

## TRANSPARENCY CALIBRATIONS FOR LAKE ST. CLAIR AND LAKE MICHIGAN

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**ABSTRACT.** Extensive measurements of water transparency using a Sea Tech transmissometer and total suspended solids (TSM) were made in the southern basin of Lake Michigan and in Lake St. Clair. The relationship between transparency and TSM in each lake can be expressed very well by a single equation. The similarity in the slopes of the lines for the two lakes suggests that the physical properties of the particles suspended in the water are very similar, while the large difference between the intercepts is due to the presence in Lake St. Clair of very fine material (particle diameter less than one micron) which is not present in Lake Michigan. Attempts to use the transparency measurements to identify different particle populations in Lake Michigan as a function of time, station, and sample depth were unsuccessful. Limited data from northern Lake Michigan, Lake Huron, and Lake Superior suggest that the material in Lake Huron is similar to that in the southern basin of Lake Michigan while the observations in northern Lake Michigan more closely resemble those from Lake Superior.

**INDEX WORDS:** Transparency, Lake Michigan, Lake St. Clair, suspended solid, particulate matter, particle size.

### INTRODUCTION

In recent years beam transmissometers have been used extensively to determine the concentration of total suspended material (TSM) both in the open ocean and in coastal waters. The instruments have been used both for vertical profiles (for instance, Gardner *et al.* 1985, Bishop 1986, Richardson 1987, and Campbell and Spinrad 1987) and as part of instrument packages deployed on the bottom for various lengths of time. The time series data from these latter investigations are often used to determine a relationship between changes in current velocity and changes in TSM as inferred from the transparency records (for instance, Baker 1984, Sternberg *et al.* 1986, Lesht and Hawley 1987, and Moody *et al.* 1987). However, in order for TSM to be calculated, a relationship between the water transparency measured by the transmissometer and TSM must be established. Although beam transmissometers have several advantages over filtering methods (simplicity, speed, and resolution), because they measure light attenuation—rather than TSM directly—it is nec-

essary to calibrate the instruments in each area where they are used. This is because the relationship between light scattering by particles and the particle volume concentration is affected by the properties of the particles, in particular their size, shape, and refractive index. Baker and Lavelle (1984) reported that the slope of the line relating beam attenuation to TSM increased dramatically as particle size decreased, Jonasz and Prandke (1986) showed that the slope increased as particles became less spherical, and Gordon *et al.* (1980) found that an increase in refractive index also increased the slope. Since TSM measures mass concentration rather than volume concentration, particle density is also important. It is the variation in these properties that necessitates separate calibrations for different times and places. Conversely, if a single calibration adequately represents data from several different settings, the particle properties must be similar, or at least mutually compensating. In this paper we report the results of calibrations made in Lake Michigan and in Lake St. Clair as well as some preliminary results from Lake Huron and Lake Superior.

## METHODS

We used a Sea Tech transmissometer with a 25 cm path length to measure transparency. In order to minimize absorption by dissolved substances, this instrument emits a nearly monochromatic light beam whose wavelength is 660 nm. Readings are reported over a nominal range of 0–5 volts. Further details regarding the instrument may be found in Bartz *et al.* (1978). In such a system, the transmittance ( $Tr$ ) of the emitted light beam is related to the pathlength ( $z$ ) and the beam attenuation coefficient ( $c$ ) of the medium by

$$Tr(z) = e^{-cz} \quad (1)$$

where  $c$  includes contributions from the absorption by water, light scattering by particles suspended in the water, and any forward scattering that occurs. Zaneveld *et al.* (1980) and Gardner *et al.* (1985) discussed these effects in detail. If the absorption of the light is small and the properties of the particles are relatively uniform, then the attenuation is a multiple of the TSM, so

$$Tr = a e^{b \cdot TSM} \quad (2)$$

where  $a$  and  $b$  are the coefficients to be determined. If one takes the logarithms of equations 1 and 2 then

$$-cz = \ln(Tr) = \ln(a) + b(TSM) \quad (3)$$

The coefficients  $a$  and  $b$  can then be found using simple linear regression techniques. Once the coefficients are known, it is a simple matter to calculate  $c$  and to construct an equation relating TSM to  $Tr$ .

$$TSM = (\ln(Tr) - \ln(a)) / b \quad (4)$$

Since the beam attenuation coefficient is the parameter actually determined, expressions relating  $c$  to TSM are used throughout this paper. Note that both the amount of light absorbed by water and the amount of scattering are wavelength dependent, so the attenuation coefficients derived in this paper are applicable only to instruments that use the same wavelength. The attenuation coefficient has the dimensions of length to the minus one.

We made measurements of transparency and TSM in southern Lake Michigan in 1983, in Lake St. Clair in 1985 and 1986, and in northern Lake Michigan, Lake Huron, and Lake Superior in 1984,

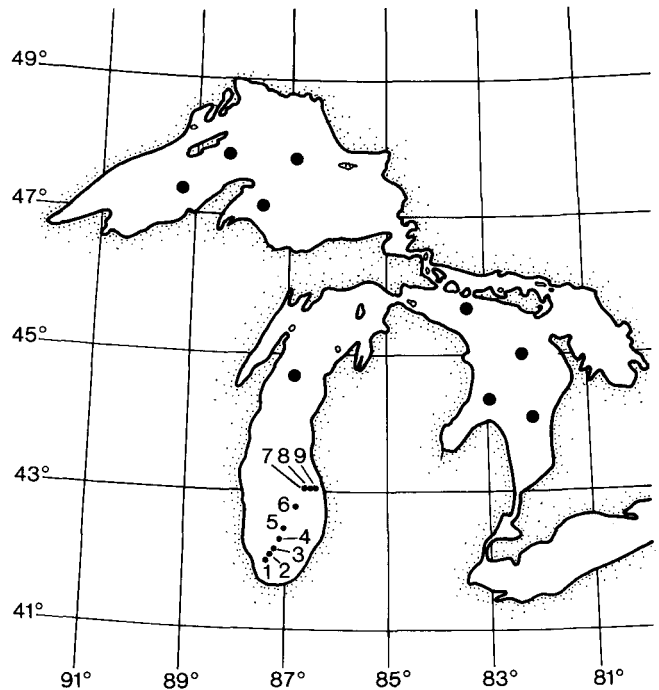


FIG. 1. Locator map of sampling stations in Lake Michigan, Lake Huron, and Lake Superior.

1985, and 1987. Although the same general procedure was used in all cases, improvements in the data recording system allowed some modifications to be made after 1983. All transparency measurements were recorded as the fraction of the transparency in air.

Measurements were made at nine different stations in southern Lake Michigan (Fig. 1) between February and November in 1983. Although Bishop (1986) noted a dependence of transparency readings on the internal temperature of the instrument, because our readings were collected over a period of only a few minutes the internal temperature did not change enough to affect our results. Transparency values were read from a transparency-depth plot recorded as the meter was lowered to the bottom while TSM was determined by filtering water collected in Niskin bottles through pre-weighed glass-fiber filters (one micron nominal pore diameter). This means that the two measurements were not exactly synchronous, although they were usually made within 5 minutes of each other. It was not possible to ensure that the depths at which the two readings were made were precisely the same. Although most of the TSM measurements were not duplicated, at three depths at station 5 three TSM

samples were collected. If possible 4 liters of water were filtered, but in many cases the filters clogged before this amount had passed through.

The stations on the east side of the lake (stations 5-9) were sampled at least 10 times between April and October, while the stations on the west side of the lake (#1-4) were only sampled during February, May, August, and September. Although samples were collected at set depths at the eastern stations, the samples collected at the western sites were chosen to coincide with differences in transparency. Many of the TSM samples, particularly those collected near the bottom and in the thermocline, were collected in regions where the transparency varied rapidly with depth. In order to minimize errors due to vertical inhomogeneity, only those samples which showed less than a 3% transparency variation over 3 meters were used. Thus of the over 450 samples collected, less than 350 were used in the analysis. Separate tests in which transparency readings were made over periods of 15 minutes showed that transparency usually varied only slightly (1-3%) over a short period of time, so we do not believe that the time difference between the transparency measurement and the water collection is important.

Sample collection in Lake St. Clair was similar, but all TSM measurements were made in triplicate, and the transparency readings were recorded digitally on cassette tape. Samples were collected at 23 stations located throughout the lake (Fig. 2), at various times between May and November. Since Lake St. Clair is vertically well mixed, usually only one sample was taken per station, but at stations where there was a pronounced variation in transparency with depth two measurements were made. Of the 116 samples collected (one filter was mangled), two sets of replicates that showed very poor agreement were discarded from the analysis. In both these sets the range of TSM values was over 10 mg/L.

Sample collection in northern Lake Michigan, Lake Huron, and Lake Superior was far less comprehensive. Only one station was occupied in northern Lake Michigan, and four in each of the other two lakes (Fig. 1). Samples were only collected on 5 different days at a few depths and no replicates were done. As in Lake St. Clair, the transparency readings were recorded digitally.

## RESULTS

Regression analysis for the Lake St. Clair samples gives

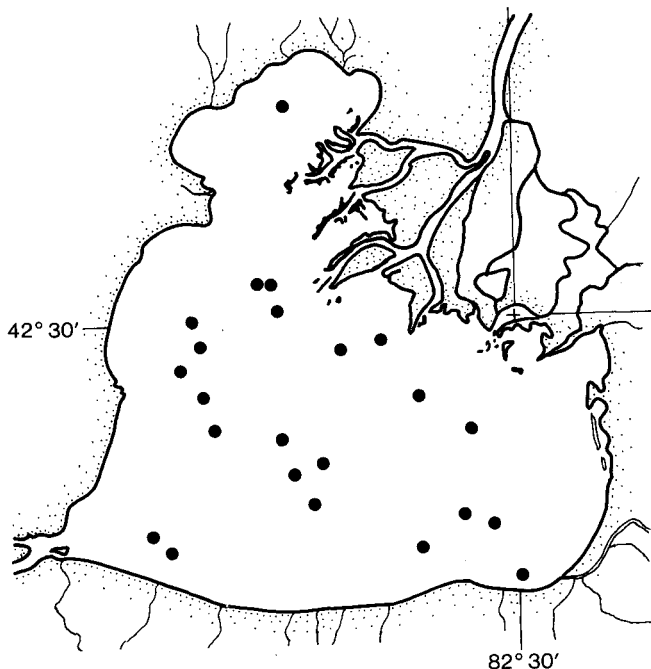


FIG. 2. Locator map of sampling stations in Lake St. Clair.

$$c = 1.16 + .49(\text{TSM}) \quad r^2 = .94 \quad (5)$$

Plots of Tr versus TSM and c versus TSM are shown in Figures 3a and 3b. The transparency readings varied only between 2 and 60%, corresponding to TSM values between 33 and 2 mg/L. The fit of equation 5 is quite good, which suggests that the particles suspended in Lake St. Clair are fairly homogeneous. The high value of  $r^2$  is somewhat dependent, however, on the six observations made with TSM values over 20 mg/L. If these measurements are deleted, the intercept changes substantially and the  $r^2$  value decreases.

$$c = .85 + .55\text{TSM} \quad r^2 = .84 \quad (5a)$$

The difference between the TSM values calculated using equations 5 and 5a is less than 0.5 mg/L for transparency values between 60% and 20%, but increases to about 1.20 mg/L at 10%. This is because the intercept values become more important as the concentration decreases.

The sample variance shows no consistent trend when plotted against the sample mean (Fig. 3c). Since typical filter weight differences before and after filtering the water were 20 mg while we estimate a weighing error of about 0.1 mg, the weigh-

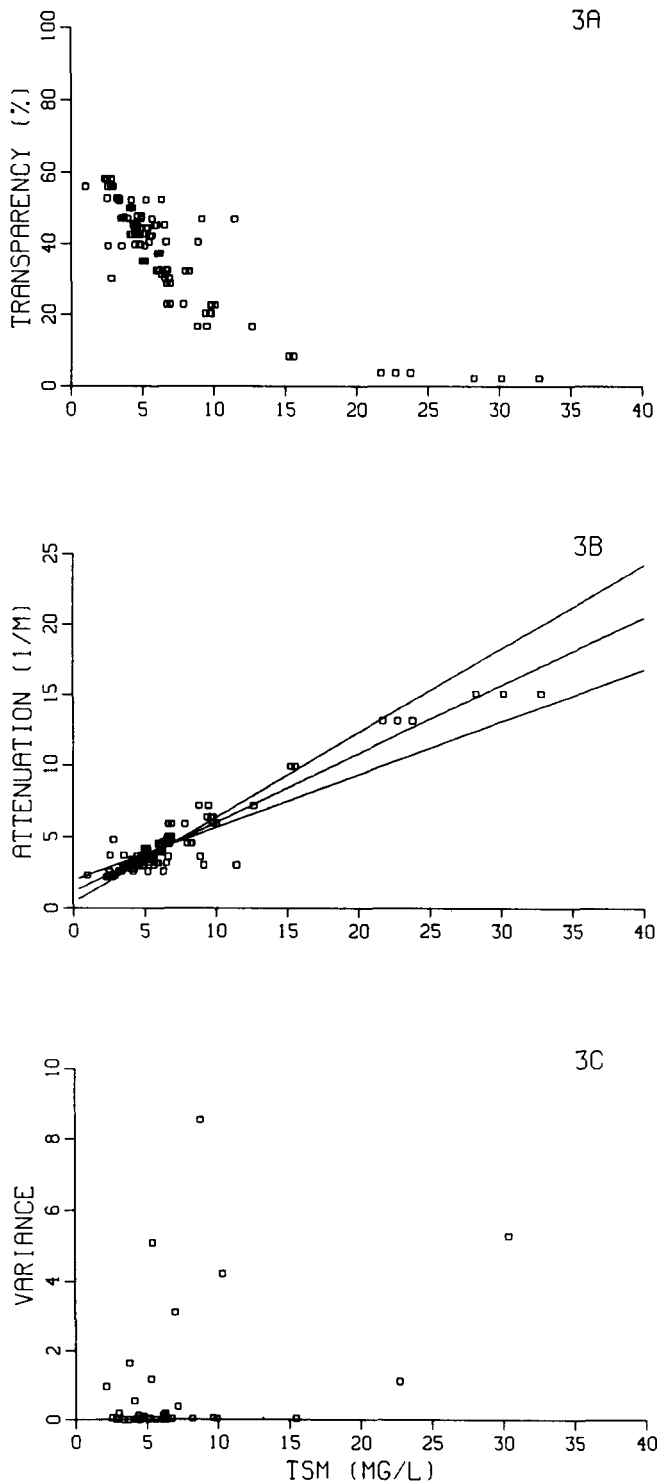


FIG. 3. Lake St. Clair observations. a) Observed transparency as a function of TSM. b) Observed attenuations and the line calculated from equation 5. The 95% confidence limits for the calculated mean are also shown. c) The sample variances of the TSM observations.

ing error is only a small percentage of the total measurement. In addition, since the replicate water samples were collected sequentially, rather than withdrawing aliquots from a single sample, the variation between the TSM measurements at a single site can reflect real differences in sediment concentration. Thus the sample variance most likely reflects the variability in the samples. If measurement errors were a significant part of the sample variance we would expect the sample variance to increase as the sample mean decreased. If anything, the trend is in the other direction.

Marmoush (1986) calibrated a Martech transparency meter in Lake St. Clair and found that (based on 82 non-replicated samples)

$$c = -.16 + .76(\text{TSM}) \quad r^2 = .79 \quad (6)$$

Since the Martech meter uses a light source that emits a wide range of wavelengths and has a peak sensitivity at about 440 nm, it is not surprising that his attenuation coefficients differ considerably from ours. Marmoush also reported calibrations for the inorganic and organic fractions.

$$c = .52 + .84(\text{Inorg}) \quad r^2 = .74 \quad (7)$$

$$c = .12 + 3.68(\text{Org}) \quad r^2 = .77 \quad (8)$$

The similarity between the slopes of equations 6 and 7 indicates that inorganic material is responsible for most of the attenuation in Lake St. Clair, while the effect of the lower density of organic material is reflected in the higher slope in equation 8.

The equation for the attenuation coefficient for southern Lake Michigan is

$$c = .50 + .53(\text{TSM}) \quad r^2 = .78 \quad (9)$$

based on 341 observations. Both the actual TSM values and their range (0.3 - 7.0 mg/L) are less than in Lake St. Clair (Fig. 4a). The corresponding transparency values are higher and also more restricted in range (95-35%). The scatter about equation 9 is considerable (Fig. 4b), but at least part of the reason for the relatively poor fit may be the restricted range of the observations. Figure 4c plots the mean and sample variance for the observations made at 3, 75, and 135 m above the bottom at station 5—the only observations which were repeated. As in Lake St. Clair there is no consistent trend, although in general the variance increases as

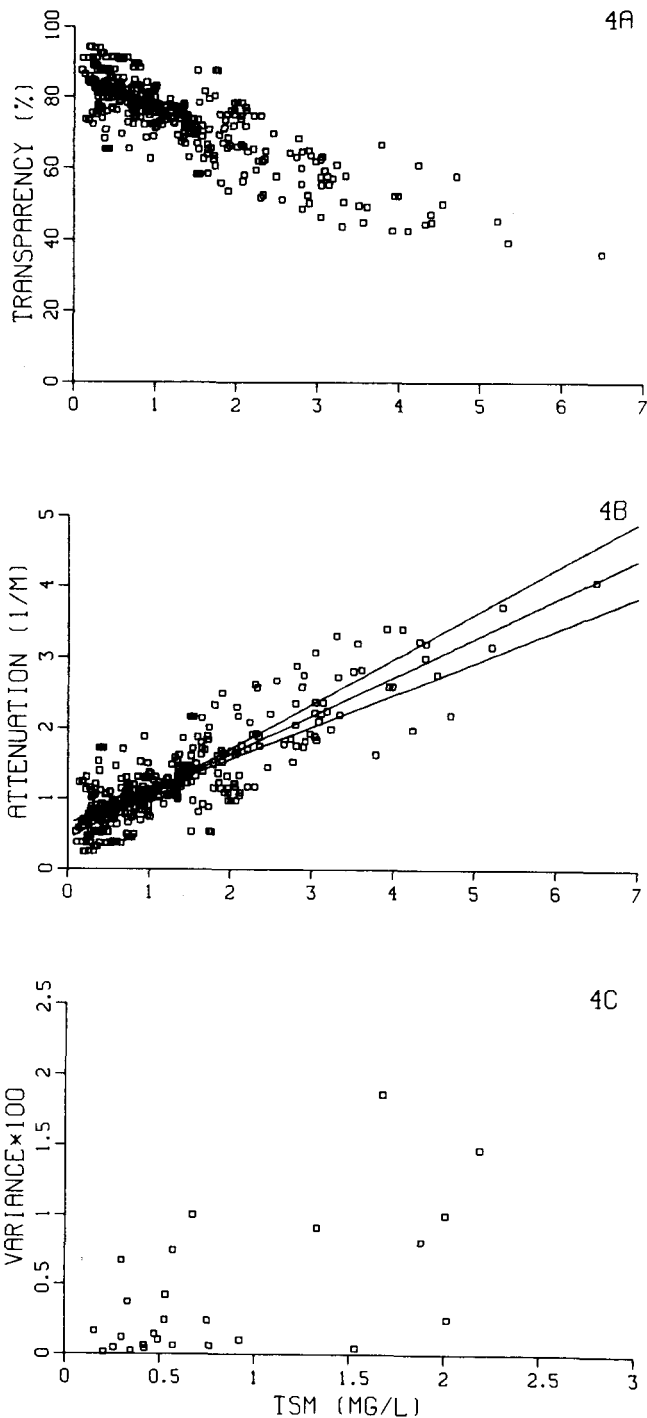


FIG. 4. Observations from the southern basin of Lake Michigan. a) Observed transparency as a function of TSM. Note the reduced range of TSM compared to that for Lake St. Clair. b) Observed attenuations and the line calculated from equation 10. The 95% confidence limits for the calculated mean are also shown. c) The sample variances for the replicated samples. Note the reduced range of the X axis.

the mean increases. Since here, as for Lake St. Clair, the weighing error is only a small fraction of the total sample weight, the sample variance most likely reflects real variability in the TSM. The sample variances for Lake Michigan, however, are much less than for Lake St. Clair. This means that even though the TSM measurements are much less than in Lake St. Clair they are still accurate to within 0.1–0.2 mg/L.

Since Lake Michigan is much larger and deeper than Lake St. Clair—and is not well-mixing during the stratified period—it is possible that much of the variability shown in Figure 4a is due to real differences in particle characteristics. If so, it might be possible to divide the data into smaller groups and calculate a regression line for each. If these groups define sets of observations where the particle characteristics are more similar than in the lake as a whole, the  $r^2$  values for each of the regression lines should be higher than that for equation 9. Such differences might be associated with changes in either station location, sample depth, or time of the year. We grouped the observations on the basis of each of these three variables, but in no case did we get a set of regression lines which all had  $r^2$  values greater than 0.77. We also tried grouping the data by two of the criteria simultaneously, but none of the three possible combinations: by time and depth, by time and station, or by station and depth produced a set of regression lines which all had high  $r^2$  values. If the data are divided using all three criteria at the same time, the sample sizes become too small to be useful.

Limited data are available from one station in northern Lake Michigan and four stations each in Lakes Huron and Superior (Fig. 1). The data and regression lines are shown in Figure 5. The regression line for northern Lake Michigan is based on 18 points

$$c = .54 + .30(\text{TSM}) \quad r^2 = .36 \quad (10)$$

The line for Lake Huron is based on 65 observations

$$c = .51 + .51(\text{TSM}) \quad r^2 = .63 \quad (11)$$

and the line for Lake Superior includes 62 observations

$$c = .46 + .29(\text{TSM}) \quad r^2 = .48 \quad (12)$$

In all cases the fits are quite poor, due, no doubt,

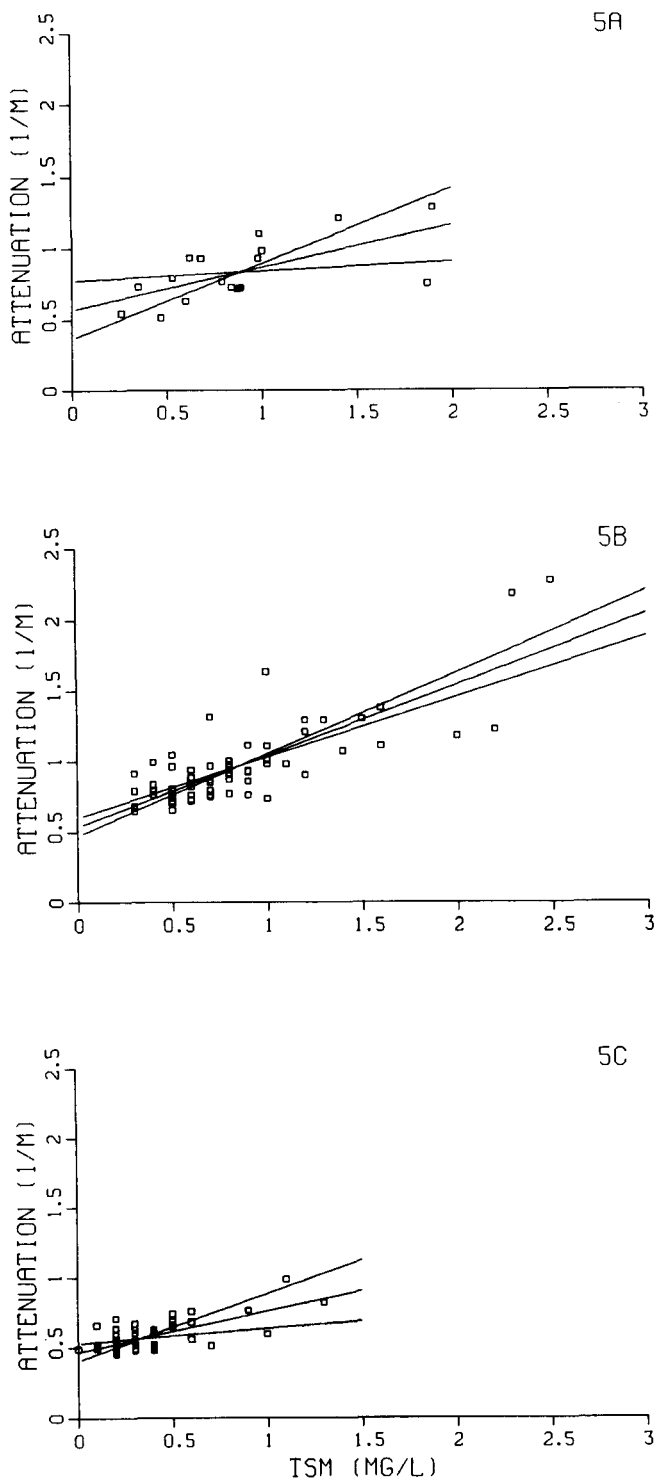


FIG. 5. Observations and calculated regression lines from a) the northern basin of Lake Michigan, b) Lake Huron, and c) Lake Superior. The 95% confidence limits of the calculated mean are also shown. The lines were calculated using equations 10, 11, and 12 for the three lakes.

to the small number of observations and the limited range of transparency and TSM values. Although these data look similar to those from southern Lake Michigan, equations 10 and 12 are both significantly different from both equation 9 and a modified version that was calculated using only those data points with TSM less than  $3 \text{ mg L}^{-1}$  ( $c = .50 + .52(\text{TSM})$ ,  $r^2 = .63$ ). Equation 11, however, is identical to the modified equation at the 90% confidence level. This indicates that while suspended particles in southern Lake Michigan and Lake Huron are quite similar, they differ in some way from those found in Lake Superior and northern Lake Michigan.

### DISCUSSION AND CONCLUSIONS

The data from both Lake St. Clair and from southern Lake Michigan show remarkable consistency, indicating that the properties of particles in these two lakes are fairly uniform. In Lake St. Clair this is not unexpected, but the fact that equation 9 accurately represents all of the samples from Lake Michigan is somewhat surprising. The slopes in equations 5 and 9 are almost identical. This is interesting because changes in the particle properties affect only the slopes of the regression lines, not the intercepts. Since the slopes of the lines do not vary much, the particle-related properties must either be similar in both lakes or mutually compensating. Marmoush's (1986) data indicate that most of the attenuation in Lake St. Clair is due to inorganic particles, so it seems likely that this is also true in Lake Michigan. Hawley (1983) examined suspended material from southern Lake Michigan and found that virtually all of the particles less than 8 microns in diameter were mineral grains. Since Baker and Lavelle (1984) showed that smaller particles are far more effective at attenuating light than are larger ones at the same mass concentration, most of the light attenuation is probably due to small mineral grains. It is thus not too surprising that the properties of these particles are roughly similar in both lakes. This implies, of course, that the size distributions are about the same.

Most of the difference between the two equations is due to the intercept, which, particularly at the relatively low TSM concentrations in Lake Michigan, is a considerable proportion of the total value of  $c$ . Tyler *et al.* (1974) reported the results of several determinations of  $c$  for particle-free water and found that the range was  $0.31\text{--}0.42 \text{ m}^{-1}$  for a

wavelength of 660 nm. This is approximately the value found in Lake Michigan but is much less than for the Lake St. Clair samples. The most likely explanation for the high intercept, which is the attenuation coefficient at zero TSM, is that large numbers of very fine particles were not filtered out during the TSM determination. We tested this by filtering some Lake St. Clair water through one of our glass-fiber filters and then measuring the transparency. The resulting attenuation coefficient was  $0.93 \text{ m}^{-1}$ . We then refiltered this water through a filter whose pore size was 0.45 microns and found that the attenuation coefficient was  $0.56 \text{ m}^{-1}$ . When we measured the attenuation of Lake Michigan water filtered through a glass fiber filter, the attenuation coefficient was  $0.65 \text{ m}^{-1}$ . We also filtered one sample of Lake St. Clair water through a 0.45 micron filter and found that the TSM was about  $0.25 \text{ mg L}^{-1}$  greater than that determined using the glass fiber filters, while for Lake Michigan water the two results were the same. These results show that there are large numbers of submicron particles suspended in Lake St. Clair which were not included in the TSM measurements. We suspect that if these particles had been included in the TSM measurements the regression coefficient would increase and the intercept decrease. Since these particles were not included, their effect becomes an additive constant, much like the effect of any absorption by dissolved substances.

The limited data from northern Lake Michigan, Lake Huron, and Lake Superior seem to indicate that the particles in Lake Huron are similar to those in southern Lake Michigan while those in northern Lake Michigan more closely resemble those in Lake Superior. The intercepts for all four of these areas are about the same, but the slopes in the equations for northern Lake Michigan and Lake Superior are much lower than for the other lakes. This suggests that the mean particle size in northern Lake Michigan and Lake Superior is somewhat larger than in the other lakes, although differences in particle density, shape, or refractive index might also account for the different slopes.

Baker and Lavelle (1984) compiled a list of field determinations of beam attenuation coefficients and found that the slopes increased as one moved from high-energy nearshore environments, where coarse-grained particles are more abundant, to lower-energy environments, where coarse-grained material is less common. Since both Lake Superior and the northern basin of Lake Michigan are somewhat deeper than either Lake Huron or the

southern basin of Lake Michigan, one might expect that the particles in these areas would be somewhat smaller, but our data implies just the opposite. Why this should be so is not known, although different sediment sources in the different basins may be involved. Another possibility is that the particles in both northern Lake Michigan and in Lake Superior are larger because of increased flocculation in these basins. Weilenmann *et al.* (1989) have shown that the efficiency of flocculation is higher in waters with low values of dissolved organic carbon (DOC). Since DOC values are lower in northern Lake Michigan and in Lake Superior than they are in Lake Huron or southern Lake Michigan, flocculation rates may be higher in those basin, resulting in larger particles.

The large number of submicron particles found in Lake St. Clair is also in contrast to the trend noted by Baker and Lavelle (1984), since in this shallow lake one would expect to find coarser particles. This may be due to local sources of fine-grained material, but we have no data to test this hypothesis.

Since beam attenuation is wavelength dependent and since TSM determinations are dependent upon the type of filter used, the calibrations reported here can be used to calculate TSM only if the observations are made using the same instruments and methods as used in this study. However the implications of the results—that the suspended particle populations in the various basins are fairly homogeneous, but that there are distinct differences between the populations in different basins—are more general. Further observations with an instrument with a longer pathlength (to increase the spread of the transparency observations) coupled with observations of the physical properties of the particles would be necessary before transparency measurements could be used to identify different particle populations. The equations presented can, however, be used to determine TSM values with a reasonable degree of confidence, at least in quiet weather. Estimating TSM measurements during storm conditions is somewhat more risky, since local resuspension of coarser bottom material is likely to occur. The presence of such material will significantly affect the calibrations and will lead to an underestimate of the TSM (Moody *et al.* 1987). However, in the absence of samples collected during high-energy events, the above equations can at least provide a lower bound estimate.

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