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Chlorophyll a distribution and sampling uncertainty  
in productive lakes.

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A simple model of phytoplankton patchiness, represented by chlorophyll a distribution, is presented to illustrate the problems encountered in designing sampling programs for lakes of different trophic status. Data are presented for 19 whole-lake chlorophyll a distribution surveys from both unproductive and productive lakes in central Alberta, Canada. Regardless of the environmental factors controlling phytoplankton patchiness in different lakes, a common trend towards a density-dependent dispersion pattern was observed, i.e., the variances of whole-lake chlorophyll a estimates can be directly related to the mean concentrations ( $\text{Log}_{10}(\underline{s}^2) = -1.99 + 2.25 \text{Log}_{10}(\bar{x})$ ,  $n = 19$ ,  $r^2 = 0.83$ ). This relationship implies that to provide similar levels of sample precision, more sample units would have to be taken from productive lakes than from unproductive lakes. The data also suggest that, as the standing crop fluctuates within a single lake the sampling program should be adjusted accordingly, or be designed in advance to account for probable fluctuations.

Key Words: chlorophyll a, heterogeneity, spatial distribution, sampling design, productive lakes, patchiness.

## Introduction

The phenomenon of spatial heterogeneity, or patchiness, in phytoplankton communities has been documented in both marine (Platt et al. 1970; Steele 1978) and freshwater environments (Richerson et al. 1978; Richards and Happey-Wood 1979). A complex interaction of biological and physical mechanisms have been implicated in patch formation. Regional differences in nutrient supply within a lake basin can give rise to differences in phytoplankton numbers, and the influence of tributary streams in this manner has been demonstrated by Goldman et al. (1972) in Lake Tahoe, Ganf (1974) in Lake George, and Riemann (1977) in Mosso Lake. The inverse relation between mean depth and phytoplankton productivity described by Fee (1979) suggests that littoral zones and shallow basins of complex lakes could produce higher standing crops than pelagial zones due to the increased probability of nutrient regeneration. Overshadowing the spectrum of internal processes contributing to patchiness is the kinetic energy of wind; several authors have reported on the dominant influence of wind speed and direction in determining the horizontal patterns of phytoplankton distribution (Small 1963; George and Edwards 1976; Harris and Smith 1977).

Unfortunately, limnologists have often ignored these observations when designing sampling strategies and assumed that conditions within various depth strata are homogenous. Many studies have been based upon a few samples collected from a single mid-lake station and may have provided misleading information with respect to the nature of the lake as a whole. Allan (1980) has described this problem in detail

for chlorophyll a concentration ([chl a]) measurements in the hypertrophic Fishing Lakes of southern Saskatchewan.

The phosphorus modelling sequence described by Dillon and Rigler (1975) is an example of an holistic approach to lake ecosystem analysis which assumes that representative data are available for the various state variables being modelled. However, in a recent evaluation of the phosphorus-chlorophyll relationship for lakes situated off the Precambrian Shield in western Canada, Prepas and Trew (1983) noted that spatial heterogeneity in [chl a] was high in the productive lakes. Furthermore, they suggested that a portion of the variance in their spring total phosphorus concentration ([TP]): summer [chl a] relationship could be due to unrepresentative summer [chl a] estimates. Since a large portion of the available phosphorus pool may be tied up in phytoplankton biomass (Lean 1973), [TP] may also exhibit spatial heterogeneity. This phenomenon could introduce errors into phosphorus budgets measured for productive lakes by reducing the accuracy of phosphorus mass calculations for the water column.

Information is required on whole-lake phytoplankton patchiness in order to design sampling strategies which will furnish improved data for modelling the eutrophication process. We present here the results of [chl a] spatial distribution surveys carried out on lakes of various trophic states in central Alberta. The data illustrate that there is a significant relationship between the variance and the mean in whole-lake survey estimates of [chl a]. As a consequence, productive lakes require more spatially intensive sampling than unproductive lakes in order to maintain the same degree of confidence in the data generated.

## Methods

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Surveys were carried out on 18 lakes in central Alberta (Table 1) to determine the spatial distribution of phytoplankton standing crop (as [chl a]); all study lakes were free from the influences of significant point-sources of water or materials.

During 1976, five surveys of surface (0 m) [chl a] were carried out on Baptiste Lake (note: the north and south basins of Baptiste Lake have been treated as two separate lakes (Prepas and Trew 1983)); the results of these pilot surveys prompted us to examine [chl a] distributions in 16 other lakes between 1980 - 1983. In each of the latter surveys vertically integrated samples were taken from the euphotic zone using weighted Tygon tubing. The euphotic zone was defined as the interval from the surface to the depth of 1% of surface penetrating light. Light measurements were made with a Protomatic underwater photometer (Protomatic, Dexter, Mich.).

Sampling was conducted throughout the open water season, and all surveys were completed within a 2 h time period. Twenty-eight sample units were recovered from the north basin of Baptiste Lake, and 25 units from the south basin using a horizontally stratified random sampling approach. All strata were of approximately equal size, and one sampling site was located randomly in each stratum; this approach ensured that the entire lake was adequately sampled and that statistical requirements for randomness were met (Snedecor and Cochran 1980). On all subsequent surveys of euphotic zone [chl a], at least 35 individual sample units were recovered using the same approach.

Individual water samples for [chl a] determination were transferred in 1-L, opaque, polyethylene bottles and kept cool and

dark until returned to the laboratory. Subsamples were prepared within 4 h of collection by filtering through glass fibre filters at a vacuum of 380 mm of mercury. The [chl a] was extracted in 90% buffered acetone and assayed using the fluorometric technique of Yentsch and Menzel (1963) as modified by Holm-Hansen et al. (1965).

The statistics calculated from the field data include: variances ( $\underline{s}^2$ ), standard deviations ( $\underline{s}$ ), and means ( $\underline{\bar{x}}$ ). The coefficients of variation (C.V.) have been calculated as  $\underline{s}/\underline{\bar{x}} \times 100$ . The regression analysis was performed on data transformed to  $\log_{10}$  (Elliott 1977).

The total variance of whole-lake [chl a] estimates will be the sum of the individual variances due to: (a) sample handling and analysis, and (b) real differences between samples. Quantification of (a) was required (after Platt et al. 1970) to clarify the significance of the latter component of the total variance. The variance due to handling and analysis was estimated by preparing five subsamples from a continuously mixed carbuoy of lake water taken from various lakes. The coefficient of variation in [chl a] estimates due to handling and analysis has been estimated at approximately 3% for concentrations in the 10 mg/m<sup>3</sup> range, 5% for concentrations in the 50 mg/m<sup>3</sup> range, and approximately 10% for samples in the 150 mg/m<sup>3</sup> range.

Tucker Lake, which is shallow and productive (Prepas and Trew 1983), was monitored throughout the open water seasons of 1981 and 1982 in order to provide data which would illustrate the large seasonal variability in [chl a] observed in such lakes. A composite sample, consisting of twenty sample units, was collected from the lake at fortnightly intervals and analyzed for [chl a] by the same methods.

## Results

The lakes chosen for sampling represent a wide range of sizes and trophic states. The mean depths range from 2.1 m (Magee Lake) to 14.1 m (Marie Lake), and surface areas range from 0.67 km<sup>2</sup> (Magee Lake) to 44.30 km<sup>2</sup> (Cooking Lake).

The data from the surface [chl a] surveys on Baptiste Lake have been superimposed on outline maps of the lake, and areas of similar concentration have been shaded accordingly (Fig. 1); the sample statistics are presented in Table 2. Patch development became most intense in summer as the standing crop peaked. The shallow, north basin displayed a higher coefficient of variation than the deeper, south basin on all sampling dates except August 15, 1976. In all cases the coefficient of variation was higher than can be explained by sample handling and analytical error alone. The highest variability in the surface distribution of [chl a], ranging from 16.2 mg/m<sup>3</sup> to 136.5 mg/m<sup>3</sup> was observed in the north basin on September 7, 1976 (C.V. = 56.4%); the largest proportional range (2.9 mg/m<sup>3</sup> to 90.3 mg/m<sup>3</sup>) was measured in the same basin on July 6, 1976. Clearly, the selection of a single sampling site on either sampling date would have provided grossly inadequate data with respect to the whole basin.

The data for the euphotic zone [chl a] surveys on the remaining lakes are presented in Table 3. The mean euphotic zone [chl a] measured during the surveys ranged from 3.7 mg/m<sup>3</sup> (Marie Lake) to 155.5 mg/m<sup>3</sup> (Nakamun Lake). The coefficients of variation ranged from 3.9% in Hilda Lake to 51.6% in Coal Lake. Chlorophyll a concentrations in the more productive lakes displayed more spatial heterogeneity, although the variances range considerably at the higher

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[chl a] (e.g. Lac La Nonne and Lower Mann Lakes). It is apparent from both integrated and discrete sample data that high variances were generally associated with high means, and vice-versa.

Many trophic assessment and lake modelling studies have been based upon data collected at single mid-lake stations which have been assumed to represent the whole system. We therefore qualitatively compared such single site estimates of [chl a] with the mean estimates of [chl a] derived from our euphotic zone surveys for each lake (Table 3). We observed an increasing divergence between these two estimates as the standing crop increased (Fig. 2).

These data suggested that a density-dependent pattern of [chl a] distribution could exist between lakes, and we found a significant relationship ( $P < 0.05$ ) between the variance and the mean for [chl a] measurements in this data set, i.e:

$$\text{Log}_{10}(\underline{s}^2) = - 1.99 + 2.25 \text{Log}_{10}(\bar{x}) \quad (1)$$

( $\underline{n} = 19$ ,  $\underline{r}^2 = 0.83$ ). This relationship between sample variance and sample mean existed over a wide range of species compositions, densities, lakes and seasons (Fig. 3, showing 95% confidence limits of the variances predicted from the measured means).

The seasonal [chl a] data collected from Tucker Lake are illustrated in Fig. 4. During August of both 1981 and 1982 a dramatic increase in [chl a] was observed. The 1981 bloom resulted in [chl a] rising from 4.2 mg/m<sup>3</sup> to 92.6 mg/m<sup>3</sup> in six weeks. According to Fig. 3, the concomitant increase in the variance of whole lake [chl a] estimates as a result of such bloom conditions could be approximately two orders of magnitude, necessitating a review of sampling design.

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## Discussion

We searched the literature for [chl a] distribution data from other productive lakes in order to test for the universality of this relationship. No data based on vertically integrated samples were found, however the variances and means of discrete surface [chl a] data for Shagawa Lake, Minnesota (Megard and Smith 1974) and Lake George, Uganda (Ganf 1974) were calculated and plotted on Fig. 3. These data points fell close to or within the 95% confidence limits, suggesting that the general pattern is widespread. The relationship defined by Eq. 1 is in essence a biological dispersion model for mixed species phytoplankton communities, and is of the same form as Taylor's power law (Taylor 1961). The latter model has been shown to fit a wide range of data describing the distributions of organisms (Green 1979).

The evidence presented in this paper clearly illustrates that productive lakes pose special problems with respect to the application of holistic management techniques. Spatial heterogeneities in [chl a] may have increased the uncertainty associated with lake data derived from traditional sampling approaches.

The robustness of the relationship between sample mean and sample variance suggests an approach for designing holistic sampling strategies. Theoretically, one could utilize Eq. 1 to determine the variance for a given mean [chl a] and consequently the sample size required to produce an estimate of the population mean within a desired standard error (see Elliott 1977). However, this presents something of a dilemma since one cannot necessarily anticipate the mean standing crop prior to the sampling event. Pilot surveys carried out in advance to estimate the means and variances of populations of

primary producers may be extremely misleading due to their capability of displaying rapid temporal fluctuations, as illustrated by the Tucker Lake data.

An alternative approach would be to establish seasonal sampling requirements on the basis of the anticipated productivity of the waterbody in question, i.e. that enough samples be taken to account for the probable fluctuations in standing crop. Most experienced workers can predict the general trophic characteristics of unsampled waterbodies based upon a knowledge of other lakes in the region, drainage basin size and land use, and lake morphology (Schindler 1971; Dillon and Rigler 1975). The required numbers of sample units can then be generated with respect to the maximum [chl a] anticipated; these numbers would vary according to the desired standard error. All sample units can then be combined to form a single composite sample representative of the lake on that day, thus reducing the analytical load to one sample.

The numbers of sample units required for standard error/arithmetical mean ratios of 5%, 10%, and 20%, and calculated by this approach, are summarized in Table 5. Because the data used in Eq. 1 represent a diversity of lake types and phytoplankton communities, a wide range of variances can be predicted from a single mean; this feature is illustrated by the 95% confidence limits shown in Fig. 3. To err on the side of caution, the variances used to calculate sample unit numbers were taken at the upper 95% confidence level.

Typical trophic categories as defined by maximum [chl a] (OECD 1982) are also indicated in Table 5; although our mean [chl a] data are not necessarily maxima, the range is sufficiently wide to

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illustrate the trophic divisions. One should also note that the use of arbitrary means coinciding more closely with the trophic boundaries would have resulted in much wider confidence limits, and consequently larger sample unit numbers (Snedecor and Cochran 1980).

Clearly, there are major differences in the sampling effort required for the [chl a] found in the study lakes over the range of standard errors selected. In the oligotrophic range of lakes ( $\leq 8.0$  mg/m<sup>3</sup>) at least 17 sample units are required for a 5% standard error, but only 1 sample unit is required for a 20% standard error. In the mesotrophic range (8.0 - 25.0 mg/m<sup>3</sup>) at least 16 sample units should comprise the composite sample for a standard error of 5%, but again only 1 sample unit is required for a 20% standard error. The higher sampling requirements for the lower concentrations reflect the behaviour of the confidence limits in that region (Fig. 3), although these differences are small. However, in the wide range of maximum [chl a] typical of eutrophic (25.0 - 75.0 mg/m<sup>3</sup>) and hypertrophic ( $\geq 75.0$  mg/m<sup>3</sup>) lakes in western Canada, the numbers of sample units required increase dramatically.

Two factors which may influence the final interpretation of these data are the reliability of chlorophyll a as an indicator of phytoplankton biomass (Cullen 1982), and the overall efficiency of our analytical techniques. We have no other biomass data to present, however we have already compared our techniques with a spectrophotometric method utilizing ethanol extraction and found no significant difference between the two (Prepas and Trew 1983). Furthermore, the fact that the data from the two independent studies (Ganf 1974; Megard and Smith 1974) coincide with Eq. 1 lends support

to the concept presented here. Finally, we have conducted similar surveys with respect to the distribution of total phosphorus in these lakes and again found productive lakes to display significant heterogeneity (Trew and Reynoldson, unpublished).

### Conclusion

Data have been presented to illustrate that as the standing crop of phytoplankton increases the degree of patchiness increases, and that in order to sample with a statistically consistent approach between lakes the productive lakes require more spatially intensive sampling. The data also suggest that sampling strategies for productive lakes must be designed to account for the large temporal fluctuations in standing crop which can occur.

The density-dependent distribution of phytoplankton implied from these data is, however, an oversimplified concept. Obviously, the degree of patchiness at a given standing crop level will be dependent upon the recent interaction of physical, biological, and chemical forces within the particular waterbody under study, i.e., the phytoplankton of productive lakes may or may not display significant heterogeneity. We have made no effort to analyze the dynamics of patch formation. Instead, we have looked for gross trends between lakes from which the degree of heterogeneity could be predicted. Using the variance predicted by the upper 95% confidence interval of Eq. 1 to calculate the number of sample units required may result in more samples units than necessary being taken, however this will always be preferable to having too few.

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## Figure Legends

- Fig. 1. The surface (0 m) distribution of chlorophyll a in Baptiste Lake on five different dates during 1976.
- Fig. 2. The relationship between chlorophyll a estimates based upon a single mid-lake sample and the mean of n lake-wide samples where n > 35 (Table 3).
- Fig. 3. The relationship between the variance ( $\underline{s}^2$ ) and the mean ( $\bar{x}$ ) in 19 whole-lake chlorophyll a survey data sets from Alberta lakes: closed circles (●), integrated samples. Also shown are the 95% confidence limits for this line. The same statistics for surface chlorophyll a data from Shagawa Lake (triangles (▲)) (Megard and Smith 1974) and Lake George (squares (■)) (Ganf 1974) have also been illustrated on the figure.
- Fig. 4. Seasonal fluctuations in euphotic zone chlorophyll a concentration in Tucker Lake during 1981 and 1982.

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Table 1. Background data for the study lakes: location, surface area, and mean depth ( $\bar{z}$ ).

LAKE	LAT. <sup>a</sup> (°N)	LONG. <sup>a</sup> (°W)	AREA <sup>b</sup> (km <sup>2</sup> )	$\bar{z}$ <sup>b</sup> (m)
BAPTISTE NORTH	54° 45'	113° 33'	4.74	5.9
BAPTISTE SOUTH	54° 45'	113° 33'	4.43	12.7
COAL	53° 05'	113° 17'	9.85	4.5
COOKING	53° 26'	113° 02'	44.30	2.4
ETHEL	59° 47'	115° 03'	4.83	6.6
HASTINGS	53° 25'	112° 55'	9.06	3.7
HILDA	54° 31'	110° 26'	3.62	6.2
JACK FISH	53° 29'	114° 15'	2.40	3.5
LAC LA NONNE	53° 55'	114° 18'	11.58	8.0
LOWER MANN	54° 10'	111° 30'	5.05	3.9
MAGEE	52° 33'	113° 23'	0.67	2.1
MARIE	54° 38'	110° 18'	36.21	14.1
MINK	53° 31'	114° 14'	0.70	3.4
NAKAMUN	53° 53'	114° 12'	3.16	3.8
NORTH BUCK	54° 41'	112° 32'	19.17	2.4
SANDY	53° 47'	114° 02'	11.40	2.6
TUCKER	54° 32'	110° 37'	7.22	2.9
VINCENT	54° 06'	111° 20'	7.93	5.7

<sup>a</sup>Gazeteer of Canada, Vol. 6, 1965

<sup>b</sup>Alberta Environment

Table 2. Sample statistics for the surface chlorophyll a distribution surveys on Baptiste Lake: n, number of sample units; s<sup>2</sup>, sample variance;  $\bar{x}$ , sample mean; C.V., coefficient of variation.

LAKE	DATE	<u>n</u>	<u>s</u> <sup>2</sup>	<u><math>\bar{x}</math></u>	C.V.
BAPTISTE NORTH	31-5-76	28	17.7	13.1	32.1
BAPTISTE SOUTH	31-5-76	25	5.0	12.3	17.9
BAPTISTE NORTH	13-6-76	28	132.3	21.7	53.0
BAPTISTE SOUTH	13-6-76	25	41.1	22.7	28.2
BAPTISTE NORTH	5-7-76	28	840.3	57.7	50.3
BAPTISTE SOUTH	5-7-76	25	972.5	86.2	36.2
BAPTISTE NORTH	15-8-76	28	102.4	66.3	15.2
BAPTISTE SOUTH	15-8-76	25	190.4	70.2	19.7
BAPTISTE NORTH	7-9-76	28	967.8	55.1	56.4
BAPTISTE SOUTH	7-9-76	25	260.8	44.5	36.4

Table 3. Sample statistics for the 19 euphotic zone chlorophyll a surveys carried out on 16 Alberta lakes: n, number of sample units; s<sup>2</sup>, sample variance; x, sample mean; C.V., coefficient of variation; Single, estimate of chlorophyll a concentration from a single mid-lake station.

LAKE	DATE	<u>n</u>	<u>s</u> <sup>2</sup>	<u>x</u>	C.V.	Single
COAL	11-8-83	39	3108.9	108.0	51.6	163.2
COOKING	17-7-81	43	674.6	119.9	21.7	73.5
ETHEL	23-7-80	42	0.6	7.0	11.6	6.2
HASTINGS	13-7-81	44	20.6	26.9	17.1	29.5
HILDA	22-7-80	45	0.5	3.7	8.3	2.6
HILDA	28-10-81	45	2.5	17.8	3.9	17.5
JACK FISH	7-9-83	40	1.7	10.7	12.1	10.0
LAC LA NONNE	24-8-83	40	2934.3	115.8	46.8	75.4
LOWER MANN	16-8-83	40	334.9	109.9	16.7	173.5
MARIE	20-8-80	40	0.6	7.3	11.0	7.1
MAGEE	10-8-83	40	18.7	39.3	10.9	45.2
MINK	7-9-83	40	5.2	15.6	14.7	18.4
NAKAMUN	24-8-83	40	304.0	155.5	11.2	166.7
NORTH BUCK	1-9-83	39	12.0	14.7	23.5	15.0
SANDY	18-8-83	35	16.4	43.9	9.2	45.5
TUCKER	3-9-80	35	41.6	18.5	35.3	13.0
TUCKER	29-9-81	35	6.7	44.8	7.3	44.2
TUCKER	28-10-81	35	11.9	35.8	9.6	29.6
VINCENT	17-8-83	40	6.9	16.4	16.0	19.9

Table 4. Sample statistics for surface chlorophyll a distribution information on Shagawa Lake (Megard and Smith 1974) and Lake George (Ganf 1974): n, number of samples; s<sup>2</sup>, sample variance;  $\bar{x}$ , sample mean; C.V., coefficient of variation.

LAKE	DATE	<u>n</u>	<u>s</u> <sup>2</sup>	<u><math>\bar{x}</math></u>	C.V.
SHAGAWA	3-6-70	6	25	11	45.5
SHAGAWA	17-6-70	6	36	21	28.6
SHAGAWA	2-7-70	6	1	15	6.7
SHAGAWA	22-7-70	6	9	21	14.3
SHAGAWA	6-8-70	6	100	28	35.7
SHAGAWA	17-8-70	6	576	67	35.8
SHAGAWA	25-8-70	6	3844	91	68.1
SHAGAWA	31-8-70	6	10000	146	68.5
SHAGAWA	5-9-70	6	169	37	35.1
SHAGAWA	17-10-70	6	16	18	22.2
GEORGE	DAY 1	20	2970.3	194.1	28.1
GEORGE	DAY 3	20	3856.4	184.9	33.6
GEORGE	DAY 5	20	1806.3	171.9	24.7
GEORGE	DAY 7	20	600.3	152.9	16.0
GEORGE	DAY 9	20	4422.3	216.6	30.7
GEORGE	DAY 11	20	2540.2	179.5	28.1
GEORGE	DAY 13	20	2256.3	188.7	25.2
GEORGE	DAY 15	20	3806.9	206.8	29.8

Table 5. Number of sample units required for one composite sample of chlorophyll a based on the trophic category, chlorophyll a concentration ([chl a]), and the desired standard error(%).

Category <sup>a</sup> (mg/m <sup>3</sup> )	[chl <u>a</u> ]	5%	10%	20%
Oligotrophic ( ≤ 8.0)	3.7	21	5	1
	7.0	18	5	1
	7.3	17	4	1
Mesotrophic (8.0 - 25.0)	10.7	16	4	1
	14.7	16	4	1
	15.6	16	4	1
	16.4	16	4	1
	17.8	16	4	1
	18.5	16	4	1
Eutrophic (25.0 - 75.0)	26.9	17	4	1
	35.8	18	5	1
	39.3	19	5	1
	43.9	20	5	1
	44.8	20	5	1
Hypertrophic ( ≥75.0)	108.0	34	8	2
	109.0	34	9	2
	115.8	35	9	2
	119.9	36	9	2
	155.5	44	11	3

<sup>a</sup>OECD (1982)

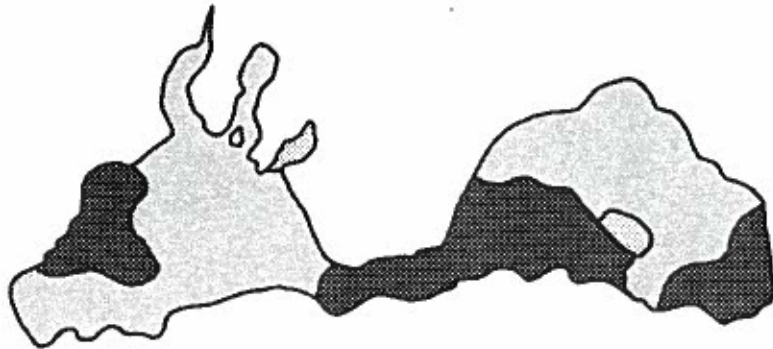
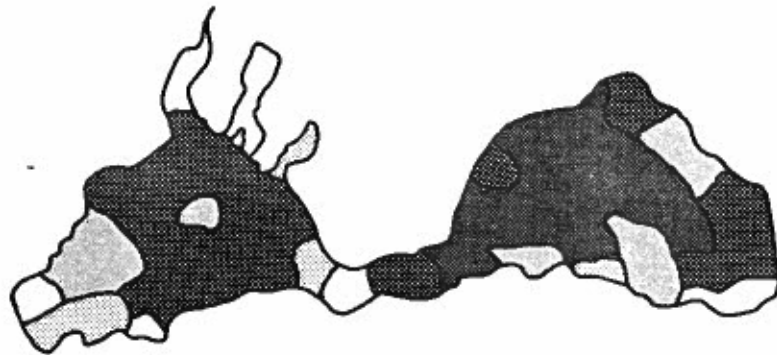
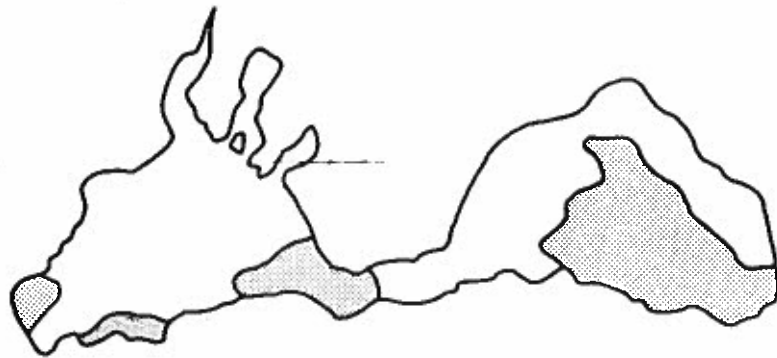
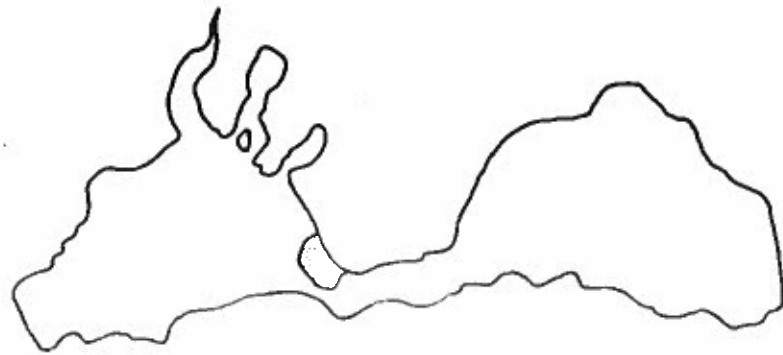
MAY 31, 1976

JUNE 13, 1976

JULY 5, 1976

AUGUST 15, 1976

SEPTEMBER 7, 1976



LEGEND:

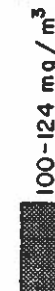
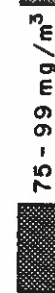
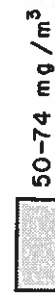
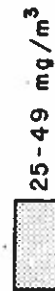
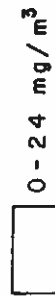


Figure 1

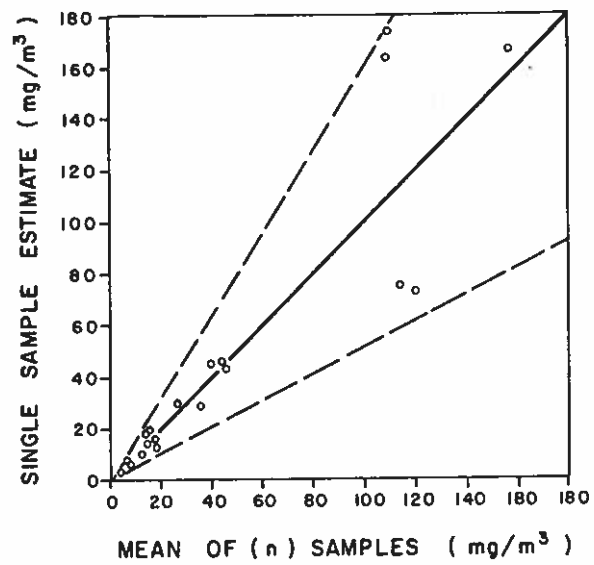


FIG. 2

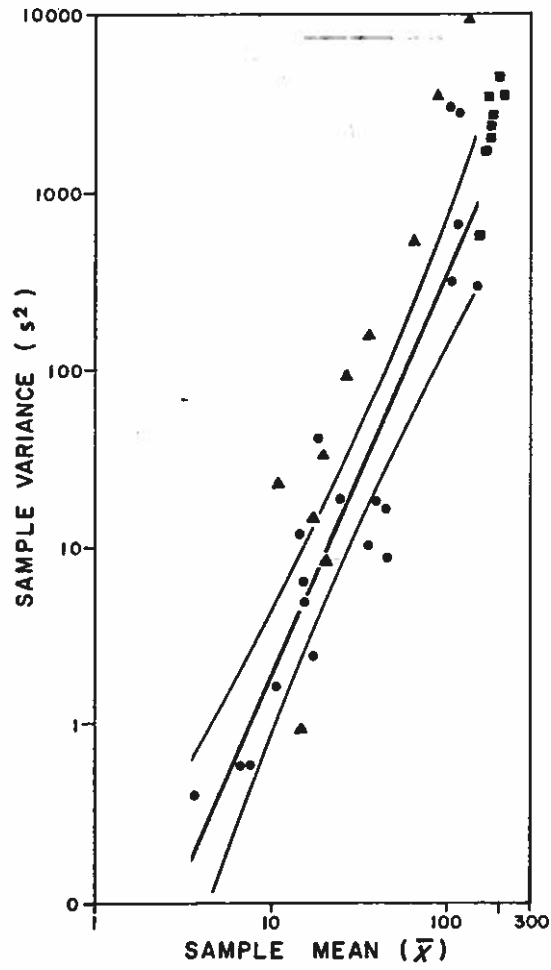


FIG. 3

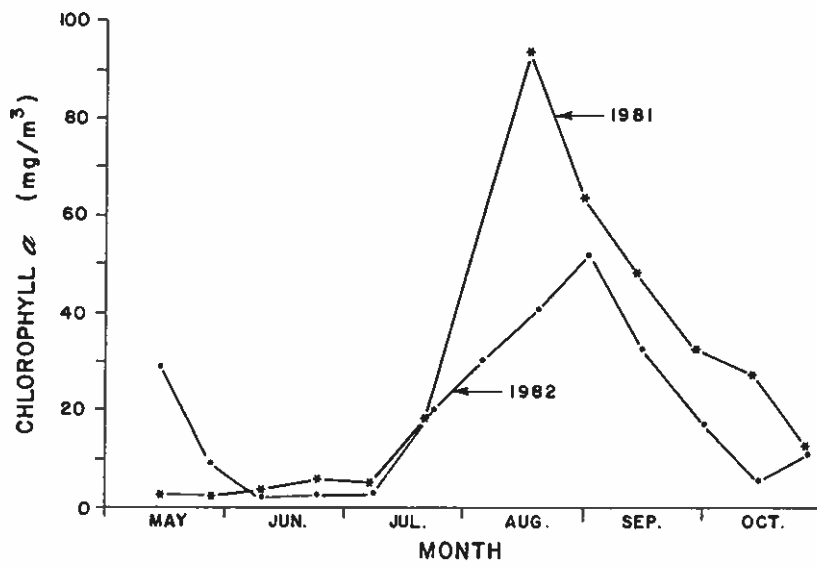


FIG. 4