Interpreting Variations in

Secchi Disk Transparencies of Crater Lake,

A Deep Caldera Lake (Oregon)

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Abstract

Maximum Secchi disk depth readings of 40 m and 39 m in Crater Lake were recorded in 1937 and 1969, respectively. Disk readings from 1978 to 1987 indicated an apparent decline in lake clarity, although some readings were in the high 30 m range. In this paper, Secchi disk readings of the lake were evaluated relative to seasonal and annual variations and how variations of chlorophyll, primary production, and phytoplankton effected the readings. Considerable temporal variation was found both within and among years. The evidence suggested that Secchi disk depth readings made during the month of August have declined about 25 percent since 1969. The mean values for July and August from 1968 to 1987 showed a decreasing trend through 1982; thereafter, the readings have steadily increased. A significant positive linear relationship was found between Secchi disk depth and the depth of 1 percent incident light. Chlorophyll and phytoplankton (density and biovolume) were poorly correlated to Secchi disk depth. A weak negative relationship was found between areal primary production (0 to 40 m) and the disk readings. It can be argued that Secchi disk clarity in clear lakes like Crater Lake are sensitive to very small changes in the density and optical characteristics of biotic and abiotic particles. As such, variations in the Secchi disk clarity of the lake are dynamic and not readily explained by small changes of lake productivity. Future optical studies of Crater Lake need to include an examination of the characteristics and optical properties of the total particle community.

Introduction

Limnological studies from 1898 to 1969 found Crater Lake to be extremely unproductive and remarkably clear (Larson, 1972). Maximum Secchi disk depth readings of 40 m and 39 m were reported in 1937 and 1969, respectively (Hasler, 1938; Larson, 1972). But readings from 1978 to 1981 were in the high 20 to low 30 m range (Larson, 1984). It was difficult, however, to substantiate that the apparent decline in clarity was associated with changes in lake productivity because the amount of historic limnological information was small, and sampling methods and techniques varied. In 1982, the United States Congress mandated a 10-year monitoring and research program to investigate the water quality of Crater Lake. One of the main goals of the project is to identify and evaluate possible changing lake conditions that could explain the apparent decrease in lake water clarity. The objectives of this paper are to: (1) describe the available Secchi disk clarity data for Crater Lake, (2) present an evaluation of relationships between the Secchi disk readings and other limnological parameters of the lake, and (3) present some preliminary thoughts about interpretations of Secchi disk data.

Study Area

Crater Lake is located in Crater Lake National Park in southern Oregon. The lake covers the floor of the Mt. Mazama caldera that formed about 6800 years ago (Bacon, 1983). The lake lies at an elevation of 1883 m, has a surface area of 48 km2, a maximum depth of 598 m, and a mean depth of 325 m (Bryne, 1965). Steep walls surround the lake. The lake area to watershed area (flat map) ratio is 3.6. Approximately 78 percent of the precipitation entering the caldera falls directly on the lake. Surface inflow is restricted to intracaldera springs and streams. There is no surface outlet.

A thermocline (5-20 m) generally forms between late July and September, pH ranges from 6.9 to 7.9, total alkalinity ranges from 25.7-30.7 mg/l, conductivity ranges from 80-125 umhos/cm , and the water column is well oxygenated. Orthophosphate-P is fairly uniform in concentration (generally 11-18 ug/l) throughout the water column. Nitrate-N, however, is below detectable concentrations from the surface to 200 m. Below this stratum, the concentration (typically 11-16 ug/l) increases with depth. Deep water maximum for chlorophyll (100-120 m) and primary production (80-100 m) occur during summer months. A secondary near-surface peak of primary production is common (Larson et al., 1987). Depending on the time of year, maximum phytoplankton cell biovolumes occur near the lake surface (0-20 m) and at several depths down to 200 m (M. Debacon and C.D. McIntire, Oregon State University, unpublished data).

Limited data are available to document changing water quality and biological conditions in the lake. Surface water samples collected in 1912 (Van Winkle and Finkbinner, 1913), 1961-1981 (Anonymous, 1962, 1964, 1965-1981) and the present work do not show any major changes in pH, conductivity, Si, Ca, Mg, Na, K, and S. Comparative chlorophyll data from 1969 and 1984-1987 suggests that there has been a slight increase since 1984 (Table 1). There also is some indication that the density of phytoplankton in the upper stratum of the water column has increased since early studies by Kemmerer et al., (1924) and Utterback et al., (1942). Comparative data on primary production suggests an increase in 1987 (Table 2).

Crater Lake Secchi Disk Data

Hasler (1938) recorded Secchi disk depths of 36, 39, and 40 m in August, 1937 (Fig. 1). Although the lake surface conditions, sky conditions, times of day, and locations on the lake were not documented, it was assumed that the environmental

Table 1. Comparative Total Chlorophyll a Concentrations (0-220m) for Crater Lake, 1969 and 1984-87.

Year	Date	mg/m2	mg/m3
1969a	July 16	60.0	0.30
	August 5	35.0	0.18
	August 31	8.4	0.04
1984b	July 31	64.1	0.32
	August 14	28.9	0.15
1985b	July 23	28.9	0.15
	August 20	54.5	0.27
1986b	July 23	103.5	0.52
	August 20	122.3	0.61
1987b	July 23	96.3	0.48
	August 20	111.5	0.56

aData from D. Larson (1970. Sample depth: 0, 20, 40, 70, 110, and 200 m (Spectrophotometer).

b1984-87, Present work. Sample depth: 0, 20, 40, 60, 80, 100, 120, and 200 m (Fluorometer).

Table 2. Comparative Net Primary Production Data from Crater Lake, 1968-69, 1983, 1986, and 1987.

Year	Date	Carbon Assimilation mg/m2
1968a	June 14	27.3
	July 16	21.4
1969a	August 5	20.7
	August 31	32.7
1983b	July 15	27.5
	July 28	23.3
1986c	August 20	21.0
1987c	June 24	34.5
	July 23	48.7
	August 19	53.5
	September 16	49.7

aLarson (1970)

bDouglas Larson, personal communication

cPresent work

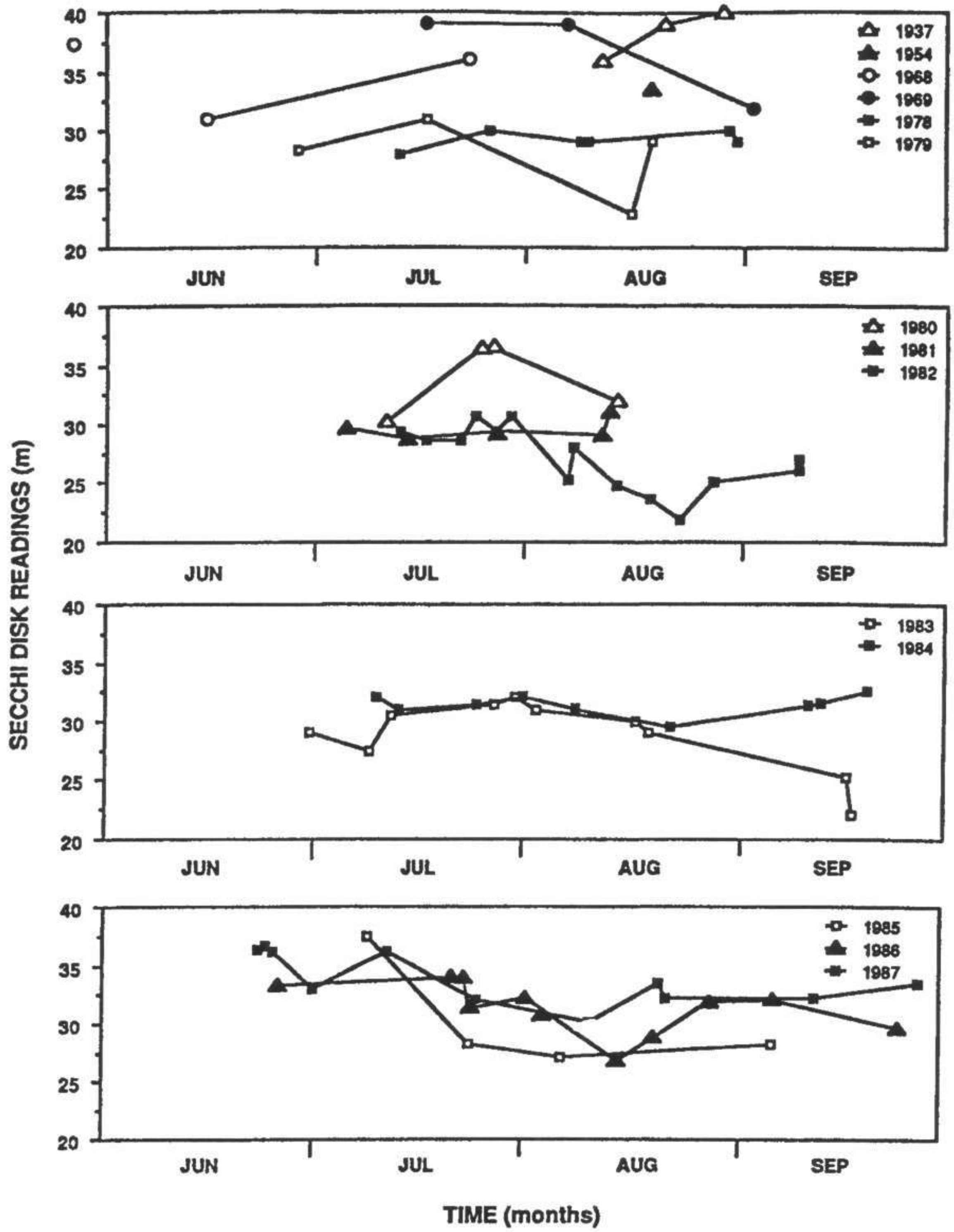

Figure 1. Secchi disk depth readings made under acceptable climatic conditions in Crater Lake by month from 1937 to 1987.

conditions were acceptable in order to obtain the high readings. All of the following data were collected under acceptable climatic conditions (Holmes, 1970; Preisendorfer, 1986). Readings in 1968 and 1969 ranged from 32 to 39 m (Larson, 1970). Measurements from 1978 to 1987 ranged from 22 to 37 m, with most in the high 20 to low 30 m range (Larson, 1984; Larson, 1987). The following general observations can be made from a comparison of these data:

1. The 40 m reading in 1937 has not been duplicated.
2. The 39 m readings in 1969 have not been duplicated since that year.
3. The highest readings since 1969 were 36 m, 37 m, and 36 m in 1980, 1985, and 1987, respectively.
4. Considerable within-year variation occurred in some years, including 1968 and 1969.
5. Temporal patterns among years were not consistent.
6. The lowest readings in 1968 and 1969 are similar to the highest measurements from 1978-87.

The results suggest that the environmental-limnological conditions that resulted in 39-40 m Secchi disk readings in 1937 and 1969 have not occurred from 1978-87. Since the 40 m and 39 m readings were made in August, comparing August readings among years suggests that the maximum lake clarity has declined about 25 percent during 1978-87 (Fig. 1). Comparing mean values for July and August from 1968 to 1987 indicates a decline in Secchi disk readings from 1968 to 1982 (Fig. 2). However, this trend has been followed by a steady increase in readings from 1983 to 1987.

Assessing Variations in Secchi Disk Clarity in Crater Lake

There is a significant linear relationship between Secchi disk readings and the depth of 1 percent incident light from 1968 to 1987 (Fig. 3). This is an expected

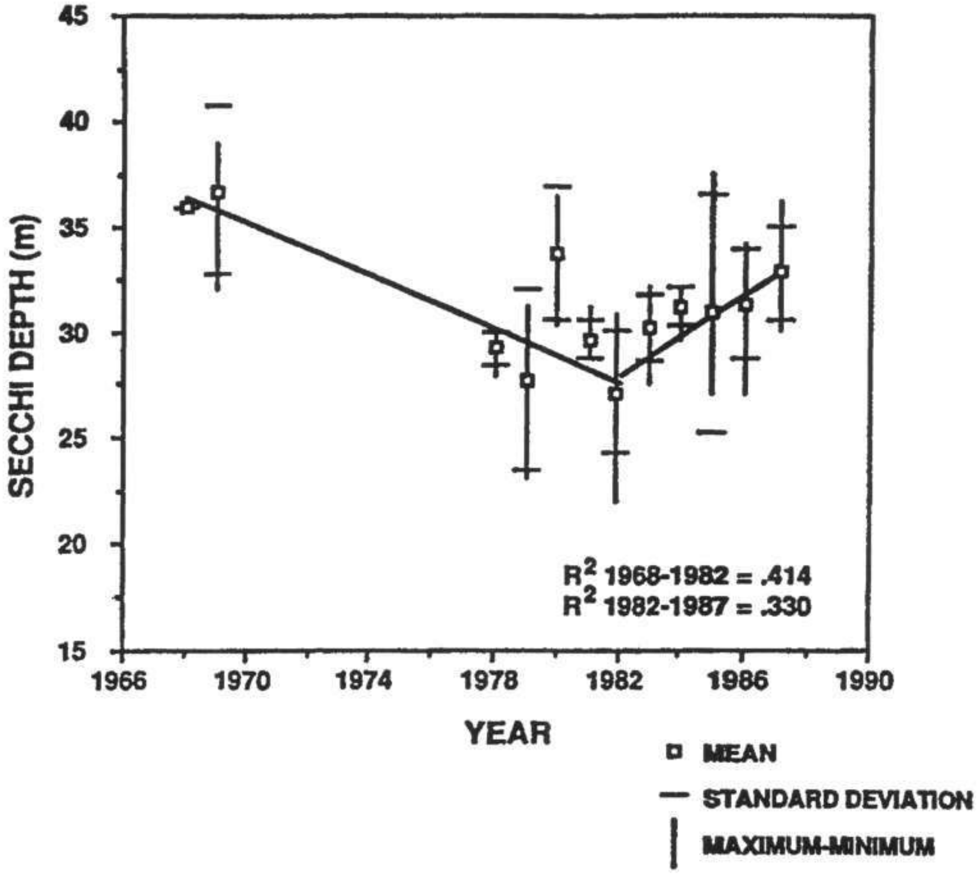

Figure 2. Mean Secchi disk depths (with maximum-minimum and standard deviation) for the months of July and August from 1968 to 1987, Crater Lake.

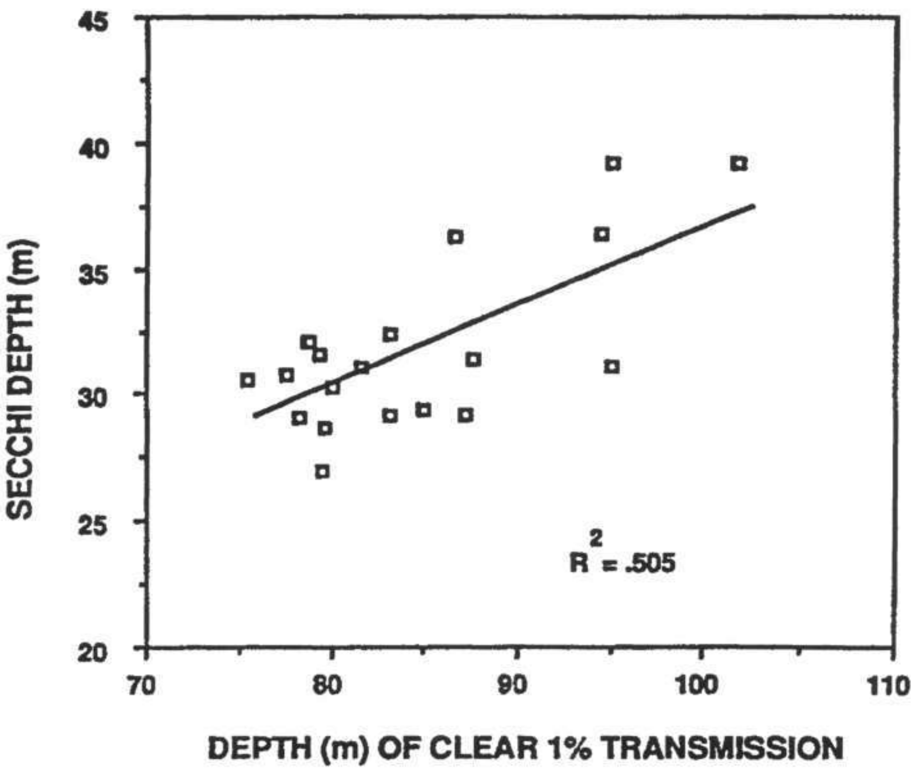

Figure 3. Relationship between Secchi disk depth and the depth of 1 percent incident light (1969-1987), Crater Lake.

result, but it is important to verify that the Secchi disk readings provide an index of the depth of light penetration into the lake.

The relationship between chlorophyll and Secchi disk clarity is hyperbolic (Edmondson, 1956; Carlson, 1977; Brezonik, 1978; Lorenzen, 1980; and Megard et. al., 1980). In Crater Lake, however, the relationship is poorly defined (Fig. 4). Furthermore, there is only a weak ($p = 0.10$) negative relationship between primary production/m2 (0-40 m) and disk depth (Fig. 5).

In theory, phytoplankton cell densities and biovolumes should have hyperbolic relationships to Secchi disk readings. In Crater Lake, there does not appear to be much of a relationship in either case based on the limited data available (Figs. 6 and 7).

Interpretation of Variations in Secchi Disk Clarity

The Secchi disk is a valuable tool for quick and inexpensive assessments of the clarity of lakes. Seasonal and annual variations of lake clarity as well as changes in lake productivity based on Secchi disk depth measurements have been well documented in the literature (Edmondson, 1956; Diller and Rigler, 1975; Shapiro et al., 1975; and Carlson, 1977). The depth at which the Secchi disk disappears is a function of the contrast between the light reflected from the disk and the scattering and absorption of incident light by water molecules, dissolved substances and particles in the water column. In lakes with low concentrations of dissolved and colored substances, particles are key to altering this optical contrast. A hypothetical relationship between particle density and Secchi disk transparency is shown in Figure 8. The relationship is not linear, because the amount of scattering and absorption of light increases exponentially as particle density increases. Two key points need to be mentioned about the relationship in Figure 8. First, how a given change in the density of particles of known characteristics will affect the

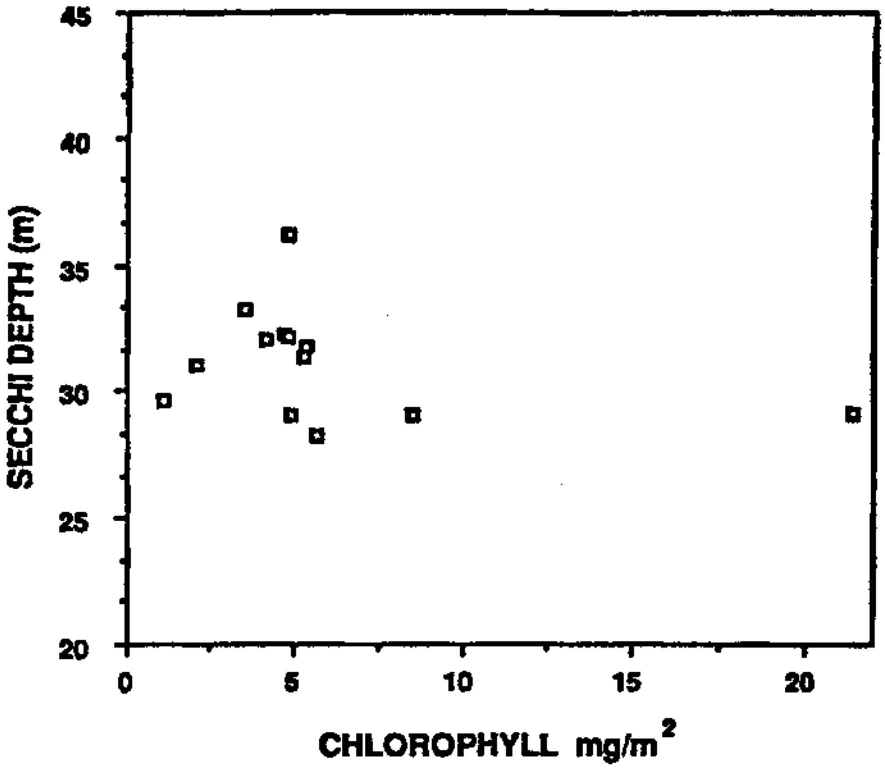

Figure 4. Relationship between chlorophyll from 0 to 40 m and Secchi disk depth (1984-1987), Crater Lake.

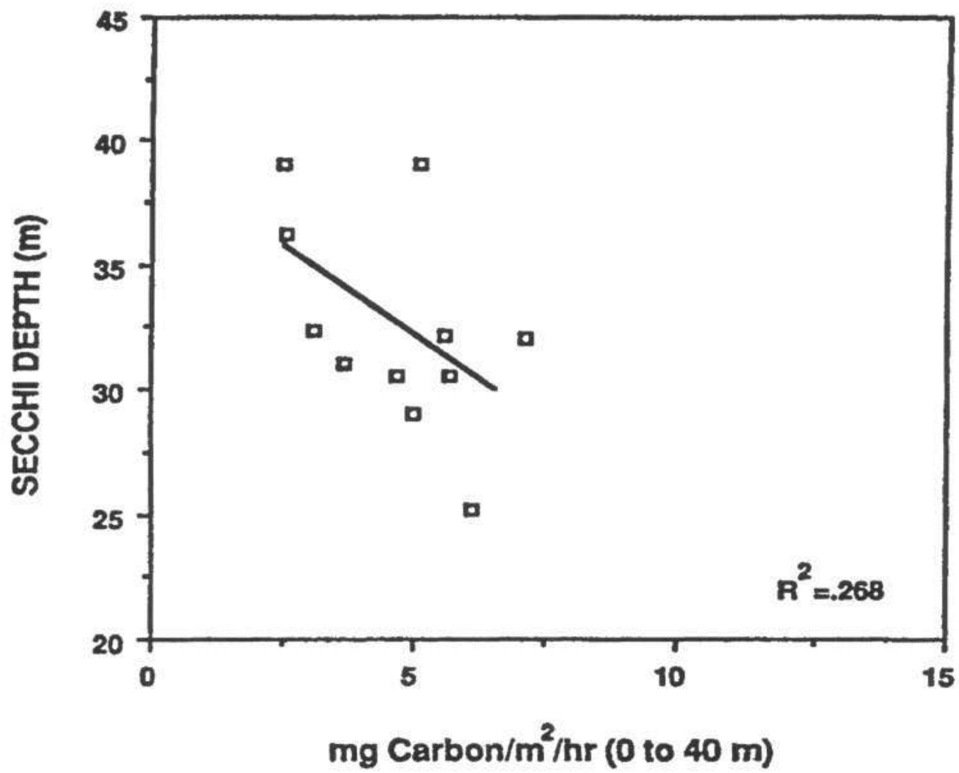

Figure 5. Relationship between primary production from 0 to 40 m and Secchi disk depth (1968-1987), Crater Lake.

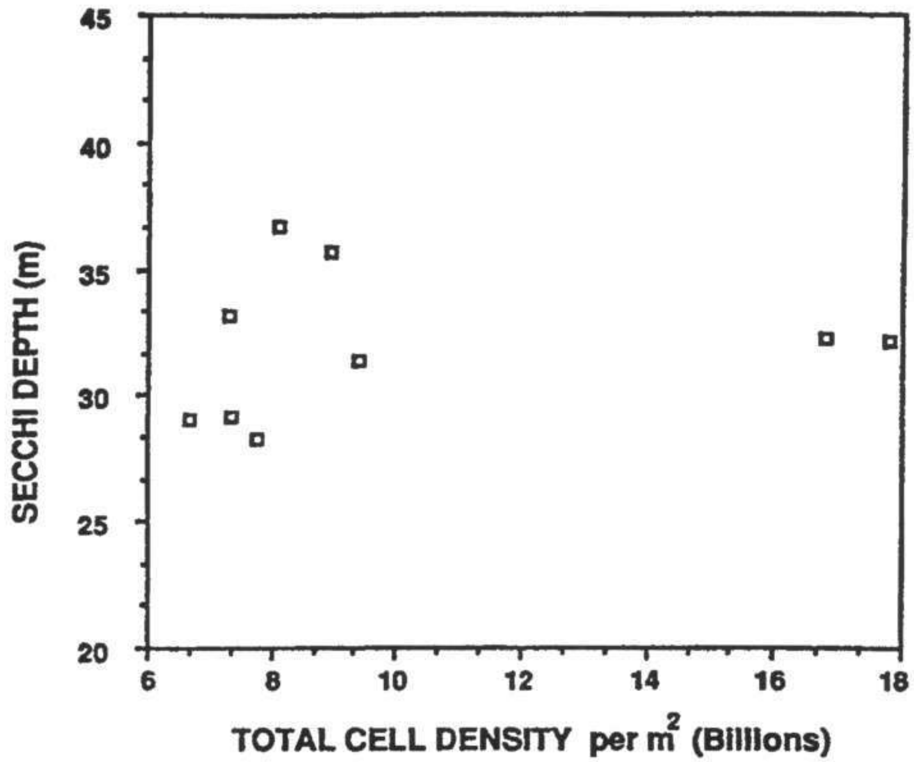

Figure 6. Relationship between total phytoplankton cell density from 0-40 m and Secchi disk depth readings (1985-1987), Crater Lake.

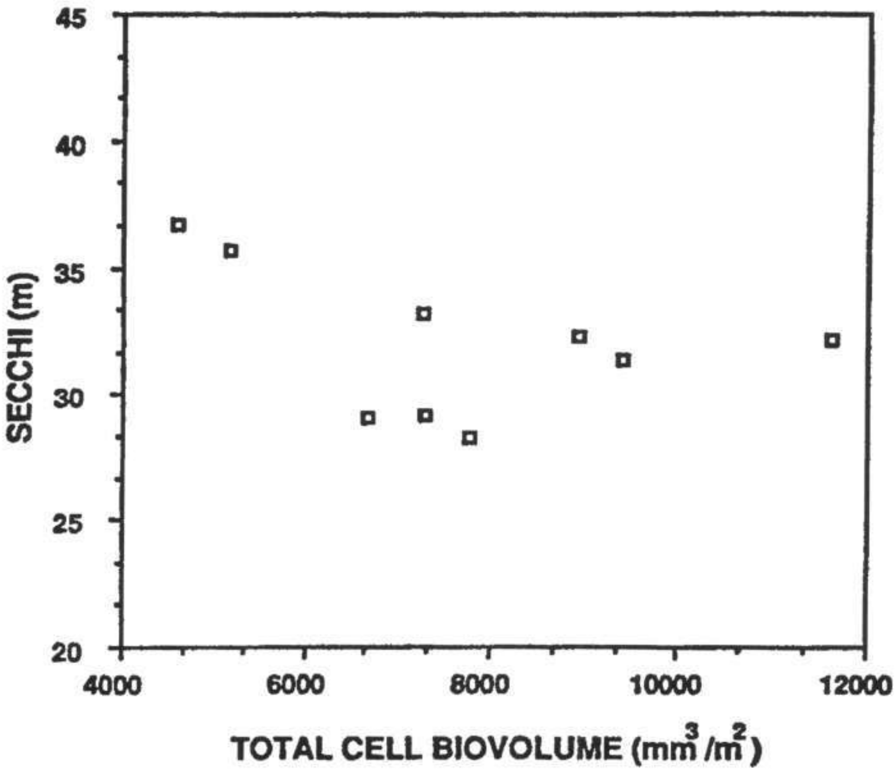

Figure 7. Relationship between total phytoplankton cell biovolume from 0-40 m and Secchi disk depth readings (1985-1987), Crater Lake.

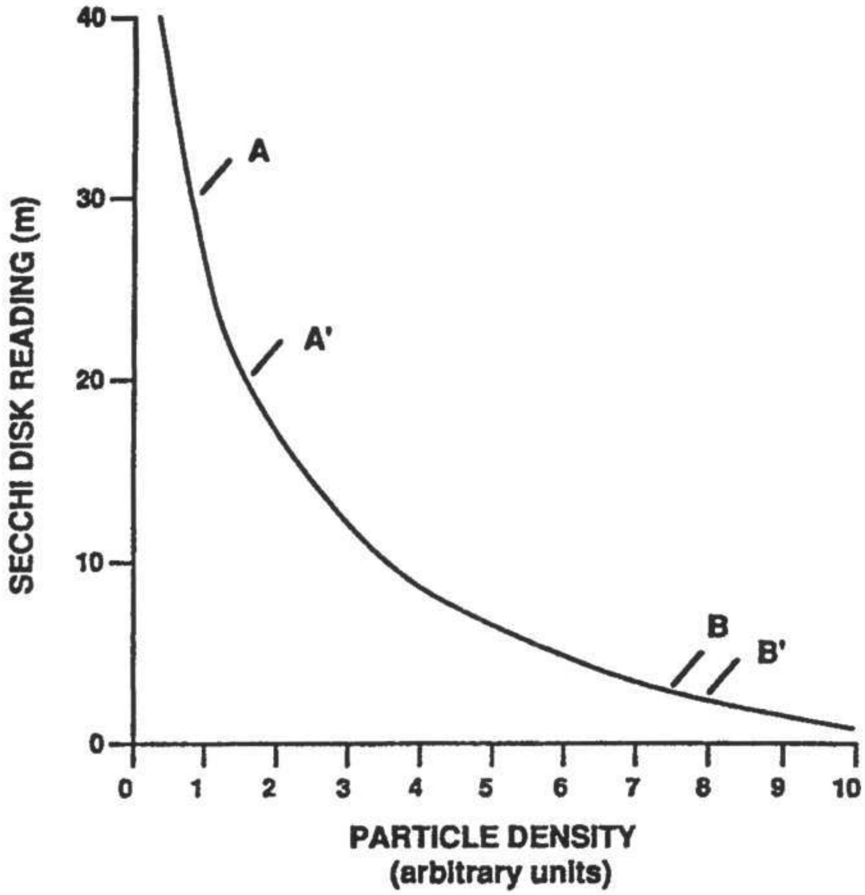

Figure 8. Hypothetical relationship between the density of particles with constant optical characteristics and Secchi disk readings.

Secchi disk reading depends on the initial particle density and the amount of change in density. If, for example, the particle density increased by 0.5 unit from point A to A' on the steep portion of the curve, the Secchi disk reading would decrease by about 10 m. But if the shift was from point B to B', the Secchi disk reading would decrease by about 0.5 m. It appears, therefore, that the Secchi disk readings in clear lakes are very sensitive to small changes in particle densities and that this sensitivity decreases exponentially as the initial particle densities increase. Second, since particles are the primary agent altering the optical contrast between the disk and the water column in clear lakes, the effects that different kinds, sizes, and shapes of particles have on the optical properties of the water are important to disk clarity (Edmondson, 1956; Halicki, 1958; Jewson, 1977; Gordon and Wouters, 1978; and Bertoni and Collieri, 1981). For this reason, the relationship between particle density and disk clarity is actually a family of curves depending on the optical properties of the particle communities.

Discussion

Variations in the Secchi disk clarity of Crater Lake are dynamic and can not be fully explained by small changes in lake productivity. Natural variation in disk clarity is great due to the sensitivy of the Secchi disk readings to small changes in particle densities and optical properties. That we did not find the expected hyperbolic relationship between Secchi disk readings and chlorophyll may represent changing optical properties of the particle community, problems with analytical detection limits, or problems of scale. For the latter, the data shown in Figure 4 may represent a small cluster of points near the upper end of the continuum between chlorophyll and disk clarity (Fig. 9). Owing to the location of the cluster, it would be difficult to detect relationships within the range of chlorophyll concentrations and disk depths in Crater Lake. In fact, it is possible that the

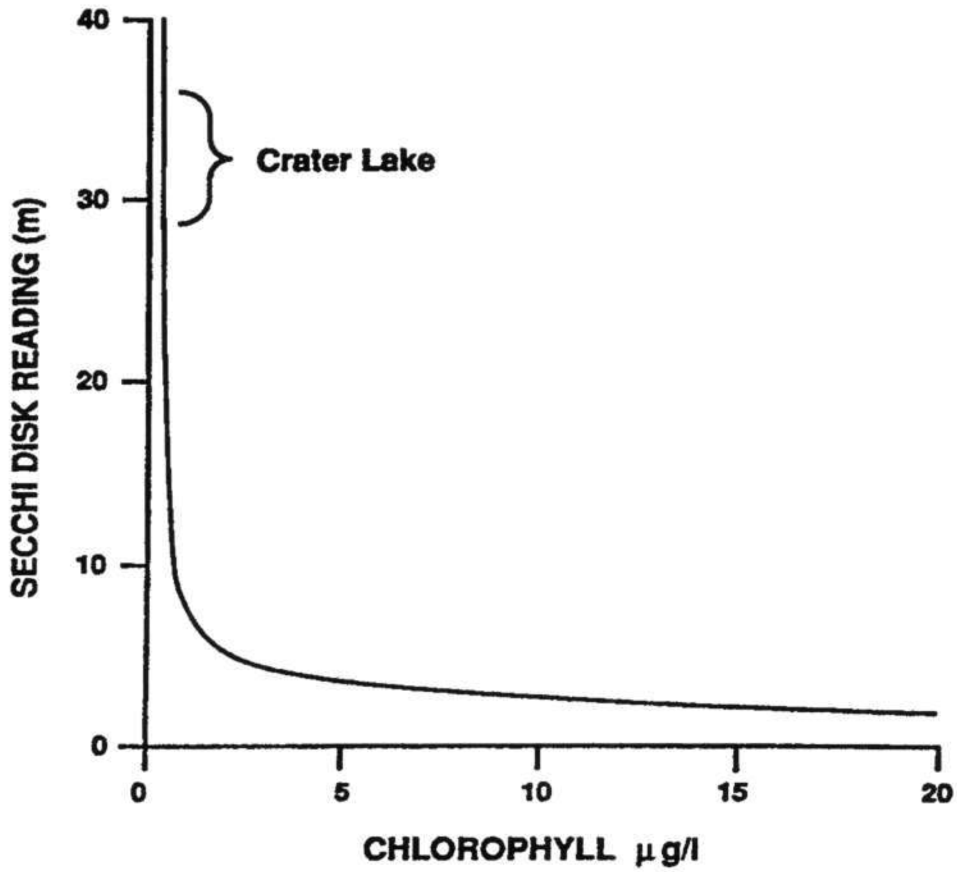

Figure 9. Relationships between chlorophyll and Secchi disk readings for lakes of different productivities (based on data from Carlson, 1977).

curve could be nearly parallel to the Y axis in Figure 4 as suggested in Figure 9. This situation is further complicated by the small effects that such low concentrations of chlorophyll probably have on the optical properties of the lake (Lorenzen, 1980; Megard et. al., 1980).

Furthermore, phytoplankton cell densities and biovolumes do not appear to offer singular explanations for interpreting variation in the Secchi disk readings. Although this may also be a problem of scale, our data suggests that other components of the particle community of the lake system may be more important to such an explanation.

Based on the above discussion, evaluating the decline in Secchi disk readings in Crater Lake will require identification of the particle community and an understanding of how it changes in density and optical properties through time. At this time, we have a poor understanding of the characteristics, sources, and fates of particles in the lake. Particle densities and types could be influenced by natural environmental conditions such as precipitation, wind, and runoff, avalanches along the caldera wall, loading of anthropogenic material from atmospheric and onsite sources, and lake processes such as hydrothermal activity, internal cycling of the deep water nitrate-N pool into the photic zone, and food web interactions among zooplanktivorous fish (kokanee), zooplankton, phytoplankton and nutrients (Carpenter, et al., 1985).

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