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Long-term trends in water clarity revealed by Secchi-disk measurements in lower Narragansett Bay

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Observations of Secchi-disk depth and related parameters were made weekly, from 1972 through 1996, in lower Narragansett Bay, Rhode Island. A significant increase in Secchi depth, at a linearized rate of 0.05 m yr^{-1}, was detected during this 25-year time series. Most of the increase in water clarity occurred between 1984 and 1994, when loading of total suspended solids (TSS) to the Bay via waste-water treatment plants decreased ca. 75%, and Secchi depths increased ca. 25%. Decreased annual TSS loading explained 43% of the variance in mean annual Secchi depth between 1983 and 1995. In addition to a long-term increase, there was also a strong seasonal pattern in water clarity. The rate of increase in Secchi depth in Narragansett Bay between 1972 and 1996 was similar to rates observed in other coastal waters that have had recent reductions in anthropogenic TSS loading.

Key words: *In situ* light, long-term trend, Narragansett Bay, Secchi-disk depth, suspended solids, transparency, time series, water clarity.

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Introduction

Over the annual cycle, temperate estuarine phytoplankton populations are subject to variability in habitat parameters (temperature, salinity, light, and nutrient concentrations) that affect their growth. Much of this variation is due to the influence of astronomical cycles which result in typical annual cycles in temperature, light, and weather patterns. High frequency variations in the parameters affecting phytoplankton growth may also result from daily and monthly tidal cycles, diel cycles, and day-to-day fluctuations (cloudy days vs. clear days) in light. Anthropogenic activities, through modification of the nutrient regime of coastal waters, have also been hypothesized to affect coastal phytoplankton composition. In this scenario, additions of nutrient-rich river run-off and sewage have altered the historical patterns of nutrient concentration and variability (Officer and Ryther, 1980; Jústic *et al.*, 1995), with a concomitant increase in phytoplankton biomass and a possible shift in the phytoplankton community from dominance by silica-requiring diatoms to non-siliceous flagellates (Granéli *et al.*, 1989; Smayda, 1990).

In addition to modifying the nutrient environment of coastal phytoplankton, anthropogenic activity, such as discharge of suspended solids into estuaries, may change the light-attenuating properties of the water column. Particle enrichment of the water column affects phytoplankton by changing the *in situ* light regime. Increasing turbidity of coastal waters affects the critical depth criteria of the phytoplankton community and may limit primary production in deep estuaries (Cloern, 1987). In shallow, well-mixed estuaries, such as Narragansett Bay, mixing below the critical depth is limited by the shallow bottom. However, increased turbidity will result in phytoplankton cells experiencing low mean irradiance levels disturbed by brief, possibly photoinhibition-inducing, exposure to high irradiance as the cells are mixed within the water column. Exposure to such rapidly changing light levels can decrease the quantum yield of photosynthesis (MacIntyre *et al.*, 1996; MacIntyre and Geider, 1996). The areal extent of estuarine phytoplankton blooms may also be affected by changes in turbidity. For example, in Delaware Bay the spring bloom, dominated by *Skeletonema costatum* (Grev.) Cleve, appears to begin in response to release of light limitation in the less turbid areas (Pennock and Sharp, 1994). Modification of the light-attenuating properties of the water column affects the cellular, population, and community growth of coastal phytoplankton.

Secchi-disk depth is a simple measure of the concentration of light attenuating particles in the water column, whether phytoplankton cells or inorganic suspended solids. A 25-year record of weekly observations of Secchi-disk depth, phytoplankton, and related parameters, including those affecting the light regime, is available for lower Narragansett Bay (Smayda, 1998). We use this time series to describe and characterize the variability of the light attenuating properties of the water column, to quantify long-term trends, and to identify possible causative mechanisms. Long-term variations in chlorophyll are described by Li and Smayda (1998).

Methods

Secchi-disk depth measurements were made weekly from January 1972 through December 1996 at sampling Station II (Fig. 1) in the unpolluted, lower west passage of Narragansett Bay, Rhode Island, USA. Water clarity was determined by lowering a 0.30 m white Secchi-disk into the water until the disk was no longer visible (see Preisendorfer, 1986). Over the 25-year time series, 1076 weekly observations (83% coverage) were made.

The guidelines described in Preisendorfer (1986) were routinely followed. The protocol included sampling within 4 h of local noon to minimize the effect of sun angle, sampling from the sun-facing side of the boat to minimize the effect of reflectance, and sampling from the same location on the research vessel deck to minimize the effect of the height of the observer above water. Another possible source of variation in the Secchi-depth observations is variation in the visual acuity of the individuals making the measurements over the 25-year period. However, earlier analyses have shown that the primary source (90–95%) of variation in Secchi-disk depth is the amount of dissolved and particulate material attenuating light within the water column and that the combined variation due to sun angle, sea surface reflectance, and differences in the visual acuity of observers is about 5–10% (Preisendorfer, 1986; Lewis *et al.*, 1988). Thus, we are confident that the introduced random methodological error was on the same order of magnitude, and that most of the variation during the time series is due to actual changes in turbidity.

Tidal height may affect the concentration of suspended material (Cadée, 1982) and Secchi depth. In our series, observations were taken independently of tidal phase. A time series taken over several tidal cycles in the turbid Providence River in upper Narragansett Bay showed differences of as much as 30% (Collins, 1976).

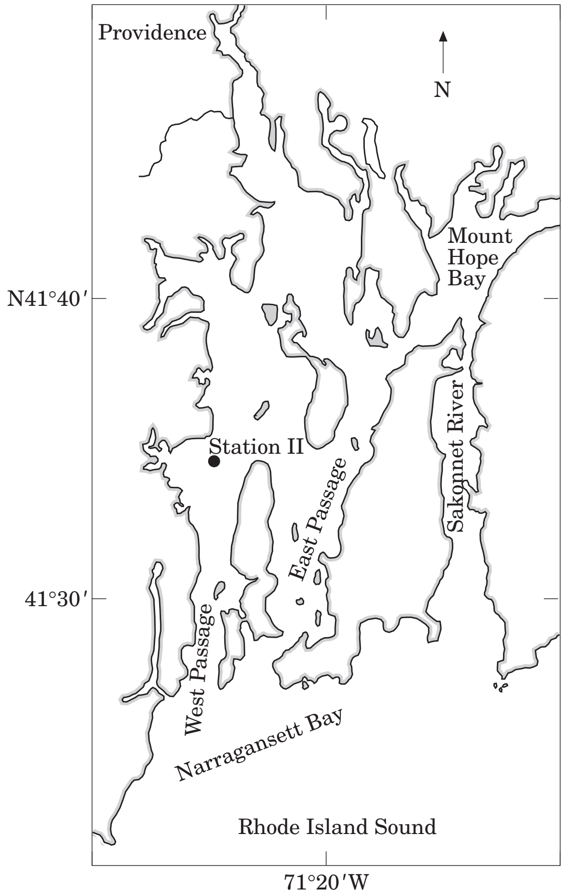

Figure 1. Location of long-term sampling Station II in the lower west passage of Narragansett Bay, Rhode Island, USA.

However, water clarity varied by only 1% over the tidal cycle in the lower west passage (Schenck and Davis, 1973), where our measurements were made. In the lower east passage, the concentration of suspended matter varied by <10% over three tidal cycles (Morton, 1972). Thus, the effect of tidal phase on suspended matter and water clarity in lower Narragansett Bay appears to be small. In addition, a tidal effect was not detected in a linear regression of a 12-year subset of observations as a function of tidal height ($r^2=0.006$, $n=496$).

Other measurements included temperature, salinity, Chl *a*, dissolved inorganic nutrients, zooplankton dry weight, and phytoplankton abundance and community composition (see trends described in Smayda, 1984; Li and Smayda, 1998). Daily measurements of ambient solar radiation at Eppley Laboratories (Newport, RI) about 10 km east of the study site are also used, as are records of local windspeed at Providence airport (located approximately 20 km from the long-term sampling site), precipitation, and river runoff.

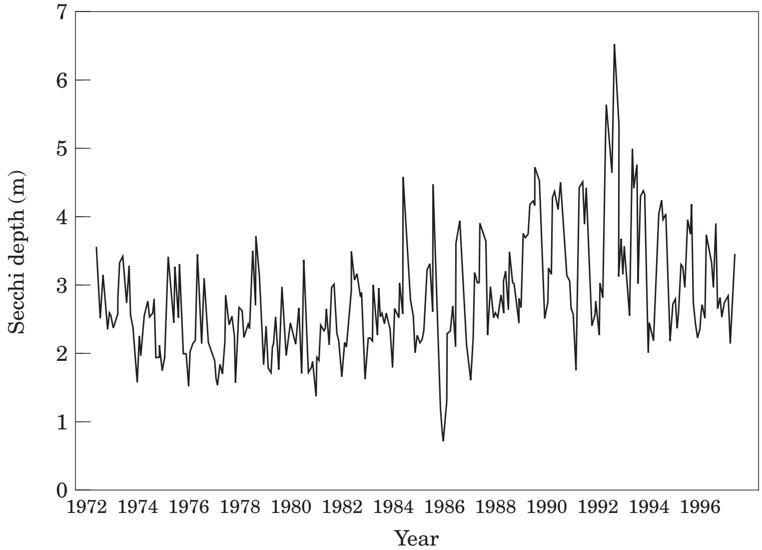

Figure 2. Mean monthly Secchi-disk depth at Station II, 1972–1996. Each data point is the mean of all observations for each month.

Secchi-disk data were tested for normality using the Kolmogorov–Smirnov test (Sokal and Rohlf, 1981) and were found not to be normally distributed. The non-parametric Mann-Whitney two-sample test (Sokal and Rohlf, 1981; SigmaStat, 1995) was then used to test the null hypothesis that two samples (e.g. measurements from two different time periods) came from populations having the same mean. Trends over the 1972–1996 time series were identified and quantified using a monotonic trend test. This ranking test, based on the Kendall test for trends and modified for use with water quality data containing seasonality (Hirsch *et al.*, 1982) and serial dependence (Hirsch and Slack, 1984), has been used to quantify long-term trends in Secchi-disk depth in the Baltic Sea (Sanden and Hakansson, 1996). Based on the sum of all positive differences (increases) between consecutive observations minus the sum of negative differences (decreases) between consecutive observations, the test detects significance of a trend in the data and quantifies the mean annual rate of change over the time series from the slope of a line fitted to the time series (Hirsch *et al.*, 1982).

Results

The monthly, averaged Secchi-disk depth revealed two major features: an apparent long-term increase in water clarity and a strong seasonal signal (Fig. 2). Measurements varied over a range of 6.5 m, and reached a minimum of 0.5 m during the summer 1985 bloom of the brown-tide chrysophyte, *Aureococcus anophagefferens* Hargraves *et* Sieburth, and a maximum of 7 m in the spring of 1992. (Note: even greater depths were recorded in the spring of 1997.) The mean value of the 1972–1996 observations was 2.75 m, with a standard deviation of 0.95 m.

Average annual Secchi-disk depth increased significantly over the time series at a linearized rate of 0.05 m year^{-1} (Fig. 3) which explained 50% of the variance. However, the true increase occurred in the decade between 1984 and 1994, while before or after this 10-year period clarity was relatively constant. Thus, three phases can be distinguished to characterize the development in water clarity (Table 1): from 1972 to 1983, there was no significant trend (mean 2.4 m); from 1984 to 1994, Secchi depth increased significantly at a rate of 0.11 m year^{-1}; in the years 1995–1996 Secchi depth remained high (mean 3 m).

Since the observed increase was not uniformly distributed throughout the year, the data were subdivided into two segments before and after the 1983 "breakpoint", and the quarterly changes between these two periods were compared using the Mann-Whitney two-sample test (Table 2). Secchi depths were significantly higher during the second period than during the first in all quarters, but the linear rates of increase were strongest in winter ($p<0.05$) and autumn ($p<0.10$) and weakest and not significant in spring and summer (Fig. 4). Further partitioning of the time series into monthly trends (Table 3) showed that the greatest increases in Secchi depth occurred in the coldest months (December to April) and the least changes during the warmer months (June to October).

There is a strong annual cycle in water clarity embedded within the long-term change (Fig. 5). Highest values

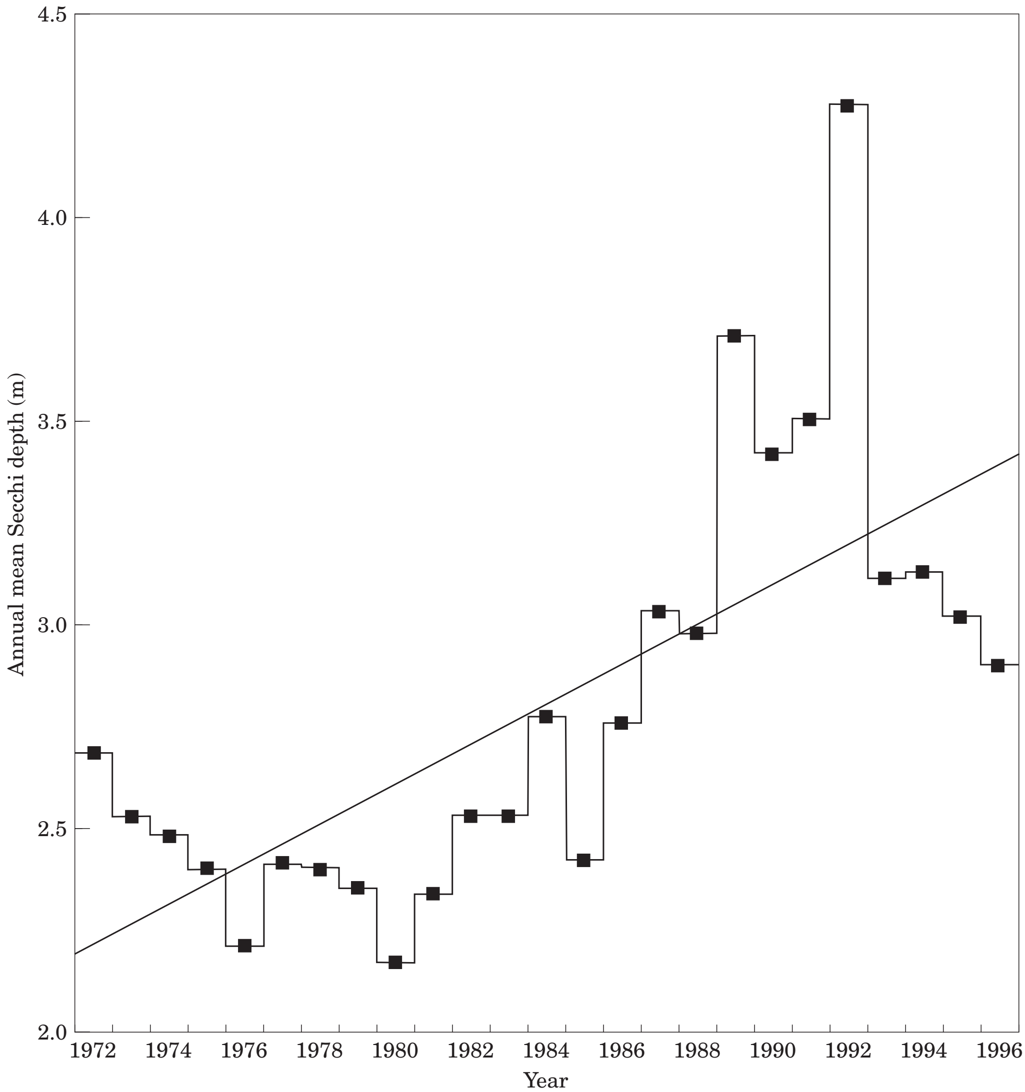

Figure 3. Mean annual Secchi-disk depth at Station II, 1972–1996. Each data point is the mean of all observations in each year. Line represents linear regression ($y=0.05x+2.16$, $r^2=0.50$).

Table 1. Changes in statistics of annual Secchi-disk depth at Station II for different periods.

Period	Mean Secchi depth (m)	Standard deviation	n	Trend
1972–1983	2.43	0.67	556	No trend
1984–1994	3.12	1.12	416	Increase (0.11 m yr^{-1}; $p=0.026$)
1995–1996	2.97	0.87	104	—
1972–1996	2.75	0.95	1076	Increase (0.05 m yr^{-1}; $p=0.014$)

(ca. 3.4 m) occur in the first 4 months of the year, followed by a rapid decrease until early summer (ca. 2.25 m), and then a gradual increase in late summer and autumn. The amplitude of the annual signal in Secchi depth, e.g., the difference between the more transparent waters during winter and the turbid mid-summer waters, has also increased, on average at least twofold (cf. Fig. 2).

Table 2. Results of Mann-Whitney test comparing Secchi depths prior to and after 1983, and quarterly trends in Secchi-disk depth, as quantified by slope of linear regression line.

Quarter	1972–1983 Median (m)	1984–1996 Median (m)	Two-sample test % Change	Two-sample test p-value	Trend test rate of change $m\ yr^{-1}$	Trend test p-value
Winter	2.73	3.81	+40%	<0.001	0.07	0.01
Spring	2.52	2.98	+18%	0.005	0.04	0.21
Summer	1.90	2.31	+22%	0.021	0.03	0.21
Autumn	2.34	3.08	+32%	<0.001	0.05	0.08

Unexpectedly, the mean weekly Secchi-depth measurements over the 25-year period (Fig. 6) correlated positively with the mean weekly riverflow into Narragansett Bay ($r=0.83$; $p<0.01$) and windspeed ($r=0.85$; $p<0.01$). Increased riverflow adds particles and humic substances to the water column, and increased windspeed stirs up bottom sediments; hence they were expected to correlate negatively with Secchi depth. However, wind data are weekly means and Secchi observations were made once per week, whereas the residence time of wind-resuspended sediment within the water column is likely less than one week due to the high sinking rate of the particles. The mismatch in measurement time scales may partially explain the lack of the expected negative correlation between wind and Secchi.

The annual cycle of water clarity impacts the annual cycle of light conditions for phytoplankton growth. The *in situ* light intensity (I bar) at Station II was calculated following the equations of Hitchcock and Smayda (1977) for each week:

$$\text{I bar} = -\left(1 - e^{-kz}\frac{I_o}{kz}\right)$$

where z is depth of the water column and k the extinction coefficient k (calculated from Secchi depth using the equation of Holmes (1970)); I_o is the daily incident irradiance. While incident irradiance in the Narragansett Bay region usually peaks near the time of the summer solstice (week 26), the *in situ* light maxima at Station II occur earlier, reaching an average annual maximum during week 20 (Fig. 7). However, the annual peak in *in situ* light intensity depends on the interaction of ambient incident irradiance and turbidity, and occurred as early as week 9 (1980) and as late as week 33 (1987) over the 25-year period.

Year-to-year variability and the long-term trend in the light attenuation of Narragansett Bay may affect the inception of the light-limited winter–spring bloom, which starts after an *in situ* light intensity threshold of approximately $21\ W\ m^{-2}$ is reached (Hitchcock and Smayda, 1977). The same threshold has also been reported for the coastal waters of the north-eastern United States (Riley, 1967) and the North Sea (Gieskes and Kraay, 1975). Over the 25-year period, the week in which the threshold was first reached has moved from a mean of week 8 in the 1970s ($n=8$), to week 6 in the 1980s ($n=10$), to week 4 in the 1990s ($n=7$). However, a clear pattern between release of light limitation alone and winter–spring bloom inception has not yet emerged. Spring bloom inception in Narragansett Bay is likely to be under multifactorial control, with factors such as temperature (Hitchcock, 1980), zooplankton grazing pressure (Martin, 1965, 1970), and light influencing time of bloom inception.

Discussion

The attenuation of light in water can be attributed to four components: the water molecules themselves, substances dissolved in the water ("gelbstoff" or "gilvin"), phytoplankton cells, or suspended inorganic ("tripton") particles (Kirk, 1994). Changes in one or more of these four components should explain the observed trend of increased water clarity in lower Narragansett Bay between 1972 and 1996. Attenuation of light by water molecules may be assumed to have remained constant over the time series. Attenuation by gilvin may also be assumed to have had no trend, since there have not been any dramatic changes in land use or riverine input to the bay during the period (Ries, 1990; USGS, 1996). While the percentage of DOC in total organic carbon loading has increased due to recent improvements in removal of POC in waste-water treatment plants, DOC loading to Narragansett Bay from these plants appears to have been relatively constant over the time series (Nixon *et al*., 1995).

Concentration of Chl *a* has decreased over the time series (Li and Smayda, 1998). However, there was no correlation between Station II Chl *a* concentration and Secchi-disk depth ($r=-0.03$). This may be due to variability in changes in chlorophyll content per cell, carbon:chlorophyll ratio, or chlorophyll to accessory pigment ratio (Falkowski and LaRoche, 1991; Kirk,

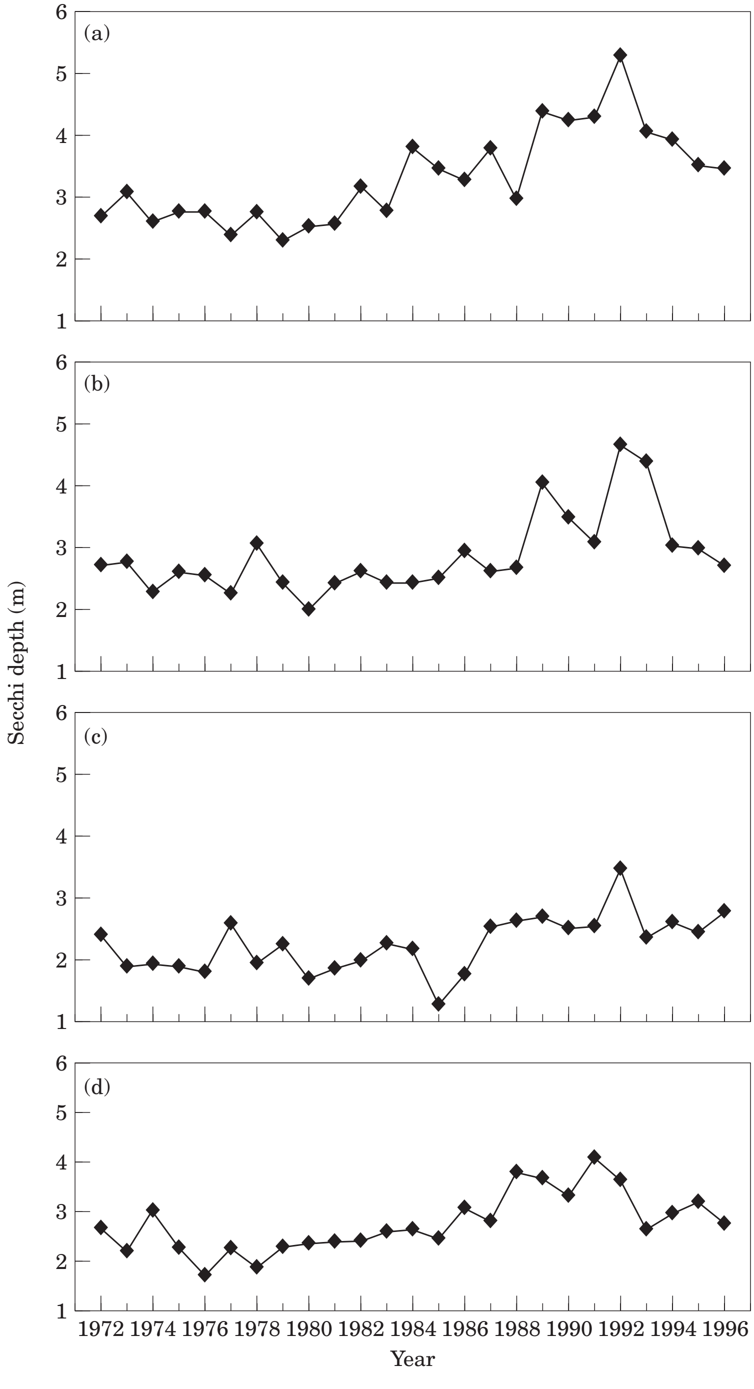

Figure 4. Mean Secchi-disk depth at Station II by quarter, 1972–1996. Each data point is the mean of all observations in that quarter in each year. (a) Winter (Jan–Mar); (b) Spring (Apr–Jun); (c) Summer (Jul–Sep); (d) Autumn (Oct–Dec).

1994). There was a significant negative correlation ($r = -0.44$, $p < 0.001$) between surface phytoplankton cell density and Secchi depth for 1972–1988. Tabulation of all weekly phytoplankton counts through 1996 is still in progress, but there have been no apparent trends in total phytoplankton abundance other than shifts in the species composition (Smayda, 1984). Relatively weak to moderate correlations between phytoplankton

Table 3. Trends in mean monthly Secchi-disk depth at Station II, 1972–1996: rates of change (m yr^{-1}) and the corresponding r^2 and p-value for the fit of the linear regression.

Month	Rate of change	r^2	p-value
Jan	+0.06	0.24	0.012
Feb	+0.07	0.36	0.001
Mar	+0.09	0.53	<0.001
Apr	+0.06	0.20	0.025
May	+0.05	0.25	0.012
June	+0.04	0.24	0.014
July	+0.03	0.16	0.046
Aug	+0.03	0.27	0.007
Sep	+0.04	0.25	0.012
Oct	+0.02	0.09	0.13
Nov	+0.05	0.34	0.002
Dec	+0.08	0.41	<0.001

abundance, either as Chl *a* or cell counts, may be expected in turbid, coastal waters ("Case 2 waters"; Gordon and Morel, 1983) in which non-phytoplankton particles largely determine the optical properties. In such waters, the attenuating effects of tripton in the form of re-suspended sediments and riverine and industrial discharge are greater than those of phytoplankton cells, which may be present in significant numbers (Kirk, 1994).

Since a strong effect was not detected in the phytoplankton component of the particles, we examined trends in the remaining tripton component. About 6% of the annual freshwater input to Narragansett Bay (approximately 2.04×10^8 m^3 $year^{-1}$) is in the form of effluent from domestic and industrial waste-water treatment plants (Pilson, 1985; Save the Bay, 1996). This discharge contains on average 16.2 mg of suspended solids per litre of effluent (mean 1993–1995) and the average annual loading of total suspended solids (TSS) for the period 1983–1995, for which data were available, was 7.11×10^6 kg. However, over these years improvements have been made in the efficiency of waste-water treatment plants. TSS loading from Rhode Island plants has markedly decreased (Save the Bay, 1996) from high values in the mid-1980s towards the present value of 2.5×10^6–3.0×10^6 kg per year (Fig. 8A). Model studies and field observations have indicated preferential transfer of suspended material from the north end of the Bay (where most waste water enters) to the West Passage, where our station is located (Corps of Engineers, 1959; Morton, 1972; Schenck and Davis, 1973; Oviatt and Nixon, 1975). The amount of suspended sediment decreases exponentially with distance down-bay from Providence (Morton, 1972) and sediment accumulation rate is slower in the lower bay (7–10 mg cm^{-2} $year^{-1}$) than in the upper bay (135–200 mg cm^{-2} $year^{-1}$; Santschi *et al.*, 1984). The upper bay has predominant

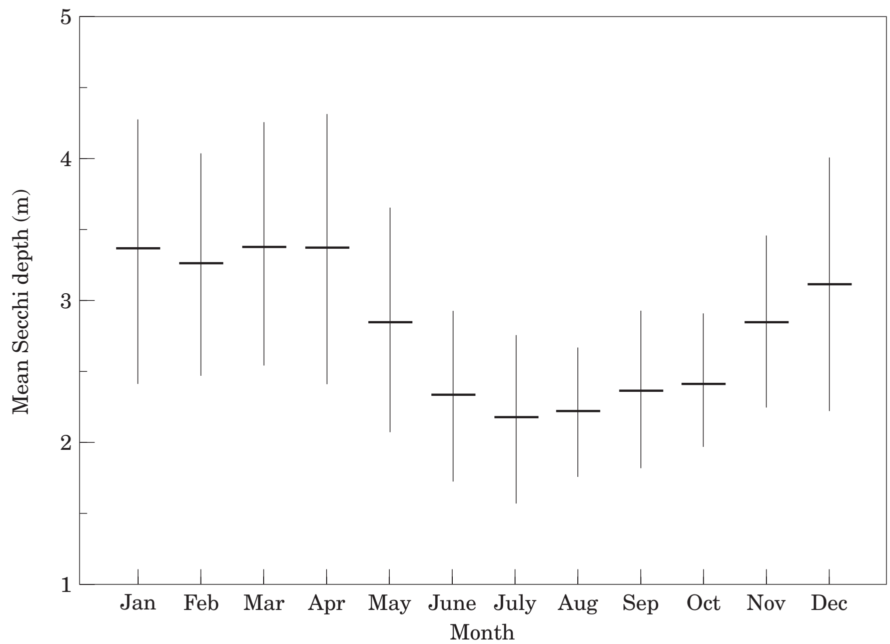

Figure 5. Mean Secchi-disk depth by month at Station II. Each data point is the mean of all observations made in each month over the time series. Error bars are ±1 standard deviation.

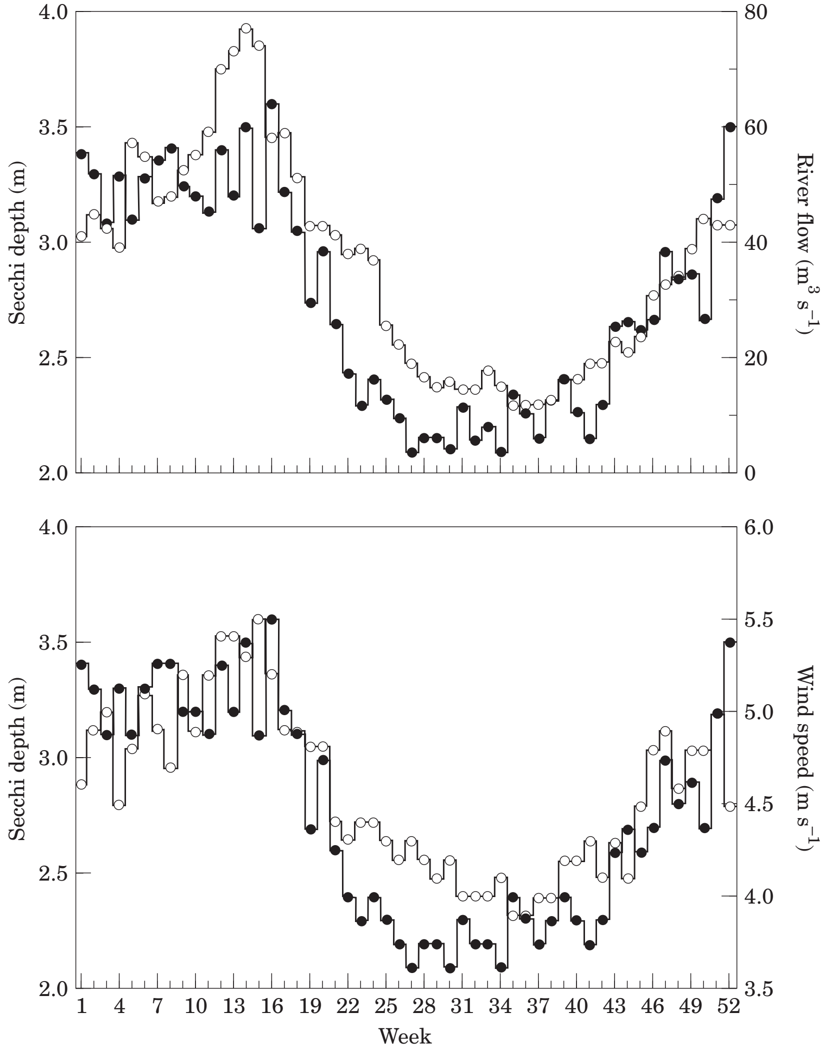

Figure 6. Mean Secchi-disk depth by week at Station II (—●—) compared with mean inflow (—○—) of four major rivers into Narragansett Bay (top), and mean wind speed (—○—) at Providence airport (bottom). Each data point is the mean of all observations made in each week over the time series.

suspended particle diameters of ca. 45 μm, while much smaller particles (ca. 8 μm diameter) are predominant in the lower bay (Collins, 1976). Smaller particles have a greater weight-specific effect on light attenuation than larger particles (Postma, 1961). Thus, changes in particle loading in the northern region of the bay would be expected to affect Station II Secchi-disk observations due to the size-selective transport of suspended particles.

Secchi depth during 1983–1995 correlated negatively with annual TSS loading ($p<0.01$; Fig. 8B) and 43% of the variance was explained by the latter. For every thousand metric tonnes decrease in TSS, Secchi depth in lower Narragansett Bay increased by 0.17 m. Accepting an extrapolation of the regression below loading of 3×10^6 kg year^{-1}, the y-intercept predicts a theoretical mean annual Secchi-disk depth of 4 m at a TSS loading of 0. However, there is an apparent lack of data on water clarity prior to the 1870s when the intensive addition of suspended-solid-laden effluent to Narragansett Bay began (Nixon, 1993). Without historical data, the light-attenuating effects of potentially increased phytoplankton biomass due to eutrophication cannot be separated from the light-attenuating effects of increased TSS loading.

In terms of water clarity, Narragansett Bay appears to have benefited from decreased anthropogenic particle loading, whereas globally many coastal waters appear to

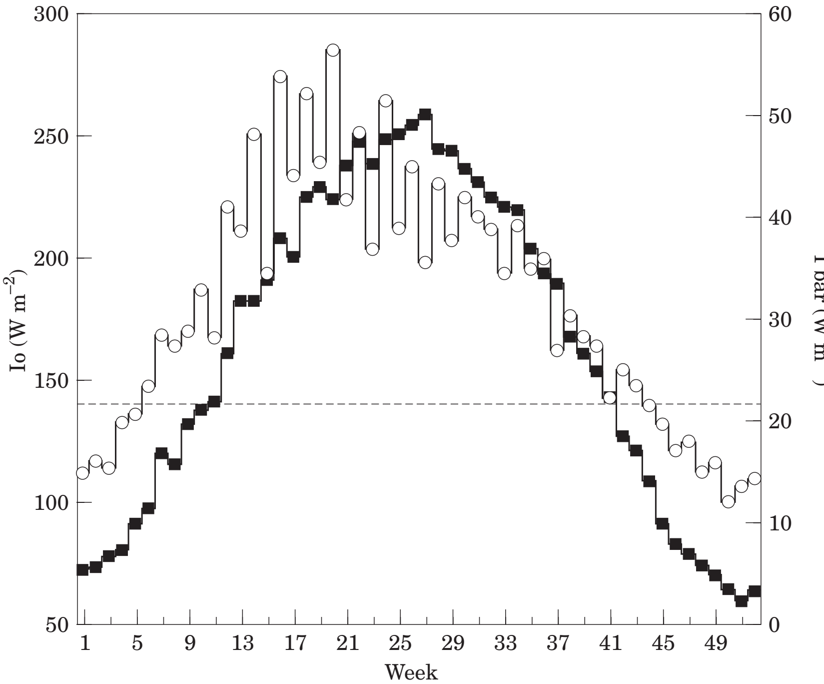

Figure 7. Mean incident irradiance (Io, —■—) and *in situ* light (I bar, —○—) by week at Station II. Each point is the mean of all data for each week over the time series. Dashed line at I bar of 21 W m^{-2} represents threshold light intensity for spring bloom inception (see text).

have become more turbid (Table 4). In the Baltic Sea, the decreasing trend between 1969 and 1991 has been linked to increased phytoplankton biomass due to eutrophication (Sanden and Hakansson, 1996). Similarly, the decreasing trend in Omura Bay, Japan between 1945 and 1975 has been related to the rapid industrialization and population growth in the surrounding area (Iizuka, 1976). Decreasing transparency has also been seen in the Seto Inland Sea (Manabe and Ishio, 1991; Yanagi, 1988). The Black Sea has exhibited a particularly rapid (-0.20 m year^{-1}) decrease in Secchi depth from 1960 through the 1980s (Zaitsev, 1992). This trend has not been directly related to eutrophication, however, but rather to changes in the structure of the food web following the introduction of the zooplanktivorous ctenophore, *Mnemiopsis ledyii* Agassiz, and subsequent decline in zooplankton abundance and increased phytoplankton standing stock (Zaitsev, 1992). In the northern Adriatic, water clarity has decreased since 1960 due to increased phytoplankton biomass related to nutrient enrichment *via* the Po River discharge (Jústic *et al.*, 1995). Eutrophication-related decreases in water clarity have also been observed in the eastern Adriatic (Baric *et al.*, 1992; Morovic, 1983).

The Marsdiep (Dutch Wadden Sea) showed no apparent trend in Secchi depth for the period 1974–1990 (Cadée and Hegeman, 1991). However, when water clarity of the Marsdiep and the Vliestroom was examined over a longer time period, a decrease was evident between 1930 and 1985, followed by an increase between 1985 and 1990 (de Jonge and de Jong, 1992). This pattern is consistent with the observed rapid decreases in suspended matter in the water column, which decreased from an annual mean of ca. 90 g m^{-3} in 1983 to 20–30 g m^{-3} in the 1989–1993 period (de Jonge *et al.*, 1996). Thus, decreased addition of suspended sediment to the water column has led to increased water clarity in these Dutch coastal waters.

Long-term patterns of Secchi depth have been detected in the comparatively deep waters of the Southern California Bight, but do not appear to be closely linked to TSS loading or other anthropogenic activity (Conversi and McGowan, 1992, 1994). Only the relatively shallow nearshore (<50 m) region of Santa Monica Bay exhibited a significant increase (0.36 m year^{-1}) between 1972 and 1987, which was much more rapid than in the other, more enclosed coastal waters (Table 4). However, this increase is believed to be related to long time-scale (T>15 years) fluctuations in the intrusion of clear, oceanic water into nearshore regions.

Like Narragansett Bay, Norwegian coastal waters have also shown recent increases in water clarity related to improvements in sewage treatment (Johannessen and Dahl, 1996). Secchi depths in the industrialized

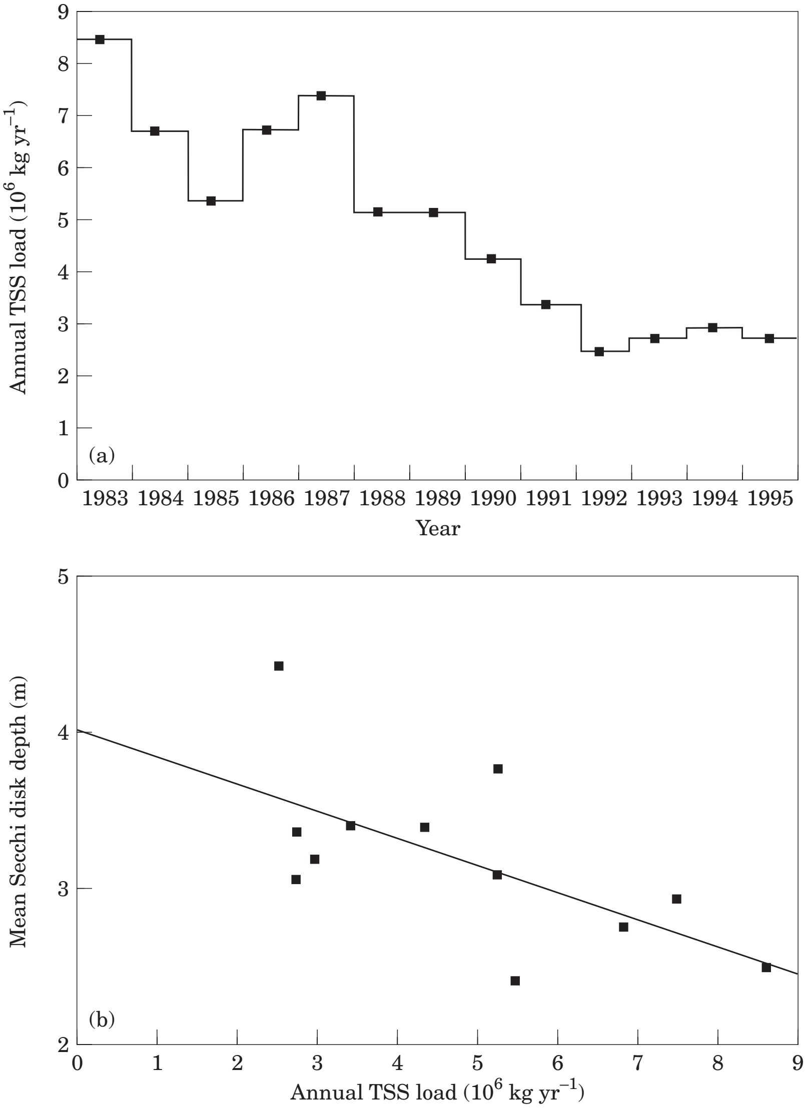

Figure 8. (a) Combined annual TSS loading from 17 Rhode Island waste-water treatment plants (data from Save the Bay, 1996) discharging into the Narragansett Bay watershed and (b) relation between mean annual Secchi-disk depth at Station II and annual TSS loading ($y = -0.17x + 4.02$; $r^2 = 0.43$), 1983–1995.

Grenland region and in the Oslofjord have increased since the early 1970s, when improvements in the treatment and disposal of sewage were made, at rates similar to those found in lower Narragansett Bay.

The changes in Secchi depth in Narragansett Bay were more closely related to decreases in particle loading than to decreased nutrient loading. No trends in dissolved inorganic nitrogen or soluble reactive phosphorus have been noted between 1972 and 1996 (Li and Smayda, 1998), nor were nutrient levels and Secchi depth correlated. Although the mechanisms may vary, with improvements attributable to either removal of particles, as in Narragansett Bay, or to reduction of nutrient, as in Oslofjord, a promising pattern of increased water clarity is emerging in the coastal waters of regions that have taken measures to reduce the impact of sewage addition.

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Table 4. Trends in Secchi depth in various coastal waters globally (D = decreasing; I = increasing; N = no trend; rates of change in m yr^{-1}).

Region	Period	Trend	Rate	Reference
Dutch Wadden Sea	1930–85	D	?	de Jonge and de Jong (1992)
Dutch Wadden Sea	1985–90	I	?	de Jonge and de Jong (1992)
Marsdiep	1974–90	N	?	Cadée and Hegeman (1991)
Baltic Sea	1969–91	D	− 0.08	Sanden and Hakansson (1996)
Black Sea	1960s–80s	D	− 0.20	Zaitsev (1992)
Omura Bay	1945–75	D	− 0.13	Iizuka (1976)
Seto Inland Sea	1926–76	D	− 0.05	Manabe and Ishio (1991)
Seto Inland Sea	1930–86	D	− 0.05	Yanagi (1988)
Northern Adriatic	1960–82	D	?	Jústic *et al.* (1995)
Adriatic – Kastella Bay	1957–90	D	− 0.09	Baric *et al.* (1991)
	1961–81	D	− 0.14	Morovic (1983)
Adriatic – Stoncica	1961–81	D	− 0.17	Morovic (1983)
Santa Monica Bay	1972–87	I	+0.36	Conversi and McGowan (1994)
Inner Oslofjord	1960–93	I	+0.09	Johannessen and Dahl (1996)
Grenland, Norway	1960–93	I	+0.07	Johannessen and Dahl (1996)
Narragansett Bay	1972–96	I	+0.05	This study

students in the course of this time series are greatly appreciated.

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