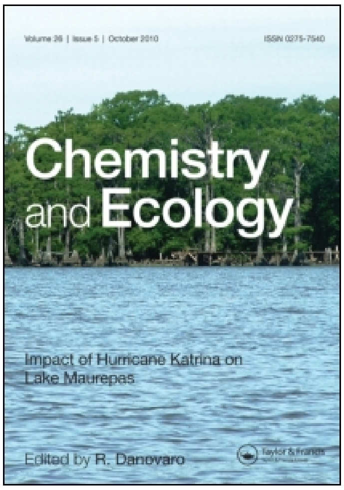

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Variability of Water Column Transparency, Volume Flow and Suspended Solids Near San Diego Sewage Outfall (California): 15 Years of Data

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VARIABILITY OF WATER COLUMN TRANSPARENCY, VOLUME FLOW AND SUSPENDED SOLIDS NEAR SAN DIEGO SEWAGE OUTFALL (CALIFORNIA): 15 YEARS OF DATA

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The spatial and temporal variability of transparency measured for 15 years at 7 stations near the San Diego sewage outfall has been investigated and compared to the temporal variability of sewage suspended solid discharge and flow rate. The purpose of the time-series analyses was to distinguish natural from human (sewage discharge) causes of temporal changes in transparency. The results show that: 1) variations in transparency are highly correlated over the entire area, but there is a gradient in means and variability in the direction perpendicular to the coast; 2) there are no long term trends for increase or decrease in the water clarity at any of the stations; 3) most of the variance of transparency is contained in the seasonal frequency band; 4) over the same time period sewage discharge has significantly increased and suspended solids decreased; 5) most of the variance of these human-caused properties is in the interannual frequency band; (6) there is no correlation at any time-lag between water clarity and suspended solid discharge or flow. These results lead to the conclusion that these anthropogenic properties are not affecting transparency, while natural factors such as seasonality and distance from coast do.

KEY WORDS: Sewage, suspended solids, transparency, coastal discharge, time-series

INTRODUCTION

As in all southern California, the population of San Diego has greatly increased in the last 20 years (by 75% in the period 1970–88, U.S. Bureau of the Census, 1990). The human impact on coastal waters has increased at the same time. For example, the sewage discharge (see Figure 1) in the period 1975–87 increased by 68%, from 413 to 693 million litres per day (Shafer, 1976; SCCWRP, 1987). One question which easily arises is whether this discharge is affecting the quality and ecology of near-coastal waters†. Several studies in the Southern California Bight have concluded that there are deleterious effects of sewage outfall discharges on benthic communities (Smith, 1974; Bascom, 1978; Bascom *et al.*, 1978; Reish *et al.*, 1980; Dhargalkar, 1986), but there is less conclusive evidence of impact on the water column (Thomas, 1972; Eppley, *et al.*, 1972; SCCWRP, 1973; Beers, *et al.*, 1979). This, however, is a part of the ocean where primary production takes place, and through which light must penetrate to permit recruitment of kelp and other benthic algae. One of the purposes of this paper is to evaluate the effects of the input of sewage on the water column transparency.

One crucial problem in the assessment of the human impact on the environment

†In fact, this has recently been the focus of a federal lawsuit which concluded by requiring San Diego to adopt secondary treatment of sewage.

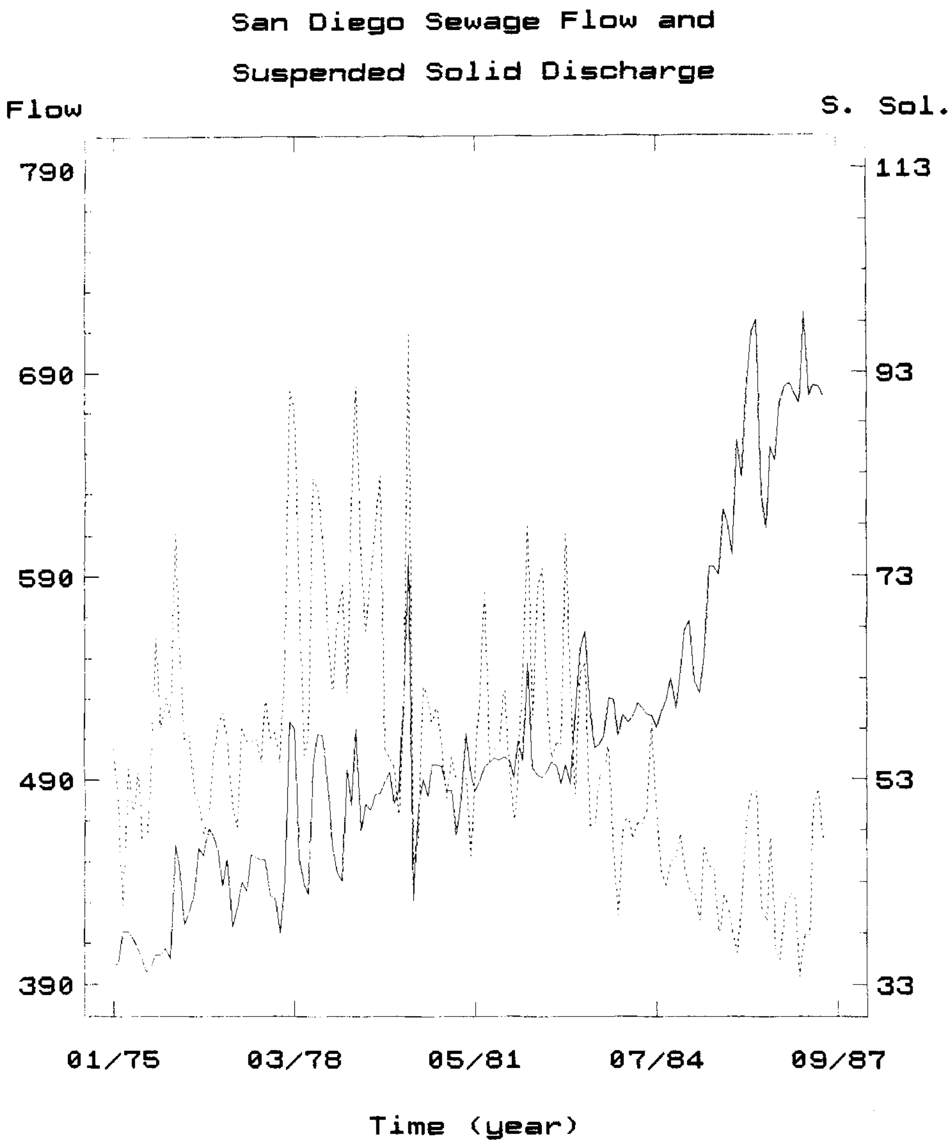


Figure 1 San Diego sewage flow (——) in 10^6 litres/day and suspended solid discharge (. . .) in tonnes/day, for the period 1975–87. Lines are plotted from monthly averages of daily data. The flow percentage change between 1975 and 1987 is +68%, the suspended solids is −54%.

is to scale it against the background of natural variability. This distinction is becoming of increasing importance in an age in which man has reached the technological ability of making permanent changes to the surrounding environment. For example, although rises in both global air temperature and atmospheric CO_2 have been substantiated, there is still debate on whether the first is caused by the latter, as a consequence of human fuel consumption, or whether it is part of a large natural fluctuation (Kuo, *et al.*, 1990). The best tool to put environmental changes in the right perspective is to have long time-series of data which can show the baseline on which humans superimpose their activity.

In this article we try to approach the problem of the influence of sewage discharge on the water column from this point of view. To this purpose, we utilized 15 years (1972–87) of water quality data collected by the Point Loma Treatment Plant (the sewer discharge for the city of San Diego) during its federally mandated monitoring plan. Two control and five test stations (see "Data, Methods and Analyses" and Figure 2) were sampled monthly for water quality parameters (temperature, transparency, transmissivity, dissolved oxygen), while suspended solid discharges and flow rate were measured daily since 1975 in the treatment plant. We utilized part of this data-set (transparency, flow and suspended solids) to investigate: a) the patterns of spatial and temporal variability of transparency at test and control stations; b) whether suspended solid discharge (or sewage flow) had affected water transparency.

Suspended solids exist naturally in all waters and consist of sand, clays, phytoplankton, zooplankton, bacteria, etc. Oceanic concentrations vary from < 0.1 mg l^{-1} in open ocean to many g l^{-1} in estuaries and nearshore waters (Jerlov, *et al.*, 1972; Jerlov, 1976). In the sewage effluent of Point Loma, suspended solids, composed of sewage solids, organic matter, bacteria, etc., are of the order of 80 mg l^{-1} after advanced primary treatment, and this concentration becomes diluted to about 1:200 (Thomas, 1972) at the diffuser ports at the end of the outfall. Suspended solids in the water diminish its transparency because of light absorption and scattering (Jerlov, *et al.*, 1972).

The pattern of variations in water quality off Point Loma is more than of abstract interest. There has been extensive debate on whether the reduction in size of the kelp beds in the area was due to a decrease in available light caused by suspended solid discharge from the outfall.

DATA, METHODS AND ANALYSES

The Point Loma Treatment Plant (San Diego City, California) became operational in 1963. It used primary treatment until July 1985, when it started advanced primary treatment, which achieved at least 75% removal of suspended solids. The treated effluent is discharged approximately 3.5 km off-shore Point Loma, at a depth of about 62 m, through two multiport diffusers 415 m long (City of San Diego, 1988).

Water transparency, suspended solid discharge and flow data were obtained from the federally mandated monitoring program at the Point Loma Treatment Plant. The monitoring plan started in the 1960s, but the data made available to us started in 1972. All the data handled, whether key-entered by the authors or by the treatment plant personnel, have been checked for errors against the plant log books.

Water column transparency was measured monthly at 5 test stations 1.8 to 3.5 km from the sewage outfall and at 2 control stations about 9 km north and south of it (see Figure 2). The 15 year sampling period used in this research, from July 1972 to June

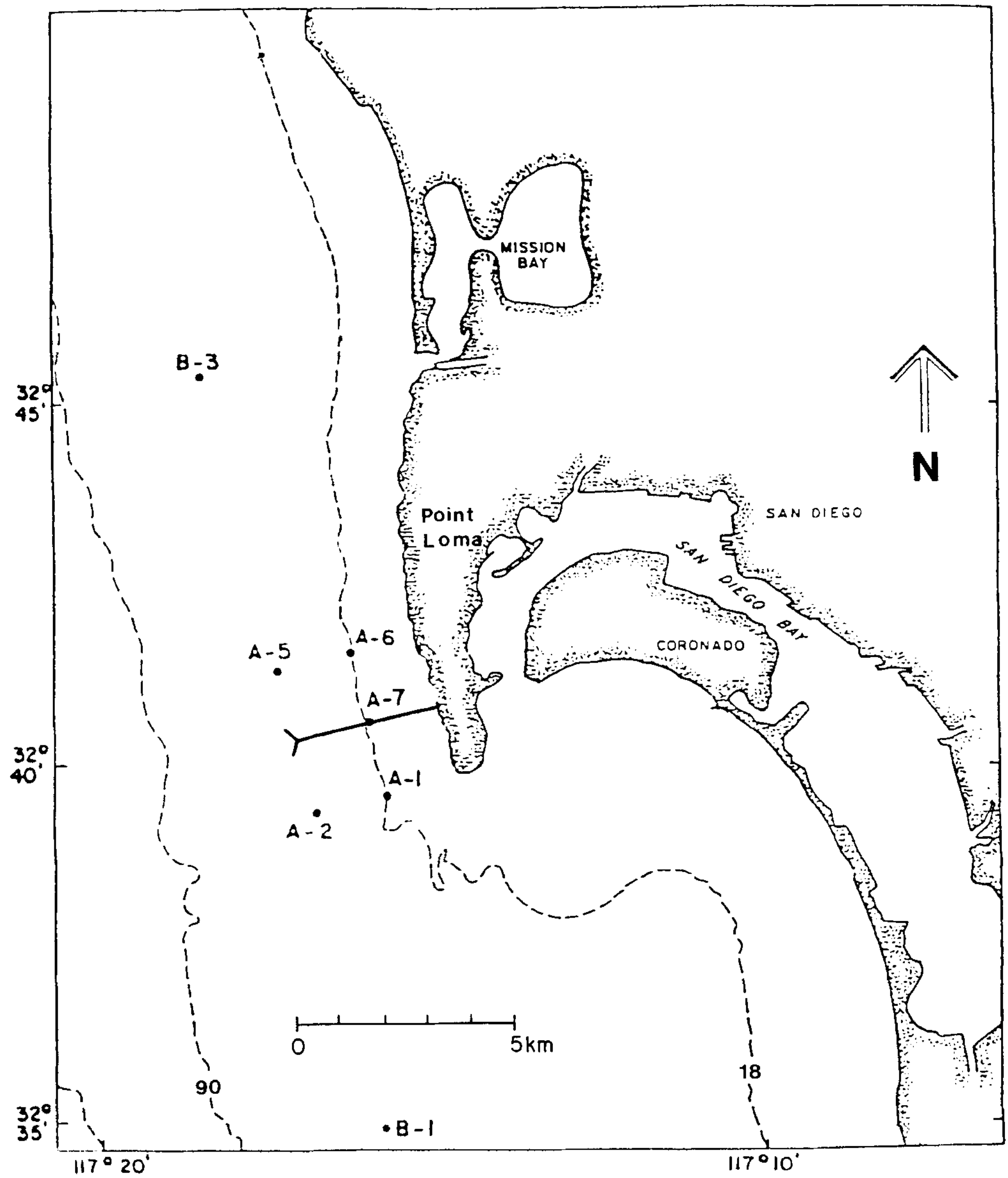


Figure 2 The seven sampling stations around San Diego City sewer outfall. Stations A are "test" stations, stations B are controls. The "y" between stations A2 and A5 represents the end of the outfall. The depth contours are indicated in metres.

1987, resulted in time-series with 180 data points for each of the 7 stations. The sampling device used was a white Secchi disc with a diameter of 30 cm. Transparency (m) was defined as the depth in metres at which the disc disappeared. The 7 sampling stations were located along isopleths of depth: the three most in-shore stations were at or about 1.8 km from the coast and along the 18 m contour. The four off-shore stations, which include the two controls, were at the same contour as the end of the sewage outfall, around 60 m.

The reliability of the Secchi disc measurement has been long questioned: it is affected by the light conditions (time of the day, weather, relative ship position), and there is uncertainty in relating it to the attenuation coefficient (Graham, 1966; Tyler, 1968; Williams, 1968; Holmes, 1970; Preisendorfer, 1986; Megard and Berman, 1989). However, Megard and Berman, after comparing Secchi transparency with underwater irradiance, state "the information obtained at sea with a Secchi disc is as accurate and precise as that obtained under these conditions with a photoelectric sensor". Further, it has the advantages of being easy to use, which reduces the operator error; relatively inexpensive; widely used in oceanography; and directly related to the euphotic depth (1% light level), and therefore to the area where most of the primary production takes place (three times Secchi depth is often equivalent to the 1% light level; calculations derived from Megard and Berman 1989).

Suspended solids and sewage flow have been measured daily at the treatment plant since January 1975, for a total of 4199 data points each. Suspended solids (mgl^{-1}) are defined as the residue retained on a standard glass fibre filter which is dried at 103–105 °C after filtration. For the analyses performed in this paper we have utilized suspended solid discharge (tonnes/day), i.e. the suspended solids times the sewage flow discharged (10^6 litres/day).

For the analysis of the spatial variability of transparency we compared the seven (control and test) time-series. For the time-series analyses we used both the individual seven time-series and their spatial average. Since the spatial analyses showed no significant differences between test and control stations (see "Results and Discussion"), the spatial average of the seven transparency time-series was used for the comparisons between transparency and flow or suspended solids. To make the series comparable, the average transparency was reduced 2.5 years in order to start together with the flow and suspended solids series (January 1975), while the daily vaues of flow and suspended solids were averaged over 30 days to derive monthly values ($n=150$ for both series).

In order to identify any relationship between transparency and sewage discharge, we analyzed the data using conventional statistics and time-series analyses. The procedures used included one-way analysis of variance, correlations, linear trend analyses, spectral analyses and cross-correlations.

To test for spatial variability of transparency we used one way analysis of variance over the whole grid. The data of each station was tested for normality (D'Agostino D test, alpha = 0.05), and in each case, the Null Hypothesis that samples belonged to a normal distribution could not be rejected. The correlation coefficients between the seven sampling stations were calculated using the Pearson product moment correlation. Linear trend analysis, by least squares fit, i.e. fitting the variable analyzed to time and minimizing the sum of squares of the residuals of the fitted line, has been used to evaluate long term temporal changes. Spectral analysis was used to identify frequencies of highest variability. After the series were detrended, tapered, and the means removed, the spectral frequencies were calculated with the Fast

Fourier Transform. The daily series were band-averaged over 4 bands giving 8 degrees of freedom; the monthly series were not averaged. In the following discussion the terms "seasonal" and "annual" will be used interchangeably to denote changes on a 12 month period. To observe lag period of highest correlation and possible lead/lag relations between variables we used the cross correlation analysis which estimates the correlation between one time-series at time t and a second series at time t+k as a function of the lag, or time differential k.

RESULTS AND DISCUSSION

Plots of individual Secchi depths versus time for each sampling station are given in Figure 3. Even before statistical analyses are done it is possible to note a few points:

a) transparency is highly variable in time at all stations.
b) there are no visible trends in any of the water clarity time-series.
c) the in-shore stations (the three in the right column in Figure 3) are generally less transparent (lower means).
d) the in-shore stations in general have also smaller fluctuations (lower variance).
e) the control stations (B) are not obviously different from the off-shore test stations (A2, A5).

First, we investigated the spatial characteristics of transparency, to answer the following questions: Is the inshore-offshore difference in the magnitude of transparency, shown in Figure 3, significant? Is there a gradient between in-shore and off-shore stations rather than between control or test stations? In spite of the differences in means, is transparency correlated between stations within the entire area? And, if so, are the transparency fluctuations synchronous or lagged?

The first question was tested with a one-way analysis of variance on the seven time series. The null hypothesis that the seven population means were equal was rejected at the 0.05 level ($0.002<p<0.005$). The individual means and 95% confidence intervals show that the stations can be subdivided in 3 groups (see Figure 4a). These groupings seem to be driven by the distance from the coast rather than the distance from the outfall: in fact, group 2 stations span a distance of 9 km in the direction parallel to the coast (1.8 to 7 km from the outfall), but have much clearer water than the stations of group 3, which are just 1.8 to 2.5 km from the sewer outfall, in the direction toward the coast. Although the southern control shows waters clearer than any other station, the northern control is indistinguishable from the off-shore test stations (group 2). This indicates the importance of both the control locations with respect to the sewer and of having more than one control.

Although the means are different, transparency does fluctuate synchronously in the entire area: multiple cross-correlation of the seven transformed time series indicated that the maximum correlation was always at lag 0. The Pearson's correlations show that all time-series are highly correlated at alpha = 0.05 (Figure 4b).

The spatial analyses reveal that transparency variations are highly correlated over the entire area, but that there is a magnitude gradient perpendicular to the coastline. Test and control stations at the same distance from coast do not differ

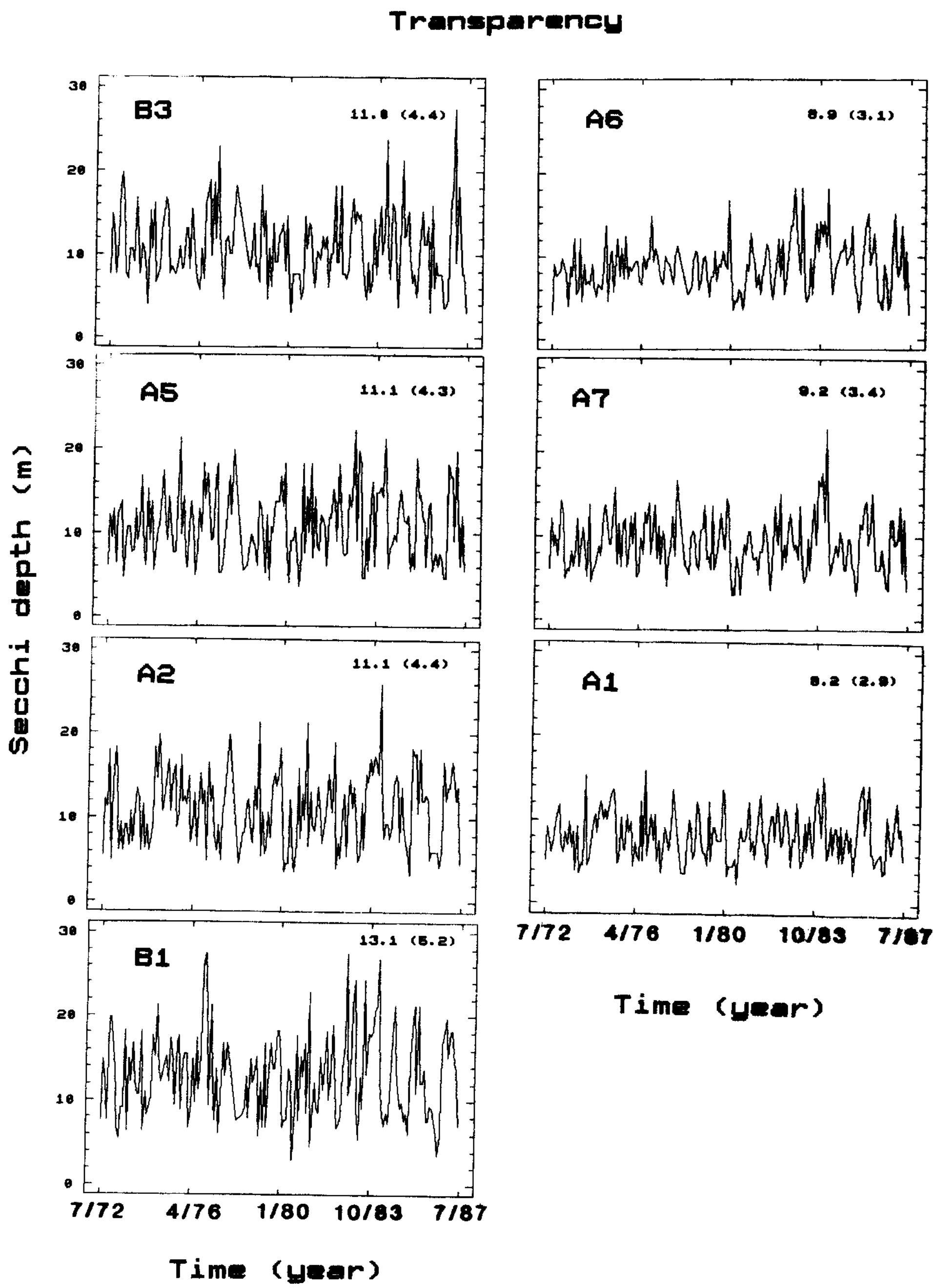


Figure 3 Seven water transparency time-series. In-shore stations are on the right, off-shore stations on the left, in the same order shown in Figure 2. In the upper right corners, means (and standard deviations) are reported. The lines are based on monthly data.

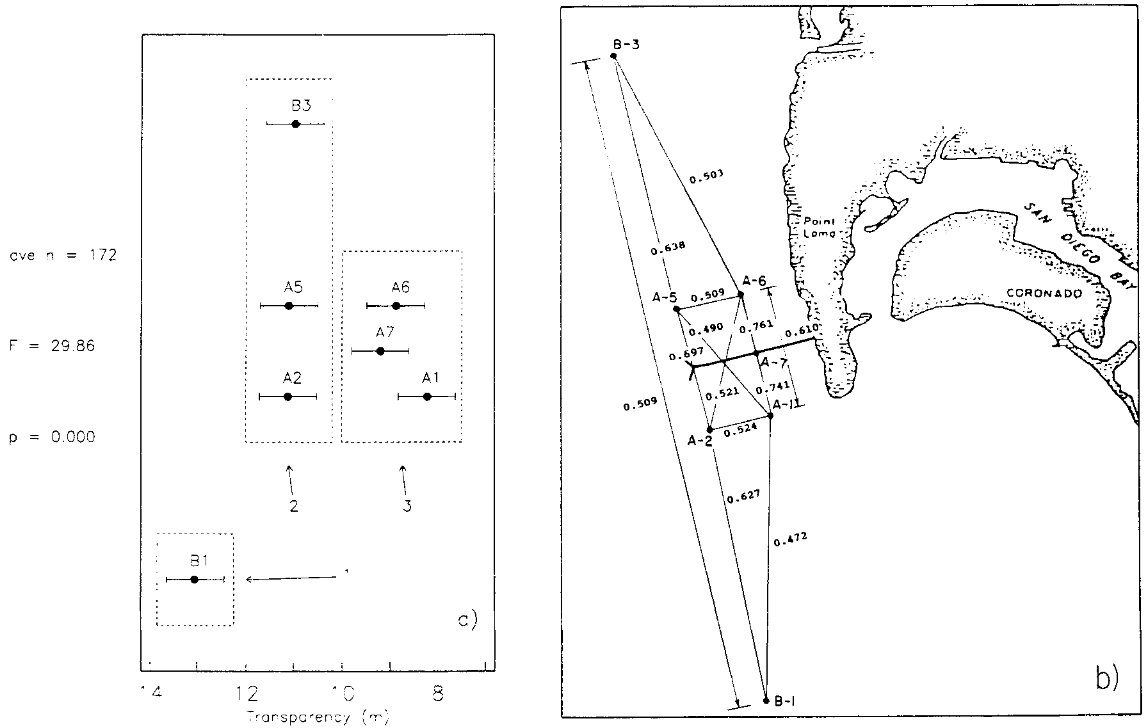


Figure 4(a) Plot of individual means of transparency (m). Bars represent the 95% confidence intervals based on pooled standard deviation. Please note that the x axis has been turned in order to emphasize the relationship between the transparency mean values and the geographic location of the stations (see Figure 4b). On the left of the plot are the results of the one-way analysis of variance (Ho: no difference between the means of the seven stations). Based on the overlapping of the confidence intervals, the stations can be divided in three groups, enclosed in dashed lines: #1 the southern control, with the clearest waters; #2 the remaining three offshore stations; and #3 the three inshore stations, with the murkiest waters. **(b)** Correlation coefficients between some of the seven water transparency time-series. All are significant at alpha = 0.05.

significantly. We then applied time-series analyses to investigate the pattern of temporal variability of transparency and suspended solid discharge, and their possible relations. Individual analyses of transparency at each station were performed and are reported, but, for clarity and space reasons, the figures show only the results regarding the 7 station average transparency.

The trend analysis (Figure 5a) confirms that water clarity off San Diego has not changed over the 15 years studied. This "no-change" has happened while flow has significantly increased and suspended solids discharge decreased, thanks to the improved treatment (see Figures 5b and Figure 1). This result indicates that there is an overall lack of response in this water quality property to the change in sewage discharge.

The spectral analysis of the average of all the stations (Figure 6a) shows that most of the variance of transparency is at the annual frequency band. However, the spectra of the individual stations show a reduction of the seasonal signal from off-shore to in-shore, revealing that the reduction in variability observed in the in-shore time-series (Figure 2) is caused mainly by the disappearance of the seasonal cycle and the onset of mostly random variability. In comparison, the predominant frequencies in the spectrum of suspended solid discharge (Figure 6b) are lower than 3 years, and seasonality is not an important component of the variance of this property. The same is true for flow.

The lack of a meaningful seasonal signal in the suspended solid discharge and its presence in the ocean transparency suggests that the major cycles of these two variables are driven by different forces, some long term change in the treatment for the first variable, natural seasonality for the second one.

Figure 7 shows the pattern of the seasonality for average transparency (a) and for the suspended solid discharge (b). In general, the water off San Diego is clearer in winter and more turbid in spring (Figure 7a). As observed in the individual spectra, the equivalent plots of the individual stations show this same winter/spring pattern at all off-shore stations, but this is suppressed in the near-shore stations. This suggests that transparency is affected by different processes in-shore and off-shore: for example sediment resuspension and mixing may be important processes at the stations where the depth is 30 m or less, while phytoplankton blooms may be more important for the stations where the depth is 60 m. Figure 7b shows that suspended solid seasonality is inconsequential with respect to the interannual variations.

As spectral and trend analyses showed a lack of relationship between the main temporal patterns of transparency and suspended solid discharge, we did a cross-correlation test to investigate whether significant correlations at any time-lag existed. Figure 8 shows that the maximum correlation between average transparency and suspended solid discharge is at lag 0 (+ or − 1 month), i.e. neither variable leads the other. This negative correlation ($r = -0.141$) is in the expected direction for a causal relationship between these two variables (the more the suspended solids, the less the water transparency), however, it is not significant ($0.10 > p > 0.05$).

The cross-correlation between transparency and flow is also not significant at any lag.

Individual cross-correlations between each transparency time-series and suspended solids discharge show no significance at any lag for any station except A2 and A6, which have some significant values at meaningless lags (such as −1 month, transparency leading suspended solids, or +16 months).

The non-significant cross-correlations suggest that there is no causal relationship between transparency and suspended solid discharge or flow.

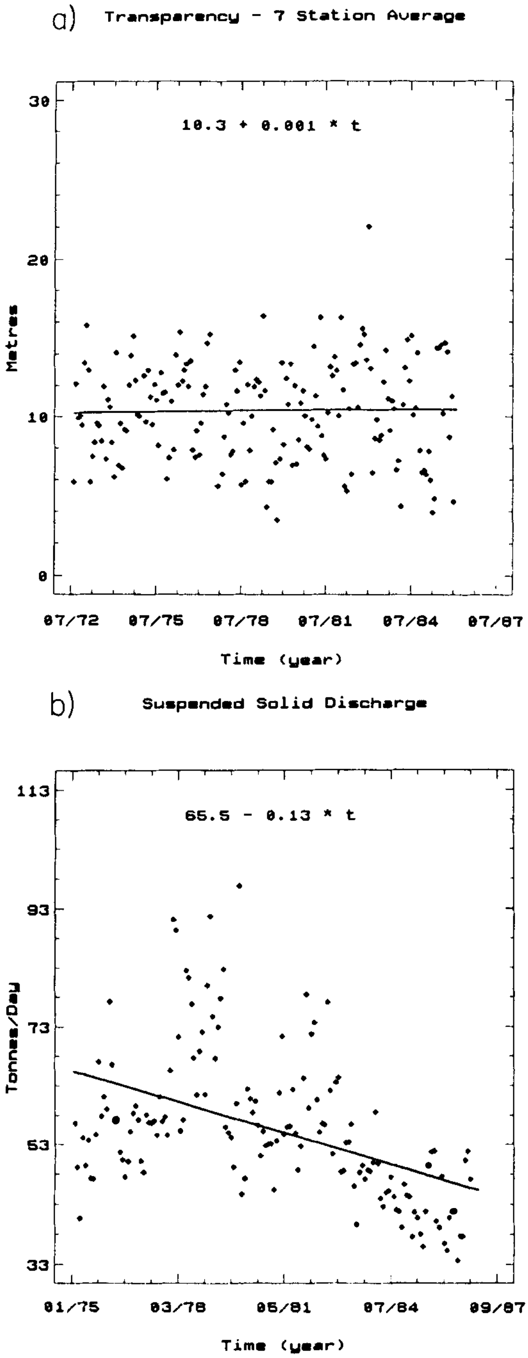


Figure 5 Linear trends (trend coefficients inside the plots). (a) Water transparency (Secchi disc depth), average of all seven stations. (b) Suspended solids discharge, monthly averages of daily data.

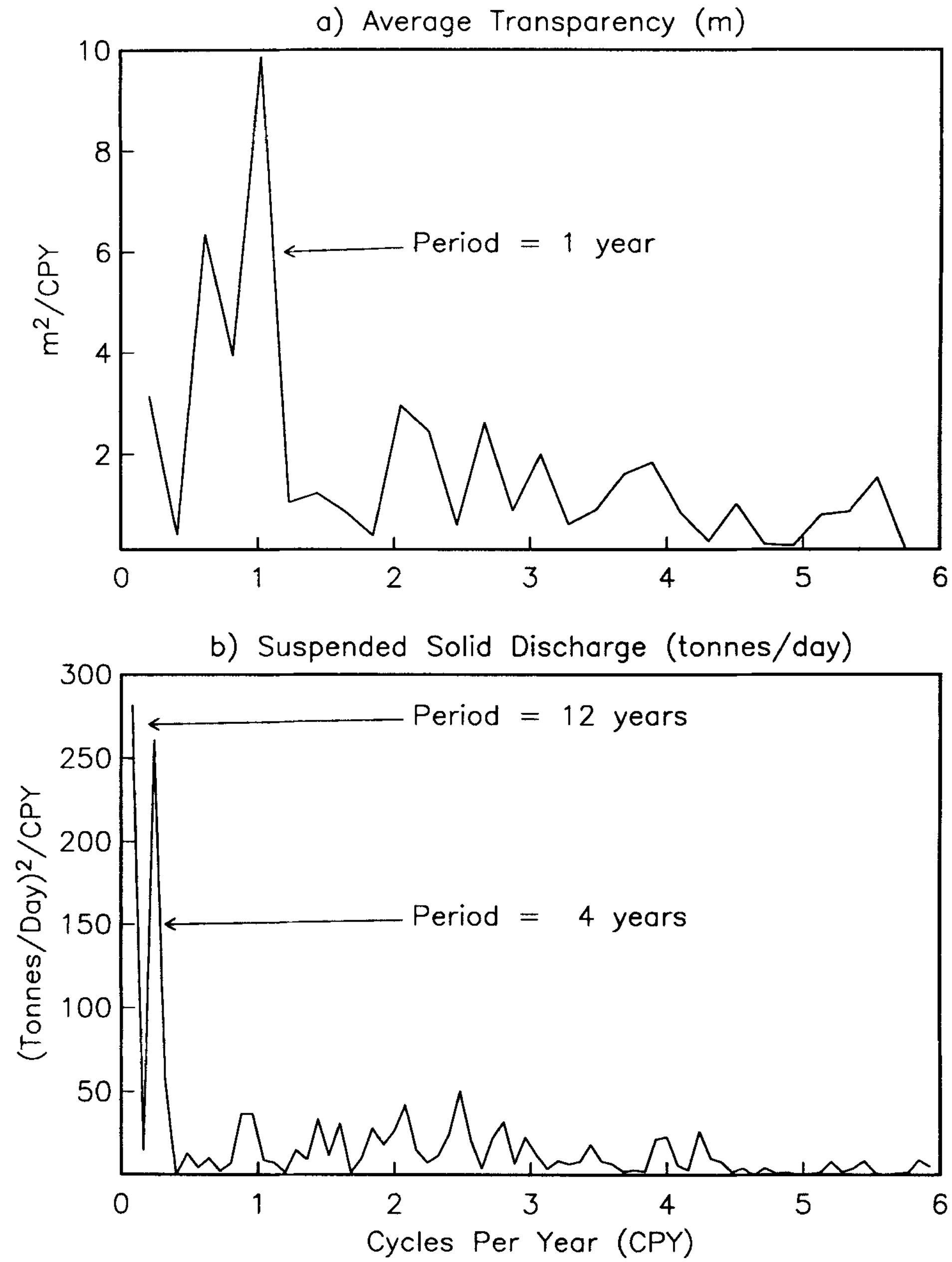
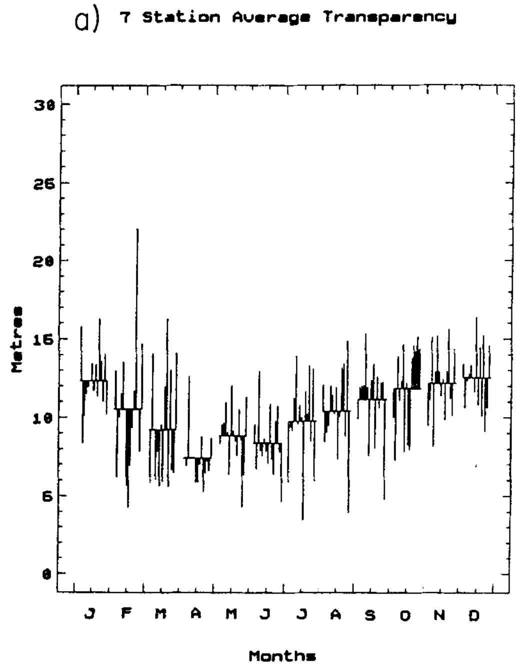


Figure 6 Spectral analysis. The arrows indicate the periodicities with most of the variance. (**a**) Average water transparency (Secchi disc depth). (**b**) Suspended solids discharge. Based on the monthly averages for convenience of comparison with a), since the spectrum of the daily discharge did not show important cycles at frequencies below 3 years.



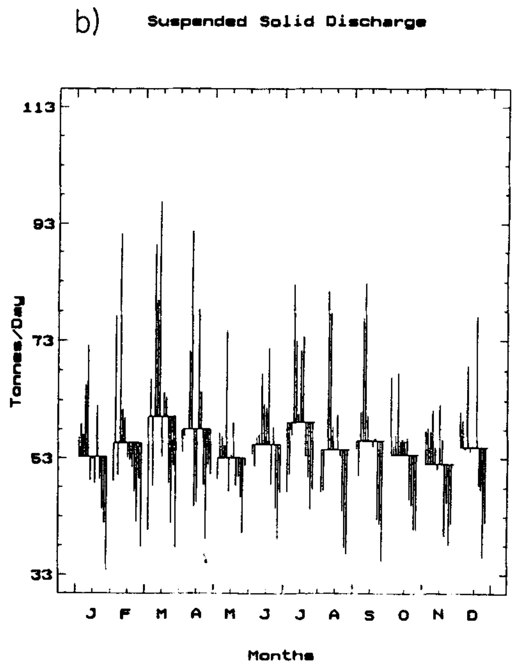


Figure 7 Monthly averages over the entire period studied. The horizontal bars represent for each month the average of the values for all years (seasonal variability), while the vertical bars represent the yearly deviations, or anomalies, from that mean (interannual and intra-annual variability). (**a**) average water transparency (Secchi disc depth). (**b**) suspended solid discharge.

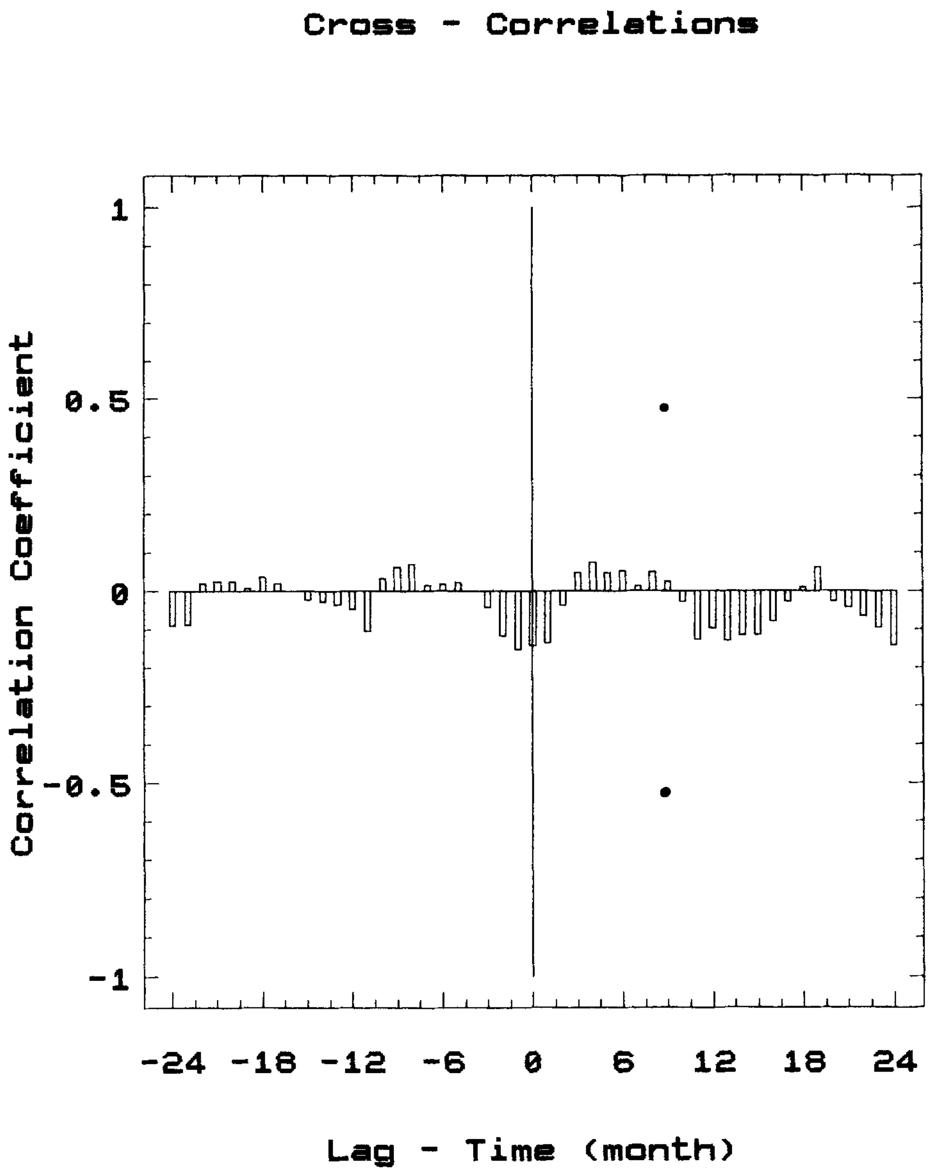


Figure 8 Cross-correlations of transparency and suspended solids discharge. The plot is drawn so that a negative lag means suspended solids lead transparency. Coefficient = 0 means no correlation, 1 means perfect correlation.

Conclusions

The spatial analysis of transparency measured for 15 years at 7 stations near the San Diego City sewage outfall shows that changes in mean and variance occurred along an inshore-offshore gradient. Analogous gradients are found in Santa Monica Bay and off Palos Verdes Peninsula, near Los Angeles (Conversi, unpublished data). In spite of these gradients, temporal variations in transparency were highly correlated at lag 0 over all 7 stations.

The temporal analysis demonstrates no overall trends in any of the 7 stations over the 15 years studied, and therefore no eutrophication in the area is implied. It also shows that an important part of off-shore transparency variance is in the seasonal band and that the inshore-offshore gradient in variance is mostly due to the flattening of the seasonal signal. The seasonal pattern indicates that the coastal water is clearer in winter and less clear in spring. Most interestingly, the spatial and temporal analyses indicate no difference in transparency between control (about 9 km from the outfall) and test (about 2–3.5 km) locations.

The temporal analysis of the anthropogenic variables displays significant trends in both variables (increased flow; decreased suspended solids discharge) over the sampled period. It also shows that most of the variability is in the interannual band.

The presence of seasonality in transparency versus its absence in flow and suspended solids discharge, the absence of trends in transparency versus its presence in flow and suspended solids discharge, and the lack of correlations at any lag between the water clarity and the sewage variables, all indicate that no causal relationship exists between sewage variables and water quality, as measured by transparency. Transparency seems to be driven by the distance from the coast and by seasonally based forces and not from the sewage discharge. In this sense, we can say that transparency fluctuations are "naturally" instead of "anthropogenically" driven.

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