

# Spatial and temporal patterns of transparency and light attenuation in the Salton Sea, California, 1997-1999

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## Abstract

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Transparency, as measured by Secchi disk depth (SD), and light attenuation ( $K_d(\text{PAR})$ ) were measured in the Salton Sea in 1997-1999. Linear regression models were used to evaluate the relative importance of phytoplankton and non-phytoplankton substances in determining SD and  $K_d(\text{PAR})$ . Paired measurements of SD and  $K_d(\text{PAR})$  made in 1999 were used to track relative changes in the importance of light absorption and scattering processes. Phytoplankton biomass was a poor predictor of both SD and  $K_d(\text{PAR})$  at mid-lake stations, and this is most likely due to high concentrations of non-phytoplankton substances such as inorganic particulate matter in the Salton Sea. During strong windstorms in the warmer part of the year, the upper water column mixes with hydrogen sulfide-laden bottom waters, causing large crashes in plankton populations. This previously reported phenomenon also strongly affects the light regime through the production of gypsum crystals, which scatter large portions of penetrating light. Since a large amount of variation in both SD and  $K_d(\text{PAR})$  is not explained by phytoplankton biomass, any use of this relationship to forecast future changes in water clarity through nutrient reductions must be done with caution.

Key words: Secchi disk,  $K_d$ , chlorophyll *a*, gypsum, saline lake

## Introduction

Eutrophic lakes often exhibit numerous water quality problems that may include frequent phytoplankton blooms, widespread anoxia and decreased water transparency. Changes in water transparency, as measured by Secchi disk depth (SD, m), are easy to measure and are often used to characterize and track changes in lake productivity (Tyler 1968; Megard *et al.* 1980). This is based on the assumption that phytoplankton biomass is the dominant factor in determining water transparency; however, a simple relationship between chlorophyll *a* (chl-*a*) and transparency or light attenuation ( $K_d$ ,  $\text{m}^{-1}$ ) does not always exist (Lorenzen 1980; Field and Effler 1983;

Koenings and Edmundson 1991; Philips *et al.* 1995; Effler and Perkins 1996). High concentrations of dissolved substances that color the water (*e.g.*, gelbstoff) and particulate matter (inorganic and organic) may be responsible for a large portion of light attenuation (Kirk 1994). Therefore, lake remediation efforts designed to control phytoplankton growth through reductions in nutrient loading may not result in increased water transparency (Effler *et al.* 1987). Without detailed information on both the composition and concentration of substances that attenuate light, incorrect conclusions may be reached as to what controls the light regime within a lake.

The relative importance of phytoplankton biomass in determining SD and  $K_d$  can be estimated by examining the effect of chl-*a* concentrations on absorption and scattering processes separately (Effler 1985). Dissolved substances are primarily responsible for light absorption, whereas particulate matter scatters light, and phytoplankton cells do both (Effler 1985). Several investigators have demonstrated that each of these light-attenuating components affects SD and  $K_d$  differently and independently (Kirk 1985; Preisendorfer 1986; Koenings

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and Edmundson 1991; Effler *et al.* 2001). For example, measurements of  $K_d$  are more strongly affected by the presence of substances that absorb rather than scatter light as shown by Kirk (1994):

$$K_d = [a^2 + (G \cdot a \cdot b)]^{0.5} \quad (1)$$

where  $a$  is the absorption coefficient ( $m^{-1}$ ),  $b$  is the scattering coefficient ( $m^{-1}$ ) and  $G$  is a coefficient determined by the shape of the scattering phase function. Based on the formalized relationship between  $K_d$  and SD (Preisendorfer 1986), the product  $K_d \cdot SD$  can be defined as:

$$K_d \cdot SD = (\Gamma \cdot K_d) / (c + K_d) \quad (2)$$

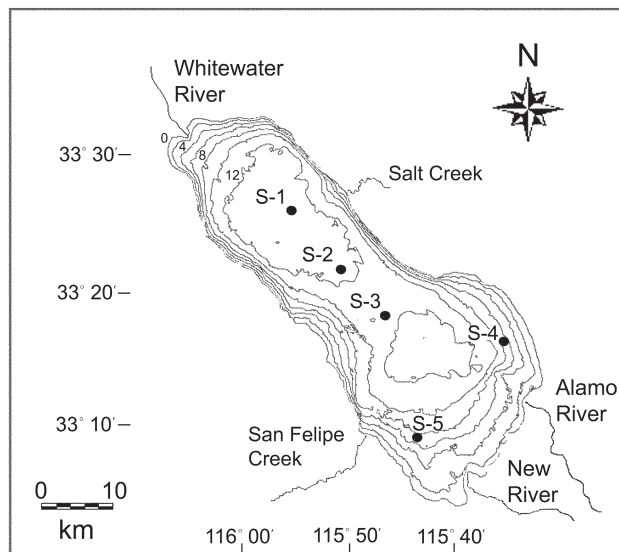
where  $c$  is the beam attenuation coefficient ( $m^{-1}$ ) and  $\Gamma$  is the coupling constant defined by Preisendorfer (1986). Changes in the value of  $K_d \cdot SD$  can therefore be used as a diagnostic tool to evaluate the relative importance of absorption and scattering processes in determining the light regime in a water body (Effler 1985; Weidemann *et al.* 1985; Effler *et al.* 1987; Koenings and Edmundson 1991).

The Salton Sea is a shallow, saline eutrophic lake that currently supports high phytoplankton biomass (up to  $107 \mu g l^{-1}$  of chl-*a*; Tiffany *et al.* 2007a). To date, seasonal and spatial patterns of water transparency, light attenuation and phytoplankton biomass in the Salton Sea have not been determined. This work is part of a long-term study that was initiated in January 1997 to characterize physical, chemical and biological aspects of the Salton Sea. In this report, patterns of water transparency, light attenuation and vertical distributions of phytoplankton biomass for 1997-1999 are presented. This study is the first to analyze several key parameters necessary for a mechanistic understanding of what regulates the light regime in the Salton Sea. By understanding the role of both phytoplankton and non-phytoplankton substances in regulating transparency and light attenuation, lake managers will be better able to determine what changes in these parameters may indicate in the Salton Sea.

## Methods

### Field measurements

Measurements of SD, chl-*a* and phaeopigments were made at three mid-lake stations (S-1, S-2 and S-3) in 1997-1999 at 2-5 week intervals (Fig. 1; see Watts *et al.* 2001 for latitude and longitude locations of stations, maximum water depth at each station and monitoring dates). In 1999, two additional nearshore stations (S-4 and S-5) were added. Depth profiles of downwelling photosynthetically active radiation (PAR; 400 to 700 nm wavelength range) were measured at all five sampling stations in 1999.



**Figure 1.**—Map of the Salton Sea showing the locations of sampling stations.

SD was measured at each station using a 20 cm, black and white quadrant weighted disk. All measurements of SD were made between 0900 and 1500 hours on the shady side of the boat. Five SDs measured at S-1 in 1998 were lost. We performed a least-squares linear regression analysis of SD on chl-*a* concentration at S-1 for 1998, and an  $r^2$  value of 0.72 was obtained. The regression equation obtained ( $SD = -1.44(\text{chl-}a; \mu g l^{-1}) + 157.64$ ,  $n = 9$ ,  $P = 0.002$ ) was used to estimate those missing SD values, though we did not use them in subsequent regression analyses.

The intensity of downwelling PAR irradiance at each station was measured as  $\mu\text{moles quanta } m^{-2} s^{-1}$  using cosine-corrected quantum sensors (Li Cor LI-190SA and LI-192SA) equipped with a data logger (Li-Cor LI-1000). The underwater sensor was attached to a metal frame, and the percent of incident light that penetrated to depth was recorded every 0.5 m from the surface down to a maximum depth of 4-5 m.

Duplicate 500 ml integrated water samples for the determination of chl-*a* and phaeopigment concentrations were collected from three depth strata (0-3, 3-6 and 6-9 m) at each station using a tube sampler. Each sample was filtered through 200  $\mu\text{m}$  mesh netting to remove larger zooplankters and stored on ice in the dark during transport to the laboratory. Within 12 hours (samples collected in 1997-1998) and four hours (samples collected in 1999), each sample was filtered through a Whatman GF/F (0.7  $\mu\text{m}$ ) filter. The amount of water filtered was noted, and the filters were immediately stored in liquid nitrogen ( $-196 \text{ }^\circ\text{C}$ ) until extraction and spectrophotometric analysis was carried out. Each filter was ground in 90 percent buffered acetone (v/v) using a tissue-grinder fitted with a Teflon<sup>®</sup> pestle. The ground material was then placed in a freezer

(-10 °C) for 24 hours to allow the pigment extraction to take place. Chl-*a* concentrations were quantified and corrected for phaeopigments using the trichromatic spectrophotometric method (APHA 1998).

### Data analysis

Geometric mean SD and chl-*a* concentrations, and their corresponding standard error factors for each date, were calculated for the three mid-lake stations in 1997-1999 and for all five sampling stations for 1999. In 1999, diffuse downwelling PAR attenuation coefficients ( $K_d(\text{PAR})$ ) were calculated for each date at each station. These are equivalent to the slope of the least-squares linear regression of the natural logarithm of light intensity versus depth. Data collected between the surface (~ 0.25 m) and 1 m were discarded prior to regression analysis. Measurements of light penetration through this surface stratum are often unreliable due to surface disturbances (Wetzel 2001).

Relationships between mid-lake chl-*a* concentration and SD in 1997-1999, and mid-lake chl-*a* concentration and  $K_d(\text{PAR})$  in 1999, were examined using least-squares linear regression analysis. None of the estimated SDs in 1998 were used in these analyses. Plankton mortality events or 'crashes' and gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) crystals were observed on three dates (16 August, 28 August and 25 September 1999) at the mid-lake stations (Tiffany *et al.* 2002; 2007a, b and c). Plankton crashes were defined as > 90 percent reductions in density of plankton species (Tiffany *et al.* 2002). To examine the influence of these events on SD and  $K_d(\text{PAR})$ , data collected on these dates were excluded and each regression analysis was repeated. In addition, the influence of phaeopigment, metazooplankton and protozooplankton concentrations on the relationships between chl-*a* and transparency/light attenuation was determined by multiple linear regression analysis. The independent variables chl-*a* and phaeopigments were used for the two-variable model, whereas metazooplankton and protozooplankton biovolume concentrations were added for the three and four-variable models, respectively. Unfortunately, measurements of total suspended solids (TSS) and colored dissolved organic matter (CDOM) were not measured and could not be included in the regression models. Arithmetic means and associated standard errors of the  $K_d(\text{PAR}) \cdot \text{SD}$  products at mid-lake stations were calculated for 1999. All statistical analyses were performed using SYSTAT™ version 9 (SPSS 1998).

## Results

### Trends in transparency and light attenuation

In general, mid-lake SD increased during the main warming period (March-September), decreased in September-October, and then increased thereafter (October-January; Fig. 2). On

average, SD was approximately 0.25 m deeper during the warming period than during the cooling period. As expected, patterns in SD follow general trends in chl-*a* concentration. Minimum values of chl-*a* were reached in August-September (6-15  $\mu\text{g l}^{-1}$ ), followed by an increase during the cooling period (October-February; Fig. 2). Differences in chl-*a* concentrations between depth strata were measured primarily during periods of thermal stratification, whereas chl-*a* concentrations were similar across all depths when the lake was well mixed (Fig. 2; Watts *et al.* 2001).

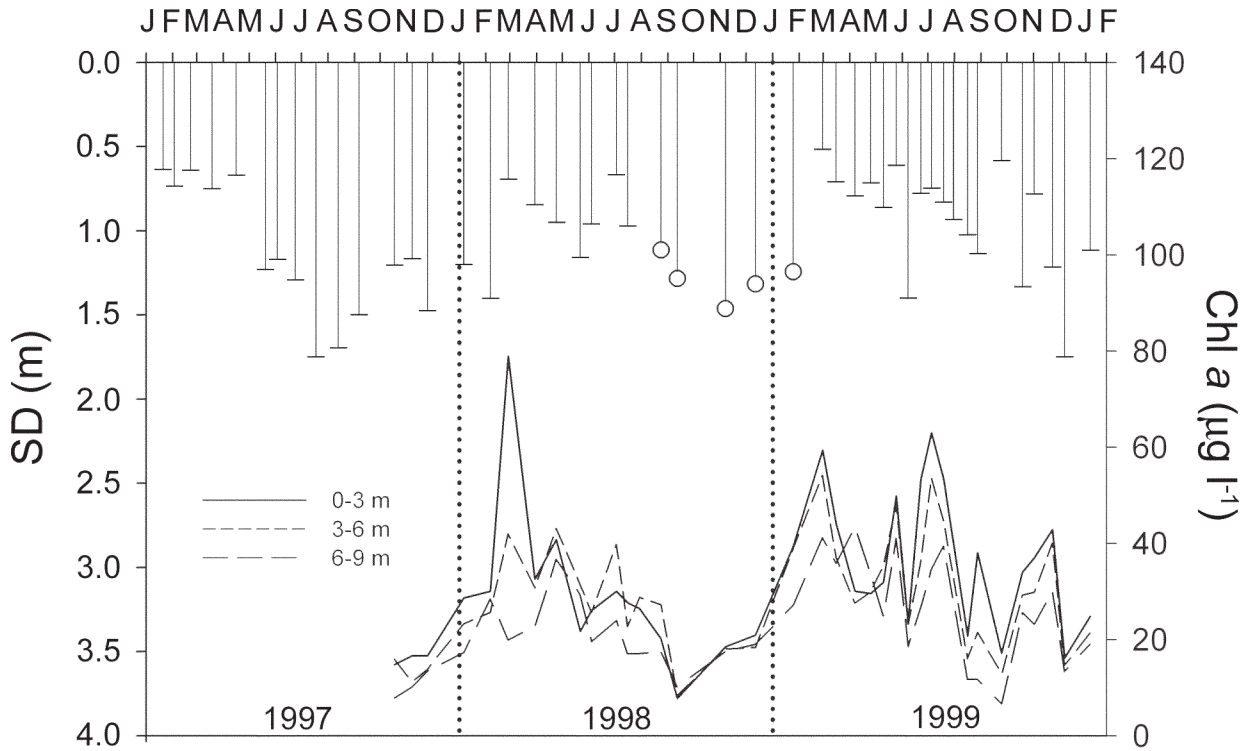
Patterns in SD at the two nearshore stations (S-4 and S-5; Fig. 1) exhibited different trends from each other (Fig. 3). Mean SD for S-1, 2 and 3 were 1.02, 0.97, 1.02 m, respectively. These mean SD values are much closer to that of S-5 (0.94 m) than S-4 (0.72 m). Also, chl-*a* concentrations were higher at nearshore stations than mid-lake stations, and differences in chl-*a* concentrations between depth strata were more pronounced at S-4 (Fig. 3).

As expected, patterns in light attenuation exhibit similar trends to those observed for water transparency (Fig. 4). During the warming period, maximal values of  $K_d(\text{PAR})$  coincided with peaks in chl-*a* concentration.  $K_d(\text{PAR})$  declined during periods when chl-*a* concentrations were minimal and the lake was well mixed; however, on 25 September  $K_d(\text{PAR})$  values were high when chl-*a* concentrations were minimal at mid-lake stations (Fig. 4A). With the exception of the decline in chl-*a* and high  $K_d(\text{PAR})$  values on 25 September,  $K_d(\text{PAR})$  patterns at mid-lake stations were similar to those at nearshore stations (Fig. 4).

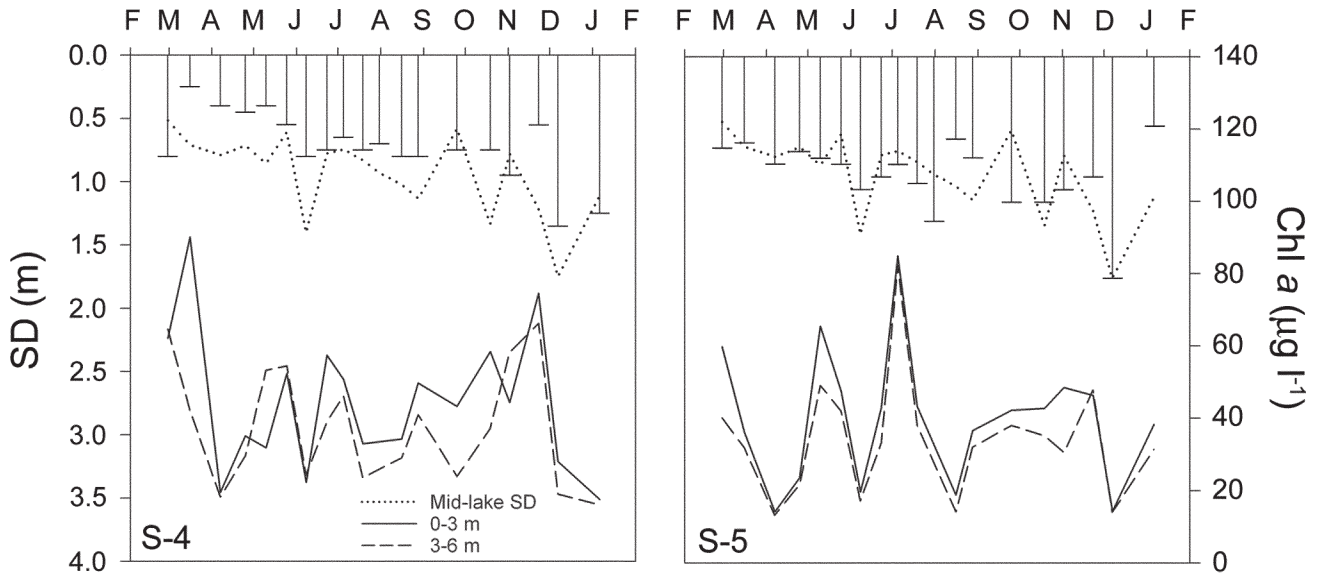
### Relationships between phytoplankton abundance, transparency and light attenuation

The overall relationships between chl-*a* concentration and  $1/\text{SD}$  and  $K_d(\text{PAR})$  were weak (Fig. 5). The variation in SD and  $K_d(\text{PAR})$  explained by chl-*a* was greatly diminished when plankton crash data were included (*e.g.*, overall regression), as was the magnitude of the chl-*a* effect (*i.e.*, slope of regression line; Fig. 5). Values of  $1/\text{SD}$  were highly variable among stations on each plankton crash date, and these differences trend negatively with changes in chl-*a* concentration (*e.g.*, negative slope; Fig. 5A), as reflected in the highest  $1/\text{SD}$  values corresponding to the lowest chl-*a* concentrations. Smaller differences in  $K_d(\text{PAR})$  values among stations were found on plankton crash dates (Fig. 5B). However, the slope of the regression line for  $K_d(\text{PAR})$  versus chl-*a* was also negative, but less so than for  $1/\text{SD}$  (Fig. 5B).

Inclusion of phaeopigment concentrations improved only the  $1/\text{SD}$  regression model, with an additional 7 percent variation explained by phaeopigments (Table 1). Effects of including metazooplankton and protozooplankton biovolume in the models were negligible (*e.g.*, little additional explained varia-



**Figure 2.**-Geometric means of Secchi disk depth (SD) and chlorophyll a (chl-a) concentration for mid-lake stations in 1997-1999. Open circles (O) represent SD values estimated from the least-squares linear regression of chl-a concentration on SD at S-1 for 1998.



**Figure 3.**-Secchi disk depths (SD) and chlorophyll a (chl-a) concentrations for nearshore stations in 1999. The dotted line represents the geometric mean SD of the mid-lake stations for 1999.

Spatial and temporal patterns of transparency and light attenuation in the Salton Sea, California, 1997-1999

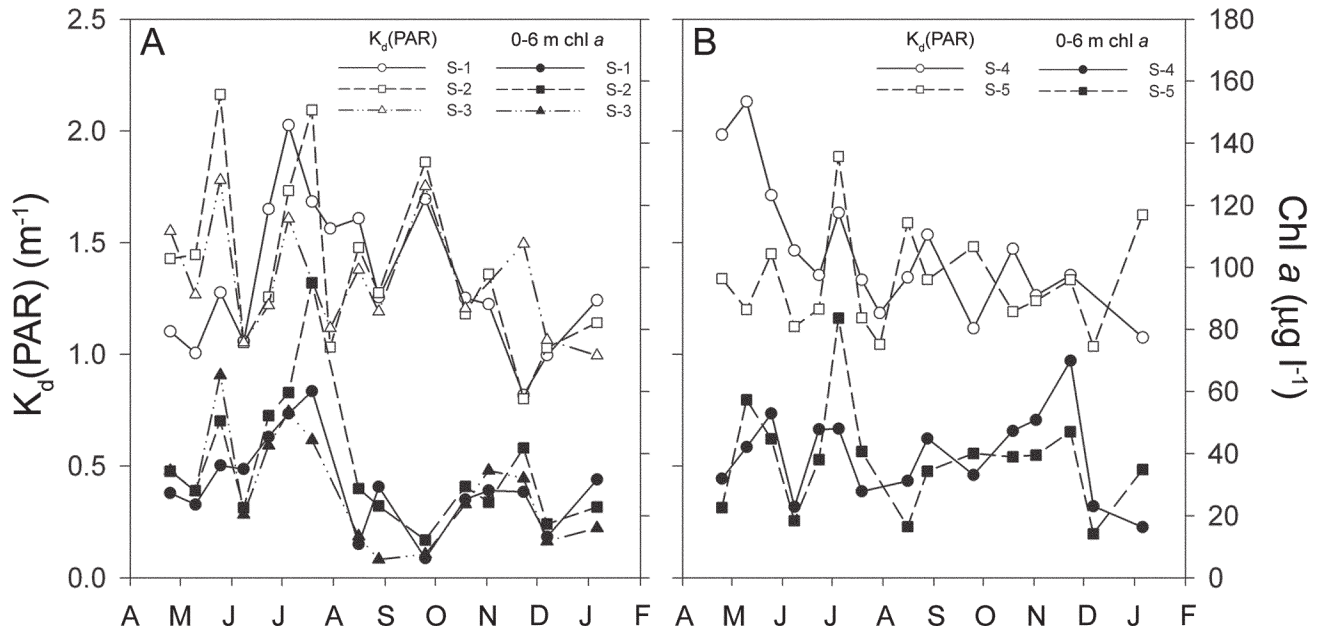


Figure 4.-Diffuse downwelling PAR attenuation coefficients ( $K_d(\text{PAR})$ ) and depth-averaged (0-6 m) chlorophyll *a* (chl-*a*) concentrations at mid-lake stations (A) and nearshore stations (B) for 1999.

Table 1.-Results of multiple linear regression analyses of  $1/\text{SD}$  and  $K_d(\text{PAR})$  on chlorophyll *a* (chl-*a*), phaeopigments, metazooplankton and protozooplankton concentration. All data for plankton crash dates were excluded prior to analyses.

Independent variable <sup>a</sup>	Dependent variable: $1/\text{SD}$								
	$r^{2b}$	$\beta^c$	$P^d$	$r^2$	$\beta$	$P$	$r^2$	$\beta$	$P$
Chl- <i>a</i>	<b>0.46</b>	0.437	< 0.0001	<b>0.46</b>	0.427	< 0.0001	<b>0.46</b>	0.415	0.001
Phaeopigments	0.52	0.349	0.003	0.52	0.362	0.002	0.52	0.364	0.002
Metazooplankton biovolume				0.53	-0.071	0.402	0.53	-0.068	0.425
Protozooplankton biovolume							0.53	0.054	0.530

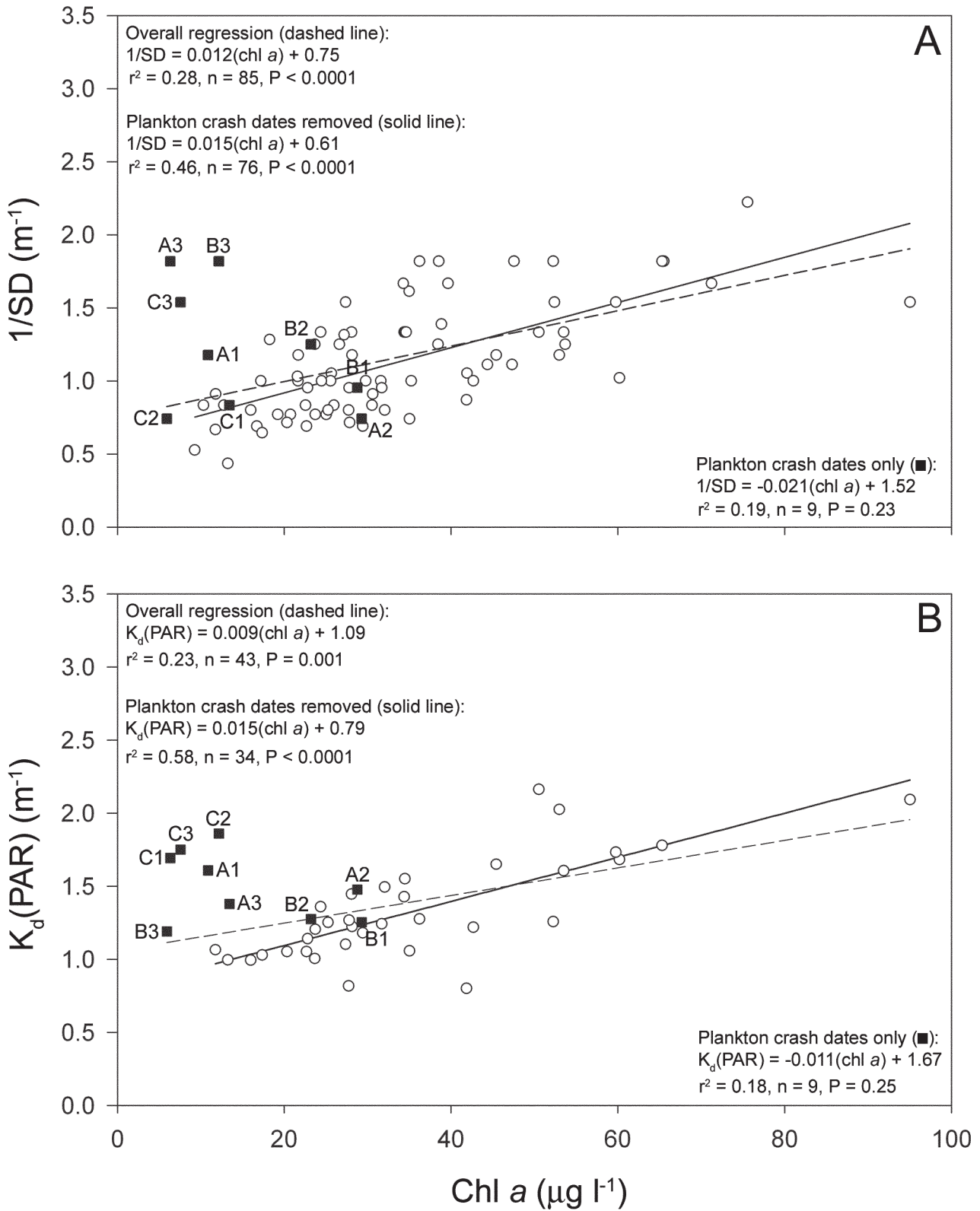
Independent variable	Dependent variable: $K_d(\text{PAR})$								
	$r^2$	$\beta$	$P$	$r^2$	$\beta$	$P$	$r^2$	$\beta$	$P$
Chl- <i>a</i>	<b>0.58</b>	0.480	0.024	<b>0.58</b>	0.465	0.032	<b>0.58</b>	0.488	0.033
Phaeopigments	0.58	0.325	0.118	0.58	0.367	0.101	0.58	0.357	0.118
Metazooplankton biovolume				0.59	-0.081	0.556	0.59	-0.082	0.561
Protozooplankton biovolume							0.59	0.053	0.694

<sup>a</sup> Chl-*a* and phaeopigment concentrations are in  $\mu\text{g l}^{-1}$  and plankton biovolume is in  $\text{mm}^3 \text{l}^{-1}$ .

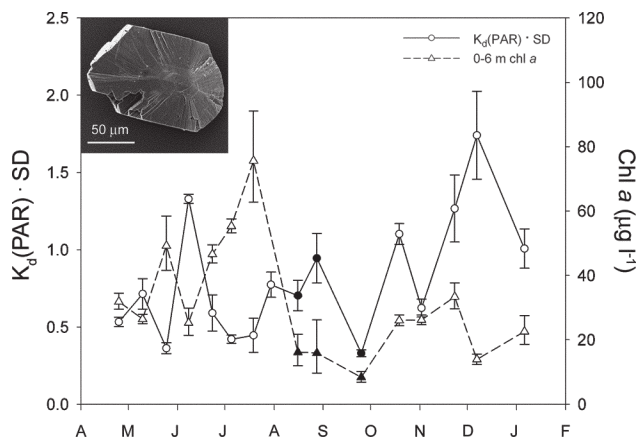
<sup>b</sup> Original  $r^2$  value obtained from linear regressions on chl-*a* (bold) and subsequent  $r^2$  values obtained from the addition of independent variables to the regression models.

<sup>c</sup> Standardized regression coefficients for each model.

<sup>d</sup> The probability that the additional variation in the dependent variable accounted for by adding the indicated independent variable to the model was equal to or greater than the additional variation expected to be accounted for under the null hypothesis that the independent variable is without effect.



**Figure 5.**—Least-squares linear regressions of (A) depth-averaged (0-6 m) chlorophyll a (chl-a) on 1/SD at mid-lake stations in 1997-1999, and (B) depth-averaged chl-a on  $K_d(PAR)$  at mid-lake stations for 1999. The labeled solid squares (■) were included in the overall regression models and represent stations (S-1, S-2 and S-3) and dates when plankton crashes were observed: 16 August (A), 28 August (B) and 9 September (C) 1999.



**Figure 6.**—Arithmetic means of  $K_d(\text{PAR}) \cdot \text{SD}$  and geometric mean depth-averaged (0-6 m) chlorophyll a (chl-a) concentration at mid-lake stations in 1999. Error bars represent  $\pm 1$  standard error. The solid symbols (●, ▲) represent dates when plankton crashes were observed. Inset: scanning electron microscopy image of a gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) crystal collected in the water column at S-1 on 9 September 2000.

tion and high P-values; Table 1). The regression coefficients obtained for metazooplankton biovolume were negative in both models, possibly indicating the effect of grazing on phytoplankton by metazooplankton.

Except on plankton crash dates,  $K_d(\text{PAR}) \cdot \text{SD}$  and chl-a concentration exhibited opposite trends, indicating that absorption was relatively more important in attenuating light (Fig. 6). The relative importance of scattering processes in regulating light attenuation increased on 25 September (*i.e.*, low  $K_d(\text{PAR}) \cdot \text{SD}$  and chl-a concentration). On some plankton crash dates, water at the mid-lake stations was green in color, concentrations of hydrogen sulfide were high and gypsum crystals were occasionally abundant in the water column (Fig. 6; Watts *et al.* 2001; Tiffany *et al.* 2002; 2007a, b and c).

## Discussion

### *Phytoplankton influence on transparency and light attenuation*

As in many shallow eutrophic lakes, the linear model used to predict SD or  $K_d(\text{PAR})$  from phytoplankton biomass performed poorly in the Salton Sea (overall regression models;  $r^2 = 0.28$  and  $0.23$ , respectively). The performance of these regression models has been found to vary greatly in other lakes, with  $r^2$  values ranging between 0.43 and 0.93 (reviewed in Field and Effler 1983). Only when several influential data points in 1999 (discussed in a later section) were removed did the  $r^2$  values approach the lower bound of this published range (0.46 and 0.58, respectively).

It is expected that the high abundances of both phytoplankton and grazers will lead to large concentrations of phaeopigments, and that these concentrations may also strongly affect transparency and light attenuation. In addition, the Salton Sea's metazooplankton community is dominated by relatively small-sized species and high numbers of ciliates (Tiffany *et al.* 2002; Tiffany *et al.* 2007a). However, phaeopigment concentration explained little additional variation between the chl-a versus  $1/\text{SD}$  regression model. This is not unexpected as absorption is relatively less important for SD than scattering (Kirk 1994). Phytoplankton biovolume densities are approximately 10-fold higher than metazooplankton biovolume densities, and the latter are about 10-fold higher than protozooplankton biovolume densities. These results indicate that the majority of light attenuation in the Salton Sea is due to the presence of substances other than those evaluated by the regression models (*i.e.*, inorganic particulate matter).

Consistently low transparency and high light attenuation were measured at the nearshore station S-4 in 1999. This station lies in the path of currents that carry freshwater inflow from the New and Alamo Rivers counterclockwise around the southern portion of the lake (Arnal 1961; Cook *et al.* 2002; Reifel *et al.* 2007). These inflows carry high concentrations of silt and clay (Holdren and Montaño 2002), which are expected to result in a high amount of light scattering.

### *Light availability and phytoplankton abundance*

During times when the lake is continuously mixing due to strong wind events and convectional circulation, solar insolation and mean water column temperatures are decreasing (Watts *et al.* 2001) and chl-a concentrations are near minimal values. The depth to which 1 percent of incident light penetrates (*i.e.*, euphotic depth) was greatest (4-5 m) during this same time period. Thus, the deepening of the euphotic depth appears to be partly due to a decline in phytoplankton biomass.

In the months of July-September, solar insolation, mean water column temperature and chl-a concentrations reach maximal values. This time period is also characterized by extended periods when the water column is stratified. Taken together, these conditions support high growth rates for phytoplankton. Also, salinity gradients have been measured in the region of S-4 on several dates during periods of low wind activity during this study and others (Arnal 1961; Watts *et al.* 2001; Reifel *et al.* 2006). Density gradients cause increased stability of the water column that reduces mixing and encourages the formation of phytoplankton blooms (Margalef *et al.* 1978; Cloern 1991; Smayda 1997). These conditions are likely responsible for the consistently high phytoplankton biomass measured at this station.

### ***Deoxygenation events: an unusual mechanism for autochthonous production of inorganic particulate matter***

It has been previously reported that during thermal stratification, widespread anoxia and high concentrations of hydrogen sulfide develop in the bottom waters of the Salton Sea (Watts *et al.* 2001). During strong windstorms, these bottom waters are mixed throughout the water column resulting in the deoxygenation of surface waters and large crashes in plankton populations (Watts *et al.* 2001; Tiffany *et al.* 2002; 2007a and b). In addition, high concentrations of gypsum crystals ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) are often found throughout the water column. These crystals are thought to form when sulfate ( $\text{SO}_4^{2-}$ ), formed via the oxidation of hydrogen sulfide ( $\text{HS}^-$ ), reacts with calcium ( $\text{Ca}^{2+}$ ) present in surface waters (Hurlbert *et al.* unpubl. data; Tiffany *et al.* 2007c). The water often appears bright green in color, and this phenomenon has historically been referred to as a 'green tide' (Watts *et al.* 2001). Satellite imagery has shown that these events have occurred almost everywhere in the lake over the last several years (Tiffany *et al.* 2007a and c). This phenomenon is very similar to 'lake whiting' events that are a common occurrence in some eutrophic, hard water lakes that are saturated with calcite (Strong and Eadie 1978; Effler *et al.* 1987; Effler *et al.* 1991). During lake whiting events, calcium carbonate ( $\text{CaCO}_3$ ) particles are produced in the upper water column and can be an important source of light attenuation (Effler *et al.* 1987). However, one important difference between lake whiting events and the phenomenon that occurs in the Salton Sea is the plankton mortality caused by the injection of hydrogen sulfide into surface waters.

In this study, both SD and  $K_d(\text{PAR})$  were strongly affected by some factor other than phytoplankton biomass on several dates in 1999. During plankton crash dates, chl-*a* concentrations were relatively low ( $6\text{--}12 \mu\text{g l}^{-1}$ ), and negative correlations between  $1/\text{SD}$  and  $K_d(\text{PAR})$  and chl-*a* concentration were found, indicating that low transparency and high light attenuation occurred where and when phytoplankton density was lowest (Fig. 5). Indirect evidence suggests the presence of gypsum crystals may have been the main source of reduced transparency and increased light attenuation on these dates. On each plankton crash date, SD decreased with a decrease in chl-*a*, whereas  $K_d(\text{PAR})$  values changed only slightly across a large range of chl-*a* concentrations (Fig. 5). Also, the  $K_d(\text{PAR}) \cdot \text{SD}$  product was lowest on these dates. The presence of gypsum crystals in the water is expected to scatter rather than absorb light, which explains why SD was more strongly affected (Davies-Colley *et al.* 2003). This argues against the possibility of dissolved substances released by damaged phytoplankton cells as a major factor in affecting the light regime during these events. In addition to gypsum, sediment resuspended during mixing events may also contribute to the high amount of light scattering (Swan *et*

*al.* 2007). A more correct term for these events in the Salton Sea would be 'greening events', as they are more similar to lake whiting events than putative phytoplankton blooms to which they are often attributed.

### ***Transparency and light attenuation: past and future***

The generally low transparency and high productivity of the Salton Sea has been previously noted (Walker 1961; Bain *et al.* 1970). In a study during 1954-1956, SD never exceeded 1 m at the one offshore sampling station (Carpelan 1961). Bain *et al.* (1970) found that SD varied between 0.5 and 2 m, with an average of 1 m. Both the average value and range of SD reported by Bain *et al.* (1970) are very similar to the overall range in mean SD measured in this study during 1997-1999 (0.25-2.3 m), conducted more than 30 years later. Holdren and Montañó (2002) also made measurements of SD and light penetration in 1999 and curiously stated that no seasonal patterns in SD could be found.

The measurement of SD is a cheap and simple way to assess water transparency when the equipment to make more exact measurements to characterize the light field is not available. However, the precision of SD measurements suffers in waters of low transparency ( $\text{SD} < 1 \text{ m}$ ). In turbid waters, the light field becomes distorted producing a glow above the white face of the Secchi disk, which increases the visual range of the Secchi disk (Davies-Colley 1990). As discussed above, SD depths in the Salton Sea are often  $< 1 \text{ m}$ . It is therefore not always possible to precisely measure SD in the Salton Sea. Measurements of other optical properties, such as  $K_d$ , would provide more meaningful and reliable information for future monitoring efforts.

Although phytoplankton biomass is high during much of the year, the majority of reduced transparency and light attenuation appears to be a function of non-phytoplankton substances. In addition, a unique phenomenon in the form of greening events appears to strongly affect transparency and light attenuation in the Salton Sea during late summer and fall months. Both the occurrence and spatial extent of greening events may increase if the salinity and supplies of external nutrients are not controlled. If salinity is allowed to increase, the elimination of fish populations that currently inhabit the lake is expected. Tilapia (*Oreochromis mossambicus* Peters) are important grazers in the food web of the Salton Sea, and their abundance exerts some control on plankton biomass (González *et al.* 1998; Hart *et al.* 1998; Tiffany *et al.* 2002; 2007a). If tilapia are eliminated from the lake, populations of some plankton species could increase, resulting in an increase in the supply of organic carbon available for hydrogen sulfide production through the process of sulfate reduction. However, increases in salinity will directly affect at least some plankton species; therefore, the overall



effects of increased salinity on plankton cannot be determined from currently available data.

This study clearly demonstrates that lake restoration managers need to consider how best to assess the optical water quality, as well as what major factors are involved in determining transparency and light attenuation in the Salton Sea. SD measurements should not be relied upon as adequate indicators of water clarity/quality in the Salton Sea due to their lack of precision. Measurements of  $K_d$  (or other optical properties such as absorption and scattering coefficients) should instead be used to track changes in optical water quality over time in the Salton Sea. The low transparency and high light attenuation that is characteristic of the Salton Sea appears to be primarily due to high concentrations of non-phytoplankton substances in the water column (*i.e.*, inorganic particulate matter), which was not quantified directly in this study. Without detailed information on the composition and abundance of these apparently important substances, any predicted change in transparency based upon anticipated reductions in phytoplankton biomass under reduced nutrient loading will likely be wrong and may lead to wasted resources that could be applied to solving the many water quality problems that currently plague the Salton Sea.

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