

## Interacting factors causing exceptional summer water clarity in Lakes Mendota and Monona

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### Introduction

Lake Mendota ( $A_0 = 39.9 \text{ km}^2$ ,  $z_{\text{max}} = 25.3 \text{ m}$ ) and downstream Lake Monona ( $A_0 = 13.3 \text{ km}^2$ ,  $z_{\text{max}} = 22.6 \text{ m}$ ) near Madison, Wisconsin, U.S.A. have regularly experienced blue-green algal blooms and hence poor water clarity during summers since at least the late 1800s (LATHROP & CARPENTER 1992, LATHROP et al. 1992). In Lake Mendota, spring P concentrations have been linked to summer algal densities (STOW et al. 1997, LATHROP et al. 1998). Internal mixing (STAUFFER & LEE 1973, SORANNO et al. 1997, LATHROP et al. 1999) and *Daphnia* grazing (LATHROP et al. 1996, 1999) also have been shown to affect summer algal densities and water clarity in the lake. Because of variability in these and other factors, the summer blooms vary in intensity resulting in variable water clarity. On occasion, relatively good summer water clarity has occurred (LATHROP et al. 1996).

The summer of 1988 was a year of exceptionally good water clarity in Lake Mendota. A massive die-off of the cold-water planktivorous cisco (*Coregonus artedii* Lesueur) in 1987 allowed the large-bodied *Daphnia pulicaria* to dominate during the spring and early summer of 1988 and in subsequent years due to low planktivory (RUDSTAM et al. 1993, LATHROP et al. 1996). In prior years, the smaller-bodied *D. galeata mendotae* dominated because of high planktivory from the large cisco population. The cisco die-off and *Daphnia* species shift was compelling evidence for the importance of food web effects as a regulator of algal densities in Lake Mendota (VANNI et al. 1990). However, summer water clarity increased almost as much in 1988 in Lake Monona, a lake where cisco do not thrive (LATHROP et al. 1992). A shift in *Daphnia* species did not also occur in Lake Monona, but climate controlled factors did affect both lakes. This paper explores those factors that may have caused the exceptional water clarity during the summer in 1988 by comparing a 20-year dataset (1976–1995) for both lakes.

### Methods

Limnological sampling during the open water period on Lakes Mendota and Monona was conducted by the Wisconsin Department of Natural Resources (WDNR) on a bi-weekly schedule for most years during 1976–94. Additional data for Lake Mendota were collected by the University of Wisconsin Center for Limnology (UW) during 1987–94 as part of a food web study funded by the WDNR (KITCHELL 1992). Since 1995, the UW has been conducting the limnological sampling on both lakes as part of its North-Temperate Lakes Long-Term Ecological Research Project funded by the National Science Foundation.

Yearly means of April P concentrations, and of July–August Secchi disk depths, *Daphnia* biomasses and Schmidt stabilities for 1976 through 1995 were previously compiled for Lake Mendota (LATHROP et al. 1999). A comparable dataset for Lake Monona was compiled for this study using similar methods summarized below. July–August mean values were computed for an 8-week period from June 29 through August 23, which best conformed to each year's biweekly sampling schedule.

All sampling was conducted at the deepest area of each lake. Secchi disk readings were recorded using a 20-cm black and white (B/W) disk. Additional readings were also recorded for Lake Mendota in 1976–80 using a 30-cm white disk; those readings were standardized to a 20-cm B/W disk by dividing by 1.129 (LATHROP 1992). Total P concentrations for April (spring mixis) were averaged from samples collected at 0 and 4 m water depths.

*Daphnia* spp. enumerations and biomass estimates were determined from vertical tow samples collected with conical zooplankton nets described in LATHROP et al. (1999). Dry weights for both juveniles and adults of each *Daphnia* species were computed from recorded average lengths using equations given in LYNCH et al. (1986). The smaller-bodied *Daphnia galeata mendotae* and the larger-bodied *D. pulicaria* were the two main species found during the 20-year

period. Biomass concentrations in the tow samples were adjusted for depths where dissolved oxygen concentrations were  $>1 \text{ mg L}^{-1}$ . Biomasses were not corrected for net efficiency.

Schmidt stabilities ( $S$ ,  $\text{g cm}^{-1}$ ) were computed from each lake's hypsometric data and summer temperature profile records using the following equation (LIKENS 1985, ROBERTSON & IMBERGER 1994):

$$S = A_0^{-1} \sum (z - z^*) (\rho_z - \rho^*) A_z \Delta z$$

where  $A_z$  is the lake area at depth  $z$ ,  $\rho_z$  is the water density at depth  $z$ ,  $\rho^*$  is the lake's mean density, and  $z^*$  is the depth where the mean density is found. The summation is taken over all depths at interval  $\Delta z = 1 \text{ m}$ .

Schmidt stability is the amount of work required by the wind to mix a lake to a uniform temperature (LIKENS 1985, ROBERTSON & IMBERGER 1994). As a mixing index for a given lake, lower mean summer stabilities indicate a higher potential for entrainment of P-rich metalimnetic waters to the epilimnion compared to summers with higher stabilities. Because Lake Monona's mean depth (8.3 m) is much less than Lake Mendota's (12.7 m), average stability values for Lake Monona are much lower.

## Results and discussion

Water clarity as measured by Secchi disk transparencies was notably greater in Lake Mendota during July–August of 1988 than in any other year during 1976–95 (Fig. 1). In 1988, the lowest spring P concentrations and highest July–August water column stabilities recorded during the 20-year period occurred in that lake. July–August *Daphnia* biomasses (*D. pulicaria*) were also high in 1988 following the massive cisco die-off the previous summer. However, *Daphnia pulicaria* biomasses were even higher in the summers of 1990 and 1993 when Secchi disk transparencies tended more towards the average.

Lake Monona also had relatively good water clarity in 1988 coincident with the lowest April P concentrations and highest water column stabilities in the 20-year record for that lake (Fig. 1). However, summer *Daphnia* biomasses were not high in 1988 even though the spring clear water phase was dominated by *D. pulicaria*. The larger species had dominated since 1986; only in 1978 to 1981, and 1985 did grazing by *D. galeata mendotae* cause the clear

water phase in that lake (LATHROP et al. 1992, WDNR unpublished data).

Analyzing the Lake Mendota database depicted in Fig. 1, LATHROP et al. (1999) developed a linear model ( $R^2 = 0.70$ ) that predicted July–August Secchi depths from April P concentrations, and July–August *Daphnia* biomasses and water column stabilities. Thus, the exceptionally good water clarity in Lake Mendota during the summer in 1988 was explained by the three factors acting in harmony – low P availability, low internal mixing, and high *Daphnia* grazing. The first two factors were present in Lake Monona that year. The somewhat greater July 1988 mean Secchi disk depth in Lake Mendota (3.8 m) compared to Lake Monona (3.2 m) can be attributed to a relatively high July mean *Daphnia* biomass in Lake Mendota (LATHROP et al. 1999).

Exceptional water clarity was also noted in Lake Mendota during the summers of 1939 and 1947 (LATHROP 1992, LATHROP et al. 1996), which coincided with periods of lowered planktivory from massive cisco and yellow perch die-offs either in those summers or the preceding summer (LATHROP et al. 1992). The nutrient status of Lake Mendota was quite low prior to the end of World War II and moderate in the immediately ensuing years (LATHROP 1992, LATHROP et al. 1996). Average monthly air temperatures in Madison were above the long-term average (1897–1996) throughout the summer of 1939, and especially so in August of 1947. As a result, water column stabilities would have been higher than normal during those summers. Similar to 1988, the exceptional summer water clarity in 1939 and 1947 probably was a result of the three factors acting in concert.

The high coherence of climate-related variates for Lakes Mendota and Monona was evident in the 20-year record (Fig. 1). Because outflow from Lake Mendota represents almost two-thirds of the P loading to Lake Monona (LATHROP 1979), and because outlet flow rates are a function of runoff patterns, the correlation for April P concentrations was high between the two lakes ( $r = 0.90$ ). Water column stabilities, which are a function of weather patterns,

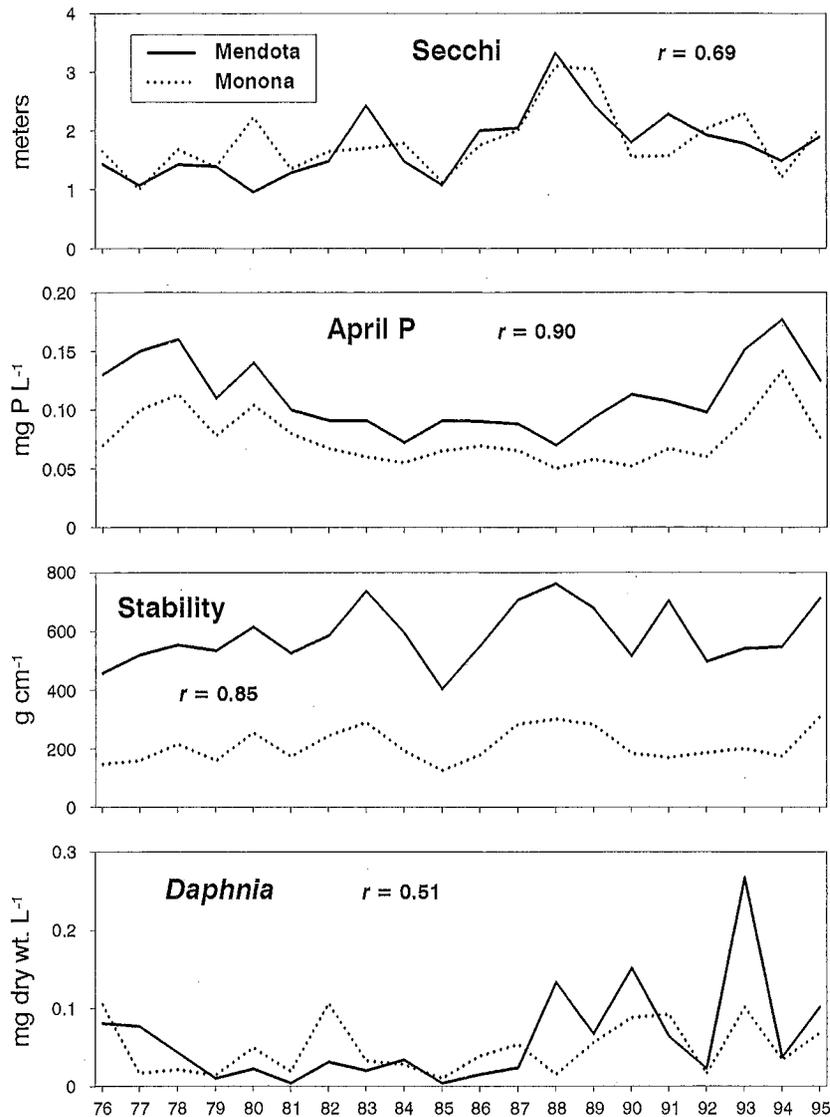


Fig. 1. July–August (June 29 to August 23) mean Secchi disk depths, April P concentrations, July–August mean Schmidt stabilities, and July–August mean *Daphnia* biomass concentrations for Lakes Mendota and Monona, 1976–1995.

were also highly correlated ( $r = 0.85$ ). As expected, summer *Daphnia* biomasses were less correlated ( $r = 0.51$ ). Summer Secchi transparencies in the two lakes had an intermediate correlation ( $r = 0.69$ ) between the physical–chemical variates affected by regional processes and the biological variate more affected by in-lake

processes. This is consistent with coherency analyses of northern Wisconsin lakes (KRATZ et al. 1998, BAINES et al. 2000).

In conclusion, this study highlights the value of long-term lake research studies which have been increasingly recognized for their contribution to the understanding of ecosystem func-

tion (SCHINDLER 1987, LIKENS 1989, EDMONDSON 1991, CARPENTER et al. 1995). Our results suggest that summer water clarity in eutrophic Lakes Mendota and Monona is directly linked to climate controlled processes, and that land use activities as well as lake food web dynamics also interact.

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