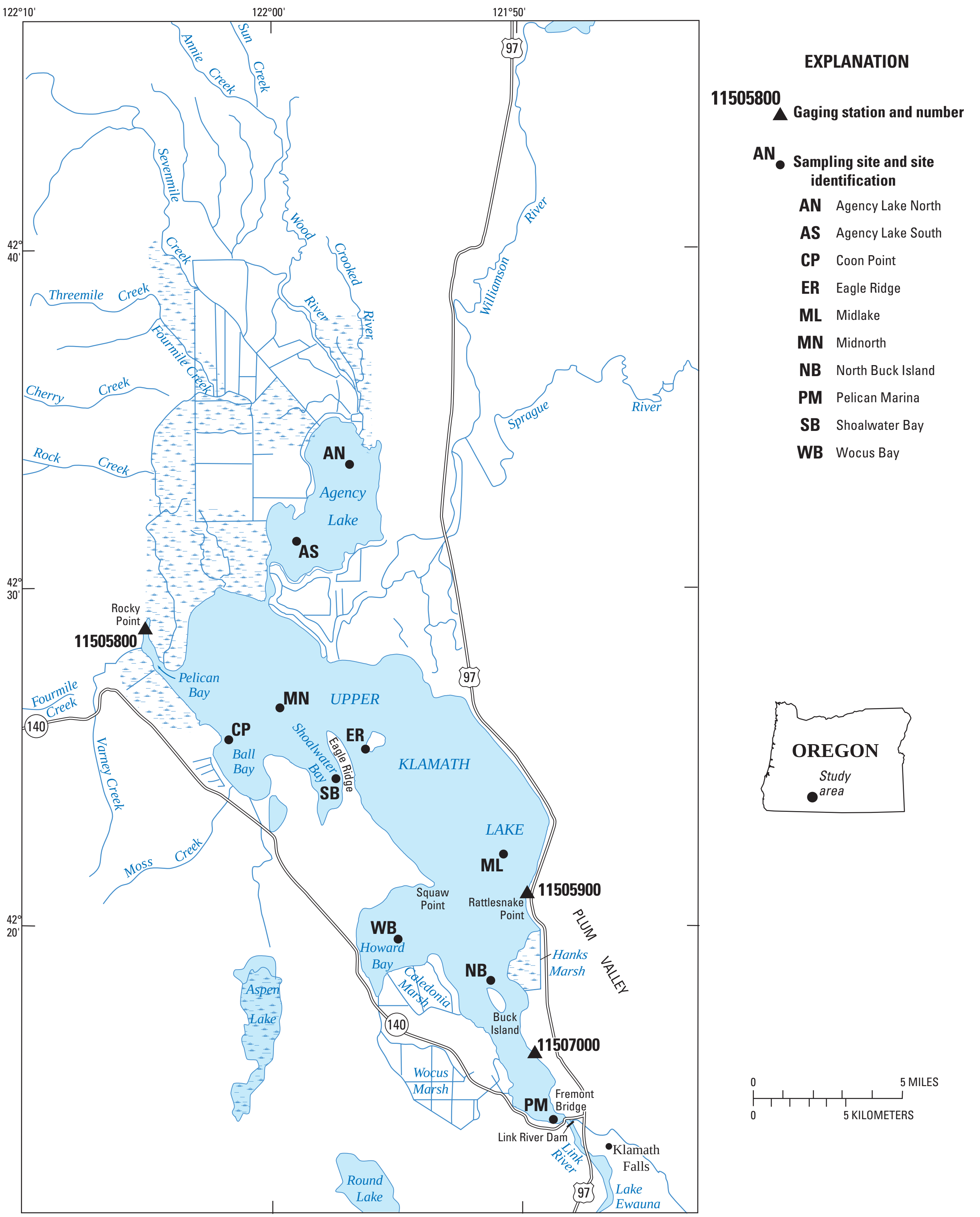


Figure 1. Sites on Upper Klamath and Agency Lakes, Oregon, with 10 or more years of water-quality data, 1990–2006.

Description of Datasets and Methods

In 1987, the Klamath Tribes began a water-quality monitoring program in Upper Klamath and Agency Lakes and contributing tributaries. The goal of this sampling program is to develop models to predict and prevent nutrient loading into Upper Klamath Lake, with the ultimate goal of "*…reducing toxic algal effects…and returning endangered species to harvestable levels for all residents of the basin*" (The Klamath Tribes, 2006). Among other sampling efforts that make up the larger program, depth-profile measurements of specific conductance, pH, water temperature, and dissolved-oxygen concentration were made at established sites throughout Upper Klamath and Agency Lakes every two weeks from May through October. Additionally, composite samples were collected for the analysis of nutrient, chlorophyll-*a*, and phaeophytin concentrations. During 1987–89, these samples were collected with a grab sampler and the sampling was not as frequent. Beginning in 1990, however, depth-integrated samples were collected and the sampling frequency was more consistent. Therefore, for this analysis, data prior to 1990 were not included.

Field-collection, analytical, and quality-assurance methods are described in The Klamath Tribes Quality Assurance Project Plan (The Klamath Tribes, 2006). For the most part, only small changes have been made to these techniques during the 17-year period (Kris Fischer, The Klamath Tribes, written commun., May 2007). The same laboratory has been used for the analyses, the sample-collection process has remained unchanged, and most of the sites have been maintained. The depth-profile measurements were made with multiparameter water-quality instruments, and typically were taken at the surface, at 0.5 m, and then at 1-m intervals descending the water column, with the last measurement taken at 0.1 m off the bottom. Depth-integrated samples, which were collected using a tube sampler lowered to within 6 inches of the sediment in an effort to represent the full water column, were composited into a churn splitter and then subsampled and preserved for the desired analyses. The types of quality-assurance samples collected by The Klamath Tribes are consistent with USGS protocols and include at least one trip blank, one equipment blank, one replicate sample, and one spike or reference sample per sampling event. These data are evaluated on a yearly basis with adjustments to sampling or analytical protocols made as needed.

Because this analysis involves examining seasonal and year-to-year variability, the desired dataset would include longer-term, regularly and consistently sampled sites. Therefore, sites with less than 10 years of data were not included. The 10 sites that met these criteria were Coon Point, Shoalwater Bay, Wocus Bay, Midnorth, Midlake, Eagle Ridge, North Buck Island, Pelican Marina, Agency Lake North, and Agency Lake South (fig. 1). For some analyses in this report, these sites are grouped together into areas—Agency Lake area (Agency Lake North and Agency Lake South), bay areas (Coon Point, Shoalwater Bay, and Wocus Bay), trench area (Eagle Ridge), open water areas (Midlake and Midnorth), and outflow areas (North Buck Island and Pelican Marina). Since 1990, most sites were sampled generally every two weeks from sometime in May through October (table 1). In some years, additional samples were collected during the rest of the year but much less frequently and not at all sites. In 1990, however, four sites were sampled almost weekly, whereas the other four sites were visited roughly monthly.

Lake level is recorded by the USGS at 30-minute intervals at three gaged sites around the lake (Rocky Point, Rattlesnake Point, and near the city of Klamath Falls). From these values a daily average is determined for each site and then these daily averages are weighted to determine a spatially averaged lake level for the entire lake. The spatially averaged lake level reported in the USGS Water Resources Data for Oregon 1974–2006 was used in this report (fig. 2). Over the 17 years discussed in this report, lake level was most variable during the first 5 years—the years discussed in the first report (Wood and others, 1996). There has been little variation in the maximum lake levels in the last 12 years, however, and little variation in the minimum lake levels in the last 5 years.

Air temperature and wind speed were the only climatic variables with long-term consistent datasets for 1990–2006. Air-temperature and wind-speed values used in this report were recorded at the Klamath Falls airport and were provided by the Oregon Climate Service (more recent data) and the National Climatic Data Center (an archive of longer-term data). Agrimet, an agricultural weather network maintained by the Bureau of Reclamation, also has a weather station (AGKO) on the banks of Agency Lake. Wind data were available for this location from 2000 to present; however, the limited time period covered by this dataset hampered the use of these data for this analysis. Besides air temperature and wind speed, the use of climatic data in this analysis was limited because the climatic datasets for the area for 1990–2006 were sporadic and not necessarily representative of conditions on the lake itself.

Table 1. Numbers of sampling dates that depth-profile measurements were recorded and composite samples were collected, Upper Klamath and Agency Lakes, Oregon , May–October 1990–2006.

[Depth-profile measurements consist of water temperature and either dissolved oxygen, pH, or both; composite samples were analyzed for at least total nitrogen, total phosphorus, and chlorophyll *a*; see figure 1 for site names and locations; –, not sampled]

Site	Number of sampling dates																	
	1990		1991		1992		1993		1994		1995		1996		1997		1998	
	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples
AN	–	–	10	10	11	11	13	12	8	8	13	13	–	–	6	6	10	10
AS	20	18	9	9	11	11	13	12	10	9	13	13	12	12	11	11	12	12
CP	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	6	11	11
ER	25	18	11	11	12	12	12	12	12	12	14	13	12	12	11	11	12	12
ML	5	5	10	10	12	12	12	12	13	13	13	13	12	12	11	11	12	12
MN	21	18	11	11	12	12	13	12	15	18	14	13	12	12	11	11	12	12
NB	5	5	10	10	12	12	12	12	9	9	13	13	–	–	11	11	12	12
PM	5	5	12	10	12	12	12	12	9	9	13	13	–	–	11	11	12	12
SB	18	16	11	11	12	12	12	12	12	12	14	13	12	12	11	11	12	12
WB	5	5	10	10	11	11	12	12	8	8	13	13	–	–	11	11	12	12
All	104	90	94	92	105	105	111	108	96	98	120	117	60	60	100	100	117	117

Site	1999		2000		2001		2002		2003		2004		2005		2006		1990–2006	
	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples	Depth profile	Composite samples
AN	10	10	14	14	11	11	11	11	10	10	11	11	11	11	12	11	161	159
AS	11	11	14	14	12	12	11	11	10	10	11	11	13	13	12	11	205	200
CP	9	9	14	14	12	12	12	12	11	11	11	11	12	12	12	11	110	109
ER	11	11	14	14	12	12	12	12	11	11	11	11	13	13	12	11	217	208
ML	11	11	14	14	12	12	12	12	12	12	11	11	12	12	12	11	196	195
MN	11	11	14	14	12	12	12	12	10	10	11	11	14	13	12	11	217	213
NB	11	11	14	14	12	12	12	12	11	11	11	11	13	13	12	11	180	179
PM	11	11	14	14	12	12	12	12	11	11	11	11	14	14	12	11	183	180
SB	11	11	14	14	12	12	12	12	11	11	11	11	13	13	12	11	210	206
WB	11	11	14	14	12	12	12	12	11	11	11	11	13	13	12	11	178	177
All	107	107	140	140	119	119	118	118	108	108	110	110	128	127	120	110	1,857	1,826

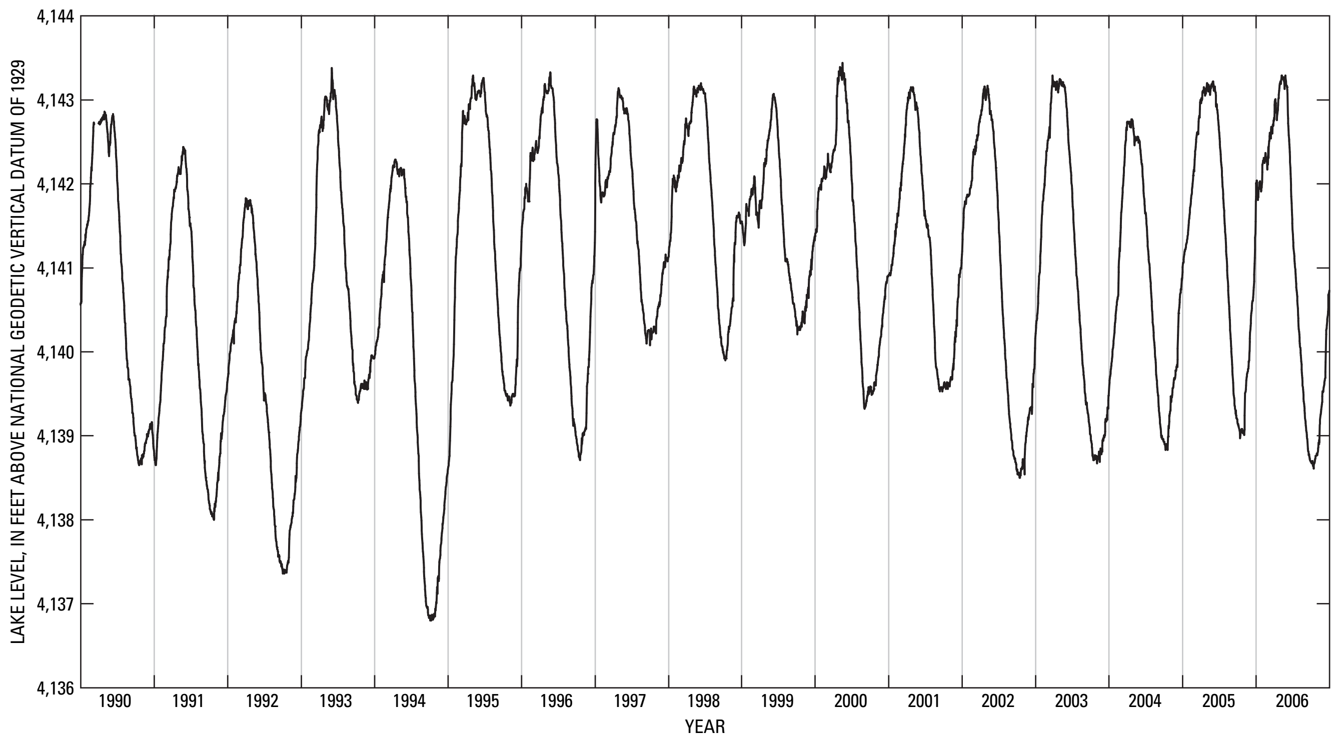


Figure 2. Daily lake level of Upper Klamath Lake, Oregon, 1990–2006.

Strengths and Limitations of Datasets

The primary limitation of the Klamath Tribes water-quality dataset for this report is that the sampling program was not designed to address the questions being asked in this report. The spatial and temporal coverage of the Klamath Tribes sampling program meets the needs of their program, but the two-week sampling interval is not ideal for assessing water-quality conditions and potentially biologically significant events over the course of the algal bloom growth and decline. To truly capture all of the variation in water-quality conditions during this period, continuous monitoring of specific conductance, pH, water temperature, and dissolved-oxygen concentration along with more frequently collected water-column samples for the analysis of nutrient and chlorophyll-*a* concentrations would be needed.

For the purpose of this report, the main and overriding strength of the Klamath Tribes water-quality dataset is the period of record and its consistency. It is the only 17-year dataset with a consistent group of sites and little change in sampling and analytical techniques available for Upper Klamath Lake. For these reasons, it is an adequate dataset to be used for looking for long-term relations between water-quality variables, climatic factors, and lake level. These same type of statements about the strengths and limitations of the water-quality dataset can be made about the climatic datasets. The climatic factors considered in this report were limited to air temperature and wind speed because these were the only datasets available for 1990–2006. The wind-speed data collected at the Klamath Falls airport were not ideal for this analysis because they were not deemed to be very representative of conditions on the lake itself, but this is discussed further in the “Wind Speed” section of this report.

Statistical Methods

When it is suspected that a dataset is not from a normally distributed population, as was assumed for this analysis, nonparametric techniques may be more appropriate for examining correlations. Nonparametric statistics use rankings of the data rather than the actual values. A Spearman test, which calculates a Spearman *rho* correlation coefficient (ρ) and a probability level (p), was used to examine correlations between datasets in this analysis. Spearman’s ρ has values from -1 to +1 for negative and positive associations and values close to 0 for little or no association. In this report, a correlation is considered “statistically significant” when the probability of two variables appear to be correlated when, in fact, they are not, is less than 0.05 (a Type 1 error, greater than 95 percent confidence level). Furthermore, a correlation is considered “strong” when the correlation is significant and the Spearman’s ρ value is greater than 0.5 (positive or negative).

For the multivariable investigations presented in this report, multiple linear regressions were calculated and then evaluated with the Akaike Information Criterion (AIC_c) to determine the “best fitting” models. This is discussed in greater detail in the “Information-Theoretic Approach to Multivariable Analysis of Water-Quality Conditions” section of this report. All statistical tests were run using P-STAT, version 2.21, rev. 8 (P-STAT, Inc., 1990).

Characterization of Years

To help in evaluating relations in water-quality conditions between the years, three factors were used to rank the years in relation to each other—end-of-month lake level, degree-days, and timing of the beginning of the AFA bloom.

Lake Level

To explore how each year from 1990 to 2006 compared to each other and to the historical record, the end-of-month lake levels were compared (fig. 3). Historically, the gage height at USGS site 11507000, at the southeastern end of the lake near the outflow, was used as a measure of lake level, so the gage height is used for the entire 1922–2006 period for this comparison, rather than the calculated spatially averaged lake level, which was not developed until 1974. It is obvious that 1992 (May–August) and 1994 (July and August) are outliers for the 1990–2006 dataset, and that lake levels in these years were low not only for this dataset but also for the historical record. It is difficult to distinguish the ranking of the rest of the 1990–2006 years from figure 3; however, it can be observed that a large overall range in lake level is represented in the 1990–2006 dataset with most years falling within the middle 50 percent of the historical data. In fact, the only years falling below the 25th percentile of the historical data are 1992, 1994, 1991, and 2002, respectively. A few years were above the 75th percentile for the historical data, but there is no consistent pattern to these years.

A statistically based convention was used to assign a ranking to each year based on lake level. Percentiles were assigned to the end-of-month lake levels for each year by month based on the corresponding distribution of the end-of-month lake levels for the historical 1922–2006 dataset (table 2). For each year, these monthly percentiles were summed for May through August. These sums were then ordered to develop an overall lake-level ranking for each year. From this ranking, once again the years 1992, 1994, and 1991 are recognized to be notably low lake-level years.

Degree-Days

Recognizing that the growth of the AFA bloom is related to the water-quality conditions in the lake, and that climatic conditions also affect the growth of the bloom, climatic factors also were considered in making year-to-year comparisons.

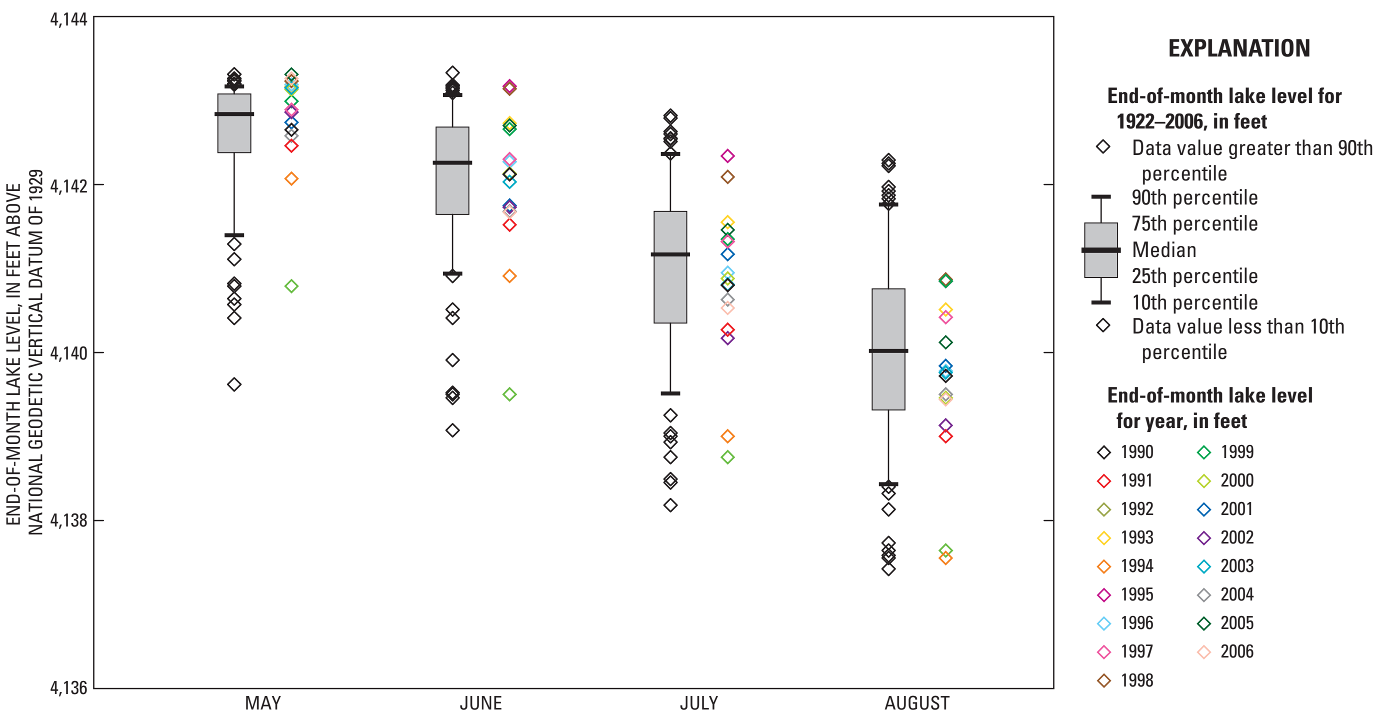


Figure 3. Comparison of May through August end-of-month lake level for 1990–2006 with the frequency distribution of the historical, post-dam, end-of-month values for 1922–2006, Upper Klamath Lake, Oregon.

Table 2. Ranking of percentiles of lake level by month for May–August 1990–2006 based on post-dam 1922–2006 end-of-month lake level and overall ranking of years, Upper Klamath Lake, Oregon.

[Breaks are shown at 25th and 75th percentiles]

Percentiles based on 1922–2006 lake level and corresponding year								Sum of May–August percentiles by year	Ranking of years
May		June		July		August			
Percentile	Year	Percentile	Year	Percentile	Year	Percentile	Year		
4.8	1992	2.4	1992	3.6	1992	1.2	1994	14	1992
13.2	1994	8.4	1994	6.0	1994	3.6	1992	29	1994
28.9	1991	18.0	1991	16.8	2002	18.0	1991	85	1991
34.9	2004	24.0	2006	20.4	1991	21.6	2002	117	2002
36.1	1990	25.3	2004	26.5	2006	27.7	2006	120	2004
38.5	2001	27.7	2002	30.1	2004	28.9	2000	148	1990
50.6	2002	30.1	2001	34.9	1990	30.1	2004	161	2001
54.2	1997	38.5	2003	36.1	2003	34.9	1990	177	2006
62.6	1999	42.1	1990	40.9	2000	38.5	2003	195	2000
81.9	2000	43.3	2000	43.3	1996	39.7	1996	199	2003
85.5	1995	50.6	1996	49.3	2001	43.3	2001	226	1996
85.5	2003	51.8	1997	59.0	1997	53.0	2005	229	1997
89.1	1993	73.4	1999	62.6	1999	63.8	1997	275	1999
92.7	1996	75.9	2005	65.0	2005	69.8	1993	294	2005
96.3	1998	78.3	1993	68.6	1993	75.9	1995	306	1993
98.7	2006	93.9	1998	83.1	1998	75.9	1999	347	1995
100.0	2005	96.3	1995	89.1	1995	79.5	1998	353	1998

Factors such as air temperature and cloud cover are expected to have an effect on when the bloom begins to grow and the rate at which it develops. One way of trying to quantify these conditions is by comparing the warmth of the springtime conditions in each year. Degree-days can be used as a measure of heating or cooling for a system. For this analysis, degree-days were calculated as the difference between the mean temperature (in degrees Celsius [°C]) for a given day and a reference temperature (0°C in this case). The mean temperature for the day was calculated as the average of the minimum and maximum air temperature for each day at the Klamath Falls airport. These degree-days were then summed for each year from April 1 to May 15. This summation then provides a way to compare how warm the spring was for each year in relation to other springs and another way to rank the 1990–2006 dataset (table 3).

Table 3. Ranking of years from warmest to coolest spring based on cumulative degree-days from April 1 to May 15, Upper Klamath Lake, Oregon, 1990–2006.

Cumulative degree-days from April 1 to May 15	Year
513	1992
470	1990
449	1997
440	1994
424	1996
392	2000
390	2004
381	2006
374	1993
336	2001
336	1995
333	2002
325	1998
318	2005
296	1991
286	1999
227	2003

Timing of Bloom

Determining the onset of the AFA bloom can be tricky. Individual chlorophyll-*a* measurements ranged from less than 2 µg/L, the approximate limit of detection, to more than

1,000 µg/L. The median chlorophyll-*a* concentration for samples collected prior to May 15 of each year was 6 µg/L with a maximum concentration of 16 µg/L. Once the bloom begins to develop each year, individual values rise quickly, and concentrations at any time vary widely throughout the lake. When more than one individual measurement was made in a day, the median of the individual measurements was selected to represent the overall condition of the lake on that date. The date the median concentration exceeded 20 µg/L was taken to represent the beginning of each year's AFA bloom. Problems arose when the onset of the bloom was determined based on the first sampling date with a median chlorophyll-*a* concentration greater than 20 µg/L. Examining the concentrations measured in 1997 illustrates this point (fig. 4). The median chlorophyll-*a* concentration measured on May 20 was 18 µg/L, closely approaching the defined onset of the bloom. The next sampling day was not until June 16, almost a month later, when the bloom was near its peak with a median chlorophyll-*a* concentration of 197 µg/L, the highest median concentration measured that year. By the method described above, the onset of the bloom would be defined as June 16 (or Julian day[1] 167), clearly much later than the "true" onset of the bloom.

[1] Julian days are a way of expressing dates, such that days in the year are numbered consecutively from 1 to 364 or 365. It is easier to make comparisons between years when using Julian days.

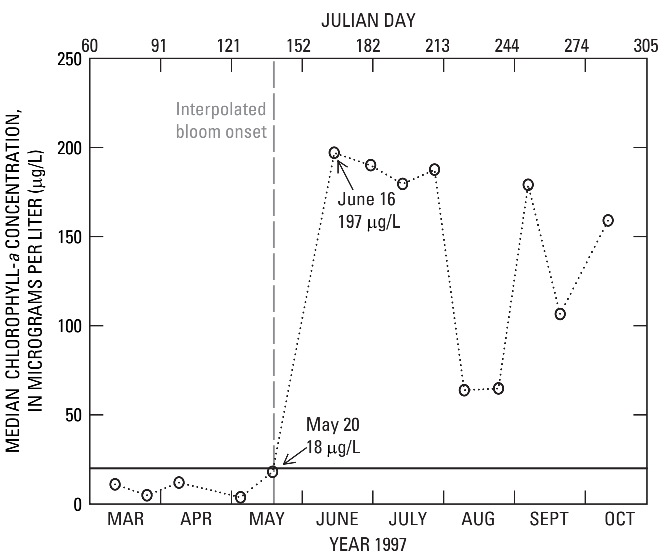


Figure 4. Median lakewide chlorophyll-*a* concentrations, Upper Klamath Lake, Oregon, 1997.

Therefore, the method used to define the onset of the bloom for this analysis was to interpolate between the sampling dates to determine when the median chlorophyll-*a* concentration would have exceeded 20 µg/L. The inherent problem with this method lies in the assumption that there is a linear relation between the sampled concentrations. Considering the pitfalls of this assumption, the data were examined for potential problems. For many of the years, one of the two samplings with chlorophyll-*a* concentrations bracketing the 20 µg/L value had concentrations fairly close to 20 µg/L; therefore the error associated with the interpolation was minimized. For a few years, there was a larger range between the chlorophyll-*a* concentrations but the samplings were closer together, again minimizing the error associated with the interpolation. So, for 1997, the onset of the bloom was defined as May 20 or Julian day 140.5 (fig. 4). Based on the Julian days assigned as the onset of the bloom from the interpolation method, a ranking of the years for the timing of the bloom was developed (table 4).

The onset of the bloom for the majority of the years occurred during the last week of May and the first week of June, with the earliest bloom starting in mid-May in 1992

Table 4. Ranking of years based on the timing of the onset of the *Aphanizomenon flos-aquae* bloom, Upper Klamath Lake, Oregon, 1990–2006.

[µg/L, micrograms per liter]

Julian day of the first sampling date when the median chlorophyll-*a* concentration was greater than 20 µg/L	Year	Julian day when the interpolated median chlorophyll-*a* concentration was greater than 20 µg/L	Year
141	1992	139.5	1992
152	2000	140.5	1997
154	1998	141	2000
159	1994	144	2001
161	1999	145.6	1998
161	2005	145.7	1994
162	1990	150.2	1990
162	2004	150.3	1996
163	1996	150.9	2002
163	2001	151	2004
164	2002	151.2	1995
166	1995	151.6	2005
167	1997	157.4	1993
168	1993	158.9	1999
169	2003	160.9	2003
182	1991	170.8	1991
186	2006	172	2006

and the latest bloom starting in mid-June in 2006. One year worth noting is 1991. The chlorophyll-*a* concentrations began to increase in early June with a median concentration of 26 µg/L, but by the next sampling date on June 19, the bloom had clearly stalled (median concentration of 13 µg/L). By the next sampling date (July 1), however, the bloom was in full production with a median concentration of 120 µg/L. The second time that the chlorophyll-*a* concentration was interpolated to exceed 20 µg/L was used as the onset of the bloom (Julian day 170.8).

Wind Speed

A ranking of the years based on median wind speed during the July–August period also was considered a way to characterize climatic conditions for the lake. As Wood and others (2006) discussed, it is the peak wind speeds of the day that are of potential concern in relation to water-quality conditions. Wind speeds throughout the day generally are low with brief periods of peak conditions. In an effort to examine these higher wind speeds and minimize the effects of the low wind speeds that dominate the dataset, only wind speeds that exceeded the median wind speed for each month as determined from the entire 17-year dataset were considered. The median wind speed of this upper half of the data was then reported for July and August (table 5).

Wood and others (2006) determined the NCDC wind-speed dataset to be somewhat troublesome and suggested that these data should be interpreted qualitatively. They noted evidence of “binning” of the data (rather than being continuous, data values tended to fall on discrete values) and numerous occurrences of zero wind speeds, perhaps suggesting the use of a threshold value for reporting the data. As a way of examining the quality of the NCDC data, the median values were compared to the median monthly wind speeds (calculated in the same manner as the NCDC medians) for July and August from the Agrimet weather station located adjacent to Agency Lake. This comparison was repeated in this report including data through 2006 (table 5). Many differences, not only in values between the years, but also in the ranking of the years based on median wind speed, exist between these two datasets. One notable discrepancy in the NCDC dataset is the large difference between the 2001 median values for July and August and the rest of the years. These discrepancies further hint at the questionable quality of these data; therefore, an overall ranking of the years based on wind speed was not pursued. Because wind speed was suspected to be a potentially important climatic factor, and because the Agrimet dataset only covered 2000–2006, the longer-term NCDC wind-speed data were used in the information-theoretic approach discussed later in this report.

Table 5. Comparison of ranking of years based on wind-speed data measured at the Klamath Falls airport and at the Agrimet site adjacent to Agency Lake, Oregon, July–August 2000–2006.

[Hourly data measured at the Klamath Falls airport were obtained from the National Climatic Data Center (NCDC), and hourly data from the weather station (AGKO) adjacent to Agency Lake were obtained from the Bureau of Reclamation’s Agrimet service. Both datasets initially were filtered by including only those wind speeds greater than the median wind speed for each month for 1990–2006 for the NCDC data and for 2000–06 for the Agrimet data. From the remaining upper one-half of the data, the median wind speeds were calculated for each month. m/s, meter per second]

NCDC		Agrimet	
Median wind speed (m/s)	Year	Median wind speed (m/s)	Year
July			
4.9	2001	2.7	2005
3.6	2005	2.2	2000
3.6	2000	2.0	2006
3.6	2002	1.9	2003
3.6	2004	1.8	2001
3.1	2003	1.8	2002
3.1	2006	1.5	2004
August			
4.5	2001	1.8	2000
3.6	2006	1.8	2001
3.6	2000	1.8	2002
3.6	2002	1.7	2005
3.6	2003	1.7	2006
3.6	2004	1.6	2003
3.1	2005	1.6	2004

Comparison of Rankings

Some interesting observations can be made when comparing the rankings resulting from these three methods of characterizing the years (table 6). The year 1992 is notable because it is at the top of all three rankings—the lowest overall lake level, the warmest spring, and the earliest onset of the bloom. Similar in lake level, 1991 has already been shown to be an unusual year. With a lower lake level and cooler spring, the bloom seemed to stall as it was ramping up, resulting in a later onset of the bloom. In 2006, lake level and degree-day rankings were in the middle of the grouping; however, the bloom had the latest onset of the 17 years. In contrast, 1997, which had a higher lake level but a warm spring, had the second earliest onset of the bloom. By examining the rankings of these variables, it would seem that a warmer spring may have a greater influence on the timing of the bloom and therefore the related poor water-quality conditions. It should be noted, however, that the pattern observed in 2006 hints that there may be more to the story.

Table 6. Ranking of 1990–2006 by lake level, degree-days, and timing of bloom onset, Upper Klamath Lake, Oregon.

[For details of how these rankings were determined, see table 2 for lake level, table 3 for degree-days, and table 4 for timing of the bloom]

Lake level	Degree-days	Timing of bloom
Lowest lake level	Warmest spring	Earliest bloom
1992	1992	1992
1994	1990	1997
1991	1997	2000
2002	1994	2001
2004	1996	1998
1990	2000	1994
2001	2004	1990
2006	2006	1996
2000	1993	2002
2003	2001	2004
1996	1995	1995
1997	2002	2005
1999	1998	1993
2005	2005	1999
1993	1991	2003
1995	1999	1991
1998	2003	2006
Highest lake level	Coolest spring	Latest bloom

Temporal and Spatial Variability of Poor Water-Quality Conditions

For this report, water-quality conditions are considered poor when they have the potential to be harmful to the endangered sucker species. Based on high-stress thresholds established to calculate stress indices for Upper Klamath Lake suckers (Reiser and others, 2000), the values used in this study to delimit poor water-quality conditions were water-temperature values greater than 28°C, dissolved-oxygen concentrations less than 4 mg/L, and pH values greater than 9.7. Additionally, the USEPA (U.S. Environmental Protection Agency) criteria (U.S. Environmental Protection Agency, 1999) were used to screen total ammonia concentrations, and un-ionized ammonia concentrations were evaluated against LC_{50} (median lethal concentrations) values of 530 µg/L for Lost River suckers and 780 µg/L for shortnose suckers (Saiki and others, 1999).

Water Temperature

Of the 7,090 water temperatures recorded during May–October 1990–2006, only 10 values were greater than 28°C. These temperatures were all measured at the surface in the afternoon, and most measurements were in the latter part of July, when air temperatures are expected to be elevated. The two warm water temperatures were recorded in June 1997 and 2000, years with warmer springs and earlier blooms (table 6). High pH values also were recorded with these June warm water temperatures, which fit with the early onset of the bloom. The period when the bloom is growing generally is associated with high dissolved-oxygen concentrations and high pH values, as photosynthesizing algae consume carbon dioxide and produce oxygen. One-half of measurements with water-temperature values greater than 28°C also were associated with dissolved-oxygen concentrations greater than 12 mg/L and pH values greater than 9.7.

Dissolved Oxygen

By filtering the 1990–2006 dataset using the dissolved-oxygen guideline for delimiting poor water-quality conditions, the mid- to late-season pattern of excursions into the less than 4 mg/L range can be observed (table 7). The highest frequency of concentrations less than 4 mg/L occurred in August, then in July, and then in September. Low dissolved oxygen was measured during 3 years (1998, 2000, 2002) as early as June.

Table 7. Summary of dissolved-oxygen concentrations in the depth-profile dataset, Upper Klamath and Agency Lakes, Oregon, May–October 1990–2006.

[Values are shown as the number of samples, whereas the percent < 4 milligrams per liter (mg/L) is shown as a percentage; shading is used to aid the visualization of the increasing percentage of values less than 4 mg/L. <, less than; ≥, greater than or equal to; –, not sampled]

Year	May				June				July				August				September				October			
	All values	Values ≥ 4 mg/L	Values < 4 mg/L	Percent < 4 mg/L	All values	Values ≥ 4 mg/L	Values < 4 mg/L	Percent < 4 mg/L	All values	Values ≥ 4 mg/L	Values < 4 mg/L	Percent < 4 mg/L	All values	Values ≥ 4 mg/L	Values < 4 mg/L	Percent < 4 mg/L	All values	Values ≥ 4 mg/L	Values < 4 mg/L	Percent < 4 mg/L	All values	Values ≥ 4 mg/L	Values < 4 mg/L	Percent < 4 mg/L
1990	38	38	0	0	80	80	0	0	93	82	11	12	49	42	7	14	57	50	7	12	71	71	0	0
1991	–	–	–	–	68	68	0	0	54	54	0	0	89	88	1	1	53	51	2	4	45	39	6	13
1992	67	67	0	0	63	63	0	0	89	78	11	12	51	40	11	22	28	26	2	7	45	45	0	0
1993	41	41	0	0	121	121	0	0	83	83	0	0	69	51	18	26	65	49	16	25	62	60	2	3
1994	81	81	0	0	73	73	0	0	47	47	0	0	56	38	18	32	49	49	0	0	34	34	0	0
1995	117	117	0	0	75	75	0	0	71	65	6	8	79	68	11	14	61	47	14	23	57	56	1	2
1996	24	24	0	0	47	47	0	0	45	41	4	9	43	43	0	0	38	38	0	0	56	51	5	9
1997	77	77	0	0	39	39	0	0	111	94	17	15	71	61	10	14	67	67	0	0	30	30	0	0
1998	43	43	0	0	127	126	1	1	71	57	14	20	73	53	20	27	71	70	1	1	70	69	1	1
1999	78	78	0	0	88	88	0	0	76	71	5	7	76	64	12	16	113	112	1	1	–	–	–	–
2000	137	137	0	0	85	80	5	6	79	66	13	16	71	41	30	42	73	69	4	5	101	100	1	1
2001	83	83	0	0	79	79	0	0	116	110	6	5	72	46	26	36	71	51	20	28	34	27	7	21
2002	131	131	0	0	86	82	4	5	77	62	15	19	70	62	8	11	30	30	0	0	31	31	0	0
2003	45	45	0	0	86	86	0	0	118	90	28	24	71	64	7	10	66	57	9	14	27	26	1	4
2004	88	88	0	0	83	83	0	0	79	69	10	13	71	54	17	24	98	93	5	5	–	–	–	–
2005	141	141	0	0	93	93	0	0	82	73	9	11	107	92	15	14	70	70	0	0	34	34	0	0
2006	90	90	0	0	88	88	0	0	112	103	9	8	70	65	5	7	63	63	0	0	30	28	2	7

Further examining the dissolved-oxygen data by site and year (table 8) revealed that the highest frequencies of low dissolved-oxygen concentrations were observed at the Eagle Ridge site. These increased frequencies are due to the larger number of measurements made at this deeper site (typically 7 to 8 measurements per visit at this deeper site and 3 to 4 measurements per visit at the other sites) and the effect of deep circulation through the trench. Light does not penetrate this deeper water enough to drive photosynthesis, yet respiration continues, depleting the water column of dissolved oxygen.

pH

Unlike the patterns of poor water-quality conditions observed in the dissolved-oxygen data, high pH values were more frequent and occurred earlier in the season (table 9). This offset in the occurrence of low dissolved-oxygen concentrations and high pH values is better for overall water-quality conditions than if these stressors were occurring together more frequently. The highest frequency of pH values greater than 9.7 occurred in June and July, with high values persisting into August and September for some years.

Table 8. Percentage of dissolved-oxygen concentrations in the depth-profile dataset less than 4 milligrams per liter by year and site, Upper Klamath and Agency Lakes, Oregon, May–October 1990–2006.

[See figure 1 for site names and locations. –, not sampled]

Year	All	AN	AS	CP	ER	ML	MN	NB	PM	SB	WB
1990	6	–	5	–	14	0	0	0	0	4	0
1991	3	0	0	–	5	0	3	0	0	9	4
1992	7	3	0	–	18	0	2	0	0	14	8
1993	8	0	11	–	19	0	0	0	0	9	28
1994	5	4	13	–	13	2	2	0	0	3	0
1995	7	0	0	–	24	0	0	0	0	8	9
1996	4	–	6	–	6	0	2	–	–	2	–
1997	7	0	19	8	14	0	4	0	0	10	6
1998	8	3	9	13	15	0	8	3	7	12	3
1999	4	3	0	8	11	0	0	0	0	12	0
2000	10	6	10	18	11	2	8	12	6	12	10
2001	13	17	6	11	22	17	4	13	3	18	9
2002	6	8	14	13	16	0	0	0	0	0	0
2003	11	3	0	24	28	4	10	0	0	5	3
2004	8	5	14	10	14	0	0	6	0	15	3
2005	5	5	0	2	13	0	7	0	0	6	3
2006	4	3	0	0	13	0	0	0	0	2	6

Table 9. Summary of pH values in the depth-profile dataset, Upper Klamath and Agency Lakes, Oregon, May–October 1990–2006.

[Values are shown as the number of samples, whereas the percent > 9.7 is shown as a percentage; shading is used to aid the visualization of the increasing percentage of values greater than 9.7. >, greater than; ≤, less than or equal to; –, not sampled]

Year	May				June				July				August				September				October			
	All values	Values ≤ 9.7	Values > 9.7	Percent > 9.7	All values	Values ≤ 9.7	Values > 9.7	Percent > 9.7	All values	Values ≤ 9.7	Values > 9.7	Percent > 9.7	All values	Values ≤ 9.7	Values > 9.7	Percent > 9.7	All values	Values ≤ 9.7	Values > 9.7	Percent > 9.7	All values	Values ≤ 9.7	Values > 9.7	Percent > 9.7
1990	10	10	0	0	80	48	32	40	93	74	19	20	49	48	1	2	57	48	9	16	71	71	0	0
1991	–	–	–	–	68	68	0	0	54	39	15	28	72	67	5	7	53	36	17	32	45	45	0	0
1992	67	67	0	0	63	30	33	52	89	87	2	2	51	51	0	0	28	27	1	4	45	45	0	0
1993	41	41	0	0	121	119	2	2	83	59	24	29	69	68	1	1	65	65	0	0	62	62	0	0
1994	81	81	0	0	73	46	27	37	47	19	28	60	54	54	0	0	49	49	0	0	34	34	0	0
1995	117	117	0	0	75	50	25	33	71	48	23	32	79	60	19	24	61	55	6	10	57	57	0	0
1996	24	24	0	0	47	44	3	6	45	40	5	11	43	38	5	12	38	38	0	0	56	53	3	5
1997	77	77	0	0	39	32	7	18	112	84	28	25	71	71	0	0	67	66	1	1	30	30	0	0
1998	43	43	0	0	127	119	8	6	71	64	7	10	73	73	0	0	71	71	0	0	70	70	0	0
1999	78	78	0	0	88	79	9	10	76	30	46	61	76	67	9	12	113	113	0	0	–	–	–	–
2000	137	137	0	0	85	28	57	67	79	49	30	38	71	70	1	1	73	71	2	3	101	101	0	0
2001	83	83	0	0	79	63	16	20	116	75	41	35	72	71	1	1	71	71	0	0	34	34	0	0
2002	131	130	1	1	86	75	11	13	77	62	15	19	70	70	0	0	58	58	0	0	31	31	0	0
2003	45	45	0	0	86	86	0	0	118	101	17	14	71	57	14	20	66	51	15	23	27	27	0	0
2004	88	88	0	0	83	62	21	25	79	57	22	28	71	68	3	4	98	97	1	1	–	–	–	–
2005	141	141	0	0	93	91	2	2	82	74	8	10	107	104	3	3	70	70	0	0	34	34	0	0
2006	90	90	0	0	88	82	6	7	112	103	9	8	70	45	25	36	63	22	41	65	30	30	0	0

Spatial patterns show that when high pH values were measured, they were often observed at sites all around the lake (table 10). During most years, there are occurrences of high pH values at most sites; however, during years with a lower overall frequency of pH values greater than 9.7, not all sites experience these poor water-quality conditions. The Agency Lake sites seem to have a higher frequency of high pH values, and in June, often had higher pH values than Upper Klamath Lake sites. The depth profiles also showed that there was little vertical variation in pH values throughout the water column. High pH values tend to occur either at the surface or throughout the water column, as can be observed by examining the depth profile pH data for 2000, a year with a high frequency of pH values greater than 9.7 (fig. 5).

Ammonia

Prior to 1999, the USEPA criteria for ammonia were established to evaluate un-ionized ammonia concentrations, because it was believed that the un-ionized part of total ammonia was much more toxic to aquatic life. It has been recognized, however, that the ammonium ion (the other part that makes up total ammonia) also may contribute significantly to ammonia toxicity under certain conditions (U.S. Environmental Protection Agency, 1999). Therefore, the current criteria are based on total-ammonia concentrations.

Table 10. Percentage of pH values in the depth-profile dataset greater than 9.7 by year and site, Upper Klamath and Agency Lakes, Oregon, May–October 1990–2006.

[See figure 1 for site names and locations. –, not sampled]

Year	All	AN	AS	CP	ER	ML	MN	NB	PM	SB	WB
1990	17	–	47	–	7	6	15	0	23	19	17
1991	13	16	18	–	3	13	8	24	8	16	29
1992	11	24	17	–	9	2	9	10	10	11	8
1993	6	23	22	–	0	0	5	0	8	0	8
1994	16	17	25	–	11	17	9	22	24	15	29
1995	16	16	22	–	5	19	10	32	38	8	17
1996	6	–	26	–	2	5	4	–	–	5	–
1997	9	5	6	0	5	14	2	21	14	10	18
1998	3	9	13	2	2	2	0	3	5	2	0
1999	15	26	21	13	4	23	12	17	18	9	21
2000	16	4	14	13	17	21	15	19	23	14	28
2001	13	6	6	6	2	17	12	24	29	8	38
2002	6	13	14	6	1	0	6	8	3	5	19
2003	11	20	30	2	4	9	3	24	17	3	23
2004	11	24	31	4	2	13	14	15	6	3	21
2005	2	10	8	0	0	0	2	0	0	6	5
2006	18	18	3	21	12	16	20	16	18	22	36

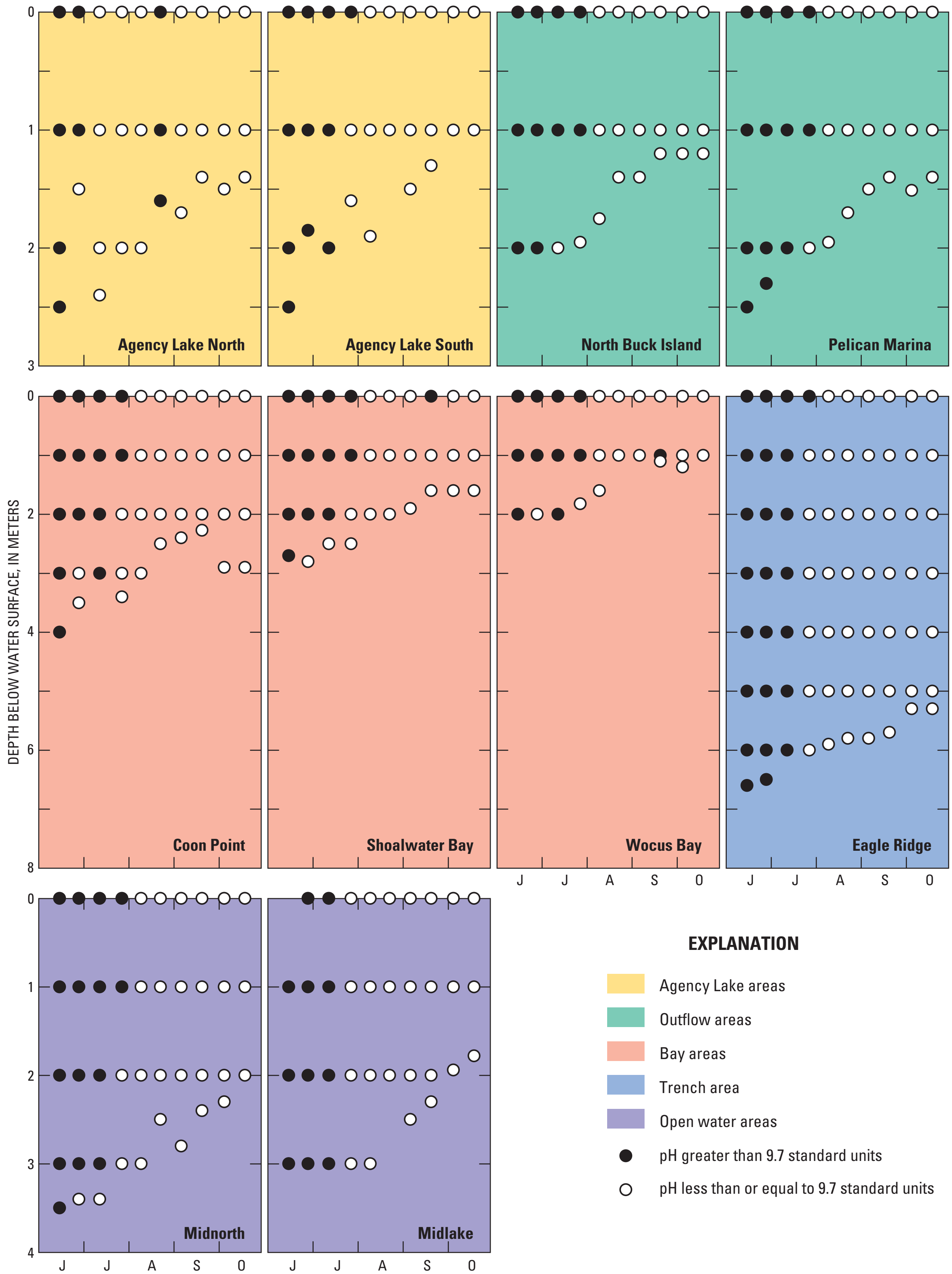


Figure 5. Depth-profile pH data, Upper Klamath and Agency Lakes, Oregon, June–October 2000.

These criteria are based on the water temperature and pH of the samples and are applicable for waters with a pH between 6.5 and 9. The guidelines used to evaluate total-ammonia concentrations for this analysis are based on the acute criterion (based on a 1-hour average concentration) for when salmonids are present and the chronic criterion (based on a 30-day average concentration) for when fish early life stages are present. For example, the criterion is 2.2 mg/L at pH 8.5 when adult salmonids are present and 0.8 mg/L at pH 8.5 and 18°C when early life stages are present.

Roughly one-half of samples collected in Upper Klamath and Agency Lakes between 1990 and 2006 had pH values of less than 9 and therefore were compared against the USEPA criteria (table 11). For those samples with exceedances, the chronic (30-day average) criteria values generally were about 70 percent lower than the acute (1-hour) criteria values. A small number of samples (less than 1 percent) exceeded the acute guideline, and one-half of these were measured in Shoalwater Bay. There were a few more exceedances (less than 10 percent) of the chronic guideline, but the data were too sparse to calculate representative 30-day environmental concentrations. Almost one-half of these exceedances were measured in the bay areas (Coon Point, Shoalwater Bay, and Wocus Bay).

The part of the dataset that could not be evaluated against the USEPA criteria because the pH was greater than 9 may be the part that signals more detrimental conditions for the suckers. When high ammonia concentrations occur with high pH and water temperatures, a significant fraction of the total concentration of ammonia will be present in the un-ionized form, which is much more toxic to aquatic life. By using the USEPA formulas (U.S. Environmental Protection Agency, 1999), un-ionized ammonia concentrations were calculated from total ammonia concentrations, pH values, and water temperatures for the entire 1990–2006 dataset. These concentrations were evaluated against the LC_{50} value of 530 µg/L for Lost River suckers, recognizing that although the LC_{50} value for shortnose suckers is higher, concentrations greater than 530 µg/L would be stressful for shortnose suckers as well. Although the acute and chronic total-ammonia USEPA criteria represent “acceptable no-effect levels” of total ammonia, the LC_{50} values for un-ionized ammonia concentrations represent “unacceptable severe-effect levels” for the health of the suckers. About 3 percent of the 2,023 un-ionized ammonia concentrations exceeded 530 µg/L, and there was at least one exceedance at each of the 10 sites (table 12). One-third of these exceedances occurred in the bay areas. All except one of these exceedances occurred between 1996 and 2003, when total ammonia concentrations were the highest of the 17-year period (Wood and others, 2006).

Interrelatedness of Water-Quality Variables

It is useful to examine how these water-quality variables that are used to delimit poor water-quality conditions are interrelated, and how they relate to the algal blooms occurring in Upper Klamath Lake. According to Wood and others (2006), bloom dynamics, as observed in the chlorophyll-*a* data, are associated with the trends and fluctuations observed in water-quality parameters. A crash in the algal bloom results in a sharp reduction in chlorophyll-*a* concentrations. As the oxygen production from photosynthesis stops or decreases, and the sediment and water-column oxygen demands continue, there is a decrease in dissolved oxygen, generally to values below saturation. In contrast, when the bloom is growing, photosynthesizing algae consume carbon dioxide and produce oxygen, resulting in supersaturated dissolved oxygen and high pH.

Four years (1992, 1991, 2006, and 1997) were used to explore how mean water temperatures, minimum dissolved-oxygen concentrations, maximum pH values, median ammonia concentrations, and median chlorophyll-*a* concentrations are related under different combinations of conditions. As a reminder, 1992 was ranked as the lowest lake level, warmest spring, and earliest bloom onset. The year 1991 also was ranked as a low lake-level year, but perhaps as a result of the cool spring, it had the second latest bloom onset. The second earliest bloom onset occurred in 1997, a year with a lake level in the middle to high end of the rankings but a warm spring. In contrast, 2006 had a middle level ranking for both lake level and spring temperatures, but had the latest bloom onset.

In every year, the dissolved oxygen decreases during July–August, but for years with large chlorophyll-*a* concentrations in June (namely 1992 and 1997), the dissolved-oxygen concentration is more likely to fall below 4 mg/L. The large early bloom in 1992 was most noticeable in the bay and outflow areas, although the dissolved-oxygen concentration did not decline as low in the outflow areas as it did in the bay areas. The later bloom in 1991 was much more apparent in the bay areas than in any other area. The dissolved-oxygen concentrations in 1991 did not fall below 4 mg/L until September-October. The pH values correspond very well with the chlorophyll-*a* concentrations—pH increasing with the increases in chlorophyll-*a*—which fits with the growth of the bloom. Ammonia concentrations in 1997 were notably larger than in any other year. This was determined by Wood and others (2006) to be correlated with discharge from the Williamson River. The fact that the ammonia concentrations were elevated in 1997 in Agency Lake also indicates that the discharge in the Wood River, which flows into Agency Lake, was probably higher during those years as well.

Table 11. Number of samples exceeding the acute and chronic total-ammonia guidelines by year and site, Upper Klamath and Agency Lakes, Oregon, 1990–2006.

[See figure 1 for site names and locations, exceedances are shown in bold type and shaded]

Based on acute criterion for when salmonid fish are present (based on a 1-hour average concentration)

Site	1990		1991		1992		1993		1994		1995		1996		1997		1998		1999		2000		2001		2002		2003		2004		2005		2006		1990–2006	
Number of	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances
AN	0	0	4	0	8	0	9	0	4	0	9	0	1	0	5	0	9	0	5	0	12	0	7	0	6	0	5	0	9	0	9	0	9	0	111	0
AS	8	0	8	0	11	0	12	0	7	0	9	0	8	0	9	0	8	0	6	0	10	0	6	0	4	0	5	0	8	0	9	0	5	0	133	0
CP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	8	0	5	0	11	0	6	0	7	0	7	0	9	0	8	0	6	0	69	0
ER	7	0	8	0	13	0	11	0	10	0	10	0	9	0	8	0	10	0	6	0	11	0	7	**1**	6	0	7	0	8	0	9	0	6	0	146	**1**
ML	0	0	7	0	9	0	10	0	9	0	8	0	7	0	8	**1**	7	0	6	0	9	0	6	0	5	0	7	0	6	0	6	0	6	0	116	**1**
MN	5	0	7	0	11	0	10	0	12	0	9	0	9	0	6	0	10	**1**	5	0	9	0	6	0	7	0	6	0	6	0	7	0	6	0	131	**1**
NB	0	0	7	0	9	0	11	0	5	0	8	0	0	0	7	0	8	0	6	0	9	0	7	0	5	0	5	0	6	0	7	0	6	0	106	0
PM	0	0	7	0	9	0	11	**1**	7	0	8	0	0	0	7	0	10	0	5	0	7	0	5	0	5	0	5	0	8	0	7	0	5	0	106	**1**
SB	7	0	7	0	13	0	14	0	9	0	10	0	11	**2**	7	**1**	10	**1**	5	0	9	0	6	**1**	5	0	7	0	9	0	8	0	6	0	143	**5**
WB	1	0	8	0	10	0	13	0	5	0	9	0	0	0	6	0	6	0	4	0	9	0	5	**1**	3	0	5	0	5	0	8	0	6	0	103	**1**
All	28	0	63	0	93	0	101	**1**	68	0	80	0	45	**2**	65	**2**	86	**2**	53	0	96	0	61	**3**	53	0	59	0	74	0	78	0	61	0	1,164	**10**

Based on chronic criterion for when fish early life stages are present (based on a 30-day average concentration)

Site	1990		1991		1992		1993		1994		1995		1996		1997		1998		1999		2000		2001		2002		2003		2004		2005		2006		1990–2006	
Number of	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances
AN	0	0	4	0	8	0	9	0	4	0	9	0	1	0	5	0	9	0	5	0	12	0	7	0	6	0	5	**1**	9	0	9	0	9	0	111	**1**
AS	8	0	8	0	11	0	12	0	7	0	9	0	8	0	9	0	8	0	6	0	10	**1**	6	0	4	0	5	0	8	0	9	0	5	0	133	**1**
CP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	**1**	8	**2**	5	0	11	**2**	6	**1**	7	**2**	7	0	9	**2**	8	0	6	**1**	69	**11**
ER	7	0	8	0	13	0	11	0	10	0	10	**1**	9	**2**	8	**2**	10	**2**	6	**1**	11	**3**	7	**3**	6	**1**	7	**1**	8	**1**	9	**1**	6	0	146	**18**
ML	0	0	7	0	9	0	10	0	9	0	8	0	7	0	8	**1**	7	0	6	0	9	0	6	**2**	5	0	7	**1**	6	0	6	0	6	0	116	**4**
MN	5	**1**	7	0	11	0	10	0	12	0	9	0	9	**2**	6	**1**	9	**1**	5	0	9	**2**	6	**2**	7	**2**	6	0	6	0	7	0	6	**1**	130	**12**
NB	0	0	7	0	9	0	11	**1**	5	0	8	0	0	0	7	0	9	**2**	6	0	9	**1**	7	**3**	5	0	5	0	6	0	7	0	6	0	107	**7**
PM	0	0	7	0	9	0	11	**1**	7	**1**	8	0	0	0	7	**2**	10	0	5	0	7	0	5	**1**	5	0	5	0	8	**1**	7	0	5	0	106	**6**
SB	7	**2**	7	0	13	0	14	**1**	9	0	10	0	11	**4**	7	**2**	10	**3**	5	0	9	**1**	6	**2**	5	0	7	**1**	9	**1**	8	0	6	**1**	143	**18**
WB	1	0	8	**1**	10	0	13	**1**	5	0	9	**1**	0	0	6	0	6	0	4	**1**	9	**3**	5	**2**	3	0	5	0	5	0	8	0	6	**1**	103	**10**
All	28	**3**	63	**1**	93	0	101	**4**	68	**1**	80	**2**	45	**8**	65	**9**	86	**10**	53	**2**	96	**13**	61	**16**	53	**5**	59	**4**	74	**5**	78	**1**	61	**4**	1,164	**88**

Table 12. Number of un-ionized ammonia concentrations exceeding 530 micrograms per liter by year and site, Upper Klamath and Agency Lakes, Oregon, 1990–2006.

[The value of 530 micrograms per liter represents the LC_{50} for the Lost River sucker (Saiki and others, 1999); see figure 1 for site names and locations, exceedances are shown in bold type and shaded]

Site	1993		1996		1997		1998		1999		2000		2001		2002		2003		Other years		1990–2006	
Number of	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances	Samples	Exceedances
AN	13	0	1	**1**	8	0	11	**1**	10	**1**	15	0	11	0	11	**1**	11	**1**	81	0	172	**5**
AS	15	0	15	0	14	**1**	14	**1**	11	0	15	**1**	12	**1**	11	0	11	0	106	0	224	**4**
CP	0	0	0	0	6	**1**	12	0	9	**1**	15	**1**	12	0	12	0	12	0	37	0	115	**3**
ER	14	0	15	0	14	**2**	14	0	11	0	15	**1**	12	**1**	12	0	12	**1**	114	0	233	**5**
ML	14	0	15	0	14	**3**	13	**2**	11	**1**	15	**1**	12	**1**	12	0	13	0	98	0	217	**8**
MN	14	0	15	0	14	**1**	14	**1**	11	0	15	**1**	12	0	12	**1**	11	0	116	0	234	**4**
NB	14	0	0	0	14	0	14	**1**	11	**1**	15	0	12	0	12	0	12	**1**	95	0	199	**3**
PM	16	**1**	0	0	14	**3**	14	**1**	11	**1**	15	**3**	12	**1**	12	0	12	0	94	0	200	**10**
SB	16	0	15	**1**	14	**3**	13	**1**	11	**1**	15	**1**	12	**2**	12	0	12	0	109	0	229	**9**
WB	16	0	0	0	14	**4**	14	**2**	11	**1**	15	**3**	12	**1**	12	0	12	**1**	94	0	200	**12**
All	132	**1**	76	**2**	126	**18**	133	**10**	107	**7**	150	**12**	119	**7**	118	**2**	118	**4**	944	0	2,023	**63**

When evaluating dissolved-oxygen concentrations, pH values, and ammonia concentrations against the criterion defined to delimit poor water-quality conditions, one year (2000) was in the top three highest frequencies of poor conditions for all three parameters. The interrelatedness of these water-quality variables was further explored in figure 6. Similar to the conditions discussed by year, the areas with the higher chlorophyll-*a* concentrations earlier in 2000 (namely the bay and outflow areas) experienced the lowest dissolved-oxygen plunges in June and July. Dissolved-oxygen concentrations measured in all areas were low in late June and early July, but the bay areas experienced low dissolved-oxygen conditions through September and into October in some years. All areas experienced elevated pH values with the onset of the bloom. The highest ammonia concentrations coincided with the elevated chlorophyll-*a* concentrations associated with the growth of the bloom. These patterns illustrate the importance of the bloom (both the magnitude and timing of the onset, growth, and decline) on water-quality conditions and why it is necessary to further explore potential correlations with lake level in an attempt to find a management tool to influence water-quality conditions.

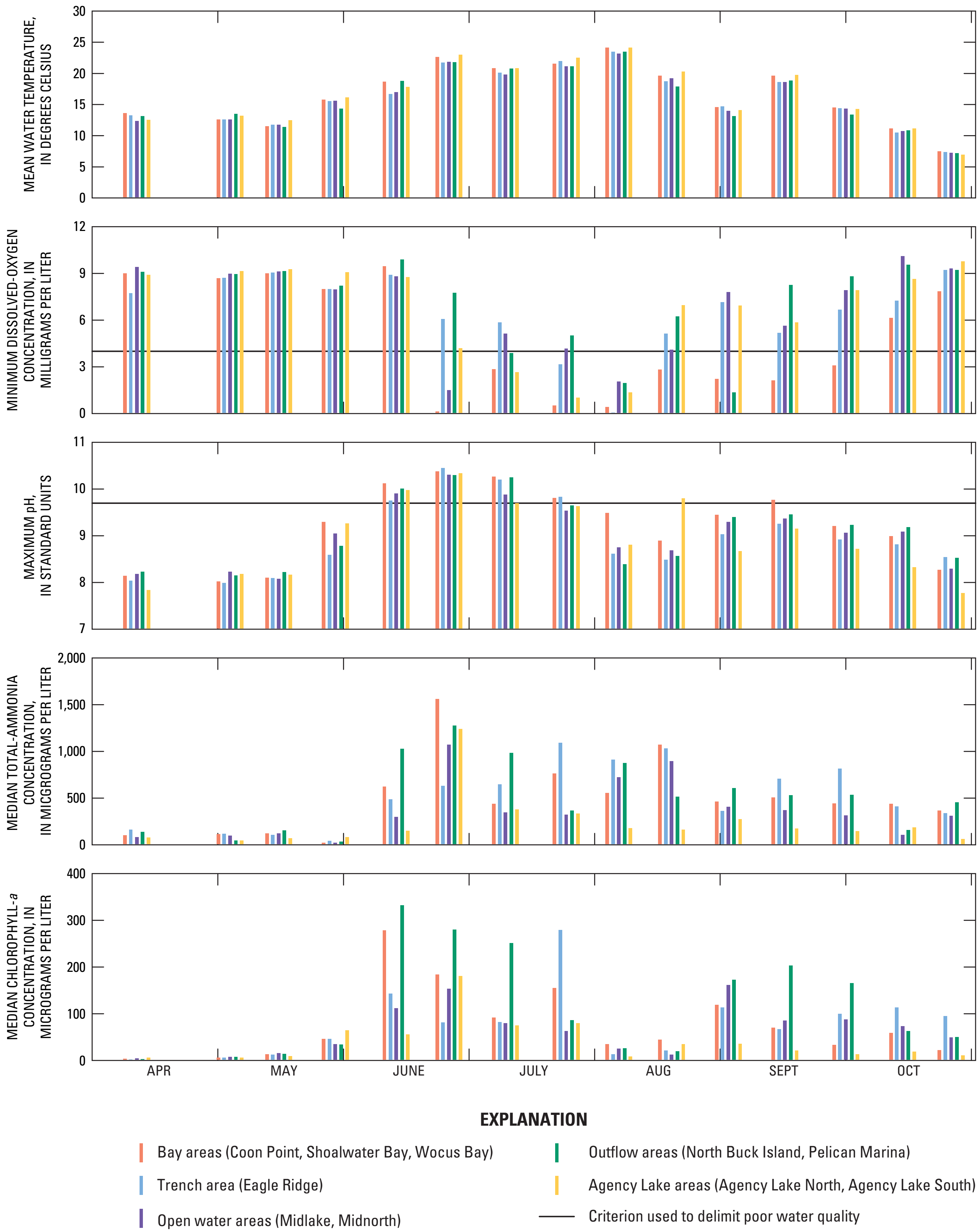


Figure 6. Water-quality conditions in 2000, Upper Klamath and Agency Lakes, Oregon.

Hypotheses Relating Water Quality to Lake Level and Climate

The hypotheses relating selected water-quality variables to lake level and climatic variables examined in Wood and others (1996) served as a starting point for this analysis, to see whether relations observed or not observed within a 5-year dataset had changed when examining a 17-year dataset. The same caveats that applied for these hypotheses in the previous analysis apply to this report. The hypotheses are purposely stated broadly to allow exploration of the data. The direction of the relation is stated because it was presupposed that water quality can be degraded at lower lake levels, but the specific form of the relation (linear, bimodal, and so forth) is not specified. With this approach, the data, rather than preconceived ideas, influence the conclusions.

The primary focus of this analysis was to establish the existence or nonexistence of relations between certain water-quality variables and lake level. The existence of a relation, however, does not imply causality. If a relation was detected, then a specific mechanism could be proposed and tested to establish causality. In the next section addressing information-theoretic approaches to the data, previous work in the basin and information emerging from the hypothesis testing will be used to guide the selection of multiple variables to examine separately and together for their ability to explain the variance observed in the data.

Chlorophyll-*a*

In Wood and others (1996), the general hypothesis addressing chlorophyll-*a* was:

> *Year-to-year differences in chlorophyll-a concentration are related to year-to-year differences in lake level, such that chlorophyll-a concentrations are lower at higher lake levels.*

The temporal patterns observed in chlorophyll-*a* concentrations in Upper Klamath Lake during May–October differed greatly between years (fig. 7). Certain similarities can be noted in the progression of the chlorophyll-*a* concentrations, however, that illustrate the onset, growth, and decline of the AFA bloom. For each year, the bloom began sometime between mid-May and mid-June, signaled by increases in chlorophyll-*a* concentration. The chlorophyll-*a* concentrations generally went through a downward trend sometime in July, with a great deal of variation between the years in how much of a decline this was and whether concentrations increased again or not. Many years experienced a second period of bloom growth between August and September (1991, 2000, and 2005, for example), although some years did not (1993 and 1994, for example). The highest median chlorophyll-*a* concentrations were observed during periods of bloom growth but occurred at very different time periods, June 1992 and October 1996. The warm autumn in 1996 most likely contributed to the magnitude of the second AFA bloom that year. The magnitude of the first spike in chlorophyll-*a* concentration does not seem to be an indicator of how long the bloom will persist. Chlorophyll-*a* concentration may decrease and the bloom may not persist as in 1992, or there may be sustained growth throughout the season as in 1995 and 1997.

There is no obvious pattern in the yearly distribution of chlorophyll-*a* concentrations when the years are arranged from lowest to highest lake level. When the distribution of chlorophyll-*a* concentrations for each year was considered by month in relation to the lake-level ranking, Wood and others (1996) did, however, observe a potential pattern in June—the median, 25th-, and 75th- percentile concentrations were higher in 1992 and 1994 than in the other 3 years (1990, 1991, 1993). This pattern did not continue for the July-September distributions. In the larger 17-year dataset (fig. 8), this pattern did not seem to hold up and this hypothesis was not supported.

Further exploration of the potential relation between chlorophyll-*a* and lake level during June by Wood and others (1996) led to the development of the following hypothesis:

> *Year-to-year differences in June chlorophyll-a concentrations are related to year-to-year differences in June lake level, such that June chlorophyll-a concentration is lower at higher lake levels.*

This hypothesis was analyzed for the larger 1990–2006 dataset by plotting the median June chlorophyll-*a* concentrations against the median June lake level in Upper Klamath Lake (fig. 9). No significant correlation was observed; however, 1992 stood out as a year with a much lower median June lake level than any of the other years. The median chlorophyll-*a* concentration for this year was the highest of the 17 years. The median June lake level for the remainder of the years, however, fell between 4,141.5 and 4,143.5 feet above sea level. This illustrates the fact that this analysis is performed on the observational data available. Perhaps the limited fluctuation in lake levels limits the variations in bloom dynamics that would be observed over a wider range of lake levels.

Although a relation between chlorophyll-*a* concentration and lake level could not be determined, Wood and others (1996) had noted an apparent progression in June chlorophyll-*a* concentrations as the number of degree-days increased. This was stated as:

> *Year-to-year differences in June chlorophyll-a concentration are related to year-to-year differences in the number of degree-days between April 1 and May 15, such that concentrations are higher at a higher number of degree-days.*

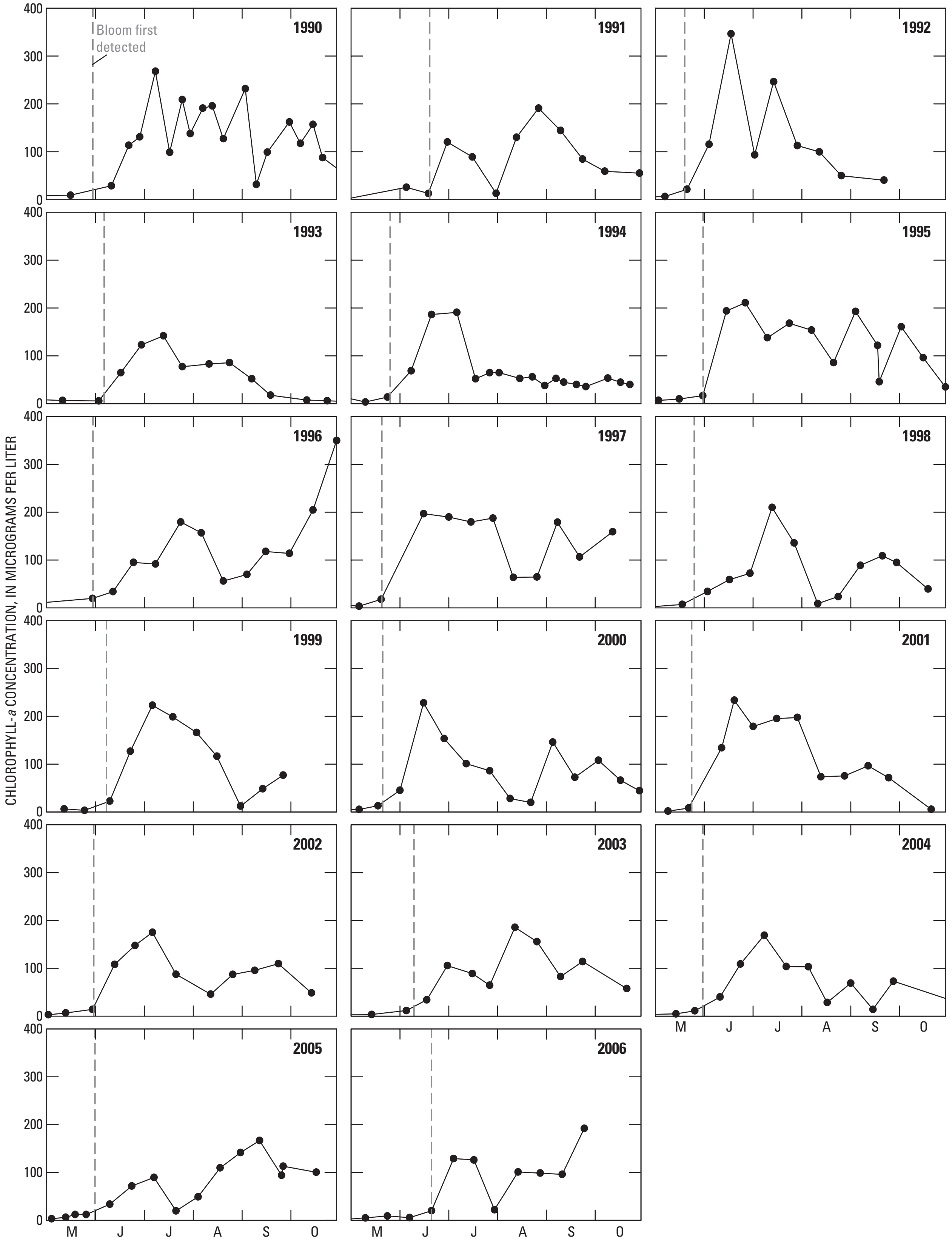


Figure 7. Median chlorophyll-*a* concentrations, May–October 1990–2006, Upper Klamath Lake, Oregon.

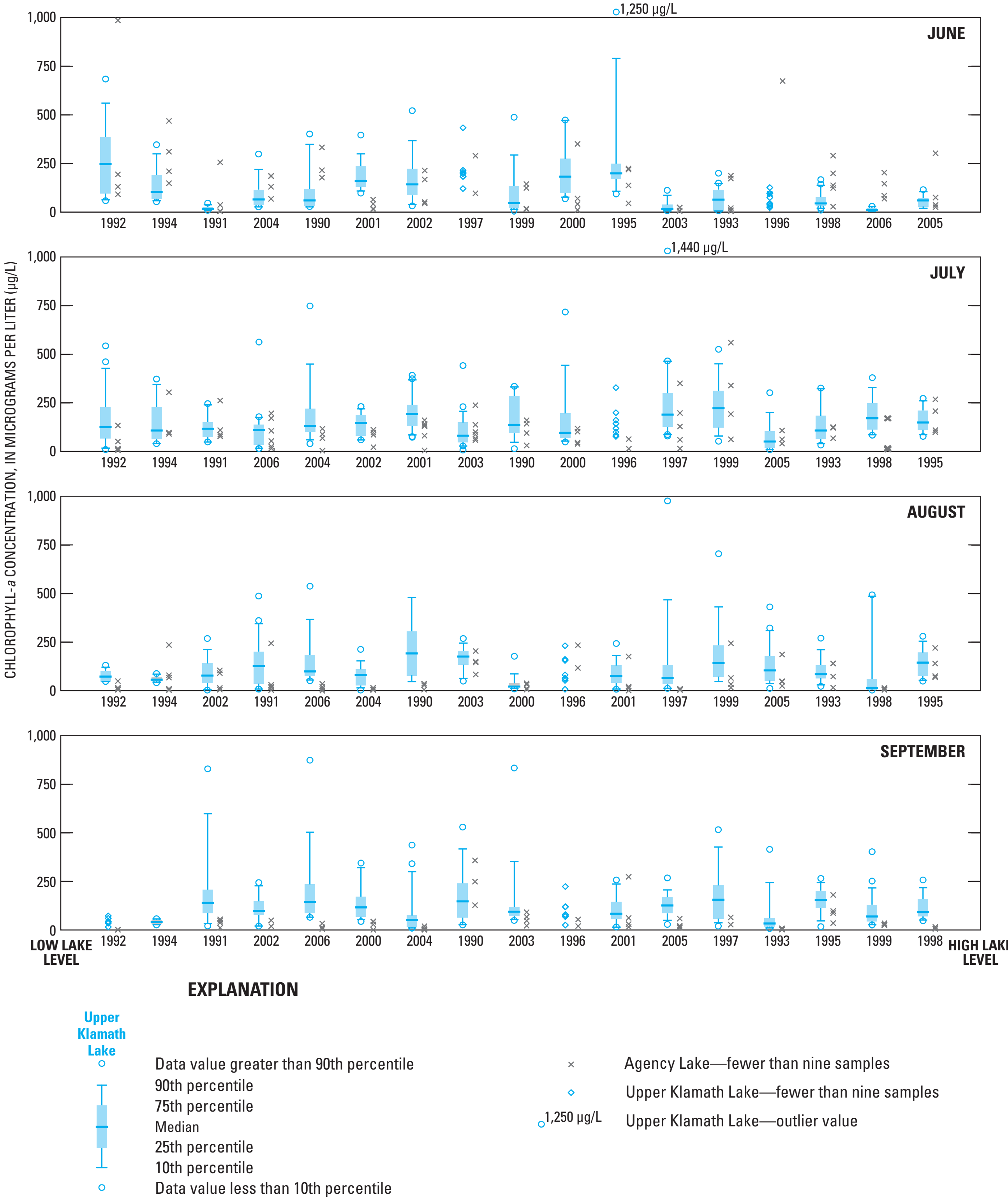


Figure 8. Frequency distributions of lakewide chlorophyll-*a* data, by month, Upper Klamath and Agency Lakes, Oregon, June–September 1990–2006. Years are displayed in order of increasing lake level based on end-of-month lake-level rankings for the preceding month (see table 2).

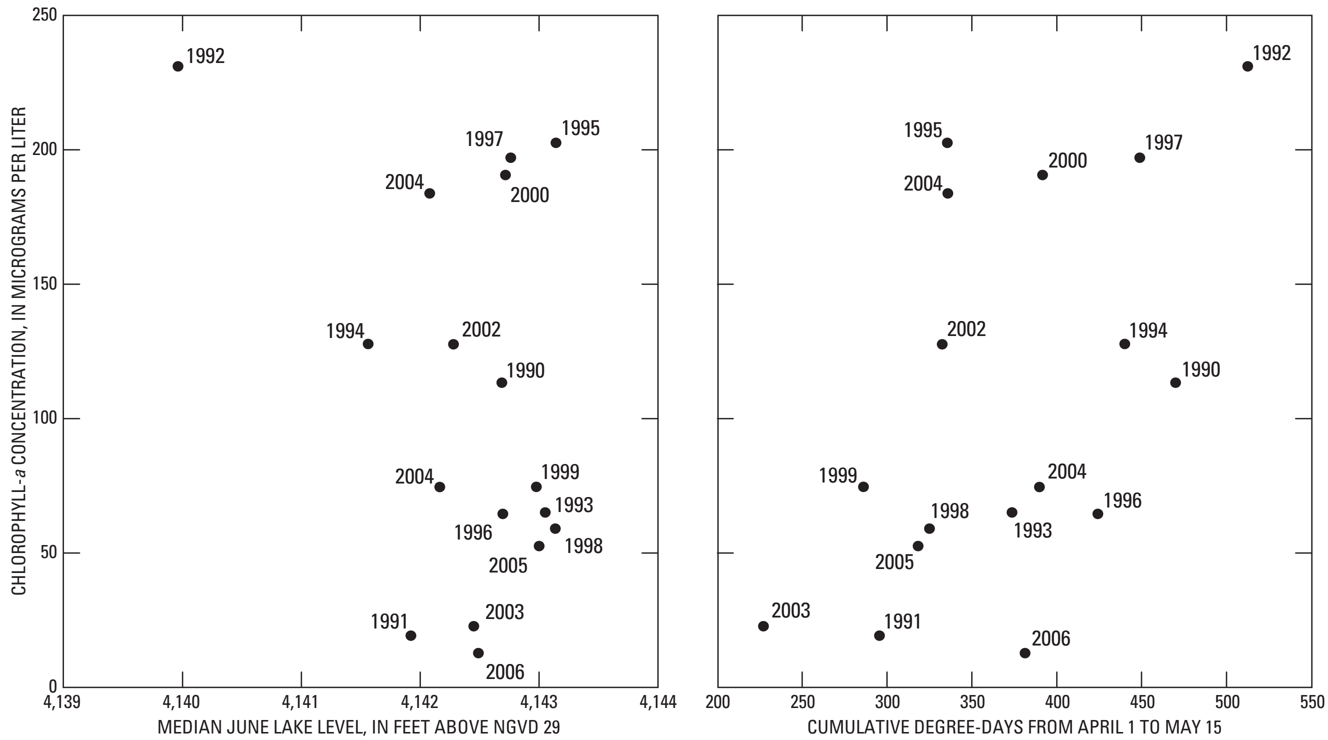


Figure 9. Relation of median June chlorophyll-*a* concentration to median June lake level and cumulative degree-days from April 1 to May 15, Upper Klamath and Agency Lakes, Oregon, 1990–2006. For lake level, no significant correlation was found. For degree-days, Spearman's ρ correlation coefficient = 0.61, $p < 0.009$.

This relation is explored for the 1990–2006 dataset in figure 9. A significant correlation was determined between the median June chlorophyll-*a* concentration and the cumulative degree-days from April 1 to May 15 (Spearman's $\rho = 0.61$, $p < 0.009$). Intuitively, it makes sense that a warmer spring (higher cumulative degree-days) would result in increased growth of the algae, and therefore, higher chlorophyll-*a* concentrations, in June.

As a natural progression, not only the magnitude of the bloom in June, but also the timing of the bloom onset, which occurred between mid-May and mid-June, was explored in relation to lake level and cumulative degree-days (fig. 10). Wood and others (1996) had observed an apparent trend toward later bloom at higher lake levels when looking at the 1990–94 dataset and therefore developed the following hypothesis:

> *Year-to-year differences in the timing of the first bloom are related to year-to-year differences in June lake level, such that the first bloom is delayed at higher lake levels.*

When this analysis was expanded to the 1990–2006 dataset, however, the trend is not apparent. In fact, correlation statistics showed no significant correlation between lake level and the onset of the bloom; therefore, this hypothesis was not supported for the 1990–2006 dataset.

The timing of the bloom also was explored in relation to the cumulative degree-days (Wood and others, 1996), stated as:

> *Year-to-year differences in the timing of the first bloom are related to year-to-year differences in the number of degree-days between April 1 and May 15, such that the bloom occurs earlier at a higher number of degree-days.*

The data support this hypothesis (fig. 10). A significant negative correlation was observed between the onset of the bloom and the cumulative degree-days between April 1 and May 15 (Spearman's $\rho = -0.65$, $p < 0.004$). The warmest spring (highest cumulative degree-days) occurred in 1992, which also had the earliest bloom (earliest Julian day of bloom onset). In contrast, 2003 had the coolest spring temperatures

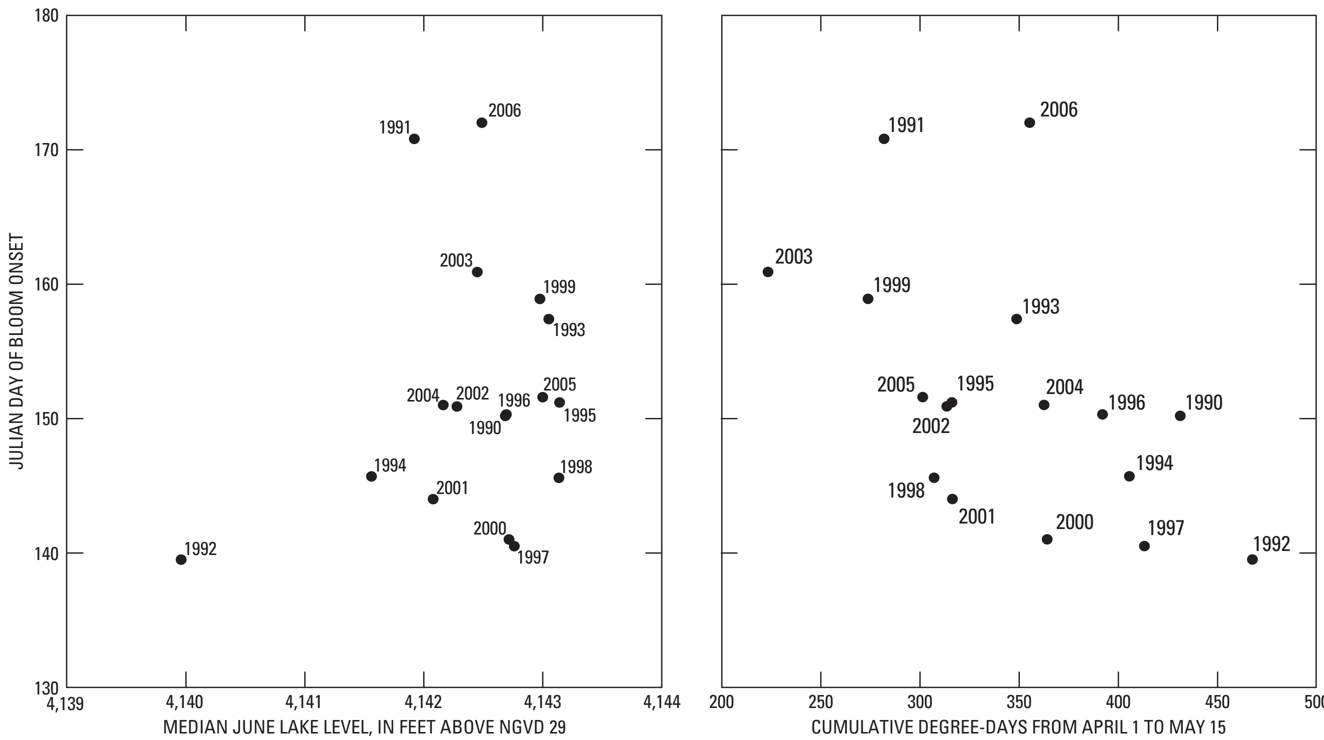


Figure 10. Relation of the timing of the onset of the bloom to the median June lake level and cumulative degree-days between April 1 and May 15, Upper Klamath Lake, Oregon, 1990–2006. The Julian day of the bloom onset was interpolated from the measured data as the day when the lakewide median chlorophyll-*a* concentration exceeded 20 micrograms per liter. For lake level, no significant correlation was found. For degree-days, Spearman's ρ correlation coefficient = 0.65, $p < 0.004$.

and had a later onset of the AFA bloom. The year 2006 is interesting because it does not "exactly" fit this pattern. The lake-level and degree-day rankings for 2006 (table 6) fall in the middle of the distribution for the 17 years, but 2006 experienced the latest bloom onset of the 17 years. This modification to the pattern in 2006 illustrates that although the onset of the bloom is related to the warmth of the spring, there are more factors to consider.

pH

During the day, pH fluctuates and typically reaches a maximum value late in the afternoon, whereas over a season, the highest frequency of potentially detrimental maximum pH values occurred in June and July (table 9). To examine how lake level may affect pH values, Wood and others (1996) proposed the following hypothesis:

Year-to-year differences in the frequency of occurrence of pH values greater than 9.7 are related to year-to-year differences in lake level, such that the frequency is lower at higher lake level.

In Wood and others (1996), 9.5 was the pH value used to delimit poor water-quality conditions; however, Reiser and others (2000) have proposed that pH values greater than 9.7 are detrimental to suckers. Therefore, this hypothesis was updated for this report to state 9.7 rather than 9.5.

As discussed previously, because the growth of the bloom results in increasing pH values, the peak pH values tend to correspond to the peak chlorophyll-*a* concentrations. Wood and others (1996) examined the relation that the onset of the bloom had on when the peak pH values were measured. To explore this relation for the 1990–2006 dataset, the maximum observed pH values recorded at each visit to Wocus Bay, a site that frequently had pH values greater than 9.7 (table 10), were plotted for each year (fig. 11). The peak pH values tended

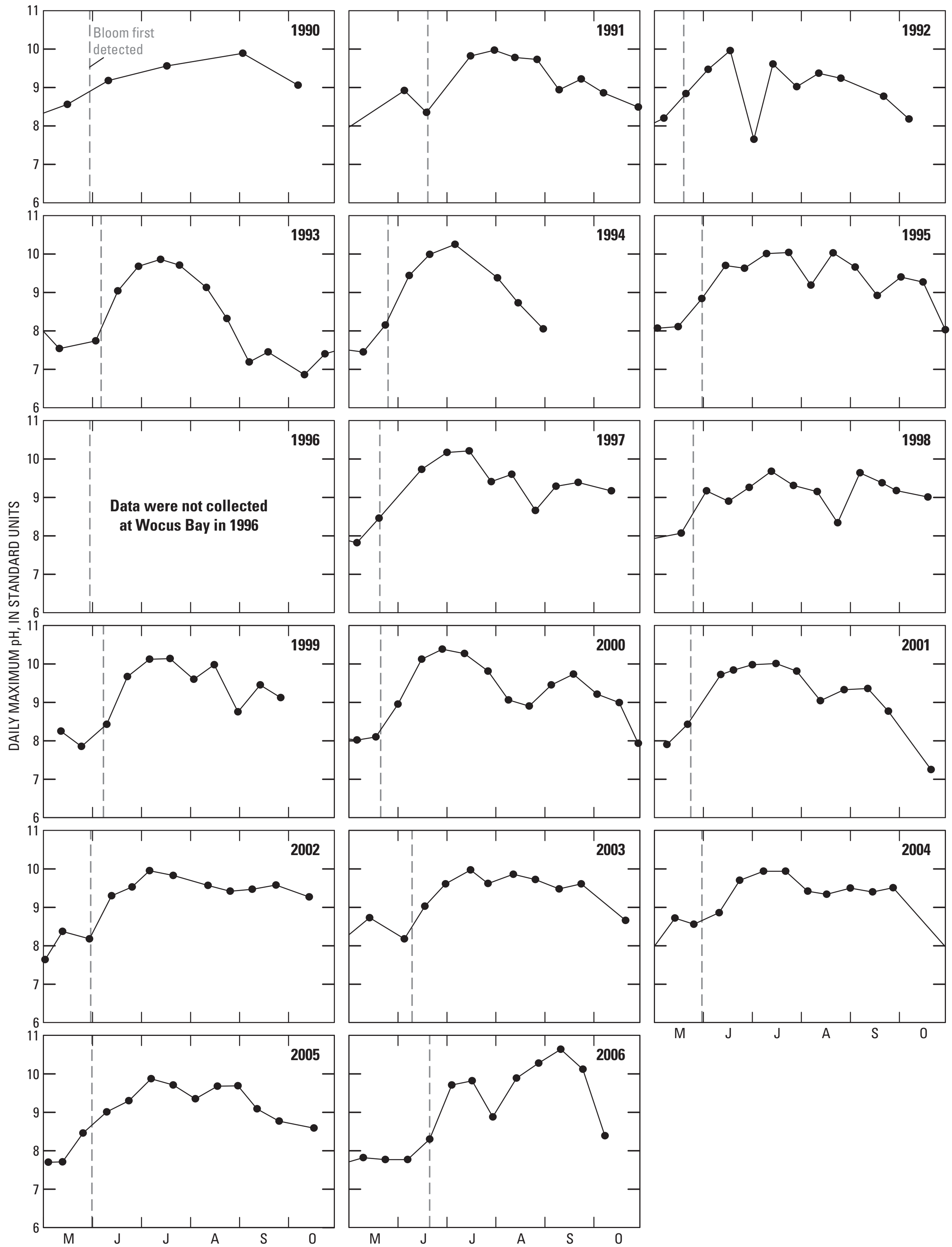


Figure 11. Daily maximum pH values measured at Wocus Bay, May–October 1990–2006, Upper Klamath Lake, Oregon.

to occur sometime during mid-June to mid-July (except for 1990 and 2006, both having peak pH values much later in the year). These peak pH values seem to occur roughly 4–6 weeks after the onset of the bloom, which always occurred sometime in mid-May to mid-June. For Wocus Bay, every year except 1998 had peak pH values greater than 9.7, signifying poor water-quality conditions even though all ranges of lake level, degree-days, and timing of the bloom onset are represented. Wood and others (1996) noted that although the peaks in pH and chlorophyll-*a* concentrations seem to be related, there is not necessarily a correspondence between the strength of a bloom and the coincident pH.

The yearly distribution of pH values for Upper Klamath and Agency Lakes was plotted by month in order of increasing lake level in an attempt to analyze the hypothesis relating pH and lake level (fig. 12). These distributions represent all pH values recorded at all depths for all sites, and thus are intended to represent the overall condition of each of the lakes. No obvious pattern with lake level is noticeable. The June and September distributions seem to be more variable than the July and August distributions. Perhaps this is related to the greater variation in pH during times of bloom growth (June) or decline (September), whereas the pH values may be less variable during maintenance of the bloom. There were sometimes large differences between the Upper Klamath Lake and Agency Lake distributions. Those for 2006 are extreme—the pH values measured in Upper Klamath Lake were much lower than those measured in Agency Lake in June, they were similar in July, and then flip-flopped in August and September with those in Upper Klamath Lake much larger than those in Agency Lake.

A few interesting patterns appear when the maximum observed pH values are examined at the site level rather than as lakewide distributions (fig. 13). June was characterized by higher lake levels and the pH values seem to be widely distributed, with some greater than 9.7. In July, however, the lake level was a little lower than in June and the majority of pH values at each site were greater than 9.7. In August and September, the pH values were again distributed across the pH range with no apparent relation to lake level. When correlation statistics were evaluated on the entire dataset for relations between maximum observed pH values and lake level, a significant ($p < 0.0001$) but very weak (Spearman's $\rho = -0.13$) negative correlation was observed. When June and July were analyzed individually, however, significant ($p < 0.0001$) but weak (Spearman's ρ values between 0.3 and 0.4) correlations were observed, but they were opposing—June was negative and July was positive (fig. 13). In June, if any pattern can be observed, it appears that higher pH values coincided with lower lake levels, as the hypothesis states. In July, however, the pattern seems to show higher pH values at higher lake levels. These weak correlations and changing patterns hint that there is not an easily defined relation between pH and lake level; there are more likely other factors, like bloom dynamics, affecting this relation.

Because June is a critical month in terms of the first bloom, relations between pH values and lake level, cumulative degree-days, and the timing of the bloom onset were further explored. Wood and others (1996), finding that the more general pH hypothesis was not supported by the data, developed a narrower hypothesis.

> *Year-to-year differences in the June frequency of pH value greater than 9.5 are related to interannual differences in lake level, such that the June frequency is lower at higher June lake level.*

The pH data from 1990-94 were observed to support this hypothesis, which was directly related to the fact that the chlorophyll-*a* data supported the hypothesis related to the timing of the bloom (see page 22). For the larger dataset, however, neither of these hypotheses is fully supported—the correlations were significant but very weak.

When the years are ranked according to cumulative degree-days and the timing of the bloom onset instead of by lake level (fig. 14), the distribution of pH values shows a distinction between the last 6 or so years in each ranking and the rest of the time period. In general, the six years with the latest bloom onset and some of the coolest spring temperatures—2006, 1991, 2003, 1999, 1993, and 2005—had lower median pH values, whereas the distributions for the other years were fairly similar. This separation in the groups is more of a symptom of the later occurrence of the bloom than evidence of a correlation. The peak pH values typically follow about 4–6 weeks after the onset of the bloom. The earliest bloom for these 6 years did not begin until May 31; therefore, the pH values in June had not reached their peak yet, but were still increasing as the bloom was growing. Looking at the distributions for these years in July (fig. 12) shows that by July the pH values for these years was similar to the other years.

The 6 years 1990, 2002, 2004, 1995, 2005, and 1993 all had bloom onset dates of May 29-31. Comparing the pH distributions for these six years illustrates that there is no clear pattern with relation to lake level, cumulative degree-days, or bloom onset (fig. 14). The median June pH distributions for 1990, 2002, 2004, and 2005 were very similar, whereas 1995 had a narrower distribution and a higher pH median and 1993 had a broader range of pH values and lower median pH. By lake level, the years are split into two groups—2002, 2004, and 1990 had lower lake levels, and 2005, 1993, and 1995 had higher lake levels. Therefore, lake level alone does not explain the differences in pH values and distributions. Likewise, the warmth of the spring does not provide a clear pattern as the years varied across the range of cumulative degree-days covered. The more likely explanation is that the interrelations between these and other factors act together to control pH conditions in the lake.

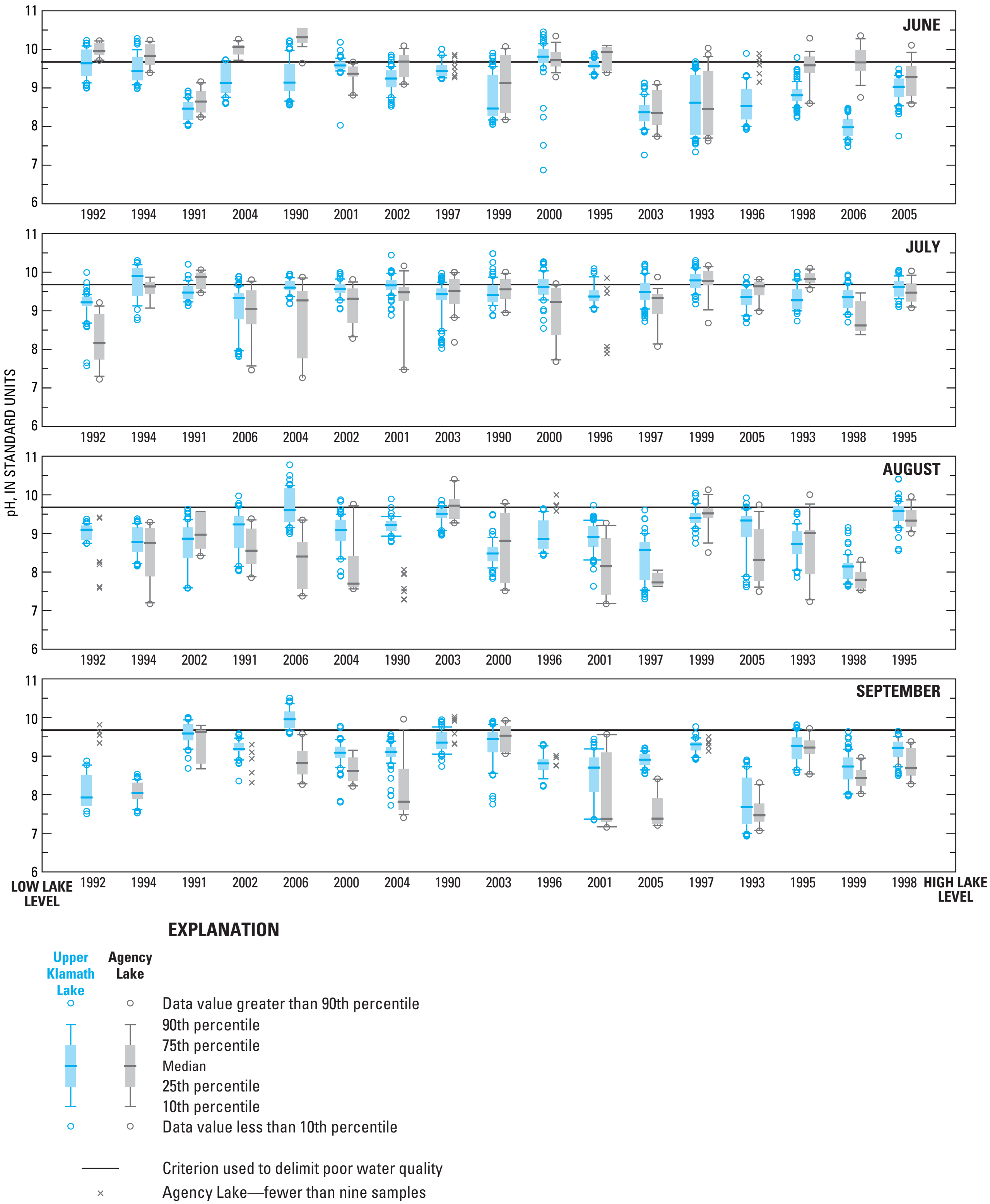
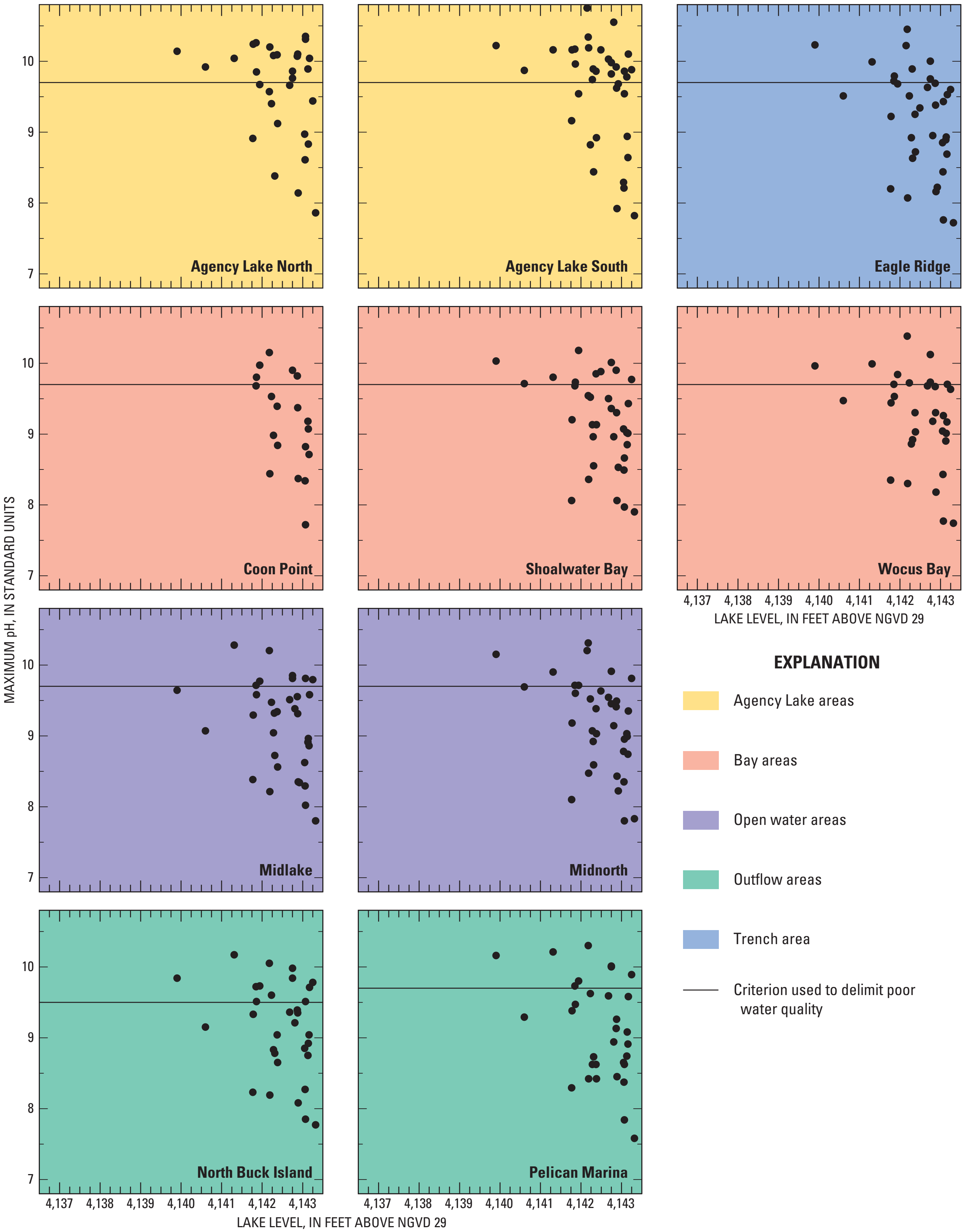
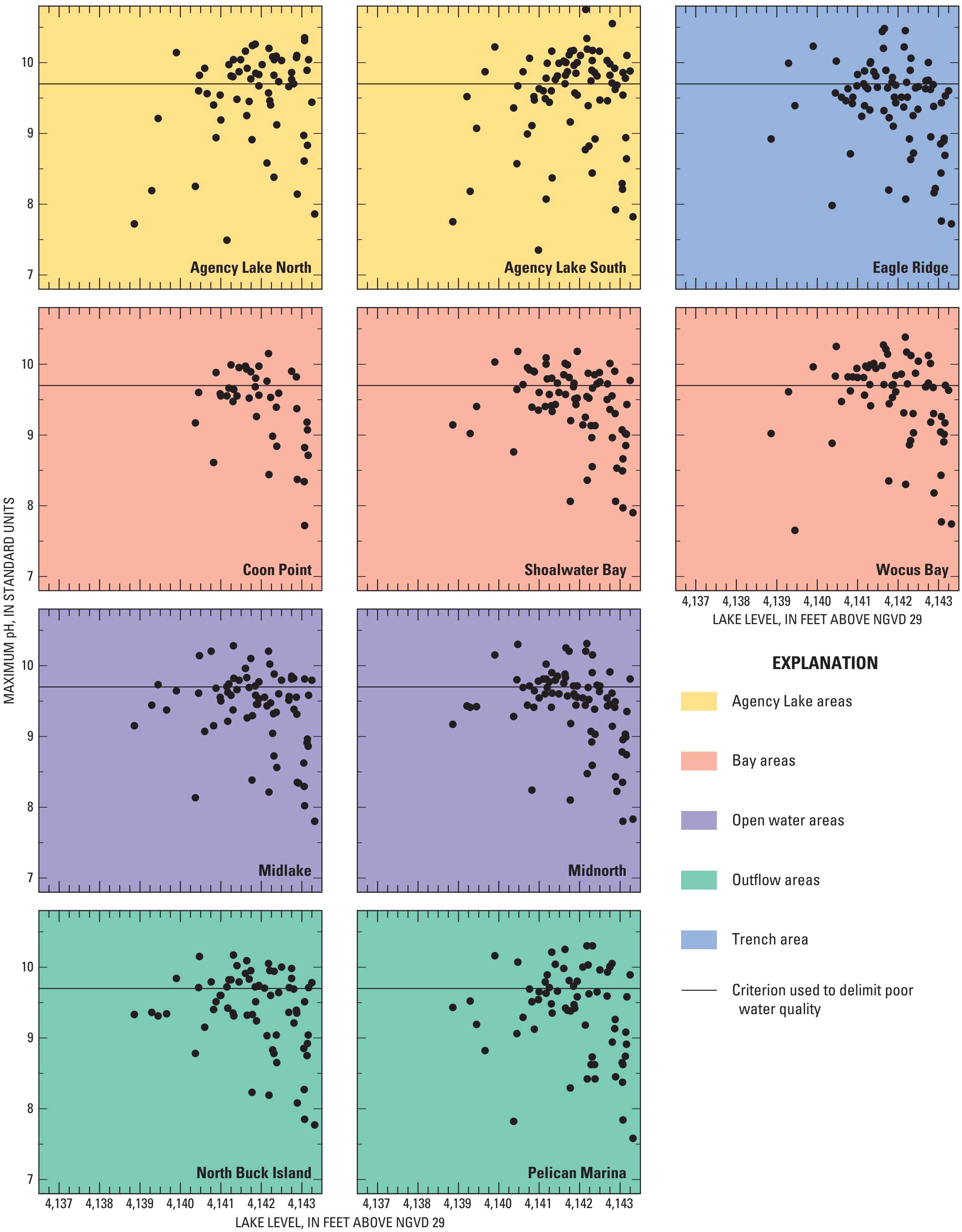


Figure 12. Frequency distribution of lakewide pH data, by month, Upper Klamath and Agency Lakes, Oregon, June–September 1990–2006. Years are displayed in order of increasing lake level based on the end-of-month lake-level rankings for the preceding month (table 2).



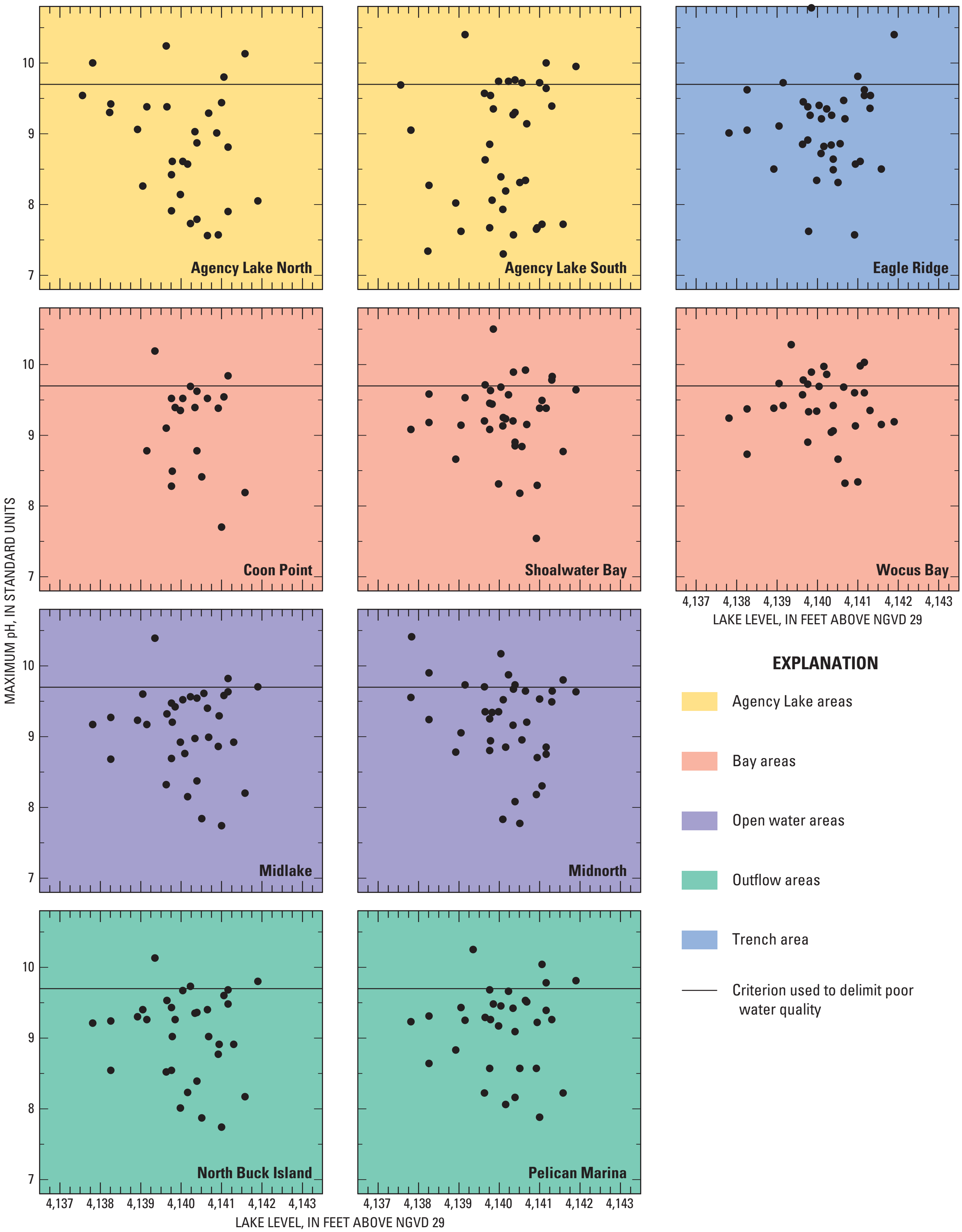
A. June 1990–2006

Figure 13. Daily maximum observed pH values at each site for June–September 1990–2006, Upper Klamath Lake and Agency Lakes, Oregon.



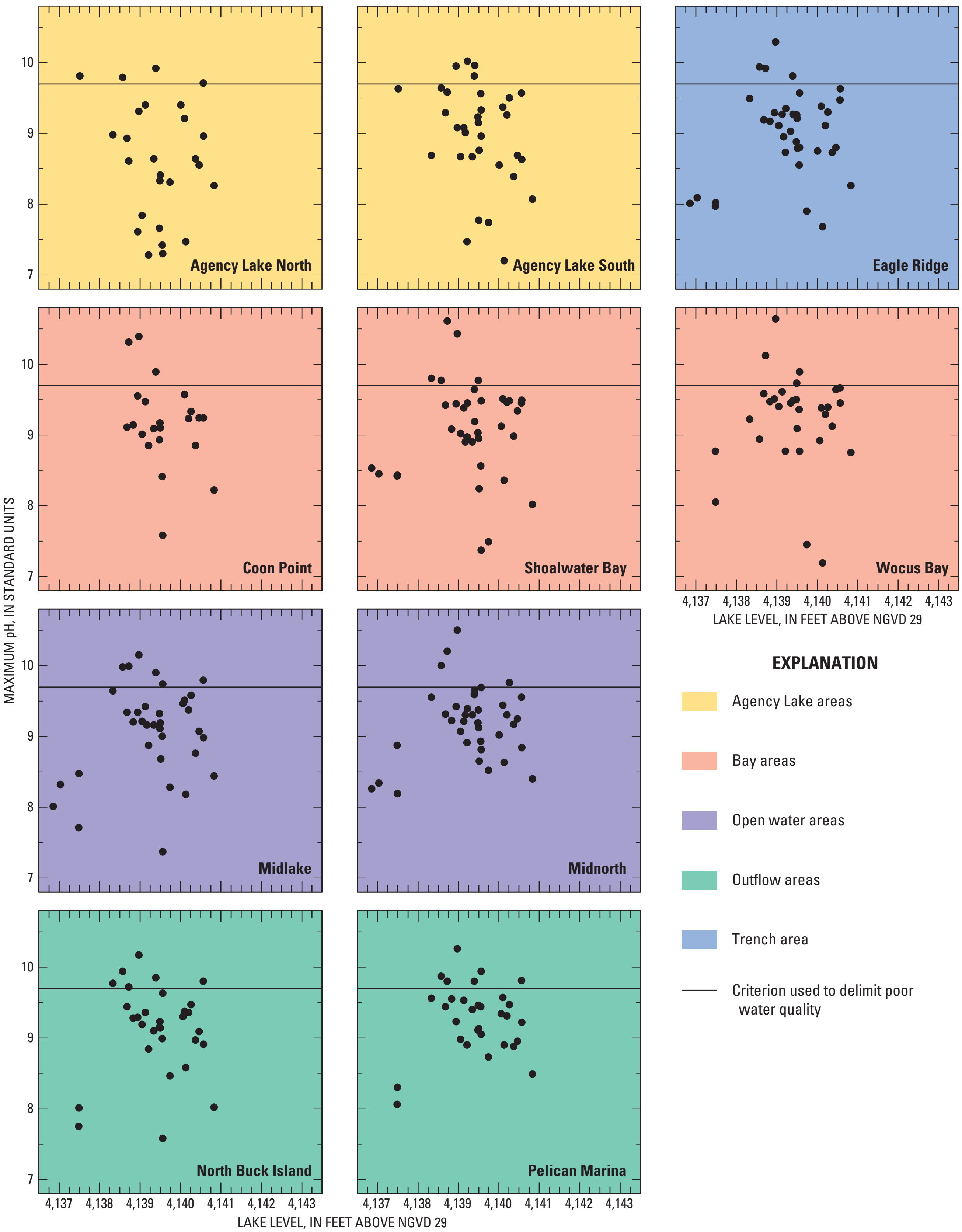
B. July 1990–2006

Figure 13. Continued.



C. August 1990–2006

Figure 13. Continued.



D. September 1990–2006

Figure 13. Continued.

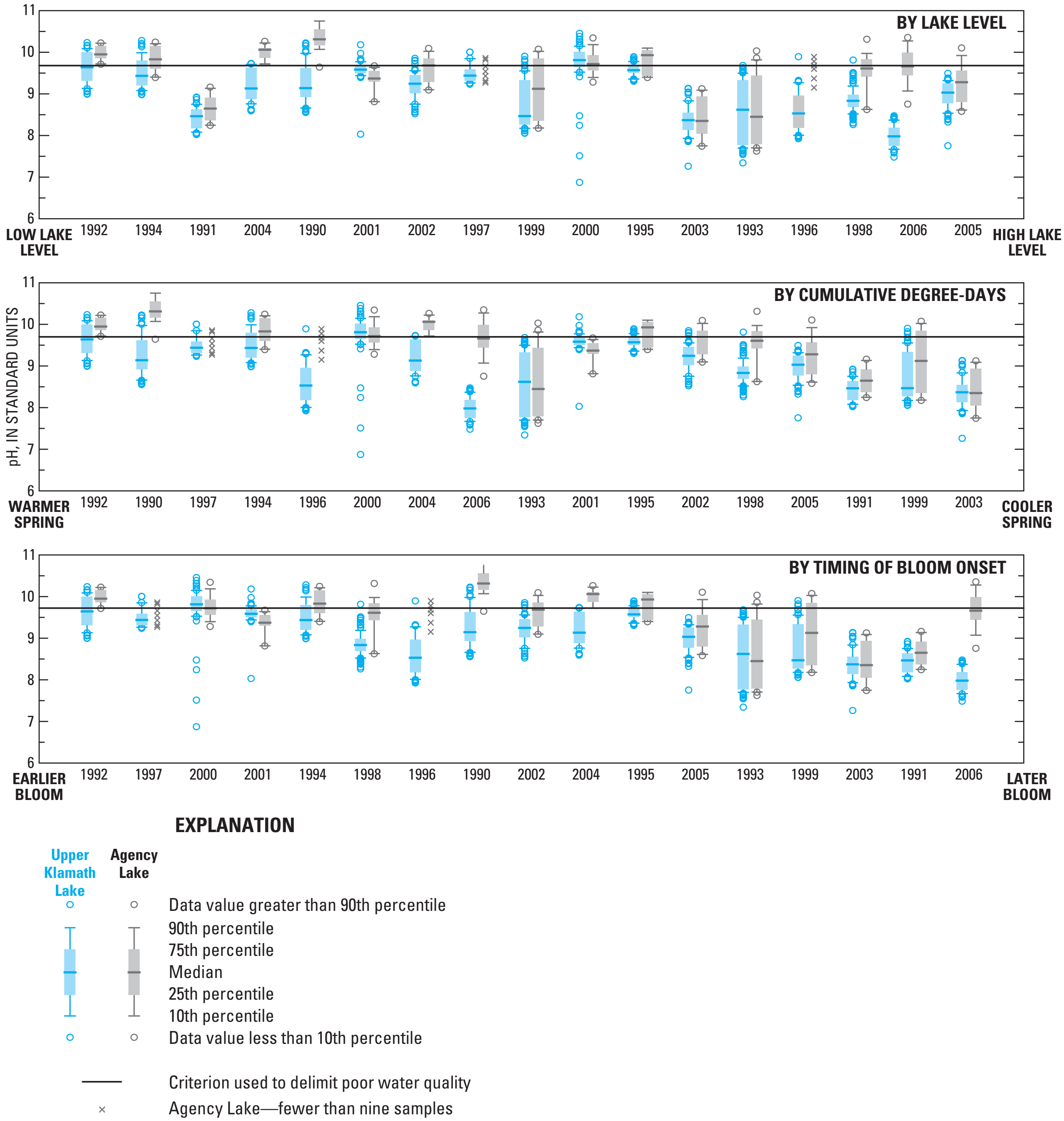


Figure 14. Frequency distribution of June lakewide pH data displayed by lake level, cumulative degree-days, and timing of the bloom onset, Upper Klamath and Agency Lakes, Oregon, 1990–2006. See table 6 for listing of rankings.

Dissolved Oxygen

During the day, the amount of oxygen dissolved in the water column fluctuates and typically reaches a minimum value early in the morning just before photosynthesis begins for the day. Dissolved-oxygen concentrations also fluctuate over the season with the growth cycle of the algae—when the bloom is growing and the algae are undergoing photosynthesis, oxygen is produced; in contrast, oxygen is consumed by senescing cells. Additional factors that may affect the seasonal fluctuation of dissolved oxygen include the decrease in the saturation concentration of dissolved oxygen as water temperature increases over the season, the increase in the effectiveness of sediment oxygen demand as the lake level decreases through the season, and the increase in biological and chemical oxygen demand from resuspended sediments which may be more likely stirred up at lower lake levels. Wood and others (1996), however, observed that increased oxygen demand (either sediment, biological, or chemical) was not the primary controlling factor of dissolved-oxygen concentrations at lower lake levels.

To further explore the relation of dissolved oxygen and lake levels, Wood and others (1996) proposed the following hypothesis:

> *Year-to-year differences in the frequency of occurrence of dissolved oxygen concentrations less than 4 mg/L are related to year-to-year differences in lake level, such that the frequency is lower at higher lake level.*

The yearly distributions of dissolved-oxygen concentrations for Upper Klamath and Agency Lakes were plotted by month in order of increasing lake level in an attempt to analyze this hypothesis (fig. 15). Dissolved-oxygen concentrations of less than 4 mg/L were common in most years in July and August, in about half the years in September, and in a few years in June and October. A pattern related to lake level is not obvious. In most years, less than 25 percent of the dissolved-oxygen concentrations were less than 4 mg/L. In August, however, nearly half of the years had more than 25 percent of their dissolved-oxygen concentrations less than 4 mg/L, including the lowest, middle, and highest ranking years for lake level. Three years (2002, 2000, and 1998) had dissolved-oxygen concentrations less than 4 mg/L as early as June.

These June low dissolved-oxygen concentrations were observed in the bay (Coon Point, Shoalwater Bay, Wocus Bay) and trench areas (Eagle Ridge) and in Agency Lake (Agency Lake North) (fig. 16*A*). This pattern of a higher frequency of low dissolved-oxygen conditions in the northern part of the lake (Eagle Ridge, Coon Point, Shoalwater Bay, Midnorth) continues into July (fig. 16*B*) and then even into August (fig. 16*C*), when the sites in the southern part of the lake (North Buck Island, Pelican Marina) start to experience these low dissolved-oxygen conditions also. The occurrence of dissolved-oxygen concentrations of less than 4 mg/L in the bay and trench areas continues even later in the season into September (fig. 16*D*). Even narrowing the targeted dataset to looking at one month at a time or one site and month at a time did not yield any significant, strong correlations (all Spearman's ρ were less than 0.5). The dissolved-oxygen data from 1990–94 (Wood and others, 1996), as well as from 1990–2006, do not support a relation between dissolved-oxygen concentration and lake level.

As was previously discussed, years with an earlier bloom were also characterized by an earlier onset of low dissolved oxygen. Therefore, relations between dissolved-oxygen concentrations and cumulative degree-days and the timing of the onset of the bloom were explored (fig. 17). Because both July and August are months with a large number of dissolved-oxygen concentrations of less than 4 mg/L, and young-of-the-year fish are more susceptible to stressful conditions earlier in the season, the month of July was chosen for this further analysis. No obvious relation was revealed between the dissolved-oxygen data and the cumulative degree-days, or the timing of the bloom onset. In fact, the data distributions are actually rather similar from year to year. There were only three years that were never observed to experience dissolved-oxygen concentrations of less than 4 mg/L—1994, 1993, and 1991. Both 1991 and 1993 had later blooms but 1994 had the fourth earliest bloom, again resulting in a lack of a relation or pattern.

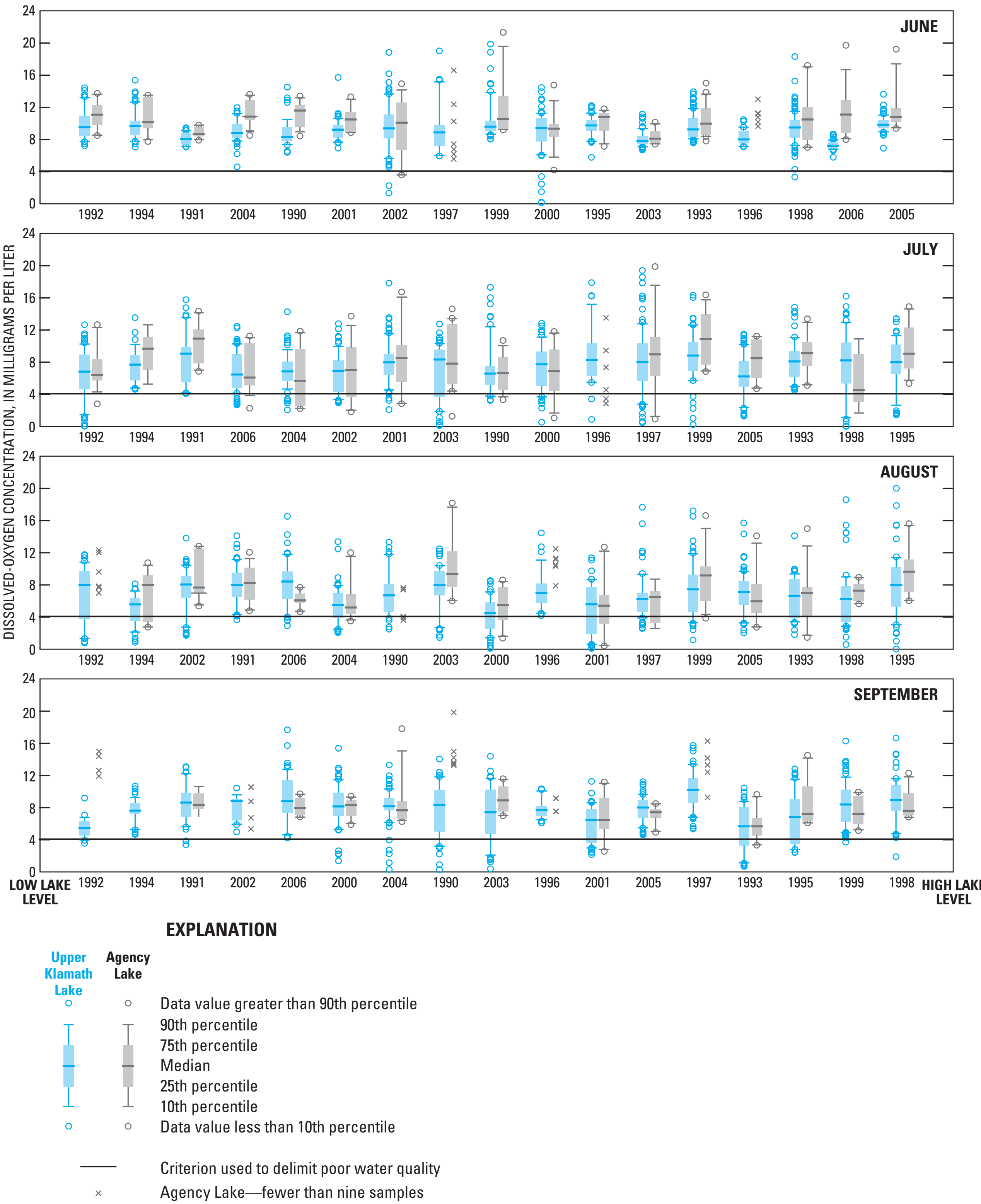
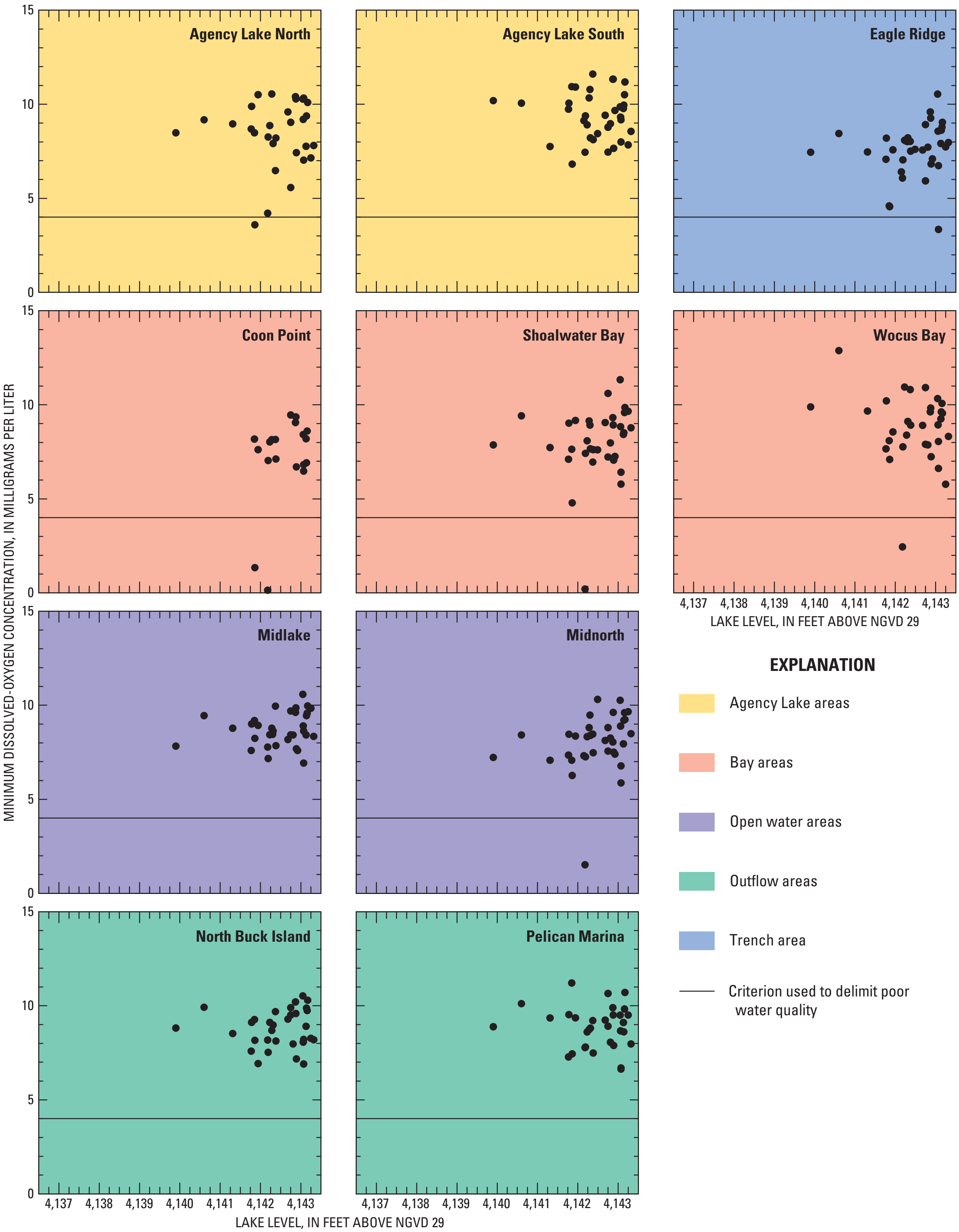
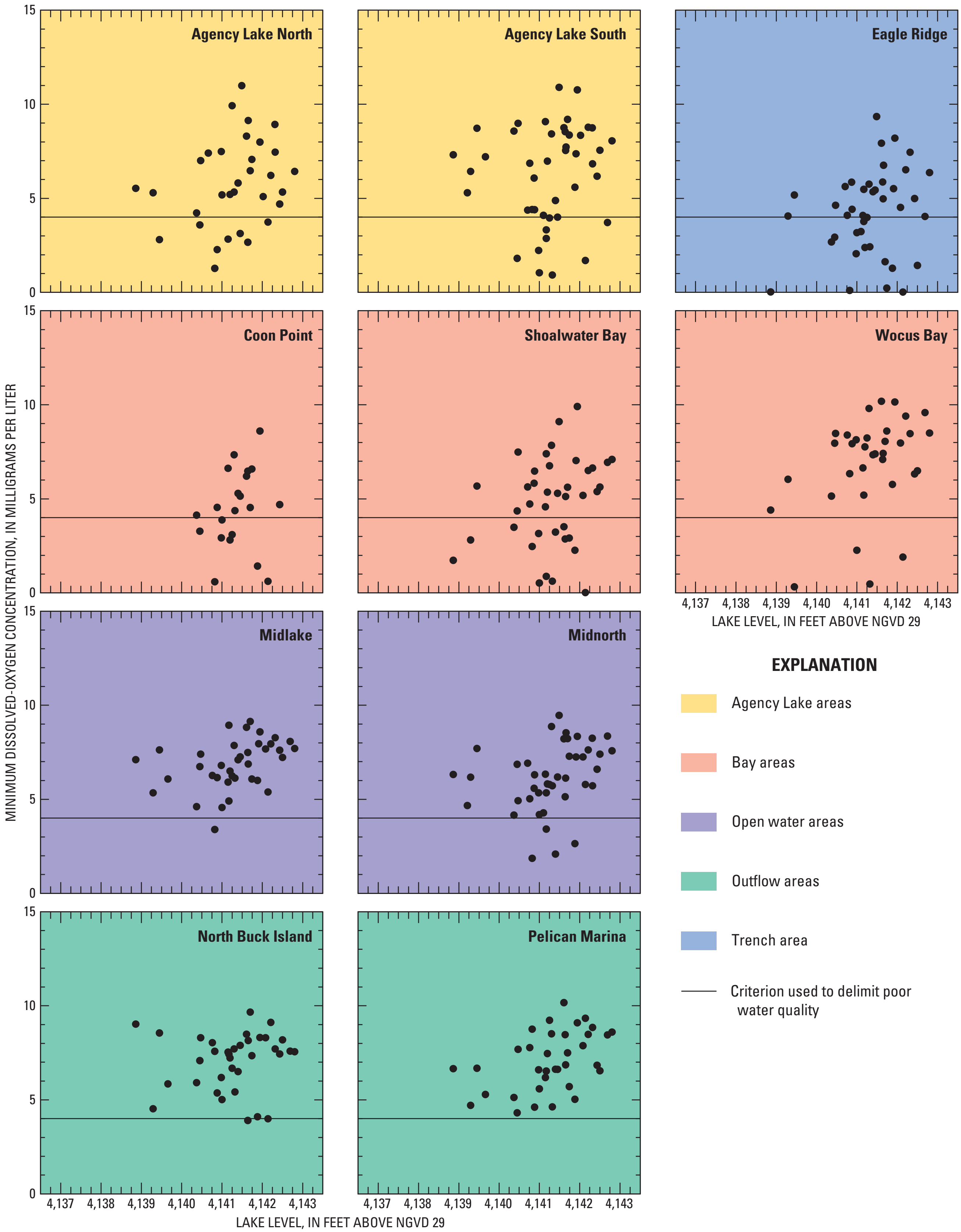


Figure 15. Frequency distribution of lakewide dissolved-oxygen data, by month, Upper Klamath and Agency Lakes, Oregon, June–September 1990–2006. Years are displayed in order of increasing lake level based on the end-of-month lake-level rankings for the preceding month (see table 2).



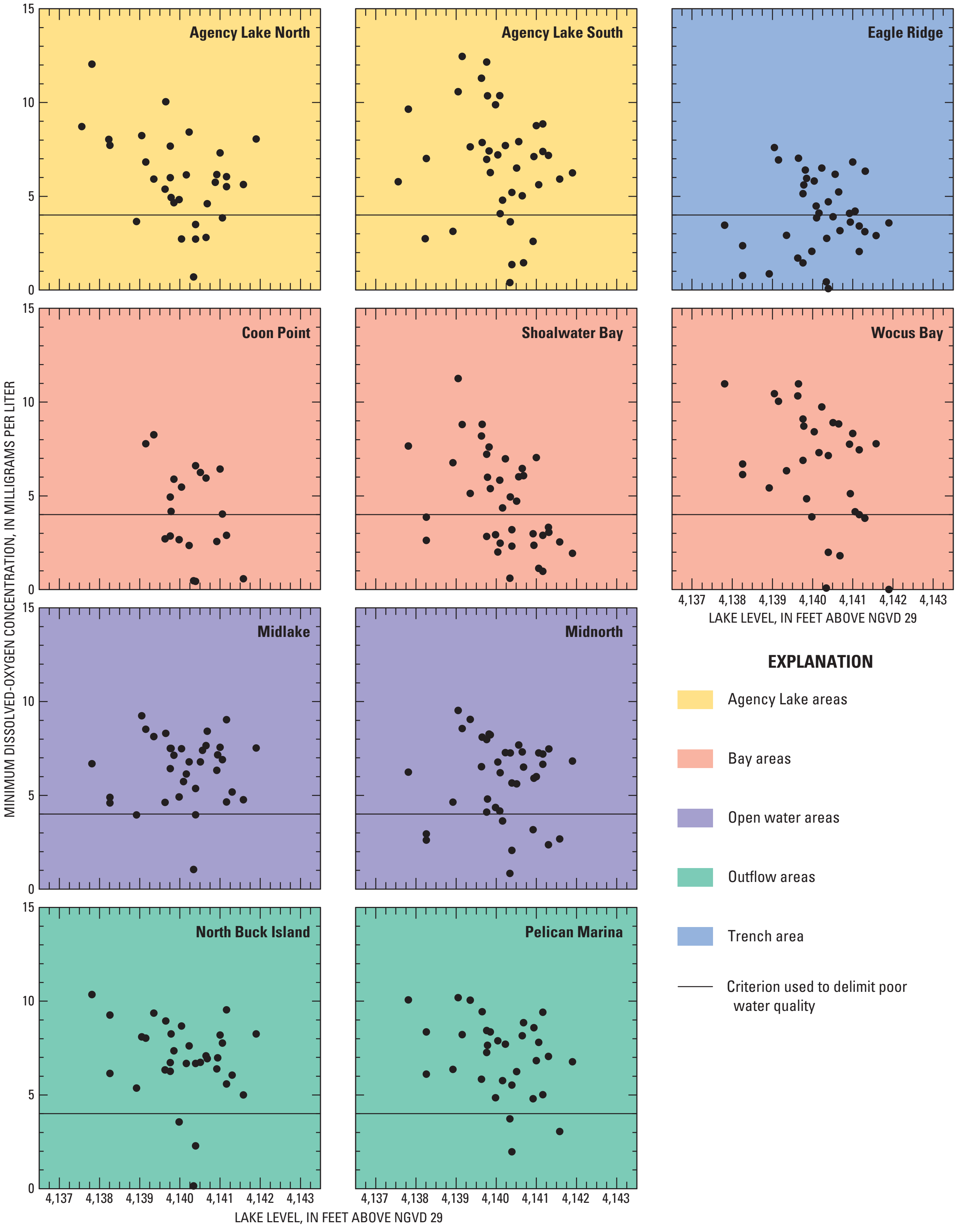
A. June 1990–2006

Figure 16. Daily minimum observed dissolved-oxygen concentrations at each site for June–September, Upper Klamath Lake and Agency Lakes, Oregon, 1990–2006.



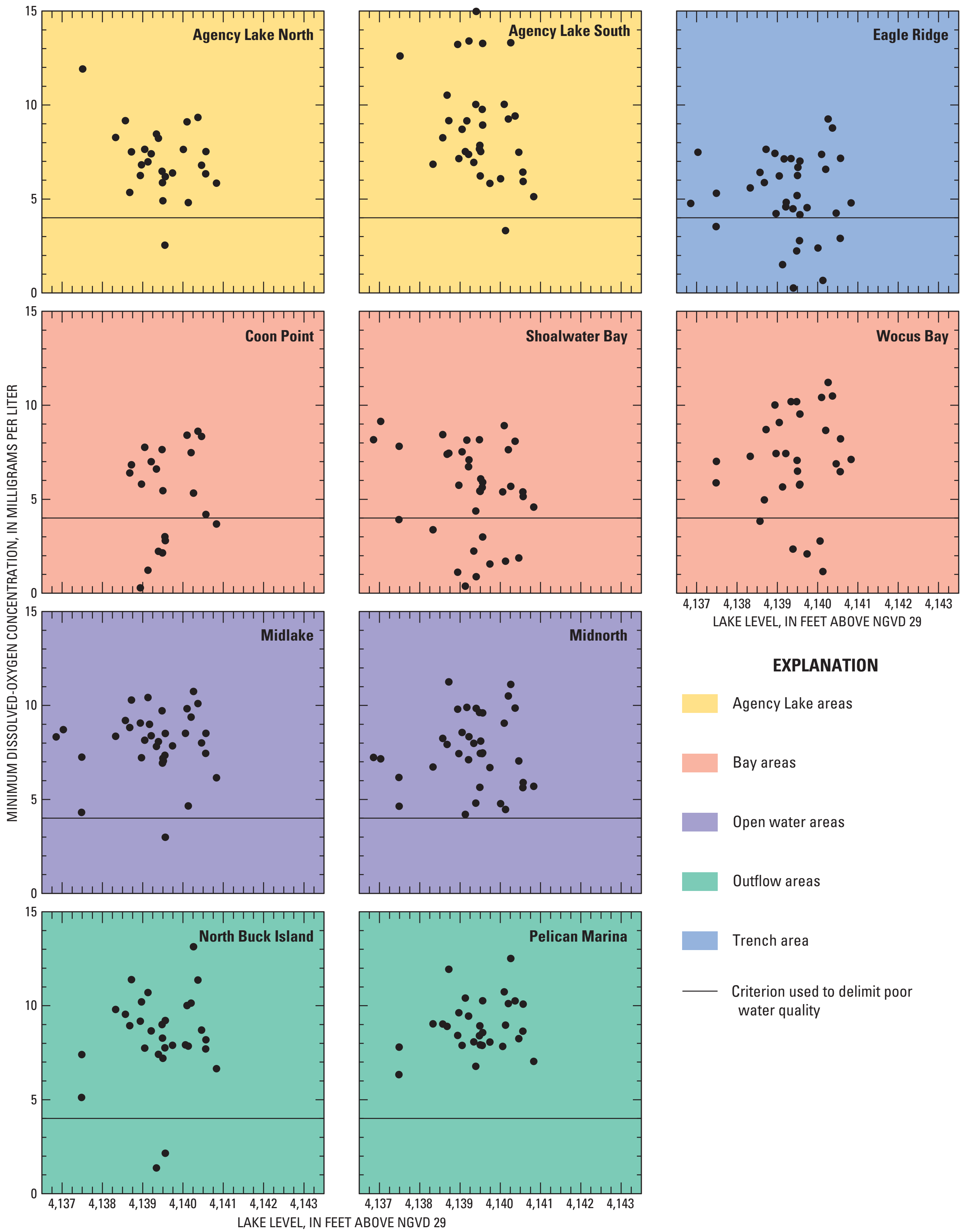
B. July 1990–2006

Figure 16. Continued.



C. August 1990–2006

Figure 16. Continued.



D. September 1990–2006

Figure 16. Continued.

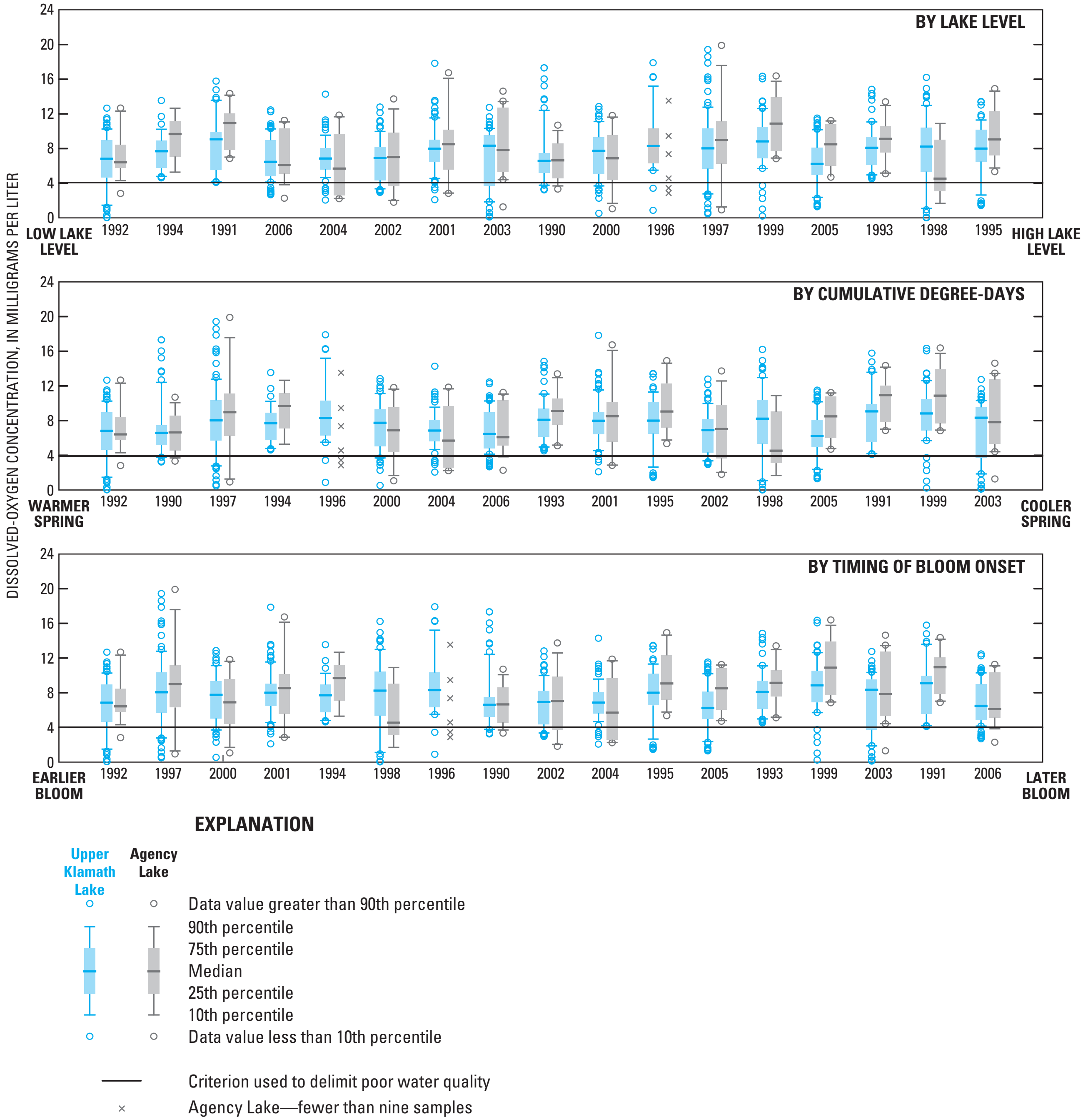


Figure 17. Frequency distribution of July lakewide dissolved-oxygen data displayed by lake level, cumulative degree-days, and timing of the bloom onset, Upper Klamath and Agency Lakes, Oregon, 1990–2006. See table 6 for listing of rankings.

Although the frequency distributions of the dissolved-oxygen data do not show a relation with the onset of the bloom, there is some evidence that when the bloom is delayed, the dip in the dissolved-oxygen concentrations also is delayed and may not be as extreme. By looking at the depth-profile data at Eagle Ridge, a site that is more susceptible to low dissolved-oxygen concentrations because of its depth, for four specific years, this relation can be explored (fig. 18).

To summarize the conditions in these four years again, 1992 had the earliest bloom of the 17 years, followed by 1997, whereas the bloom in 1991 started and stalled, resulting in the second latest bloom onset, followed by 2006. The onset of the low dissolved-oxygen concentrations for 1992 and 2006 both began at the end of July; even though 1992 had the earliest bloom onset and 2006 had the latest bloom onset.

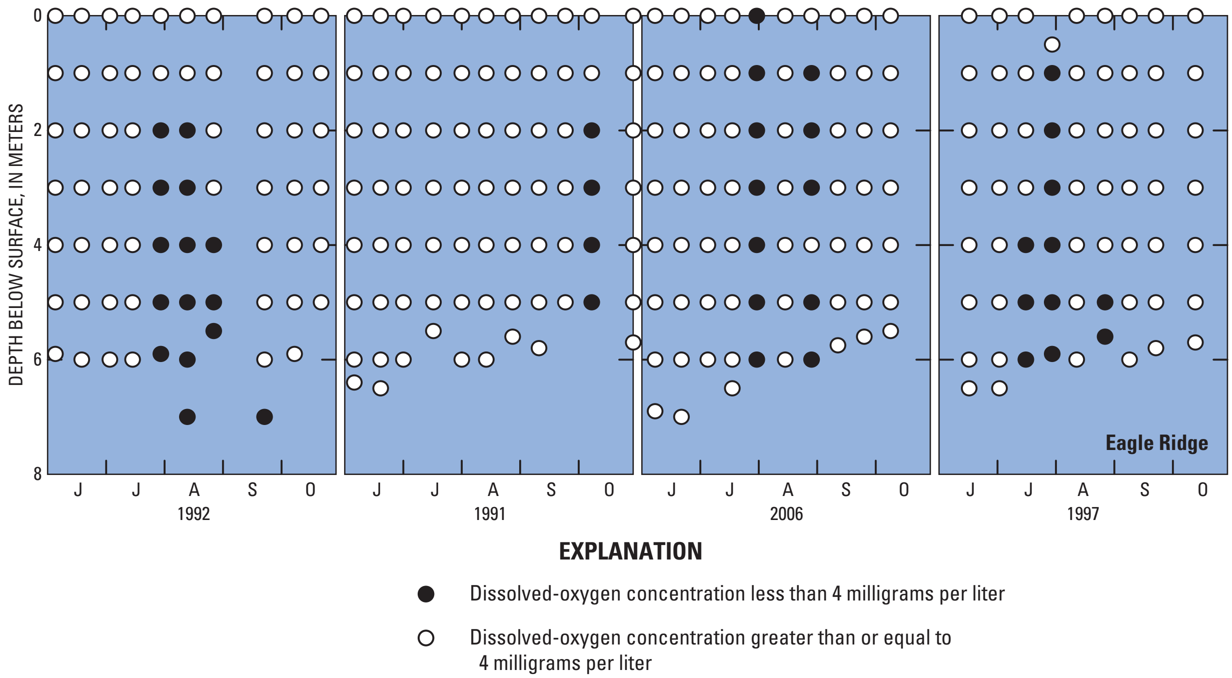


Figure 18. Depth-profile dissolved-oxygen data at Eagle Ridge for 4 years, Upper Klamath Lake, Oregon.

The low dissolved-oxygen concentrations in 1997 (in mid-July) were detected one sampling earlier than in 1992 and 2006. In contrast, low dissolved-oxygen concentrations were not measured until early October in 1991, the year with the smaller early bloom followed by the larger bloom at the end of August (fig. 7). So, for certain circumstances, the years with a later bloom also had a delayed occurrence of low dissolved-oxygen concentration (like 1991), though this did not hold for all years with later blooms (like 2006).

Total Phosphorus

Phosphorus can play an important role in Upper Klamath Lake because high concentrations of phosphorus can lead to heavy algal blooms. As previously discussed, these blooms then lead to elevated pH during the growth of the bloom and associated photosynthesis, and low dissolved oxygen when then the bloom declines. The hypothesis for analysis with regards to phosphorus from Wood and others (1996) is:

> *Year-to-year differences in phosphorus concentration are related to year-to-year differences in lake level, such that phosphorus concentration is lower at higher lake levels.*

The yearly distributions of total-phosphorus concentrations for Upper Klamath and Agency Lakes were plotted by month in order of increasing lake level in an attempt to analyze this hypothesis (fig. 19). As was noted by Wood and others (1996), the data from 1992 stand out. The range of data measured in June and July of 1992 is larger than in any other year for those months. There does not appear to be a significant pattern in the data with relation to lake level. For both the 1990–94 dataset and the larger 1990–2006 dataset, the data are not consistent with this hypothesis. The distributions across the years in a particular month do not show a lot of variability—the more interesting variability to notice is between the months for certain years. Elevated total phosphorus concentrations were measured into September and October for those years that experienced blooms later in the season (1996, 1991, 1995, 1990), either as a second bloom or sustained growth from earlier in the season (fig. 7). Similar to the pattern noted in the frequency distributions of the pH data (fig. 12), and most likely because of related processes, Upper Klamath Lake and Agency Lake had quite different distributions in some years. The elevated concentrations measured in Agency Lake may be an indication of different contributing sources for the lakes.

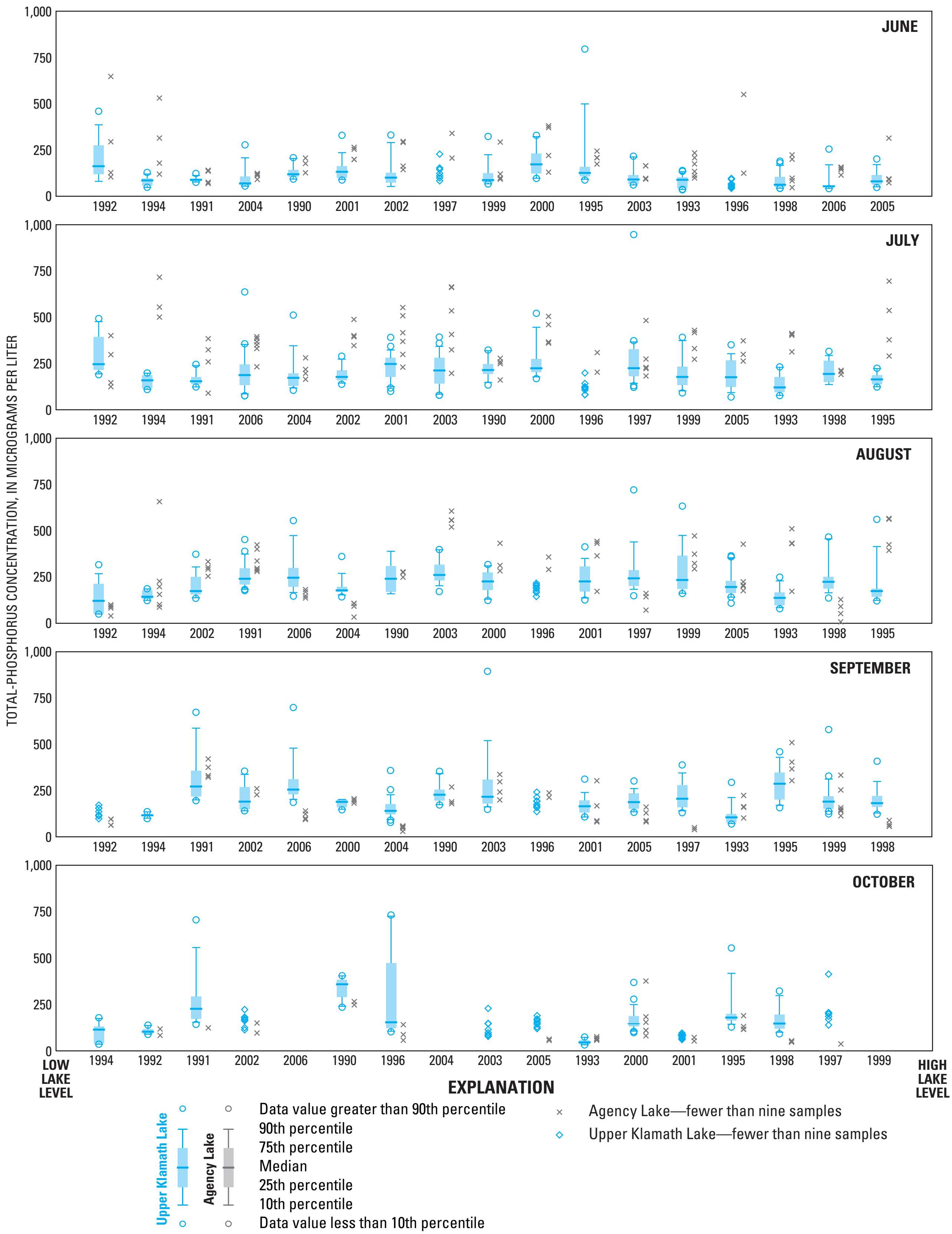


Figure 19. Frequency distribution of lakewide total-phosphorus data, by month, Upper Klamath and Agency Lakes, Oregon, June–October 1990–2006. Years are displayed in order of increasing lake level based on the end-of-month lake-level rankings for the preceding month (see table 2).

Because of the importance of the bloom onset on delayed poor water-quality conditions and because of the effect of total-phosphorus concentrations on the algal bloom, the period of the bloom onset (June) was explored further for relations to lake level. Total phosphorus and chlorophyll-*a* concentrations in June were determined to be strongly correlated (Spearman's $\rho = 0.80$, $p < 0.0001$) (fig. 20). This indicates that the first bloom is phosphorus-limited. The years with earlier blooms (1992, 1997, 2000, 2001) had higher median concentrations of both total phosphorus and chlorophyll-*a*, most likely because the bloom had gone through more growth throughout the month of June. Examining the distribution of the years in figure 20 with respect to their lake-level ranking did not reveal any relation or pattern with lake level.

These June median chlorophyll-*a* and total phosphorus concentrations also were plotted by the area of the lake where the measurements were made (fig. 21). All areas retained strong, significant correlations between chlorophyll-*a* and total phosphorus. This figure makes it easier to see that the total phosphorus and chlorophyll-*a* concentrations in Agency Lake in June were higher than in Upper Klamath Lake. The correlation between the two, however, was the weakest in Agency Lake. The bay areas experienced a wider range of total phosphorus and chlorophyll-*a* concentrations.

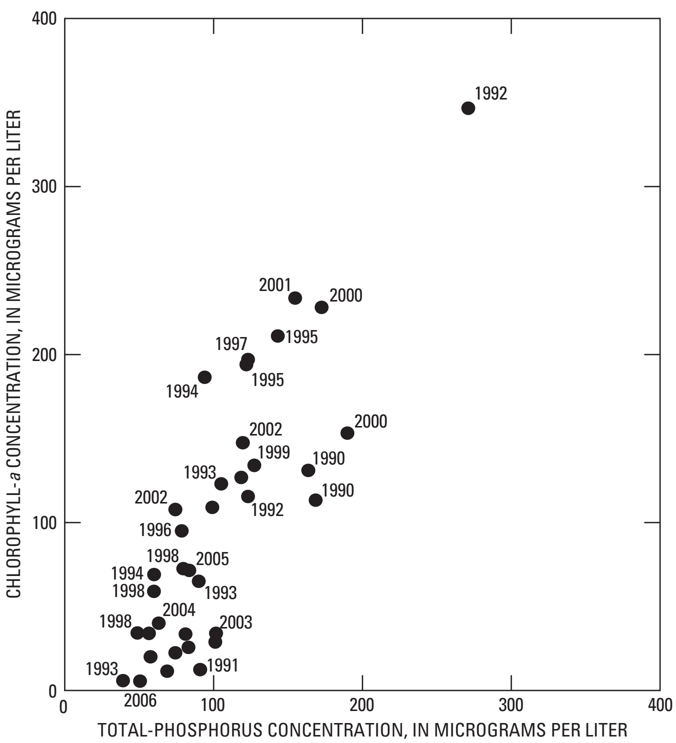


Figure 20. Relation of lakewide median chlorophyll-*a* concentration to lakewide median total-phosphorus concentration, Upper Klamath Lake, Oregon, June 1990–2006. Data values represent the median of measurements on each June sampling date. Spearman's ρ correlation coefficient = 0.80, p < 0.0001. Years are not shown for all data values but are included here to aid in making comparisons.

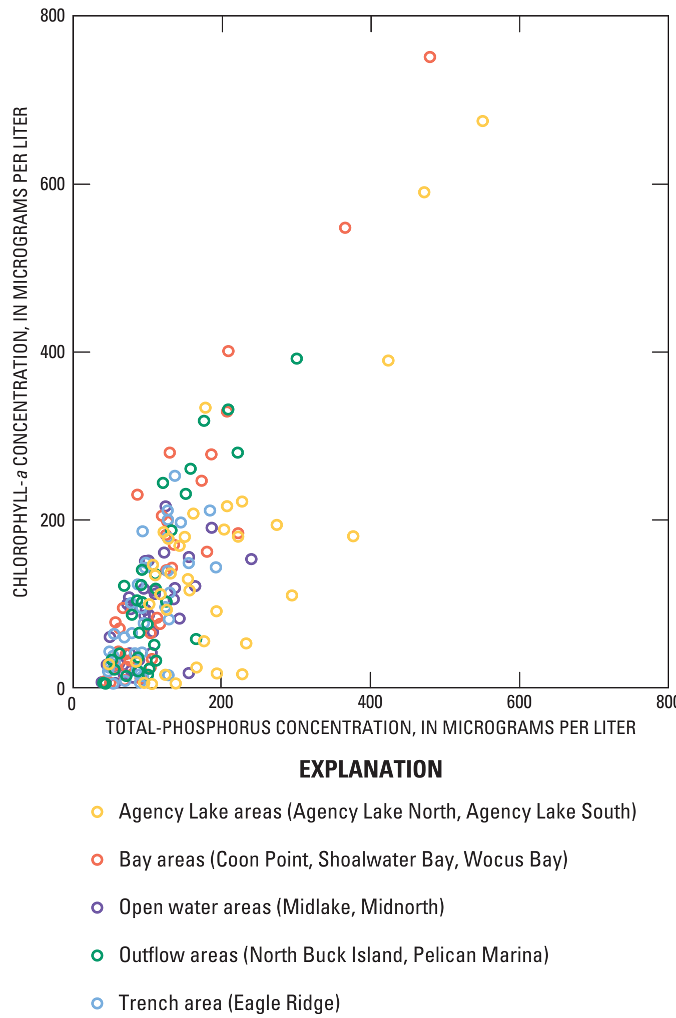


Figure 21. Relation of lakewide median chlorophyll-*a* concentration to lakewide median total phosphorus concentration, by area, Upper Klamath and Agency Lakes, Oregon, June 1990–2006. Data values represent the median of measurements on each June sampling date. Spearman's ρ correlation coefficients, all with p < 0.0001, except for Agency Lake areas, which had a p = 0.0007: Agency Lake areas = 0.52, Bay areas = 0.82, Trench area = 067, Open water areas = 0.66, Outflow areas = 0.72.

Water Temperature

The hypothesis related to water temperature from Wood and others (1996) is:

> *Year-to-year differences in the rate of spring warming of the lake are related to year-to-year differences in lake level, such that water temperature increases more slowly when the lake level is higher.*

The pattern in median surface water temperatures typically observed in Upper Klamath Lake is shown in figure 22. Temperatures typically start out between 10 and 15°C in early May, rise to around 25°C in July and then slowly decline to less than 10°C in late October. Two exceptions to this are the two years with the lowest lake level, 1992 and 1994. These two years started out in early May with surface water temperatures greater than 15°C. The warmest water

Figure 22. Lakewide median surface water temperature, Upper Klamath Lake, Oregon, May–October 1990–2006. Years are separated into four plots to facilitate viewing the data for individual years.

temperatures of the season (greater than 25°C) were measured in July in 1990, 1996, and 2003, and in late June in 2000. In contrast, the warmest May water temperatures were measured in 1992, 1997, 2001 and 1995. Comparing this list to the degree-days ranking (table 6), based on air temperature from April 1 to May 15, is very enlightening. The years 1992 and 1997 had the first and third warmest springs based on air temperature, but 2001 and 1995 were ranked in the middle of the 17 years based on degree-days. Further exploration of the differences in these lists sheds some light on patterns observed in the timing of the bloom onset.

The years 1990 and 1994 were in the top four ranked years based on cumulative degree-days, but the water temperatures in these years did not warm until later in June and July, respectively. In contrast, water temperatures in 2001 were warming in May, but 2001 was ranked tenth in the degree-days ranking. The fact that the water temperature was on a warming trend that was not apparent in the air temperature perhaps explains why it was the year with the fourth earliest bloom onset (table 13). Likewise, 2000 had a similar lake-level ranking to 2001 and a middle-range degree-day ranking, but had the third earliest bloom onset. This may be related to the median surface water temperature reaching 25°C in late June (fig. 22). One other year that showed an interesting pattern in the rankings is 2006 (table 13). Again it had a similar lake-level ranking to 2000 and 2001 and middle-range ranking of cumulative degree-days; however, it was the year with latest bloom onset. Surface water temperatures did not get over 20°C until July in 2006. Comparing these 3 years illustrates that similar lake levels can have very different bloom onset outcomes—perhaps related to both air and water temperature effects, among other factors.

These varying patterns in air and water temperatures reveal that air temperature can be used as an estimate of water temperature but most likely does not give an accurate estimate of the absolute temperature of the lake. An overall heat budget would be needed for that determination. Generally, the largest components of the heat budget for a lake are incoming shortwave solar radiation and incoming long-wave atmospheric radiation, both of which would be affected by cloud cover. This could partly explain why there is not more correlation between air and water temperatures. The differences observed in the water-temperature patterns for these 3 years of similar lake levels and air temperatures do not support the hypothesis addressing water temperature relations (fig. 23).

Table 13. Ranking of years 1990–2006 by lake level, degree-days, and timing of bloom onset shaded to illustrate the relation between water temperature and lake level, Upper Klamath Lake, Oregon.

Lake Level	Degree-days	Timing of the bloom
Lowest lake level	Warmest spring	Earliest bloom
1992	1992	1992
1994	1990	1997
1991	1997	**2000**
2002	1994	**2001**
2004	1996	1998
1990	**2000**	1994
2001	2004	1990
2006	**2006**	1996
2000	1993	2002
2003	**2001**	2004
1996	1995	1995
1997	2002	2005
1999	1998	1993
2005	2005	1999
1993	1991	2003
1995	1999	1991
1998	2003	**2006**
Highest lake level	Coolest spring	Latest bloom

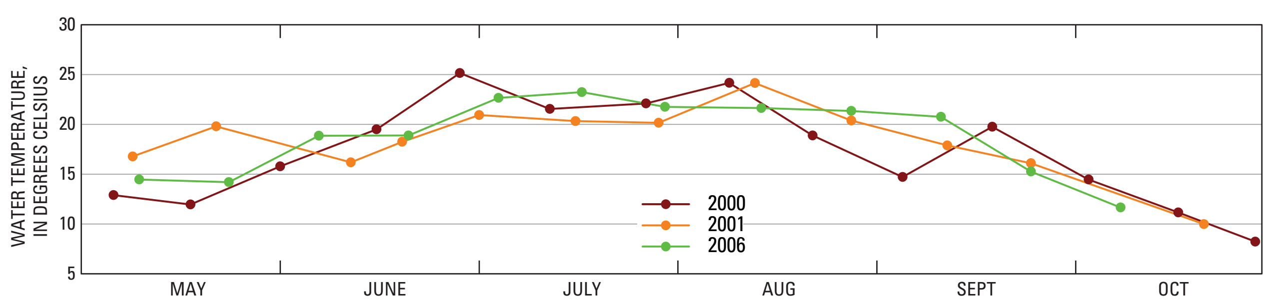


Figure 23. Lakewide median surface water temperatures for 2000, 2001, and 2006, Upper Klamath Lake, Oregon.

Wood and others (1996) speculated that “it is unlikely that a higher lake level is effective in slowing down the spring warming of the lake.” The pattern in rankings for the year 1998 (table 12) offers support for this speculation. The year 1998 had the highest-ranked lake level, leading some to believe that the warming of the lake would be slower. The cumulative degree-days ranking for 1998 was in the cooler third of the years, yet the water warmed to greater than 20°C by the end of June and up to 25°C by the end of July (fig. 23), with the fifth earliest bloom onset. Therefore, the high lake level did not appear to have a slowing effect on the warming of the lake.

Information-Theoretic Approach to Multivariable Analysis of Water-Quality Conditions

Although the exploration of the univariate relations proposed by the hypotheses yielded no direct correlations between lake level and water-quality conditions, it was suspected that some combination of variables, including lake level, was affecting water-quality conditions. To examine these more complex interrelations, multivariable analyses were performed and then assessed using an information-theoretic approach.

The analyses were designed to examine the effect of multiple physical and biological variables on some measure of water-quality conditions. July and August were chosen for further exploration because poor water-quality conditions commonly occur during this time period and create stressful conditions in the lake for the suckers. Four lakewide water-quality measures were evaluated—the percentage of dissolved-oxygen concentrations less than 4 mg/L for July and August (table 7) and the percentage of pH values greater than 9.7 for July and August (table 9). The explanatory variables included in the analysis were peak chlorophyll-*a* concentrations as a measure of the strength of the bloom, degree-days from April 1 to May 15 as a measure of how warm the spring was, 75th-percentile water temperature, median October–May discharge in the Williamson River, median monthly wind speed measured at Klamath Falls airport, and median monthly lake level in Upper Klamath Lake.

Poor water-quality conditions related to low dissolved-oxygen concentrations or high pH values are expected to be a result of bloom dynamics. Therefore, the explanatory variables selected for further examination were chosen because of their observed or theorized effects related to the occurrence, strength, or duration of the algal bloom. Peak chlorophyll-*a* concentration is an obvious water-quality variable to include when considering conditions related to the bloom, and was included in the analysis as a measure of the strength of the bloom. Kann and Smith (1999) have proposed that a reduction in chlorophyll-*a* concentration in the lake from 200 µg/L to 100 µg/L would decrease the probability of potentially harmful pH values of greater than 9.5 by about half. Welch and Burke (2001) demonstrated that the growth and strength of the bloom are strongly affected by available light, air temperature, and indirectly lake level as it relates to these two variables. Unfortunately, long-term cloud-cover data were not available to assess the effects of available light in this analysis. Long-term air temperature data, however, were available, and cumulative degree-days were calculated from April 1 to May 15 as a measure of springtime warming. Kann (1998) proposed using cumulative degree-days for this same time period as an index of lake warming. To this extent, water temperature was included in this analysis as a direct measure of lake warming.

Nutrient inputs to the lake are recognized as an important factor affecting the growth and development of the bloom. The Williamson River accounts for about half of the inflow to Upper Klamath Lake and transports nutrients from the surrounding landscape to the lake with this inflow. Wood and others (2006) found a correlation between ammonia concentrations in the lake and the Williamson River discharge from the previous October–May, representing the period of nutrient loading to the lake before the onset of the bloom. Therefore, the mean October–May discharge from the Williamson River was included in this analysis to represent the effect of nutrient loading on bloom dynamics. Another source of nutrient loading to consider because of the potential effect on bloom strength is increased phosphorus loading in the lake itself due to bed-sediment resuspension. Low lake levels combined with summer wind conditions were shown by Laenen and LeTourneau (1996) to affect as much as 75 percent of the lake with bed-sediment resuspension, and consequently increased phosphorus loading.

As discussed earlier, wind speed is suspected to be an important factor affecting water-quality conditions in Upper Klamath Lake, but good-quality wind-speed data representing conditions on the lake itself is lacking. Kann and Welch (2005) noted that the severity of both low dissolved oxygen and high ammonia was related to water-column stability, which was dependent on wind speed. An inverse correlation between wind speed and the surface-to-bottom difference in dissolved oxygen averaged over July–August was reported for profile data for data collected from 1990 to 2000. Wood and others (2006), however, found insignificant or weak correlations between daily wind speed and daily minimum dissolved oxygen for the 2002–05 data collected by USGS. They reported that wind speed did appear to influence the degree of stratification in the water column, but was found to have has less influence over when the lowest dissolved-oxygen concentrations occurred. Therefore, even though the wind-speed data available for inclusion in this analysis was not ideal, it was considered as a factor for this analysis.

Lake level, being the only factor of those included in this analysis that can be directly controlled by Bureau of Reclamation, has already been discussed in this report as a factor related to water-quality conditions. The 2002 Biological Opinion for the Lost River and shortnose suckers (U.S. Fish and Wildlife Service, 2002), acknowledges “evidence that water levels directly or indirectly affect factors that affect water quality, and that water quality impacts suckers.” Barbiero and Kann (1994) have applied these lake level considerations to the recruitment of algal cells from the sediments, which has been shown to be an important contributor to water column biomass increases in AFA. It is proposed that greater light intensity at the sediment surface, as a result of low lake levels in early spring, may speed sediment recruitment.

Model sets were developed with the first five explanatory variables (peak chlorophyll-a concentration, degree-days, water temperature, Williamson River discharge, and wind speed) using different combinations of one variable, two variables, three variables, and so on. These model sets were regressed against each water-quality measure, and then each of these model combinations was repeated including lake level as an additional explanatory variable in an effort to assess the effect of lake level on water-quality conditions. These multiple regression models also were compared to each other as a means of explaining the variation observed between years in water-quality conditions in the lake.

The Akaike Information Criterion (AIC_c), corrected for small sample size, and the corresponding Akaike weights (w_i) were used to evaluate the relative likelihood of each multiple regression model (Burnham and Anderson, 2002). The AIC_c statistic provides a relative measure and is designed to compare “sets” of models to each other and is not designed to analyze a model independently. Models with a smaller AIC_c value fit the data better and do a better job of explaining the variance observed in the dataset. The AIC_c statistic also is designed to reward parsimony, such that the reduction in the residual sum of squares (RSS) that is obtained by adding an explanatory variable to a model will only result in a lower AIC_c statistic if the reduction is more than enough to compensate for the degree of freedom that has been added to the model. For all four water-quality measures tested and for all possible variable combinations, two possible models were generated—one including lake level as an explanatory variable and one without lake level. In every instance, the addition of lake level to the regression resulted in an increase in the AIC_c value of somewhere between 2 and 5, indicating that the model without lake level as a variable offered a better fit of the data. In other words, the addition of lake level does not explain enough additional variance in the observed water-quality condition to justify its inclusion as an additional explanatory variable, relative to the same model without lake level as an explanatory variable.

The generation of these multiple models with varying numbers of explanatory variables yielded no single overarching equation to explain the variation in water-quality conditions observed between years. For each water-quality measure tested, the models with the lowest AIC_c statistics, and therefore the best fit, were the models that considered each physical variable individually. For example, the model set considering water temperature alone was a better fit for explaining the variance observed in the percentage of June dissolved-oxygen concentrations of less than 4 mg/L than the models of water temperature and any other explanatory variable. These univariate models were examined as a set for each water-quality measure (percent DO less than 4 mg/L and percent pH greater than 9.7, July and August) and the Akaike weights were calculated to provide more insight into each variable’s role in the larger context of water-quality conditions in the lake (tables 14 and 15).

These models do not reveal the presence or absence of a statistically significant relation between the variables as determined by the acceptance or rejection of a null hypothesis of no relation, but rather provide insight into variables that help to explain the variance observed in the water-quality parameters. For instance, for the occurrence of low dissolved-oxygen concentrations in July, wind speed appears to be the best variable of those examined at explaining the variance observed in the data. The Akaike weight of 0.49 for the wind speed model, relative to the weights of all the other univariate models, which range from 0.02 to 0.39 (table 14), indicates that there is a 49-percent chance that wind speed is the best model of the set. The next best model, with an Akaike weight of 0.39, reveals that water temperature also may help explain the observed variance. By removing the wind-speed model from the first set and reevaluating the remaining 5 models, the water-temperature model does rise to the top (with an Akaike weight of 0.76), as the next best model for explaining the variance in the July dissolved-oxygen data. Likewise for the occurrence of low dissolved-oxygen concentrations in August, water temperature and wind speed play important roles.

Water temperature emerges as an important variable in explaining the variance observed in the occurrence of high pH values in July and August as well (table 15), based on the Akaike weights of that model (0.48 in July and 0.35 in August) relative to the rest of the models in the set, which varied from 0.08 to 0.17 in July and from 0.06 to 0.20 in August. Removing the water-temperature model from the first set and reevaluating the remaining five models, reveals that the wind-speed model for July (with an Akaike weight of 0.32) and the peak chlorophyll-*a* concentration model for August (with an Akaike weight of 0.31) were the next best models. The Akaike weights for the remaining variables were fairly

Table 14. Akaike weights and supporting variables for evaluating the percentage of dissolved-oxygen concentrations less than 4 milligrams per liter, Upper Klamath and Agency Lakes, Oregon, 1990–2006.

[n=17 for all; K, number of parameters in the model; RSS, residual sum of squares; AIC_c, Akaike information criterion; Δ_i, AIC_i minus the minimum AIC_c for the set; w_i, Akaike model weight; shading indicates the best fit model for each set]

Model	July						August					
	K	RSS	AIC_c	Δ_i	$e^{(-0.5*\Delta_i)}$	w_i	K	RSS	AIC_c	Δ_i	$e^{(-0.5*\Delta_i)}$	w_i
Peak chlorophyll-*a* concentration	3	795.7	73.2	6.8	0.03	0.02	3	2,207.6	90.6	4.7	0.10	0.06
Degree-days from April 1 to May 15	3	778.3	72.9	6.4	.04	.02	3	2,145.6	90.1	4.2	.12	.08
75th-percentile water temperature	3	549.3	66.9	.5	.79	.39	3	1,677.5	85.9	.0	1.00	.61
Cumulative October–May Williamson River discharge	3	673.2	70.4	3.9	.14	.07	3	2,153.8	90.2	4.3	.12	.07
Median monthly wind speed	3	534.6	66.5	.0	1.00	.49	3	2,031.5	89.2	3.3	.20	.12
Median monthly lake level	3	784.4	73.0	6.5	.04	.02	3	2,201.4	90.5	4.6	.10	.06
Remove "best fit" model and reanalyze												
Peak chlorophyll-*a* concentration	3	795.7	73.2	6.3	0.04	0.03	3	2,207.6	90.6	1.4	0.49	0.15
Degree-days from April 1 to May 15	3	778.3	72.9	5.9	.05	.04	3	2,145.6	90.1	.9	.63	.19
75th-percentile water temperature	3	549.3	66.9	.3	1.00	.76	–	–	–	–	–	–
Cumulative October–May Williamson River discharge	3	673.2	70.4	3.5	.18	.13	3	2,153.8	90.2	1.0	.61	.19
Median monthly wind speed	3	–	–	–	–	–	3	2,031.5	89.2	.0	1.00	.31
Median monthly lake level	3	784.4	73.0	6.1	.05	.04	3	2,201.4	90.5	1.4	.50	.16
Remove "best fit" model and reanalyze												
Peak chlorophyll-*a* concentration	3	795.7	73.2	2.8	0.24	0.13	3	2,207.6	90.6	0.5	0.78	0.22
Degree-days from April 1 to May 15	3	778.3	72.9	2.5	.29	.16	3	2,145.6	90.1	.0	1.00	.28
75th-percentile water temperature	–	–	–	–	–	–	–	–	–	–	–	–
Cumulative October–May Williamson River discharge	3	673.2	70.4	.0	1.00	1.00	3	2,153.8	90.2	.1	.97	.27
Median monthly wind speed	–	–	–	–	–	–	–	–	–	–	–	–
Median monthly lake level	3	784.4	73.0	2.6	.27	.27	3	2,201.4	90.5	.4	.80	.23
Remove "best fit" model and reanalyze												
Peak chlorophyll-*a* concentration	3	795.7	73.2	0.4	0.83	0.30	–	–	–	–	–	–
Degree-days from April 1 to May 15	3	778.3	72.9	.0	1.00	.36	–	–	–	–	–	–
75th-percentile water temperature	–	–	–	–	–	–	–	–	–	–	–	–
Cumulative October–May Williamson River discharge	–	–	–	–	–	–	–	–	–	–	–	–
Median monthly wind speed	–	–	–	–	–	–	–	–	–	–	–	–
Median monthly lake level	3	784.4	73.0	.1	.94	.34	–	–	–	–	–	–

Table 15. Akaike weights and supporting variables for evaluating the percentage of pH values greater than 9.7, Upper Klamath and Agency Lakes, Oregon, 1990–2006.

[n=17 for all; K, number of parameters in the model; RSS, residual sum of squares; AIC_c, Akaike information criterion; Δ_i, AIC_i minus the minimum AIC_c for the set; w_i, Akaike model weight; shading indicates the best fit model for each set]

Model	July						August					
	K	RSS	AIC_c	Δ_i	$e^{(-0.5*\Delta_i)}$	w_i	K	RSS	AIC_c	Δ_i	$e^{(-0.5*\Delta_i)}$	w_i
Peak chlorophyll-*a* concentration	3	4,418.0	102.4	3.6	0.17	0.08	3	1,484.3	83.8	1.1	0.57	0.20
Degree-days from April 1 to May 15	3	4,370.4	102.2	3.4	.18	.09	3	1,526.9	84.3	1.6	.44	.16
75th-percentile water temperature	3	3,579.9	98.8	.0	1.00	.48	3	1,388.1	82.7	.0	1.00	.35
Cumulative October–May Williamson River discharge	3	4,295.8	101.9	3.1	.21	.10	3	1,549.9	84.6	1.9	.39	.14
Median monthly wind speed	3	4,058.9	100.9	2.1	.34	.17	3	1,695.0	86.1	3.4	.18	.06
Median monthly lake level	3	4,434.5	102.4	3.6	.16	.08	3	1,636.5	85.5	2.8	.25	.09
Remove "best fit" model and reanalyze												
Peak chlorophyll-*a* concentration	3	4,418.0	102.4	1.4	0.49	0.16	3	1,484.3	83.8	0.0	1.00	0.31
Degree-days from April 1 to May 15	3	4,370.4	102.2	1.3	.53	.17	3	1,526.9	84.3	.5	.79	.24
75th-percentile water temperature	–	–	–	–	–	–	–	–	–	–	–	–
Cumulative October–May Williamson River discharge	3	4,295.8	101.9	1.0	.62	.20	3	1,549.9	84.6	.7	.69	.21
Median monthly wind speed	3	4,058.9	100.9	.0	1.00	.32	3	1,695.0	86.1	2.3	.32	.10
Median monthly lake level	3	4,434.5	102.4	1.5	.47	.15	3	1,636.5	85.5	1.7	.44	.13
Remove "best fit" model and reanalyze												
Peak chlorophyll-*a* concentration	3	4,418.0	102.4	0.5	0.79	0.23	–	–	–	–	–	–
Degree-days from April 1 to May 15	3	4,370.4	102.2	.3	.86	.25	3	1,526.9	84.3	0.0	1.00	0.35
75th-percentile water temperature	–	–	–	–	–	–	–	–	–	–	–	–
Cumulative October–May Williamson River discharge	3	4,295.8	101.9	.0	1.00	.29	3	1,549.9	84.6	.3	.88	.31
Median monthly wind speed	–	–	–	–	–	–	3	1,695.0	86.1	1.8	.41	.14
Median monthly lake level	3	4,434.5	102.4	.5	.76	.22	3	1,636.5	85.5	1.2	.55	.19
Remove "best fit" model and reanalyze												
Peak chlorophyll-*a* concentration	–	–	–	–	–	–	–	–	–	–	–	–
Degree-days from April 1 to May 15	–	–	–	–	–	–	–	–	–	–	–	–
75th-percentile water temperature	–	–	–	–	–	–	–	–	–	–	–	–
Cumulative October–May Williamson River discharge	–	–	–	–	–	–	–	–	–	–	–	–
Median monthly wind speed	–	–	–	–	–	–	3	1,695.0	86.1	0.6	0.74	0.43
Median monthly lake level	–	–	–	–	–	–	3	1,636.5	85.5	.0	1.00	.35

evenly distributed, indicating that there was no clear hierarchy of importance among those variables.

These analyses were based on water-quality measures calculated from the lakewide dataset. To explore whether the explanatory variables could be defined more clearly for a localized measure of water quality, similar analyses were performed to examine the minimum dissolved-oxygen concentrations measured at Midnorth during the July-August time period (table 16). Midnorth was chosen because it was shown to be an important indicator site for water quality in the adult sucker habitat located in the northern part of the lake. Wood and others (2006) found that, at the Midnorth site, "die-off years could be successfully identified in the historical data by screening for water characterized by exceptionally low chlorophyll-*a* concentration, exceptionally low dissolved-oxygen concentration throughout the water column (not just near the bottom), and exceptionally high ammonia concentration and water temperature, just prior to or coincident with the start of a fish die-off." As with the lakewide analysis, the best models were those with just one explanatory variable, and water temperature provided the best fit when examining the individual parameter models. Removing water temperature and reevaluating revealed that lake level also played an important role. The relation with water temperature was explored further by examining a set of models that included water temperature along with each of

Table 16. Akaike weights and supporting variables for evaluating the minimum July–August dissolved-oxygen concentration at Midnorth, Upper Klamath Lake, Oregon, 1990–2006.

[n=17 for all; K, number of parameters in the model; RSS, residual sum of squares; AIC_c, Akaike information criterion; Δ_i, AIC_i minus the minimum AIC_c for the set; w_i, Akaike model weight; shading indicates the best fit model for each set]

Model	K	RSS	AIC_c	Δ_i	$e^{(-0.5*\Delta_i)}$	w_i
Peak chlorophyll-*a* concentration	3	43.1	23.7	4.4	0.11	0.07
Degree–days from April 1 to May 15	3	43.2	23.7	4.4	.11	.07
75th-percentile water temperature	3	33.3	19.3	.0	1.00	.62
Cumulative October-May Williamson River discharge	3	43.2	23.7	4.4	.11	.07
Median monthly wind speed	3	42.8	23.6	4.3	.12	.07
Median monthly lake level	3	40.9	22.8	3.5	.17	.11
Remove "best fit" model and reanalyze						
Peak chlorophyll-*a* concentration	3	43.1	23.7	0.9	0.65	0.18
Degree–days from April 1 to May 15	3	43.2	23.7	.9	.63	.18
75th-percentile water temperature	–	–	–	–	–	–
Cumulative October-May Williamson River discharge	3	43.2	23.7	.9	.63	.18
Median monthly wind speed	3	42.8	23.6	.8	.68	.19
Median monthly lake level	3	40.9	22.8	.0	1.00	.28
Remove "best fit" model and reanalyze						
Peak chlorophyll-*a* concentration	3	43.1	23.7	0.1	0.96	0.27
Degree–days from April 1 to May 15	3	43.2	23.7	.1	.93	.26
75th-percentile water temperature	–	–	–	–	–	–
Cumulative October-May Williamson River discharge	3	43.2	23.7	.1	.93	.26
Median monthly wind speed	3	42.8	23.6	.0	1.00	.28
Median monthly lake level	–	–	–	–	–	–

Table 17. Akaike weights and supporting variables for evaluating models of water temperature and a second physical variable in relation to minimum July–August dissolved-oxygen concentration at Midnorth, Upper Klamath Lake, Oregon, 1990–2006.

[Water temperature is 75th percentile; n=17 for all; +/-, sign of the coefficient in the model, respectively; K, number of parameters in the model; RSS, residual sum of squares; AIC_c, Akaike information criterion; Δ_i, AIC_i minus the minimum AIC_c for the set; w_i, Akaike model weight; shading indicates the best fit model for each set]

Model	+/-	K	RSS	AIC_c	Δ_i	$e^{(-0.5*\Delta_i)}$	w_i
Water temperature	-	3	33.3	19.3	0.0	1.00	0.40
Water temperature and median monthly wind speed	-, -	4	29.2	20.6	1.3	.53	.21
Water temperature and median monthly lake level	-, +	4	30.7	21.4	2.1	.35	.14
Water temperature and cumulative October–May Williamson River discharge	-, -	4	32.0	22.1	2.8	.25	.10
Water temperature and peak chlorophyll-a concentration	-, -	4	33.3	22.8	3.5	.17	.07
Water temperature and degree-days from April 1 to May 15	-, -	4	33.2	22.7	3.4	.18	.07

the other variables (table 17). The best model was still the one with water temperature alone.

The implication that wind speed may be an important variable in predicting the occurrence of low dissolved-oxygen concentrations was noted in the lakewide analysis, but was not apparent for the Midnorth-only dataset. A possible explanation for this may be that wind speed does not affect all of the lake equally. For example, lower wind speeds increase residence time in the trench and can result in low dissolved-oxygen concentrations there, where oxygen consumption exceeds photosynthetic production, but Wood and Cheng (2006) showed that another consequence of low wind speeds is that they are less effective at pushing water from the trench into the northern part of the lake. This would complicate the relation between water quality and wind speed at the Midnorth site, particularly in comparison to the trench, where the lowest dissolved-oxygen concentrations in the lake often occur. These mechanisms, along with the fact that the wind-speed data used in this analysis was of questionable quality and perhaps not very representative of actual wind conditions on the lake, may make wind speed less effective as an explanatory variable.

Because this report has focused on the relation of water-quality conditions and lake level, and lake level was revealed as perhaps an important explanatory variable of the variance observed in the minimum dissolved-oxygen concentrations at Midnorth in July–August, models with lake level were explored further (table 18). Model sets were developed to compare lake level with each physical or biological variable used in this analysis, and Akaike weights were calculated. These sets revealed that the univariate lake-level model always was a better fit than when combined with some other variable, except for the univariate water-temperature model, which provided a better fit than lake level alone. So, water temperature and lake level do appear to be important variables in explaining the variance observed in minimum dissolved-oxygen concentrations at Midnorth. Wood and Cheng (2006) did not address the question of how lake level affects transport from the trench into the northern part of the lake, so the emergence of lake level as an alternative second-most-important explanatory variable remains as a question to be explored with further modeling work.

Although water temperature and wind speed appear to be important explanatory variables when examining the variance observed in different water-quality measures throughout the lake, no one overarching variable or combination of variables was revealed. It is suspected that these variables all play important roles in affecting water quality in Upper Klamath Lake to varying degrees and at varying times based on the overall interrelation between these influencing factors. This conclusion makes sense when considering that no clear pattern has emerged from multiple approaches to examining interrelations among water-quality conditions and lake level and climatic factors. No two years from the 17 years considered in this analysis were exactly the same for any of the considered variables, and poor water-quality conditions occur at the same time in every year. This analysis does reveal that many of these variables are important, and perhaps with better resolution of the datasets (wind-speed data for conditions affecting the lake itself and continuous water temperature rather than measurements every two weeks, for

Table 18. Akaike weights and supporting variables for evaluating models of lake level in relation to minimum July–August dissolved-oxygen concentration at Midnorth, Upper Klamath Lake, Oregon, 1990–2006.

[n=17 for all; +/-, the sign of the coefficient in the model, respectively; K, number of parameters in the model; RSS, residual sum of squares; AIC_c, Akaike information criterion; Δ_i, AIC_i minus the minimum AIC_c for the set; w_i, Akaike model weight; shading indicates the best fit model for each set]

Model	+/-	K	RSS	AIC_c	Δ_i	$e^{(-0.5*\Delta_i)}$	w_i
Lake level and peak chlorophyll-*a*							
Median monthly lake level	+	3	40.9	22.8	0.0	1.00	0.55
Peak chlorophyll-a concentration	-	3	43.1	23.7	.9	.65	.35
Median monthly lake level and peak chlorophyll-*a* concentration	+, +	4	40.7	26.2	3.4	.18	.10
Lake level and degree-days							
Median monthly lake level	+	3	40.9	22.8	0.0	1.00	0.55
Degree-days from April 1 to May 15	-	3	43.2	23.7	.9	.63	.35
Median monthly lake level and degree-days from April 1 to May 15	+, +	4	40.6	26.2	3.4	.19	.10
Lake level and water temperature							
Median monthly lake level	+	3	40.9	22.78	3.5	0.17	0.11
75th-percentile water temperature	-	3	33.3	19.28	.0	1.00	.66
Median monthly lake level and 75th-percentile water temperature	+, -	4	30.7	21.40	2.1	.35	.23
Lake level and Williamson River discharge							
Median monthly lake level	+	3	40.9	22.8	0.0	1.00	0.54
Cumulative Ocober–May Williamson River discharge	-	3	43.2	23.7	.9	.63	.34
Median monthly lake level and cumulative October–May Williamson River discharge	+, -	4	39.9	25.9	3.1	.22	.12
Lake level and wind speed							
Median monthly lake level	+	3	40.9	22.8	0.0	1.00	0.53
Median monthly wind speed	+	3	42.8	23.6	.8	.68	.36
Median monthly lake level and median monthly wind speed	+, +	4	39.9	25.8	3.0	.22	.11

instance) and more examples of the interrelations to examine (more years of data), the relations can be further refined.

Data Caveats and Future Directions

The major limitation of the Klamath Tribes dataset is the two-week sampling interval. The sampling program was designed to assess long-term trends in water quality and to provide a yearly status of the lake ecosystem by sampling at a consistent set of sites representing conditions all around the lake, and doing so on a consistent and sustainable interval over a long period of time. It was not designed to address the relation between water quality in the lake in any given year and various forcing functions, both of which vary significantly on time scales as short as a few days. Therefore this dataset lends itself to the types of empirical approaches to the data analysis that are presented in this report. If a particular variable was of overwhelming importance, and particularly if the predominant time scale were a month or more, then this empirical approach could be counted on to demonstrate this strong relation. In reality, it seems that many variables are of nearly equal importance, and that water quality is a result of the complex interaction of a number of processes at once.

This limitation was suspected after the first attempt was made to correlate water-quality variables with lake level and climatic factors (Wood and others, 1996). Since that time, new data-collection efforts have begun. Specific conductance, pH, water temperature, and dissolved oxygen have been measured in-situ around the lake with continuous water-quality data sondes since 2002. Nutrients and chlorophyll-*a* have been collected at a small subset of representative sites on a weekly time interval. The availability of these datasets has confirmed that water quality varies significantly on time scales as short as a few days. In addition, a hydrodynamic model of the lake has been developed that shows that wind-driven currents play a large role in determining the water quality in the lake, particularly in the northern third of the lake, and that these currents respond to changes in the wind forcing in a matter of hours. The model (Wood and Cheng, 2006), as well as supporting light/dark bottle experiments (Mary Lindenberg, U.S. Geological Survey, unpub. data, 2005, 2006), also indicates that the deep trench along the western shoreline is important because it is an area of net consumption of dissolved oxygen. The datasets currently being collected and the modeling effort are providing the opportunity to explore relationships among variables using a process-based, rather than empirical, approach. In the long term, this approach will likely provide more insight into the complex interaction of processes that determine water quality at a particular place in the lake at a specific point in time.

Summary

Growth and decomposition of dense blooms of *Aphanizomenon flos-aquae* in Upper Klamath Lake frequently cause extreme water-quality conditions that have led to critical fishery concerns for the region. Two species of suckers endemic to the lake, the Lost River sucker and the shortnose sucker, are listed as endangered. The poor water-quality conditions associated with the long and productive algal blooms are believed to be the primary threat to these adult endangered suckers. The Bureau of Reclamation has asked the USGS to examine the water-quality data collected by the Klamath Tribes for relations with lake level. This work, which evaluates a 17-year dataset (1990–2006), serves as an update to the original analysis of a 5-year dataset (1990–94) performed by Wood and others (1996).

Both univariate hypothesis testing and multivariable analyses evaluated using an information-theoretic approach revealed the same results—no one overarching factor emerged from the data. No one single factor could be relegated from consideration either. The lack of statistically significant, strong correlations between water-quality conditions, lake level, and climatic factors does not necessarily show that these factors do not influence water-quality conditions; it is more likely that they all work in conjunction with each other to affect water quality. A few different conclusions could be drawn with the larger dataset than with the smaller dataset examined by Wood and others (1996), but for the most part, the outcome was the same. Using an observational dataset that may not capture all variation in water-quality conditions (samples were collected on a two-week interval) and that has a limited range of conditions for evaluation (confined to the operation of lake) may have confounded the exploration of explanatory factors. In the end, all years experienced some variation in poor water-quality conditions, either in the timing of the occurrence of the poor conditions or in their duration. The dataset of 17 years simply provided 17 different patterns of lake level, cumulative degree-days, timing of the bloom onset, and poor water-quality conditions, with no overriding causal factor emerging from the variations.

Water-quality conditions measured during 1990–2006 were evaluated for their potential to be harmful to the endangered sucker species. Based on high-stress thresholds established to calculate stress indices for Upper Klamath Lake suckers (Reiser and others, 2000), the values used in this study to delimit poor water-quality conditions were: water-temperature values greater than 28°C, dissolved-oxygen concentrations less than 4 mg/L, and pH values greater than 9.7. Only a few water temperatures recorded during May–October 1990–2006 were greater than 28°C. These were all measured at the surface, in the afternoon, and most were in the latter part of July, when air temperatures are expected to be elevated as well. Dissolved-oxygen concentrations of less than 4 mg/L were generally recorded in mid- to late-summer—most frequently in August, then July, and finally in September. Unlike the patterns in the dissolved-oxygen data, high pH values were more frequent and occurred earlier in the season and parallel with growth in the algal bloom, typically in June and July. Spatial patterns show that when high pH values were measured, they were often observed at sites all around the lake.

Total ammonia concentrations were screened against USEPA criteria, which apply only to samples with pH values of less than 9. For the half of the dataset that these criteria applied to, only a few samples (less than 1 percent for the acute criterion and less than 10 percent for the chronic criterion) exceeded the criteria; however, half of these exceedances occurred in the bay areas. Un-ionized ammonia concentrations were calculated for the entire dataset and evaluated against LC_{50} values of 530 µg/L for Lost River suckers (Saiki and others, 1999). About 3 percent of the un-ionized ammonia concentrations exceeded 530 µg/L, and there was at least one exceedance at each of the 10 sites. Although the USEPA criteria for total ammonia represent “acceptable no-effect levels” of total ammonia, the LC_{50} values for un-ionized ammonia concentrations represent “unacceptable severe-effect levels” for the health of the suckers.

To help evaluate relations in water-quality conditions between the years, three factors were used to rank the years in relation to each other: lake level, cumulative degree-days from April 1 to May 15, and timing of the onset of the AFA bloom. The end-of-month lake levels for May–August were compared to each other and to the post-dam historical (1922–2006) record. The years 1992, 1994, and 1991 were recognized as notably low lake-level years. The degree-days ranking serves as a measure of how warm each spring was, recognizing that climatic factors such as air temperature and cloud cover are expected to have an effect on when the bloom begins to grow and the rate at which it develops. The onset of the bloom for each year was defined by when the chlorophyll-*a* concentration exceeded 20 µg/L. For the majority of the years, this occurred during the last week of May and the first week of June, with the earliest bloom starting in mid-May in 1992 and the latest bloom starting in mid-June in 2006. Comparison of the years by these three ranking variables reveals that these variables are interlinked, but no single one emerged as an overall controlling factor.

The 10 hypotheses relating water-quality variables, lake level, and climatic factors from Wood and others (1996) evaluation of the 1990–1994 dataset were tested in this analysis for the larger 1990–2006 dataset. These hypotheses proposed relations between lake level and chlorophyll-*a*, pH, dissolved oxygen, total phosphorus, and water temperature. As in the previous study, there was no evidence in the larger dataset for any of these relations based on a seasonal (May–October) distribution. When analyzing just the June data, the previous study did find evidence for three hypotheses relating lake level to the onset of the bloom, June chlorophyll-*a* concentrations, and the frequency of high pH values in June. These hypotheses were not supported, however, by the 1990–2006 dataset, but the two hypotheses related to cumulative degree-days from the previous study were: chlorophyll-*a* concentrations were lower and the onset of the algal bloom was delayed when spring air temperatures were cooler. Other relations between water-quality variables and cumulative degree-days were not determined to be significant.

Multivariable analyses of the data revealed similar results. Multiple regressions were performed between lakewide water-quality measures—the percentage of low dissolved-oxygen concentrations in July and August and the percentage of high pH values in July and August—and six physical and biological variables—peak chlorophyll-*a* concentrations, degree-days, water temperature, median October–May discharge in the Williamson River, median monthly wind speed, and median monthly lake level in Upper Klamath Lake. Model sets were developed for each combination of these chosen factors, both with and without lake level as an explanatory variable, and evaluated using an information-theoretic approach. In every instance, the addition of lake level to the regression resulted in an increase in the Akaike Information Criterion value of somewhere between 2 and 5, indicating that the model without lake level as a variable offered a better fit of the data.

The multiple regression models also were compared to each other as a means of explaining the variation observed between years in water-quality conditions in the lake. The generation of these multiple models with varying numbers of explanatory variables yielded no single overarching equation. For each water-quality measure tested, the models with the lowest AIC_c statistics, and therefore the best fit, were the models that considered each physical variable individually. The variables with the best fit for dissolved oxygen were water temperature and wind speed, whereas the variable with the best fit for pH was water temperature. The Akaike weights for the remaining variables were fairly evenly distributed, indicating that there was no clear hierarchy of importance among those variables.

Although water temperature and wind speed appear to be important explanatory variables for the variance observed in different water-quality measures, no overarching variable or combination of variables was revealed. As with the conclusion from the univariate analyses, it is suspected that these variables work in combination to affect water quality in Upper Klamath Lake. This conclusion makes sense when considering that no clear pattern has emerged from multiple approaches to examining interrelations among water-quality conditions, lake level, and climatic factors. Although the water-quality conditions and climatic factors around the lake can be defined, the dynamic nature of these variables and their interactions from year to year, within a season, and between sites around the lake confounds our ability to explain or predict water-quality conditions in Upper Klamath Lake. At present, no single causal factor can be clearly identified.

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