Inland Waters

ISSN: 2044-2041 (Print) 2044-205X (Online) Journal homepage: http://www.tandfonline.com/loi/tinw20

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Article

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Received 21 April 2015; accepted 25 August 2015; published 5 January 2016

Abstract

Using data collected with 3 different methods, we found no decreases in the average water clarity of Maine (USA) lakes over different periods of time. Field measurements of Secchi disk depths in the summer months by volunteer samplers in several hundred lakes showed a small, statistically significant increase in water transparency during the period 1976 through 2013. A reanalysis of satellite-inferred Secchi depths between 1990 and 2010 showed no trend over time. In addition, diatom-inferred Secchi depths from short sediment cores in a randomly selected group of Maine lakes analyzed by the US Environmental Protection Agency showed no statistically significant difference between the average Secchi depths in a pre-1850 time period and the early 1990s. Lake maximum depth was the most important morphological variable associated with water clarity among Maine lakes. In individual lakes, both water color and chlorophyll were inversely correlated with Secchi disk depths. The statewide annual average Secchi depths for the summer months were inversely correlated with water color and the amount of precipitation for the months of January through June. Drought years led to increased Secchi depths.

Key words: chlorophyll, citizen scientists, eutrophication, Maine lakes, morphometry, remote sensing, Secchi, water clarity, water color

Introduction

The state of Maine has some of the clearest lake waters in the United States due to edaphic factors (Bigham Stevens et al. 2015). Given the low nutrient content of these waters, lake cultural eutrophication has been a major concern of citizens since the formation of the Maine Volunteer Lake Monitoring Program (VLMP) in 1970. Citizens were and still are concerned that watershed development and increased recreational activity could result in increased nutrient enrichment and biological productivity, ultimately leading to a decline in water clarity. For non-scientists, the "quality or health" of a lake in the United States is often judged by its clarity, and increased water clarity corresponds to greater lakefront property values (Boyle et al. 1999).

The concerns of Mainers are representative of global concerns regarding cultural eutrophication (Schindler and Vallentyne 2008). By the middle of the 20th century, it was recognized that nutrient enrichment from raw and treated municipal wastewater was advancing the eutrophication of waters throughout the world, but it was also recognized that cultural eutrophication was reversible (Hasler 1969). Major efforts during the 1960s, 1970s, and early 1980s were initiated to reduce phosphorus in wastewater effluents in North America and Europe (Rast and Thornton 1996). These efforts generally resulted in the control of point-source eutrophication, albeit with varying degrees of success (Søndergaard et al. 2007); however, eutrophica-

DOI: 10.5268/IW-6.1.864

tion-control efforts with notable successes in lakes focusing on phosphorus control (Schindler and Vallentyne 2008) shifted focus in the 1980s to diffuse sources of nutrients, especially agricultural sources. In the United States, nonpoint nutrient controls were mandated in 1987 when the Clean Water Act was extensively overhauled and expanded (Davidson and Delogu 1989).

By the mid-1990s, paleolimnological evidence from Canada and the United States began to indicate that cultural eutrophication of lakes due to nonpoint sources was not as extensive as hypothesized (Hall and Smol 1996, Dixit et al. 1999, Whittier et al. 2002). Bachmann et al. (2013, 2014) subsequently used paleolimnological data from the US Environmental Protection Agency's (USEPA) 2007 National Lakes Assessment to estimate the extent that natural lakes in the conterminous United States had been changed by anthropogenic activities and demonstrated that the proportions of lakes categorized as oligotrophic, mesotrophic, eutrophic, and hypereutrophic for the presettlement time period were not significantly different from the proportions found in 2007. Other studies further showed long-term stability in the clarity of US lakes (Carlson et al. 2012, Lottig et al. 2014).

Consequently, when McCullough et al. (2013) used satellite-inferred Secchi disk depths from 1995 through 2010 to propose that water clarity in Maine lakes was declining due in part to eutrophication, it seemed further investigation of changes in the water clarity of Maine lakes over time was necessary because: (1) the Maine Department of Environmental Protection (MDEP) had not reported extensive eutrophication of Maine lakes; and (2) concerns about the extent of cultural eutrophication of natural lakes in the United States have generated considerable interest in the scientific community (Bachmann et al. 2013, 2014, McDonald et al. 2014, Smith et al. 2014).

In this study, we use the measured Secchi readings collected by the citizen scientists of VLMP between 1976 and 2013 to ascertain trends in lake water clarity. This program sampled >100 lakes in 1976 and expanded to >300 in 2013, providing excellent statewide coverage (Fig. 1). Additional measurements such as water color, chlorophyll, and total phosphorus were obtained during August by MDEP staff every 3–5 years. By 2013 the database on Maine lakes from both professionals and volunteers had >13 500 lines of yearly average information (not all parameters were available for each line), providing information on the range of conditions for each lake in the program that would allow the detection of any changes that might indicate a problem such as eutrophication. This unique dataset on Maine lakes also allowed us to investigate which factors, such as lake morphometry, chlorophyll, and water color, were important in determining Secchi disk depths among Maine lakes.

We were further interested in determining temporal trends in the water clarity of Maine lakes over various periods of time using the VLMP volunteer data, satellite data, and data from a prior paleolimnological study. Specifically, were Secchi disk depths increasing, decreasing, or staying about the same? Finally, we examined the suggestion of McCullough et al. (2013) that satellite monitoring of water clarity was an effective method to monitor water quality of Maine lakes over time.

Methods

Data sources

Maine lake data

Maine's VLMP collected most of the Secchi disk data used in our study. Volunteers are trained and certified to collect water clarity data with a 20 cm Secchi disk with black and white quadrants and a viewing scope provided by VLMP. Volunteers typically collect data every 2 weeks from May to October at the deepest point in a lake. The VLMP staff and MDEP staff review the data before uploading them to the state database, where each Maine lake is identified by a Maine Information Display Analysis System code (MIDAS). In later years, the volunteers collaborated with MDEP (Bacon 2013) to collect surface water for laboratory analysis of pH, specific conductance, color, chlorophyll, and total phosphorus.

Standard methods (APHA 1998) were used to determine pH (Method #4500-HB), specific conductance (Method #2510B), and chlorophyll (Method #10200H-2). Total phosphorus was measured using Lachat Method 10-115-01-1-F. Since 1996, water color has been measured using Hach Method 8025 for true and apparent (nonfiltered) color expressed in platinum–cobalt (Pt–Co) units (Hach Water Analysis Handbook at http://www.hach.com/wah). Prior to 1996, apparent color was measured by use of a Hach color wheel and Nessler Tubes.

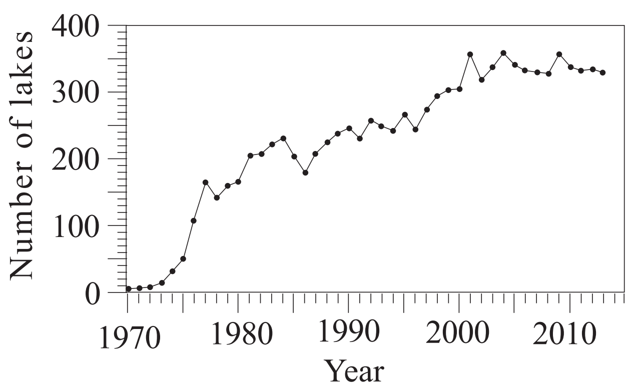

Fig. 1. Number of lakes sampled by volunteers each year from 1970 through 2013.

 DOI: 10.5268/IW-6.1.864

In 2000, MDEP measured both apparent color and true color (filtered sample) and averaged the readings for reporting summary data. The accuracy of the nonspectrophotometric methods is about ±5 Pt–Co units, and the accuracy of the spectrophotometric method is closer to ±1 Pt–Co units.

For lakes with more than one sampling station, we used a single waterbody average for the day in our data analyses. After removing lakebed Secchi depth readings from the dataset, we had Secchi depth information on 920 lakes. Of these, 246 had 20 or more years of Secchi depth information, and 10 lakes had field-measured Secchi readings spanning >40 years.

Other Maine data

MDEP provided us with morphometric data on lake areas, maximum depths, and mean depths for 675 of the lakes in our study. As a measure of the potential for wind resuspension of sediments in these lakes, we calculated the dynamic ratio for each lake by dividing the square root of the surface area in kilometers by the mean depth in meters (Håkanson 1982). We also used the website of the National Centers for Environmental Information (http://www.ncei.noaa.gov) to obtain monthly precipitation (Jan–Jun) from 1975 through 2014 for the airport weather station at Portland, Maine.

Satellite-inferred Secchi depths

McCullough et al. (2012) combined Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) brightness values for TM bands 1 (blue) and 3 (red) to develop a method for estimating Secchi disk depths in 1511 Maine lakes with areas >8 ha. These lakes were located in Landsat paths 11–12, rows 27–30, which cover most of the eastern and western portions of the state, with an overlap in the center (Fig. 2). Data from single days from 9 August to 14 September were used for years 1990, 1995 (2 estimates), 1999, 2002, 2004, 2005, 2009, and 2010. We obtained their satellite-inferred Secchi depths from the supplementary data tables of McCullough et al. (2012).

Paleolimnological data

As a part of the USEPA's Environmental Monitoring and Assessment Program (Larsen et al. 1991), a probabilistic study of lakes and reservoirs in the northeastern United States (Fig. 2: Maine, New York, New Hampshire, Massachusetts Vermont, Connecticut, New Jersey, and Rhode Island) was carried out in the mid-1990s (Dixit and Smol 1994, Dixit et al. 1999). Short sediment cores were taken and used to describe the diatom communities at the tops and bottoms of the cores. The bottoms of the cores were examined using pollen and 210Pb dating to determine if the cores had reached a pre-1850 level.

As others have shown (Akbulut and Dugel 2008), it is possible to develop transfer functions to infer Secchi disk depths from the diatom community structures. In addition, diatom-inferred values were also found for total phosphorus, pH, and chloride. This sample of randomly selected lakes included data from 65 Maine lakes and 97 from the other states, all of which had bottom of core samples for a pre-1850 time period. We obtained the diatom-inferred data from the USEPA.

Statistical analyses

A flow chart was constructed to show the datasets and subsets with the most analyses (Fig. 3). All statistical analyses were performed using the JMP statistical package (SAS 2000). Where and when needed, data were log10-transformed to accommodate heteroscedasticity (Sokal and Rohlf 1981). Unless noted otherwise, all statements of significance are at $p < 0.05$.

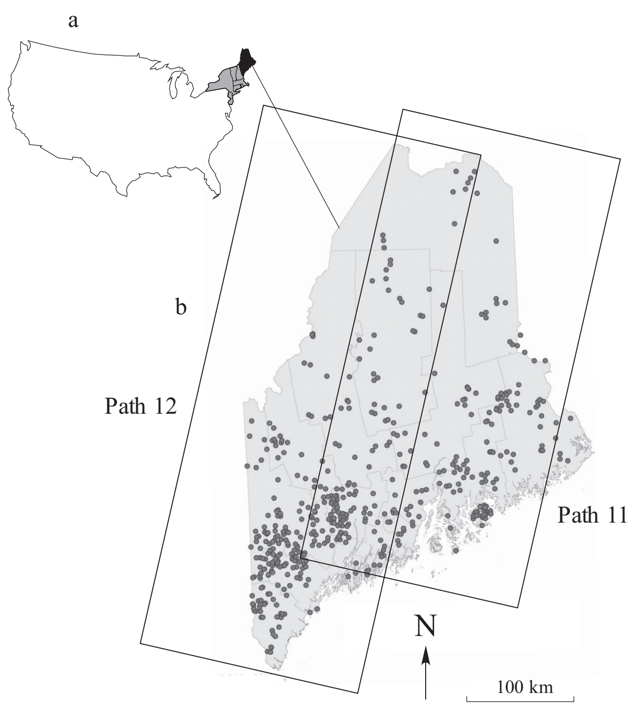

Fig. 2. (a) Outline of the continental United States. Areas shaded in grey or black show states with lakes with paleolimnological data on Secchi depths in 1850. (b) Map of Maine with dots for lakes sampled by volunteer monitors in 2012. The rectangular boxes are the satellite paths with satellite-inferred Secchi depths in the study of McCullough et al. (2012). The area where the 2 paths overlap contains the lakes used by McCullough et al. (2013) to infer Secchi depths in Maine lakes.

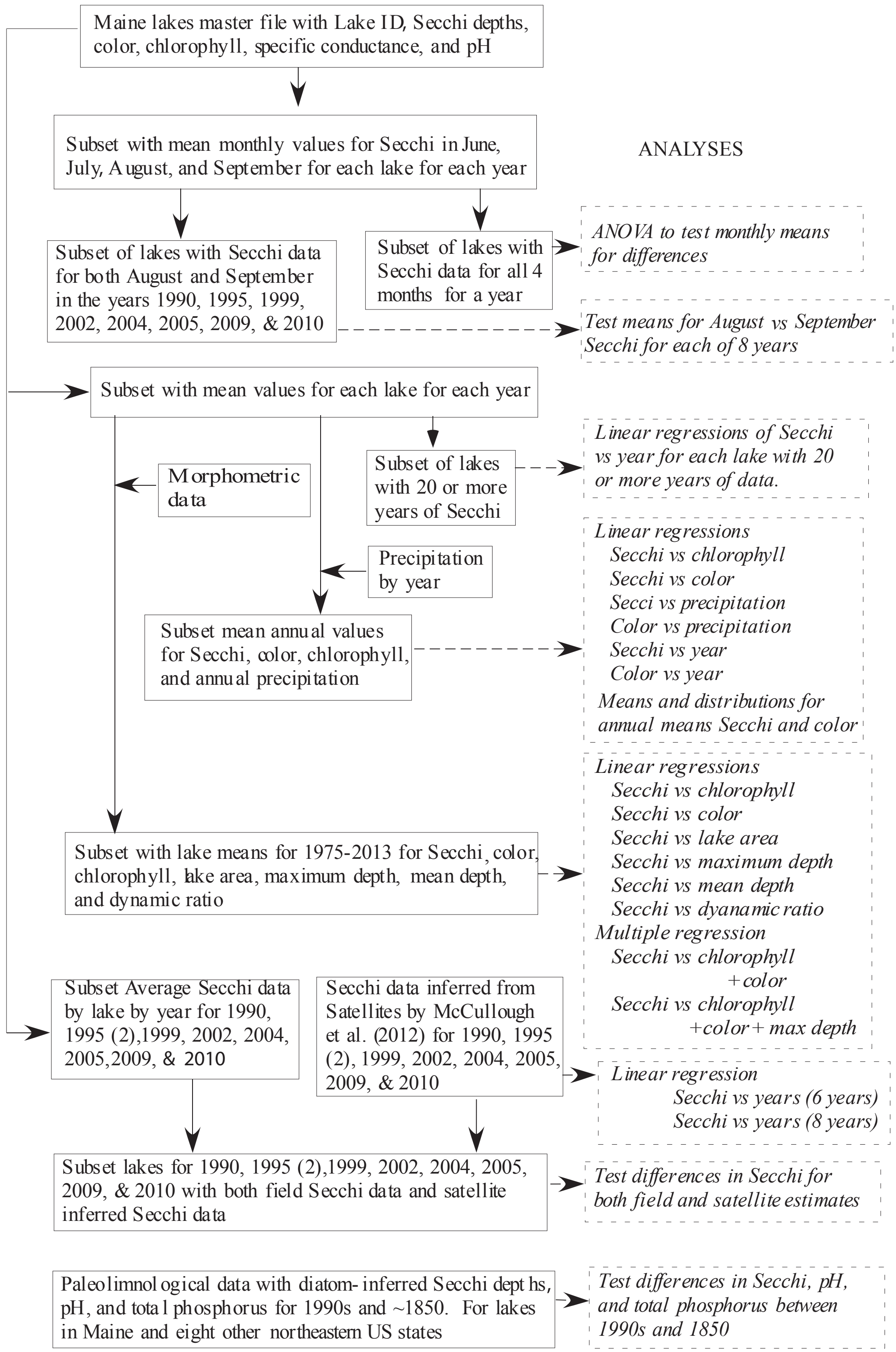

Fig. 3. Flow chart of analyses of data on Maine lakes. Boxes with solid lines represent datasets. Those with heavy lines are original data, and those with thinner lines are subsets derived from them. The dashed boxes hold lists of analyses made on the respective datasets.

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Seasonal changes

We used the Maine dataset to determine patterns in Secchi disk transparency during June through September. For each year, we extracted lakes that had Secchi disk readings for all 4 months and calculated monthly average Secchi disk depths of each lake for each month. These data were combined into a single dataset with data from 538 lakes, totaling 6436 readings for each month during 1975–2013. We used analysis of variance (ANOVA) to compare the mean monthly Secchi disk depths to determine any seasonal patterns. A Tukey-Kramer honest significant difference (HSD) test was used to compare all pairs of months for statistically significant differences.

To determine if Secchi disk depths decreased from August to September for the 8 years with satellite-inferred Secchi data, we used the Maine volunteer dataset to find all lakes with both August and September data. We determined the 2 monthly averages for each year and used *t*-tests to determine if the Secchi depths were significantly different.

Differences in the lakes over time

We used the Maine lake data to create a file with mean values for Secchi depths, chlorophyll, specific conductance, and water color for each lake for each year. A subset of 246 lakes with 20 or more years of Secchi data was used to run linear regressions of Secchi depths versus time for each of the lakes. Because we were conducting a large number of statistical tests on the same dataset, we used the false discovery rate (FDR) procedure of Benjamini and Hochberg (1995) to calculate an adjusted p-value. In addition to using the common alpha value of 0.05 to determine statistical significance, we also used alpha levels of 0.10 and 0.20 for these regressions to assess the effects of more relaxed criteria for statistical significance.

Differences among lakes

We used the Maine lakes data to create a subset with means for Secchi depths, water color, and chlorophyll for each lake during 1975–2013. We then added the morphometric data on lake areas, maximum depths, mean depths, and dynamic ratios to find basic distributional statistics for the Secchi depths and other physical and chemical variables. We created a subset of the lake averages by selecting lakes that had data for Secchi depths, color, and chlorophyll and used it for linear regressions for Secchi depth versus chlorophyll, water color, lake area, maximum depth, mean depth, and dynamic ratio. To determine the relative importance of color versus chlorophyll in determining Secchi depths, we found partial correlation coefficients for color and chlorophyll. Multiple regressions were also run for Secchi depth versus chlorophyll plus color and for Secchi depth versus chlorophyll plus color plus mean depth.

Comparison of field versus satellite-inferred Secchi depths

We developed a subset of annual average Secchi disk depths for each of the 8 years with satellite-inferred Secchi data, as reported by McCullough et al. (2012), and combined these data with the satellite-inferred data for the same years and the same lakes. For each year we compared the annual averages for both the field and satellite data using *t*-tests.

Satellite-inferred Secchi depths versus time

We used the satellite-inferred Secchi data from both Landsat paths 11 and 12 to find average Secchi depths for each of the 8 years including the 2 values for 1995 (Fig. 2). We ran linear regressions for Secchi disk depths inferred for all 8 years versus time, and also ran the same regression for satellite data collected for the 6 years used by McCullough et al. (2013).

Analyses of paleolimnological data

For the Maine lakes with paleolimnological data, we calculated the average diatom-inferred Secchi depths, pH values, and total phosphorus concentrations for the tops of the cores representing the early 1990s and the averages for the bottoms of the cores representing ~1850 and compared them with *t*-tests. For comparison we ran the same tests for the lakes in the other 8 states in the northeastern lakes survey.

Results

Characteristics of Maine lakes

The Maine lakes in the MDEP database exhibited a considerable range of limnological conditions (Table 1). As a group, the Maine lakes had clear water; of 920 lake-average Secchi readings, 75% were between 3 and 6 m, with an average of 4.9 m (Table 2).

The lakes are basically circumneutral with a mean pH of 6.9, but lakes with a pH as low as 4.2 or as high 9.5 exist. Chlorophyll and total phosphorus concentrations in the database averaged 5.0 and 11.5 µg/L, respectively, and averaged <3.7 and 9 µg/L, respectively, in 50% of the lakes, clearly indicating that most Maine lakes can be classified as oligotrophic or mesotrophic (Forsberg and Ryding 1980, McCullough et al. 2013). Most lakes also had a low specific conductance and color, with 50% of the lakes having conductance values <36 µS/cm and color values <23 Pt–Co units.

Table 1. Limnological conditions recorded by the Maine Department of Environmental Protection (1975–2013) for Maine lakes. The summary statistics are based on lake averages, and the numbers of lakes (n) with data varies because not all variables were measured in each lake. Water chemistry variables are based on surface grab samples.

Variable	n	Average	Minimum	Maximum	25th Quartile	75th Quartile
Secchi (m)	920	4.9	0.6	14.1	3.4	6.1
Color (Pt–Co units)	770	30	3	224	15	35
Chlorophyll (µg/L)	762	5.0	0.7	172	2.5	5.2
Total P (µg/L)	357	12	1	116	6	13
pH	733	6.9	4.2	9.5	6.6	7.1
Specific conductance (µS/cm)	748	47	3	807	26	52
Lake area (ha)	918	363	0.4	30 256	22	259
Maximum depth (m)	852	14	1.2	96	7	18
Mean depth (m)	834	5.6	0.9	30.8	3.4	6.7
Dynamic ratio	834	0.3	0.02	1.8	0.1	0.3

Seasonal changes in Secchi depths in the summer months

In our examination of monthly average Secchi disk readings, we found little difference among the months (Table 2). June was the lowest at 5.29 m followed by July at 5.46 m, August at 5.54 m, and September at 5.50 m. In general, the average values for the 4 months only differed from each other by about 4%. Individual lakes, particularly eutrophic lakes with chronic algal blooms, may not show the same even pattern. For the 8 years with satellite measurements, we found no statistically significant difference between the average Secchi depths for August and September (Table 3).

Factors related to differences in Secchi depths among lakes

Linear regression analyses of Secchi depths among lakes (Table 4) showed that color and chlorophyll were 2 important limnological factors influencing Secchi transparency in Maine lakes. There were hyperbolic relationships between measured Secchi disk depths and both color and chlorophyll, similar to those seen in Florida lakes (Canfield and Hodgson 1983).

When the data were logarithmically (base 10) transformed, Secchi disk depths were negatively and significantly related to color (R^2 = 0.60) and chlorophyll (R^2 = 0.51; Fig. 4a and b). A multiple regression of Secchi depths versus color and chlorophyll (Table 4) increased the amount of variance explained (R^2 = 0.74). Because color and chlorophyll were significantly correlated with each other (R^2 = 0.25; Table 4, Fig. 4e), we used partial correlation analyses to determine the relative affect of the 2 variables. The partial coefficient of correlation for the effect of color holding chlorophyll constant (r = 0.71) was similar to that for the effect of chlorophyll holding color constant (r = 0.62), indicating that both were important factors in determining the Secchi depths of Maine lakes. There were insufficient total phosphorus measurements to include them in the analyses.

Lake morphometry was also associated with differences in water transparency among Maine lakes.

Table 2. Mean values and standard errors for Secchi disk depths measured during June, July, August, and September based on annual lake averages over 38 years. Lakes with the same code letter are not significantly different from each other based on the Tukey-Kramer HSD test.

	June	July	August	September
Secchi disk (m)	5.29^{A}	5.46^{AB}	5.54^{B}	5.50^{B}
SE (m)	0.05	0.05	0.05	0.04

Table 3. Mean Secchi disk depths (m) and standard errors of the means in parentheses for August and September, along with the numbers of lakes (n) with samples in each month and the values for Student's t-test (t) for the differences between the 2 means and the probabilities that the differences are not different from 0. Data are from lakes in the Maine Volunteer Sampling Program. Years used are those with satellite-inferred Secchi disk depths (McCullough et al. 2013).

Year	n	August mean Secchi (m)	September mean Secchi (m)	t	Probability
1990	199	5.63 (0.16)	5.56 (0.17)	0.96	0.34
1995	201	5.90 (0.17)	5.78 (0.16)	0.93	0.35
1999	210	5.74 (0.15)	5.57 (0.15)	0.90	0.37
2002	242	5.82 (0.16)	5.77 (0.16)	0.97	0.33
2004	251	5.60 (0.14)	5.52 (0.15)	0.95	0.34
2005	248	5.72 (0.14)	5.71 (0.15)	0.99	0.32
2009	255	5.16 (0.12)	5.36 (0.13)	0.88	0.38
2010	230	5.83 (0.15)	5.74 (0.15)	0.95	0.34

DOI: 10.5268/IW-6.1.864

Table 4. Regression equations for different datasets (Fig. 3) using Secchi depths in m (Secchi), water color in Pt–Co units (Color), chlorophyll in µg/L (Chl-*a*), annual precipitation for Jan–Jun in cm (PPt), time in years (Year), lake area in ha (Area), maximum depth in m (z_{max}), mean depth in m (z_{mean}), and the dimensionless dynamic ratio (DR). Equation numbers are given in parentheses.

Regression equation	n	R^2	p
Annual means for all lakes sampled			
(1) log Secchi = 0.822 − 0.119 log Color	39	0.45	<0.0001
(2) log Secchi vs. Chl-*a* (Not significant)	39		0.17
(3) log Secchi = 0.767 − 0.000800 log PPt	39	0.30	<0.0001
(4) log Color = 1.193 + 0.00295 log PPt	39	0.13	0.026
(5) Secchi = −12.1 + 0.00876 Year	39	0.17	0.01
(6) Color vs. Year (Not significant)	39		0.42
Lake means for 1975–2013			
(7) log Secchi = 1.340 − 0.495 log Color	723	0.60	<0.0001
(8) log Secchi = 0.940 − 0.471 log Chl-*a*	723	0.51	<0.0001
(9) log Secchi = 1.317 − 0.356 log Color −0.287 log Chl-*a*	723	0.74	<0.0001
(10) log Secchi = 1.070 − 0.305 log Color −0.228 log Chl-*a* + 0.210 log z_{mean}	678	0.81	<0.0001
(11) log Color = 1.725 − 0.536 log z_{mean}	678	0.22	<0.0001
(12) log Chl-*a* = 0.902 − 0.469 log z_{mean}	678	0.18	<0.0001
(13) log Chl-*a* = −0.079 + 0.485 log Color	703	0.25	<0.0001
(14) log Secchi = 0.542 + 0.0618 log Area	723	0.06	<0.0001
(15) log Secchi = 0.238 + 0.403 log z_{max}	691	0.41	<0.0001
(16) log Secchi = 0.338 + 0.481 log z_{mean}	678	0.43	<0.0001
(17) log Secchi = 0.732 − 0.204 DR	678	0.07	<0.0001
Annual mean Secchi depths for lakes with satellite measurements for the 6 years used by McCullough et al. (2013)			
(18) log Secchi vs. Year (Not significant)	6		0.16
Annual mean Secchi depths for lakes with satellite measurements for the 8 years sampled by McCullough et al. (2013)			
(19) log Secchi vs. Year (Not significant)	9		0.69

Average Secchi depths for individual lakes were directly correlated with both mean depths (r = 0.43; Fig. 4f) and maximum depths (r = 0.41), but were only weakly correlated with lake areas (r = 0.06) and dynamic ratios (r = 0.07; Table 4). Both color and chlorophyll concentrations showed decreases with increasing mean depths in the Maine lakes (Fig. 4c and d). When mean depth was added to the multiple regression of Secchi depth versus color plus chlorophyll, the R^2 value increased from 0.74 to 0.81 (Table 4).

Factors related to differences in annual average Secchi depths

From 1975 through 2013, the annual average Secchi depths ranged from 4.6 m to 5.7 m, with an average of 5.3 m (Table 5). In the same time period, color ranged from 10 to 35 Pt–Co units and averaged 24 Pt–Co units (Table 5). The curve of annual precipitation for January through June versus time seems to be approximately the inverse of the Secchi depth curve (Fig. 5a and b), with peaks of rainfall matching lower Secchi depths and low rainfall years associated with greater Secchi depths. Annual average Secchi depths were inversely correlated with color (Table 4, Fig. 6a). Unlike the case with average values for individual lakes, there was no statistically significant correlation between annual average Secchi depths and annual average chlorophyll values (Table 4).

Annual average Secchi depths were negatively correlated with annual precipitation, and color was positively correlated with precipitation (Table 4, Fig. 4c and d). Over the period of record, the Secchi depths showed a small but statistically significant increase ($R^2 = 0.17$; Table 4, Fig. 5b), but color showed no statistically significant change.

Trends in Secchi depths over time in individual lakes

Our analyses of trends in Secchi depths for 246 individual lakes with 20 or more years of data found 22% of the lakes had increasing Secchi disk depths and 10% had decreasing depths when we used the FDR procedure of Benjamini and Hochberg (1995) to calculate an adjusted *p*-value with an alpha of 5% (Table 6). When we changed our criteria for statistical significance and used alphas of 10% and 20%, the same pattern was found, with more lakes showing increases in Secchi disk depths over time than those showing decreases over time.

Satellite-inferred Secchi depths

Comparison of field and satellite-inferred Secchi depths

When we compared the average summer Secchi depths in each lake with the average satellite-inferred Secchi depths from the same lakes, as estimated by McCullough et al. (2012), we found that the 2 averages were about the same for each year (Table 7). For some lakes, however, there were substantial differences between individual satellite-inferred Secchi depths and the average summer field Secchi depths as determined from measurements in the same lakes (Fig. 7a and b). The differences in the 2 measurements showed that the satellite data tended to underes-

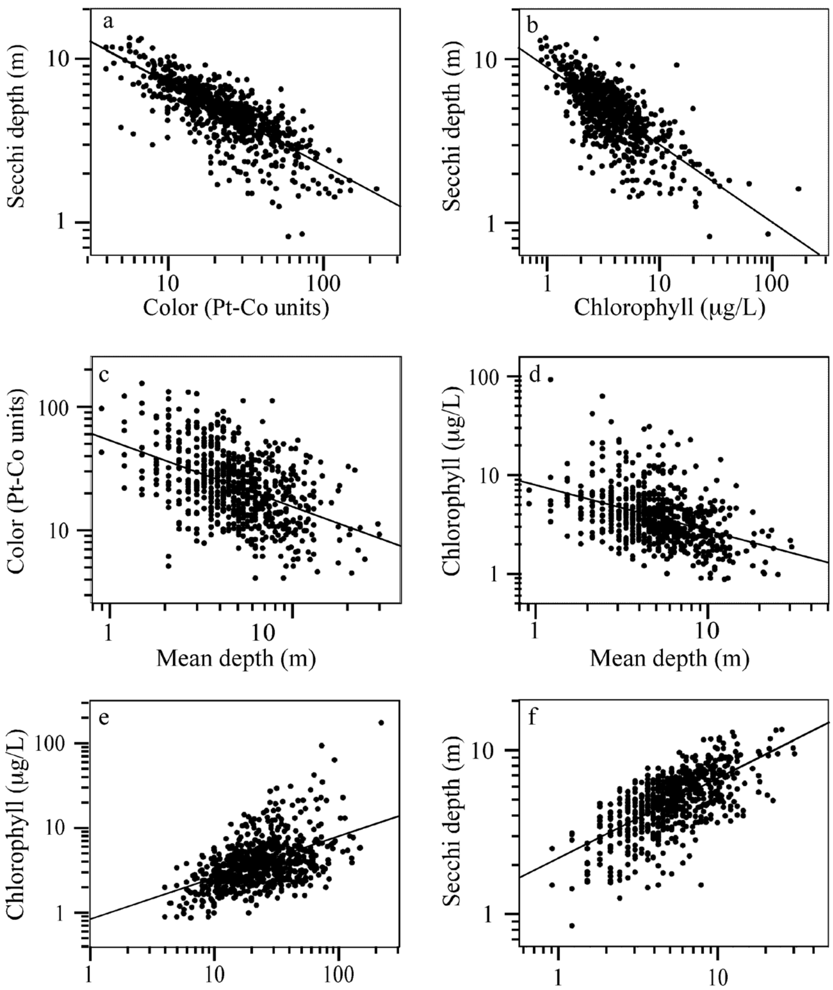

Fig. 4. Linear regressions with lake averages for 723 Maine lakes for (a) Secchi depth against color; (b) Secchi depth against chlorophyll; (c) color against mean depth; (d) chlorophyll against mean depth; (e) chlorophyll against color; and (f) Secchi depth against mean depth.

 DOI: 10.5268/IW-6.1.864

Table 5. Field measured Secchi disk depths and color from the Maine Department of Environmental Protection (MDEP) after averaging data by individual MIDAS identification code number and year. CV is the coefficient of variation for the mean value and color data were obtained from MDEP.

Year	n Secchi lakes	Mean Secchi (m)	Median Secchi (m)	Minimum Secchi (m)	Maximum Secchi (m)	CV	Color (Pt–Co units)	n color lakes
1975	97	5.5	5.1	1.7	14.1	38	19	35
1976	156	5.1	5.0	0.9	9.6	35	20	49
1977	195	5.1	4.8	1.2	11.6	40	28	39
1978	158	5.2	5.1	0.7	11.5	39	26	55
1979	181	4.9	4.8	0.4	15.5	44	35	87
1980	195	5.1	4.8	0.8	14.0	43	32	82
1981	244	5.0	4.6	0.8	12.5	44	30	101
1982	238	4.8	4.8	0.7	12.0	41	29	102
1983	252	5.0	4.8	0.6	12.5	43	23	102
1984	256	5.0	4.7	1.2	11.4	40	26	114
1985	225	5.7	5.4	1.4	15.2	41	20	85
1986	226	5.4	5.0	0.8	14.2	42	20	77
1987	231	5.3	5.2	0.8	13.7	40	19	89
1988	247	5.3	5.1	1.1	13.9	41	20	55
1989	343	5.0	4.7	1.0	13.0	41	32	98
1990	290	5.2	5.1	1.1	13.3	38	27	98
1991	284	5.2	5.0	1.1	15.9	40	25	137
1992	283	5.3	5.1	0.7	15.7	40	24	39
1993	262	5.6	5.5	1.1	13.3	36	10	49
1994	255	5.3	5.3	0.9	13.3	38	15	93
1995	286	5.7	5.5	1.1	17.1	39	15	100
1996	342	5.3	5.0	1.4	13.4	37	25	211
1997	320	5.3	5.2	1.1	17.8	38	22	140
1998	338	5.0	4.9	0.9	15.2	40	26	195
1999	391	5.4	5.3	1.0	17.7	40	18	227
2000	362	5.1	5.0	0.5	14.3	39	22	192
2001	433	5.4	5.3	0.7	17.5	41	24	246
2002	364	5.5	5.3	1.0	15.0	40	22	173
2003	404	5.6	5.5	1.0	15.0	41	22	226
2004	421	5.3	5.2	0.7	14.7	40	22	218
2005	381	5.2	5.1	0.9	13.8	38	24	198
2006	370	5.0	4.8	1.2	13.3	38	31	186
2007	349	5.6	5.6	0.8	12.5	34	22	173
2008	352	5.3	5.2	1.1	12.9	25	25	175
2009	390	5.1	4.9	0.9	11.8	27	27	111
2010	383	5.5	5.5	0.8	15.0	24	24	100
2011	375	5.3	5.1	0.7	15.2	23	23	145
2012	358	5.2	5.0	0.9	13.4	27	27	171
2013	367	5.3	5.1	0.8	13.6	37	30	186

Table 6. Regression analyses of annual average lake Secchi depths vs. years (1975–2013) for each of the 246 Maine lakes with 20 or more years of Secchi depth data, showing the percentages of lakes with increases or decreases in Secchi depths over time using 3 different levels of statistical confidence. The false discovery rate (FDR) procedure of Benjamini and Hochberg (1995) was used to calculate adjusted *p*-values.

Alpha level	Increasing Secchi depths	Decreasing Secchi depths
0.05	22	10
0.10	28	12
0.20	36	12

timate the Secchi depths when the field measurements were greater than ~7 m. The standard deviation for the differences between the satellite-inferred versus the field estimates of Secchi depth (Fig. 7b) is 1.53 m; therefore, the 95% confidence limits on an individual satellite-inferred measurement would be ±3.00 m.

Changes in satellite-inferred Secchi depths over time

Plots of annual average satellite-inferred Secchi depths using all 9 data points for the 8 years show no visible decline from 1990 through 2010 (Fig. 8). Linear regressions of satellite-inferred Secchi depths for the 6 years used by McCullough et al. (2013) showed no statistically significant change over time (Table 4). Further, there was no statistically significant change using all 9 points over the 8 years with data, as reported by McCullough et al. (2012). We also found no statistically significant correlation between average Secchi depths as determined by field measurements and years for the periods 1990–2010 (p = 0.96) and 1995–2010 (p = 0.74).

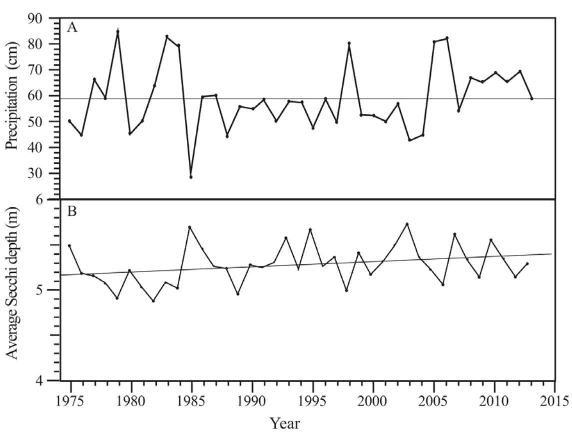

Fig. 5. (a) Precipitation in January through June at Portland, Maine, and (b) average Secchi disk depths from 1975 to 2013. The dashed line represents the statistically significant regression line.

Table 7. Comparison of field measured Secchi depths with satellite-inferred Secchi depths for the same lakes for 8 different years. Standard errors are in parentheses.

	Average Secchi depths (m)			
Year	n	Field	n	Satellite
1990	82	4.96 (0.19)	82	4.67 (0.16)
1995	90	5.30 (0.22)	90	5.44 (0.22)
1999	113	5.39 (0.20)	113	6.08 (0.21)
2002	97	5.14 (0.21)	97	4.75 (0.22)
2004	109	5.05 (0.21)	109	4.63 (0.13)
2005	66	4.98 (0.23)	66	5.52 (0.23)
2009	94	4.84 (0.20)	94	4.76 (0.21)
2010	101	5.50 (0.22)	101	5.14 (0.18)

Changes in Secchi depths in Maine lakes since 1850

The paleolimnological investigation revealed no statistically significant difference between the average diatom-inferred Secchi disk depths from diatoms deposited historically (pre-1850) to those deposited more recently in the early 1990s (Table 8). The same is true for pH and the concentration of total phosphorus. We also found the same was true for randomly selected lakes in the states of New York, New Hampshire, Massachusetts, Vermont, Connecticut, New Jersey, and Rhode Island that were sampled at the same time (Table 8).

Discussion

Geological setting for Maine lakes

Maine is a geographic area that was completely covered by glacial ice 16 000 years ago (Maine Geological Survey 2003). About 15 000 years ago, the glacier retreat began, freeing southern Maine from ice cover. The last continental glacier was so thick and heavy that it depressed the Earth's bedrock crust, allowing the sea to flood lowland areas in southern Maine. Thus, one of Maine's distinctive glacial legacies is a blanket of marine sediments across southern portions of the state. The final recession of the ice sheet caused the land to rise, and a variety of sedimentary deposits (e.g., sand and gravel) were released from the melting glacier. Present-day surficial geology is dominated by glacial till and exposed bedrock with a thin glacial sediment cover, but there are areas of recent swamp, marsh, and bog deposits where surficial waters are highly colored

DOI: 10.5268/IW-6.1.864

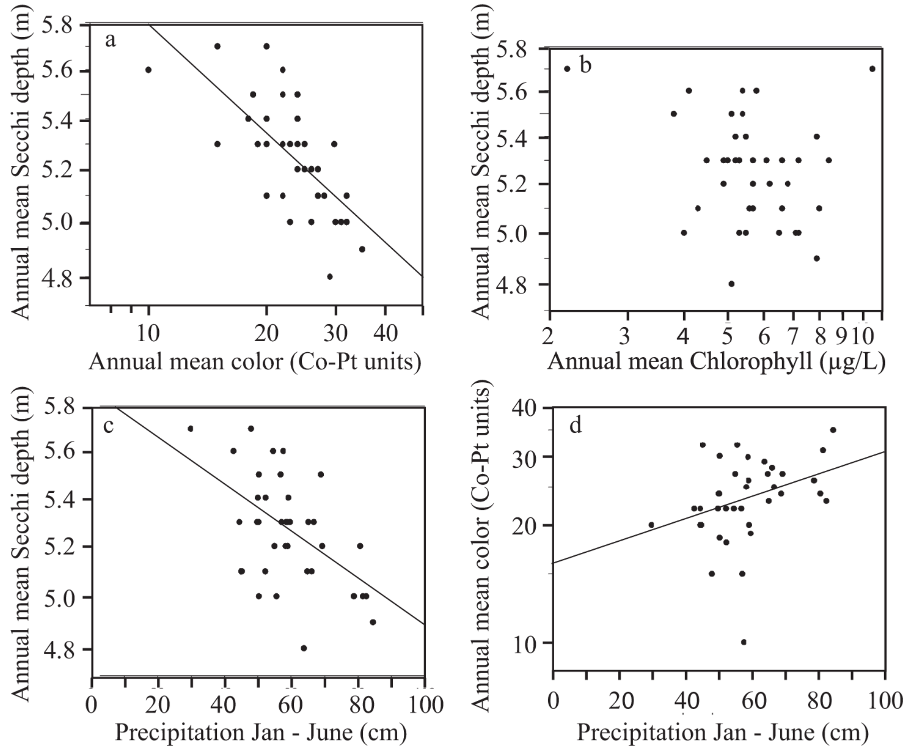

Fig. 6. (a) Annual mean Secchi depths vs. annual mean water color based on lakes sampled; and (b) annual mean Secchi depths vs. annual mean chlorophyll from 1975 to 2013. (c) Annual mean Secchi depths vs. annual precipitation and (d) annual mean water color vs. annual precipitation from January through June. Logarithmic scales used for Secchi depths, water color, and chlorophyll. Best-fit regression lines are shown for statistically significant regressions ($p < 0.05$).

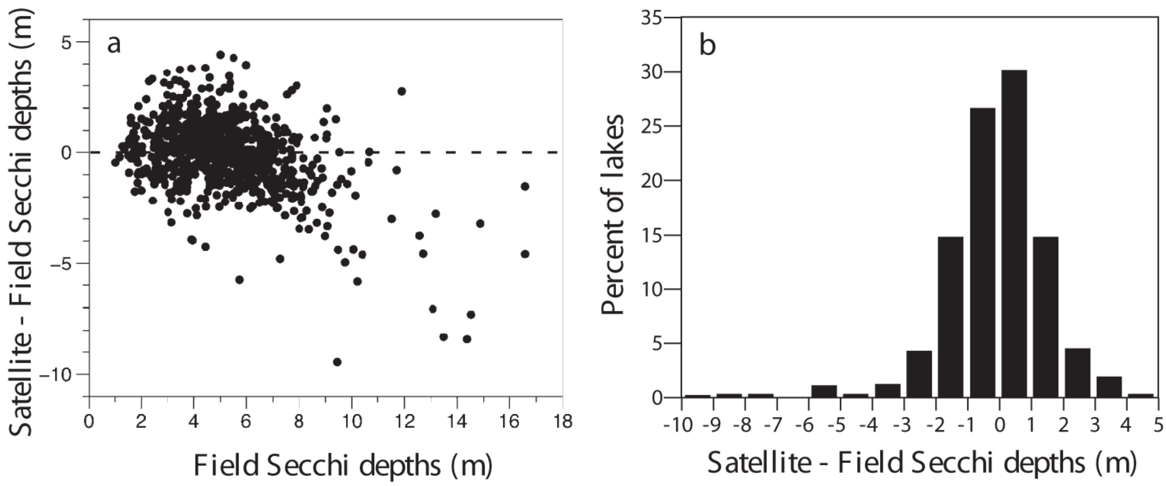

Fig. 7. (a) The differences between the satellite-inferred Secchi depths and the field measured Secchi depths in the same lakes for 8 summers. The dashed line represents no difference. (b) Frequency distribution of differences in the satellite-inferred Secchi depths and the field measured Secchi depths.

(www.maine.gov/dacf/mgs/pubs/online/surficial/surficial11x17.pdf). Maine is also the most heavily forested state in the United States (90% coverage), and the forest coverage has been essentially stable for the last several decades (Maine Forest Service 2005).

Factors related to average Secchi depths among Maine lakes

Water quality:

Both water color and chlorophyll were important factors in determining differences in Secchi depths among Maine lakes (Fig. 4a and b, Table 4). Higher concentrations of either variable were associated with reductions in Secchi depths. Color has long been known to absorb light in lakes and reduce Secchi depths (Davies-Colley and Vant 1987), and the same is true for algal populations as represented by chlorophyll concentrations (Tilzer 1988). Because there was a weak correlation between color and chlorophyll (Table 4, Fig. 4e), we used a partial correlation analysis to find that both were equally important for determining water transparency in our sample lakes. A combination of both color and chlorophyll in a multiple regression showed the strongest relationship and accounted for 74% of the variance (Table 4). This is similar to the results of Nürnberg and Shaw (1998), who found an R^2 of 0.78 when they ran the same multiple regression with data from >600 lakes in North America, Europe, New Zealand, and Asia. Because we did not have measurements of suspended inorganic solids, we could not evaluate their importance to Secchi depths in the Maine lakes.

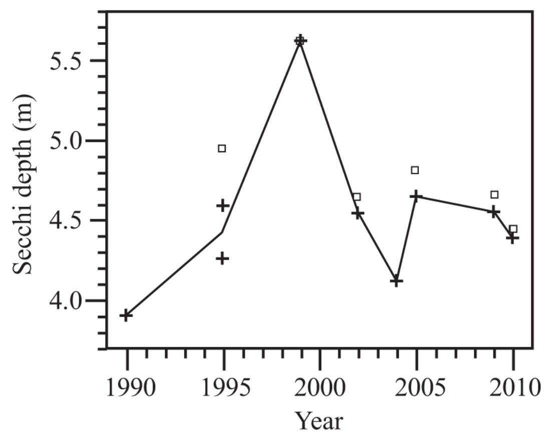

Fig. 8. Average Secchi disk depths in a group of Maine lakes as inferred from satellite images. Open squares represent 6 points as published by McCullough et al. (2013). The 9 crosses represent our averages as calculated from the data for McCullough et al. (2013).

Morphometry

We found that Secchi depths were related to lake depths whether expressed as maximum depths or mean depths, with deeper lakes on average having the greater Secchi depths (Table 4), in accord with the well-known finding that deep lakes tend to be less productive than shallow lakes and thus have more transparent waters (Rawson 1952). Others have developed models to predict Secchi depths in lakes using mean depths as well as other morphometric features of lakes and their watersheds (Håkanson 1995, Håkanson and Boulion 2001, 2003). Other factors being equal, deeper lakes will provide more dilution to incoming loads of nutrients or other dissolved substances. For the Maine lakes, both color and chlorophyll were inversely correlated with mean depth

Table 8. Mean values for diatom-inferred Secchi depths, pH, and total phosphorus concentrations for a pre-1850 time and the early 1990s as determined by short sediment cores taken as a part of the USEPA EMAP program (Dixit and Smol 1994, Dixit et al. 1999). Data shown for lakes in Maine and other lakes in the northeastern states. Standard errors are in parentheses. Student's *t*-value (*t*) between the time periods and statistical probability for the comparisons are provided. Secchi data for 1850 and 1990s in 15 Maine lakes and 8 lakes in other northeastern states were excluded because the recent field Secchi disk readings were on the bottom of the lake and were underestimates of the true transparency.

Variable	n	Average 1850 Secchi	Average early 1990s Secchi	*t*	Probability
		Maine lakes in study			
Secchi (m)	53	3.7 (0.26)	3.8 (0.28)	0.24	0.81
TP (µg/L)	65	11.8 (0.99)	12.3 (1.22)	0.33	0.73
pH	65	7.44 (0.05)	7.44 (0.08)	−0.02	0.99
		Other lakes in northeastern United States			
Secchi (m)	89	3.6 (0.21)	3.5 (0.22)	−0.59	0.55
TP (µg/L)	97	12.3 (1.67)	21.6 (5.33)	1.66	0.10
pH	97	7.37 (0.06)	7.41 (0.08)	0.36	0.71

 DOI: 10.5268/IW-6.1.864

(Table 4, Fig. 4c and d). Secchi depths were only weakly correlated with lake area or the dynamic ratio (Table 4). When the mean depth is added to our multiple regression of Secchi depths versus color plus chlorophyll, 81% of the variance in Secchi depths among lakes is explained (Table 4), and no further statistically significant increase in R^2 is found when the dynamic ratio is added to this multiple regression. This finding indicates no effect of potential sediment resuspension on Secchi depths for our sample of Maine lakes, although for some individual lakes it might be important.

Factors related to annual average Secchi depths for Maine lakes

The average annual Secchi depths and water color for all lakes sampled in the volunteer program for each year from 1975 through 2013 fluctuated between 4.8 and 5.7 m (Table 5, Fig. 5b). In examining the factors involved in changes in Secchi depths from year to year, we found that the annual average Secchi depths were inversely correlated with the annual average color values but not annual average chlorophyll values (Table 4). This finding indicates that color is the dominant variable in determining yearly changes in Secchi depths, and that changes in average chlorophyll values from year to year are not important in determining fluctuations in average annual Secchi depths.

We found that both water color and Secchi depths in the summer months were inversely related to the accumulated precipitation in January through June at the airport in Portland (Table 4, Figs. 6a and d), a finding in accord with the idea that increases in precipitation increase the amount of colored organic materials produced in wetlands of the lake watersheds. That color seems to be the key to annual variations in the annual average Secchi depths for Maine lakes is not unexpected because other studies have shown the same result (Pace and Cole 2002). For example, a long-term study of water clarity in Lake Annie, Florida, showed that color was the most important factor in determining Secchi depths in that lake (Gaiser et al. 2009a). Like Maine during drought periods, the water color decreased and the Secchi depths increased; when a dry period was replaced by a series of years with abundant rainfall, the water color increased and the Secchi depths decreased. The explanation for this phenomenon was that the rainfall washed in humic materials that had accumulated in the adjacent wetlands during the droughts. Changes in Secchi depths were related to the cycles of rainfall associated with the Atlantic Multidecadal Oscillation (Gaiser et al. 2009b). McCullough et al. (2013) also discussed the importance of color (i.e., dissolved organic carbon) for Maine lakes and noted that the greatest average Secchi depth in their 6-year study was during a drought.

Are there trends in Secchi disk depths in Maine lakes over time?

Long-term trends

The paleolimnological investigation of randomly selected lakes by the USEPA (Dixit et al. 1999) indicated that on average the lakes in Maine have not changed over the past 140 years (Table 8). There were no statistically significant differences between the average diatom-inferred Secchi disk depths from diatoms deposited around 1850 and those deposited more recently in the early 1990s (Table 8), and the same was true for pH and the concentration of total phosphorus, indicating that most Maine lakes have not been impacted by cultural eutrophication. Some Maine lakes, however, had been impacted by point-source sewage pollution in the past, such as Lake Sebasticook (Mackenthun et al. 1968), but such pollution has now been removed. The paleolimnological results for the Maine lakes are similar to those for the other lakes in the northeastern United States studied by the USEPA that also show no change (Table 8).

Trends for recent 20-year to 39-year periods

During 1976 through 2013, there is a small but statistically significant upward trend in the statewide average annual Secchi disk depths in the Maine lakes in our sample (Table 4, Fig. 5b), indicating that on average the Maine lakes are becoming clearer in recent decades. These 2 analyses based on the volunteer Secchi data did not show that cultural eutrophication has reduced Secchi depths in Maine lakes during 1975 to 2013.

Short-term changes

Our findings do not support the conclusion of McCullough et al. (2013) that during 1995 to 2010 Secchi depths in Maine lakes were decreasing and that cultural eutrophication might be responsible. Although they had collected and analyzed satellite data from 9 sets of satellite images over 8 years in establishing their methodology (McCullough et al. 2012), they used only satellite-inferred Secchi depths for 6 of the years to draw their downward trend conclusions (McCullough et al. 2013). They excluded data from 8 September 1990, 6 September 1995, and 14 September 2004 on the assumption that fall turnover had started at the time of data collection and that this would lead to decreased Secchi depths not representative of the conditions in August and early September when the other values were estimated. Field experience indicates that Maine lakes do not show an overturn that early in the fall, so we tested that assumption by comparing average Secchi disk depths for August and September for each of the years with satellite measurements. We found no statistically significant difference between the averages for the

2 months (Table 3), so we used statewide annual average satellite-inferred Secchi disk depths for each of the 9 dates reported in the methods paper by McCullough et al. (2012). The resulting plot showed fluctuations but no declining trend in Secchi depths for the Maine lakes during that time period (Fig. 8). Regressions of satellite-inferred Secchi depths with both 6 and 9 data points showed no statistically significant differences with time (Table 4). Similar regressions using yearly averages of the field-measured Secchi depths for time periods 1990–2010 and 1995–2010 also did not show statistically significant trends. There is no evidence that the lakes in Maine as a group are being changed by cultural eutrophication. We found that any changes in the average annual Secchi depths from year to year are most closely related to changes in water color rather than algal chlorophylls.

Field measurements versus satellite imagery to monitor regional water quality

McCullough et al. (2013) recommended using satellite data for monitoring regional water quality in Maine lakes because the imagery permitted assessment of remote, inaccessible lakes and eliminated the biases of nonrandom sampling typically used in acquiring field measurements. They noted, however, several years when they could not obtain cloud-free images. In the 21 years from 1990 through 2010 they only obtained usable data for 8 summers, leaving gaps in the dataset. The problem of cloudiness has been noted by other authors (Härmä et al. 2001, Wu et al. 2008,). In their study using Landsat TM at Poyang Lake in China, Wu et al. (2008) found that during 2000 to 2005, there were on average only 9 days a year with high quality images.

Further, McCullough et al. (2013) found that the method needed to be recalibrated each summer using data from a variety of Maine lakes with different vegetation patterns including samples from remote lakes. These field measurements needed to be conducted within a few days of the passage of the satellite, which would involve a large field sampling effort in a short period of time, with a chance that the satellite would not obtain a cloud-free image on that date. McCullough et al. (2013) also found the satellite method could only be used with lakes with surface areas of 8 ha or greater, and, according to them, would account for only 1550 of the 5700 lakes present in Maine, so this is not a random sample of all lakes in the state. We found that the 95% confidence limit on a satellite-inferred estimate was ±3.0 m, which limits their usefulness for documenting transparency for individual lakes (Fig. 7b). McCullough et al. (2013) noted that the satellite-inferred Secchi depths were less accurate in lakes with clear water. We found that satellite-inferred Secchi depths underestimated the field-measured values when Secchi depths were 7 m or more. Li and Li (2004) noted that lakes with deeper Secchi depths deliver less signal reflectance from algal turbidity in the water column to the satellite sensor, so they are not well detected with current sensors. This shortcoming is important because Secchi depths in clear lakes are most sensitive to small changes in chlorophyll concentrations.

The value of using citizen scientists in all types of monitoring programs has recently been recognized (Silvertown 2009), and the Maine program has provided information on a large number of lakes in which people are interested enough to sample on a regular basis in the summer. Information generated by citizens has proved comparable to that produced by professionals (Obrecht et al. 1998, Canfield et al. 2002, Hoyer et al. 2012), and, in the case of volunteer field measurements of Secchi depths, the data are much more precise than those for satellite-inferred depths. The citizen scientists have provided multiple samples during the summer and, through their dedication, decades of yearly data on many lakes. They also have provided the state of Maine other information such as oxygen profiles, color, chlorophyll, and nutrients, and as a result, Maine now has site-specific information for implementing or evaluating future management actions (e.g., Total Daily Maximum Loads or nutrient criteria).

The Maine VLMP does not use a random sample of all Maine lakes. Although a probabilistic or satellite sampling program might provide a statistically valid statewide trend evaluation for a given water quality variable that might show changes over time, these approaches do not provide site-specific information that can be used for solving problems in individual lakes. From a practical point of view, Carlson et al. (2012) noted that the chief advantage of citizen science monitoring is obtaining information biased toward waterbodies that volunteers, and presumably others like political leaders, find important. For volunteers, the data of importance is the current status of “their” lake and whether or not the lake is changing. VLMP volunteers have monitored Maine lakes year after year, providing an excellent picture of trends in transparency for specific waterbodies.

Implications for lake management

When water clarity declines in a waterbody, cultural eutrophication is frequently invoked as a possible causative agent, as McCullough et al. (2013) did for the Maine lakes. Year-to-year transparency fluctuations, based on direct Secchi measurements made by VLMP volunteers, ranged between 4.6 and 5.7 m. The changes

DOI: 10.5268/IW-6.1.864

over time illustrated the importance of long-term data; there were periods of years with a downward trend and other periods with a trend toward increasing water transparency. Although chlorophyll concentrations can influence water clarity in Maine lakes, long-term data analyses indicated that color is the dominant variable in determining yearly changes in Secchi depths. Water color and Secchi depths in the summer months were also inversely related to the accumulated precipitation in January through June, suggesting the importance of long-term changes in precipitation. For the Maine lakes, the volunteer Secchi data provided evidence that cultural eutrophication did not reduce Secchi depths in Maine lakes during 1975 to 2013. Cultural eutrophication, therefore, is not a widespread problem in Maine lakes.

Although 35+ years of water quality monitoring is a long time, it is short relative to anthropogenic activities around lakes in the United States. Bachmann et al. (2013, 2014) used paleolimnological data from the USEPA 2007 National Lakes Assessment to demonstrate that the proportions of lakes categorized as oligotrophic, mesotrophic, eutrophic, and hypereutrophic for the presettlement time period were not significantly different from the proportions found in 2007, indicating the cultural eutrophication problem from nonpoint sources may not be as widespread as first thought. Using paleolimnological data collected as a part of an earlier USEPA study, the Environmental Monitoring and Assessment Program (Larsen et al. 1991), there was no statistically significant difference between the average diatom-inferred Secchi disk depths from diatoms deposited historically (pre-1850) in Maine lakes to those deposited more recently in the early 1990s. The same was true for pH and the concentration of total phosphorus. Similarly, the same was true for randomly selected lakes in the states of New York, New Hampshire, Massachusetts, Vermont, Connecticut, New Jersey, and Rhode Island sampled at the same time. Focusing solely on cultural eutrophication by nonpoint sources may therefore not be the best use of financial resources for managing lakes.

Maine is the most forested state in the United States and is fortunate to have many clear lakes. Knowing that the overall clarity of Maine lakes is stable allows Maine's lake managers to focus their financial resources on obtaining water quality information from lakes previously not monitored and restoring waters definitely in violation of their water quality standards. Targeting the problematic lakes rather than all lakes will also focus resources on the protection of lakes identified as being at risk due to population growth/watershed/shoreline development and/or those having morphometric features that predispose them to the effects of cultural eutrophication. More important, monies can be allocated for other management issues such as aquatic plant management or the management of harmful invasive species. Resources will also become available for working more closely with citizens living along the lakes so that misinformation does not become the basis of poor management decisions.

Acknowledgements

We thank the many volunteers of VLMP and MDEP staff that have contributed to the establishment of the unique long-term Secchi database used in this study. Through the efforts of dedicated citizen scientists in Maine and elsewhere, professionals now have the information to begin testing the factor(s) causing changes in lakes, ultimately helping lake management become a scientifically based endeavor.

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