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Wind Control on Water Quality in Shallow, Hypereutrophic Upper Klamath Lake, Oregon

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Abstract

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Large blooms of cyanobacteria, primarily *Aphanizomenon flos-aquae*, are linked to poor water quality in Upper Klamath Lake, Oregon. High pH and high un-ionized ammonia concentrations are associated with the blooms when algae are actively growing, followed by low dissolved oxygen (DO) conditions when the blooms decline in mid- to late summer. Over a 12-year study period, algal biomass was strongly related to total phosphorus concentration (TP) and pH. Minimum water column DO was strongly related to net negative changes (*i.e.*, declines) in algal biomass during July and August. The severity of both low DO and high ammonia was positively related to water column stability, which was dependent on wind speed. Bloom dynamics, coupled with climate, dominated year-to-year variability in water quality dynamics in Upper Klamath Lake. These data provide the empirical basis for previous research linking high mortalities of endangered sucker species with years of low wind and high water column stability.

Key Words: wind mixing, water column stability, water quality, blue-green algal blooms, fish kills

Declines in populations of Lost River (*Deltistes luxatus*) and shortnose (*Chasmistes brevirostris*) suckers related to poor water quality in hypereutrophic Upper Klamath Lake have been a concern for several decades. The declines were severe enough that both species were listed as endangered in 1988 by the U.S. Fish and Wildlife Service (Federal Register 53[137]:27130-27134). Causes for the declines have been ascribed to a combination of habitat alteration, elimination of spawning habitat, over-utilization, and poor water quality associated with the collapse of large algal blooms.

Although the causes of bloom collapses are not well understood (Barica 1975a,b 1978), they can lead to summer fish kills, such as those observed in the Upper Klamath Lake system (Scoppettone and Vinyard 1991). Recently, Perkins *et al.* (2000) documented substantial mortalities of Lost River and shortnose suckers in Upper Klamath Lake during the late summers of 1995, 1996 and 1997. Fish kills were preceded by and initiated during a period of high algal biomass, high pH, high un-ionized ammonia, and low off-bottom DO. Massive mortality of adult suckers then coincided with periods of algal biomass decline (bloom crash) and low DO that extended throughout the water column for several days to weeks (Perkins *et al.* 2000). The authors concluded that photosynthetically elevated pH, low DO, and high un-ionized ammonia caused chronic stress that ultimately affected fish condition and survival. In addition, analyses of otolith increment widths showed that reduced juvenile sucker growth in Upper Klamath Lake was related to high temperature and low nighttime DO (Terwilliger *et al.* 2003).

The Upper Klamath Lake system appears to have been eutrophic since the earliest known records from the mid-1800s (Cope 1884). A transition, however, took place between the late 1800s and the early to mid-1900s, when major changes in land use and hydrology occurred in the watershed and lake, and the current bloom-forming cyanobacteria, *Aphanizomenon flos-aquae*, became prevalent. Although eutrophic conditions in Upper Klamath Lake were described from an early limnological survey in 1913 (Kemmerer *et al.* 1923), increased eutrophication has occurred since that time (Bortelson and Fretwell 1993). In addition to a changed phytoplankton species composition, the total cyanobacterial biomass has apparently increased during at least the past 50 years when *A. flos-aquae* has dominated the summer phytoplankton and created frequent nuisance bloom conditions (Kann 1998). The appearance of *A. flos-aquae* around the turn of the century was recently confirmed in two independently collected sediment cores showing that *Aphanizomenon* akinetes did not appear in Upper Klamath Lake until the latter part of the 19th century (Eilers *et al.* 2004, Bradbury *et al.* 2004).

Poor water quality in lakes is often driven by increased algal production and accumulation of algal biomass. If nutrients and light are sufficient, algal biomass can reach “bloom” proportions. Coupled with minimal mixing and reaeration, pH in the water can commonly exceed levels of 9.5 during summer in hypereutrophic lakes, and can be detrimental to fish (Kann and Smith 1999). This high level of algal production and high pH can also lead to high concentrations of un-ionized ammonia. During the same bloom conditions, particularly when coupled with high rates of nighttime respiration, DO concentrations can drop to levels that restrict fish growth or can even be lethal to some fish species. In addition, microbial degradation of dead algae and oxygen demand by sediment can further deplete DO concentrations and increase the concentrations of ammonia, adversely affecting fish (Barica 1975a). The extent of DO depletion and increased pH and ammonia by these processes can be accentuated by low lake volume due to shallow depth and by low wind velocities that promote water column stability (Barica 1975b, Mathias and Barica 1979, Barica 1984, Miranda *et al.* 2001).

While increased eutrophication in Upper Klamath Lake is the principal cause of worsening water quality and subsequent related fish mortalities (Eilers *et al.* 2004, Perkins *et al.* 2000), year-to-year variability in the severity of water quality has been shown to be strongly related to climate, specifically wind that controls water column stability (Perkins *et al.* 2000, Welch and Burke 2001). In the study presented here, we examined inter-annual patterns and relationships among water quality, wind, and algal biomass over a 12-year period in Upper Klamath Lake.

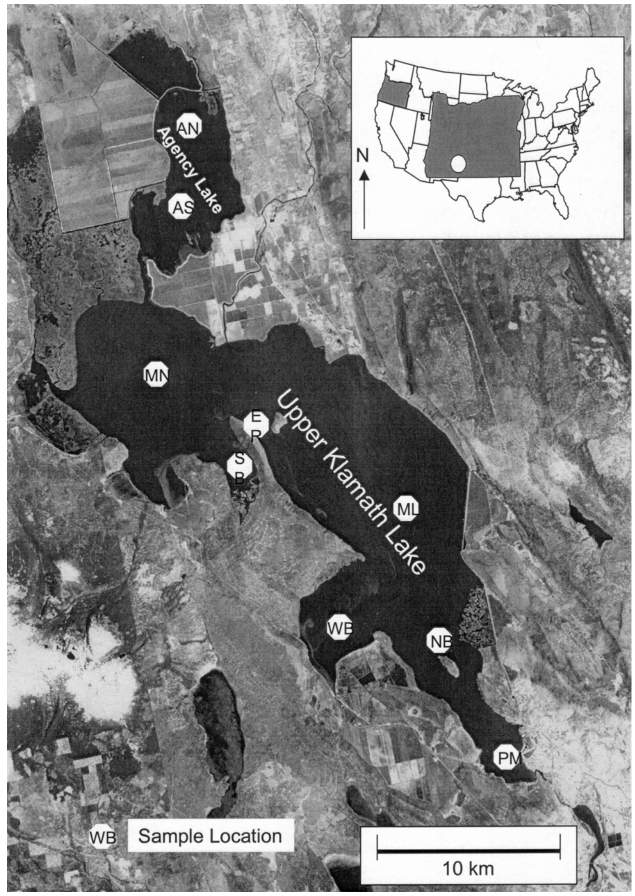

Figure 1.-Location of Upper Klamath Lake, Oregon, showing sampling stations for water quality parameters.

Site Description

The extremely shallow Upper Klamath Lake system (including both Upper Klamath Lake and Agency Lake, its northern most basin), located in south-central Oregon at the base of the eastern slope of the Cascade Mountains (Fig. 1), is a graben type (*i.e.*, formed by tectonic faulting) that is one of the largest natural freshwater lakes in the Western United States. At a mean summer lake elevation of 1262.12 m (4,140.8 ft above mean sea level), the surface area of the system is 26,800 hectares (66,300 acres) with a volume of 536 x 10^6 m^3 (435,800 acre-ft) and mean depth of 2.0 meters (6.5 ft). Although historically a natural lake system, the ability to artificially lower lake levels to supply irrigation water to the U.S. Bureau of Reclamation Klamath Project was achieved in 1921 by cutting a channel through a natural rock reef at the outlet of the lake. Subsequent regulation by a dam at this location enables manipulation of water levels and volume that result in more extreme annual water elevation fluctuations, with late summer minimum elevations as much as 1 m lower (reducing mean depth and volume by nearly

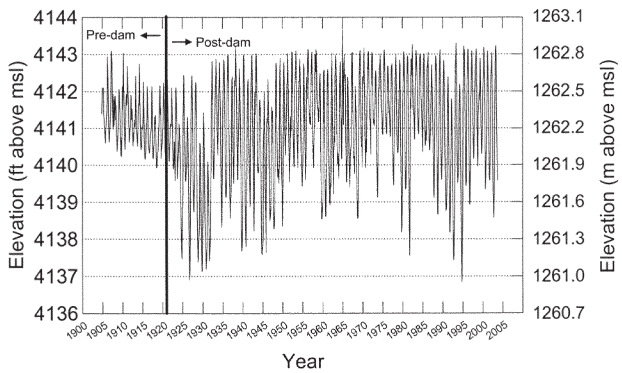

Figure 2.-Water surface elevation in feet above msl (mean sea level) 1904-2003 (source: U.S. Bureau of Reclamation, Klamath Falls Project Office).

50% to 1 m and 247 x 10^6 m^3, respectively) than pre-dam conditions (Fig. 2).

Methods

Upper Klamath and Agency Lakes were regularly sampled from January 1990 through October 2001 to monitor seasonal water quality and nutrient dynamics related to algal blooms. Water samples were taken biweekly during the June-September growing period and approximately monthly during the winter-early spring period, except when prevented by ice cover or storms. Analyses herein are based on 9 stations, 2 in Agency Lake and 7 in Upper Klamath Lake (Fig. 1). Hourly wind speed data were obtained from the National Climatic Data Center for the Klamath Falls airport (DATSAV3 Global Surface Hourly Data: Station LMT 725895 located 8 km south of the lake). Water column profiles of temperature, pH, DO, and conductivity were determined using a Hydrolab Surveyor multi-parameter probe at each sample site and date.

Because the lake is polymictic with periods of weak and intermittent water column stability, a depth-integrated water sample of the entire water column was taken coincidentally with the water quality profiles by combining a minimum of three replicate hauls from a weighted 5-cm diameter plastic tube at each site. This composite sample was then mixed and distributed to appropriate collection bottles for the analysis of chlorophyll *a* (chl *a*; Nusch 1980), total phosphorus (TP) and ammonia nitrogen (NH_4-N; APHA 1985), and total nitrogen (TN; D'Elia *et al.* 1977). The toxic un-ionized fraction of ammonium (ammonia) was computed based on water column mean pH and temperature (Emerson *et al.* 1975). All sampling trips included field duplicates and blanks, and laboratory analysis included split samples as well as samples spiked with a known concentration of the constituent to be analyzed. Specific sampling methods are further outlined in Kann (1998).

The water column stability was calculated as the relative thermal resistance to mixing (RTRM), which is a dimensionless index of water column stability based on gradients in water density (Jones and Welch 1990). RTRM is defined as the difference in densities between two water layers divided by the density difference between water at 4°C and 5°C. Weak density gradients result in low RTRM values and indicate little resistance to wind-induced mixing. High RTRM values indicate high resistance to mixing; calm periods generally produce high RTRMs.

Mean net change in algal biomass within the July-August period was computed from chl *a* data as:

$$\frac{(B_{t2} - B_{t1}) + (B_{t3} - B_{t2}) + ...(B_{tn} - B_{tn\text{-}1})}{n}, \ t\text{=}1,...,n$$

Where B is the biomass (chl *a*) at sample time t, and n is the number of sample dates in the July-August period.

In general, water quality constituents were related to mixing and climate using data from the northern area of Upper Klamath Lake (Fig. 1: stations ER, MN, and SB) during the July-August period. This is the area where the greatest majority of endangered suckers were located and fish kills were most concentrated, as well as the period when fish kills and poor water quality are most prevalent.

Results

Massive blooms recurred each summer in the Upper Klamath Lake system, and although the timing of cyanobacterial blooms varied, blooms usually began sometime in June (Fig. 3). The earliest-forming bloom and one of the largest recorded was in June 1992, with maximum lake-wide mean chl a concentrations higher than other years by 50-100 µg/L chl *a*. Biomass increase also began early in 1994, 1995, 1997, 2000, and 2001, and high algal biomass also occurred as late as September in 1990, 1991, 1995, and 1997 when chl *a* concentrations nearly reached or exceeded 200 µg/L. Although sometimes masked when using lake-wide means, algal periodicity usually consisted of a peak during July, a bloom crash in August, and a second smaller peak in September (Fig. 3).

TP and chl *a* were strongly related in Upper Klamath Lake when lake-wide summer (June-September) means (calculated from whole-lake, volume-weighted mean concentrations) of TP, and chl *a* from each sampling interval were used (Fig. 4). The observed relationship agrees with those from other published equations, and predicted chl:TP ratios from the equation in Fig. 4 fall within the range of 0.5-1.0 typically found for lakes (Jones and Bachmann 1976, Ahlgren *et al.*

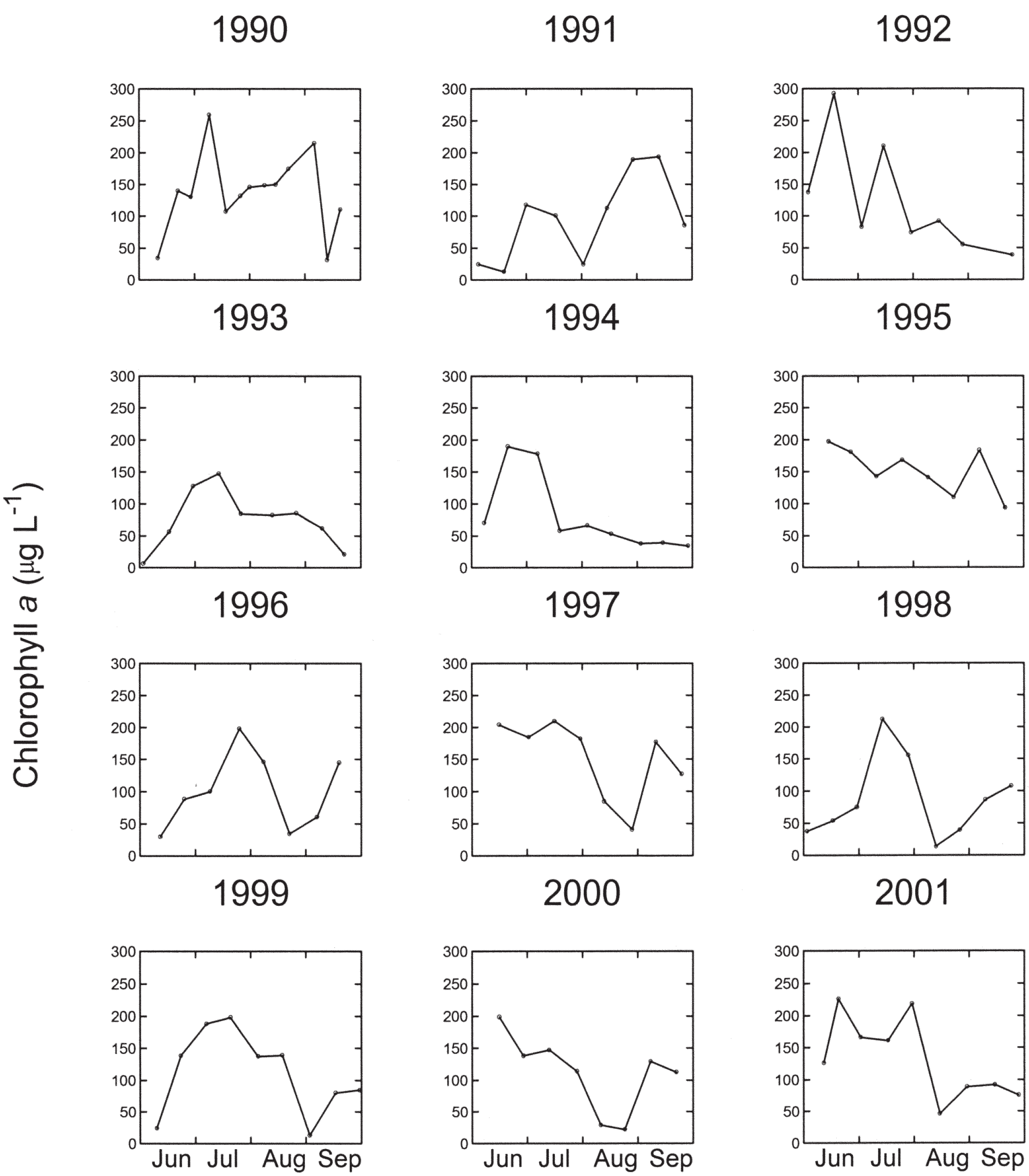

Figure 3.-June–September time series for lake-wide volume-weighted mean chl *a* in Upper Klamath Lake, 1990-2001.

1988). Some ratios, such as 1991 at 0.57, were at the lower end of the typical range which could be due to several factors. Algal bloom development began late in 1991, reaching a maximum later than any other year (Fig. 3). Growth conditions (light and temperature) were poorer in spring 1991, likely accounting for lower than normal utilization of available TP (Walker 2001, Welch and Burke 2001).

The level of algal biomass is a strong predictor of pH in Upper Klamath Lake, as shown by Kann and Smith (1999). Levels of pH usually exceeded 9.5 and approached or exceeded 10 due to the high rate of photosynthesis and low alkalinity. The relationship between chl *a* and pH during June was stronger ($r^2 = 0.95$) than during the summer as a whole ($r^2 = 0.72$), because algal cells were healthier and grew rapidly during

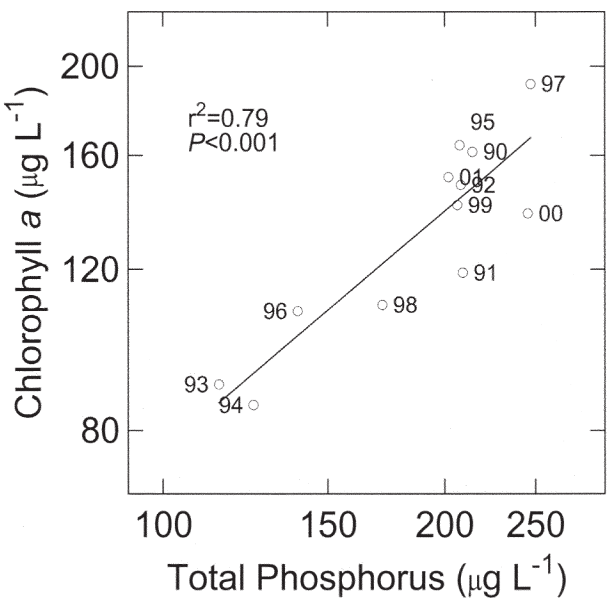

Figure 4.-Relationship between log-transformed volume-weighted lake-wide means for TP and chl *a* during twice-monthly sampling during June through September, 1990-1991.

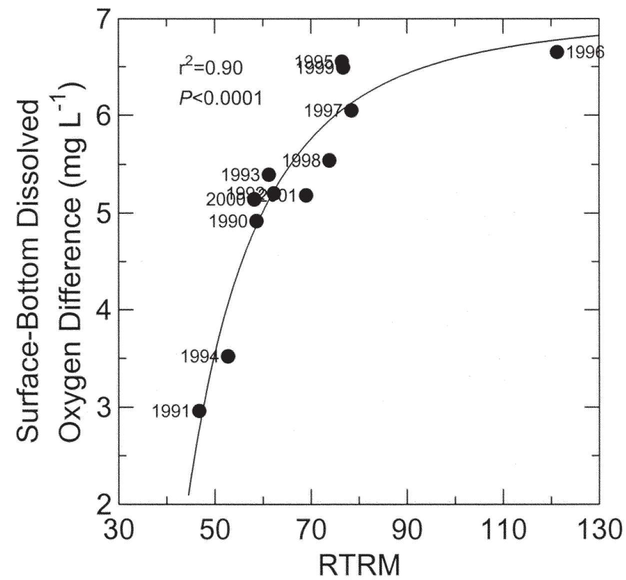

Figure 6.-Mean July-August RTRM related to mean July-August surface-to-bottom DO difference at three northern stations (ER, SB, MN) in Upper Klamath Lake, Oregon during 1990-2001.

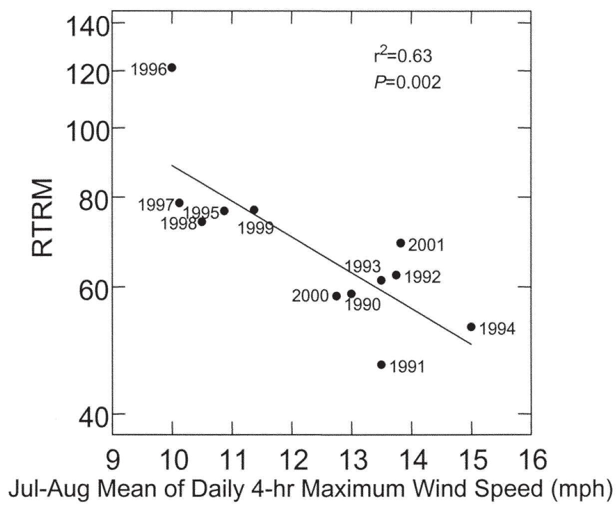

Figure 5.-Mean July-August maximum daily 4-hour running mean wind speed in mi/hr at Klamath Falls Airport related to July-August mean water column stability (as RTRM) at northern sampling sites (ER, SB, MN) in Upper Klamath Lake for 1990-2001.

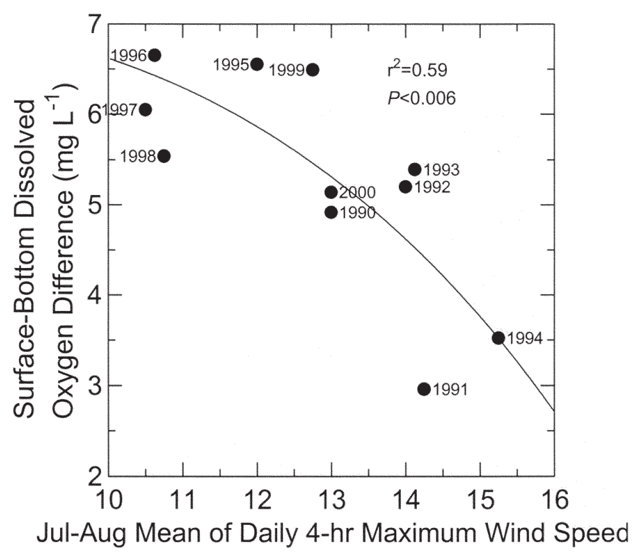

Figure 7.-Mean July-August maximum daily 4-hour running mean wind speed in mi/hr at Klamath Falls airport related to July-August surface-to-bottom DO difference at three northern stations (ER, SB, and MN) in Upper Klamath Lake, Oregon, during 1990-2000.

June, while the whole summer period included declines in algal biomass and non-growing periods.

Low levels of DO usually occurred in Upper Klamath Lake during mid-summer (July-August) and were associated with periods of algal decline, high water temperature, minimal mixing due to increased water column stability, and lake level declines to seasonal minima. Over the 12-year study period, the relationships between wind speed and RTRM (Fig. 5), RTRM and surface-to-bottom mean difference in DO (Fig.6), and wind speed and surface-to-bottom mean difference in DO (Fig. 7) clearly show the dependence of water column DO on water-column stability, which is in turn was dependent on wind.

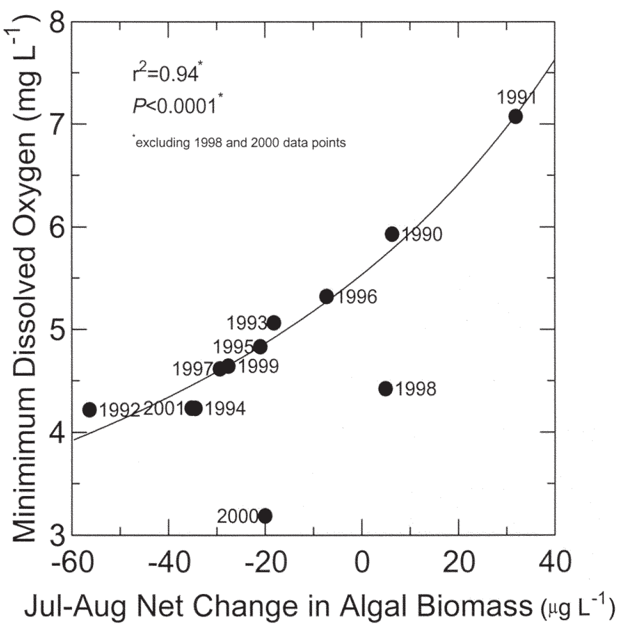

Figure 8.-Relationship between mean July-August minimum water column DO and mean July-August net change in algal biomass (chl *a*) in Upper Klamath Lake 1990-2001. Means are computed from three northern stations (ER, SB, and MN) for all sample dates within the July-August period. Statistics and regression line are computed without including years 1998 and 2000 (see text for explanation).

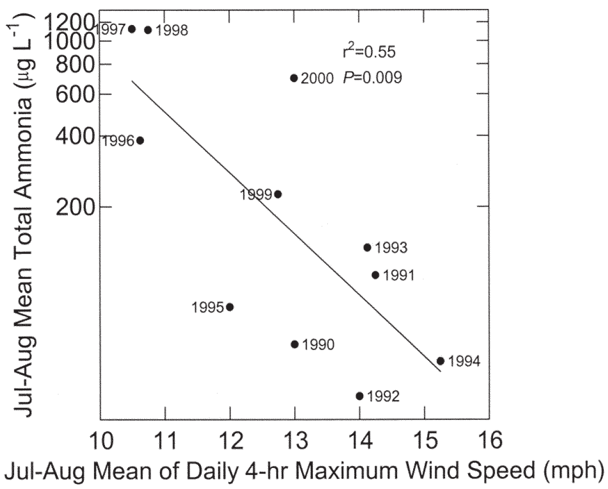

Figure 9.-July-August mean total ammonia in Upper Klamath Lake, Oregon, related to wind speed index. Index calculated by computing 4-hr running mean wind speeds and averaging the daily maximum for each day in the July-August period, 1990-2000.

The magnitude of algal bloom collapse in Upper Klamath Lake was related to water-column DO minima (Fig. 8). For example, relatively large July-August algal bloom net declines in biomass and relatively low DOs occurred in 1995 and 1997 (two of the fish kill years), while 1990 and 1991 had less algal biomass, less decline and consequently higher DO following the algal biomass declines. As noted earlier, the low spring algal biomass in 1991 was due to low temperature and reduced inputs of solar energy (Walker 2001). The relatively low DO concentrations in 1998 and 2000 do not correspond as well with algal bloom declines, due largely to the July-August period chosen in the analysis. The bloom decline in 1998 was actually large, but re-growth had already begun in August, causing higher July-August values of net algal change. The magnitude of the bloom collapse in 2000 was also underestimated by rigidly computing net change over the July-August time period. Note that the large algal blooms of 1992 and 1994 (also low lake-level years) produced the largest bloom declines and very low DO values, although not as low as in 2000 (Fig. 8).

To indicate the relative importance of algal bloom decline on water column DO, average daily demands and sources of DO at the beginning and end of the algal declines were estimated during 1995-1997 (the three fish-kill years) and are shown in Table 1. Beginning biomass for the three years averaged slightly greater than 200 μg/L of chl *a*, with ending biomass at about 70 μg/L and an average 23-day rate of decline of 7.3 μg/L-day of chl *a*. The analysis shows that increased biological oxygen demand (BOD) from decomposition of dead cells and decreased photosynthesis were principal causes for the decreased water column DO.

Ammonium was also related to climatic conditions. Decomposition of large June algal blooms should result in high July-August ammonia concentrations, if other rates of supply and loss are constant. However, wind affects ammonium because the magnitude of wind mixing of the water column determines the extent of reaeration and nitrification. Ammonium and ammonia concentrations were strongly related to mean wind speed (Figs. 9 and 10). Except for 2000, highest ammonium and ammonia concentrations in July and August were associated with low mean wind speed and less mixing of the water column. These conditions apparently allowed ammonia to accumulate due to reduced loss of ammonia to the atmosphere and/or reduced nitrification. In contrast, the climatic effect precluded any direct relationship between algal biomass and total ammonium or un-ionized ammonia. The year with highest June biomass (1992; Fig. 3) had very low un-ionized ammonia (and ammonium) in July-August (Fig. 10). Except for two July ammonia values around 100 μg/L, all values were less than 25 μg/L, with the median about

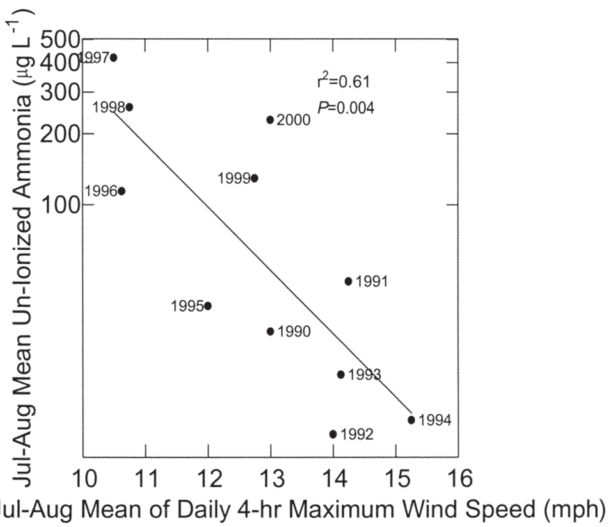

Figure 10.-July-August mean un-ionized ammonia in Upper Klamath Lake, Oregon, related to wind speed index. Index calculated by computing 4-hr running mean wind speeds and averaging the daily maximum for each day in the July-August period, 1990-2000.

Table 1.-Estimated daily DO balance in g O_2/m²-day in a 2.2 m water column of Upper Klamath Lake at the beginning and end of algal bloom declines during 2-4 week periods in 1995-1997.[1]

	Daily DO Balance (g O_2/m²-day)	
Source/Demand	**Beginning, 200 µg chl/L**	**End, 70 µg chl/L**
BOD	0	-2.6
Respiration of live cells (R)	-2.3	-0.8
Sediment oxygen demand (SOD)	-1.7	-1.7
PS	+29	+10
Net Effect	+25	+4.9

[1]Assumptions are: photosynthesis as PS_{max} = 13.2 mg O_2/mg chl - hr (Pechar 1992), PS for 10 hr period with available light of 12% Io (@ k = 3.7/m) = 0.5 PS_{max} (Steele 1962); respiration of live cells (R) = 0.08 PS (nominal value from Bowie *et al.* 1985); BOD based on mean 3-year, 23-day decline rate of 7.3 mg chl/m³-day x 50C/chl x O_2/C atomic ratio of 1.2; sediment oxygen demand (SOD) = 1.7 determined by USGS (Wood 1999).

6 µg/L. However, these relationships indicate that wind, by its influence on water column stability, was an important controlling factor on ammonia. Low wind and greater stability allowed ammonia to accumulate to high levels. During the large algal blooms in 1992 and 1994, ammonia content would likely have been much higher had wind speed been low during those years.

Discussion

Causes of low DO in Upper Klamath Lake are complex and are strongly related to algal bloom timing, bloom maximum and declines, as well as to wind and RTRM. As indicated in Fig. 8, declining algal blooms in Upper Klamath Lake exerted a strong influence on water column DO minima. While water column stability resulting from low-wind conditions allows low water-column DO to occur (Fig. 6), the organic matter produced in algal blooms is an important source of DO demand. Moreover, reduced photosynthesis with declining blooms decreases the input of DO to the water column. The magnitude of estimated DO demand by algae was substantial (Table 1); however, the ending photosynthesis was probably overestimated, because decreased algal growth rate would be the expected cause for the decline. Nevertheless, photosynthesis at the end of the decline was probably sufficient to have prevented anoxia from occurring.

BOD may also be underestimated by assuming that the entire BOD formed each day is decomposed, because there is probably an accumulation as well as an increasing BOD rate with time. This analysis shows that bloom decline is a principal cause of low DO concentrations, so minimizing bloom magnitude would have a significant positive effect on fish habitat. While water-column stability was important in allowing low DO concentrations to persist (*i.e.*, low atmospheric reaeration), bloom decline was nevertheless the important source of oxygen demand, as well as reduced photosynthetically produced DO. Moreover, Perkins *et al.* (2000) demonstrated that water column stability was an important determinant of low off-bottom DO, but that bloom decline was the principle cause of water column-wide low DO that coincided with the fish kills.

As suggested, water column DO depletion during summer was partly offset by reaeration from the atmosphere and algal photosynthesis (except during bloom decline). Nevertheless, water column DO content can fall to very low levels (<1 mg/L) during calm periods in shallow lakes in summer, especially following the rapid decline of algal blooms, such as the blue-green alga *Aphanizomenon* (Barica 1984). A rapid bloom decline exerted intense demand on DO and was exacerbated because photosynthetic production of DO essentially stopped, but respiration continued. In addition, bacterial decomposition of the dying algal cells increased. Even if blooms do not decline, DO can still be depleted during relatively calm periods due to sediment demand. The magnitude of reaeration during these periods of bloom decline is determined by wind speed and degree of water column stability, as indexed by RTRM. Continuous monitoring at depths of 0.15 m and 1.4 m in a water column 1.5 m deep in Moses Lake, Washington, showed that DO content declined sharply when wind speed dropped below 3 m/s (6.7 mph), but was not markedly affected at greater wind speeds. Those results indicated aeration was adequate to offset DO demand in the water column when wind speed exceeded about 3 m/s (de Walle 1970).

Although algal biomass is the source of the DO demand, climate can affect year-to-year variations in both DO conditions and algal biomass. For example, 1991 was a year of exceptional water quality due in part to a cooler and cloudier-than-normal spring and early summer period, which led to a delayed algal bloom. Moreover, no precipitous bloom crash occurred in 1991 (Fig. 8), and minimum water column DO remained higher than all other years (Fig. 8). In addition, the wind speed index was the second highest for 1991 and water column stability the lowest of the 10 years of record (Figs. 6 and 7). Thus, a delayed bloom, lack of a significant summertime bloom crash along with high wind and low stability probably led to high DO conditions in 1991.

Lake surface elevation, and hence lake depth, is known to affect DO conditions. However, the strong influence of climate on water column stability as well as on algal bloom periodicity (as occurred in 1991) in Upper Klamath Lake obscured any direct effect of lake elevation on water quality. Nevertheless, the importance of depth observed in other shallow lakes deserves mention here with respect to its potential effect in this lake. The surface elevation of Upper Klamath Lake usually decreases from about 1262.8 m (4143 feet) above sea level in June to between 1261.8 m (4140 feet) and 1261.6 m (4139 feet) due to irrigation withdrawal (Fig. 2). However, elevations can decline to as low as 1261.0 m (4137 feet) during years with low runoff. An elevation change of 1.8 m (6 feet) corresponds to a decrease in mean depth from 2.7 m to 1.1 m. This represents more than a doubling of the surface-to-volume ratio in the lake and translates to a directly proportional increase in sediment DO demand per unit volume on the remaining water column (Livingstone and Imboden 1996). While this effect may be partly offset by increased reaeration with shallower depths, data from Upper Klamath Lake indicate that RTRM and minimum DO are primarily determined by wind and not lake level (Welch and Burke 2001). Moreover, there is evidence that lowered lake depth increases the risk of lowered DO in other lake systems. Miranda *et al.* (2001) developed a model to predict the distribution of DO with depth and area in a shallow lake (area = 1870 ha; mean depth = 3 m) and found that the risk of dawn DO reaching levels < 1.5 mg/L increased nearly four-fold if mean lake depth decreased from 3 m to 1 m. They concluded that water level management in shallow eutrophic lakes can greatly affect large areas.

Algal biomass may also be affected by lake depth due to changing light climate. In Lake Võrtsjärv (Estonia; mean depth 2.8 m, area 27,000 ha), phytoplankton biovolume decreased during long-term increase in lake elevation of 1.5 m during the 1980s (Nõges *et al.* 2003). Drought conditions in 1996 decreased lake volume by 58% and the late summer mean depth to 1.4 m, which increased water column light. As a result, phytoplankton biomass (especially N-fixing cyanophytes) greatly increased, although integral productivity remained similar to that in 1995. The shallower depth also resulted in increased TP during 1996 due to greater resuspension of bottom sediments (Nõges and Nõges 1999).

These water depth effects underscore the importance of considering the interactions between climate and lake level. During many years, climate exerted a strong influence on algal biomass and DO in Upper Klamath Lake. The effect of lake level could be either exacerbated or ameliorated by climatic conditions, and so would be obscured in any attempt to develop simple bivariate relationships between lake level and DO or other water quality variables.

The effect of ammonia on fish is determined by the concentration of the toxic un-ionized fraction, which is dependent on pH, temperature, and total ammonium concentration. Higher pH in June, when the algae are healthier and growing, results in a higher proportion of the total ammonium as toxic un-ionized ammonia. Lower pH during July-August would result in less un-ionized ammonia even if ammonium levels resulting from decomposition of the large June biomass were high. Greater wind mixing would also tend to increase loss of gaseous ammonia to the atmosphere, as well as supply DO for oxidation of ammonia to nitrate (nitrification). Lake depth (*i.e.*, lake volume) would also affect the amount of water column dilution of the ammonium flux from organic matter decomposition in bottom sediments. Therefore, decline of large algal blooms, together with low wind speed and low lake level, would tend to increase ammonia concentration.

As noted above, Upper Klamath Lake water column stability is primarily controlled by wind and not lake level (Welch and Burke 2001). Moreover, high ammonia levels, such as those occurring in the fish kill years, were significantly associated with low wind conditions (Figs. 9 and 10), but not lake level. Thus, in Upper Klamath Lake, high algal biomass creates poor water quality, which combined with climatic conditions can worsen, creating stressful and sometimes lethal conditions for endangered suckers. Stated another way, large algal blooms set the stage for lethal water quality, and climatic conditions interact with bloom dynamics in a way that strongly influences the severity of water quality. The two largest fish kill years of 1996 and 1997 (Perkins *et al.* 2000) were clearly associated with the lowest July-August wind distribution of the decade (Fig. 11).

Further underscoring the importance of both lake level and climate, Markle *et al.* (2002) showed that: (1) juvenile shortnose and Lost River sucker production was positively related to June lake elevation and June wind power in Upper Klamath Lake; (2) juvenile shortnose sucker production was

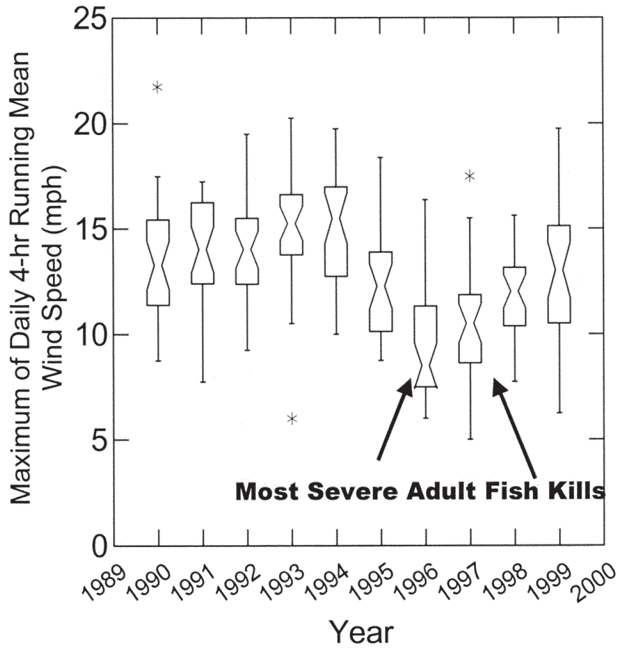

Figure 11.-Distribution of July-August wind speed index. Index calculated by computing 4-hr running mean wind speeds and selecting the daily maximum for each day in the July-August period, 1990-1999.

positively related to August lake elevation, and; (3) juvenile production of both species was negatively related to median August air temperature. These authors further concluded that even when August lake elevation was high, low August wind speed and high median air temperature were associated with lower juvenile production, thus concluding that lake elevation and summer weather interact significantly with annual shortnose and Lost River sucker juvenile production in Upper Klamath Lake.

Climatic conditions cannot be managed, so other approaches, such as reduction of nutrients and management of lake elevations to reduce the magnitude and intensity of algal blooms are key options to ameliorate poor water quality in Upper Klamath Lake.

Acknowledgments

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