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Statistical Analysis of the Water-Quality Monitoring Program, Upper Klamath Lake, Oregon, and Optimization of the Program for 2013 and Beyond

By Sara L. Caldwell Eldridge, Susan A. Wherry, and Tamara M. Wood

Prepared in cooperation with the Bureau of Reclamation

Open-File Report 2014–1009

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

Cover: Water Quality monitoring and sampling on Upper Klamath Lake, Oregon (Photographs by S. Eldridge and D.B. Eldridge, U.S. Geological Survey, 2009–2010)

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
gram (g)	0.03527	ounce, avoirdupois (oz)
milligram (mg)	3.527×10^{-5}	ounce, avoirdupois (oz)
microgram (µg)	3.527×10^{-8}	ounce, avoirdupois (oz)
liter (L)	1.057	quart (qt)

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

$$°F=(1.8\times°C)+32$$

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).
Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).
Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Datums

Vertical coordinate information is referenced to the Bureau of Reclamation datum, which is 1.78 feet above National Geodetic Vertical Datum of 1929 (NGVD 29).
Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).
Elevation, as used in this report, refers to the vertical distance above the Bureau of Reclamation datum.

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Summary

Background

Upper Klamath Lake in south-central Oregon has become increasingly eutrophic over the past century and now experiences seasonal cyanobacteria-dominated and potentially toxic phytoplankton blooms. Growth and decline of these blooms create poor water-quality conditions that can be detrimental to fish, including two resident endangered sucker species. Since 1921, Upper Klamath Lake has been the primary water supply to agricultural areas within the upper Klamath Basin. Water from the lake is also used to generate power and to enhance and sustain downstream flows in the Klamath River.

Water quality in Upper Klamath Lake has been monitored by the Klamath Tribes since the early 1990s and by the U.S. Geological Survey (USGS) since 2002. The data collected have been the basis for extensive restoration and management activities; however, management agencies and other stakeholders have determined that a re-evaluation of the goals for water-quality monitoring is warranted to assess whether current data-collection activities will continue to adequately provide data for researchers to address questions of interest and to facilitate future natural resource management decisions. The purpose of this study was to (1) compile an updated list of the goals and objectives for long-term water-quality monitoring in Upper Klamath Lake with input from upper Klamath Basin stakeholders, (2) assess the current water-quality monitoring programs in Upper Klamath Lake to determine whether existing data-collection strategies can fulfill the updated goals and objectives for monitoring, and (3) identify potential modifications to future monitoring plans in accordance with the updated monitoring objectives and improve stakeholder cooperation and data-collection efficiency.

Data collected by the Klamath Tribes and the USGS were evaluated to determine whether consistent long-term trends in water-quality variables can be described by the dataset and whether the number and distribution of currently monitored sites captures the full range of environmental conditions and the multi-scale variability of water-quality parameters in the lake. Also, current monitoring strategies were scrutinized for unnecessary redundancy within the overall network. Discrete sample datasets were analyzed for consistent long-term trends, and continuous datasets were analyzed for short-term (less than 1 week) variability in the phytoplankton bloom. The data considered were (1) the Klamath Tribes' discrete sample dataset collected bimonthly (alternate weeks) from 1990 to 2010, (2) the USGS discrete sample dataset collected weekly from 2005 to 2010, and (3) the USGS continuous monitoring dataset collected from 2005 to 2011.

Goals for future water-quality monitoring in Upper Klamath Lake identified during a meeting of upper Klamath Basin stakeholders on June 26, 2012, were to (1) measure lake parameters (po-

tentially) related to fish population dynamics, (2) assess the effects of lake and watershed management, (3) collect water-quality data to support studies that guide management decisions, create synergies among the datasets, and improve data collection efficiency, (4) provide data to advance understanding of Upper Klamath Lake water quality in relation to downstream conditions, (5) create publicly available databases, high-quality publications or other formal documentation of water quality and related data, and to present water-quality data at inter- and intra-organizational meetings, conferences, and/or other scientific gatherings.

Study Findings

The multiple monitoring sites used by the Klamath Tribes for data collection were not redundant: Principal components analysis (PCA) using Klamath Tribes data from 1990 to 2010 demonstrated that monitoring sites grouped naturally into regions defined by location and depth and that water-quality parameters within these groups were relatively consistent. Although few trends were statistically significant in the Klamath Tribes dataset using the seasonal Mann-Kendall (SMK) test at individual sites, trends became discernible when sites were combined. The regional Kendall (RK) test applied to the same dataset (for all sites combined) identified significant ($p < 0.05$) increases in Secchi depth and specific conductance, and significant decreases in dissolved oxygen (DO) concentration and water temperature. Similarly, the RK test applied to a shorter dataset identified significant decreases in total nitrogen, total phosphorus, and Secchi depth, and a significant increase in chlorophyll *a* between 2005 and 2010 that were not apparent at any single site. These results indicate that the Tribes' sites generally were not redundant because the power to detect trends increased when data from the individual sites were combined.

Continued long-term (multi-decadal) monitoring is necessary to identify trends in indicators of bloom intensity and other water-quality variables: The experimental, locally weighted regression on time, air temperature, and season method was applied to the Klamath Tribes' dataset to identify trends from 1990 to 2010. Beginning in 2002, annual mean soluble reactive phosphorus (SRP) concentrations decreased at eight of nine sites, and total phosphorus (TP) concentrations decreased at all sites. Regression slopes (particularly for SRP) were positive at most sites until 2002 and negative at all sites thereafter. Such short-term (decadal scale) variability can obscure longer term trends when the dataset spans only a few decades. For example, the RK test applied to open-water sites in Upper Klamath Lake over the entire 21-year dataset did not identify significant trends in nutrients, but over the shorter time period from 2005 to 2010 the RK test applied to open-water sites identified significant decreases in total nitrogen and phosphorus in both the Klamath Tribes and the USGS datasets. In addition, over the 6 years between 2005 and 2010, the RK test identified inconsistent trends between the two datasets in other variables related to phytoplankton bloom intensity (pH, dissolved oxygen, chlorophyll *a*), some of which were attributable to changes in analytical methods and differences in sampling protocols. Although most trends were not statistically significant, the differences between the datasets were sufficiently notable to warrant continued monitoring to confirm long-term trends in bloom intensity.

A weekly sampling frequency may not have more power to determine multi-year trends than bimonthly sampling: The power of weekly (USGS) versus bimonthly (Klamath Tribes) sampling to detect trends was investigated over the period of concurrent sampling by both agencies (2005–2010) by subsampling the USGS data. The resulting trends were usually, but not always, of the same sign and in the same order of magnitude as the weekly dataset, but the significance level of the trend test varied greatly depending on which dataset was used. Therefore, the weekly data were not shown to have greater power to detect trends.

USGS and Klamath Tribes monitoring sites combined capture information that either agency's sites alone cannot: PCA of combined Klamath Tribes and USGS total nutrient data at open-water sites showed that both programs sampled some regions of Upper Klamath Lake defined by water-quality characteristics (the northern part of the trench on the western edge of the lake and north of Ball Point), but also that each program sampled sites that contributed unique information to the network, including Agency Lake, the Upper Klamath Lake bays, and the southern part of the lake (monitored by the Klamath Tribes), and offshore of the mouth of the Williamson River, and the entire trench (monitored by the USGS).

Short-term variability in water-quality constituents can be captured only by continuous monitors: Wavelet analysis of USGS continuous monitoring data showed substantial variability at shorter intervals than the approximately 28-day period that can be resolved by bimonthly sample collection, supporting the use of continuous monitors to supplement discrete sample collection. (Wavelet analysis is a mathematical method of extracting information from time-series data). Synoptic surveys of Upper Klamath Lake water chemistry also revealed spatial variations in water-quality parameters at scales not resolved by the fixed-site monitoring networks; this small-scale variability contributes to the short-term temporal variability at fixed sites and further supports the usefulness of continuous monitoring along with discrete sample collection.

Weather contributes substantially to the variability in water quality: USGS continuously monitored water-quality variables (pH, DO, specific conductance, and water temperature) showed significant variability at time scales of around 6–7 days, which indicated that photosynthetically driven DO concentration and pH were highly influenced by weather.

A daily index based on USGS-measured pH and DO concentration was determined to be a suitable biomass surrogate for phytoplankton bloom activity. Increases in the daily bloom index correlated with increases in air temperature and with decreases in wind speed over 1–4 days. Daily bloom index values generally increased when the water column was stable during the day and mixed during the previous 1–2 nights. These results underscored the importance of short-term weather patterns in bloom activity and the need to measure short-term variability in water quality and meteorological variables with continuous monitors.

Further investigation is needed to develop a reliable regression model that can estimate biomass using continuously monitored water-quality variables: A multiple linear regression model developed from USGS continuous (hourly) data that included instantaneous values of phycocyanin fluorescence measured near the lake surface, pH measured from near the lake bottom, and the cosine of the Julian day, explained the variability in chlorophyll-*a* concentrations relatively well, indicating that such a model may be further developed to act as a surrogate to reveal short-term changes in depth-integrated phytoplankton biomass. A daily time series of chlorophyll-*a* concentrations reconstructed using the regression model revealed substantial variability between sample dates that was not measured in the weekly water samples. Such daily information leveraged different data types used to create the model, and can be used to inform process-based studies of cause-and-effect relations.

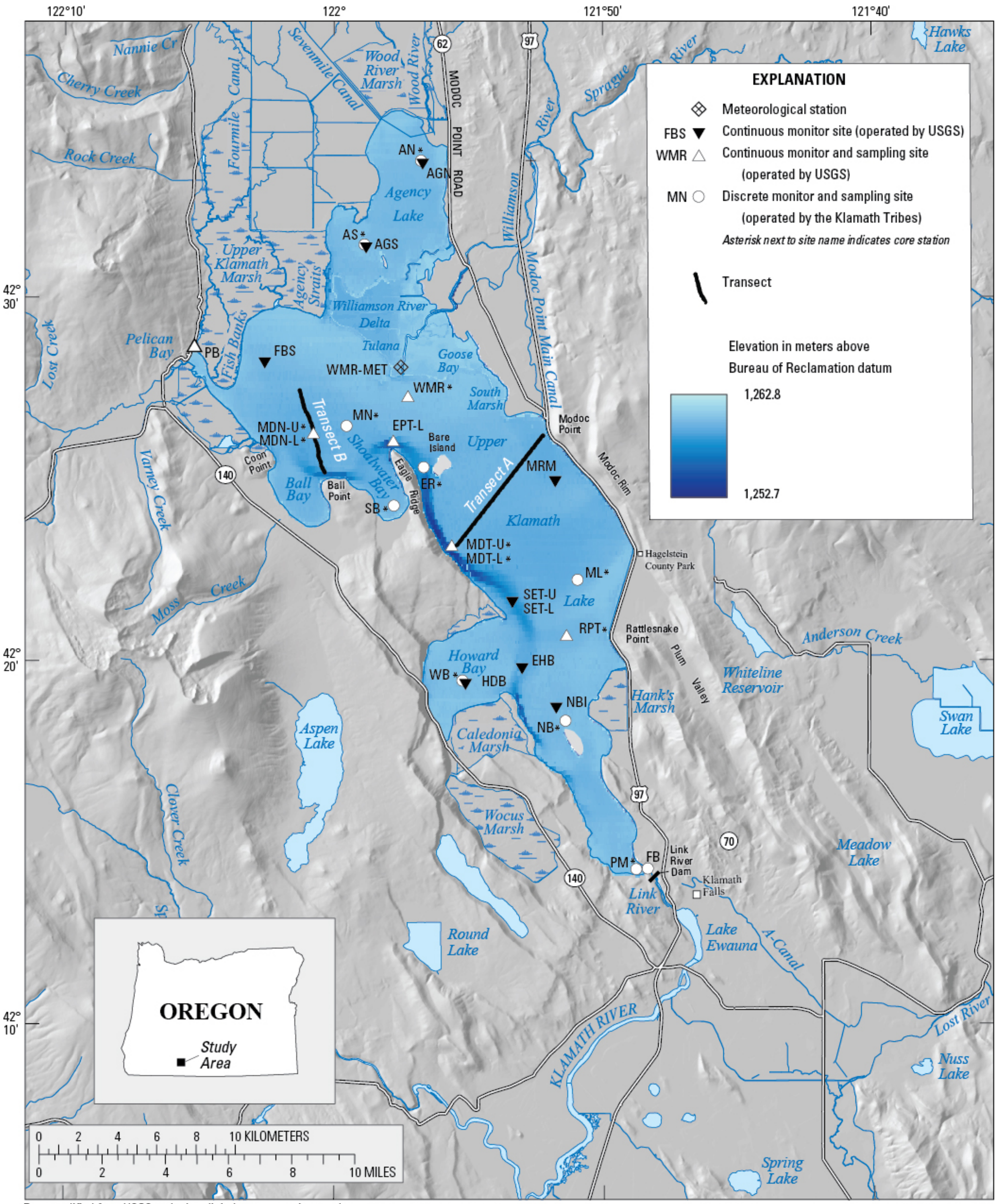
The study findings indicate that future water-quality monitoring in Upper Klamath Lake can be improved by establishing monitoring sites in a few areas not currently monitored by the network and by combining continuous measures of water quality with discrete sampling. A much longer dataset over multiple decades is needed to resolve overall data trends and trend inconsistencies in datasets collected by the USGS and Klamath Tribes monitoring programs. Short-term and small-scale changes in water-quality parameters also must be measured to support process-based research and other projects with different data needs. A better understanding of the role of Upper Klamath Lake water quality in downstream water-quality dynamics also requires data collection from Upper Klamath Lake year-round. Continued analysis, publication, and public presentation of data collected in the monitoring programs also will greatly multiply the value of these long-term datasets.

Introduction

Upper Klamath Lake (fig. 1), located in the Klamath Graben structural valley on the eastern slope of the Cascade Mountains in south-central Oregon, is a large (surface area 305 km^2), shallow (mean depth 2.6 m), freshwater lake that has become increasingly eutrophic over the past century. Since at least the mid-1800s, major changes to the watershed and lake, such as forest clearcutting, cattle grazing in upstream flood plains, degradation of riparian corridors, and the conversion of neighboring wetlands to flood-irrigated pasture and agricultural fields (Klamath Tribes, 1994), have led to the occurrence of dense phytoplankton blooms dominated by a single species of cyanobacteria, *Aphanizomenon flos-aquae*, during the summer and autumn of each year (Bradbury and others, 2004; Eilers and others, 2004; Wood and others, 2013). Photosynthesis by these and other phytoplankton cells elevates lake water pH (9.5 and higher during bloom periods; Bortelson and Fretwell, 1993; Kann and Smith, 1999), which also increases concentrations of unionized ammonia to toxic levels (>0.5 mg/L; Perkins and others, 2000). Further, decomposition during episodes of bloom decline consumes dissolved oxygen (DO), driving concentrations to near anoxia (DO concentrations less than 1 mg/L; Bortleson and Fretwell, 1993; Martin and Saiki, 1999; Wood and others, 2006).

Degradation in water quality resulting from bloom development is one of the major factors that has been attributed to the decline in populations of Lost River suckers (*Deltistes luxatus*) and shortnose suckers (*Chasmistes brevirostris*; Williams, 1988; Buettner and Scoppettone, 1990; Scoppettone and Vinyard, 1991; Perkins and others, 2000), two fish species endemic to the Upper Klamath basin that were listed as endangered under the Federal Endangered Species Act in 1988 (U.S. Fish and Wildlife Service, 1993). In addition**,** blooms that develop during the latter part of summer contain toxigenic cells of *Microcystis aeruginosa* that produce microcystins, which have been associated with gastroenteritic and hepatic diseases and tumor promotion in humans, livestock, domestic animals, and wildlife (Sivonen and Jones, 1999). Juvenile suckers may be particularly susceptible to microcystins, and recent work shows that elevated concentrations of this toxin in the lake from late July to early September in some years (Eldridge, Wood, and others, 2012) may be the cause for a lack of juvenile recruitment into the spawning population (Burdick, 2012).

Water quality in Upper Klamath Lake has been monitored since 1989, beginning with the Klamath Tribes' monitoring program. Since 2005, the U.S. Geological Survey (USGS) also has been collecting lakewide water-quality data. USGS monitored sites only in the northern part of the lake from 2002 to 2004, but these are not the same sites used since 2005 (Wood and others, 2006).



Base modified from USGS and other digital sources, various scales.
Coordinate system is UTM, Zone 10N; North American Datum of 1927.

Figure 1. Sample and data-collection sites used by the Klamath Tribes and USGS, and transects followed during synoptic surveys of water quality of Upper Klamath Lake, Oregon, 2012.

Klamath Tribes water-quality monitoring in Upper Klamath Lake consists of bimonthly (alternate weeks) measurements of nutrient (total and dissolved) concentrations, silica concentrations, chlorophyll-*a* concentrations, zooplankton and phytoplankton identification and enumeration, and instantaneous in situ profiles of photosynthetically active radiation (PAR), DO concentrations and saturation, pH, water temperature, specific conductance, and oxidation reduction potential from mid-April to mid-October (table 1); the Klamath Tribes also collect samples and data from Agency Lake (fig. 1). Zooplankton samples are analyzed for species composition, density, biomass and fecundity (for daphnids). This program also includes monitoring of nutrient loading from the major tributaries to the lake (twice monthly, year-round). Jassby and Kann (2010) provides a more comprehensive summary of the Klamath Tribes' water-quality monitoring program, and further data summaries are provided in Walker and others (2012). The USGS network currently includes continuous measurements of water temperature, DO concentration and saturation, pH, specific conductance and phycocyanin fluorescence from late-May through September (table 1). Water samples for analyses of nutrient (total and dissolved) and chlorophyll-*a* concentrations collected weekly during this time provide context for continuous monitoring data. Phytoplankton identification and enumeration is determined from water samples periodically to validate phycocyanin probe data. The USGS also currently (2013) collects meteorological data (wind speed and direction, air temperature, relative humidity) recorded every 10 minutes at two floating sites from May to September.

Table 1. Data collection programs used by the Klamath Tribes and the USGS for long-term water-quality monitoring in Upper Klamath Lake, Oregon, 20

[*Data intermittent in some years. **Abbreviation:** PAR, photosynthetically active radiation]

Program	Number of Sites	Number of Core Sites	Constituent	Data Collection Method	Frequency	Season
Klamath Tribes	12	9	Total nutrients	Depth-averaged water sample	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	Dissolved nutrients	Depth-averaged water sample	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	Silica	Discrete water sample	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	Chlorophyll *a*	Depth-averaged water sample	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	Zooplankton	Discrete water sample	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	Phytoplankton	Discrete water sample	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	PAR	In-situ profile (monitor) during sample collection	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	Dissolved oxygen	In-situ profile (monitor) during sample collection	Bi-monthly	mid-April to mid-October

Table continued on next page.

Table 1. Data collection programs used by the Klamath Tribes and the USGS for long-term water-quality monitoring in Upper Klamath Lake, Oregon, 2013—continued

[*Data intermittent in some years. **Abbreviation:** PAR, photosynthetically active radiation]

Program	Number of Sites	Number of Core Sites	Constituent	Data Collection Method	Frequency	Season
Klamath Tribes	12	9	pH	In-situ profile (monitor) during sample collection	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	Water temperature	In-situ profile (monitor) during sample collection	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	Specific conductance	In-situ profile (monitor) during sample collection	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	Oxidation-reduction potential	In-situ profile (monitor) during sample collection	Bi-monthly	mid-April to mid-October
Klamath Tribes	12	9	Secchi depth	In-situ during sample collection	Bi-monthly	mid-April to mid-October
Klamath Tribes	1	1	All constituents	Discrete water samples and in-situ profiles	Bi-monthly	mid-April to mid-October and November–
USGS	4	4	Total nutrients	Depth-averaged water sample	Weekly	mid-April to mid-October
USGS	4	4	Dissolved nutrients	Depth-averaged water sample	Weekly	mid-April to mid-October
USGS	4	4	Chlorophyll *a*	Depth-averaged water sample	Weekly	mid-April to mid-October
USGS	4	4	Total microcystins	Depth-averaged water sample	Weekly	mid-April to mid-October
USGS	4	4	Phytoplankton	Discrete sample	Weekly	mid-April to mid-October
USGS	6	6	Dissolved oxygen	Continuous monitor	Hourly	mid-April to mid-October
USGS	6	6	pH	Continuous monitor	Hourly	mid-April to mid-October
USGS	6	6	Water temperature	Continuous monitor	Hourly	mid-April to mid-October
USGS	6	6	Specific conductance	Continuous monitor	Hourly	mid-April to mid-October
USGS	2	2	Phycocyanin	Continuous monitor	Hourly	mid-April to mid-October
USGS	2	2	Wind speed, direction	Continuous monitor	Every 10 minutes	mid-April to mid-October
USGS	2	2	Air temperature	Continuous monitor	Every 10 minutes	mid-April to mid-October
USGS	2	2	Relative humidity	Continuous monitor	Every 10 minutes	mid-April to mid-October

The Klamath Tribes water-quality monitoring program in Upper Klamath Lake was designed to establish seasonal, inter-annual, and long-term trends in water quality and lake storage calculations for nutrient mass balance determinations. Results from this program have contributed significantly to the understanding of phytoplankton ecology, bloom and water-quality dynamics, and hydrologic and nutrient balances (including internal nutrient loading) in the lake. Analyses of Klamath Tribes' data may be found in Kann (1998), Kann and Smith (1999), Kann and Walker (1999), Walker (2001), Terwilliger and others (2003), Kann and Welch (2005), Morace (2007), Jassby and Kann (2010), Walker and others (2012), and Wood and others (2013). Data summary reports are provided annually by the Klamath Tribes and, although they are not intended to provide an exhaustive perspective, they provide major trends for the year and comparisons with previous years.

Water-quality monitoring on Upper Klamath Lake by the USGS has contributed to the creation of a long-term dataset, but, in contrast to the Klamath Tribes program, the USGS monitoring plan has included data collection to describe short-term water-quality conditions in the lake on a real-time or nearly real-time basis with the use of continuous sensors. The Biological Opinion released in April 2001 by the U.S. Fish and Wildlife Service (USFWS) regarding the endangered suckers in Upper Klamath Lake listed several alternatives for the continued operation of the Klamath monitoring project. One of those alternatives was for Bureau of Reclamation to determine how "water quality refuge" areas in the lake influence adult sucker survival. As a result, the Bureau of Reclamation and the USGS formed a cooperative agreement to monitor water quality through a network of multi-parameter instruments while tagging and tracking (by radio telemetry) a representative sample of the endangered suckers in the lake starting in 2002 (under the 2008 Biological Opinion, water-quality monitoring in Upper Klamath Lake is no longer a requirement for the Bureau of Reclamation).

In 2005, the existing USGS water-quality monitoring program expanded to become lakewide in Upper Klamath Lake and to include Agency Lake. These changes created an improved program designed to establish long-term status and trends of water-quality dynamics within the lakes. Meteorological sites were also added to the USGS monitoring network in 2005 at four locations along the shore around Upper Klamath Lake, and the two floating meteorological sites used in previous years were retained, which provided greater resolution of wind speed, wind direction, air temperature, and relative humidity to support development of a hydrodynamic model (Hoilman and others, 2008).

Monitors were added in 2006 at five nearshore sites (5–10 m) to compare monitoring data from nearshore areas and the water column near the surface in open waters of the lake. Few differences in water-quality dynamics were observed between the nearshore and open-water sites, although median daily water temperatures and DO concentrations generally were higher in nearshore areas (DO concentrations were higher only during bloom episodes; Lindenberg and others, 2009). Therefore, the nearshore sites were removed from the network when the continuous monitoring program contracted to fit resource constraints prior to the 2011 field season. At the same time, the number of open-water sites was reduced from 12 locations (16 sites) to the 4 locations (6 sites) selected to represent distinct areas of the lake—the northern part of Upper Klamath Lake west of Eagle Ridge, the deep trench (along the western shoreline), off-shore from the Williamson River Delta, and the southern part of Upper Klamath Lake (fig. 1). Land-based meteorological stations that recorded data year-round were decommissioned in 2010, leaving only the two floating stations that record data during May–September. In situ optical sensors were added to the continuous monitors at two sites, MDN-U and MDT-U ("U" indicating the top 1 m), in 2011 to measure phycocyanin fluorescence, a surrogate for cyanobacterial biomass.

During 2007–2009, the concentrations of toxic microcystins and cylindrospermopsins were measured in water samples, and sediment samples were collected in 2009, to relate the spatial and temporal concentration trends to water quality and other environmental variables (Eldridge, Wood, and others, 2012).

Since 2005, the USGS water-quality monitoring program also has included short-term interpretive studies to further an understanding of ecological and limnological processes, which have included modeling of lake circulation and heat transport and investigating the buoyancy characteristics of *A. flos-aquae* (Wood and others, 2008; Lindenberg and others, 2009). In 2007, samples were analyzed for dissolved organic carbon concentrations to monitor conditions prior to and during the weeks following the breaching of levees at the Williamson River Delta (Kannarr and others, 2010). In addition, data from the recently added phycocyanin sensors were evaluated for their ability to help predict depth-integrated biomass measurements at a daily resolution. Site-specific models were developed by the USGS for chlorophyll *a* in 2011 and 2012 as a "proof of concept," (Sara Eldridge, U.S. Geological Survey, unpub. data, 2012), which show potential for future success. Sample collection in the deep trench was designed in 2011 to quantify short-term variability in phytoplankton biomass, particulate nutrients, and total suspended solids. These data are currently being evaluated.

Much has been learned from data collected by the Klamath Tribes and the USGS, and extensive restoration and management activities using these data have occurred in the Upper Klamath basin since water-quality monitoring of the lake began. Nonetheless, a re-evaluation of the long-term monitoring programs is warranted to determine whether the current effort will continue to be adequate to address new and ongoing questions of interest to scientists and managers and to provide data needed to facilitate future natural resource management decisions. To that end, the spatial and temporal schemes of current data collection were critically examined with statistical analyses of the existing data by addressing the following questions:

1. Are the current monitoring sites redundant within or between the Klamath Tribes and the USGS programs?
2. Is the spatial distribution of currently monitored sites adequate to measure the range in environmental conditions in Upper Klamath Lake necessary to support the objectives of process-based studies using the data?
3. Can consistent long-term trends in water quality variables be identified in the existing datasets?
4. Are the monitoring programs able to capture important short-term variability in water-quality parameters?

Purpose and Scope

This report presents the results of a study to evaluate the efficacy of current long-term USGS and Klamath Tribes water-quality monitoring networks in providing the data necessary to understand water-quality conditions and dynamics in Upper Klamath Lake. The purposes of the study were to (1) compile an updated list of the goals and objectives for long-term water-quality monitoring in Upper Klamath Lake with input from Upper Klamath basin stakeholders, (2) assess the current water-quality monitoring programs in Upper Klamath Lake to determine whether data collection strategies are designed to fulfill the updated goals and objectives for monitoring, and (3) identify potential modifications to future monitoring plans in accordance with the updated monitoring objectives and improve stakeholder cooperation and data collection efficiency.

Existing water-quality data (from 1990 to 2011) were evaluated by comparing data collected by the Klamath Tribes and the USGS to determine whether there were significant differences between the two, identify sites or variables that produced redundant data or data that might be missing from the monitoring networks, compare the site networks and temporal sampling strategies using various optimization techniques, and evaluate relations within the USGS's continuously monitored meteorological and water-quality data. Results of synoptic surveys performed along prescribed transects in Upper Klamath Lake are presented and evaluated to identify dominant spatial scales of variability in the phytoplankton bloom not resolved by the Klamath Tribes or USGS programs.

This report presents a summary of the goals and objectives for future monitoring as developed by the USGS, Klamath Tribes, Bureau of Reclamation, and other Upper Klamath basin stakeholders, including issues not recognized when monitoring began and for which data are limited or absent in the 21-year dataset (for example, the presence of microcystins and arsenic in lake water, responses to wetland restoration, and influences on downstream conditions). Therefore, assessments of status and trends in the existing database are restricted to the original set of monitored variables, including water temperature, pH, specific conductance, and concentrations of chlorophyll *a*, nutrients, and DO.

Water-quality data collection is often designed to address specific goals or objectives, and might vary depending on the data needs of a given project. In such cases, optimizing the monitoring network requires careful consideration of the spatial and temporal scale necessary to meet those objectives. However, the purpose of the current project was to evaluate the current water-quality monitoring programs for their ability to provide data to support an updated set of comprehensive and broad goals, and objectives that cross multiple disciplines and agencies and require an understanding of large- and small-scale, short- and long-term trends in a variety of environmental parameters. To meet the needs of such broad goals, including future goals not yet identified, analyses of the data collection effort was done from the perspective of trying to capture the full range of conditions in the lake, and along all possible spatial and temporal scales, the maximum and minimum values and all those in between. So, for example, although variability in the data alone does not determine whether the existing datasets are adequate to answer certain questions, it is important to know that such variability exists, and whether or not the current monitoring efforts capture it or not, particularly when the objectives encompass many different aspects of the ecosystem.

The optimization of long-term water-quality monitoring in Upper Klamath Lake to meet management objectives with the most efficient allocation of resources is consistent with the USGS mission of providing reliable data and scientific information to support management of the Nation's water resources (U.S. Geological Survey, 2007). The results of this work relate directly to current and future scientific studies and management of Upper Klamath Lake and the Upper Klamath River basin.

Methods

Determination of Goals and Objectives for Future Water-Quality Monitoring in Upper Klamath Lake

In coordination with Bureau of Reclamation, a meeting of all Upper Klamath basin stakeholders was hosted by the USGS on June 26, 2012, to discuss Upper Klamath Lake (Upper Klamath Lake) water-quality data needs and related projects within the basin, and to create an updated list of goals and objectives for future long-term water-quality monitoring. Meeting attendees included representatives from the USGS, Water Mission Area (Klamath Falls, Oregon; Portland, Oregon; and Menlo Park, California); the USGS Ecosystems Mission Area (Klamath Falls, Oregon); Bureau of Reclamation (Klamath Basin Area Office); the Klamath Tribes' Research Station (Chiloquin, Oregon); U.S. Fish and Wildlife Service (Klamath Falls, Oregon); Aquatic Ecosystem Sciences (Ashland, Oregon); Bureau of Land Management (Klamath Falls Resource Area, Lakeview District); The Nature Conservancy

(Klamath Basin Office); and the Oregon Department of Environmental Quality (ODEQ; Klamath Basin Office). The resulting list developed during this meeting was finalized after a follow-up meeting with Reclamation and subsequent correspondence with the project stakeholders.

Datasets

Discrete Water Samples and Field Parameter Measurements

The Klamath Tribes dataset used in this study included discrete water column samples and field parameter measurements (pH, specific conductance, DO concentration, and water temperature) collected from Upper Klamath and Agency Lakes from 1990 to 2010. Water column samples were collected bimonthly (on alternate weeks) from mid-April to mid-October (table 2). Additional samples were collected at the outlet of Upper Klamath Lake monthly from November through March. However, annual data are intermittent for these months in some years. Nine core sites were used for statistical analyses: AN, AS, MN, ER, SB, ML, WB, NB, and PM (fig. 1). Data collected from site FB was used to supplement the record of site PM because the sites were close together. Klamath Tribes water samples were analyzed for depth-averaged concentrations of total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), total ammonia, and chlorophyll *a* as described in Klamath Tribes (2006). Secchi disc depth was collected at each site, and field parameter measurements were collected at 0.5–1.0 m intervals below the water surface (Klamath Tribes, 2006). Water column profile data were averaged at each site. So, as a result of the depth distribution among Klamath Tribes sites, the lakewide averages included a distribution in the vertical, heavily weighted toward the photic zone; 52 percent of the measurements were made at 1 m or less, and 76 percent of the measurements were recorded at depths of 2 m or less.

The USGS discrete water sample dataset consisted of nutrient and chlorophyll-*a* concentrations measured from four core sites from 2005 to 2011; data collected from 2002 to 2004 were not included. Sampling was performed weekly from mid-May to early October. The core USGS sites were MDN, WMR, MDT, and RPT (fig. 1). Site RPT was only sampled in 2006, 2007, 2009, and 2011. Site EPT, which also was sampled every year from 2005 to 2011, was included in the trend analysis, but was not considered a core USGS site. Depth-averaged samples were collected for determination of chlorophyll *a*, TP, and TN concentrations following established USGS protocols (U.S. Geological Survey, variously dated; table 2). Dissolved nutrient (orthophosphate and ammonia) concentrations and associated field parameters were measured at one-half the water column depth at shallow sites (MDN, WMR, and RPT) and at one-quarter and three-quarters of the total depth at the deep sites (EPT and MDT; Eldridge, Eldridge, and others, 2012). For the current study, measurements made at one-quarter and three-quarters of the water column depth were averaged for each site. This resulted in a distribution in the vertical for the lakewide averages that were more evenly distributed over the water column than the averaged Klamath Tribes data; 36 percent of measurements were made at 2 m or less, 34 percent were from 2 to 6 m, and 30 percent were from 6 m or deeper.

Terminology note: In natural systems, SRP consists largely of the inorganic orthophosphate (PO_4^{3-}) form, which is directly taken up by phytoplankton, and the concentration of this fraction constitutes an index of the amount of phosphorus immediately available for phytoplankton growth. The Klamath Tribes report this phosphorus fraction as “SRP,” and the USGS uses the term “orthophosphate.” These terms are distinguished in this report to be consistent with previous publications, although they refer to the same form of phosphorus.

Table 2. Tables and figures cited in the text with their corresponding datasets and the analytical methods used for each, Upper Klamath Lake, Oregon.

[**Abbreviations:** NOAA NCDC, National Oceanic and Atmospheric Administration National Climatic Data Center, USGS; TP, total phosphorus; SRP, soluble reactive phosphorus; chl *a*, chlorophyll *a*; DO, dissolved oxygen; SD, Secchi depth; AT, air temperature; TN, total nitrogen; WT, water temperature; PC, phycocyanin fluorescense,; cond, specific conductance; WS, wind speed; AL, Agency Lake; UKL OW, Upper Klamath Lake open water; A, transect A on figure 1; B, transect B on figure 1. **Symbol**: -, no table or figure]

Table	Figure(s)	Analysis	Purpose of analysis	Data source	Data collection frequency of original data set	Data collection period	Analyzed data set	Analyzed variables	Analyzed sites
3	2	Principal components	Spatial groupings of sites	Klamath Tribes	Bi-monthly	May–September 1990–2010	All	TP, chl *a*, SD, DO	All
5, A rows	-	Seasonal Mann-Kendall	Seasonal trends	Klamath Tribes	Bi-monthly	May–September 1990–2009	Monthly means	All	All
5, A rows	-	Regional Kendall	Regional trends	Klamath Tribes	Bi-monthly	May–September 1990–2009	Annual means	All	All
5, B rows	-	Seasonal Mann-Kendall	Seasonal trends	Klamath Tribes	Bi-monthly	May–September 1990–2010	Monthly means	All	All
5, B rows	-	Regional Kendall	Regional trends	Klamath Tribes	Bi-monthly	May–September 1990–2010	Annual means	All	All
5, C rows	3	Seasonal Mann-Kendall with LOWESS	Seasonal trends without exogenous variable	Klamath Tribes	Bi-monthly	May–September 1990–2010	Monthly means	All	All
5, C rows	-	Regional Kendall with LOWESS	Regional trends without exogenous variable	Klamath Tribes	Bi-monthly	May–September 1990–2010	Annual means	All	All
6	5 and 6	Weighted regressions on time, air temperature, and season	Seasonal trends	Klamath Tribes; NOAA NCDC	Bi-monthly, hourly	May–September 1990–2010	All, daily mean	Chl *a*, TP, SRP, AT	All; Airport, Klamath Falls, Oregon
7	-	Seasonal Mann-Kendall	Seasonal trends	Klamath Tribes	Bi-monthly	May–September 2005–2010	Monthly means	All	All

Table continued on next page.

Table 2. Tables and figures cited in the text with their corresponding datasets and the analytical methods used for each, Upper Klamath Lake, Oregon—continued

[**Abbreviations:** NOAA NCDC, National Oceanic and Atmospheric Administration National Climatic Data Center, USGS; TP, total phosphorus; SRP, soluble reactive phosphorus; chl *a*, chlorophyll *a*; DO, dissolved oxygen; SD, Secchi depth; AT, air temperature; TN, total nitrogen; WT, water temperature; PC, phycocyanin fluorescense,; cond, specific conductance; WS, wind speed; AL, Agency Lake; UKL OW, Upper Klamath Lake open water; A, transect A on figure 1; B, transect B on figure 1. **Symbol**: -, no table or figure]

Table	Figure(s)	Analysis	Purpose of analysis	Data source	Data collection frequency of original data set	Data collection period	Analyzed data set	Analyzed variables	Analyzed sites
7	-	Regional Kendall	Regional trends	Klamath Tribes	Bi-monthly	May–September 2005–2010	Annual means	All	All
8	-	Seasonal Mann-Kendall	Seasonal trends	USGS	Weekly	May–September 2005–2010	Monthly means	All	All
8	-	Regional Kendall	Regional trends	USGS	Weekly	May–September 2005–2010	Annual means	All	All
4	3	Principal components	Spatial groupings of sites	Klamath Tribes; USGS	Bi-monthly, weekly	May–September 2005–2010	All, combined by Julian week	Chl *a*, TP, TN	UKL OW; core sites
-	11 and 12	Time series	Variability in transect vs fixed-site data	USGS	Every 100 m	August 3, 2012 8:07 a.m.–2:00 p.m. (A), August 6, 2012 8:56 a.m.–12:07 p.m. (B)	All	WT, DO, pH, PC	Transect A and Transect B in figure 1
-	13, 14, 15, and 16	Wavelet	Small-scale spatial variation	USGS	Every 100 m	August 3, 2012 8:07 a.m.–2:00 p.m. (A), August 6, 2012 8:56 a.m.–12:07 p.m (B)	All	WT, DO, pH, PC	Transect A and Transect B in figure 1
-	7	Wavelet filter	Filtered vs unfiltered time series	USGS	Hourly	June 4–September 28, 2006	Daily medians	WT, DO, pH, cond	WMR
-	8	Wavelet and global wavelet spectrum	Frequencies of high variance (power)	USGS	Hourly	May 1–October 31, 2006	Daily medians	WT, DO, pH, cond	WMR
-	9	Wavelet and global wavelet spectrum	Frequencies of high variance (power)	USGS	Every 10 min	May 1–October 31, 2006	Daily medians	AT, WS	WMR-MET

Table continued on next page.

Table 2. Tables and figures cited in the text with their corresponding datasets and the analytical methods used for each, Upper Klamath Lake, Oregon—continued

[**Abbreviations:** NOAA NCDC, National Oceanic and Atmospheric Administration National Climatic Data Center, USGS; TP, total phosphorus; SRP, soluble reactive phosphorus; chl *a*, chlorophyll *a*; DO, dissolved oxygen; SD, Secchi depth; AT, air temperature; TN, total nitrogen; WT, water temperature; PC, phycocyanin fluorescense,; cond, specific conductance; WS, wind speed; AL, Agency Lake; UKL OW, Upper Klamath Lake open water; A, transect A on figure 1; B, transect B on figure 1. **Symbol**: -, no table or figure]

Table	Figure(s)	Analysis	Purpose of analysis	Data source	Data collection frequency of original data set	Data collection period	Analyzed data set	Analyzed variables	Analyzed sites
9	-	Scale-averaged global wavelet spectrum	Site-specific, scale averaged variance (power)	USGS	Hourly	May 1–October 31, 2006	Daily medians	WT, DO, pH, cond	AGN, AGS, EHB, EPT-L, FBS, HDB, MDN-L, MDN-U, MDT-L, MDT-U, MRM, NBI, RPT, SET-L, SET-U, WMR
10	10	Principal components and wavelet filter	Spatial groupings of sites based on 2–28 day filtered data set	USGS	Hourly	June 4–September 28, 2006	Daily medians	DO, pH, cond	AGN, AGS, EHB, EPT-L, FBS, HDB, MDN-L, MDN-U, MDT-L, MDT-U, MRM, NBI, RPT, SET-L, SET-U, WMR
11	-	Principal components and Euclidian distances between sites	Visualize spatial groupings from table 10 and figure 10 in multi-dimensional space	USGS	Hourly	June 4–September 28, 2006	Daily medians	DO, pH, cond	AGN, AGS, EHB, EPT-L, FBS, HDB, MDN-L, MDN-U, MDT-U, MRM, NBI, RPT, SET-L, SET-U, WMR

Table continued on next page.

Table 2. Tables and figures cited in the text with their corresponding datasets and the analytical methods used for each, Upper Klamath Lake, Oregon—continued

[**Abbreviations:** NOAA NCDC, National Oceanic and Atmospheric Administration National Climatic Data Center, USGS; TP, total phosphorus; SRP, soluble reactive phosphorus; chl *a*, chlorophyll *a*; DO, dissolved oxygen; SD, Secchi depth; AT, air temperature; TN, total nitrogen; WT, water temperature; PC, phycocyanin fluorescense,; cond, specific conductance; WS, wind speed; AL, Agency Lake; UKL OW, Upper Klamath Lake open water; A, transect A on figure 1; B, transect B on figure 1. **Symbol**: -, no table or figure]

Table	Figure(s)	Analysis	Purpose of analysis	Data source	Data collection frequency of original data set	Data collection period	Analyzed data set	Analyzed variables	Analyzed sites
12	17	Time series and Pearson product-moment correlation	Relation between bloom index, chl *a*, AT, and WS	USGS	Hourly	June–September 2005–2010 or 2011	All (time series) and annual medians (correlation)	Bloom index (DO and pH), chl *a*, AT, WS	WMR, MDN-U, MDT-U, RPT
13	-	Contingency tables	Bloom index changes vs AT, and WS changes calculated over 1, 2, 3, or 4 days	USGS	Hourly (DO and pH) and every 10 min (AT and WS)	June–September 2005–2010	Daily medians	Bloom index (DO and pH), AT, WS	MDT-U and MDT-L
14	-	Contingency tables	Bloom index changes from previous day vs number of consecutive days since water column fully mixed	USGS	Hourly (DO and pH) and every 10 minutes (AT and WS)	June–September 2005–2010	Daily medians	Bloom index (DO and pH), WT	MDT-U and MDT-L
15	-	Multiple linear regression	Estimate chl-*a* concentrations between sample collections	USGS	Hourly	May–September 2011	All	WT, DO, pH, PC	MDN-U and MDN-L
-	18	Multiple linear regression	Compare regression-estimated and measured chl-*a* concentrations	USGS	Hourly (pH and PC) and weekly (chl *a*)	May–September 2011	Values on the hour closest to sample collection time	pH, chl *a*, PC	MDN-U and MDN-L
-	19	Multiple linear regression and time series	Compare regression-estimated and measured chl-*a* concentrations	USGS	Hourly (pH and PC) and weekly (chl *a*)	May–September 2011	Values on the hour closest to sample collection time	pH, chl *a*, PC	MDN-U and MDN-L

Continuous Water-Quality Monitor and Meteorological Data

Continuously recording (hourly) water-quality monitors and meteorological stations have been operated and maintained by the USGS since 2002, although the numbers and locations of these sites have varied (see summary in Eldridge, Eldridge, and others, 2012). Six USGS water-quality monitoring sites were considered core sites in this study because complete records were available for these sites from June through September 2005–2011: MDN-U, MDN-L, WMR, MDT-U, MDT-L, and RPT (fig. 1). Sites MDN and MDT were considered deep sites and consisted of two monitors located at 1 m below the water surface ("upper, U") and at 1 m above the sediment surface ("lower, L"). All monitors recorded water temperature, DO concentration, pH, and specific conductance; phycocyanin fluorescence was monitored at two sites, MDN-U and MDT-U, in 2011 only (table 2). Procedures for monitor use and data processing are described in Eldridge, Eldridge, and others (2012). Corrections to water temperature, DO concentration, pH, and specific conductance data due to biological fouling and calibration drift were calculated and applied according to Wagner and others (2006). Air temperature and wind speed were recorded every 10 minutes from June 4 through September 27, 2005–2010 at a site in the delta near the mouth of the Williamson River (fig. 1). The site was moved twice during this time to accommodate construction during the delta restoration (Kannarr and others, 2010). Data from all three locations were combined to create a composite set, which was designated as WMR-MET (fig. 1). All stations were operated and the data were processed as described in Eldridge, Eldridge, and others (2012).

Data collected in 2006 were used for evaluation of spatial variability in the USGS dataset because the monitoring network was larger and more data were available from that season (Lindenberg and others, 2009). Sixteen monitoring sites were used: AGN, AGS, FBS, MDN-U, MDN-L, WMR, EPT-L, MRM, MDT-U, MDT-L, SET-U, SET-L, RPT, EHB, HDB, and NBI (fig. 1); sites AGN and AGS were located in Agency Lake. The record for site MDT-L contained a gap in pH data greater than 3 days, so this site was excluded from evaluations requiring pH. Hourly air temperature measurements from 1990 to 2010 were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) station at the Klamath Falls Airport (ID 94236).

Principal Components Analysis to Investigate Site Redundancy

Principal Components Analysis (PCA) was performed with three datasets, each for a different purpose. First, site redundancy in the Klamath Tribes core monitoring network (nine sites) was investigated. The period of record from 1990 to 2010 was included in this PCA with the exception of 1990 and 1996, which were excluded because data from those years were not available at sites AN, NB, and WB. Second, PCA was used to look for overlap in discrete sample data between sites visited by the Klamath Tribes and those visited by the USGS. In this case, a shorter period of record, 2005–2010, when the Klamath Tribes and USGS datasets overlapped, was included. To create datasets of equal size (collected bimonthly) for this analysis, USGS data were subsampled from the full USGS dataset by Julian week. Finally, site redundancy within the USGS continuous monitor dataset was evaluated with PCA by comparing data from the 16-monitor array maintained in 2006 with data from the 6-monitor core array used since 2011. Data from the continuous monitors were first filtered with a wavelet analysis (see section, "Wavelet Analysis of Continuous Monitoring Data").

All PCAs were performed in R version 2.15.2 (R Development Core Team, 2009; Revelle, 2012). Site groupings were evaluated along selected components following the methods described in Haykin (1999). Data were standardized by subtracting the mean and dividing by the standard deviation prior to calculating principal component scores in order to avoid disproportionate influence by variables with high variance. Significance statistics dependent on normal distributions were not assigned to PCA results. Principal components generally were selected using an eigenvalue threshold of 0.7 (Jolliffe, 1972), but, in some cases, eigenvalues just under this threshold were evaluated based on high loading coefficients.

PCA was selected for exploratory, descriptive data analysis. Tests for long-term trends in the Klamath Tribes discrete sample dataset also helped to determine whether sites that grouped together in the PCA provided similar information about trends. PCA is a linear-based procedure and is, therefore, susceptible to bias from non-normal data and the presence of outliers. However, because the purpose of the PCA in this study was not to test hypotheses, which would require known data distributions to determine significance levels, non-normality and the existence of outliers were considered part of the information content of the data and, therefore, were not treated as impediments to using the technique (Jolliffe, 2002). Other statistical procedures, such as Harmancioglu's entropy-based method (Harmancioglu and Alpaslan, 1992; Ozkul and others, 2000), which evaluates joint probability distributions of sites and the information gained by including or excluding sites, would permit the assignment of quantitative significance to statistical tests. However, these procedures assume the data are of normal or log-normal distribution, and the data used in this study are neither. Improvements to the use of PCA to investigate site redundancy might be made in the future by using non-linear techniques such as artificial neural networks (Shu and Ouarda, 2007) or nonlinear PCA (Hsieh, 2004; Khalil and Ouarda, 2009).

Determination of Long-Term Trends from Discrete Samples

Trend analysis of four discrete sample datasets was performed with a unique purpose. First, trends over the longest period of record (1990–2010) were determined on site-specific and regional bases from the Klamath Tribes dataset. Second, trend differences were identified in Klamath Tribes data before and after the establishment of the total maximum daily load for phosphorus in the lake tributaries. To do this, the 1990–2010 dataset was divided into the intervals 1990–2002 and 2002–2010, and site-specific and regional trends were calculated over those two intervals. Third, site-specific and regional trends in the Klamath Tribes and USGS discrete sample datasets from 2005 to 2010, the period of overlap, were compared. Finally, regional trends were calculated from two bimonthly datasets covering the period 2005–2010 that were created by subsampling the weekly USGS dataset on alternate weeks. These trends were then compared to regional trends calculated from the weekly dataset containing twice the number of sample points as the bimonthly sets.

Mann-Kendall Suite

Evaluations of long-term trends were performed using the temporal and spatial versions of the non-parametric seasonal Mann-Kendall (SMK) test and the regional Kendall (RK) test (Hirsch and others, 1982; Helsel and others, 2006). The SMK test for trend (Hirsch and others, 1982; Hirsch and Slack, 1984) was developed by the USGS in the 1980s to analyze trends in surface-water quality throughout the United States. This test has since become the most frequently used test for trend (Helsel and others, 2006). The SMK test was modified from the Mann-Kendall trend test (MK, a measure of rank correlation to measure the association between measured quantities), in that the MK test is first performed for individual seasons (or months, as in the current study), and the individual results are combined into an overall test for whether the dependent variable changes in a consistent direction (monotonic trend) over time (Helsel and others, 2006). The RK test is an expansion of the SMK test applied to locations rather than seasons (Hirsch and others, 2006). To perform the RK test, SMK tests are first computed for individual locations, and these results are combined into an overall test for consistent regional trend (Helsel and Frans, 2006). The test is applicable to data collected from numerous locations when a single, overall test is needed to determine whether the same trend is evident across those locations (Helsel and others, 2006). A non-parametric trend slope (Sen's slope) was calculated to provide quantitative estimates of changes in variables over the time of record; it has the same statistical significance as Kendall's *tau* correlation coefficient. The Sen's slope value was determined by calculating the median of all slopes between all points. SMK and RK statistics were calculated using a USGS published program that runs an executable file in the Windows operation system (Helsel and others, 2005).

The SMK test was applied to monthly mean values of Klamath Tribes data recorded May through September, and the RK test was performed using the annual average of monthly means from the same time period. Sites were grouped into the following regions for the RK test: (1) all sites, (2) Agency Lake sites (AN and AS), and (3) sites in the open waters of Upper Klamath Lake (UKL OW; ER, ML, MN, and NB).

SMK tests of USGS data collected from 2005 to 2010 were based on monthly mean values measured from May through September, and the annual average of monthly mean values from May through September were used for the RK test. Two additional bimonthly USGS datasets were created by subsampling the weekly dataset on alternate weeks, and the RK test was repeated with the resulting datasets. Data were subsampled by assigning Julian week numbers (1 through 52) to each collection date and selecting either the odd or even weeks to represent a bimonthly sample.

Heterogeneity

Tests for heterogeneity on seasonal data were performed to validate the use of the SMK test for determining seasonal trends in notoriously heterogeneous water-quality variables (van Belle and Hughes, 1984). This technique compared the individual SMK results for each season and based significance on a Chi-square distribution, focusing on high level significance ($p=0.01$). Significant heterogeneity ($p \leq 0.015$) over the period of record was found in the water temperature dataset from seven Klamath Tribes sites, indicating that the data were too heterogeneous for SMK analysis. No other variables in the Klamath Tribes dataset indicated such consistent results across the test sites, and no variables in the USGS dataset indicated significant heterogeneity that would negate the SMK test results.

LOWESS

The SMK test also is sensitive to the effects of naturally occurring, random phenomena that might skew trend results. Water temperature, particularly, is seasonally heterogeneous and responds readily to changes in radiation and air temperature. Therefore, to remove exogenous variation from water temperature, regression and locally weighted scatterplot smoothing (LOWESS) techniques were used (Helsel and Hirsch, 2002). In a time-series context, LOWESS is an improvement over least-squares smoothing when the data are not equally spaced. For LOWESS smoothing, the size of the smoothing window can be varied. This size is given as the fraction (0 to 1) of the data that the window should cover. All non-water-temperature variables were LOWESS-smoothed using a window-span of 0.7 (the proportion of data to use for smoothing). This span was selected subjectively to create a smoothed line with few local minima and maxima and that indicates true changes in slope (Helsel and Hirsch, 2002).

WRTTS

One problem with the SMK analysis is that water-quality variables are dependent on other explanatory variables that are changing in time, primarily wind, air temperature and, to a lesser extent, lake elevation (Jassby and Kann, 2010). Therefore, a simple statistical analysis of the trend in the sample values might not be indicative of a trend in the population of actual concentrations during the period of record. An alternative strategy is to use the sample values to ‘‘inform’’ a flexible statistical model of the behavior of concentrations over the period of record. The weighted regressions on time, discharge, and season (WRTDS) method modified from Hirsch and others (2010), in which discharge was replaced with air temperature (WRTTS), was used to determine trends in concentrations of chlorophyll *a* and TP, which have been shown to be dependent on air temperature (Jassby and Kann, 2010). This flexible model can then be used to make estimates of the concentration for every day of the entire period of record. The WRTTS procedure was used in this study to locally fit the regression model containing terms to describe a linear trend, seasonal cycle, and a linear function of air temperature within a specified time window that moves through the record. The coefficients of the model were allowed to vary with time over the length of the record. R version 2.15.2 (R Development Core Team, 2009) was used with the packages dataRetrieval and Exploration and Graphics for RivEr Trends (EGRET; *https://github.com/USGS-R/EGRET/wiki*). The model was calibrated for each of the nine core Klamath Tribes sites from 1990 to 2010, and average daily air temperatures calculated from NOAA NCDC data recorded hourly over the same time period.

The WRTTS method fits coefficients for a regression equation that relates concentration to the trend over time, the inherent seasonal cycle, the influence of air temperature, and a random component (modified from Hirsch and others, 2010):

$$\ln(c) = \beta_0 + \beta_1 t + \beta_2 \ln(A) + \beta_3 \sin(2\pi t) + \beta_4 \cos(2\pi t) + \varepsilon \quad (1)$$

where:

β = the fitted coefficients

c = concentration

A = air temperature

t = time in years

ε = the unexplained variation

Each day in the dataset was assigned a unique set of β coefficients to develop a fully predicted daily concentration time series. Coefficients for every combination of A and t were determined by evaluating other combinations “close” to the air temperature recorded on each day. Closeness was described by the time of record, season, and magnitude of A, and weights were assigned using the Tukey tri-cube weight function. The overall weight for each temperature was the product of the three individual weights. Once the weights were determined, the coefficients for each day were estimated using the survival regression approach (Hirsch and others, 2010).

Determination of Small-Scale and Short-Term Variability

Monthly to annual lakewide mean values of water-quality parameters do not reflect short-term fluctuations and small-scale spatial variability. Therefore, optimizing the collection of a long-term data set to calculate decade-scale trends might require more attention to consistency between sites and sampling frequency over a longer period of record than to obtaining dense temporal information at the subweekly time scale. Other monitoring objectives, however, such as process-based studies, do benefit from high-resolution temporal information provided by continuous monitors. In a hypereutrophic lake, such as Upper Klamath Lake, data collected with continuous monitors are strongly influenced by the effects of photosynthesis and vertical mixing, which, in turn, are controlled (in part) by meteorological forcing. This results in wide fluctuations within the dataset across the frequency range from diel to seasonal that might not be resolved with bimonthly (14-day) discrete sample collection.

Wavelet Analysis of Continuous Monitoring Data

To quantify the variability in water-quality data at frequencies between diel and 28 days, which is uniquely measured by continuous monitors, wavelet analysis was used to filter USGS continuous monitor data. Wavelet analysis is a common tool for analyzing localized variations within a time series. By decomposing a time series into time–frequency space, both the dominant modes of variability and how those modes vary in time can be determined (Torrence and Compo, 1998). Power (variability) as a function of frequency in time series of water-quality variables measured by the USGS continuous monitors was evaluated with wavelet transformations of data collected in 2006 from an expanded 16-site array. The transformations were performed with R version 2.15.2 (R Development Core Team, 2009; package dplR; Bunn, 2008) and used the Morlet wavelet base function (Torrence and Compo, 1998; Kang and Lin, 2007) applied to daily median water temperature, DO concentration, pH, and specific conductance. Gaps up to 3 days were filled by linear interpolation. The deep trench core site, MDT-L was not included because a gap in the pH data precluded the use of the wavelet transform. The global wavelet spectrum (GWS), which averaged the power at each frequency over the length of the time series, was used to identify frequencies at which peaks in power occurred (Torrence and Compo, 1998). The time series were reconstructed using only the wavelet components in the 2–28 day period, effectively filtering the time series to exclude the band of frequencies less than 1 day (diel variability) and greater than 28 days (minimum period resolved by bimonthly sample collection). The variance in the filtered datasets was compared among sites in order to determine the entire range in variance among 16 sites and where the currently monitored 6 sites fit on the continuum between least and most variance. Filtered datasets were limited to June 4–September 28, and were evaluated with PCA to identify redundant sites.

Synoptic Surveys

Synoptic surveys were performed to quantify the spatial variability in phycocyanin fluorescence and other environmental parameters at scales not resolved by either the Klamath Tribes or USGS monitoring programs and that contribute to the variability measured by monitors at fixed sites. Surveys of Upper Klamath Lake water chemistry were performed as synoptically as logistically possible along prescribed transects near USGS sites MDT (denoted transect A) and MDN (denoted transect B; fig. 1). Water temperature, DO concentration, pH, and phycocyanin fluorescence were measured and recorded every 100 m along each transect and at 1 m below the water surface. Transect A was primarily east-to-west in the central portion of the lake and extended approximately 7.6 km. These data were collected on August 3, 2012, from 8:07 am to 2:00 pm PDT. Transect B ran primarily north-to-south in the northern part of the lake. These data were collected on August 6, 2012, from 8:56 am to 12:07 pm PDT and extended approximately 4.4 km. During each survey, field crews allowed the probe measurements to stabilize for at least 2 minutes before recording the data at each point in the transects. Monitors were operated as outlined in Eldridge, Eldridge, and others (2012), and the data were processed as described in Wagner and others (2006). Phycocyanin data were corrected following a post-calibration check of the sensors and comparison to laboratory-performed, direct cell counts of water samples collected during sonde retrievals according to the manufacturer’s (YSI, Inc., Yellow Springs, OH) recommendations. Transect data were transformed using the wavelet technique described above to determine power (variability) as a function of wavelength along each transect.

Biomass Surrogates Based on Continuously Monitored Data

Bloom Index

A daily bloom index was developed using pH and DO saturation recorded at USGS sites MDN-U, WMR, MDT-U, and RPT (fig. 1) from June 4 to September 27, 2005–2011. At sites MDN and MDT, only the upper monitors were used because they were in the photic zone. Daily weighted pH scores calculated from data recorded hourly at each site were used. The lower threshold pH was determined to be 8.2, because this value was the lowest observed at the onset of rapid bloom growth during this time period. pH was weighted at intervals of 0.5 from 1 to 5. For example, values greater than or equal to 8.2 and less than 8.7 were given a weight of 1; values greater than or equal to 8.7 and less than 9.2 were given a weight of 2, and values greater than or equal to 10.2 and less than 10.7 were weighted as 5. pH values less than the lower threshold were assigned a weight of 0. For each site, a daily pH value was calculated as the weighted average of all hourly pH data available. The lakewide weighted pH score was calculated from the average of all sites on each day. Daily weighted DO saturation scores were calculated similarly to the daily weighted pH scores, and calculated over the same time period from hourly temperature data (Bowie and others, 1985). Data were corrected for atmospheric pressure according to Duke and Masch (1973). The lower threshold was set at 100 percent saturation. Weighting intervals were as follows: values greater than or equal to 100 and less than 150 percent were weighted as 1, values greater than or equal to 150 and less than 200 percent were weighted as 2, and so on. DO saturation values below 100 percent were given a weight of 0. As with pH, daily DO saturation scores for each site were calculated as the weighted averages of all hourly data. The lakewide DO saturation score was calculated from the average across all sites on each day. The overall bloom index was determined by standardizing (subtracting the mean and dividing by the standard deviation) both the pH and DO components for the entire dataset, and adding the unitless values for each day.

To evaluate use of the daily bloom index as a mass surrogate in Upper Klamath Lake, weekly index values were compared to weekly depth-integrated chlorophyll-*a* concentrations averaged over the four core sites using Spearman rank order correlation analysis. Weekly index values were calculated from the median pH and median DO saturation recorded over 3 days in each week covering the time span in which chlorophyll-*a* samples were collected. Daily bloom index values were also compared with daily median values of air temperature and wind speed using correlation analysis after subsampling meteorological data every 3 days to avoid serial autocorrelation. Changes in the daily bloom index over 1–4 days were evaluated by calculating the differences of each daily bloom index value from the value calculated on the previous 1st, 2nd, 3rd, or 4th day. This created four time series of the change in daily bloom index values that were subsampled every 3 days. Time series of the change in daily values of air temperature and wind speed were similarly calculated and subsampled. Correlations between bloom index values and chlorophyll-*a* concentrations were determined separately for each year from 2005 to 2011, excluding 2007, for which chlorophyll-*a* data were not available. Correlations between bloom index values and air temperature, wind speed, or changes in these variables were determined for each year from 2005 to 2010 (meteorological station WMR-MET, from which the meteorological data were collected, was decommissioned in 2010). Correlations were considered significant at $p < 0.05$. All correlation analyses were performed in R version 2.12.1 (R Development Core Team, 2009).

Multiple Linear Regression

The use of continuous water-quality monitor data (single variables or combinations of variables), such as nutrient or suspended-solids concentrations, as a surrogate for discrete biomass measurements is well established

(Rasmussen and others, 2009; Wood and Etheridge, 2011), and chlorophyll *a* has been shown to adequately represent phytoplankton biomass in Upper Klamath Lake (Kann, 1998). Therefore, continuous monitoring data, primarily phycocyanin fluorescence, DO concentration, and pH, might act as a surrogate for chlorophyll-*a* concentration. To evaluate the use of such continuous monitoring data as a biomass surrogate in Upper Klamath Lake, a multiple linear regression model for chlorophyll-*a* concentration was developed with data collected at site MDN in 2011 using the stepwise model selection procedure (Helsel and Hirsch, 2002) in R version 2.12.1 (R Development Core Team, 2009) and in S+ version 8.1 (TIBCO Spotfire, Somerville, MA.). Water temperature, pH, DO concentration, and phycocyanin fluorescence (n=19) measured at discrete depths (at 1 m from the lake surface and 1 m from the lake bottom), and sine and cosine functions of the Julian day were considered possible explanatory variables and were compared graphically to chlorophyll-*a* concentration to identify correlated variables. Different combinations of untransformed and $\log_{10}$-transformed data were evaluated in the data plots and in the linear model selection process. To identify the model that best described the variability in the chlorophyll-*a* data, the independent variables were entered as either (1) the instantaneous values on the hour closest to the sample collection time, (2) the running median values within 6 hours of the sample collection time, and (3) the daily median values on each sample date. The dataset that resulted in the best model (based on residuals analysis) was retained, and the explanatory variables were further scrutinized for multicollinearity based on their variance inflation factors (VIF). Model residual analysis and calculations of the 90 percent prediction intervals and VIF were performed according to Rasmussen and others (2009) and Helsel and Hirsch (2002).

Goals and Objectives for Future Upper Klamath Lake Long-Term Water-Quality Monitoring

The meeting of Upper Klamath basin stakeholders, held in June 2012, to discuss future Upper Klamath Lake water-quality monitoring culminated in the following list of goals and objectives, which was further modified based on additional input from the Bureau of Reclamation and other project stakeholders. The order is not significant, as the goals or objectives were not prioritized:

Goal 1: To measure and record the physical, chemical, and biological parameters in Upper Klamath Lake related to (or potentially related to) the success of native fish populations.

Objective 1: Maintain a monitoring network that provides a real-time measure of water- quality parameters, including water temperature, pH, DO, phycocyanin fluorescence, and specific conductance, and measures of chlorophyll-*a* concentration, total nutrient concentrations (TP and TN), dissolved nutrient concentrations (orthophosphate, ammonia, and nitrite-plus-nitrate), and total microcystins concentration on an appropriate time scale that contributes to understanding factors related to episodes of high apparent fish mortality at all life stages.

Objective 2: Provide data, primarily the parameters listed under Goal 1, Objective 1, for others to develop water quality indices for fish population model(s) to be used for status reviews and for down- or de-listing decisions.

Goal 2: To assess the effects of lake and watershed management.

Objective: Monitor the response of Upper Klamath Lake to various remediation activities or restoration programs/projects, such as implementation of a total maximum daily load (TMDL) and restoration of lake-fringe wetlands, such as of the Williamson River Delta and others, as manifested in long-term trends in water quality, plankton biomass, and related data.

Goal 3: To provide water-quality data that support long- and short-term studies designed to (1) contribute to the understanding of physiochemical and biological processes in Upper Klamath Lake that guides management decisions, (2) facilitate the use of statistical or other analytical techniques to create synergies among the datasets and enhance the information content, and (3) improve data collection efficiency over time by using state-of-the-art techniques and technologies.

Objective 1: Compile a comprehensive dataset at sufficient spatial and temporal scales that contributes to:

- Understanding phytoplankton and zooplankton community dynamics and predicting (with a reasonable degree of certainty) periods of severe bloom declines.
- Supporting nutrient mass balance determinations.
- Developing site-specific surrogate relationships between continuously monitored (hourly/daily) and discretely sampled (weekly/bimonthly) data that can be used to provide continuous estimates of discrete quantities.
- Calibrating and validating water-quality models.
- Calculating lakewide average values for water-quality variables.

Objective 2: Collect meteorological data to support understanding of cyanobacterial bloom and water quality dynamic response to atmospheric conditions on time scales from seasonal to climatic, and to support further development of hydrodynamic and water-quality models.

Objective 3: Use rapid and more informative techniques for phytoplankton community analysis to replace weekly or twice-monthly microscopic identification and enumeration.

Goal 4: To advance understanding of water quality in Upper Klamath Lake as it relates to downstream conditions.

Objective : Provide measurements of nutrient concentrations, biological oxygen demand, water temperature, arsenic, and/or other parameters that accurately describe conditions in Upper Klamath Lake year-round in order to understand how downstream conditions are regulated by processes in Upper Klamath Lake.

Goal 5: To make Upper Klamath Lake water-quality data publicly available, and to contribute to analyses and interpretations of water-quality monitoring data and data collection as described under Goals 1-4.

Objective 1: Add data to a publicly available database reasonably soon after receiving approved (official) results.

Objective 2: Create high-quality, peer reviewed and/or agency approved, publicly available reports, journal articles, technical notes, or other formal documentation of organized (in tables, figures, and maps, for example) water quality and related data with or without interpretation.

Objective 3: Present and/or describe results of water-quality monitoring (data and data interpretations) at inter- and intra-organizational meetings, conferences, and/or other scientific gatherings, as deemed appropriate by the organization collecting the data.

Assessing Site Redundancy Using Principal Components Analysis of Discrete Sample Data

Principal components analysis (PCA) reduces the dimensionality of a dataset and aids in interpretation of spatial or temporal relationships (Haykin, 1999). In this study, PCA was used to describe groupings of discretely sampled sites in the untransformed Klamath Tribes monitoring program based on coherent variability in measured water-quality variables. The first two principal components (PC) described 71, 63, and 65 percent of the cumulative variance in TP concentration, chlorophyll-*a* concentration, and Secchi depth, respectively (table 3). Loadings for PC 1 and 2 (fig. 2) showed distinct clustering for these variables at sites located in Agency Lake (AS and AN, fig. 1), which were most dissimilar to site WB. The two bay sites (SB and WB) and the Upper Klamath Lake outlet site (PM) clustered together for TP concentration, as did the four open-water Upper Klamath Lake sites (ER, ML, MN, and NB; fig. 1). Groupings of Secchi depth were similar to those of TP, with the exception of site PM, which clustered with the Upper Klamath Lake open-water sites and not with the bay sites. In the chlorophyll-*a* data, site WB was isolated, and the Upper Klamath Lake open-water sites clustered with sites SB and PM. Sites generally were more similar for DO, but distinct clusters were observed for Upper Klamath Lake open-water sites and sites ER and SB. These results were consistent with previous multidimensional scaling analysis of monthly chlorophyll-*a* concentrations measured from the Klamath Tribes sites (Jassby and Kann, 2010) and corroborated a (variable-specific) separation of the Agency Lake sites from the Upper Klamath Lake open-water sites for most variables (Kann and Smith, 1999; Walker and others, 2012).

Table 3. Loadings of nine core Klamath Tribes' monitoring sites from 1990 to 2010 onto the first two principal components. The loadings in each column are scaled from blue (minimum value) to red (maximum value).

[**Abbreviation:** PC, principal component. **Symbol:** %, percent]

Total Phosphorus			Chlorophyll *a*			Secchi Depth			Dissolved Oxygen		
Site	PC1	PC2	Site	PC1	PC2	Site	PC1	PC2	Site	PC1	PC2
PM	0.59	-0.27	AN	0.51	0.71	AN	0.61	0.71	WB	0.64	0.25
AN	0.66	0.67	WB	0.56	-0.59	AS	0.69	0.51	AN	0.69	0.48
WB	0.68	-0.39	AS	0.61	0.44	WB	0.70	-0.35	AS	0.70	0.38
SB	0.77	-0.25	SB	0.65	-0.074	SB	0.72	-0.19	ER	0.76	0.13
AS	0.79	0.48	PM	0.73	-0.25	MN	0.72	-0.091	PM	0.76	-0.43
NB	0.82	-0.10	ML	0.77	-0.076	NB	0.77	-0.17	MN	0.81	-0.19
ML	0.84	-0.002	MN	0.81	-0.046	ML	0.77	-0.080	SB	0.81	0.10
MN	0.87	-0.084	ER	0.84	0.079	PM	0.80	-0.20	NB	0.87	-0.28
ER	0.88	-0.049	NB	0.84	-0.042	ER	0.83	0.018	ML	0.89	-0.25
Variance Explained by PC	59.9%	11.0%		50.6%	12.4%		54.1%	11.2%		59.9%	9.18%

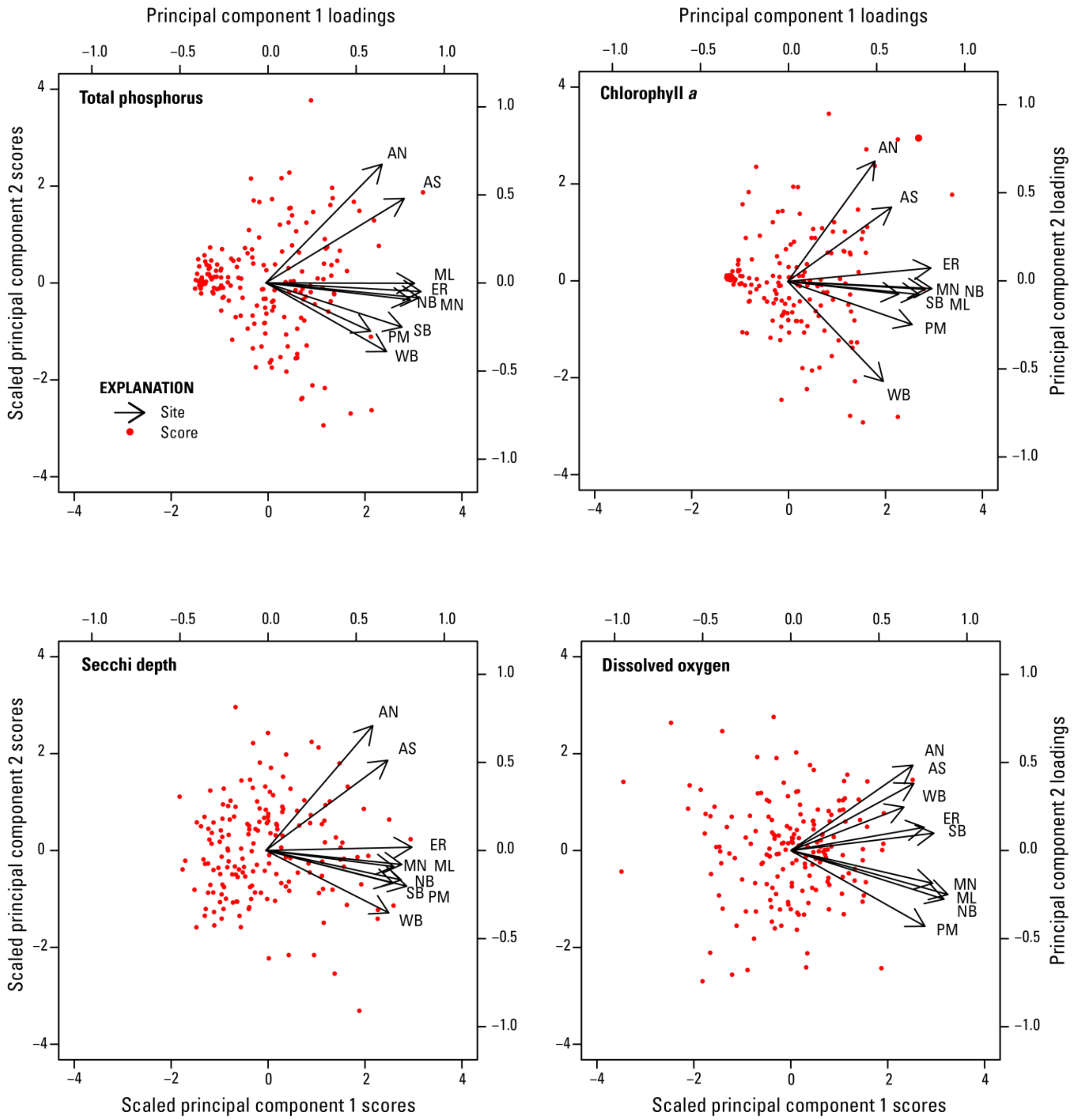


Figure 2. Biplot showing loadings of nine core Klamath Tribes' monitoring sites on the first two principal components, Upper Klamath Lake, Oregon, 1990–2010.

PCA of Klamath Tribes and USGS depth-integrated chlorophyll-*a* and total nutrient concentrations combined by Julian week to identify redundant sites showed that USGS sites generally did not group with Klamath Tribes sites, particularly for chlorophyll-*a* concentration (fig. 3). PC 1 for TP and TN concentrations showed high (>0.7) loadings in both Klamath Tribes and USGS sites, and two sets of Klamath Tribes/USGS sites (MN [Klamath Tribes]/MDN [USGS] and ER [Klamath Tribes]/EPT [USGS]), located in relatively close proximity and occupying similar depth regimes, were similarly loaded on the first two principal components (table 4). The south-centrally located Klamath Tribes site ML also showed scores similar to the north centrally located sites MDN (USGS) and MN (Klamath Tribes). Sites near the mouth of the

Williamson River (WMR), in the deepest part of the trench (MDT), and near the southern end of Upper Klamath Lake (NB) generally scored independently. For chlorophyll-*a* concentration, however, sites from the same program were more likely to have similar scores, such that Klamath Tribes sites showed high loadings on PC 1, whereas USGS sites were more evenly loaded onto the first four components (table 4). Concentrations of chlorophyll *a*, TP, and TN are indicative of water column biomass during the growing season and typically are correlated, so the anomalous PCA result for chlorophyll-*a* concentration was likely due to a sampling artifact. Resolution of this discrepancy is beyond the scope of this study, but the change in analytical method used to determine chlorophyll-*a* concentrations in the Klamath Tribes dataset starting in 2009 could be responsible. This method change might also have complicated the long-term trend analyses with Klamath Tribes data (see section, "Long-Term Trends in Discrete Samples").

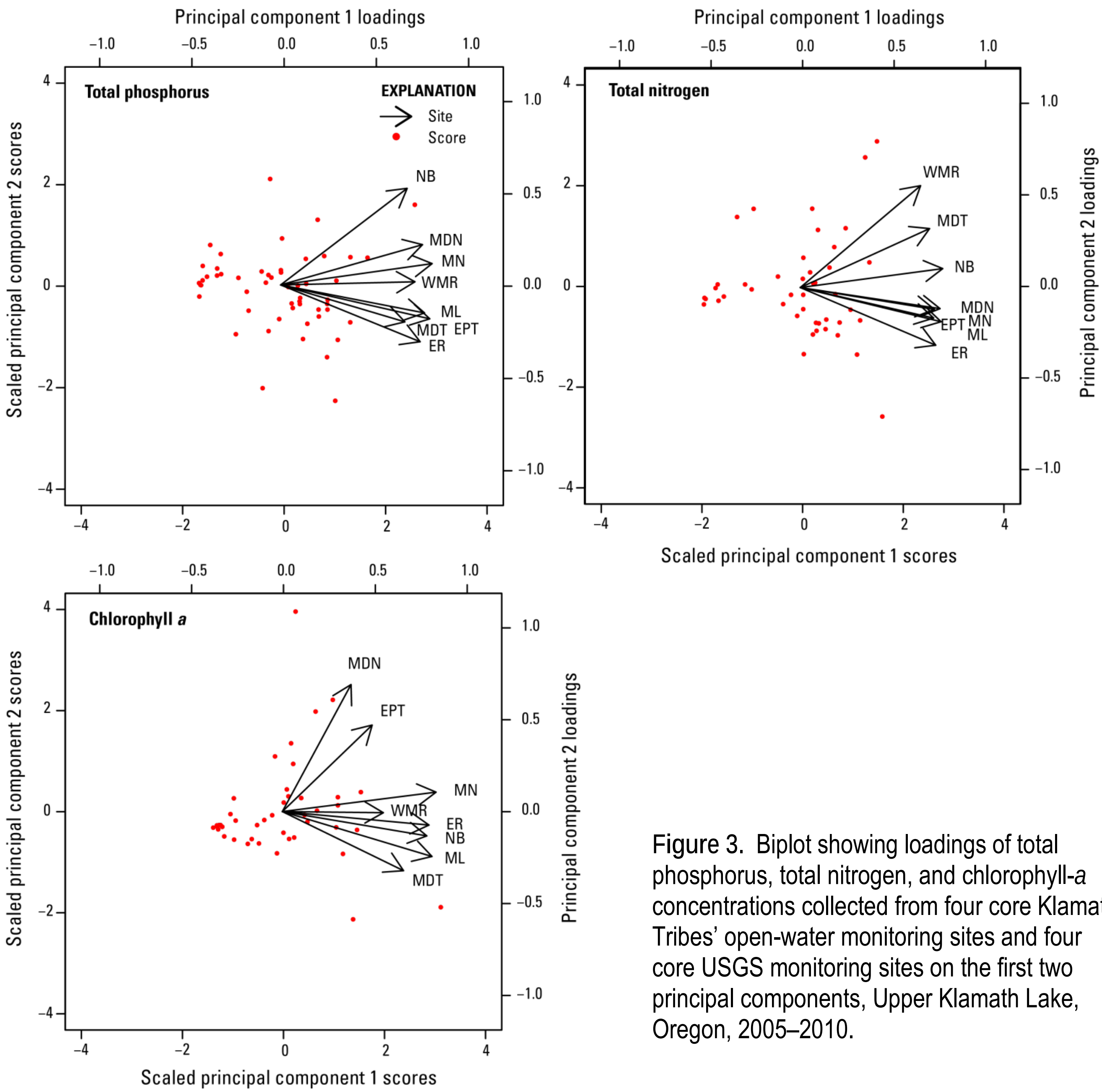


Figure 3. Biplot showing loadings of total phosphorus, total nitrogen, and chlorophyll-*a* concentrations collected from four core Klamath Tribes' open-water monitoring sites and four core USGS monitoring sites on the first two principal components, Upper Klamath Lake, Oregon, 2005–2010.

Table 4. Loadings of four core Klamath Tribes' open-water monitoring sites and four core USGS sites from 2005 to 2010 onto the first four principal components, Upper Klamath Lake, Oregon..

[The loadings in each column are scaled from blue (minimum value) to red (maximum value). Abbreviation: PC, principal component. Symbol: %, percent]

Chlorophyll *a*					Total Phosphorus			Total Nitrogen		
Site	PC1	PC2	PC3	PC4	Site	PC1	PC2	Site	PC1	PC2
MDN	0.408	0.754	0.373	-0.341	MDT	0.735	-0.218	WMR	0.717	0.607
EPT	0.534	0.514	-0.520	0.361	NB	0.749	0.571	MDT	0.771	0.351
WMR	0.600	0	0.537	0.591	WMR	0.795	0	EPT	0.795	0
MDT	0.720	-0.351	0	-0.208	ER	0.825	-0.336	MN	0.799	-0.130
NB	0.858	-0.144	0	0	MDN	0.839	0.238	ER	0.807	-0.344
ER	0.871	0	0	-0.143	ML	0.851	-0.166	MDN	0.833	-0.126
ML	0.889	-0.267	0	0	EPT	0.882	-0.200	ML	0.839	-0.204
MN	0.913	0.115	-0.113	-0.102	MN	0.896	0.126	NB	0.849	0.113
Variance Explained by PC	55.6%	13.3%	9.2%	8.5%	Variance Explained by PC	67.8%	7.8%	Variance Explained by PC	64.4%	9.1%

Detection of Long-Term Trends in Discrete Samples

Site-Specific Trends

One of the most important goals of water-quality monitoring in Upper Klamath Lake has been the identification of long-term data trends. Regulatory actions, such as implementation of a total maximum daily load (TMDL) for phosphorus, and large-scale restoration projects, such as the reconnection of the Williamson River Delta to the lake, are predicated on the idea that these actions will improve water quality over multiple decades. Therefore, monitoring programs must be designed to adequately observe the variation in key water-quality parameters over time periods necessary to observe these changes. The Klamath Tribes monitoring program, for example, was designed and implemented to observe long-term trends. The program has been uninterrupted since 1990 and has consistently maintained nine core sites.

Long-term trends in the Klamath Tribes monthly mean water-quality data collected from May to September, 1990–2009, were evaluated similarly to Jassby and Kann (2010) using the seasonal SMK trend test. The results for ammonia shown in table 5 differ from Jassby and Kann (2010) because the current study used total ammonia, whereas Jassby and Kann (2010) used un-ionized ammonia in their analysis. Few trends were statistically significant using the SMK test at individual sites, and those that were significant were small. Trends in nutrient (TP, TN, SRP, ammonia) or chlorophyll-*a* concentrations were not significant at $p < 0.05$ (table 5, row A). Two sites showed significant, increasing trends in Secchi depth, and four sites showed decreasing trends in DO concentration ($p < 0.05$). Trends in pH, water temperature, and specific conductance generally were not significant. Inclusion of an additional year of data (2010) had little effect on the seasonal trend results, although three sites acquired a significantly increasing trend in specific conductance (table 5, row B). LOWESS-smoothing prior to applying the SMK test (Helsel and Hirsch, 2002) using temperature as an exogenous variable did not increase the number of statistically significant trends (fig. 4).

Table 5. Results of seasonal Mann-Kendall (SMK) and regional Kendall (RK) tests for trends in the Klamath Tribes' dataset, Upper Klamath Lake, Oregon.

[A: Monthly means, period of record 1990–2009, first reported in Jassby and Kann (2010); B: Monthly means, period of record 1990–2010; C: Residuals of a LOWESS smooth of the monthly means using temperature as an exogenous variable, period of record 1990–2010. **Bold** Sen's slope values indicate significance at $p \leq 0.05$. **Abbreviations:** RK, regional Kendall test, AL, Agency Lake, UKL, Upper Klamath Lake. **Symbols:** -, no data, p, probability that the null hypothesis is true]

		Agency Lake		Upper Klamath Lake open-water				Singular sites			All sites	AL	UKL
		AN	AS	ER	ML	MN	NB	PM	SB	WB	(RK)	(RK)	(RK)
		Total phosphorus (micrograms per liter per year)											
A	Sen's slope	-0.79	-0.36	0.75	0.81	0.15	-0.21	0.50	0.18	0.50	0.32	-	-
	p	0.57	0.78	0.40	0.14	0.86	0.79	0.41	0.79	0.73	0.56	-	-
B	Sen's slope	-1.03	-0.65	0.31	0.67	-0.23	-0.79	0.13	-0.18	-0.10	-0.30	-1.76	-0.039
	p	0.40	0.55	0.72	0.22	0.74	0.34	0.92	0.77	0.92	0.55	0.46	0.96
C	Sen's slope	-0.16	0.36	0.68	0.78	0.027	-1.14	0.13	0.024	-0.56	0.13	-1.48	0.50
	p	0.88	0.97	0.54	0.38	0.97	0.25	0.85	1.00	0.69	0.79	0.52	0.51
		Soluble reactive phosphorus (micrograms per liter per year)											
A	Sen's slope	0.80	1.12	0.42	0.083	0.36	0.045	-0.15	0.50	0.063	**0.55**	-	-
	p	0.61	0.15	0.32	0.57	0.15	0.83	0.44	0.11	0.69	0.047	-	-
B	Sen's slope	0.47	0.56	-0.024	-0.027	0.13	-0.19	-0.28	0.25	-0.089	0.15	-0.54	0.31
	p	0.72	0.54	0.93	0.85	0.63	0.44	0.071	0.47	0.62	0.46	0.68	0.26
C	Sen's slope	0.86	0.66	-0.009	0.052	0.28	-0.25	**-0.44**	0.36	-0.21	0.41	-0.51	0.32
	p	0.40	0.46	0.92	0.79	0.29	0.28	0.047	0.18	0.54	0.11	0.93	0.25
		Total nitrogen (micrograms per liter per year)											
A	Sen's slope	0.54	1.41	9.44	11.29	2.83	4.50	16.2	8.45	9.36	3.91	-	-
	p	0.90	0.82	0.10	0.056	0.77	0.68	0.042	0.51	0.23	0.62	-	-
B	Sen's slope	0.52	4.34	6.71	9.24	-2.71	-2.67	11.6	2.50	5.46	-1.30	-0.52	-2.24
	p	0.90	0.48	0.24	0.12	0.79	0.73	0.16	0.91	0.48	0.69	0.89	0.63
C	Sen's slope	10.9	14.1	10.5	13.3	-3.45	-1.84	12.2	-1.65	5.28	-3.32	3.67	1.09
	p	0.22	0.23	0.28	0.25	0.79	0.86	0.38	0.97	0.69	0.51	0.75	0.75

Table continued on next page.

Table 5. Results of seasonal Mann-Kendall (SMK) and regional Kendall (RK) tests for trends in the Klamath Tribes' dataset, Upper Klamath Lake, Oregon—continued

[A: Monthly means, period of record 1990–2009, first reported in Jassby and Kann (2010); B: Monthly means, period of record 1990–2010; C: Residuals of a LOWESS smooth of the monthly means using temperature as an exogenous variable, period of record 1990–2010.**Bold** Sen's slope values indicate significance at p ≤ 0.05. **Abbreviations:** RK, regional Kendall test, AL, Agency Lake, UKL, Upper Klamath Lake. **Symbols:** -, no data, p, probability that the null hypothesis is true]

		Agency Lake		Upper Klamath Lake open-water				Singular sites			All sites (RK)	AL (RK)	UKL (RK)
		AN	AS	ER	ML	MN	NB	PM	SB	WB			
		Total ammonia nitrogen (micrograms per liter per year)											
A	Sen's slope	0.0	-1.26	2.30	0.29	1.50	-0.17	0.088	2.06	0.50	0.056	-	-
	p	1.00	0.14	0.22	0.61	0.18	0.85	0.93	0.21	0.64	0.96	-	-
B	Sen's slope	-0.53	**-1.44**	0.43	-0.021	0.65	-0.50	-0.42	0.45	-0.18	-1.09	-1.80	-0.56
	p	0.33	0.028	0.85	0.94	0.51	0.54	0.67	0.75	0.85	0.30	0.29	0.79
C	Sen's slope	-0.29	-1.22	1.09	-0.67	1.08	-1.34	-1.13	0.80	0.42	-2.13	-3.25	-1.99
	p	0.66	0.068	0.66	0.48	0.47	0.17	0.21	0.71	0.89	0.12	0.22	0.45
		Chlorophyll *a* (micrograms per liter per year)											
A	Sen's slope	-0.57	-0.11	-0.25	-0.025	-0.40	0.53	0.40	-0.49	0.35	-0.62	-	-
	p	0.35	0.71	0.48	0.88	0.17	0.14	0.30	0.18	0.38	0.13	-	-
B	Sen's slope	-0.15	0.09	-0.16	0.011	-0.36	0.63	0.43	-0.41	0.49	-0.27	-0.81	-0.31
	p	0.67	0.86	0.71	0.93	0.21	0.11	0.30	0.30	0.29	0.48	0.46	0.53
C	Sen's slope	0.73	1.03	0.85	0.65	-0.53	1.09	1.28	-0.27	1.35	-0.33	0.15	-0.22
	p	0.48	0.20	0.32	0.30	0.49	0.18	0.27	0.86	0.21	0.37	0.93	0.63
		Secchi depth (meters per year)											
A	Sen's slope	0.005	0.007	0.006	0.011	**0.014**	0.002	-0.003	**0.017**	0.005	**0.009**	-	-
	p	0.71	0.42	0.28	0.082	0.026	0.71	0.71	0.004	0.23	0.0001	-	-
B	Sen's slope	-0.003	0.003	0.003	0.010	**0.014**	0.002	-0.001	**0.015**	0.005	**0.007**	0.007	**0.008**
	p	0.85	0.65	0.70	0.089	0.030	0.80	0.89	0.005	0.30	0.003	0.49	0.009
C	Sen's slope	-0.006	-0.002	0.001	0.011	0.010	0.000	-0.003	**0.014**	0.005	**0.008**	0.0002	**0.007**
	p	0.51	0.65	0.89	0.092	0.10	1.00	0.70	0.016	0.26	0.0002	0.96	0.007

Table continued on next page.

Table 5. Results of seasonal Mann-Kendall (SMK) and regional Kendall (RK) tests for trends in the Klamath Tribes' dataset, Upper Klamath Lake, Oregon—continued

[A: Monthly means, period of record 1990–2009, first reported in Jassby and Kann (2010); B: Monthly means, period of record 1990–2010; C: Residuals of a LOWESS smooth of the monthly means using temperature as an exogenous variable, period of record 1990–2010.**Bold** Sen's slope values indicate significance at $p \leq 0.05$. **Abbreviations:** RK, regional Kendall test, AL, Agency Lake, UKL, Upper Klamath Lake. **Symbols:** -, no data, p, probability that the null hypothesis is true]

		Agency Lake		Upper Klamath Lake open-water				Singular sites			All sites	AL	UKL
		AN	AS	ER	ML	MN	NB	PM	SB	WB	(RK)	(RK)	(RK)
						Water temperature (degrees Celsius per year)							
A	Sen's slope	-0.030	-0.006	0.008	0.004	-0.016	0.001	0.005	-0.012	-0.011	**-0.015**	-	-
	p	0.36	0.75	0.81	0.78	0.39	0.95	0.84	0.66	0.65	0.017	-	-
B	Sen's slope	-0.041	-0.015	0.010	0.005	-0.017	-0.005	-0.0001	-0.015	-0.015	**-0.020**	-0.035	**-0.015**
	p	0.14	0.48	0.71	0.75	0.30	0.90	1.00	0.57	0.49	0.001	0.061	0.026
C	Sen's slope	-	-	-	-	-	-	-	-	-	-	-	-
	p	-	-	-	-	-	-	-	-	-	-	-	-
						Dissolved oxygen (milligrams per liter per year)							
A	Sen's slope	-0.073	-0.013	-0.035	-0.023	-0.040	-0.024	-0.008	-0.040	-0.046	-0.023	-	-
	p	0.014	0.48	0.049	0.16	0.032	0.16	0.72	0.049	0.11	0.0004	-	-
B	Sen's slope	-0.042	-0.005	-0.021	-0.009	-0.029	-0.014	-0.005	-0.022	-0.041	-0.013	-0.025	-0.011
	p	0.14	0.81	0.30	0.54	0.092	0.45	0.79	0.26	0.15	0.065	0.29	0.19
C	Slope	-0.042	0.020	-0.008	0.004	-0.024	-0.003	0.004	-0.016	-0.025	-0.006	-0.012	-0.004
	p	0.15	0.29	0.54	0.92	0.18	0.93	0.72	0.36	0.40	0.31	0.62	0.59
						pH (per year)							
A	Sen's slope	-0.009	0.003	0.007	0.014	0.009	0.006	0.012	0.003	0.008	0.004	-	-
	p	0.33	0.65	0.32	0.068	0.18	0.33	0.11	0.64	0.26	0.090	-	-
B	Sen's slope	-0.008	0.003	0.007	0.011	0.006	0.005	0.009	0.005	0.006	0.004	0.003	0.004
	p	0.47	0.62	0.32	0.11	0.28	0.45	0.18	0.52	0.39	0.097	0.52	0.24
C	Slope	0.006	0.019	0.014	0.015	0.012	0.010	0.010	0.010	0.008	0.004	0.007	0.005
	p	0.50	0.083	0.10	0.054	0.15	0.26	0.16	0.23	0.28	0.14	0.34	0.15

Table continued on next page.

Table 5. Results of seasonal Mann-Kendall (SMK) and regional Kendall (RK) tests for trends in the Klamath Tribes' dataset, Upper Klamath Lake, Oregon—continued

[A: Monthly means, period of record 1990–2009, first reported in Jassby and Kann (2010); B: Monthly means, period of record 1990–2010; C: Residuals of a LOWESS smooth of the monthly means using temperature as an exogenous variable, period of record 1990–2010.**Bold** Sen's slope values indicate significance at $p \leq 0.05$. **Abbreviations:** RK, regional Kendall test, AL, Agency Lake, UKL, Upper Klamath Lake. **Symbols:** -, no data, p, probability that the null hypothesis is true]

		Agency Lake		Upper Klamath Lake open-water				Singular sites			All sites	AL	UKL
		AN	AS	ER	ML	MN	NB	PM	SB	WB	(RK)	(RK)	(RK)
		Specific conductance (microsiemens per centimeter per year)											
A	Sen's slope	-0.16	-0.045	0.077	0.039	0.028	-0.017	0.058	0.16	0.16	0.071	-	-
	p	0.14	0.75	0.38	0.68	0.82	0.90	0.61	0.26	0.24	0.37	-	-
B	Sen's slope	-0.042	0.10	**0.20**	0.19	0.16	0.14	0.17	**0.26**	**0.35**	**0.19**	0.045	0.19
	p	0.81	0.48	0.038	0.12	0.16	0.25	0.088	0.029	0.024	0.014	0.85	0.094
C	Slope	0.054	0.11	0.16	0.20	0.14	0.18	0.14	**0.28**	**0.32**	**0.17**	0.17	0.18
	p	0.60	0.49	0.11	0.14	0.19	0.31	0.12	0.038	0.026	0.015	0.17	0.12

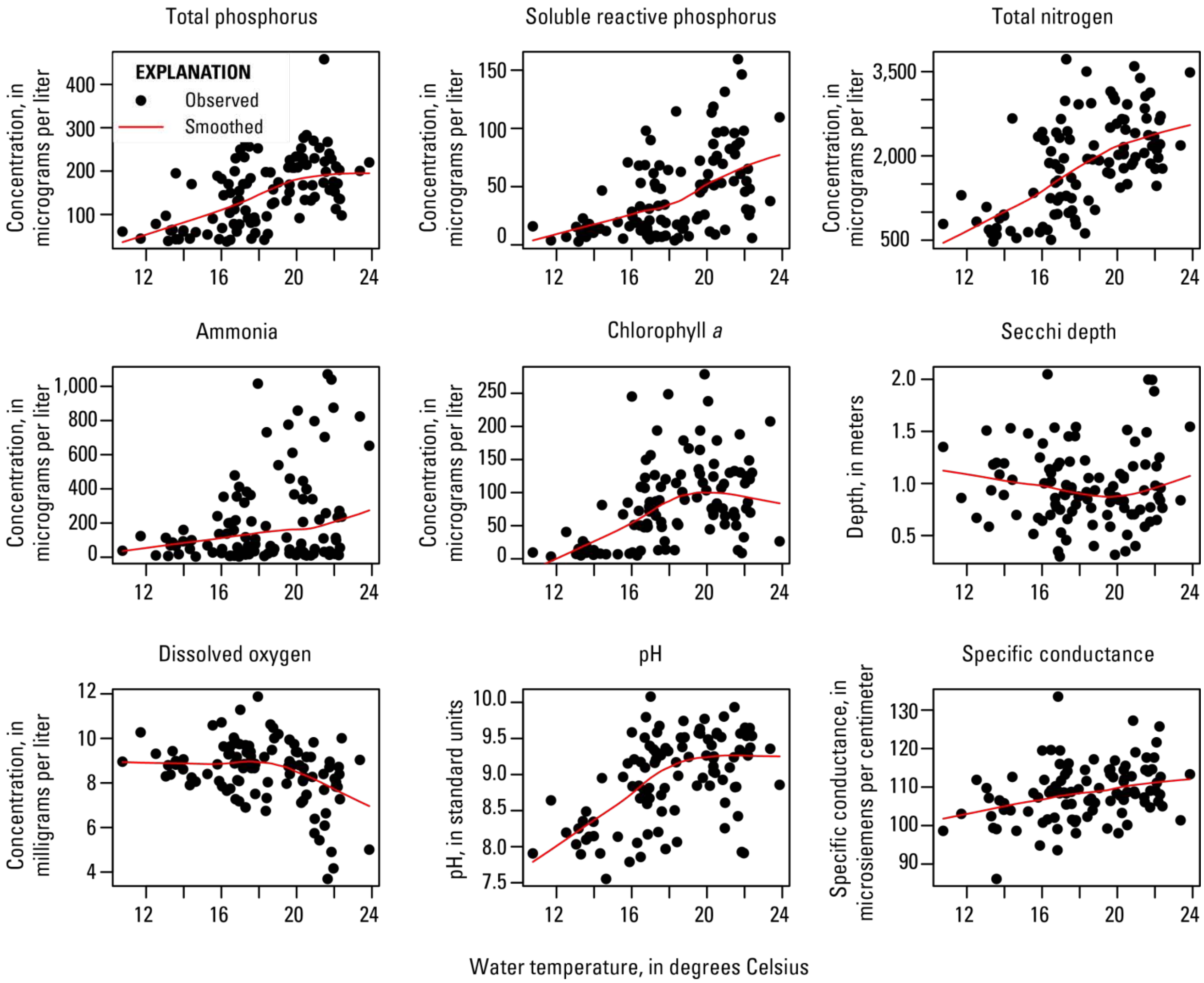


Figure 4. Measured and LOWESS smoothed data collected from Klamath Tribes' site MN, from May to September, 1990–2010, using water temperature as an exogenous variable, Upper Klamath Lake, Oregon.

The WRTTS procedure was applied to the Klamath Tribes data to graphically evaluate trends that might change over the 20-year dataset. Comparisons of WRTTS modeled and observed chlorophyll-*a* data in natural log space resulted in R^2 values of 0.36–0.63, which were consistent with results from applications of the model to rivers, where the independent variable was discharge instead of air temperature, and the dependent variable was TP (Hirsch and others, 2010). The model fit chlorophyll-*a* concentrations in Agency Lake with more residual error (R^2 = 0.36–0.37) than concentrations measured at sites in Upper Klamath Lake (R^2=0.48–0.63). Comparisons of WRTTS modeled and measured TP concentrations in natural log space resulted in R^2 values of 0.46–0.63, which generally were higher than those for chlorophyll *a*. The WRTTS TP model also fit TP concentrations in Upper Klamath Lake (R^2=0.59–0.63) better than concentrations in Agency Lake (R^2=0.46–0.49). Examination of the model residuals indicated some skewness, particularly for chlorophyll *a*, because the trigonometric functions on which the seasonal cycle is based cannot capture the rapid decline in the bloom that happens most years. For this reason, the analysis presented here should be considered a demonstration of this type of extension of the WRTTS approach to lake data, and one that should be improved.

The temperature-normalized trends in annual mean chlorophyll-*a* concentrations resulting from the WRTTS analysis of Klamath Tribes data showed increasing concentrations early in the period of record, 1990 through about 1996, decreasing concentrations from about 1996 through about 2006, and increasing concentrations again from about 2006 through 2010 at most sites (fig. 5; table 6). At two sites (AS and SB), annual mean chlorophyll-*a* concentrations decreased from 1990 to 2003, and increased from 2003 to 2010. These results appeared to indicate an overall increasing trend in chlorophyll-*a* concentration. However, the WRTTS model provides results with less certainty at the margins of a time series due to its windowed weighting procedure (Hirsch and others, 2010).

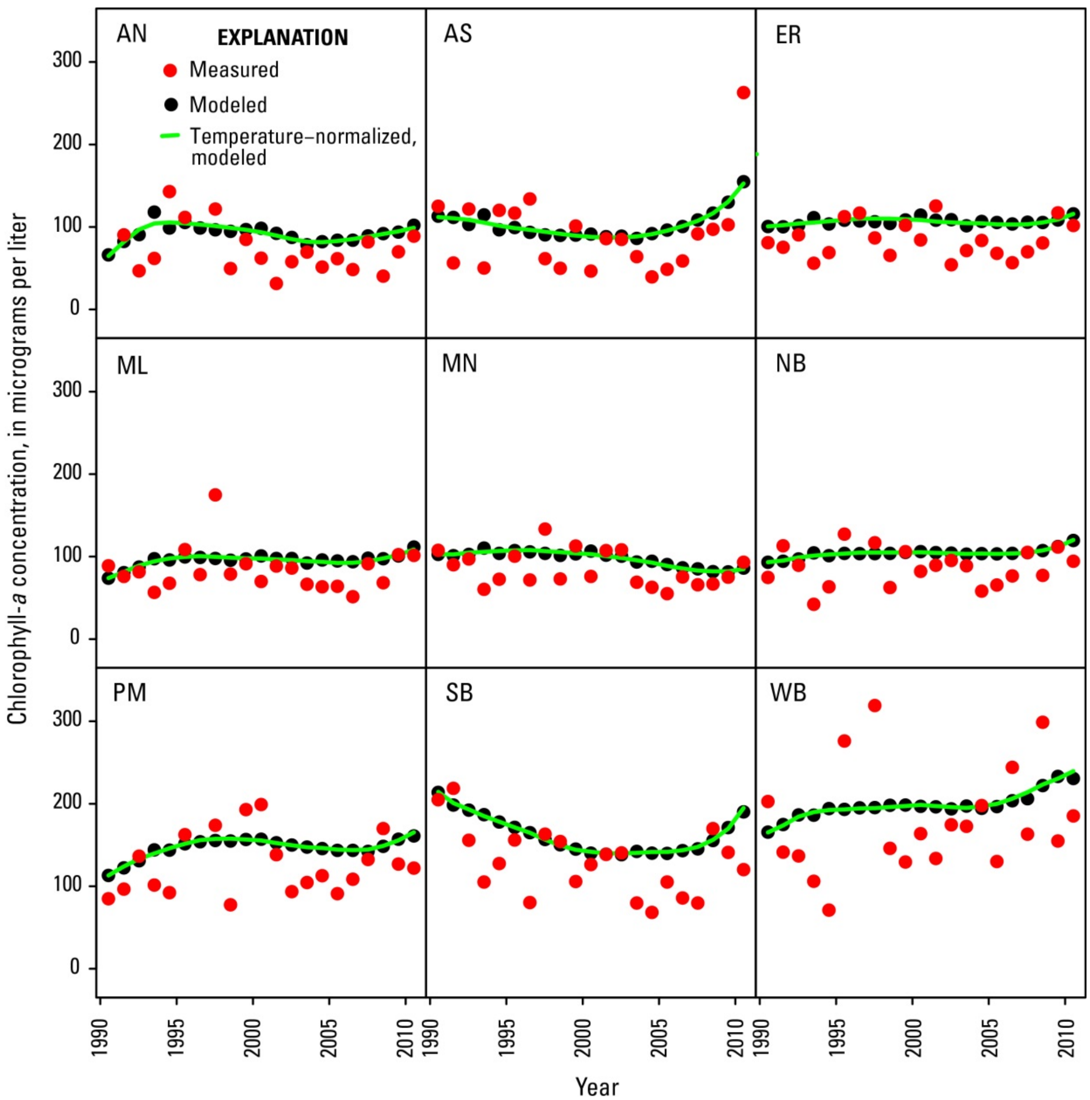


Figure 5. Measured and modeled annual means of chlorophyll-*a* concentration at nine core Klamath Tribes' monitoring sites using locally weighted regression on time, air temperature, and season (WRTTS), Upper Klamath Lake, Oregon. Slopes determined by linear regression and significance levels are presented in table 6.

Table 6. Slope determined by linear regression on the temperature-normalized weighted regressions on time, air temperature, and season (WRTTS) using the Klamath Tribes' dataset for time periods prior to (1990–2002) and after (2002–2010) establishment of the total maximum daily load (TMDL), Upper Klamath Lake, Oregon.

[**Bold** R^2 values indicate significance at $p \leq 0.05$. **Abbreviations:** SD, standard deviation, AL, Agency Lake, UKL, Upper Klamath Lake.]

	Agency Lake		Upper Klamath Lake open-water				Singular sites					
	AN	AS	ER	ML	MN	NB	PM	SB	WB	Average of all sites ± 1 SD	Average of AL sites ± 1 SD	Average of UKL open-water sites ± 1 SD
Chlorophyll *a* (micrograms per liter per year)												
slope 1990–2002	0.59	-2.30	0.48	1.40	-0.29	0.84	2.92	-6.33	2.14	-0.061 ± 2.62	-0.86 ± 1.45	0.61 ± 0.61
R^2	0.04	**0.97**	**0.37**	**0.46**	0.16	**0.68**	**0.64**	**0.96**	**0.69**			
slope 2002–2010	1.97	7.51	0.94	1.39	-2.02	1.66	1.55	5.72	5.79	2.72 ± 2.83	4.74 ± 2.77	0.49 ± 1.47
R^2	**0.79**	**0.87**	0.39	**0.51**	**0.83**	**0.63**	0.37	**0.71**	**0.92**			
Total phosphorus (micrograms per liter per year)												
slope 1990–2002	-1.24	-0.55	-0.020	0.040	-1.76	-0.32	1.50	-2.77	-2.94	-0.90 ± 1.35	-0.90 ± 0.35	-0.52 ± 0.73
R^2	**0.75**	**0.37**	0.000	0.002	**0.33**	0.05	**0.78**	**0.54**	**0.81**			
slope 2002–2010	-0.81	-0.65	-1.64	-1.68	-3.56	-3.44	-5.83	-2.72	-3.30	-2.63 ± 1.54	-0.73 ± 0.080	-2.58 ± 0.92
R^2	0.36	**0.49**	**0.82**	**0.94**	**0.91**	**0.91**	**0.99**	**0.87**	**0.79**			
Soluble reactive phosphorus (micrograms per liter per year)												
slope 1990–2002	-0.70	2.09	0.18	0.73	0.15	0.78	0.19	-0.17	-0.18	0.34 ± 0.75	0.70 ± 1.40	0.46 ± 0.30
R^2	**0.41**	**0.91**	0.09	**0.89**	0.04	**0.97**	**0.62**	0.06	0.21			
slope 2002–2010	4.52	-1.68	-0.79	-0.68	-0.44	-1.25	-1.36	-0.45	-0.56	-0.30 ± 1.75	1.42 ± 3.10	-0.79 ± 0.29
R^2	**0.88**	**0.82**	**0.75**	**0.95**	**0.69**	**0.97**	**0.99**	**0.53**	**0.81**			

In contrast to the WRTTS results for chlorophyll-*a* concentrations, temperature-normalized trends in annual mean TP concentration resulting from the WRTTS analysis of Klamath Tribes data generally were decreasing throughout the entire 1990–2010 record (fig. 6). TP trends were more consistent across sites than trends in chlorophyll *a*, particularly in the post-TMDL-adoption period (2002–2010), when decreasing trends were observed at all sites, and the site-averaged trend was larger than the standard deviation (table 6).

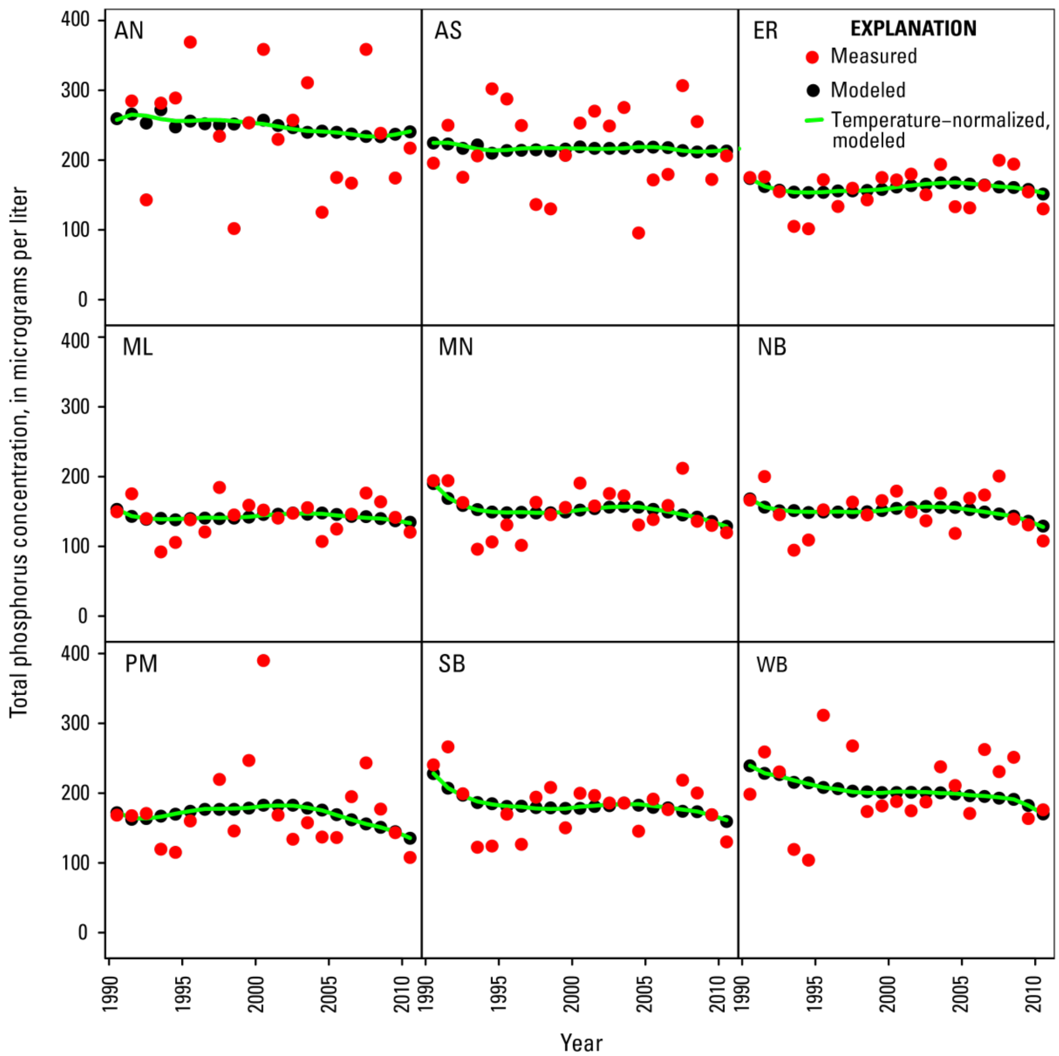


Figure 6. Measured and modeled annual means of total phosphorus at nine core Klamath Tribes' monitoring sites using locally weighted regression on time, air temperature, and season (WRTTS), Upper Klamath Lake, Oregon.

To compare trends quantitatively among sites, the pre-TMDL (1990–2002) and post-TMDL (2002–2010) trends in WRTTS temperature-normalized chlorophyll-*a* concentrations were calculated by linear regression over those time periods (table 6). Site WB was the only site that showed a relatively consistent increasing trend in chlorophyll *a* across all years. This analysis does not lend itself to rigorous hypothesis testing, but the resulting slopes varied in both magnitude and sign, and there was no obvious consistency between sites. The standard deviations among all sites combined, or the Agency Lake and Upper Klamath Lake open-water sites considered separately, generally were larger than the averages (table 6), and there was considerable overlap in the mean ± standard deviation chlorophyll-*a* concentrations between the pre- and post-TMDL periods.

Because the WRTTS analysis showed variable trends in chlorophyll *a* over the 21-year Klamath Tribes data set, the SMK test was applied to the more recent 5 years (2005–2010) of data that overlapped with weekly USGS nutrient and chlorophyll-*a* data collection. Trends were significantly decreasing for TP, TN, SRP, and ammonia at several sites (table 7); trends were significantly increasing for chlorophyll-*a* concentration at one Agency Lake site (AS), two Upper Klamath Lake open-water sites (ML and NB), and at one of the bay sites (SB). The significantly increasing trends in chlorophyll-*a* concentration observed in these years (2005–2010) are likely due to the change in analytical method in 2009. Prior to 2009, chlorophyll *a* was determined spectrophotometrically, and after 2009, chlorophyll *a* was determined fluorometrically. This method change resulted in higher concentrations being subsequently reported (J. Kann, Aquatic Ecosystem Sciences LLC, written commun., 2013). Trends in Secchi depth were also significantly decreasing at both Agency Lake sites (AN and AS), and trends in DO concentration were significantly increasing at the outlet site (PM) and at two Upper Klamath Lake open-water sites (ML and NB). Therefore, although results of the SMK test indicated decreasing nutrient concentrations at some sites, the test also showed increased bloom intensity, as determined by Secchi depth and DO concentrations (increasing chlorophyll *a* also would indicate increased bloom density, but this observation might have resulted from the change in analytical method in 2009).

When applied to the USGS 2005–2010 (May–September) dataset of monthly mean nutrient and other water-quality data values calculated from four sites sampled weekly (sites MDN, WMR, EPT, and MDT, fig. 1), the SMK trend analysis resulted in few statistically significant trends. Trends were significantly decreasing for TP at site MDN, for DO concentration at site MDT, and for TN at sites MDN and WMR. In addition, a trend was significantly increasing for chlorophyll-*a* concentration at site EPT (table 8). Trends were also significantly increasing for specific conductance at all sites except RPT, a result consistent with the trend results for specific conductance in the Klamath Tribes data. The implication of this change in specific conductance is not known. Lake levels declined overall from 2005 to 2010 (Jassby and Kann, 2010), but a corresponding increase in specific conductance would be expected only if the decrease in lake level was a consequence of increased evaporation rather than lake management. The extent to which this change can be attributed to tributary inputs also is unknown.

Table 7. Results of seasonal Mann-Kendall (SMK) and regional Kendall (RK) tests for trends in the Klamath Tribes' dataset (monthly means, 2005–2010), Upper Klamath Lake, Oregon.

[**Bold** indicates significance at $p \leq 0.05$. **Abbreviations:** RK, regional Kendall test, AL, Agency Lake, UKL, Upper Klamath Lake, **Symbol:** p, probability that the null hypothesis is true]

	Agency Lake		Upper Klamath Lake open-water				Singular sites						
	AN	AS	ER	ML	MN	NB	PM	SB	WB	All sites (RK)	AL sites (RK)	UKL open-water sites (RK)	USGS sites RPT, MDT, EPT, MDN, WMR (RK)
Total phosphorus (micrograms per liter per year)													
Sen's slope	3.67	-1.50	-2.13	1.28	-7.83	**-16.3**	-9.21	-8.17	-5.97	**-8.23**	4.42	**-8.92**	**-7.49**
p	0.867	0.737	0.614	0.614	0.0929	0.0032	0.313	0.179	0.614	0.0332	0.690	0.0307	0.0265
Soluble reactive phosphorus (micrograms per liter per year)													
Sen's slope	12.1	-4.50	-1.92	-0.333	-1.79	-1.50	**-3.50**	-2.72	-3.00	**-4.00**	-1.28	-5.02	-2.25
p	0.401	0.401	0.152	0.737	0.614	0.273	0.0438	0.273	0.179	0.0332	0.894	0.0743	0.460
Total nitrogen (micrograms per liter per year)													
Sen's slope	9.33	75.4	-20.5	-1.67	**-80.0**	-50.8	-32.5	-17.4	-17.0	**-48.0**	50.6	**-90.0**	**-110**
p	1.00	0.131	0.614	1	0.0186	0.179	0.240	0.502	0.313	0.0495	0.352	0.0112	0.0003
Total ammonia nitrogen (micrograms per liter per year)													
Sen's slope	0	-0.75	-14.4	**-4.67**	-7.17	-2.75	-1.33	-11.7	-6.22	0.0111	5.97	-2.22	10.00
p	0.932	0.401	0.240	0.0350	0.313	0.206	0.398	0.0929	0.179	1.00	0.352	0.511	0.355
Chlorophyll *a* (micrograms per liter per year)													
Sen's slope	2.03	**9.77**	6.52	**7.07**	1.81	**5.70**	5.80	**9.83**	2.85	**8.05**	**11.9**	**7.06**	-6.58
p	0.502	0.0445	0.131	0.0445	0.401	0.0438	0.179	0.0425	0.401	0	0.0116	0.0005	0.0888
Secchi depth (meters per year)													
Sen's slope	-0.121	-0.0825	-0.0640	-0.0258	-0.0150	-0.0583	-0.0525	-0.0500	-0.0167	-0.0386	-0.0671	-0.0346	
p	0.0438	0.0186	0.107	0.401	0.555	0.131	0.206	0.502	0.614	0	0.0053	0.0036	

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Table 7. Results of seasonal Mann-Kendall (SMK) and regional Kendall (RK) tests for trends in the Klamath Tribes' dataset (monthly means, 2005–2010), Upper Klamath Lake, Oregon—continued

[**Bold** indicates significance at p ≤ 0.05. **Abbreviations:** RK, regional Kendall test, AL, Agency Lake, UKL, Upper Klamath Lake, **Symbol:** p, probability that the null hypothesis is true]

	Agency Lake		Upper Klamath Lake open-water				Singular sites						
	AN	AS	ER	ML	MN	NB	PM	SB	WB	All sites (RK)	AL sites (RK)	UKL open-water sites (RK)	USGS sites RPT, MDT, EPT, MDN, WMR (RK)
Water temperature (degrees Celsius per year)													
Sen's slope	-0.0217	-0.0458	-0.0192	0.0450	-0.0293	0.0158	0.0178	0.0113	-0.0352	-0.0442	-0.0680	-0.0415	
p	1.00	0.313	1.00	1.00	0.867	0.867	0.867	1.00	0.737	0.260	0.690	0.398	
Dissolved oxygen (milligrams per liter per year)													
Sen's slope	0.219	0.199	0.168	**0.224**	0.165	**0.182**	**0.103**	0.258	0.0893	**0.0782**	0.136	0.0635	-0.0598
p	0.313	0.401	0.313	0.0429	0.240	0.0429	0.0429	0.240	0.401	0.0332	0.507	0.398	0.460
pH (per year)													
Sen's slope	0.118	0.0400	0.0350	0.0348	0.0194	0.0247	0.0455	0.0246	0.0208	**0.0271**	**0.100**	0.0139	-0.0389
p	0.240	0.240	0.502	0.7368	0.737	0.614	0.2395	0.401	0.502	0.0059	0.0239	0.302	0.196
Specific conductance (microsiemens per centimeter per year)													
Sen's slope	0.738	0.750	1.50	1.75	1.44	1.68	**1.66**	1.46	**2.20**	1.41	-1.29	1.55	**1.01**
p	0.737	0.737	0.0645	0.0929	0.131	0.0929	0.0289	0.152	0.0117	0.0795	0.352	0.0743	0.0055

Table 8. Results of seasonal Mann-Kendall (SMK) and regional Kendall (RK) tests for trends in USGS data, Upper Klamath Lake, Oregon, 2005–2010.

[Subsamples (1) and (2) are monthly means of bi-monthly data sets created by sub-sampling alternate weeks. **Bold** indicates significance at $p \leq 0.05$. **Abbreviation:** RK, regional Kendall test. **Symbol:** p, probability that the null hypothesis is true.]

	RPT 2006–2007, 2009	MDT 2005–2010	EPT 2005–2010	MDN 2005–2010	WMR 2005–2010	All sites (RK) 2005–2010	All sites (RK) subsample (1) 2005–2010	All sites (RK) subsample (2) 2005–2010
Total phosphorus (micrograms per liter per year)								
Sen's slope	-4.13	-5.98	-9.43	**-13.25**	-8.17	**-7.49**	**-12.0**	-5.86
p	0.350	0.319	0.175	0.0455	0.175	0.0265	0.0017	0.139
Soluble reactive phosphorus (micrograms per liter per year)								
Sen's slope	-2.75	-0.669	-1.12	-1.70	-6.50	-2.25	-4.10	0.0875
p	0.640	0.928	0.928	0.628	0.191	0.460	0.0961	1.00
Total nitrogen (micrograms per liter per year)								
Sen's slope	50	-97.5	-41.88	**-138**	**-121.2**	**-110**	**-149**	**-173**
p	0.613	0.800	0.280	0.0502	0.0450	0.0003	0.0087	0.0318
Total ammonia nitrogen (micrograms per liter per year)								
Sen's slope	-1.25	-5.47	6.33	-1.56	2.28	10.00	2.01	6.67
p	1.00	0.786	0.319	0.772	0.191	0.355	0.579	0.267
Chlorophyll *a* (micrograms per liter per year)								
Sen's slope	0.833	-0.583	**4.01**	-9.51	-6.38	-6.58	**-4.43**	-7.50
p	1.00	1.00	0.0450	0.104	0.233	0.0888	0.0075	0.224
Dissolved oxygen (milligrams per liter per year)								
Sen's slope	0.167	**-0.1894**	-0.17	-0.0750	-0.0133	-0.0598	0.0688	-0.0958
p	1	0.0473	0.415	0.625	0.920	0.460	0.557	0.227
pH (per year)								
Sen's slope	0.125	-0.0144	-0.0234	-0.0100	0.0142	-0.0389	-0.0675	-0.0167
p	0.161	0.928	0.786	0.697	0.763	0.196	0.0976	0.712
Specific conductance (microsiemens per centimeter per year)								
Sen's slope	2.60	**1.10**	**1.17**	**1.94**	**1.35**	**1.01**	**1.35**	**1.32**
p	0.161	0.0087	0.0236	0.0027	0.0458	0.0055	0.0250	0.0031

A qualitative comparison of data collected from 2005 to 2010 from comparable USGS and Klamath Tribes sites (Upper Klamath Lake open water; data not shown) showed all USGS sites with decreasing trends in TP and orthophosphate, four out of five sites (MDT, EPT, MDN, and WMR), with decreasing trends for TN, and three out of five sites (RPT, MDT, and MDN) with decreasing trends for ammonia. Three out of five sites (MDT, MDN, and WMR) showed decreasing trends for chlorophyll-*a* concentration, three out of five sites (MDT, EPT, and MDN) showed decreasing trends in pH, and four out of five sites (MDT, EPT, MDN, and WMR) showed decreasing trends for DO concentrations. Trends in SRP, TN, and ammonia were also decreasing for all Klamath Tribes Upper Klamath Lake open-water sites, and three out of four of these sites (ER, MN, and NB) showed a decreasing trend for TP. All Klamath Tribes sites, including the four Upper Klamath Lake open-water sites most directly comparable to USGS sites (sites MN, ER, ML, and NB), showed increasing trends for chlorophyll-*a* and DO concentrations and pH, and decreasing trends in Secchi depth. These results suggested an overall decline in USGS-measured and Klamath Tribes-measured nutrient concentrations from 2005 to 2010. However, results of the analysis of trends in USGS data indicated decreasing phytoplankton bloom densities (based on decreasing chlorophyll-*a* and DO concentration and pH) whereas analysis of trends in the Klamath Tribes data indicated increasing bloom densities (based on increasing chlorophyll-*a* and DO concentration, pH, and decreasing Secchi depth) during this time.

The difference in the trends in USGS and Klamath Tribes chlorophyll-*a* concentrations might be explained by the Klamath Tribes' change to a more sensitive method for chlorophyll-*a* analysis in 2009. Furthermore, nutrient and chlorophyll-*a* concentrations are depth-integrated quantities in the Klamath Tribes and USGS datasets, whereas Secchi depth indicates both quantity and near-surface accumulation of biomass where the bloom is dominated by buoyant phytoplankton (primarily *Aphanizomenon flos-aquae* in Upper Klamath Lake). This could explain overall decreasing bloom intensity occurring in the Klamath Tribes dataset with decreasing Secchi depth and increasing pH and DO conditions, variables that are elevated by photosynthesis. Differences were observed in the trends in pH and DO concentrations between the Klamath Tribes and USGS datasets, but it was difficult to interpret these differences because parameters measured by the Klamath Tribes were more heavily weighted by measurements from the photic zone than were the USGS parameters.

Regional Trends

The RK test performed by Jassby and Kann (2010) using Klamath Tribes data collected from 1990 to 2009 (data from all sites combined) was repeated here and updated as a starting point for determination of regional trends in all available monitoring data. Slight differences were found in slope and significance of ammonia from those previously reported because Jassby and Kann (2010) used un-ionized ammonia, while the current study evaluated total ammonia concentrations. The repeated test also identified a small but significant increasing Sen's slope (an estimate of the overall slope based on the median value of slopes determined for all ordinal time points) for Secchi depth (9 mm/yr) and a small but decreasing slope for DO and chlorophyll-*a* concentrations [-0.023 (mg/L)/yr and -0.62 (µg/L)/yr, respectively), consistent with a trend toward smaller blooms over the 20-year period (table 5). The trend in chlorophyll-*a* concentrations, however, was not highly significant ($p=0.13$). Sen's slopes were also significantly increasing for SRP concentration and pH [0.552 (µg/L)/yr and 0.004, respectively], and slope was decreasing for water temperature (-0.015 ºC/yr). When Klamath Tribes data collected in 2010 were included, results of the RK test showed a significant trend in specific conductance that was not present in the previous analysis, and the trend in SRP concentration became insignificant (table 5). The magnitude and direction of significant trends in Secchi depth, water temperature, DO concentration, and pH were retained in the updated test. Based on results of the PCA that identified Agency Lake and Upper Klamath Lake open water as distinct regions, additional RK tests were applied to these regions separately. The directions of trends identified in both regions were similar, but there were fewer significant trends detected than when all sites were placed into a single region.

To determine whether trends in the Klamath Tribes dataset were more significant from 2005 to 2010 than from 1990 to 2010, and to compare trends in the Klamath Tribes and USGS datasets, the RK test was further applied to Klamath Tribes and USGS data collected over the shared time period (2005–2010). When all Klamath Tribes sites were combined, the RK test resulted in significant trends for most parameters. Trends were significantly decreasing for TP, SRP, and TN [-8.2, -4.0, and -48.0 (µg/L)/yr, respectively; table 7]. The trends in chlorophyll-*a* and DO concentrations, and pH were significant and positive [8.0 (µg/L)/yr, 0.08 (mg/L)/yr, and 0.03 pH units/yr, respectively], and the trend in Secchi depth was significant and negative (-39 mm/yr). When Agency Lake and Upper Klamath Lake open-water sites in the Klamath Tribes program were considered as separate regions, significant trends of the same direction remained for chlorophyll-*a* concentration (increasing) and Secchi depth (decreasing) in both regions, and for nutrient concentrations in Upper Klamath Lake open-water sites (decreasing).

Results of the RK test of USGS data revealed significant trends in TP and TN concentrations, which were quantitatively similar to those determined for the Klamath Tribes Upper Klamath Lake open-water sites [-8.9 and -7.5 (µg/L)/yr for TP in the Klamath Tribes and USGS datasets, respectively, and -90 and -110 (µg/L)/yr for TN in the Klamath Tribes and USGS datasets, respectively; tables 7 and 8]. As with results of the site-specific trend analysis, trends observed in chlorophyll-*a* concentration diverged between the datasets, in that the Klamath Tribes data showed a significant increasing trend [7.1 (µg/L)yr], whereas the USGS dataset showed a significant decreasing trend [-6.6 (µg/L)/yr]. Because the Klamath Tribes and USGS datasets both show decreasing trends in TP and TN, this discrepancy is likely due to the Klamath Tribes method change for chlorophyll-*a* concentration in 2009. The Klamath Tribes dataset showed a significant decreasing trend in Secchi depth (-0.035 m/yr) that conflicts with an overall declining trend in bloom intensity as measured by TN, TP, and chlorophyll *a*, but this discrepancy might be explained by the fact that nutrient and chlorophyll-*a* concentrations were measured from depth-integrated samples, whereas Secchi depth measurements are affected by the surface-intensification of the bloom and overall bloom magnitude. The Klamath Tribes dataset showed increasing trends in DO concentration and pH, whereas the USGS dataset showed decreasing trends in DO concentration and pH. These trends in DO concentration and pH were not statistically significant in either the Klamath Tribes or USGS datasets, but these differences may indicate differences in how water-quality parameters were weighted over the water column; Klamath Tribes data were weighted more heavily toward the photic zone, and USGS measurements were more evenly distributed vertically.

Comparison of Weekly and Bimonthly Sampling

Weekly and bimonthly sampling strategies were compared for their ability to detect trends in nutrient and chlorophyll-*a* concentrations. To do this, subsamples of the USGS discrete sample dataset were taken on alternate weeks (odd and even Julian weeks), creating two bimonthly datasets, which were then evaluated with the RK test to identify significant trends. Trends were significantly negative in subsample 1 for TP and TN concentrations, which generally were of similar magnitude to those detected in the weekly data (table 8). A trend also was significant in the subsample of chlorophyll-*a* data, but the chlorophyll-*a* data trend was not significant in the weekly dataset. Results for subsample 2 indicated a reduced ability of the bimonthly dataset to detect trends, in that only a trend in TN was significantly decreasing. These results did not provide definitive evidence that weekly samples have more power to detect long-term trends than bimonthly samples, as three significant trends were detected among eight measured variables in the weekly data set, two significant trends were detected in one bimonthly dataset, and the other bimonthly data set showed four significant trends.

Small-Scale and Short-Term Variability

Wavelet and Principal Components Analyses of Continuous Monitoring Data

In 2006, the USGS water-quality monitoring network was the largest it has ever been and included sites in both Upper Klamath and Agency Lakes (Lindenberg and others, 2009), so this season was selected for analysis by wavelet transformation to determine the power in monitored water-quality variables as a function of frequency in the time series. Sixteen sites with the most complete records from 2006, including the six core sites, were evaluated. The resulting wavelet spectra of all water-quality variables showed peaks in power between approximately 5.8 and 7.6 days. Some sites, WMR for example (fig. 8), showed high local maxima at approximately 13.9 days. The wavelet spectra for air temperature and wind speed measured at site WMR-MET in 2006 also showed peaks in power around 6–7 days (fig. 9), indicating that weather contributed significantly to the variability in water-quality parameters, including those largely driven by photosynthesis, such as pH and DO concentration.

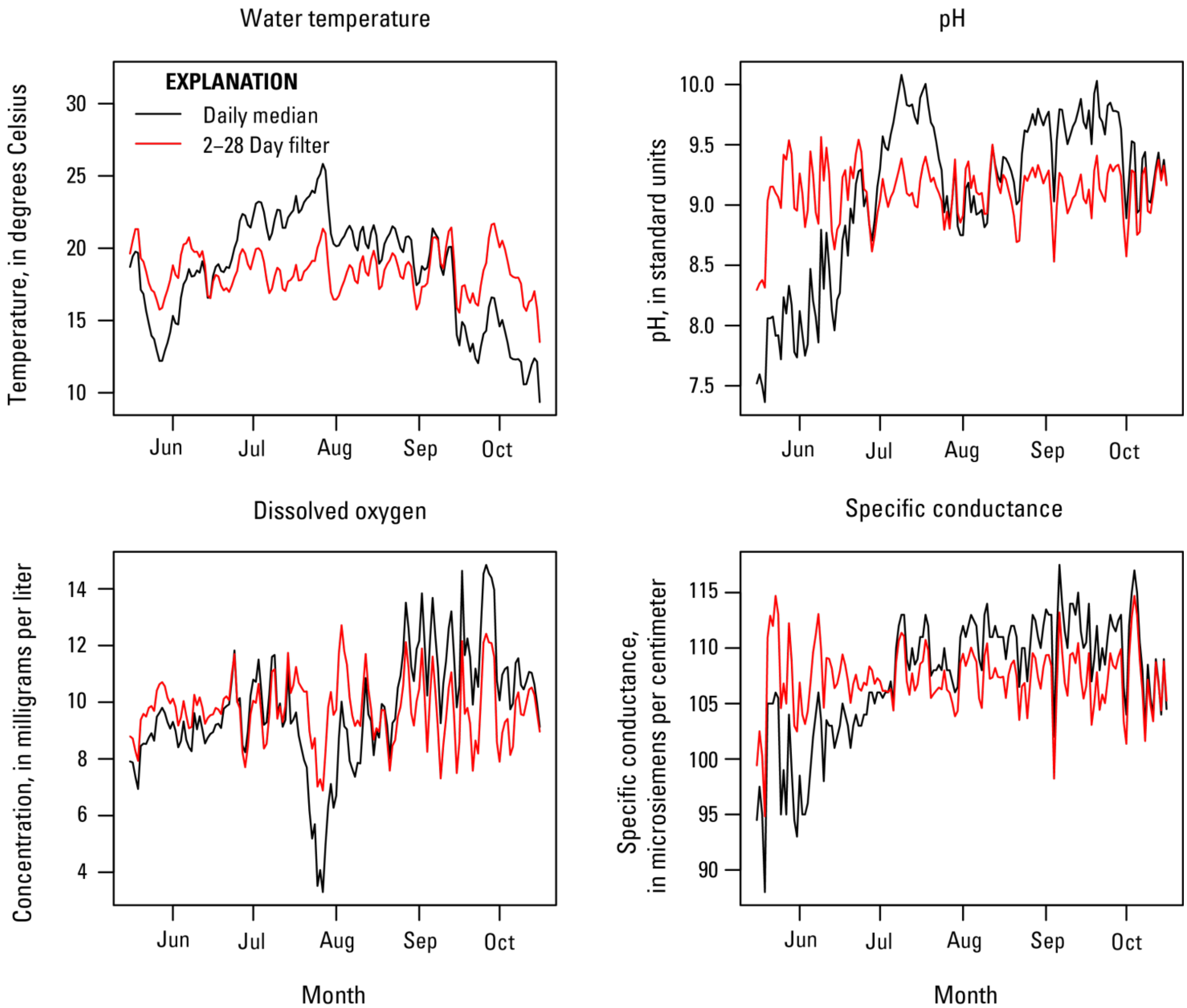

Figure 7. Time series of daily median water temperature, pH, dissolved oxygen concentration, and specific conductance at continuous-monitor site WMR from May 16 to October 16, 2006, and the reconstructed time series using only the wavelet components in the 2–28 day period, Upper Klamath Lake, Oregon.

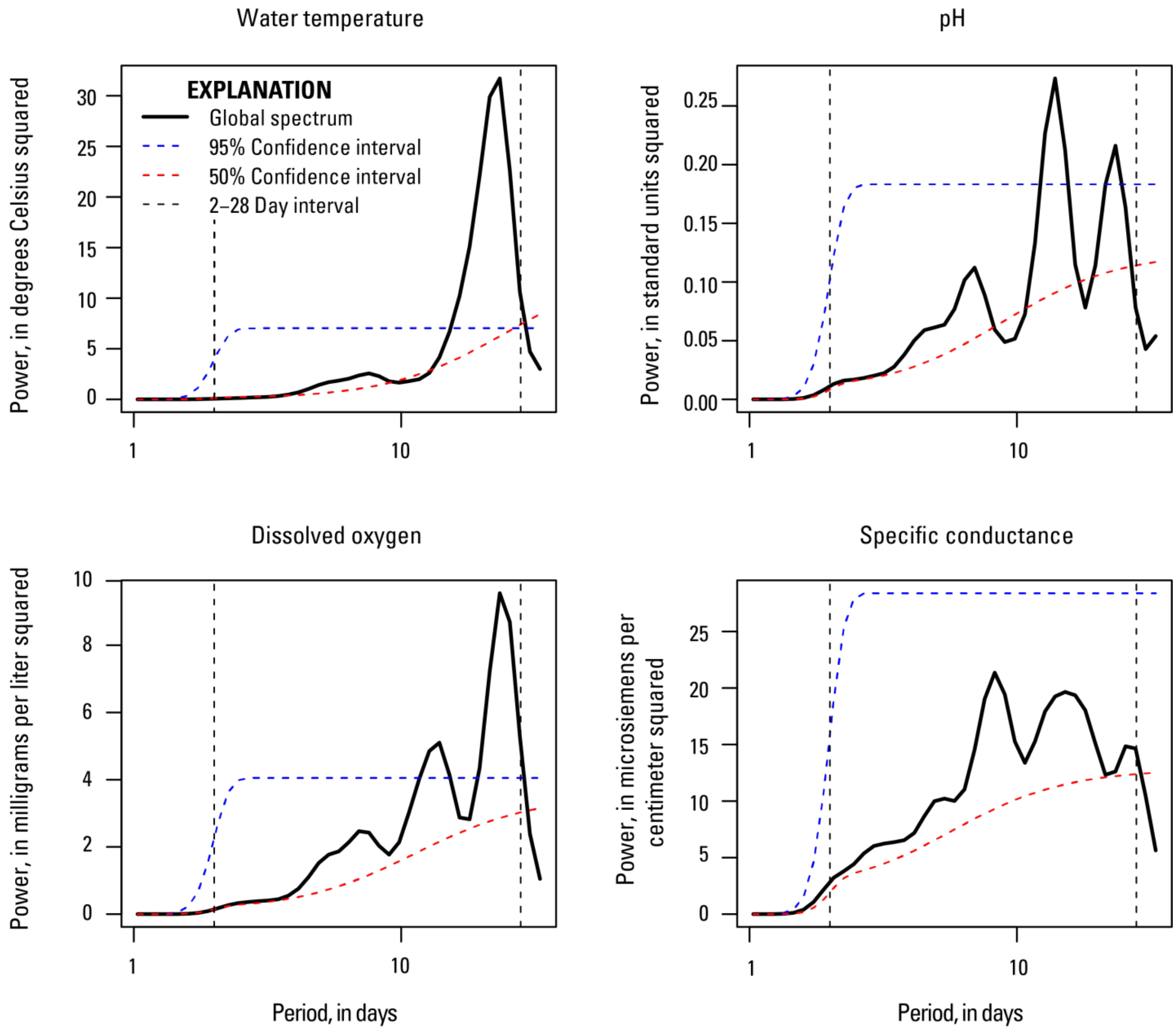

Figure 8. Variance in pH, dissolved oxygen concentration, specific conductance, and water temperature as a function of period length at continuous-monitor site WMR from May 16 to October 16, Upper Klamath Lake, Oregon, 2006.

Time series of pH, specific conductance, and DO concentration at each of the 16 sites were reconstructed by including only the variance (power) in the 2–28 day period band as determined by the wavelet analysis. For simplicity, results from a single site, WMR, are shown in figure 7. Such filtering was performed to isolate variability at frequencies that the network of unattended sensors was designed to measure and to minimize the effects of large, diel variability. Variance in the time series reconstructed over the 2–28 day band varied by a factor of 3.8 in pH, 10.6 in DO concentration, 9.2 in specific conductance, and 2.0 in temperature (table 9). When the six core monitoring locations currently used in the program were considered, the total power varied by a factor of 2.1 in pH, 2.9 in DO concentration, 4.6 in specific conductance, and 2.0 in water temperature. The 2–28 day variances observed in non-core sites were 102 percent higher in specific conductance (site AGN in Agency Lake), 130 percent higher in DO concentration (site HDB, the only bay site), and 82 percent higher in pH (site FBS, in the northern part of the lake) than core site WMR, which showed the most 2–28 day variance of any core site. Site

HDB, in Wocus (Howard) Bay, and site FBS, along the northwestern shoreline, showed higher 2–28 day variance in pH, DO, and specific conductance than any of the core sites; the Agency Lake sites (sites AGN and AGS) showed higher variance in specific conductance and pH (AGN only) than any core site. Therefore, comparison between the core and expanded networks indicated substantial variability in water quality not captured by the core network along the northwestern shoreline, in the bays, and in Agency Lake.

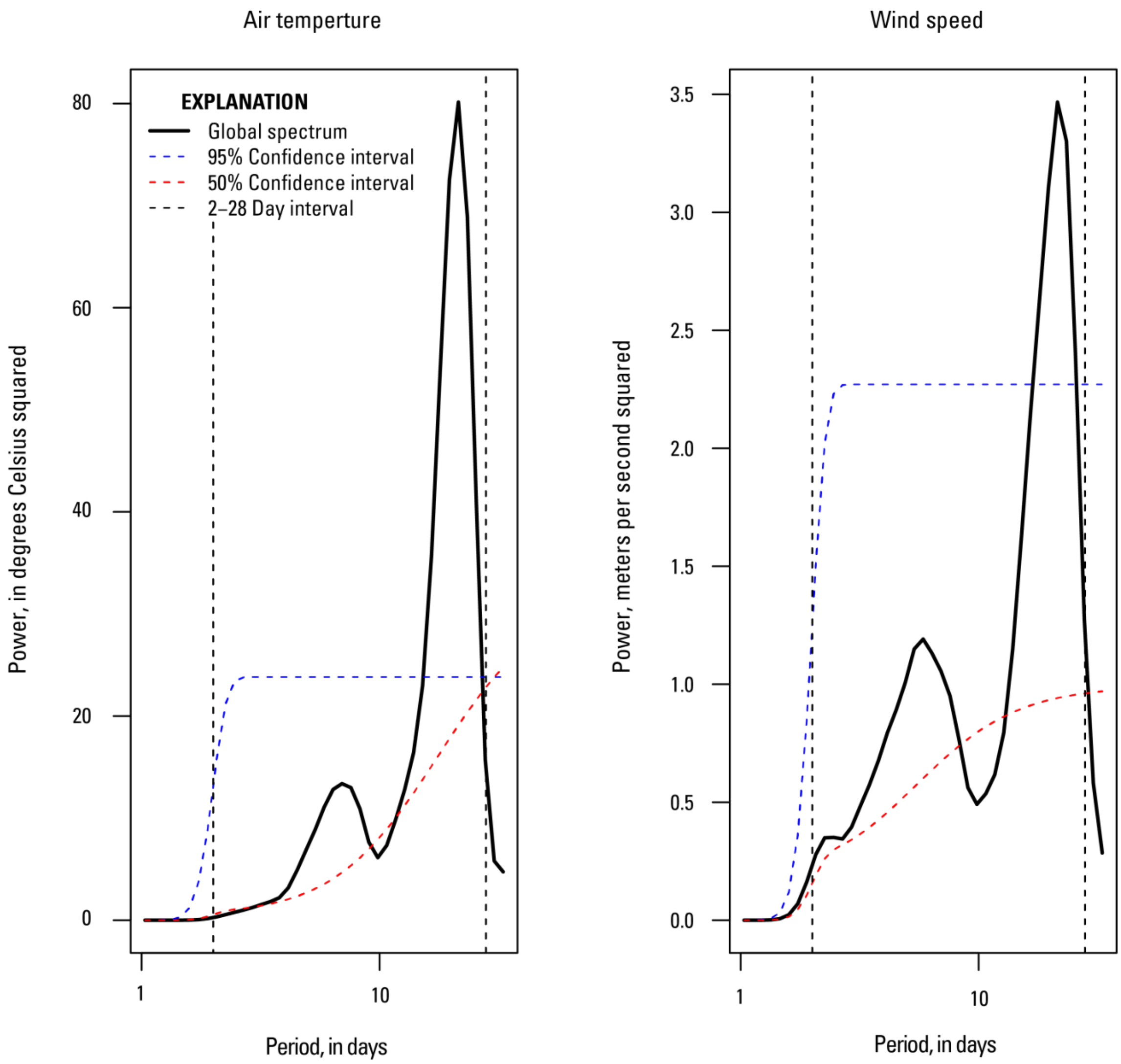

Figure 9. Variance in air temperature and wind speed as a function of period length in days at meteorological monitor site WMR-MET from May 1 through October 31, Upper Klamath Lake, Oregon, 2006.

Table 9. Variance in time series of continuously monitored water-quality variables at 16 USGS sites in Upper Klamath and Agency Lakes monitored in 2006, as reconstructed from the wavelet power in the 2–28 day period band.

[Each column is sorted from smallest to largest. **Symbols:** Asterisk (*****), core monitor site, mg/L, milligrams per liter, µS/cm[2] microsiemens per square centimeter, °C, degrees Celsius, --, no data.]

Site	pH $(pH)^2$	Site	Dissolved oxygen concentration $(mg/L)^2$	Site	Specific conductance $(\mu S/cm^2)^2$	Site	Temperature $(°C)^2$
MDN-L*	0.0239	EHB	0.341	MDN-L*	1.08	MDN-L*	0.832
MDN-U*	0.0246	MRM	0.509	EHB	1.22	EPT-L	0.847
MRM	0.0333	RPT*	0.545	RPT*	1.24	MDN-U*	0.856
NBI	0.0344	AGN	0.650	SET-L	1.45	RPT*	0.900
EHB	0.0359	MDN-L*	0.669	EPT-L	1.67	MDT-L*	0.929
RPT*	0.0362	SET-L	0.675	MDT-L*	1.75	MDT-U*	0.979
SET-U	0.0364	MDT-L*	0.913	MDN-U*	2.14	MRM	0.988
MDT-U*	0.0395	MDN-U*	1.02	NBI	2.96	NBI	1.000
AGS	0.0402	AGS	1.06	SET-U	3.04	SET-L	1.05
SET-L	0.0463	NBI	1.38	MDT-U*	4.01	SET-U	1.10
WMR*	0.0499	MDT-U*	1.40	MRM	4.43	EHB	1.15
EPT-L	0.0596	SET-U	1.44	WMR*	4.94	HDB	1.25
HDB	0.0608	EPT-L	1.50	HDB	6.94	FBS	1.30
AGN	0.0702	WMR*	1.57	FBS	8.26	AGS	1.38
FBS	0.0908	FBS	2.00	AGS	8.85	AGN	1.61
MDT-L*	--	HDB	3.60	AGN	9.96	WMR*	1.68

Reconstructed time series were used in a PCA analysis in order to compare data from the 16-monitor array with data from the 6 core sites, with the goal of detecting redundancy in the current monitoring network. The total variance explained by the first principal component from a PCA of 16 USGS sites monitored in 2006 ranged from 25.5 percent for specific conductance to 48.5 percent for pH. Principal components were retained based on the eigenvalue greater than 0.7 criterion and explained 70.3, 69.7, and 66.1 percent of the total variance in pH, DO concentration, and specific conductance, respectively (table 10). The locations of site loadings in the two-dimensional space defined by the first two components (fig. 10) does not provide a complete picture of which sites group together because some sites had large loadings on a third or fourth component. To visualize how sites group together in multi-dimensional space, the Euclidian distances between sites based on the loadings in table 10 for pH, DO concentration, and specific conductance combined were calculated (table 11). The screening level used to interpret this information is somewhat arbitrary, but a distance of 20 percent of the maximum distance between any two sites was used to demonstrate the feasibility of this approach. With this screening level, the Upper Klamath Lake open-water shallow sites (NBI and MRM) in the southern part of the lake and a monitor located at 1 m from the lake surface at a deep site, also in the southern part of the lake (SET-U), were within this distance of a core monitor site, and exhibited characteristics similar to the core site. Site HDB, in Howard (Wocus) Bay, also was within the 20 percent maximum distance of core site MDT-U (the near-surface monitor). Deep sites located along the trench (sites EPT-L and SET-L) and site FBS in the northern part of the lake, as well as Agency Lake sites (AGN and AGS) and Wocus Bay site EHB, were not within this distance, and water quality at those sites was distinct from that of the core network. The Euclidian distance analysis supports the conclusion that data from the core monitor data did not represent water quality in the northwestern part of the lake, the deep trench, and Agency Lake.

Table 10. Loadings onto the selected principal components at 16 sites monitored in 2006 from June 4 to September 28, 2006, Upper Klamath Lake, Oregon.

[The loadings in each column are scaled from blue (minimum value) to red (maximum value). **Abbreviations:** PC, principal component; **Symbols:** Asterisk (*), primary monitor site; %, percent.]

pH			
Site	PC1	PC2	PC3
AGS	-0.459	0.413	0.552
AGN	-0.331	0.322	0.354
FBS	0.164	0.844	-0.150
WMR*	0.393	0.512	0.207
MRM	0.512	0.610	0.0458
EPTL	0.560	0.400	-0.598
HDB	0.628	0.0655	0.411
NBI	0.805	-0.176	0.0787
MDN-L*	0.813	0.260	-0.223
RPT*	0.836	-0.182	0.237
EHB	0.849	-0.157	-0.114
MDT-U*	0.857	-0.259	0.141
MDN-U*	0.869	0.0358	0.0799
SET-L	0.875	-0.217	0.0012
SET-U	0.903	-0.0276	0.213
Variance explained by PC:	48.5%	13.7%	8.10%
Total variance		70.3%	

Dissolved oxygen concentration				
Site	PC1	PC2	PC3	PC4
AGN	-0.0246	-0.114	-0.141	0.872
FBS	0.316	0.217	0.638	-0.248
EPT-L	0.401	0.614	-0.308	-0.0471
AGS	0.432	0.495	0.183	0.557
MRM	0.601	-0.206	0.400	0.0935
MDN-L*	0.606	-0.0213	0.347	-0.201

Table continued on next page.

Table 10. Loadings onto the selected principal components at 16 sites monitored in 2006 from June 4 to September 28, 2006, Upper Klamath Lake, Oregon—continued

[The loadings in each column are scaled from blue (minimum value) to red (maximum value). **Abbreviations:** PC, principal component; **Symbols:** Asterisk (*), primary monitor site; %, percent.]

Dissolved oxygen concentration (continued)				
Site	PC1	PC2	PC3	PC4
MDT-U*	0.615	-0.412	-0.541	-0.0658
MDT-L*	0.642	0.508	-0.319	-0.101
MDN-U*	0.690	-0.533	0.0310	0.0942
NBI	0.708	-0.365	0.114	0.0330
WMR*	0.730	0.0729	0.265	0.233
SET-L	0.740	0.325	-0.193	-0.153
HDB	0.754	-0.285	-0.103	0.0162
EHB	0.790	0.355	0.0163	0.0445
SET-U	0.796	-0.18	-0.225	-0.148
RPT*	0.816	-0.0697	0.0208	-0.0315
Variance explained by PC:	40.7%	12.0%	8.80%	8.20%
Total variance		69.7%		

Specific conductance						
Site	PC1	PC2	PC3	PC4	PC5	PC6
MRM	0.0177	0.0720	0.460	-0.683	0.178	-0.0151
FBS	0.0183	0.0933	0.277	0.237	0.625	-0.478
AGN	0.0705	0.587	0.116	0.185	0.343	0.158
HDB	0.133	0.432	-0.420	0.0761	0.355	-0.0570
AGS	0.148	-0.161	-0.799	-0.180	0.223	-0.0491
MDN-L*	0.240	-0.757	0.0240	-0.0898	0.232	0.249
WMR*	0.289	0.103	0.0505	0.400	0.112	0.715
MDN-U*	0.357	-0.639	0.099	0.0790	0.323	-0.0175
RPT*	0.377	-0.226	0.300	0.508	-0.142	-0.171
MDT-U*	0.667	0.234	0.181	-0.221	0.0855	0.178
NBI	0.670	0.146	-0.183	-0.106	-0.0948	0.0143
EPT-L	0.681	-0.172	-0.0565	-0.154	0.168	0.0277
EHB	0.725	-0.0158	-0.261	0.0860	-0.179	-0.220
MDT-L*	0.733	0.178	0.158	-0.216	-0.228	-0.0665
SET-L	0.741	0.0162	0.0469	0.238	-0.199	-0.223
SET-U	0.809	0.148	0.0775	-0.0733	0.0835	0.0536
Variance explained by PC:	25.5%	11.1%	8.70%	7.70%	6.80%	6.30%
Total variance				66.1%		

Table continued on next page.

Table 10. Loadings onto the selected principal components at 16 sites monitored in 2006 from June 4 to September 28, 2006, Upper Klamath Lake, Oregon—continued

[The loadings in each column are scaled from blue (minimum value) to red (maximum value). **Abbreviations:** PC, principal component; **Symbols:** Asterisk (*****), primary monitor site; %, percent.]

pH, dissolved oxygen, specific conductance combined			
Site	PC1	PC2	PC3
AGN	-0.489	0.459	0.525
AGS	-0.462	0.581	0.431
EPT-L	-0.0896	0.829	-0.214
FBS	0.404	-0.661	0.178
HDB	0.466	0.374	0.408
MDN-L*	0.538	0.364	-0.0742
SET-L	0.559	0.656	-0.331
MRM	0.607	-0.445	-0.0489
MDT-U*	0.609	0.433	0.213
WMR*	0.623	-0.365	0.110
MDN-U*	0.736	-0.172	0.360
NBI	0.740	-0.110	0.294
EHB	0.744	0.267	-0.399
RPT*	0.789	0.162	-0.0732
SET-U	0.804	0.265	0.128
Variance explained by PC:	36.5%	20.7%	8.50%
Total variance		65.7%	

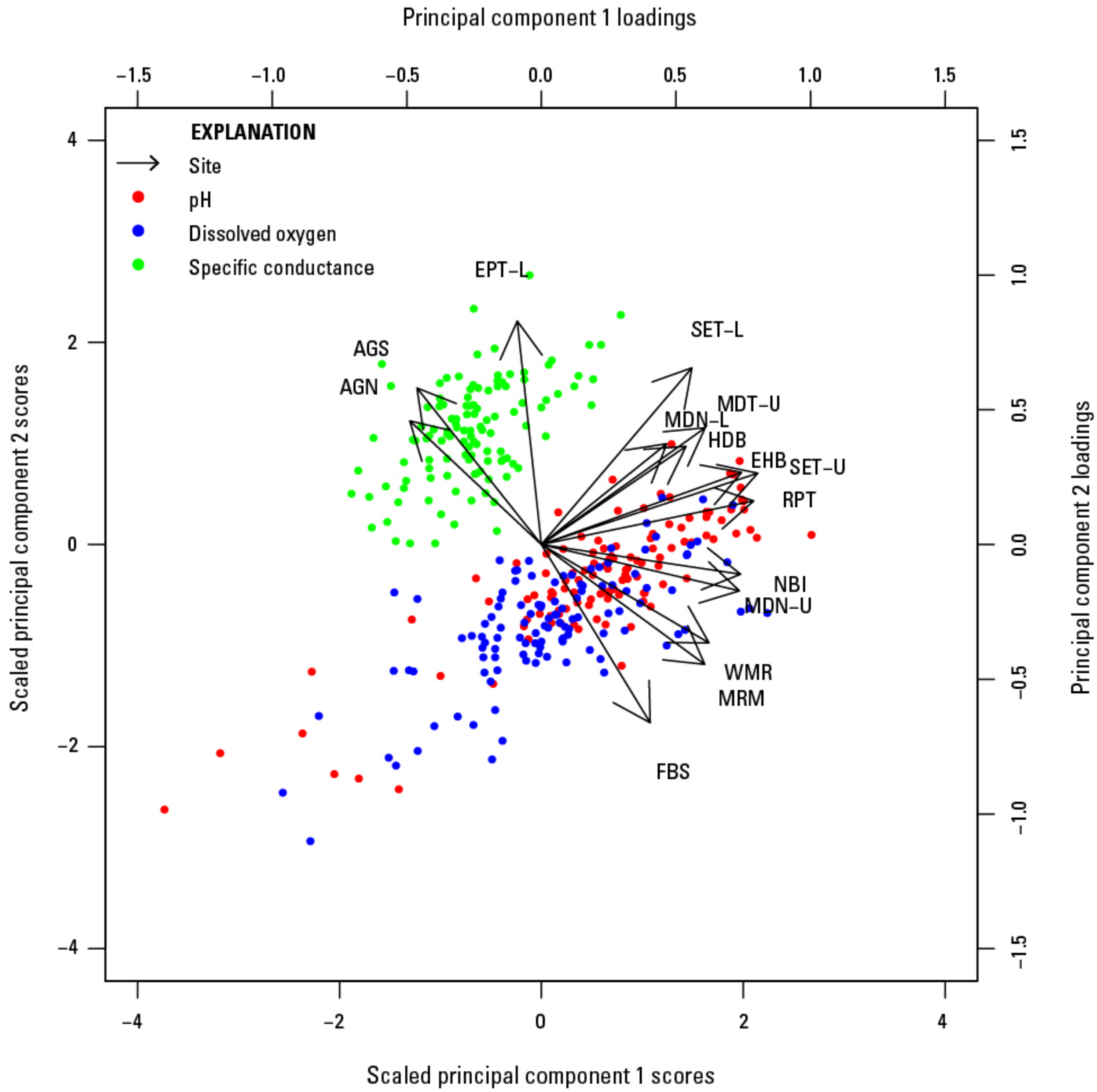

Figure 10. Biplot showing loadings of pH, specific conductance, and dissolved oxygen concentration measured from May 15 to October 16, 2006, and from continuous-monitor sites onto the first two principal components, Upper Klamath Lake, Oregon. Specific conductance, pH, and dissolved oxygen concentration were reconstructed from the 2 to 28-day variance as determined by wavelet analysis. Sixteen sites were evaluated, but the record of pH data from site MDT-L was incomplete, and, therefore, not shown in the figure.

Table 11. Euclidian distances between continuous monitor sites based on loadings onto the first three principal components at 15 sites monitored from June 4 to September 28, 2006, Upper Klamath Lake, Oregon.

[Values of pH, dissolved oxygen concentration, and specific conductance were included in the principal components analysis. Distances less than 0.324 (20 percent of the maximum distance in the table) are highlighted. Dissolved oxygen concentration, pH, and specific conductance were included in the principal components analysis. **Abbreviation**: PC, principal component. **Symbol:** Asterisk (*****), core monitor site.]

	AGN	AGS	EPT-L	FBS	HDB	MDN-L*	SET-L	MRM	MDT-U*	WMR*	MDN-U*	NBI	EHB	RPT*	SET-U
AGN	0	0.156	0.918	1.47	0.966	1.19	1.37	1.53	1.14	1.44	1.39	1.37	1.55	1.44	1.37
AGS		0	0.785	1.54	0.951	1.14	1.28	1.56	1.10	1.47	1.42	1.39	1.50	1.41	1.34
EPT-L			0	1.62	0.950	0.793	0.682	1.46	0.909	1.43	1.42	1.35	1.02	1.11	1.11
FBS				0	1.06	1.06	1.42	0.373	1.11	0.374	0.619	0.656	1.14	0.942	1.01
HDB					0	0.488	0.797	0.948	0.249	0.812	0.611	0.568	0.860	0.617	0.452
MDN-L*						0	0.389	0.813	0.303	0.757	0.718	0.634	0.397	0.323	0.349
SET-L							0	1.14	0.589	1.11	1.09	1.01	0.435	0.603	0.651
MRM								0	0.916	0.178	0.508	0.497	0.805	0.634	0.757
MDT-U*									0	0.805	0.636	0.565	0.648	0.433	0.272
WMR*										0	0.335	0.336	0.821	0.582	0.656
MDN-U*											0	0.09	0.876	0.549	0.499
NBI												0	0.789	0.460	0.415
EHB													0	0.345	0.531
RPT*														0	0.23
SET-U															0

Synoptic Surveys of Upper Klamath Lake Water-Quality Conditions

Synoptic surveys were performed near USGS monitoring sites MDT and MDN in Upper Klamath Lake to measure small-scale variability in water temperature, DO concentration, pH, specific conductance, and phycocyanin fluorescence. The transect data were compared to measurements of the same parameters made by fixed monitors (recording hourly) deployed at sites MDT and MDN during the same time intervals in order to determine how much of the observed spatial variability could be attributed to temporal differences during the time intervals required to complete the measurements. Overall, data from the fixed site monitors showed less variability than the transect data, which provided confidence that the transect measurements were approximately synoptic (figs. 11 and 12). A wavelet transformation, which analyzes the frequency components of a signal based on small wavelets with limited duration, was used to determine the dominant spatial scales of variability along the transects. The wavelet transformation is an extension of the Fourier transform, used to analyze the frequency components of a signal. The Fourier transform taken over an entire time axis cannot show at what instant a particular frequency rises. Alternatively, the short-time Fourier transform uses a sliding window to give information of both time and frequency. But, the length of the window limits the resolution in frequency. Wavelet transforms seem to be a solution to this problem because they are based on small wavelets with limited duration (wavelets are purposefully created to have specific properties that make them useful for signal processing).

Results of the wavelet transform in this study indicated that water temperature was relatively stable across both transects, as expected for a variable that is determined mostly by large-scale forcing over the water surface (fig. 13). Wavelet spectra for pH and DO concentration showed peaks in variability at scales of about 1.5 km (figs. 14 and 15), while the wavelet spectra for phycocyanin fluorescence showed variability at scales as small as 0.25 km (fig. 16). This indicated much more spatial patchiness in phycocyanin than in pH or DO concentration. Because phycocyanin fluorescence is directly proportional to the abundance of cyanobacterial cells in the water column, this patchiness was likely a result of vertical and horizontal colony migration. Overall, these results indicated significant spatial and temporal variability in some water-quality parameters at scales smaller than the whole lake-scale patterns currently resolvable by the monitoring networks. However, integrated water column samples (for total or dissolved nutrients, for example) are not subject to vertical migration issues and that these data might not be as patchy, making it easier to obtain an accurate lakewide average of these variables from a small core network.

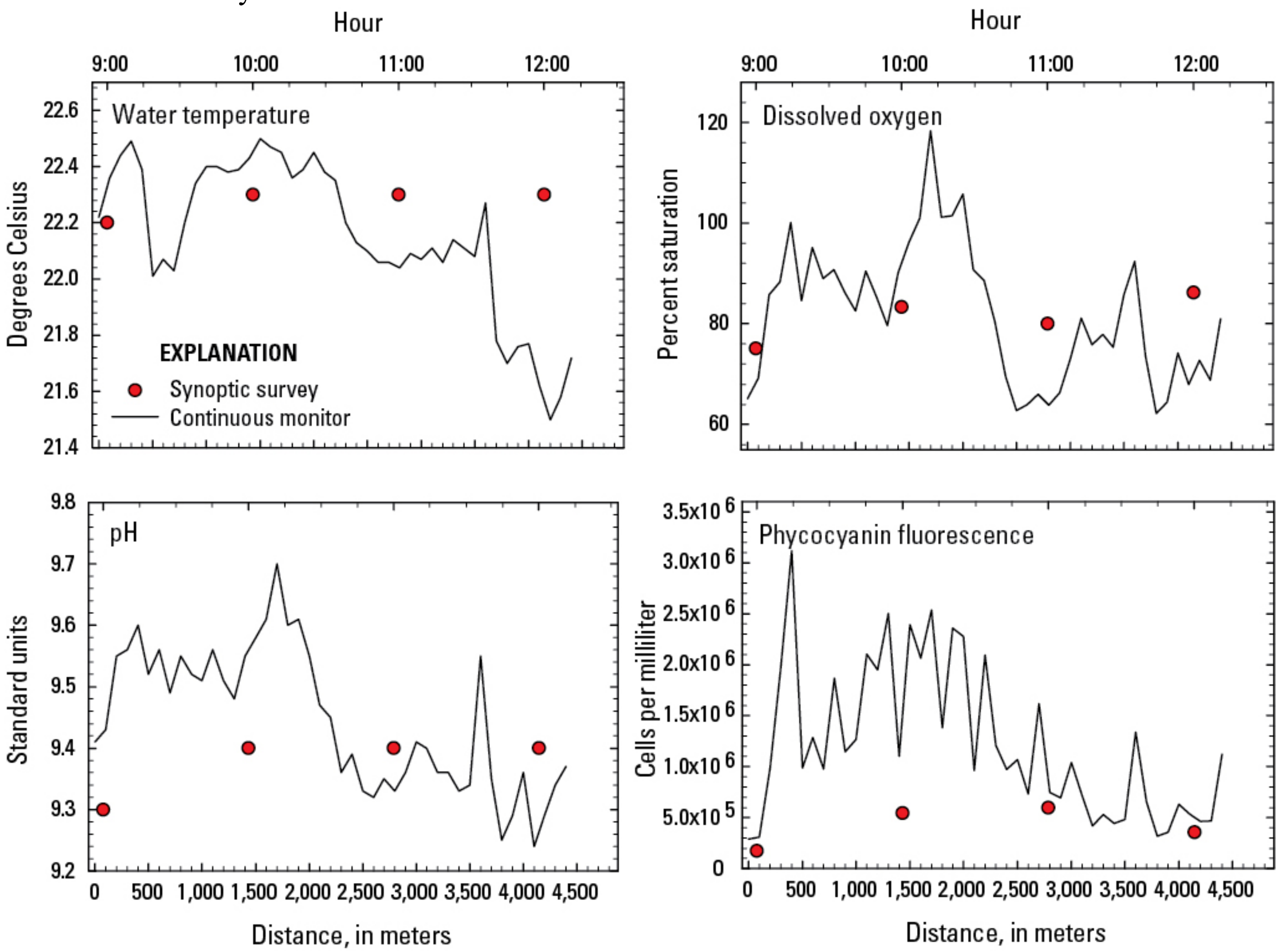

Figure 11. Water temperature, dissolved oxygen percent saturation, pH, and phycocyanin fluorescence measured along a 100 meter-interval transect (transect A) and at 1 meter below the water surface on August 3, 2012, between site MDT and the eastern shoreline of Upper Klamath Lake, Oregon. The red circles are plotted against time (upper horizontal axis) and represent hourly monitor data from site MDT while the survey was performed.

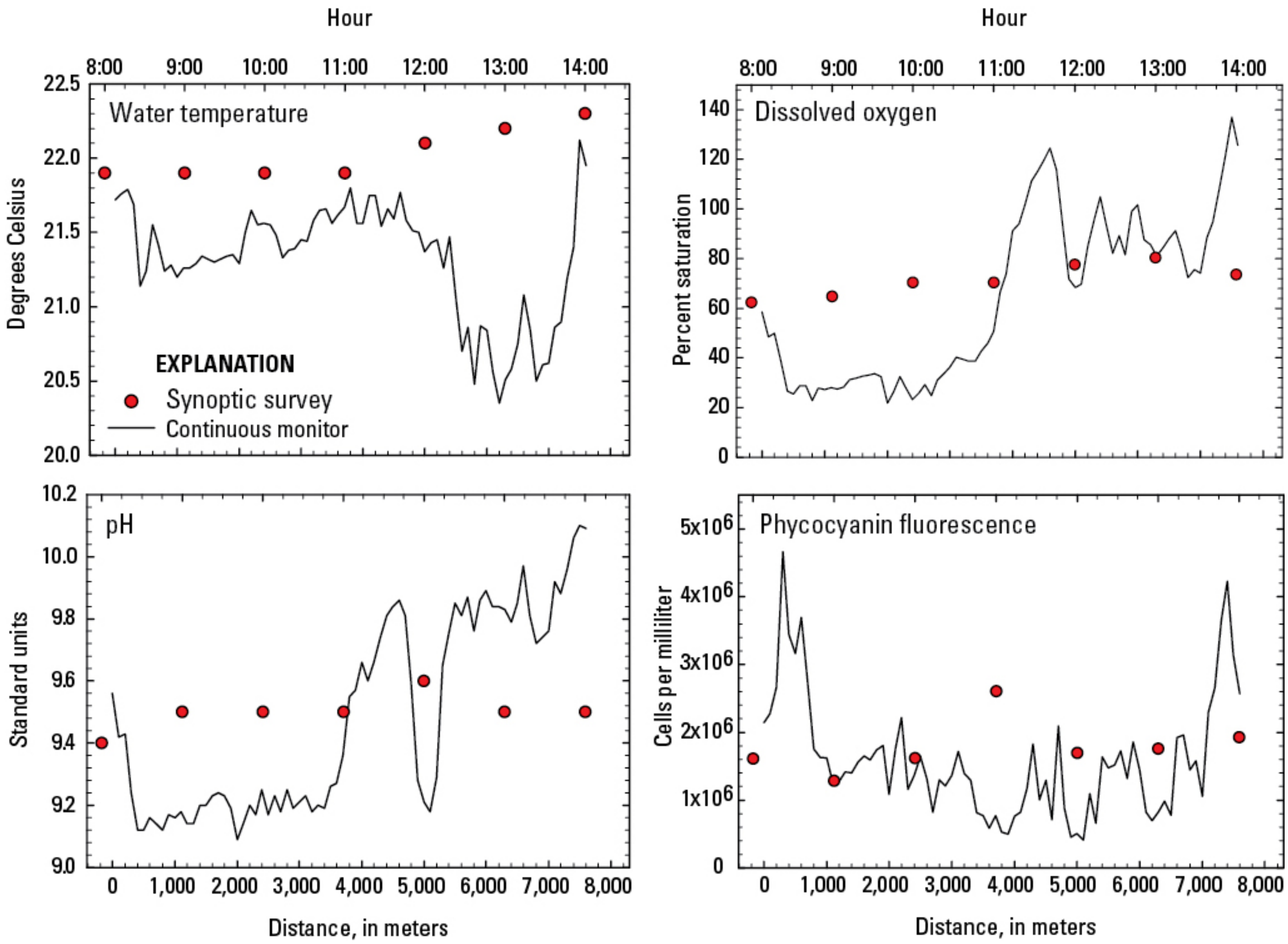

Figure 12. Water temperature, dissolved oxygen percent saturation, pH, and phycocyanin fluorescence measured along a 100 m-interval transect (transect B) and at 1 meter below the water surface on August 6, 2012, between Ball Point and site MDN, Upper Klamath Lake, Oregon. The red circles are plotted versus time (the upper horizontal axis) and represent hourly monitor data collected at site MDN while the survey was performed.

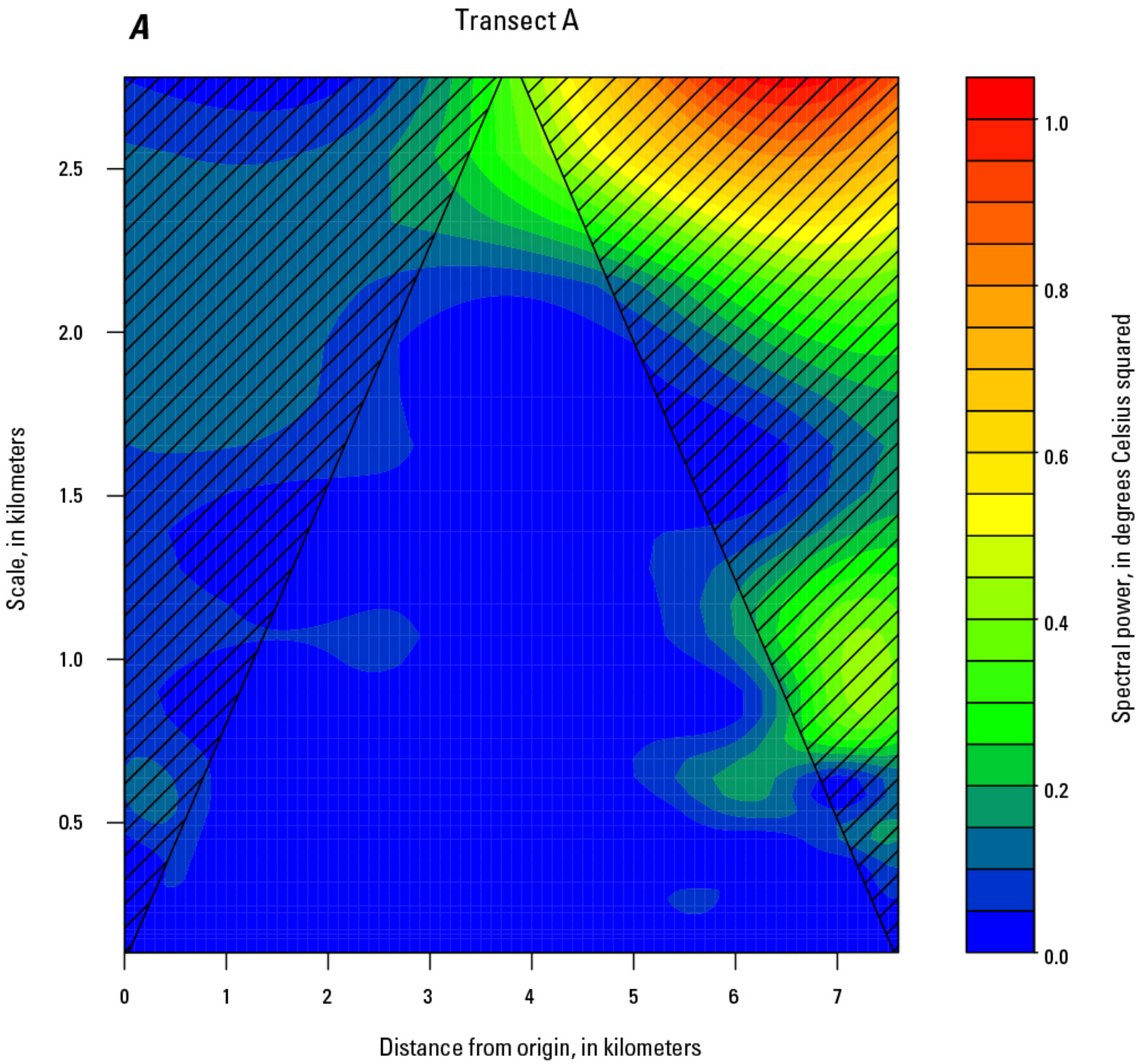

Figure 13*A*. Wavelet spectra for water temperature measured along transect A on August 3, Upper Klamath Lake, 2012.

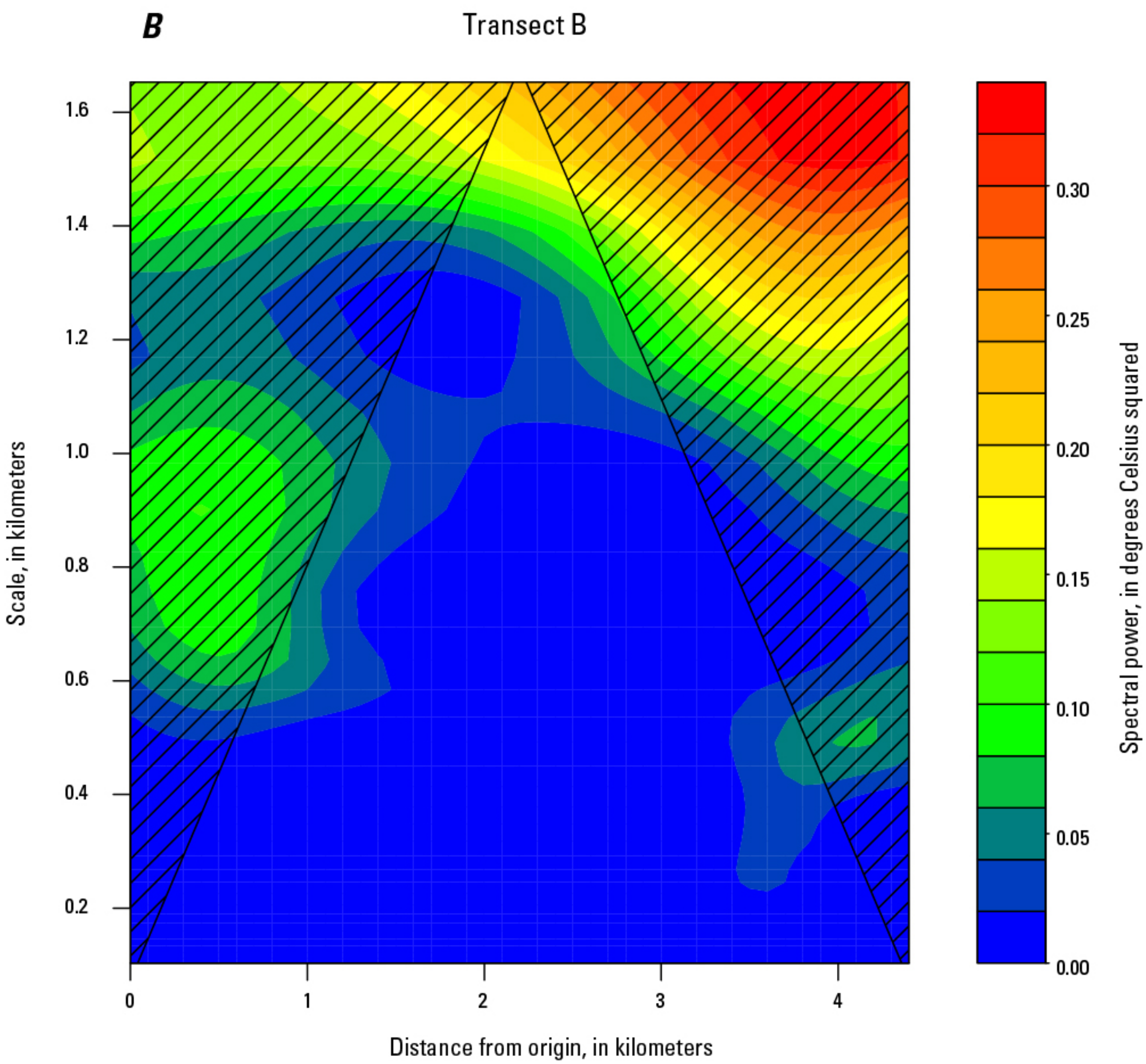

Figure 13*B*. Wavelet spectra for water temperature measured along transect B on August 6, Upper Klamath Lake, 2012.

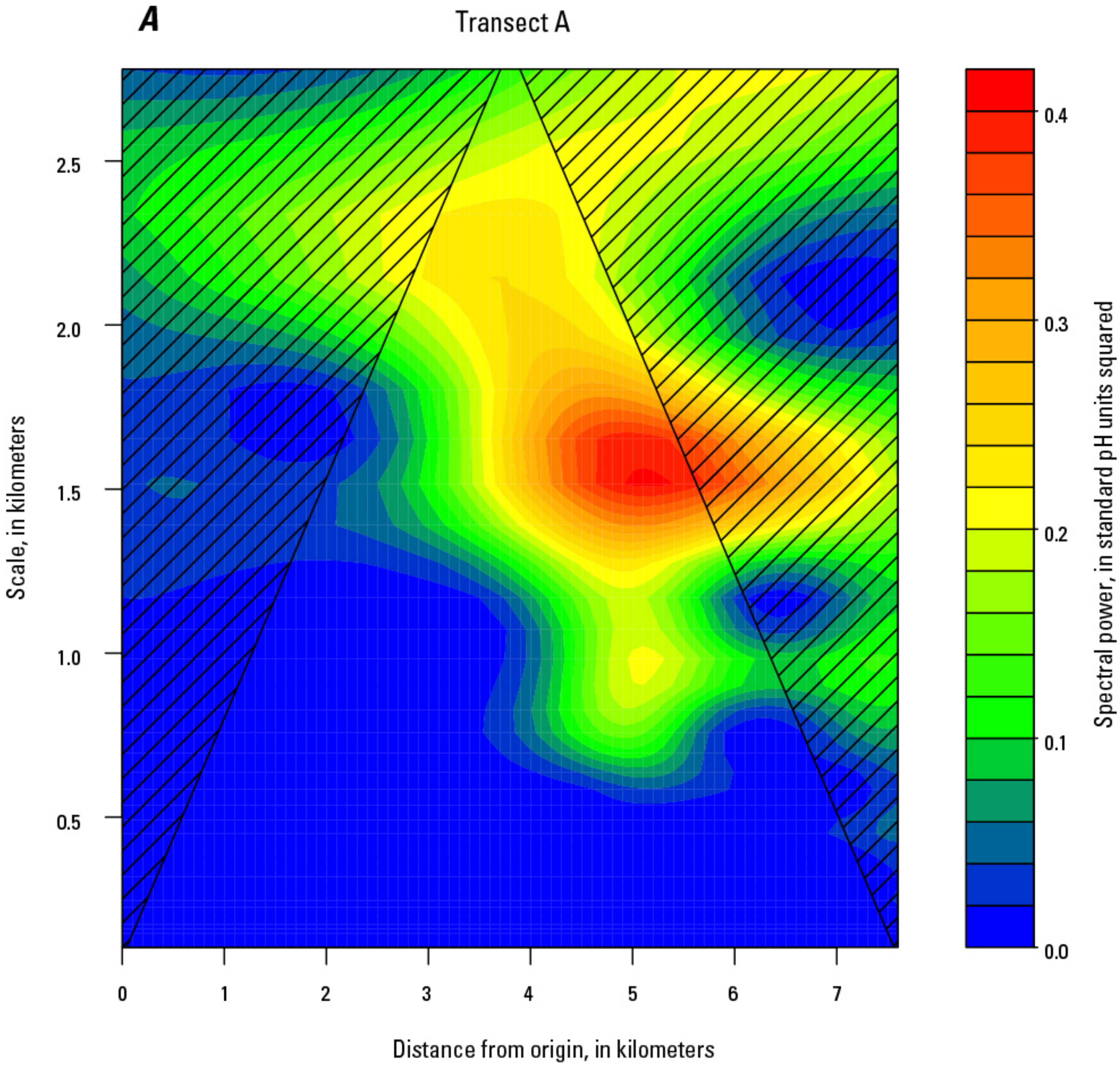

Figure 14*A*. Wavelet spectra for pH measured along transect A on August 3, Upper Klamath Lake, Oregon, 2012.

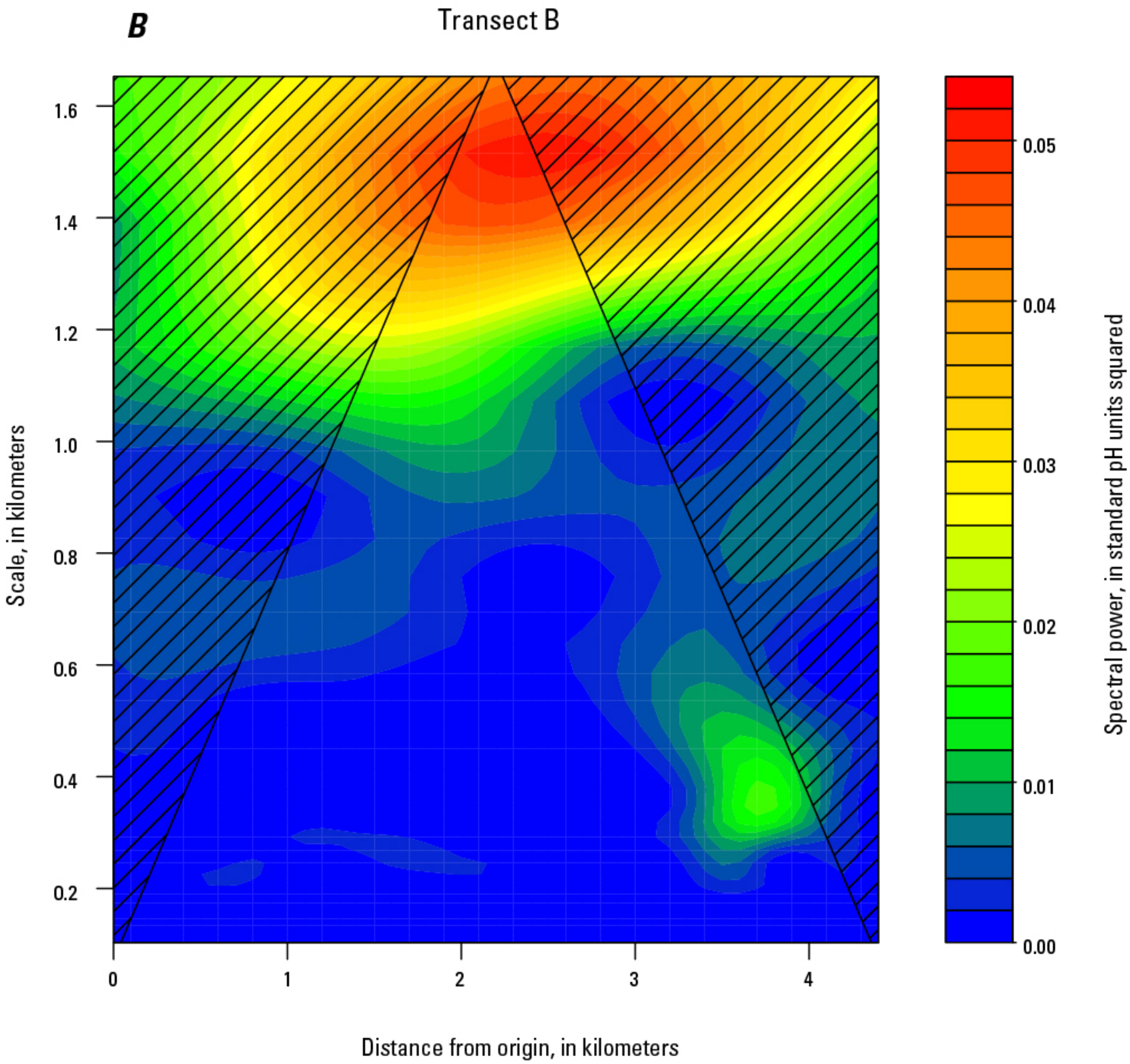

Figure 14*B*. Wavelet spectra for pH measured along transect B on August 6, Upper Klamath Lake, Oregon, 2012.

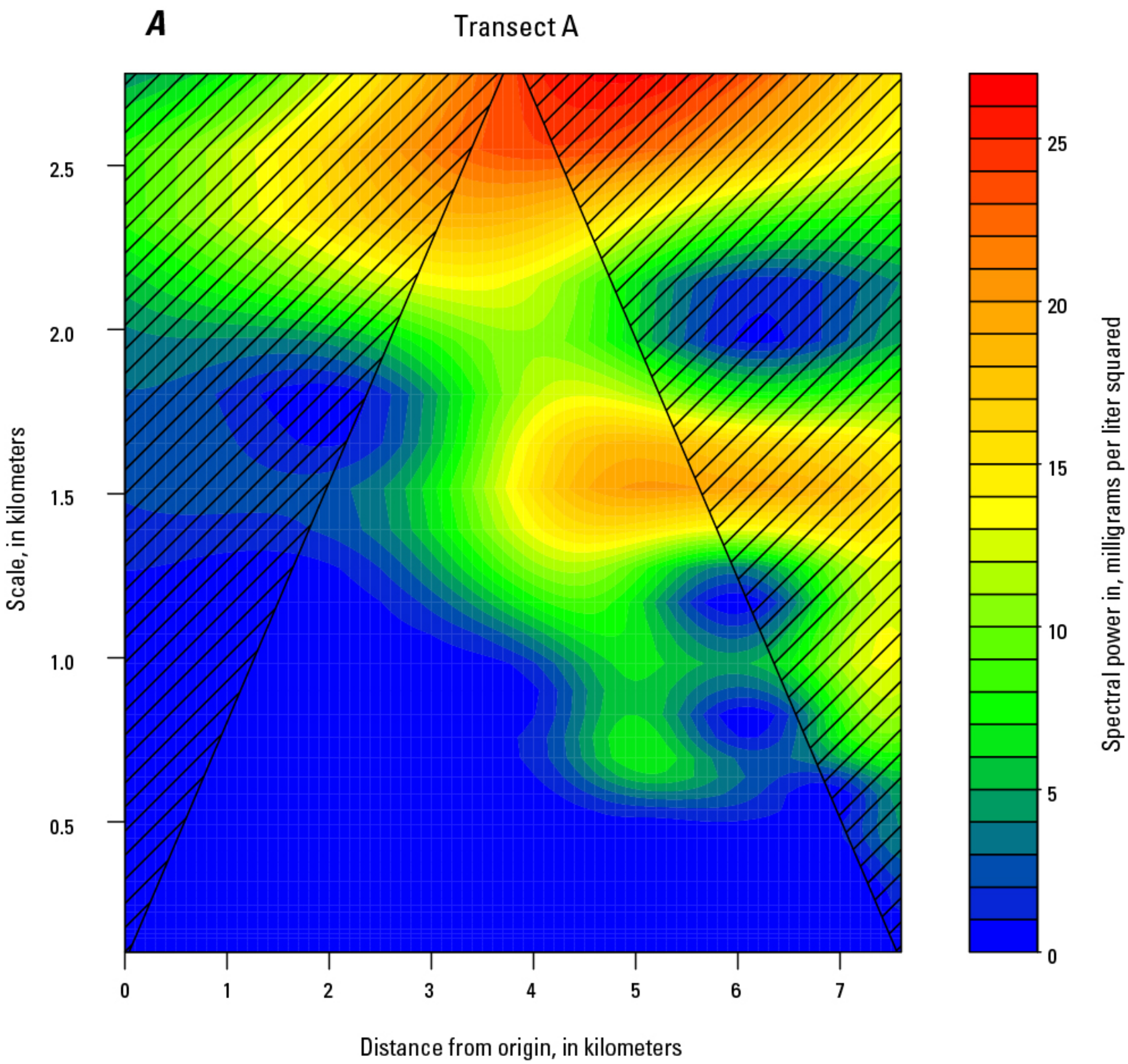

Figure 15*A*. Wavelet spectra for dissolved oxygen concentration measured along transect A on August 3, Upper Klamath Lake, Oregon, 2012.

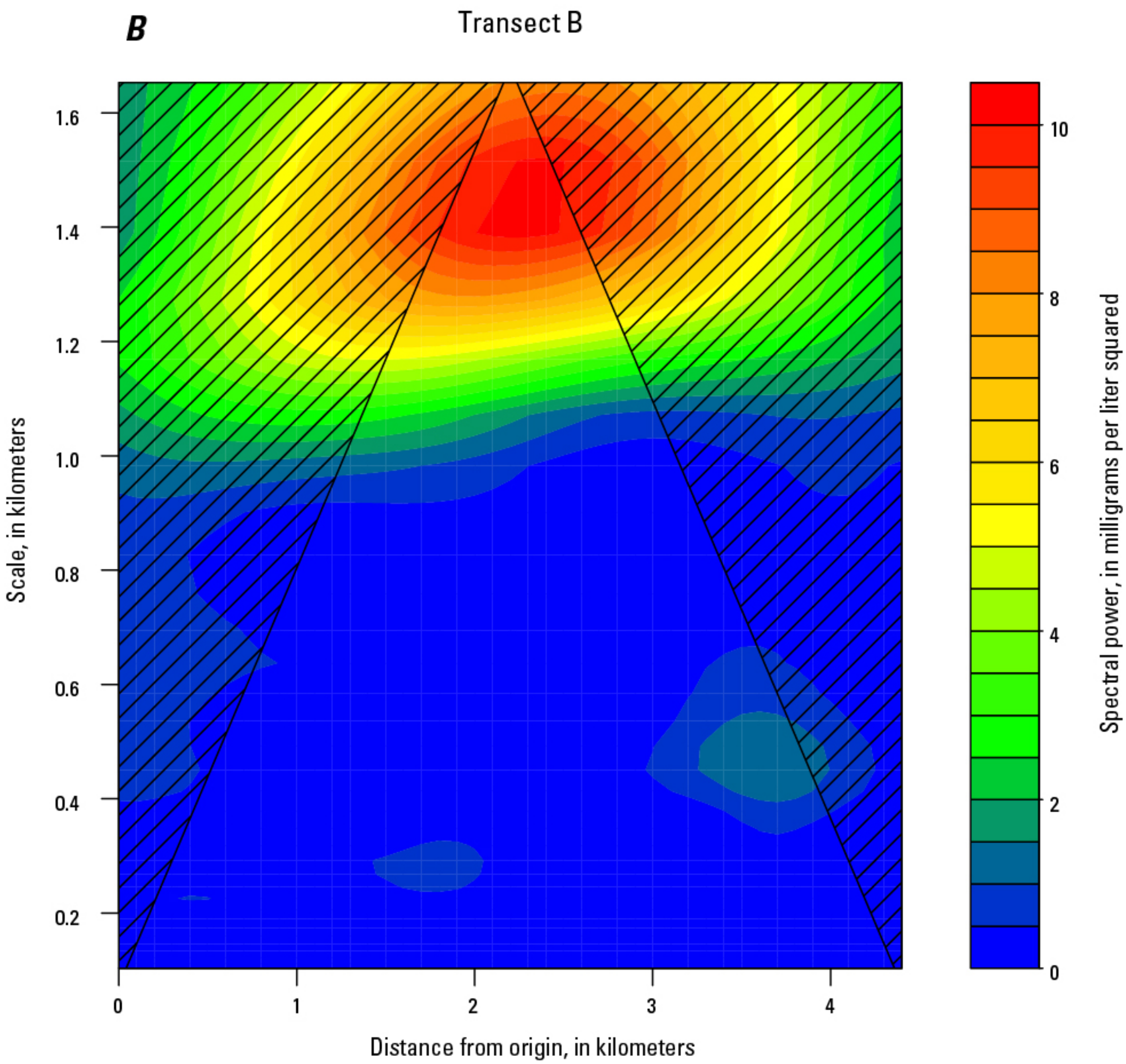

Figure 15*B.* Wavelet spectra for dissolved oxygen concentration measured along transect B on August 6, Upper Klamath Lake, Oregon, 2012.

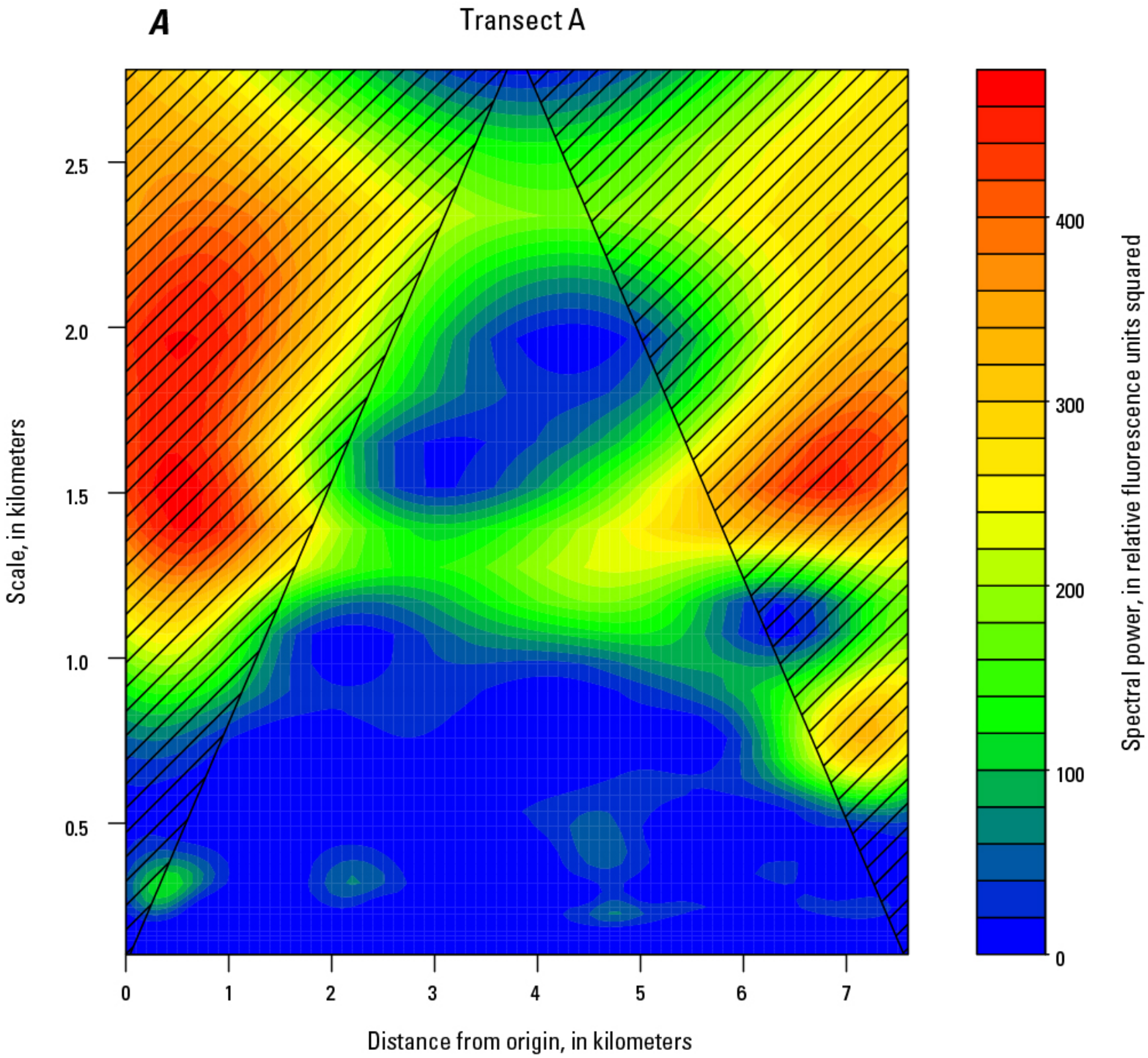

Figure 16*A*. Wavelet spectra for phycocyanin fluorescence measured along transect A on August 3, Upper Klamath Lake, Oregon, 2012.

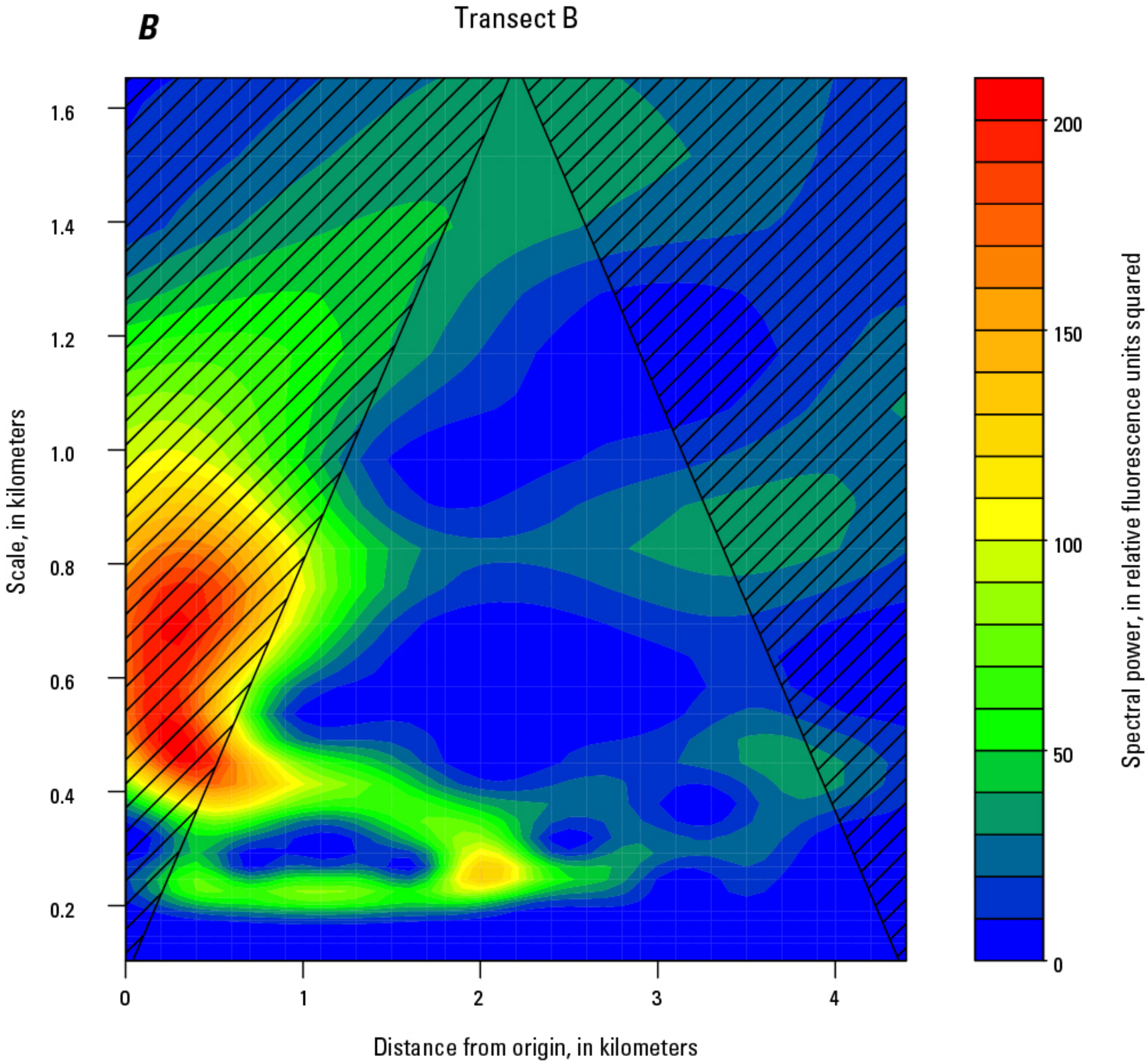

Figure 16*B*. Wavelet spectra for phycocyanin fluorescence measured along transect B on August 6, Upper Klamath Lake, Oregon, 2012.

Creating Synergy by Merging Datasets—Use of Monitoring Data as a Biomass Surrogate

Poor water quality in Upper Klamath Lake is driven largely by cyanobacterial bloom cycles and is often accompanied by the production and release of toxic microcystins associated with these blooms. Therefore, water-quality monitoring in the lake, from the beginning, has included sampling for chlorophyll-*a* concentration as a measure of phytoplankton biomass, and microscopic analysis to determine taxonomic composition of the blooms and cell counts. These methods are routinely used globally and are standardized. However, both methods are time-consuming and logistically do not permit monitoring of cyanobacteria with sufficient spatio-temporal resolution to fully characterize short-term (less than 1 week) bloom dynamics. An objective identified for future water-quality monitoring in the lake by stakeholders was to develop a method for describing water quality as an index that might be used with fish population models. Therefore, an index that discretely characterizes phytoplankton bloom density was developed in this study using continuously monitored pH and DO concentrations, based on the previously described effects of photosynthesis during rapid bloom expansion on water quality (Hoilman and others, 2008; Lindenberg and others, 2009; Eldridge, Eldridge, and others, 2012).

In addition, in vivo phycocyanin (a blue pigment that belongs to a group of light harvesting proteins called phycobiliproteins, specific to cyanobacteria) fluorescence measurements using field probes have been used to monitor blooms dominated by cyanobacteria in natural environments, to selectively detect potentially toxic cells, and to optimize sampling strategies (Gregor and others, 2007; Bastien and others, 2011). The relation observed in these studies between total cyanobacterial biovolume and cell density was significant, and the quantification limits of the fluorescence probes were low enough to permit such monitoring. Empirically derived linear regression models also have recently been used to estimate water-quality parameters based on continuously measured physical and chemical data (Christensen and others, 2000; Ryberg, 2006; Wood and Gartner, 2010). This “surrogate” approach has been used in rivers to estimate the concentration and, with stream gage data, the load (concentration multiplied by discharge) of water-quality constituents that cannot be measured continuously. In lakes or reservoirs, the quantity of interest is often the storage, or whole-lake integrated mass of a constituent, rather than the load. In Upper Klamath Lake, the storage of biomass and nutrients is used for calculating lake mass balances (Kann and Walker, 1999; Walker and others, 2012) and for calibrating and validating models to establish total maximum daily loads (Walker, 2001). In the current study, continuously measured water-quality monitoring data were used to create a daily index of bloom intensity and to estimate daily depth-averaged measures of chlorophyll *a* (as a biomass indicator; measured weekly by sampling) based on results of multiple linear regression analysis.

Daily Bloom Index and Relation to Meteorological Variables

A daily index based on USGS-measured pH and DO concentration was calculated as a surrogate for phytoplankton bloom activity from June 4 to September 27, 2005–2011; chlorophyll-*a* data measured by the USGS in 2007 were of poor quality and, therefore, not reported. An SMK test of monthly median bloom index values from 2005 to 2011 showed a statistically significant decreasing trend over those 7 years (τ=-0.476; p=0.003), which was consistent with results of the SMK test for TP, TN, and chlorophyll-*a* concentrations measured from 2005 to 2010 (table 7). Time series (fig. 17) and results of correlation analysis (table 12) comparing weekly bloom index values with weekly chlorophyll-*a* concentrations validated the index as a suitable biomass surrogate in most years. With the exception of 2008, correlations between bloom index values and chlorophyll-*a* concentrations were at least moderately strong (R ≥ 0.466) and significant ($p < 0.06$). Correlations between daily bloom index values and daily median air temperature or wind speed were not always significant and were not significant during the same years that correlations with chlorophyll-*a* concentration were significant. However, correlations between bloom index values and air temperature were positive in most years, indicating generally higher bloom index values at higher temperatures. In most years on Upper Klamath Lake, air temperatures increase and wind speeds decrease during the spring or early summer to their seasonal limits (maximum air temperature and minimum wind speed) in July or August. Years with more severe mid-season bloom declines (2005, 2006, and 2009; defined, in part, as extended periods of very low chlorophyll-*a* and DO concentrations occurring lakewide; fig. 17) showed particularly low correlations (although not always significant) between bloom index values and meteorological parameters, because bloom decreases tend to coincide with seasonal maximum air temperatures and with minimum wind speeds.

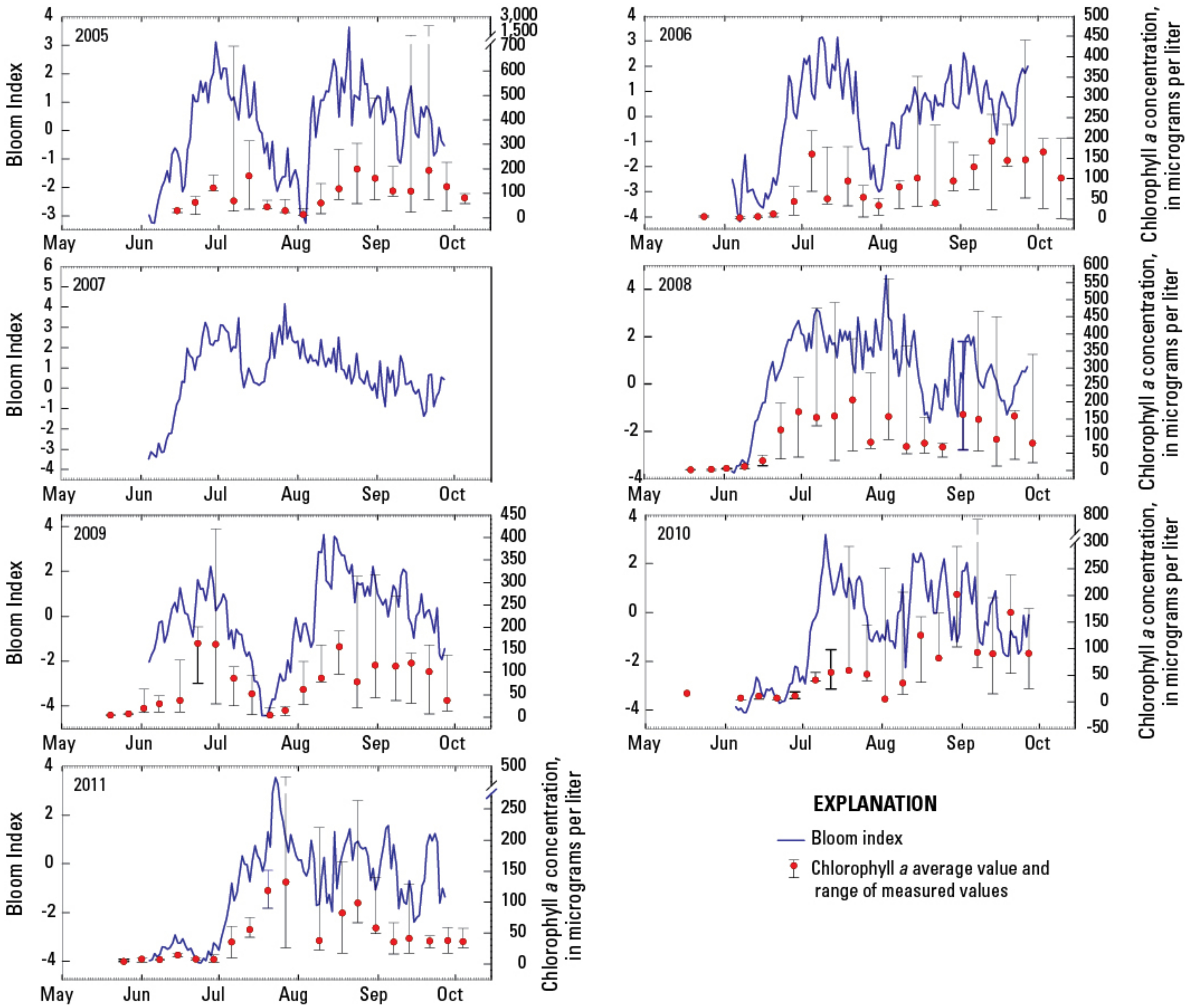

Figure 17. Daily bloom index and weekly chlorophyll-*a* concentration from four core USGS continuous monitoring sites, Upper Klamath Lake, Oregon, 2005–2011. Chlorophyll-*a* concentrations measured in 2007 were of poor quality and not reported.

Table 12. Spearman rank order correlations between bloom index, chlorophyll-*a* concentration, air temperature, and wind speed (median values) at USGS monitoring sites, Upper Klamath Lake, Oregon, from 2005 to 2010 or 2011.

[**Bold** indicates significance at $p < 0.05$. **Symbols:** R, correlation coefficient, n, number of samples, p, probability that the null hypothesis is true, -, data not available, Δ, change in values over a given time interval.]

	2005			2006			2007			2008		
	R	n	p	R	n	p	R	n	p	R	n	p
	Correlation with Daily Bloom Index											
Chlorophyll *a*	0.492	16	0.0531	**0.748**	17	0.0006	-	-	-	0.412	16	0.113
Air temperature	0.0260	36	0.880	**0.366**	38	0.0237	**0.519**	38	0.0008	**0.614**	38	< 0.0001
Wind speed	0.0382	36	0.825	**-0.378**	38	0.0192	0.0923	38	0.582	-0.119	38	0.478
	Correlation of Δ Air Temperature with Δ Daily Bloom Index											
Over 1 day	**0.484**	35	0.0033	0.0987	38	0.556	0.108	38	0.520	0.313	38	0.0555
Over 2 days	**0.483**	35	0.0033	**0.517**	38	0.0009	0.263	38	0.110	0.197	38	0.236
Over 3 days	0.226	35	0.191	**0.718**	38	< 0 .0001	**0.418**	38	0.0091	**0.419**	38	0.0088
Over 4 days	**0.486**	34	0.0036	**0.415**	38	0.0097	**0.464**	38	0.0034	0.194	38	0.243
	Correlation of Δ Wind Speed with Δ Daily Bloom Index											
Over 1 day	-0.159	35	0.363	**-0.326**	38	0.0461	-0.277	38	0.0927	**-0.350**	38	0.0315
Over 2 days	**-0.368**	35	0.0294	**-0.457**	38	0.0039	-0.153	38	0.358	-0.203	38	0.221
Over 3 days	**-0.451**	35	0.0066	**-0.515**	38	0.0009	-0.176	38	0.290	-0.248	38	0.133
Over 4 days	-0.167	34	0.345	**-0.442**	38	0.0054	**-0.502**	38	0.0013	-0.283	38	0.0847

	2009			2010			2011		
	R	n	p	R	n	p	R	n	p
	Correlation with Daily Bloom Index								
Chlorophyll *a*	**0.699**	17	0.0018	0.466	17	0.0596	**0.871**	16	< 0.0001
Air temperature	-0.114	38	0.495	**0.645**	38	< 0.0001	-	-	-
Wind speed	0.0280	38	0.867	-0.302	38	0.0651	-	-	-
	Correlation of Δ Air Temperature with Δ Daily Bloom Index								
Over 1 day	0.0108	37	0.950	**0.546**	38	0.0004	-	-	-
Over 2 days	**0.419**	37	0.0099	**0.422**	38	0.0083	-	-	-
Over 3 days	**0.346**	38	0.0336	**0.607**	38	< 0.0001	-	-	-
Over 4 days	0.286	38	0.0820	**0.639**	38	< 0.0001	-	-	-
	Correlation of Δ Wind Speed with Δ Daily Bloom Index								
Over 1 day	0.0775	37	0.649	-0.230	38	0.166	-	-	-
Over 2 days	-0.199	37	0.239	-0.0466	38	0.781	-	-	-
Over 3 days	-0.0945	38	0.573	-0.186	38	0.263	-	-	-
Over 4 days	-0.293	38	0.0740	-0.0595	38	0.723	-	-	-

Changes in daily bloom index values and air temperature or wind speed were calculated over 1, 2, 3, and 4 days, and compared using correlation analysis to investigate the relation between short-term changes in bloom activity and mesoscale weather on the lake. In 2005, 2006, and 2009, when more severe mid-season bloom declines occurred, correlations were more significant between short-term changes in daily bloom index values and short-term changes in meteorological variables than when daily values were compared (table 12). Furthermore, correlations between the short-term value changes generally were highest and more significant when calculated over 2–4 days. The contingency table comparing positive or negative changes in the bloom index to the sign (positive or negative) of changes in air temperature and wind speed over the same period (data from 2005 to 2010 combined) showed statistically significant ($p < 0.0001$) results when changes were calculated over 1, 2, 3, or 4 days (table 13). Increases in bloom index values were more often associated with increases in air temperature and with decreases in wind speed.

Table 13. Contingency tables showing the frequency of positive and negative changes in bloom index values calculated over 1, 2, 3, or 4 days, and the corresponding change (positive or negative) in air temperature and wind speed calculated over the same time period, Upper Klamath Lake, Oregon, 2005–2010.

[In all cases, the probability that the null hypothesis of no relation between the variables is true is less than 0.0001. **Symbols:** +, increasing, -, decreasing.]

		Change in air temperature over 1 day				Change in wind speed over 1 day	
		+	-			+	-
Change in bloom index over 1 day	+	174	98	Change in bloom index over 1 day	+	143	197
	-	107	164		-	202	135
		Change in air temperature over 2 days				Change in wind speed over 2 days	
		+	-			+	-
Change in bloom index over 2 days	+	196	94	Change in bloom index over 2 days	+	144	211
	-	99	154		-	190	128

Previous studies highlighted the importance of water column thermal stratification in the shallow Upper Klamath Lake system (for example, Kann and Welch, 2005; Wood and others, 2006). As an extension of this work, the influence of weather on water quality in the lake, particularly the bloom cycle, was characterized here by determining daily mixing intervals at USGS site MDT based on water temperatures measured at the upper (1 m from the lake surface) and lower (1 m from the sediment surface) monitors. On days with minimum differences in water temperature between the upper and lower monitors less than 0.3°C (twice the manufacturer's estimate of the sensor's accuracy), the water column was assumed to be fully mixed. Using this criterion, the number of prior consecutive days without full mixing (0, 1, 2, or more) was determined for each day and compared to the change in the bloom index. On days with 0 prior consecutive days without mixing, the water column mixed within the previous 24 hours. Days with 1 prior consecutive day experienced no mixing within the previous 24 hours, but the water column did mix within the previous 24–48 hours. When the number of consecutive days was 2, the water column did not mix within the past 48 hours, but it did mix between the previous 48–72 hours. Bloom index values increased more often than they decreased when the water column mixed within the previous 1 or 2 days. However, on days when no full mixing occurred within the previous 2 or more consecutive days, bloom index values more often decreased than increased (table 14). This association between daily or alternate-day mixing of the water column at site MDT with increases in bloom index values indicated that routine water column stability, in which the water column mixed once per day or once per 2 days, facilitated the accumulation of bloom-forming cells near the lake surface and provided favorable conditions for bloom expansion. Persistent stratification over more than 2 days, however, was shown to be more often associated with reduced photosynthetic activity, in that those days mostly coincided with decreases in bloom index values. This suggested that extended periods of increasing air temperature and low winds contributed to the decline of blooms in the lake, consistent with findings reported by Wood and Gartner (2010).

Table 14. Contingency table showing frequency distribution of changes in bloom index values from the previous day to the number of consecutive days since the water column was fully mixed at site MDT, Upper Klamath Lake, Oregon.

[The probability that the null hypothesis of no relation between the variables is true is less than 0.018167. **Symbols:** +, increasing, -, decreasing.]

Change in bloom index over 1 day		Prior consecutive days without mixing the water column: 0 or 1	Prior consecutive days without mixing the water column: 2 or more
	+	346	61
	-	308	84

In this study, periods of stratification at a single site, MDT, the deepest site monitored in Upper Klamath Lake, were compared to bloom index values that generally represent lakewide conditions, although stratification (or mixing) may not occur at all sites at the same time. Mixing frequencies do vary between shallow (< 10 m) sites and the deepest part of the lake (the trench along the western shoreline; fig. 1). At site MDN, for example, mixing is so frequent that stratification rarely persists for more than 2 days, so the relation between mixing frequency and bloom index values at that site may not be the same as at site MDT. However, as we have demonstrated here, mixing frequency at site MDT can be related to trends in the bloom on a lakewide basis as represented by the bloom index. Two possibilities for the observed relation between lakewide bloom index values and mixing frequency at site MDT are that (1) temperature and/or wind speed, which directly influence mixing frequency at site MDT, also directly influence bloom development and, by extension, bloom index values, or (2) mixing frequency in the trench, where site MDT is located, reflects local processes that produce local changes in phytoplankton biomass that quickly become widespread as a result of wind-driven circulation patterns in the lake. This circulation ensures that much of the lake water passes (northward) through the trench every few days before spreading out again over the rest of the lake (Wood and others, 2008). It is unlikely that the relation between bloom index values and mixing frequency at site MDT is simply an extension of the relation between bloom index values and air temperature or wind, because direct comparisons between bloom index and air temperature or wind speed show that the bloom index is more likely to increase when air temperature increases or wind speed decreases (table 13). Further exploration of these possibilities is beyond the scope of this report, but it is important to note that clues to the relation between bloom conditions, meteorological variables, and water column stability may be revealed with continuous monitoring data.

Estimating Biomass from Continuous Phycocyanin Fluorescence Using Multiple Linear Regression

Instantaneous values of phycocyanin fluorescence (converted to cells/mL) at 1 m from the lake surface, pH measured at 1 m from the lake bottom, and the cosine of the Julian day were selected as the best model by evaluation of residual plots, the model standard percentage error (MSPE), the prediction error sum of squares (PRESS) statistic, and the p-values of the independent variables. Measurements were recorded from May 25 to October 4, 2011, at site MDN. All data in the model were untransformed. The final regression analysis for chlorophyll *a* is summarized in eq. 2 and in table 15:

(Chl *a*) = 27.2378(COSJD)+0.0003(UPCInst)+ 14.2759(LpHInst)-88.57 (2)

where:

Chl *a* is depth-averaged chlorophyll-*a* concentration, in µg/L;

COSJD is cosine of the Julian day;

UPCInst is instantaneous phycocyanin fluorescence measured at 1 m from the lake surface in cells/mL; and

LpHInst is instantaneous pH measured at 1 m from the lake bottom in standard units.

Additional model information is presented below:

Number of measurements = **19**

Root-mean-squared error (RMSE) = **13.8 µg/L**

Model standard percentage error (MSPE) = **± 34 percent**

Adjusted coefficient of determination (R^2_a) = **0.87**

Table 15. Summary of final regression analysis for chlorophyll-*a* concentration at site MDN in Upper Klamath Lake, Oregon, 2011.

[**Abbreviations:** COSJD, cosine of the Julian day, UPCInst, instantaneous phycocyanin fluorescence in cells per milliliter measured at 1 meter from the lake surface, LpHInst, instantaneous pH in standard units measured at 1 m from the lake bottom. **Symbol:** p, probability that the null hypothesis is true.]

	Coefficient	Standard error	t-statistic	p
Intercept	-88.6	66.2	-1.34	0.201
COSJD	27.2	10.6	2.58	0.021
UPCInst	0.0003	0	7.01	< 0.0001
LpHInst	14.3	7.69	1.86	0.083

The regression model explained the variability in depth-averaged chlorophyll-*a* concentrations relatively well, in that the adjusted R^2_a for the model was 0.87. Comparison of measured and model-estimated chlorophyll-*a* concentration indicated that the regression model developed in the current study predicted chlorophyll-*a* concentrations more accurately when concentrations were lower, because these points fell closer to the 1:1 line in figure 18. Time series created from the same set of measured and model-estimated chlorophyll-*a* concentrations (fig. 19) showed that most sample concentrations were similar to predicted values earlier and later in the sample season and that, during periods of high bloom density, sample concentrations were within the 90-percent prediction interval for the estimated values, with the exception of July 20, when the measured chlorophyll-*a* concentration was below the lower prediction interval.

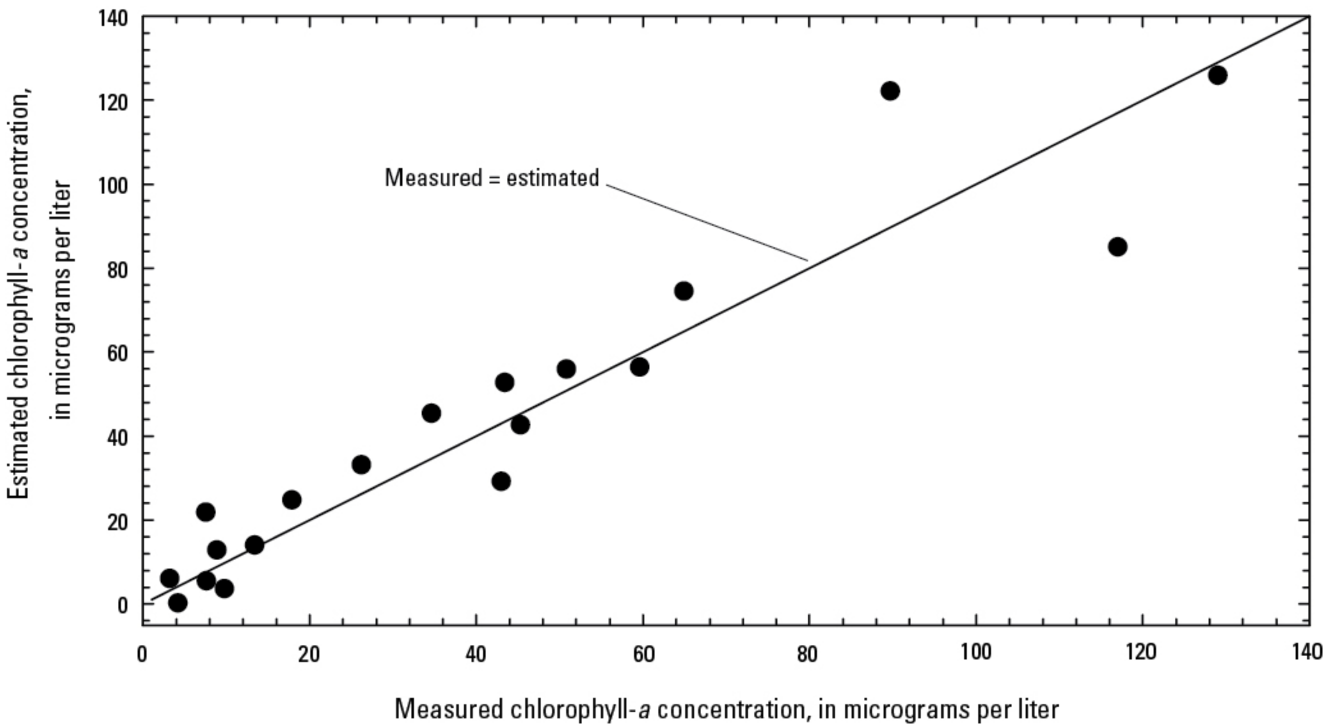

Figure 18. Regression estimated versus measured values of depth-averaged chlorophyll-*a* concentration at site MDN, Upper Klamath Lake, Oregon, 2011.

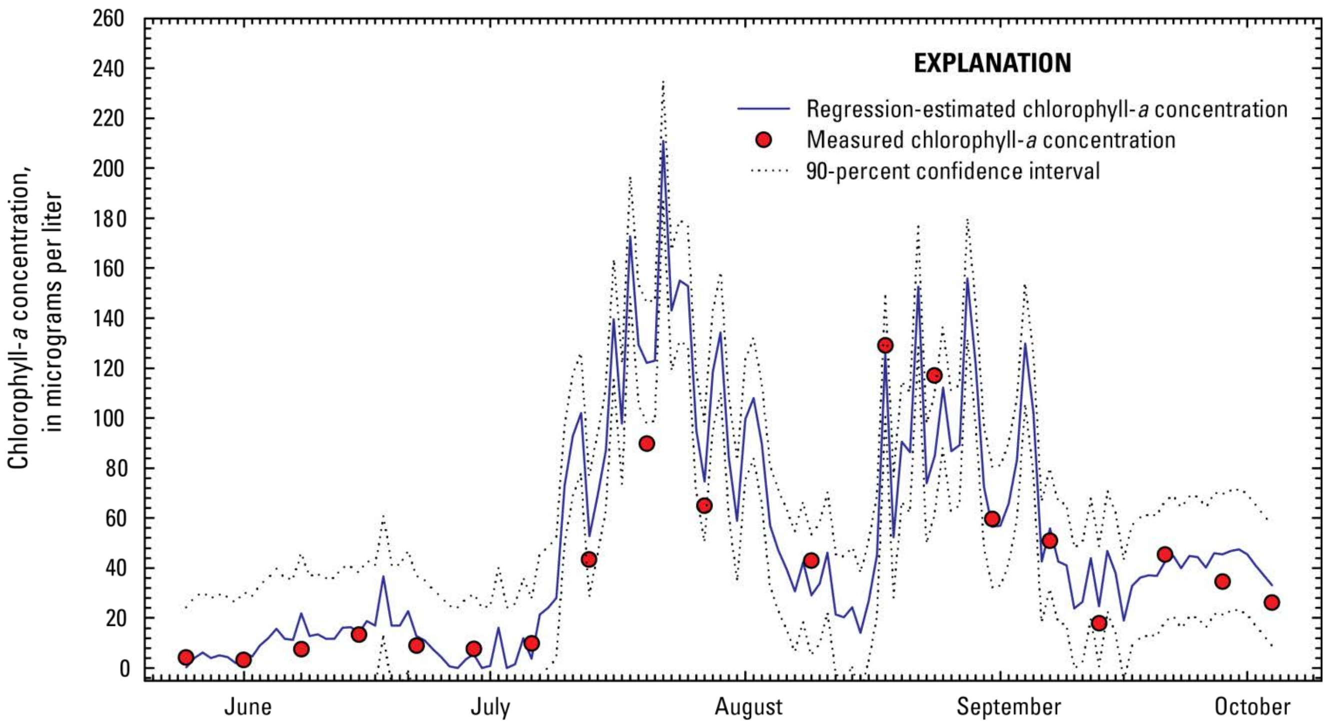

Figure 19. Time series of regression-estimated versus measured values of chlorophyll-*a* concentration and the 90-percent prediction interval for regression-estimated values at site MDN, Upper Klamath Lake, Oregon, 2011.

Changes in chlorophyll-*a* concentrations estimated at a daily time step (fig. 19) showed the same two bloom periods in 2011 as measured in water samples collected weekly, but also revealed variability between sample dates not measured in the water samples. Although model-estimated values deviated somewhat from measured chlorophyll-*a* concentrations during bloom episodes (early July to early August and mid-August to early September), estimates showed fluctuations in chlorophyll-*a* concentration between samplings that were not otherwise detected. For example, chlorophyll-*a* concentrations measured in samples collected from July 6 to July 20 appeared to steadily increase, but the model-estimated values reached a higher peak and decreased before the July 13 sample. In addition, two peaks were estimated to occur before the July 20 sample. Further work is needed to optimize and standardize the use of phycocyanin fluorescence data as a cyanobacteria surrogate in Upper Klamath Lake, but use of these sensors may be the first step toward developing a surrogate as a cost-effective alternative for obtaining more short-term (daily or hourly) estimates of water-column biomass.

Discussion and Synthesis with Implications for Future Monitoring Design

Analysis of the Existing USGS and Klamath Tribes Monitoring Programs

Statistical analyses of the Klamath Tribes' discrete sample water-quality dataset (collected bimonthly from 1990 to 2010) and the USGS discrete (collected weekly) and continuous water-quality datasets (2005–2011) were performed to address the following questions concerning the use and efficiency of data collection from Upper Klamath Lake (Upper Klamath Lake) in these programs:

1. Are any current monitoring sites redundant within or between the Klamath Tribes and the USGS programs?

2. Is the spatial distribution of currently monitored sites adequate to measure the range in environmental conditions in Upper Klamath Lake necessary to support the objectives of process-based studies using the data?
3. Are the monitoring programs able to capture important short-term variability in water-quality parameters? and
4. Can consistent long-term trends in water-quality variables be identified in the existing datasets?

Results of this study offered the following answers to these questions.

None of the nine core Klamath Tribes sites appeared to be redundant based on analyses of the long-term discrete sample dataset. In a PCA using both the Klamath Tribes and USGS datasets, Agency Lake sites grouped together, open-water sites within Upper Klamath Lake grouped together, and Upper Klamath Lake bay sites, particularly those in Wocus (Howard) Bay, were distinct. As shown in previous studies of Upper Klamath Lake (most recently, Jassby and Kann [2010]), results of seasonal SMK and other trend tests applied to individual sites were inconsistent across sites that grouped together with PCA and demonstrated few significant trends. When these sites were combined and the regional Kendall test was used, however, more significant trends emerged. This was true for both the 21-year dataset and a 6-year subset of the data. These results indicate that the Tribes' sites generally were not redundant because the power to detect trends increased when data from the individual sites were combined.

Neither the Klamath Tribes nor USGS datasets alone captured the full range of conditions within the open waters of Upper Klamath Lake. A PCA that combined the discrete sample data from four Klamath Tribes open-water sites with four USGS core sites (all in open water) indicated that, although some Klamath Tribes sites that were geographically close and/or of similar depth to some USGS sites overlapped, both monitoring programs included sites that contributed unique information to the overall datasets, indicating that Klamath Tribes and USGS sites were not interchangeable. Results of a comparison of the overall variance in time series constructed from the USGS expanded array in 2006 and an assessment of the distance between all USGS sites in the coordinate space defined by PCA indicated that the distribution of four current USGS continuous monitor core sites may not capture data that represents the full range in expected lake conditions. Particularly, conditions measured by the expanded array in Agency Lake, in the bays of Upper Klamath Lake, at the northern end of the trench along the western shoreline, and along the western shoreline in the northern part of the lake were shown to be substantially different that year from the conditions measured at any of the core sites. Together, these results suggested that, to capture the full range of conditions in the lake, the current network of continuous monitoring and/or discrete data-collection sites would include Agency Lake, the Upper Klamath Lake bays, the southern end of Upper Klamath Lake, the eastern shoreline offshore from the mouth of the Williamson River, the trench along the western shoreline (the deepest part of the lake), including the southern part of the trench, and the western shoreline along the northern part of Upper Klamath Lake. The southern trench and northwestern shoreline of Upper Klamath Lake were previously monitored by the USGS, but are not currently included in either the Klamath Tribes or USGS core networks.

Over the longest period of record available for this study, 1990–2010, few significant long-term trends in Upper Klamath Lake water-quality variables were found in the Klamath Tribes discrete sample dataset on either a site-specific or regional basis, so it was difficult to determine whether nutrient concentrations have decreased and blooms have become less extreme or nutrient concentrations have increased and blooms have become more extreme over those 21 years. From

2005 to 2010, when Klamath Tribes and USGS monitoring overlapped, the Klamath Tribes and USGS datasets consistently showed decreasing trends of similar magnitude in nutrient (particularly TN and TP) concentrations. However, trends in Klamath Tribes-measured chlorophyll-*a* concentrations generally indicated an increase in the intensity of phytoplankton blooms from 2005 to 2010, while trends in USGS data collected during the same 6 years generally indicated an overall decrease in phytoplankton blooms as characterized by chlorophyll-*a* concentration. Given the consistency in nutrient concentration trends between the datasets, the Klamath Tribes' change to a more sensitive analytical method for analyzing chlorophyll-*a* concentrations in 2009 probably contributed to this difference. Trends in pH and DO concentrations were generally increasing in the Klamath Tribes dataset and generally decreasing in the USGS dataset, but these parameters were more heavily weighted toward the photic zone in the Klamath Tribes dataset than in the USGS dataset. Therefore, a comparison of these trends does not resolve the contradiction in chlorophyll *a*. Secchi depth also generally decreased in the Klamath Tribes dataset, which was difficult to reconcile with overall decreasing bloom intensity. Total nutrient and chlorophyll-*a* concentrations were measured as depth-integrated quantities, whereas Secchi depth indicated surface intensification of buoyant plankton. Therefore, the discrepancy in Klamath Tribes and USGS data may be interpreted as an overall decrease in bloom intensity throughout the water column, with a concurrent increase in surface accumulation from 2005 to 2010. Consistent patterns will likely emerge only from larger, multi-decadal datasets.

Differences in data collection frequency contributed to the differences in trends between the 2005 to 2010 Klamath Tribes and USGS datasets. USGS samples were collected weekly, whereas Klamath Tribes samples were collected bimonthly. The trend analyses used here included monthly mean values, but the amount of information used to calculate the monthly means differed between the Klamath Tribes and USGS datasets. Trends resulting from an analysis of USGS data subsampled to duplicate the frequency of Klamath Tribes data collection were usually, but not always, of the same sign and in the same order of magnitude as the full, weekly dataset, but the significance level of the trend test varied greatly depending on which dataset was used. Therefore, it was not demonstrated conclusively that weekly sampling created a dataset with more power to determine multi-year trends than bimonthly sampling; many of the same trends in biomass and nutrient concentrations were observed in both the Klamath Tribes and USGS datasets. A more in-depth investigation of sample collection frequency is beyond the scope of this work, but such a study may explain some of the differences between the Klamath Tribes and USGS datasets.

Weekly or biweekly sampling may provide data to determine long-term trends in annual or monthly means, but other research objectives require data with enough resolution to investigate cause and effect relations and to test ecological function hypotheses. Continuous monitoring is essential to measuring this important short-term variability. Results of wavelet analysis of USGS continuous monitoring data showed substantial variance in time series at periods shorter than 28 days (roughly, the shortest period that can be resolved with bimonthly sampling; 14 days is, roughly, the shortest period that can be resolved with weekly sampling). A peak in power between 5.8 and 7.6 days was identified in all water-quality time series, which roughly corresponded to a peak in power at 6–7 days in air temperature and wind speed measured near the lake, indicating that meteorological forcing contributed to the water-quality variability. Furthermore, contingency table analysis demonstrated that the correlation between changes in bloom activity and changes in weather-related variables was maximized at 2–3-day lag times. Given the strong relation between weather and water quality in Upper Klamath Lake, investigations of what causes water-quality parameters to change would benefit from the collection of continuous meteorological data, including wind speed and direction, air temperature, relative humidity, and solar insolation, on or near the lake.

Results of this study also showed that substantial variability in parameters continuously monitored by the USGS, including temperature, pH, DO concentrations, and phycocyanin fluorescence, may occur at spatial scales too small to be resolved by current monitoring. In synoptic surveys performed across two transects near USGS sites MDT and MDN in 2012, DO concentrations and pH varied substantially at scales as small as about 1.5 km, and phycocyanin fluorescence varied at scales as small as about 0.25 km. Over short periods of time, however, water-quality constituents are transported conservatively, so spatial variability may be manifested as temporal variability at a single location. Current velocities in Upper Klamath Lake have been shown to vary between an order of 11 cm/s in the trench (near USGS site MDT) and an order of 4 cm/s in the shallower, central part of the lake (near Klamath Tribes site ML; Wood and others, 2008). At these speeds, water-quality conditions that vary along a 1.5-km scale pass through USGS site MDT in 3.7 hours and through Klamath Tribes site ML in 10.2 hours; conditions that vary along a 0.25-km scale pass through site MDT in 0.6 hours and through site ML in 1.7 hours. This further underscores the usefulness of continuous monitoring along with discrete sample collection, and indicates that hourly measurements of water-quality data adequately capture the variability expected from advection past a given site.

To bridge the gap in data collection frequency between constituents that are not measured continuously (they require collection and analysis of discrete water samples and include chlorophyll *a*, nutrients, and microcystins) and those that are measured continuously (DO concentration, water temperature, pH, and phycocyanin fluorescence), preliminary methods for creating biomass "surrogates" were proposed in this study and will be further developed. First, a lakewide daily index of bloom activity determined from hourly DO concentration and pH data; and second, a site-specific regression equation to calculate daily depth-averaged chlorophyll-*a* concentrations from hourly phycocyanin fluorescence and pH demonstrated that continuous monitor data may be used to estimate the quantities needed to create daily mass balances, to investigate short-term correspondence between bloom activity and weather variables, or to test hypotheses regarding ecological functioning on short time scales. Given the demonstrated value of these measurements when used in conjunction with supporting data from discrete samples, future water- quality monitoring in Upper Klamath Lake may be improved by establishing more continuous monitoring sites where discrete samples or data also are collected, particularly in areas not currently included in the network, such as Agency Lake, the Upper Klamath Lake bays, and along the western shoreline in the northern part of the lake.

Goals for Optimization of Future Water-Quality Monitoring and Suggestions for Achieving Them

The results of this study indicate that future water-quality monitoring in Upper Klamath Lake can be optimized. A meeting of Upper Klamath basin stakeholders produced a draft of five goals with specific objectives for water- quality monitoring. Together, the analyses of existing water-quality data and the list of goals and objectives discussed in this report point to improvements in the monitoring programs that would help attain the specified goals and promote cooperation, efficiency, and the ability to meet the needs of resource managers and interpretive research projects related to Upper Klamath Lake water quality.

Goal 1

The first goal was to measure and record the physical, chemical, and biological parameters in Upper Klamath Lake related to (or potentially related to) the success of native fish populations. Since monitoring began in the early 1990s, a primary goal of water-quality monitoring in Upper

Klamath Lake has been to measure and record the physical, chemical, and biological parameters in the lake related to (or potentially related to) the success of native fish populations. This continues to be a goal for future monitoring, so the parameters that affect fish health, including water temperature, pH, DO concentrations, phycocyanin fluorescence, specific conductance, chlorophyll-*a* concentrations, total nutrient concentrations (TP and TN), dissolved nutrient concentrations (SRP or orthophosphate, ammonia, and nitrite-plus-nitrate), and total microcystin concentration, which were explicitly identified in the first objective, also will be important targets for further monitoring. This objective also required these variables to be measured in "real-time" and as frequently as necessary to permit the study of fish mortality at all life stages. To satisfy the need for high-frequency data collection with "real-time" availability, the USGS monitoring network in Upper Klamath Lake currently (2013) records hourly water temperature, DO concentrations, pH, specific conductance, and phycocyanin fluorescence. At least one site, MDN, also is equipped to telemeter data remotely the instant these parameters are measured, and there are plans to increase the number of telemetered sites.

All parameters specified in the first objective of the first goal are currently being monitored by the USGS, the Klamath Tribes, or both. However, some variables, such as total microcystins concentration, are highly variable within a short time period and across short distances (Eldridge, Wood, and others, 2012). Microcystin concentrations are currently measured weekly and at only four core sites. This may limit the ability to relate these factors to episodes of high fish mortality or to the underlying causes of poor juvenile recruitment. Therefore, an optimized monitoring plan would include an expanded network of sites to measure total microcystin concentrations in more areas of the lake, including nearshore and wetland areas, which overlap with known fish habitats. During episodes of poor water quality associated with intense bloom growth or decline, and the production of toxic microcystins, sampling for total microcystin concentrations and collection of associated data would, ideally, become more frequent than once per week. In addition, optimum water- quality monitoring in Upper Klamath Lake would consist of more continuous measures of biomass than the weekly or bimonthly sample collection for chlorophyll *a* that currently exists. Results of this study identified two potential means for obtaining more continuous measures of biomass, a daily bloom index and a model developed from continuous water-quality parameters to estimate changes in chlorophyll-*a* concentration between sample collections. Either or both of these methods would be further developed and implemented in an optimized monitoring program.

Goal 2

The second goal written by Upper Klamath basin stakeholders was to assess the effects of lake and watershed management. The ability to detect long-term trends is critical to achieving this goal. The results of this study have demonstrated that accurately detecting long-term trends in lake water quality over the past 21 years was influenced by substantial variability over time scales of 10 years and less that was superimposed onto longer trends. This illustrates the importance of collecting data for multiple decades and from a network of monitoring sites that captures regional as well as local variations in water-quality data. Broad, regional trends in water quality are likely being captured by current monitoring, but inconsistencies between the Klamath Tribes and USGS datasets from 2005 to 2010 revealed the need for more comprehensive coverage of the lake, which includes areas uniquely monitored by both programs. For example, the Klamath Tribes program does not monitor water quality on the eastern side of the lake, and the USGS program does not monitor water quality in Agency Lake. Further exploration of whether weekly sampling provides a more powerful dataset for the detection of long-term trends also is needed.

Accurately determining long-term, lakewide trends may be inhibited by a lack of data from areas of the lake system that have never been monitored, or have not been monitored recently, to compare with data from core sites. A long-term plan to remedy this lack of data could be implemented at an incremental cost each year. A grid of evenly spaced loci, approximately 2 km apart and representing potential sites for continuous monitoring, could be placed over the lake to identify sites in addition to the core network that could be monitored during a given season. Site(s) within the grid could be selected randomly or systematically and added to the program each year. This "supplemental" site could be removed from the network the following year, and a new "supplemental" site could be added. PCA or another appropriate statistical analysis could then be used to compare data collected from the "supplemental" and core sites each year. This program would work best with continuous monitoring data, as these datasets are larger. After monitoring at all possible "supplemental" sites over many years, a more complete understanding of how individual core sites represent conditions in the lake would emerge so that the locations of these sites could be optimized to capture the full range in environmental conditions.

Goal 3

The third goal, specified by basin stakeholders, was to provide water-quality data that support long- and short-term studies of the physiochemical and biological processes in Upper Klamath Lake, statistical or other analytical techniques that create synergies among the datasets and enhance the information content, and technologies that may improve data collection efficiency. To fully achieve this goal, short-term or small-scale changes in water-quality parameters and the full range of conditions across all temporal and spatial scales also must be measured. Results of synoptic surveys, wavelet analysis, and biomass estimations based on a multiple linear regression model indicated high variation in water-quality parameters related to the dominant phytoplankton bloom across distances less than approximately 2 km and in a subweekly time frame. The only feasible way to capture variability on this scale is with an Eulerian approach, using fixed-site continuous monitors recording data at subdaily intervals. However, the data needs of future projects and new technologies or analytical techniques that might be brought to bear on the Klamath Tribes and USGS datasets cannot be predicted with certainty.

The stakeholders identified currently conceivable and attainable objectives for accomplishing the third goal, including the collection of data for understanding phytoplankton and zooplankton dynamics, nutrient mass balance determinations, developing surrogate relationships, calibrating and validating water-quality models, and calculating lakewide averaged values for water-quality variables. The collection of meteorological data also was specified as necessary for understanding how seasonal and climatic atmospheric conditions influence changes in the phytoplankton blooms. Monitoring the water-quality parameters listed under the first goal, and at multiple temporal and spatial scales as discussed above, serves these objectives. In addition, the Klamath Tribes currently collects bimonthly samples to monitor changes in the zooplankton and phytoplankton communities, and the USGS currently collects meteorological data continuously from two sites on Upper Klamath Lake from May to October. Results of this study demonstrated that nutrient data from discrete samples can be combined with continuously monitored variables that enable daily changes in biomass to be estimated. These surrogate-based techniques could be applied to create daily estimates of nutrient concentration, as well; daily mass balance estimates can provide greater understanding of the processes of nutrient recycling, particularly phosphorus, from the sediments.

To further support the third goal, investigators who implement the monitoring programs could stay informed of emerging monitoring technologies and test or implement technologies that may enhance their programs. For example, sensors are currently available to measure fluorescence from dissolved organic matter (useful for understanding the fate of cyanobacteria colonies), orthophosphate, and ammonia. These have detection limits that could make them useful for monitoring in Upper Klamath Lake. In addition, DNA-based detection of cyanobacteria at various levels of specificity would circumvent the dependence on time-consuming, more error-prone, and less informative microscopic identification and cell counts of phytoplankton in water samples. Such molecular techniques allow large numbers of samples to be analyzed rapidly and can reveal the proportion of cells in each sample that are potentially toxigenic. Implementation of a molecular approach to describing the cyanobacterial community can be designed to address essentially any question related to community or population structure and/or function. For example, quantitative analysis of the cyanobacterial community structure can be done using clone library analysis and DNA sequencing, and polymerase chain reaction (PCR) or quantitative PCR can be used to rapidly detect and/or quantify toxic and nontoxic strains of *Microcystis aeruginosa* and other groups of interest, such as *Aphanizomenon flos-aquae*, or cyanobacteria as a whole (see, for example, Ouellette and others, 2003; Rinta-Kanto and others, 2005; Saker and others, 2007; Bozarth and others, 2010). With some modifications, the same techniques can be applied to different sample types, including water, sediment, and tissue.

Goal 4

The fourth goal identified by stakeholders was to advance understanding of water quality in Upper Klamath Lake as it relates to downstream conditions. Water quality downstream of Upper Klamath Lake in the Klamath River (from the Link River to Keno Dam) is poor during the summer, due primarily to high loads of organic matter coming out of Upper Klamath Lake and the resulting high oxygen demand (Sullivan and others, 2013). During the winter, high concentrations of ammonia enter the Klamath River from Upper Klamath Lake, causing this reach to be included on Oregon's 303d list for ammonia toxicity (Oregon Department of Environmental Quality, 2007) in winter as well as summer, when the source of ammonia to the reach is largely autochthonous. Therefore, to accurately describe and model conditions downstream of Upper Klamath Lake, accurate year-round load measurements near the lake outlet, moving from Upper Klamath Lake to the Klamath River, are required. As of this writing, a suite of constituents, including chlorophyll-*a* concentrations, nutrient concentrations, suspended solids concentrations, carbonaceous biological oxygen demand (CBOD) and the source material (dissolved organic carbon [DOC] and particulate organic carbon [POC]), and total microcystin concentrations are measured year-round just upstream of the Link River Dam to comply with the Klamath Hydrologic Settlement Agreement. These measurements will help to achieve the goal of understanding how conditions in Upper Klamath Lake affect downstream water quality, but monitoring additional analytes also may be necessary. Arsenic in particular is known to occur in the Klamath River at concentrations of concern and was identified during the meeting of Upper Klamath basin stakeholders as a potential target for continued monitoring.

A process-based understanding of how conditions in Upper Klamath Lake, particularly changes in summer CBOD and winter ammonia concentrations, affect downstream conditions would require year-round data collection in the lake and that CBOD, DOC, and POC be added to the suite of analytes measured. Both monitoring programs in Upper Klamath Lake currently collect data from May to October, so an optimized program designed to accomplish this goal also would include data collection from November to April. Lakewide patterns in Upper Klamath Lake water quality during the winter have not been previously described, so it is unclear what sampling frequency may be required and what spatial resolution may be needed to fully characterize conditions in the lake that may influence those downstream. In addition, at least one land-based meteorological station recording data year-round would be needed to provide a weather context for the year-round water-quality measurements.

Goal 5

The fifth goal was to make Upper Klamath Lake water-quality data publicly available and to contribute to analyses and interpretations of water-quality monitoring data and data collection as described under the first four goals. Data collected by the USGS already is publicly available through the online database of water-quality data, the National Water Information System (NWIS; *http://waterdata.usgs.gov/nwis/qw*) and the Oregon Water Resources data page (*http://or.water.usgs.gov/datapage.html*). The Klamath Tribes and USGS also make their data publicly available through investigative reports, journal articles, and summary reports (see section, “Introduction” of this report for examples). In addition, representatives from the USGS and Klamath Tribes regularly present data at public or inter- and intra-organizational meetings, conferences, and other scientific gatherings. Publication of data collected in the monitoring programs and the scientific interpretation of those data greatly increase the value of long-term datasets. Such publications can be produced at a fraction of the cost of collecting the data, but interpretations of data and subsequent publication require adequate funding and dedication to making information available to managers, the scientific community, and the public. Future monitoring programs may accommodate this need by incorporating partnerships, allocating time and resources to database development and/or maintenance, and emphasis on the preparation of formal reports and presentations.

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Appendix: Synoptic survey data, Upper Klamath Lake, Oregon, 2012

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