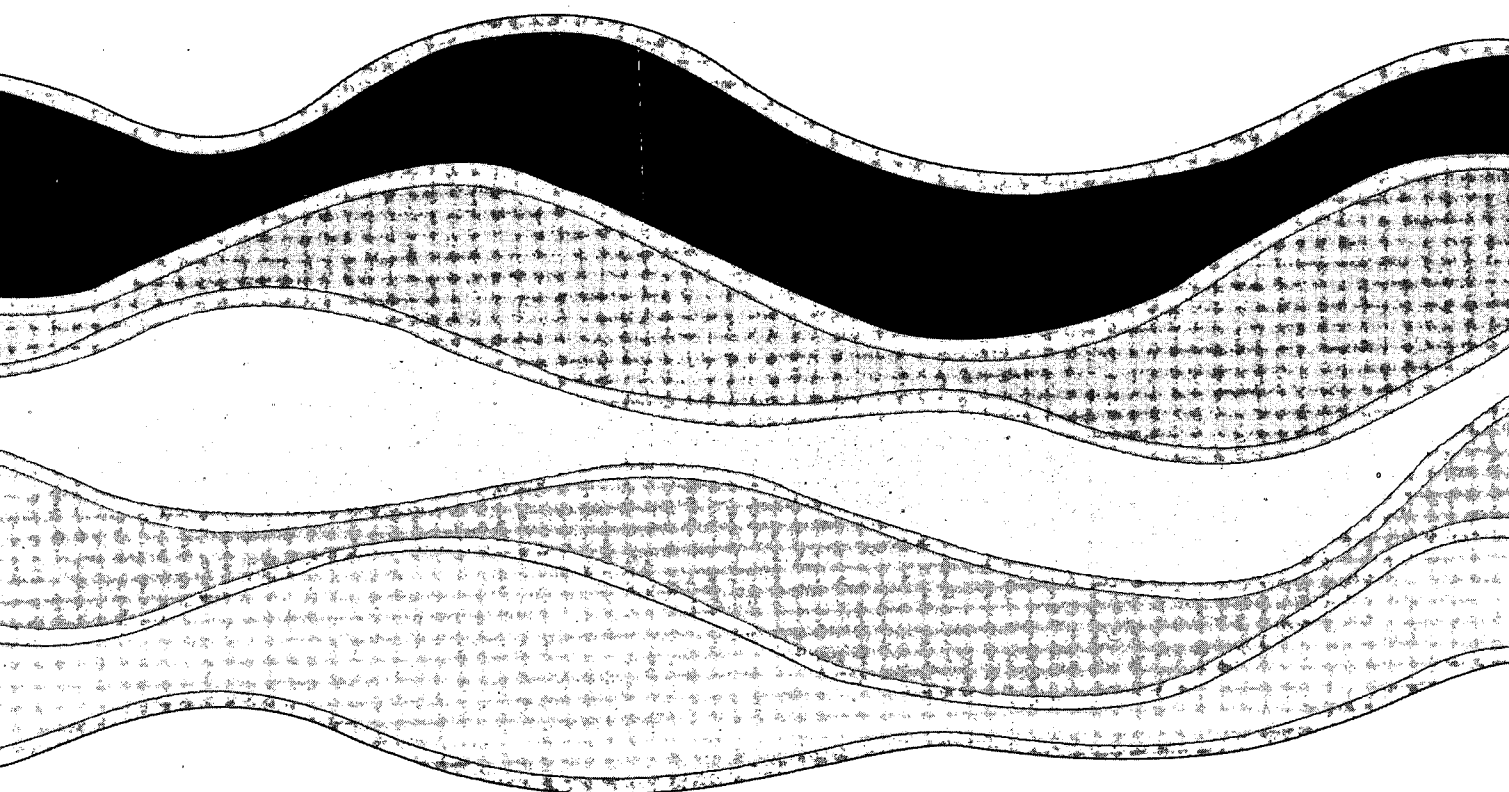


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**TRANSPORT OF CONTAMINANTS BY
THE NEPHELOID LAYER IN LAKE ONTARIO**

A. Mudroch and P. Mudroch

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**TRANSPORT OF CONTAMINANTS BY
THE NEPHELOID LAYER IN LAKE ONTARIO**

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MANAGEMENT PERSPECTIVE

In preparing a management plan for Lake Ontario, knowledge of the processes which control the transport of contaminants is equally important to information on quantities of contaminants entering the lake from different external sources. In the early 1980's, the presence of a nepheloid layer in Lake Ontario was reported, and it was suggested that the nepheloid layer may be important in the transport of different contaminants across the lake. A comprehensive study was carried out in 1987-89 to investigate the origin and character of the nepheloid layer in Lake Ontario, and to evaluate its role in transport of contaminants in the lake. Results from this study suggest that the suspended matter transported from Lake Erie by the Niagara River may become incorporated into the nepheloid layer in Lake Ontario.

The concentrations of Pb, Zn and Cu in the suspended matter in the nepheloid layer were greater than those in the bottom sediments; however, the concentrations of As, Co, Ni, Cr, V and Hg were similar or lower than those in the bottom sediments. The concentrations of total PCBs in the suspended matter in the nepheloid layer were also greater than those in most of the bottom sediments. The suspended matter in the nepheloid layer contained more lower chlorinated biphenyls, particularly tetra- and pentachlorobiphenyls, than the bottom sediments suggesting the loss of lower chlorinated PCB congeners from the sediments with subsequent accumulation in the suspended matter in the nepheloid layer.

Study results suggest that particles transported into Lake Ontario from Lake Erie, as well as those particles which originate from primary production in Lake Ontario, become enriched by trace elements and organic contaminants while in the water column. These particles accumulate in the nepheloid layer prior to settling on

the lake bottom. The dissolution of some particles and the decomposition of organic matter in this suspended matter would result in the release of contaminants which were associated with these particles.

These processes lengthen the time that the Lake Ontario ecosystem takes to respond fully to any reduction in contaminant loading and must be factored into the models used to predict the results of the Lake Ontario Toxics Management Plan.

PERSPECTIVES DE LA DIRECTION

En vue de l'élaboration d'un plan de gestion pour le lac Ontario, la connaissance des processus qui régissent le transport des contaminants est tout aussi importante que les informations sur la quantité de contaminants qui pénètrent dans le lac en provenance de différentes sources externes. Au début des années 1980, on a relevé la présence d'une couche néphéloïde dans le lac Ontario, et on a fait remarquer que cette couche pouvait jouer un rôle au niveau du transport des différents contaminants dans le lac. Une étude détaillée a été menée entre 1987 et 1989 afin d'étudier l'origine et la nature de cette couche, et d'évaluer son rôle au niveau du transport des contaminants dans ce plan d'eau. D'après les résultats de cette étude, il semble que les matières en suspension transportées par les eaux de la rivière Niagara en provenance du lac Érié puissent être intégrées dans la couche néphéloïde du lac Ontario.

Les teneurs en Pb, Zn et Cu des matières en suspension de la couche néphéloïde étaient supérieures à celles relevées dans les sédiments de fond; toutefois, les teneurs en As, Co, Ni, Cr, V et Hg étaient similaires ou inférieures à celles des sédiments de fond. Les teneurs en BPC totaux dans les matières en suspension dans la couche néphéloïde étaient également supérieures à celles de la plupart des sédiments de fond. Les matières en suspension de cette couche contenaient plus de biphényles chlorés inférieurs, notamment des tétrachlorobiphényles et des pentachlorobiphényles, que les sédiments de fond ce qui semble dénoter la perte par les sédiments de congénères des BPC chlorés inférieurs avec accumulation subséquente dans les matières en suspension de la couche néphéloïde.

Il semble d'après les résultats de l'étude que des particules transportées dans le lac Ontario en provenance du lac Érié, ainsi que les particules issues de la production primaire dans le lac

Ontario, ont été enrichies par des éléments traces et des contaminants organiques pendant qu'elles étaient dans la colonne d'eau. Ces particules s'accumulent dans la couche néphéloïde avant de se déposer au fond du lac. La dissolution de certaines particules et la décomposition de la matière organique dans ces matières en suspension entraîneraient la libération de contaminants associés à ces particules.

En raison de ces processus, il faut plus de temps à l'écosystème du lac Ontario pour réagir complètement à toute réduction de la charge en contaminant, et ils doivent être décomposés en facteurs dans les modèles de prévision des résultats du Plan de gestion pour les toxiques dans le lac Ontario.

ABSTRACT

The nepheloid layer formation in Lake Ontario commenced in July and its thickness increased gradually up to about 40 m in September. During the lake's fall turnover, the suspended matter in the nepheloid layer became mixed throughout the water column. Silica, calcite and organic matter were the major components of the suspended matter in the nepheloid layer, particularly in the central and eastern basins. The suspended matter in the nepheloid layer in the western basin contained more sediment particles than that in the central and eastern basins. The light transmission profiles and the geochemistry of the particles suggested that the nepheloid layer in the central and eastern basins originated mainly from primary production and precipitation of calcite in surficial waters during summer. The results indicated that sediment particles in the nepheloid layer in the western basin originated from resuspension of bottom sediments by currents generated by vertical mixing of warmer water transported from Lake Erie with ambient water at the Niagara River mouth in early spring. The concentrations of Pb, Zn and Cu in the suspended matter in the nepheloid layer (up to 683, 1,180 and 396 $\mu\text{g/g}$, respectively) were greater than those in the bottom sediments (up to 203, 665 and 298, respectively). However, the concentrations of As, Co, Ni, Cr, V and Hg were similar or lower than those in the sediments. The concentrations of PCBs in the suspended matter in the nepheloid layer ranged from 151 to 728 ng/g, and were greater than those in most of the sediments. Further, the suspended matter in the nepheloid layer contained more lower chlorinated biphenyls,

particularly tetra- and pentachlorobiphenyls, than the sediments. The results of the study indicated that the suspended matter in the nepheloid layer is an important medium in accumulation, recycling and transport of contaminants in Lake Ontario.

RÉSUMÉ

La formation de la couche néphéloïde du lac Ontario a débuté en juillet et son épaisseur a augmenté progressivement pour atteindre environ 40 m en septembre. Pendant la période de brassage convectif des eaux du lac à l'automne, les matières en suspension de la couche néphéloïde ont été mélangées dans toute la colonne d'eau. La silice, la calcite et des matières organiques étaient les principaux composants des matières en suspension de cette couche, notamment dans les bassins central et oriental. Les matières en suspension de la couche néphéloïde du bassin occidental contenaient plus de particules de sédiments que celle des bassins central et oriental. D'après les profils de transmission de la lumière et les propriétés géochimiques des particules, la production primaire et les précipitations de calcite dans les eaux superficielles pendant la période estivale seraient les principaux processus responsables de la formation de la couche néphéloïde des bassins central et oriental. Les résultats ont montré que les particules de sédiments de la couche néphéloïde du bassin occidental résultaient de la remise en suspension des sédiments de fond par des courants générés par le brassage vertical d'eau chaude en provenance du lac Érié avec l'eau ambiante à l'embouchure de la rivière Niagara au début du printemps. Les teneurs en Pb, Zn et Cu dans les matières en suspension de la couche néphéloïde (jusqu'à respectivement 683, 1 180 et 396 ug/g) étaient plus élevées que celles des sédiments de fond (jusqu'à respectivement 203, 665, et 298). Toutefois, les teneurs de As, Co, Ni, Cr, V et Hg étaient similaires ou inférieures à celles relevées dans les sédiments. Les teneurs en BPC dans les matières en suspension de la couche néphéloïde étaient comprises entre 151 et 728 ng/g, et elles étaient supérieures à celles de la plupart des sédiments. De plus, les matières en suspension de la couche néphéloïde contenaient plus de biphényles chlorés, notamment des tétrachlorobiphényles et des pentachlorobiphényles, que les sédiments. Les résultats de l'étude ont montré que les matières en suspension dans la couche néphéloïde

sont un milieu important d'accumulation, de recyclage et de transport des contaminants dans le lac Ontario.

INTRODUCTION

Light scattering maxima were observed by many oceanographers in specific regions throughout the water column in several areas of the world oceans. This increased light scattering region was referred to as the nepheloid layer (Plank et al., 1972). Further investigations indicated that the nepheloid layer contains increased amount of suspended particles and that possible sources of these particles could be material on the continental slopes, suspended material brought by a large river, or fine-grained bottom sediments resuspended by currents (Connary and Ewing, 1972; Eittreim and Ewing, 1972; Eittreim et al., 1972). A reduction of light transmission by increased concentrations of particles near the bottom were observed in the Great Lakes (Bell et al., 1980; Chambers and Eadie, 1981), and Eadie et al. (1983), Baker et al. (1985), and Eisenreich (1987) studied the distribution of chlorinated hydrocarbons in benthic nepheloid layer in Lakes Huron and Superior. Occurrence and extent of the nepheloid layer in Lake Ontario were reported by Sandilands and Mudroch (1983). The suspended matter in the nepheloid layer in Lake Ontario consisted of diatoms, calcite particles and some clay minerals. Further, it was suggested that the nepheloid layer may be an important medium for lake-wide transport of contaminants originating from the atmospheric deposition and inputs from lake's drainage basin.

The objectives of this study were to investigate the origin of the nepheloid layer in Lake Ontario, to determine the concentrations of

major and trace elements and PCBs contained in the suspended matter of the nepheloid layer and those in the bottom sediments, and to evaluate the role of the nepheloid layer in transport of contaminants accross the lake.

MATERIALS AND METHODS

Sampling procedures

Suspended matter in the nepheloid layer was collected at eleven stations in Lake Ontario (Figure 1). The sampling was carried out in the western basin at stations NL1, NL2, 206 and 210 in August 1987, in the central basin at stations 623, 624, 625 and 626 in August 1988, and in the eastern basin at stations 974, 976 and 999 in August 1989. Selection of the sampling stations was based on light transmission profiles of the water column obtained monthly at 94 stations from August to November 1981 by Sandilands and Mudroch (1983), as well as light transmission profiles obtained at 102 monitoring stations during surveillance cruises in Lake Ontario in 1982, 1985 and 1987 by Environment Canada, Water Quality Branch, Inland Waters Directorate. Sampling stations 206, NL1, 625, 999, 974 and 976 (Figure 1) were selected to represent the three depositional basins in the lake. Station 210 was in the vicinity of the Niagara River plume, and stations NL2 and 624 in the high-energy zone in the northern part of the lake. Stations 623 and 626 were at the Whitby-Olcott and Scotch-Bonnet sills, respectively. Limited deposition of recent fine-grained sediments exists at stations NL2, 623, 624 and 626 (Thomas et al., 1972). Light

transmission profiles of the water column were also obtained immediately prior to the sampling to select a proper water depth for collection of the suspended matter from the nepheloid layer. A horizontal beam transmissometer with a 25 cm path length and Wratten 45 filter was used to record the transmission profiles in the lake. In this study, an arbitrary percent scale was used to describe the light transmission profiles. The sampling depth at each station was chosen to be at the center of reduced light transmission above the lake bottom. For example, the water was pumped at 10 m above the bottom when the light transmission profile started to decrease at 20 m above the lake's bottom. About 6,000 liters of water were collected by means of pumps from the nepheloid layer from eleven stations in the lake (Figure 1) to collect sufficient quantity of material for analyses. In addition, 6,000 liters of water were pumped from a 3-m water depth at station 976. Suspended solids were recovered using a pair of continuous-flow Westfahlia separators. The flow rate for each centrifuge was maintained at 6 l/min.

Sample processing and analysis

The particulate residue collected by the separators was freeze-dried, weighted, and homogenized by grinding in an automatic power grinder equipped with an achate grinding dish, and used in subsequent analysis. At each sampling station, bottom sediment samples were obtained by a box corer. From each box corer, several sediment cores were collected using procedure described by Mudroch

and MacKnight (1991). The cores were subsampled into 3-cm sections. One part of the sub-samples was freeze-dried, ground, and used for analyses. At selected stations, the second part was used for separation into six different particle size fractions using the method described by Mudroch and Duncan (1986). The size of the particles in the six fractions was 43 to 53 μm , 37 to 43 μm , 29 to 37 μm , 19 to 29 μm , 13 to 19 μm and <13 μm . Separated sediment fractions were freeze-dried and used for analyses.

Concentrations of major elements (Si, Al, Fe, Mg, Ca, K, Na, Ti, P, Mn and P) and trace elements (As, Cu, Co, Cr, Ni, Pb, V and Zn) in the nepheloid layer and sediment samples were determined by x-ray fluorescence spectrometry (Mudroch, 1985). The concentrations of Hg were determined by the method described by Water Quality Branch (1979). The concentrations of organic carbon were determined by Leco carbon analyzer. Mineralogical composition of particles collected from the nepheloid layer was determined by powder x-ray diffraction spectrometry using Cu K(a) radiation with a Ni-filter.

Concentrations of PCBs were determined by dual-column capillary gas chromatography method using 30 m long DB1 and SE54 columns with electron capture detectors. Soxhlet extraction of samples by dichloromethane was followed by a fractionation and pre-cleaning by column chromatography described by Carey and Hart (1986) prior to the analysis. National Research Council, Canada, standard material CLB-1A,B,C and D, a mixture of 51 PCB congeners, obtained from the

Atlantic Research Laboratory, National Research Council, Halifax, Nova Scotia, was used as the standard in the analyses. The accuracy of the determination of PCB congeners was confirmed by analysis of sediment reference material HS-1 and HS-2 obtained from the National Research Council, Canada, Halifax, N.S. Reproducibility of the analysis on replicate samples was $\pm 10\%$. The concentrations of total PCBs in the samples are reported as the sum of determined 51 PCB congeners.

RESULTS AND DISCUSSION

Light transmission profiles

The existence of the nepheloid layer in Lake Ontario was confirmed by the light transmission profiles of the water column obtained (a) at 94 stations from August to November 1981 by Sandilands and Mudroch (1983); (b) at 102 monitoring stations during surveillance cruises carried out by Water Quality Branch in Lake Ontario every month from April till November in 1982, 1985 and 1987. The light transmission profiles from the selected five stations are presented in Figure 2. These stations represented a transect across the lake, and were close to the nepheloid layer sampling stations in 1987-1989. The light transmission profiles were generally similar to those obtained at the other offshore monitoring stations in the lake every year (Figure 3). Small changes from one year to the other were probably due to different weather conditions which affected the surface water temperature and thus the commencement of the primary production. The general pattern of the light

transmission and development of the nepheloid layer appeared to similar every year and can be described as follows: in April and May, the light transmission ranged from 85 to 95% and was uniform throughout the water column, from the surface to the bottom, at all stations (Figure 2). Reduced light transmission near the lake bottom occurred only at some stations in the depositional areas with recent fine-grained bottom sediments, for example, at station 63 in the eastern basin. These results indicated that reduced light transmission near the lake bottom resulted from the resuspension of fine-grained sediments in April and May. A reduction of the light transmission commenced in the surface waters between June and July, and indicated an increase of primary production during increasing surface water temperature (Figure 4). Further reduction of the light transmission in epilimnetic waters occurred in August and continued at several locations in September. Following the reduction in surface waters, the light transmission gradually decreased below the thermocline at the center of the water column from 85 to 95% in April/May to 50 to 60% in October/November (Figure 2). This decrease can be attributed to the sinking of decaying plankton from the surface waters to the lake bottom. Considerable reduction of the light transmission near the lake bottom commenced in July and continued until October over most of the open lake suggesting the accumulation of sinking particles at this depth. This area with the minimum light transmission near the lake bottom is referred to as the nepheloid layer in this study.

The thickness of the nepheloid layer increased gradually from July to October at most stations, and reached about 40 m (and more) at some areas in the lake during the study years from 1981 to 1987. The thickness of the nepheloid layer varied from one station to the other across the lake, and was different in each year from 1981 to 1987. Generally, the intensive reduction of the light transmission observed in the surface waters in July and August did not occur during September, October and November. In November, after the lake's turnover, the light transmission became almost uniform throughout the water column, and was still lower near the lake bottom than in the rest of the water column over most of the lake indicating increased quantity of particles. Every year the light transmission decreased from about 90% in April/May to about 60% in November in the entire water column (Figure 2) indicating increased amounts of suspended particles in the water after lake's turnover.

Suspended matter in the nepheloid layer

The quantity of the suspended matter recovered from the nepheloid layer at each sampling station ranged from 0.5 to 2.1 mg/l, and that of suspended matter collected from 3 m surface water at station 976 was 1.83 mg/l (Table 1). Nriagu et al. (1981) collected suspended matter at different water depths in western, central and eastern basins of Lake Ontario in 1978, and found that the quantity ranged between 0.40 and 0.49 mg/l in May/June, and between 0.59 and 1.3 mg/l in October. In 1981, Sandilands and Mudroch (1983) found 0.38 to 1.72 mg/l suspended solids in a 60-m

water column above the lake bottom at one station in each depositional basin of Lake Ontario. These findings indicated that the quantity of suspended matter in Lake Ontario water increased from April to November. However, the quantity of suspended matter in the entire water column, including the nepheloid layer, was similar.

Sandilands and Mudroch (1983) suggested that the reduction of the light transmission originates from light scattering in Lake Ontario waters. In the oceans, this scattering has been attributed to small mineral and organic particles which are kept in suspension by turbulence resulting from the interactions of abyssal currents and the sea floor topography. Attempts have been made to relate particle mass concentrations to the intensity of light scattering (Eittreim and Ewing, 1972). Good correlations have been lacking largely because light scattering is a complex function of particle size, refractive index, light absorption, and shape, as well as amount of particles (Connary and Ewing, 1972). The results obtained from the previous study of nepheloid layer in Lake Ontario suggested that the reduction of light transmission was due to the different features of the particles, such as colour, shape and size. The reduction of the light transmission and small differences between the weight of suspended matter recovered from the nepheloid layer in this study and that of suspended matter collected from different water depths in other studies in Lake Ontario (for example, Nriagu et al., 1981) confirmed that light

scattering in Lake Ontario bottom waters is a function of particle properties similar to those observed in the oceans (Connary and Ewing, 1972).

Using sediment traps at three locations in Lake Ontario deposition basins from 1982 to 1986, Oliver et al. (1989) found greater quantities of settling particulate matter in the water column in winter (November to May) than in summer months (May to November). They attributed this difference to intensive lake mixing and resuspension of bottom sediments during isothermal conditions in winter. However, the light transmission profiles and geochemical composition of the suspended matter in the nepheloid layer suggested that the lake's fall turnover accompanied by mixing and settling material from summer primary production were responsible for greater quantities of settling suspended matter in winter, and that resuspended bottom sediments represent only a portion of settling suspended matter in the lake. Studying settling velocities of organic mineral aggregates, Chase and Tissue (1976) noticed that typical aggregates ranging in size from a few to a few hundred micrometers had a loose articulated structure and were deformable and susceptible to disruption under high shear conditions. According to these studies, flocculated suspended matter sinking from the surface waters to the bottom of the lake becomes dispersed into smaller particles by currents, particularly intensive vertical mixing during the fall turnover. Dispersed particles reduced the light transmission to the values observed in

the water column during October and November (Figure 2).

Geochemistry of suspended matter in the nepheloid layer

The concentrations of major elements in the suspended matter in the nepheloid layer are compared to those in surficial sediments (0 to 3 cm) at each sampling station in Table 2. At most of the stations, the suspended matter in the nepheloid layer consisted mainly of organic matter, and silica and calcium carbonate particles. The concentrations of Ca, which was in the form of calcium carbonate, was always greater in the suspended matter in the nepheloid layer than in the sediments. In addition to silica and calcite, the nepheloid layer contained alumino-silicate particles, particularly illite and feldspar. The quantity of the alumino-silicates in the nepheloid layer was greatest in the western basin.

Studies of the phytoplankton community at different areas in Lake Ontario showed that diatoms were one of the dominant groups (Munawar and Nauwerck, 1971; Vollenweider et al., 1974; Makarewicz, 1987), particularly in spring-early summer (Sreenivasa and Nalewajko, 1975; Munawar et al., 1987). As indicated by biogenic silica in bottom sediments, diatoms have been an important component of the phytoplankton assemblage in Lake Ontario (Schelske et al., 1986). Nriagu (1978) found that a massive episodic flux of biogenic silica to the sediments follows the crash of diatom blooms in Lake Ontario, and that about 90% of the silica from the diatoms

becomes converted to the soluble form at the sediment-water interface. Further, Sandilands and Mudroch (1983) found many diatoms by an electron microscopy examination of the particles from the nepheloid layer in Lake Ontario. Results of the above studies suggested that SiO_2 in the suspended matter in the nepheloid layer was derived from the diatoms which contain opal (i.e., $\text{SiO}_2 \cdot n\text{H}_2\text{O}$ with a 3 to 10% water content; Bates, 1969).

Calcium carbonate precipitation is common in the lower Great Lakes (Eadie and Robbins, 1987). In Lake Ontario surface waters, CaCO_3 starts to precipitate in spring during the increase of surface water temperature, and following increased primary production accompanied by an increase of pH annually in July and August (Sylvestre et al., 1987). Calcium carbonate was the major component of particles collected at the 3 m water depth at station 976 in August 1989 (Table 2). On the other hand, the suspended matter in the nepheloid layer collected at the same time at this station contained only about 40%, and the bottom sediments only about 12% of the CaCO_3 -amount in the suspended matter in surface water. These results suggested that after precipitating in surface waters in July and August, CaCO_3 particles start to sink through the water column where they can partially dissolve under lower pH or reach the nepheloid layer and become subsequently deposited on the lake bottom.

Generally, the concentrations of Al_2O_3 and Fe_2O_3 were greater in the

bottom sediments than in the suspended matter in the nepheloid layer (Table 2) indicating limited presence of resuspended bottom sediments in the nepheloid layer. Studies of the geochemistry of suspended matter in the oceans and freshwater lakes showed that Al is almost entirely associated with alumino-silicates (Spencer and Sachs, 1970; Mudroch, 1984). According to the above studies and results obtained by the investigation of mineralogical composition of the suspended matter in the nepheloid layer in Lake Ontario, the concentrations of Al_2O_3 in the suspended matter in the nepheloid layer represented mainly the quantity of alumino-silicate mineral particles resuspended from the bottom sediments. The concentrations of Al_2O_3 in sediments in Lake Ontario depositional basins ranged from 7 to 13.1%. On the other hand, the concentrations of Al_2O_3 in suspended matter in the nepheloid layer ranged from 2.7 to 8.3%. These results suggested that between 37 and 63% of the suspended matter in the nepheloid layer originated from the resuspension of the bottom sediments. Greatest concentrations of Al_2O_3 in the suspended matter in the nepheloid layer were found in the western basin.

The SiO_2 - Al_2O_3 ratio in the suspended matter in the nepheloid layer is compared to that in the bottom sediments in Figure 5. The ratio in the suspended matter in the nepheloid layer was most similar to that in the bottom sediments in the western basin. The ratio was greater, up to about five times, in the suspended matter in the nepheloid layer than in the bottom sediments in the other basins,

particularly the central basin. These results further supported the finding that the high concentrations of silica in the nepheloid layer originated from diatoms sinking through the water column, particularly in the central and eastern basins. Similar $\text{SiO}_2\text{-Al}_2\text{O}_3$ ratios in the suspended matter in the nepheloid layer and bottom sediments from the western basin indicated the presence of resuspended bottom sediment particles in the nepheloid layer.

The concentrations of Mg, K, Ti and Mn were generally greater in the bottom sediments than those in the suspended matter in the nepheloid layer (Table 2). The concentrations of Mg were between 1.25 and 2.55% MgO in the sediments with greatest concentrations at station 210 in the western basin, and were more uniform (between 1.18 and 1.96% MgO) in the suspended matter in the nepheloid layer with greatest concentrations at station 999 in the eastern basin. The concentrations of K were between 2.11 and 3.20% K_2O in the sediments with greatest concentrations at station 624 in the central basin, and ranged from 0.91 to 2.33% K_2O in the suspended matter in the nepheloid layer with greatest concentrations at station 974 in the eastern basin. The concentrations of Ti were between 0.35 and 0.73% TiO_2 in the sediments with greatest concentrations at station 974 in the eastern basin, and ranged from 0.11 to 0.53% TiO_2 in the suspended matter in the nepheloid layer with greatest concentrations at station 210 in the western basin. There was no relationship between concentrations of Mg, K and Ti in the suspended matter in the nepheloid layer and those in the bottom

sediments. The concentrations of Mn were between 0.1 and 1.4% MnO in the sediments, and between 0.04 to 0.25% MnO in the suspended matter in the nepheloid layer. The greatest concentrations of Mn were in the suspended matter in the nepheloid layer and sediments in the western basin.

Mg, K, Ti and Mn were found in different concentrations in biogenic particles, particularly plankton, in Lake Erie water (Mudroch, 1984). However, they also were abundant in inorganic mineral particles in the suspended matter and bottom sediments. Bates (1969) reported the concentrations of Mg and K in diatoms between 0.1 and 2.0% MgO and 0.2 to 1.5 K₂O, and Mg, K, Ti and Na were found in different phytoplankton species (Vinogradov, 1953). Small differences existed between the concentrations of Na in the suspended matter in the nepheloid layer and those in the bottom sediments. The greatest difference was at station 999 in the eastern basin with 1.83% and 0.67% Na₂O in the suspended matter in the nepheloid layer and bottom sediments, respectively. Consequently, in the suspended matter in the nepheloid layer in Lake Ontario, Mg, Ti, K, Mn and Na may be in both organic matter or mineral particles sinking from surface waters or in resuspended mineral particles from bottom sediments.

The concentrations of P ranged from 0.24 to 0.68% and 0.16 to 0.82% P₂O₅ in the suspended matter in the nepheloid layer and bottom sediments, respectively, and both were greatest at station NL1 in

the western basin. Generally, the concentrations of P were greater in the sediments in the western basin than in the other two basins. On the other hand, with the exception of station 210, the concentrations of P were greater in the suspended matter in the nepheloid layer in the central and eastern basins than those in the western basin. The results indicated that in the suspended matter in the nepheloid layer P originated from plankton sinking from the surface water, particularly in the central and eastern basins. Further, a relationship existed between Ca and P in the suspended matter in the nepheloid layer (correlation coefficient 0.68, no. samples 11) suggesting a coprecipitation of P with calcite similar to that observed in other studies (Rossknecht, 1980; Murphy *et al.*, 1983; Mudroch, 1984).

The concentrations of organic carbon in the suspended matter in the nepheloid layer varied between 5 and 13% with no clear pattern. The concentrations of organic carbon in surficial sediments were in the range of 0.3 to 7.5% with the majority of concentrations around 4%. A continuous reduction of the light transmission below the thermocline from June to September (Figure 2) indicated increasing quantities of suspended matter sinking from the epilimnion to the hypolimnion. This sinking material, mainly derived from the primary production, was responsible for greater concentrations of organic carbon in the suspended matter in the nepheloid layer than those in the sediments.

Another important source of suspended matter in Lake Ontario is the material transported from Lake Erie by the Niagara River which represents an annual input of about 4 million tons of suspended matter to Lake Ontario (Kemp and Harper, 1976). Mudroch (1984) found considerably greater concentrations of organic matter, SiO_2 and CaCO_3 in suspended matter collected from Lake Erie surface waters in May, August and September 1978 than in bottom sediments from Lake Erie depositional basins (Table 3). Examination by electron microscopy and calculated Si/Al ratio in Lake Erie suspended matter showed that some SiO_2 was of biogenic origin and appeared mostly in diatom frustules. The major components of the suspended matter in Lake Erie surficial waters, organic matter, SiO_2 and CaCO_3 , were similar to those found in the nepheloid layer in Lake Ontario. Large quantities of suspended matter transported from Lake Erie into Lake Ontario and the geochemical composition of Lake Erie suspended matter suggested that the latter contributes material to the nepheloid layer in Lake Ontario. During summer stratification in Lake Ontario, the static stability of the layer of warm water floating on cool water restricts vertical circulation (Boyce et al., 1989). Warm surface water transported from Lake Erie merges with Lake Ontario epilimnetic waters enriching them by suspended matter derived mostly from primary production in Lake Erie. This gradually increasing quantity of suspended matter starts to sink from the epilimnion to the hypolimnion in Lake Ontario, and contributes to the continuous reduction of light transmission of Lake Ontario water column from June to October.

The geochemical composition of the suspended matter in the nepheloid layer supported the findings obtained from the light transmission profiles, and showed that the nepheloid layer in Lake Ontario contained autochthonous material from the primary production in the surface waters. The differences in geochemical composition of the suspended matter in the nepheloid layer in the three Lake Ontario basins were attributed to the origin of the nepheloid layer in each basin. Chambers and Eadie (1981) studied the benthic nepheloid layer in south-eastern Lake Michigan, and suggested that the currents, generated during the thermal bar period, resuspended fine-grained, high organic matter-containing surficial sediments from the shelf, and transported it lakeward creating a nepheloid layer. Similar processes responsible for the formation of the nepheloid layer can occur in the western basin of Lake Ontario. During early spring, surficial sediments on the slope at the Niagara River mouth consist of freshly deposited, fine-grained organic matter-rich particles transported by the river from Lake Erie during winter. The Niagara River discharge is usually slightly warmer (about 6 to 8°C in early spring) than the ambient Lake Ontario surface water with early spring temperatures <4°C (Masse and Murthy, 1990). The warmer water from the river mixes with the colder lake water at the river mouth generating a large volume of water with temperatures about 4°C. This high density water mass sinks to the bottom generating strong currents which, in turn, resuspend the surface fine-grained material on the Niagara River slope (Murthy, 1991). The resuspended material is

further transported into the western basin offshore area and becomes incorporated in the nepheloid layer. Sinking plankton, particularly diatoms, and precipitated CaCO_3 reach the nepheloid layer in summer and fall. Therefore the suspended matter in the nepheloid layer sampled from the western basin in August 1987 contained a mixture of inorganic particles, SiO_2 , CaCO_3 and organic matter derived from the processes described above. On the other hand, the suspended matter in the nepheloid layer in the central and eastern basins consisted mainly of plankton, including diatoms, and precipitated CaCO_3 sinking during late spring, summer and fall to the lake bottom.

Concentrations of trace elements in the nepheloid layer

The concentrations of As, Co, Cr, V, Zn, Ni, Cu, Hg and Pb in the nepheloid layer are compared to those in the surficial (0 to 3 cm) sediments at each sampling station in Table 4. The lowest concentrations of As, Zn, Cu and Pb in surficial sediments were found at the high-energy zone at the northern shore (stations NL2 and 624), and at the Whitby-Olcott and Scotch-Bonnet sills. No recent fine-grained sediment accumulation exists at these areas, and surficial sediments are mainly glacial-lacustrine clay. The association of As, Zn, Pb and Cu, mainly of anthropogenic origin, with recent fine-grained sediments in the Great Lakes explains their low concentrations in the sediments at the nondepositional areas in the lake.

Association of soluble and particulate trace elements in Lake Ontario water with organic matter, and calcite and silica particles sinking to the lake bottom were most likely responsible for the enrichment of the suspended matter in the nepheloid layer by trace elements. The concentrations of Zn in the sediments varied between 50 and 607 $\mu\text{g/g}$ and those in the suspended matter in the nepheloid layer between 118 and 1,180 $\mu\text{g/g}$. The concentrations of Zn in the suspended matter in the nepheloid layer were significantly greater than those in the sediments at seven stations. However, they were similar to those in the sediments at stations 210 and 625, and were lower than those in the sediments at stations NL1 and 206 in the western basin (Table 4). The lack of a relationship between the Zn concentrations in the suspended matter in the nepheloid layer and those in the sediments suggested that resuspended sediment particles were not the source of Zn in the nepheloid layer. The results indicated that the source has been anthropogenic inputs, such as atmospheric deposition and industrial and municipal effluents, providing an annual input of 1,660 tons of Zn to Lake Ontario (Nriagu, 1986). Generally, the concentrations of Zn in the suspended matter in the nepheloid layer increased from the western to the eastern basin. The concentrations ranged from 118 to 218 $\mu\text{g/g}$ in the western basin, from 420 to 560 $\mu\text{g/g}$ in the central basin, and from 456 to 1,180 $\mu\text{g/g}$ in the eastern basin. Based on results of the studies of circulation and thermal structure in the Great Lakes, particularly in Lake Ontario (Boyce *et al.*, 1989), the time required for the transport of suspended matter from the

western basin to the eastern basin was estimated to be between 14 and 30 days. This time period can be sufficient for enrichment of suspended matter in the lake water by Zn. The effect of circulation, particularly well defined currents in Lake Ontario, can be responsible for the enrichment of the suspended matter in the nepheloid layer by Zn in the eastern basin.

The enrichment of the suspended matter in the nepheloid layer in the eastern basin by Cu was similar to that observed for Zn. The concentrations of Cu in the suspended matter in the nepheloid layer ranged from 31 to 91 $\mu\text{g/g}$ in the western basin, from 142 to 325 $\mu\text{g/g}$ in the central basin, and from 271 to 396 $\mu\text{g/g}$ in the eastern basin (Table 4). There was no relationship between the concentrations of Cu in surficial sediments and the suspended matter in the nepheloid layer. The concentrations of Cu in the sediments were greater in the western basin (from 18 to 298 $\mu\text{g/g}$) than in the other two basins (from 15 to 90 $\mu\text{g/g}$).

With exception of sampling stations NL1 and 206 in the western basin and 625 in the central basin, the concentrations of Pb were considerably greater in the suspended matter in the nepheloid layer than in the sediments. The concentrations of Pb ranged from 23 to 203 $\mu\text{g/g}$ in surficial sediments with the greatest concentrations in the western basin, and from 41 to 683 $\mu\text{g/g}$ in the suspended matter in the nepheloid layer with greatest concentrations in the western and eastern basins (Table 4). The lowest concentrations of Pb in

the suspended matter in the nepheloid layer were in the central basin. There was a considerable difference in the concentrations of Pb in the suspended matter in the nepheloid layer at stations NL2 and 624 located at the high-energy zone in the northern part of the lake. The concentrations of Pb in the suspended matter in the nepheloid layer and surficial sediments were 260 $\mu\text{g/g}$ and 29 $\mu\text{g/g}$, respectively, at station NL2. On the other hand, these concentrations were 41 $\mu\text{g/g}$ and 23 $\mu\text{g/g}$, respectively, at station 624. This difference could reflect an increased input of automotive Pb from the highly populated urban area around Toronto. No relationship was observed between the concentrations of Pb in the suspended matter in the nepheloid layer and those in surficial sediments in the three basins. Further, a continuous increase of Pb concentrations in the suspended matter in the nepheloid layer from the western to the eastern basin as observed for Zn and Cu did not exist.

The concentrations of Ni in surficial sediments, between 13 and 155 $\mu\text{g/g}$, were similar to those in the suspended matter in the nepheloid layer which ranged between 37 and 75 $\mu\text{g/g}$ (Table 4). The concentrations of Co were similar in the suspended matter in the nepheloid layer to those in the surficial sediments (Table 4). The concentrations of As in surficial sediments were between 2 and 69 $\mu\text{g/g}$. On the other hand, they were more consistent in the suspended matter in the nepheloid layer ranging from 9 and 24 $\mu\text{g/g}$. There was no relationship between the concentrations of Co and As

in the suspended matter in the nepheloid layer and those in the sediments.

With few exceptions, the concentrations of Cr in the suspended matter in the nepheloid layer were similar to those in fine-grained surficial sediments from Lake Ontario depositional basins (from 70 to 120 $\mu\text{g/g}$, A. Mudroch, unpublished data). The concentrations of V in the suspended matter in the nepheloid layer were similar or lower than those in the surficial sediments (Table 4). In addition, these concentrations were similar to the concentrations of V (60 to 120 $\mu\text{g/g}$) in fine-grained sediments in Lake Ontario depositional basins (A. Mudroch, unpublished data).

Combustion of fuels, including gasoline, is the major source of anthropogenic Pb, V and Ni in the environment. Manufacturing of iron and steel ferroalloys is an important source of As and Cr, and primary nonferrous metal production, mining and smelting account for most of anthropogenic Zn and Cu (Nriagu, 1980; Pacyna, 1986). Many of these anthropogenic activities occurring in Lakes Ontario and Erie drainage basins are potential sources of trace elements in Lake Ontario. Similar concentrations of Cr, V, Ni and Co in the suspended matter in the nepheloid layer and bottom sediments indicated that upon entering the lake these elements become associated with suspended matter which settles on the lake bottom.

The concentrations of Hg in the suspended matter in the nepheloid

layer are compared to those in three subsamples from different sediment depths (0 to 3 cm, 3 to 6 cm, and 6 to 9 cm) in Figure 6. At all stations, the concentrations of Hg were lower or similar in the suspended matter in the nepheloid layer than those in the sediment subsamples. The greatest concentrations of Hg were in subsamples from the 6 to 9 cm sediment depth, showing increased inputs of Hg to Lake Ontario around the 1970s (Thomas, 1972; Mudroch, 1983).

In the lower Great Lakes, the atmosphere accounts for over 50% of the Pb and Zn inputs, and for about 28 to 23% of the Cu and Ni inputs, respectively (Nriagu, 1986). The rest of the metal inputs come from industrial, municipal and other sources in the drainage basin. Suspended particulates accounted for 50 to 80% of the Cu, 10 to 40% of the Ni, and over 60% of the Pb concentrations during 1978 studies of particulate and dissolved trace metals in Lake Ontario (Nriagu et al., 1981). In Table 5, the concentrations of Cu, Ni, Pb and Zn in the suspended matter and particulate metal concentrations in the nepheloid layer are compared to those found in Lake Ontario offshore waters by Nriagu et al. (1981) in Table 5. The concentrations of metals in the suspended matter as well as particulate metal concentrations were greater in the nepheloid layer than the lake-wide average reported by Nriagu et al. (1981). Considerably greater particulate metal concentrations in the nepheloid layer were due to greater amount of suspended particles in the nepheloid layer than in lake water collected from different

depths in 1978.

The concentrations of trace elements in the suspended sediments collected at several locations in the upper and lower Niagara River in 1977 were reported by Kauss (1983). The maximum concentrations in the suspended sediments in the lower Niagara River were 23 $\mu\text{g/g}$ As, 85 $\mu\text{g/g}$ Cr, 150 $\mu\text{g/g}$ Cu, 170 $\mu\text{g/g}$ Pb, 0.69 $\mu\text{g/g}$ Hg, 53 $\mu\text{g/g}$ Ni, 390 $\mu\text{g/g}$ Zn, and 230 ng/g PCBs. With the exception of Pb and Hg, these concentrations were similar or greater than those found in the suspended matter in the nepheloid layer in the western basin. However, with few exceptions, they were lower than those in the suspended matter in the nepheloid layer in the central and eastern basins. The results suggested further trace elements enrichment of the suspended matter transported from the Niagara River during its residential time in Lake Ontario.

Concentrations of PCBs in the suspended matter in the nepheloid layer and bottom sediments

With the exception of station NL1 in the western basin, the concentrations of PCBs were considerably greater in the suspended matter in the nepheloid layer than those in surficial sediments (Table 6). This observation agrees with that of Oliver et al. (1989) who found 1,300 and 1,900 ng/g of PCBs in suspended matter collected by sediment traps and 510 to 690 ng/g in bottom sediments in Lake Ontario depositional basins in 1982/83 and 1981, respectively. The suspended matter in the nepheloid layer

contained more lower chlorinated biphenyls, particularly tetra and penta chlorobiphenyls, than the sediments (Figure 7). Oliver et al. (1989) found that PCB composition in Lake Ontario sediments changed with sediment depth, and that the quantity of the lower chlorinated isomers (tri to penta) decreased with sediment depth. They explained these changes as a shift in usage pattern from more heavily chlorinated to less chlorinated PCBs in recent years. However, they also suggested the increase of highly chlorinated PCBs with sediment depths may be due to preferential partitioning processes and possibly to greater mobility and loss of the lower chlorinated congeners from the sediments. Greater quantities of lower chlorinated PCBs in the suspended matter in the nepheloid layer than in the bottom sediments indicated the changes in usage pattern suggested by Oliver et al. (1989) or may be due to the preferential partitioning processes, particularly the loss of lower chlorinated PCBs from the sediments with subsequent accumulation in the suspended matter in the nepheloid layer.

Eisenreich et al. (1981a; 1981b) showed that the atmospheric input is the most important source of organic contaminants, including PCBs, to the Great Lakes, and that without significant biodegradation these contaminants may accumulate in the system. Doskey and Andren (1981) and Eisenreich et al. (1981a) suggested that PCBs are associated with submicrometer particles in the atmosphere. It was further suggested that PCBs entering the water column from the air may remain dissolved and unassociated, bind

with dissolved or colloidal organics, adsorb onto particle surface, or become absorbed into organic detritus (Eisenreich et al., 1981a). In Lake Ontario surface waters, sinking organic detritus, and silica and calcium carbonate particles provide a large surface and sufficient time for processes controlling the association of contaminants entering the lake from the atmosphere with suspended matter. Stevens and Neilson (1989) found that about 40% of PCBs were associated with particulates in surface 1 m water in Lake Ontario in April. In Stevens and Neilson study, suspended particles from the water were separated by the same technique used in our study. Rice et al. (1983) found that about 17, 21 and 39% of total PCBs were associated with particulates in April 1980, July 1980 and August 1979, respectively, in subsurface waters in Lake Michigan. The concentrations of suspended solids were 1.57 and 2.01 mg/L during the sampling time in April and July 1980, respectively. Significant enhancement (up to 65%) of particulate phase PCBs was found in the surface (300 μ m) microlayer in Lake Michigan indicating a dryfall input followed by the transitory accumulation of airborne particles containing PCBs at the air-water surface. The authors concluded that these particles have the potential to aggregate and sink through the water column. Baker et al. (1985) found the suspended matter in the benthic nepheloid layer was enriched in PCBs relative to the suspended matter in the overlying water in western Lake Superior during the stratified period of 1983. Mean PCB concentrations were 0.56 ng/L in surface waters and 0.87 ng/L in the benthic nepheloid layer, with average

surface and nepheloid layer suspended solids concentrations 1.1 and 4.8 mg/l, respectively. The above studies indicated the importance of suspended particles in cycling of PCBs in the Great Lakes.

The concentrations of PCBs associated with particles calculated from the quantity of suspended matter and PCBs in the nepheloid layer in Lake Ontario ranged from 0.145 to 1.40 ng/l. Provided about 40% of PCBs in the nepheloid layer were associated with particles, estimated concentrations of dissolved and particulate PCBs in the 10 to 20 m water layer above the lake bottom ranged from 0.637 to 6.16 ng/l during the nepheloid layer sampling period. This estimate is greater than the concentrations of PCBs (0.484 to 2.614 ng/l) in Lake Ontario surface waters reported by Stevens and Neilson (1989). However, it should be noted that in our study the concentrations of total PCBs were expressed as the sum of 51 congeners in the National Research Council of Canada standard and total PCBs reported by Stevens and Neilson were based on a standard containing congeners in a mixture of Aroclors 1242, 1254 and 1260. Therefore, the concentrations of total PCBs in the nepheloid layer could be underestimated. Further, the Westfahlia separator used in both Stevens and Neilson and our study is not efficient in collection of submicron particles which may contain considerable amounts of PCBs (Eisenreich et al., 1981a). Further, some of the particulates collected by centrifuges are biotic and their crushing with associated release of body fluids to the aqueous phase or breakup of naturally occurring aggregates could affect the

estimation of particulate/aqueous partitioning of contaminants (Allan, 1986). However, the data from Stevens and Neilson and our studies indicated that particulate PCBs represent considerable amount of total PCBs in Lake Ontario surface and bottom waters.

The concentrations of PCBs in the topmost 3 cm of sediments were lower than those in the subsurface 3 to 9 cm of sediments from the depositional areas (Table 7), indicating an recent decrease in PCBs loadings to Lake Ontario due to the restrictions of PCBs production in North America (Erickson, 1986). These results agree with observations of Oliver et al. (1989) who found lower concentrations of PCBs in surficial sediments than in deeper sediments in Lake Ontario. However, the concentrations of PCBs were greater in the suspended matter in the nepheloid layer than in the topmost 3 cm of sediments at most sampling stations (Table 6). These results suggested the desorption of PCBs prior to the settling and burial of the suspended matter in the nepheloid layer on the lake bottom. On the other hand, greater concentrations of tetra and pentachlorobiphenyls in the suspended matter in the nepheloid layer than in surficial sediments indicated the desorption of more soluble lower chlorinated biphenyls from resuspended bottom sediments and their subsequent adsorption onto the suspended matter in the nepheloid layer. Furthermore, there was no relationship between organic matter and PCBs concentrations or between SiO_2 (and CaCO_3) and PCBs in the suspended matter in the nepheloid layer. The lack of a relationship between the

concentrations of PCBs and chemistry of suspended matter suggested that the quantity rather than chemistry of the suspended matter was important in the partitioning of PCBs between soluble and particulate phases in the nepheloid layer. In a study of chlorinated organic contaminants in settling particles at the Niagara River mouth in Lake Ontario Oliver and Charlton (1984) noticed that only a small portion of most studied chemicals entering the lake, including PCBs, were adsorbed by settling particles and reached bottom sediments.

Concentrations of Zn, Cu, Pb and PCBs in different particle size fractions of bottom sediments

The concentrations of Pb and PCBs were greater in the suspended matter in the nepheloid layer than in individual sediment particle size fractions at station 210 in the western basin (Table 8). On the other hand, the concentrations of Zn and Cu in the suspended matter in the nepheloid layer were similar to those in different sediment particle size fractions. These results were similar to those obtained by analyses of bulk surficial sediment (0 to 3 cm) from the same station, and indicated that high concentrations of Pb and PCBs in the suspended matter in the nepheloid layer at station 210 did not originate by resuspension of fine-grained ($<13\ \mu\text{m}$) sediment particles in the surficial sediments.

Concentrations of trace elements and PCBs in suspended matter in surface water and the nepheloid layer

The concentrations of major and trace elements and PCBs in suspended solids in the surface (3 m) water and in the nepheloid layer at station 976 (Figure 1) are shown in Table 9. With the exception of Ni, the concentrations of all trace elements and PCBs were greater in the suspended matter in the nepheloid layer than those in the suspended solids from the surface water. The results suggested that the geochemical composition of the suspended matter and biological or physico-chemical processes, particularly sorption, during its residence time in the water column could account for the differences in the concentrations of particle-associated contaminants in surface and bottom waters.

Quantity of material in the nepheloid layer

According to our calculations, using a 20-m average thickness of the nepheloid layer and a 9,150-km² total area of depositional basins, about 260,000 tons of suspended solids were in the nepheloid layer during the sampling period. Calculated, 260,000 tons represented about 10% of estimated total annual accumulation of sediments in Lake Ontario depositional basins (Thomas *et al.*, 1972). Using estimated settling velocity of particles in the Great Lakes about 1 m per day (Eadie and Robbins, 1987), the particles in a 20-m thick nepheloid layer will settle to the bottom in 20 days. If the supply of particles to the nepheloid layer and their settling speed repeat about every month from August to December,

the supply of suspended particles from the nepheloid layer to the sediments would represent about 60% of total annually accumulated sediment weight estimated by Thomas et al. (1972). Further, the increasing thickness of the nepheloid layer indicated by lower light transmission in the water column in September and October (Figure 2) suggested an increasing quantity of settling particles during late fall. On the other hand, an intensive vertical mixing of the water column during the fall turnover will considerably increase the residential time of the particles in the lake water.

Lower concentrations of metals and PCBs in surficial sediments than those in the suspended matter in the nepheloid layer suggested an additional source of less contaminated sedimenting particles which would dilute the concentrations of contaminants in surficial sediments in Lake Ontario depositional basins. Desorption or solubilization of trace elements and PCBs from the suspended matter in the nepheloid layer prior to its settling and burial on the lake bottom would also result in lower concentrations of contaminants in surficial sediments than those in the suspended matter in the nepheloid layer. For example, the dissolution of particulate silica at the sediment/water interface found by Nriagu (1978) and calcite under lower pH in bottom water as well as the decomposition of sinking organic matter could affect solubilization of contaminants associated with these particles. With an estimated hydraulic retention time of about eight years for Lake Ontario (Eadie and Robbins, 1987) desorbed or solubilized contaminants

would have considerably greater residential time in the lake water than particulate contaminants settling to the bottom. Calculations showed about 61 tons of Pb, 119 tons of Zn, 51 tons of Cu, 13 tons of Ni, and 118 kg of PCBs were in the 20-m thick nepheloid layer during the sampling period. This represented about 10%, 7%, 15% and 4% of total annual input of Pb, Zn, Cu and Ni, respectively, into Lake Ontario, estimated by Nriagu (1986), and about 2.4% of total PCBs input from the Niagara River (Stevens and Neilson, 1989) and atmospheric deposition (Eisenreich et al., 1981a). These results suggested that the nepheloid layer is an important media in accumulation, recycling and transport of contaminants in Lake Ontario.

SUMMARY

The origin and characteristics of the nepheloid layer was investigated in Lake Ontario, using light transmission profiles of the water column and geochemical composition of suspended matter in the nepheloid layer collected in the western, central and eastern basins of the lake in 1987, 1988 and 1989, respectively. The concentrations of trace elements (As, Co, Cu, Cr, Pb, Ni, Zn, V and Hg) and PCBs were determined in the suspended matter in the nepheloid layer and in bottom sediments to evaluate the role of the nepheloid layer in accumulation and transport of contaminants within the lake.

The lake-wide formation of the nepheloid layer commenced in July,

and its thickness increased gradually until October, particularly following the primary production peak in surface waters in August. Following the lake's turnover in November, the suspended matter in the nepheloid layer became mixed throughout the water column. The weight of the suspended matter in the nepheloid layer was only slightly greater than that in the rest of the lake water. Different physical properties of suspended particles rather than their quantity were responsible for the reduction of the light transmission in the nepheloid layer. Silica, calcite and organic matter were the major components of the suspended matter in the nepheloid layer in the central and eastern basins. In the western basin, the suspended matter in the nepheloid layer contained more mineral particles, such as clay minerals and other aluminosilicates, than in the other two basins. The results indicated that the nepheloid layer in the western basin contained bottom sediment particles transported from the slope at the Niagara River mouth following vertical mixing of warmer water from Lake Erie with cooler Lake Ontario water. On the other hand, the nepheloid layer in the central and eastern basins originated mainly from the primary production in surface waters and calcite precipitation associated with the photosynthesis during the summer. The suspended matter in the nepheloid layer in Lake Ontario had a similar geochemical composition to that of the suspended matter in the surface waters of Lake Erie. The results suggested that the suspended matter transported from Lake Erie by the Niagara River may become incorporated into the nepheloid layer in Lake Ontario.

With few exceptions, the concentrations of Pb, Zn and Cu were considerably greater in the suspended matter in the nepheloid layer than those in the topmost 3 cm bottom sediments. However, the concentrations of As, Co, Ni, Cr, V and Hg were similar or lower than those in the sediments. The concentrations of PCBs in the suspended matter in the nepheloid layer ranged from 151 to 728 ng/g, and were greater than those in most of the sediments. Further, the suspended matter in the nepheloid layer contained more lower chlorinated biphenyls, particularly tetra and pentachlorobiphenyls, than the sediments. This was ascribed to the changes in usage pattern of PCBs or to preferential partitioning processes, particularly the loss of lower chlorinated congeners from the sediments with subsequent accumulation in the suspended matter in the nepheloid layer.

Generally, the concentrations of trace elements and PCBs in the suspended matter in the nepheloid layer were greater than those in the suspended matter collected in the lower Niagara River in previous studies. Further, the concentrations Zn, Cu and Cr in the suspended matter in the nepheloid layer increased from the western to the eastern basin, and the concentrations of most of the trace elements and PCBs were greater in the suspended matter in the nepheloid layer than those in the suspended matter collected from the surface water in the eastern basin of Lake Ontario. These results suggested that particles transported into Lake Ontario from Lake Erie as well as autochthonous particles originating from

primary production in Lake Ontario become enriched by trace elements and organic contaminants during their residential time in the lake water. These particles accumulate in the nepheloid layer prior to their settling on the lake bottom. Dissolution of some particles in the suspended matter in the nepheloid layer, such as silica and calcium carbonate, and decomposition of organic matter would result in desorption of contaminants associated with these particles extending their residential time and recycling in Lake Ontario as documented by a lower concentration of some trace elements, particularly Pb, Zn and Cu, and PCBs in the bottom sediments than in the suspended matter in the nepheloid layer.

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**TABLE 1. WATER DEPTH, THICKNESS OF THE NEPHELOID LAYER AND
QUANTITY OF SUSPENDED MATTER IN THE NEPHELOID LAYER**

Station	Water depth (m)	Thickness of the nepheloid layer (m)	Weight of suspended matter in the nepheloid layer (mg/l)
<u>Western Basin</u>			
August 1987			
NL-1	134	18	0.97
NL-2	96	10	1.38
206	105	10	1.92
210	70	15	1.91
<u>Central Basin</u>			
August 1988			
623	150	30	0.96
624	63	7	2.23
625	180	30	0.60
626	165	30	0.50
<u>Eastern Basin</u>			
August 1989			
974	85	25	2.12
999	240	30	0.71
976	54	14	2.10
976	sampled 3 m surface water		1.83

**TABLE 2. GEOCHEMICAL COMPOSITION OF THE SUSPENDED MATTER IN THE
NEPHELOID LAYER AND SURFICIAL SEDIMENTS
(in % dry weight)**

Sample No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	MnO	P ₂ O ₅	OC ⁴
NL1 ¹	15.6	2.6	1.31	1.34	28.3	0.83	0.99	0.13	0.08	0.68	11.9
NL1 ²	55.5	10.4	6.05	2.05	7.5	1.40	2.28	0.58	1.40	0.82	4.6
NL2 ¹	52.8	6.3	2.60	1.36	18.5	1.16	1.34	0.26	0.19	0.29	6.5
NL2 ²	73.2	7.2	3.40	2.00	3.5	1.25	2.35	0.51	0.99	0.68	1.8
206 ¹	53.2	8.3	3.82	1.45	14.6	0.95	1.58	0.36	0.25	0.24	6.0
206 ²	49.5	9.1	5.04	1.70	8.1	1.03	2.11	0.49	1.32	0.50	4.5
210 ¹	52.9	9.8	4.85	1.75	14.1	0.88	1.95	0.53	0.24	0.27	5.5
210 ²	67.2	11.5	4.85	2.55	4.6	1.55	2.30	0.65	0.15	0.35	2.4
623 ¹	66.6	2.8	1.16	1.18	21.3	1.58	0.97	0.11	0.04	0.44	7.4
623 ²	63.2	12.5	3.89	1.25	5.5	1.05	2.90	0.35	0.10	0.16	0.9
624 ¹	65.1	4.3	2.23	1.22	15.2	1.19	1.52	0.23	0.06	0.48	12.9
624 ²	81.2	7.7	1.58	1.80	1.6	1.10	3.20	0.41	0.12	0.19	1.2
625 ¹	66.9	2.7	1.13	1.39	19.3	0.92	1.13	0.11	0.04	0.53	8.7
625 ²	46.9	9.9	4.59	1.63	10.1	0.69	2.90	0.44	0.36	0.34	7.4
626 ¹	57.9	2.7	1.15	1.45	16.9	1.98	0.91	0.11	0.04	0.50	9.2
626 ²	62.8	13.1	3.95	1.35	5.6	1.05	3.10	0.41	0.11	0.17	0.3
974 ¹	51.9	8.3	4.10	1.73	15.8	1.09	2.33	0.51	0.13	0.32	6.6
974 ²	51.2	11.3	6.06	2.04	5.2	0.85	3.07	0.73	0.19	0.27	4.2
976 ¹	47.5	7.4	3.23	1.59	20.7	0.93	2.13	0.35	0.09	0.33	5.6
976 ²	55.8	10.5	4.83	2.04	6.1	0.97	2.79	0.67	0.14	0.25	4.1
999 ¹	54.0	4.2	2.47	1.96	18.4	1.83	1.25	0.48	0.11	0.50	12.5
999 ²	45.4	9.7	5.27	1.86	10.1	0.67	3.06	0.54	0.55	0.31	4.2
976 ³	4.9	0.7	0.40	1.35	50.7	0.71	0.60	0.05	0.04	0.85	9.8

¹ nepheloid layer

² surficial sediments (0-3 cm)

³ suspended matter from surface 3 m water

⁴ organic carbon

TABLE 3. GEOCHEMICAL COMPOSITION OF SUSPENDED MATTER FROM SURFACE WATERS AND BOTTOM SEDIMENTS FROM LAKE ERIE DEPOSITIONAL BASINS¹
(concentration range in % dry weight)

	Suspended sediments			Bottom sediments
	May	August	September	(0-1 cm)
org.c	17.5-25.5	21.9-34.6	18.0-29.8	3.3- 5.1
SiO ₂	20.1-26.3	28.5-34.3	32.4-39.4	53.4-56.8
Al ₂ O ₃	3.5- 4.9	4.7- 5.3	4.9- 5.4	12.6-15.4
Fe ₂ O ₃	1.4- 2.5	1.6- 2.4	1.6- 2.0	7.1- 7.6
MgO	0.2- 1.0	0.3- 0.7	0.2- 0.6	2.1- 3.2
CaO	9.8-19.7	6.6- 9.6	3.7- 7.6	1.4- 2.1
K ₂ O	1.1- 1.4	1.2- 1.3	1.1- 1.3	3.5- 3.8
Na ₂ O	1.3	0.3	0.2	no data
TiO ₂	0.14-0.23	0.16-0.24	0.18-0.22	0.52-0.57
MnO	0.05-0.06	0.05-0.06	0.06	0.13-0.20
P ₂ O ₅	0.90-1.40	0.90-1.30	0.40-0.70	0.30-0.40

¹ after Mudroch (1984)

**TABLE 4. CONCENTRATIONS OF TRACE ELEMENTS IN THE SUSPENDED MATTER
IN THE NEPHELOID LAYER AND SURFICIAL SEDIMENTS
(in $\mu\text{g/g}$ dry weight)**

Sample No.	Cr	Co	As	Zn	Ni	Cu	V	Pb	Hg
NL1 ¹	55	11	15	118	52	31	13	160	0.055
NL1 ²	120	20	69	550	91	110	115	170	0.788
NL2 ¹	59	11	19	194	54	82	35	260	0.229
NL2 ²	37	5	2	50	20	18	25	29	0.210
206 ¹	67	15	14	205	51	91	57	64	0.296
206 ²	116	18	47	665	155	298	82	203	1.110
210 ¹	74	15	24	218	54	87	68	680	0.266
210 ²	106	18	20	205	42	121	60	70	0.835
623 ¹	76	11	10	560	46	325	18	94	0.170
623 ²	80	8	9	105	50	23	105	30	0.200
624 ¹	90	13	10	420	41	142	41	41	0.170
624 ²	37	5	2	49	13	15	125	23	0.180
625 ¹	73	10	9	430	40	277	15	72	0.172
625 ²	105	9	28	410	86	90	90	131	0.850
626 ¹	78	10	11	460	37	179	21	57	0.148
626 ²	75	7	8	95	45	25	110	28	0.200
974 ¹	135	8	16	815	59	281	78	373	0.170
974 ²	119	16	22	298	80	77	114	87	0.950
976 ¹	109	15	12	456	72	271	65	97	0.200
976 ²	100	12	18	213	58	45	91	51	1.050
999 ¹	186	4	13	1180	75	396	47	683	0.185
999 ²	114	19	27	321	88	72	94	99	1.150

¹ nepheloid layer

² surficial sediments (0-3 cm)

**TABLE 5. CONCENTRATIONS OF METALS IN THE SUSPENDED MATTER
AND PARTICULATE METAL CONCENTRATIONS IN OFFSHORE
WATERS¹ AND THE NEPHELOID**

Concentration of metals (µg/g)		Particulate metal concentration (ng/l)		
	offshore water	nepheloid layer	offshore water	nepheloid layer
Ni	48	54	34	80
Pb	190	247	110	384
Cu	180	207	130	206
Zn	410	490	230	607

¹ Lake-wide average of metal concentrations in suspended particles based on samples from three different depths in each basin collected in May/June and October, 1978 (Nriagu et al., 1981)

**TABLE 6. CONCENTRATIONS OF PCBs IN THE SUSPENDED MATTER
IN THE NEPHELOID LAYER AND SURFICIAL SEDIMENTS
(in ng/g dry weight)**

Station No.	Nephel. Layer	Sediments (0-3 cm)
NL1	208	247
NL2	584	50
206	728	405
210	384	95
623	151	<1
624	351	<1
625	411	346
626	491	<1
974	594	125
976	543	74
999	550	180

**TABLE 7. CONCENTRATIONS OF PCBs IN SEDIMENTS
(ng/g dry weight)**

Station	Sediment depth (cm)		
	0 - 3	3 - 6	6 - 9
NL1	247	350	270
206	405	450	350
210	95	247	380
625	346	741	460
974	125	195	389
976	74	85	215
999	180	566	620

**TABLE 8. CONCENTRATIONS OF Zn, Cu, Pb and PCBs IN THE SUSPENDED
MATTER IN THE NEPHELOID LAYER AND DIFFERENT PARTICLE SIZE
FRACTIONS OF SURFICIAL SEDIMENT AT STATION 210
($\mu\text{g/g}$ dry weight)**

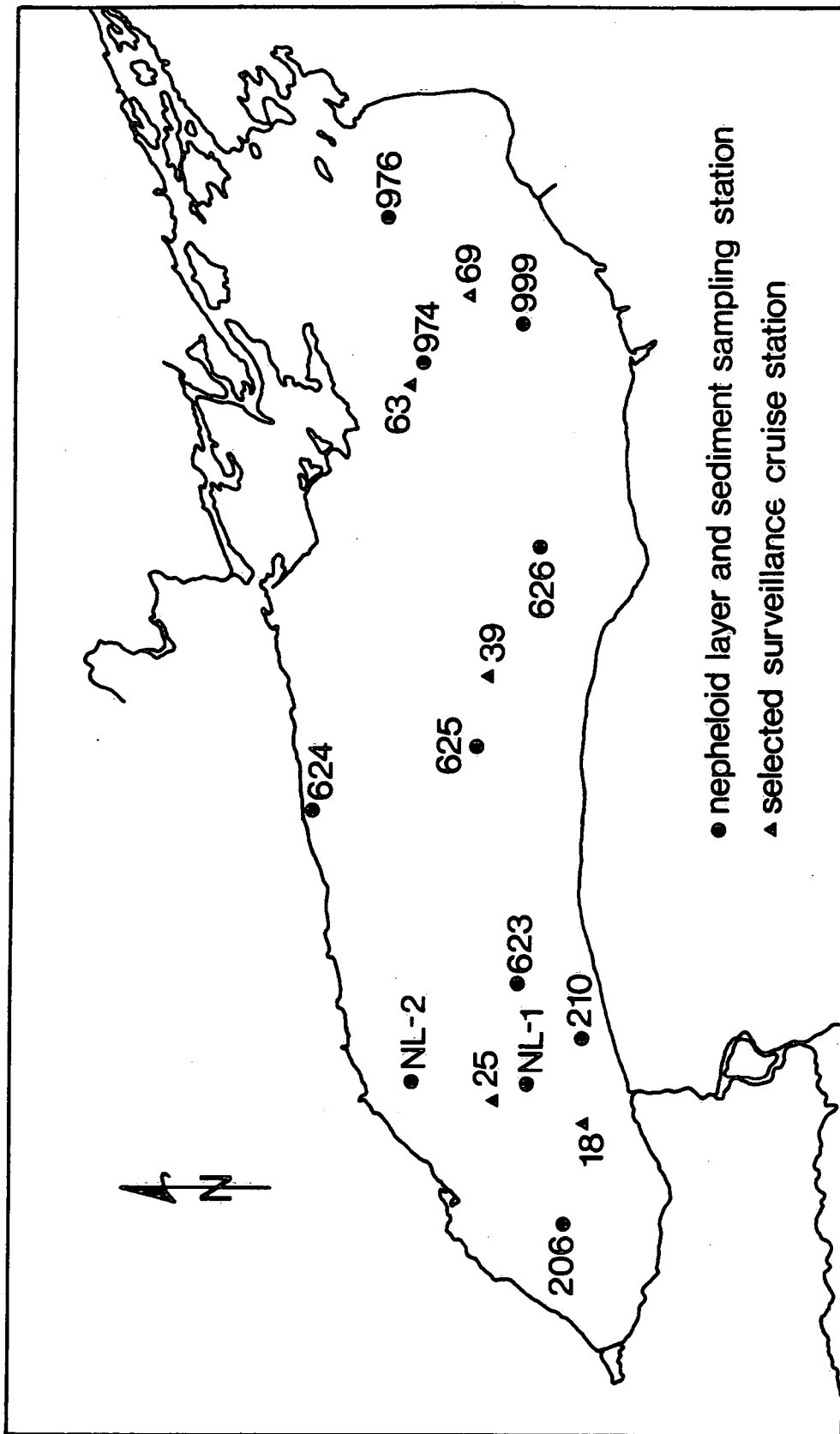
Particle size fraction um	Zn	Cu	Pb	PCBs
43 - 53	118	105	115	0.050
37 - 43	230	110	115	0.080
29 - 47	200	110	115	0.090
19 - 29	180	135	110	0.090
13 - 19	200	130	110	0.080
<13	340	110	150	0.070
Nepheloid layer	218	87	680	0.384

**TABLE 9. CONCENTRATIONS OF MAJOR TRACE ELEMENTS AND PCBs
IN THE SUSPENDED MATTER IN SURFACE WATER AND
NEPHELOID LAYER AT STATION 976**

Parameter	Surface 3 m	Nepheloid layer
	% dry weight	
SiO ₂	4.900	47.500
Al ₂ O ₃	0.700	7.400
Fe ₂ O ₃	0.400	3.230
MgO	1.350	1.590
CaO	50.670	20.680
Na ₂ O	0.710	0.930
K ₂ O	0.600	2.130
TiO ₂	0.050	0.350
MnO	0.040	0.090
P ₂ O ₅	0.850	0.330
	μg/g dry weight	
PCBs	0.148	0.543
Cr	54.000	109.000
Co	7.000	15.000
As	4.000	12.000
Zn	414.000	456.000
Ni	116.000	72.000
Cu	59.000	271.000
V	9.000	65.000
Pb	89.000	97.000
Hg	0.050	0.200

FIGURE CAPTIONS

- Figure 1. Nepheloid layer and bottom sediments sampling stations in Lake Ontario.
- Figure 2. Light transmission profiles recorded monthly at stations 18, 25, 34, 39, 63 and 69 in Lake Ontario.
- Figure 3. Light transmission profiles recorded at station no. 25 in August 1982, 1985, 1986 and 1987.
- Figure 4. Temperature and light transmission profiles recorded in August 1988 in the central basin of Lake Ontario.
- Figure 5. $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio in the suspended matter in the nepheloid layer and in bottom sediments.
- Figure 6. Concentrations of Hg in the suspended matter in the nepheloid layer and at different sediment depths.
- Figure 7. Distribution of PCB congeners in the suspended matter from the nepheloid layer and surficial (0-3 cm) sediments.



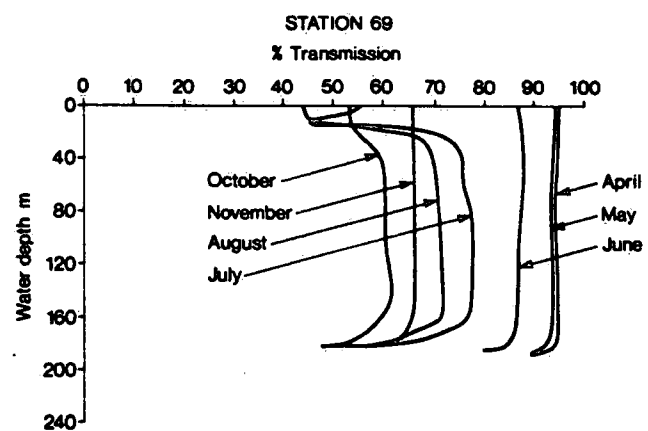
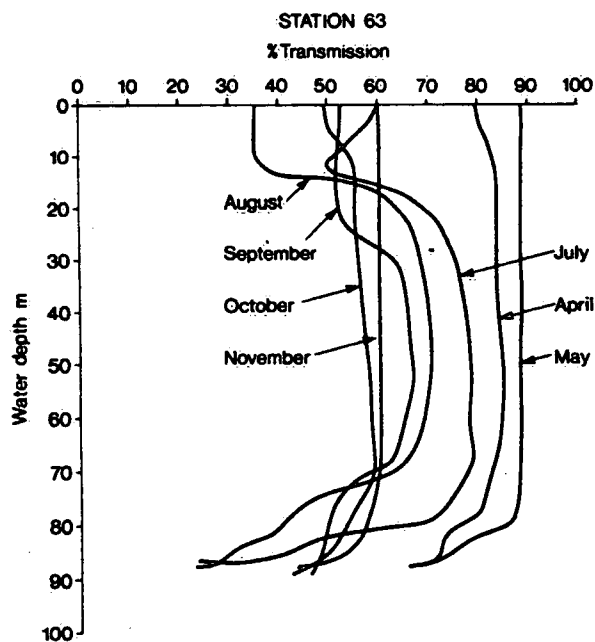
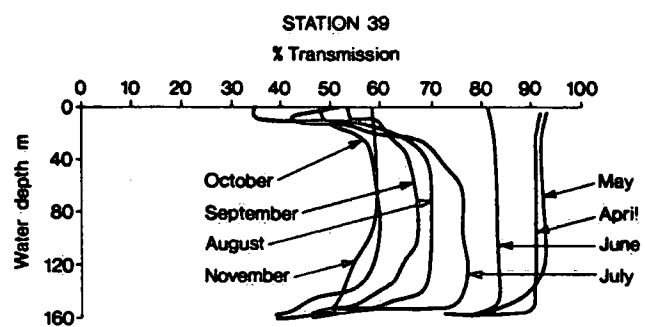
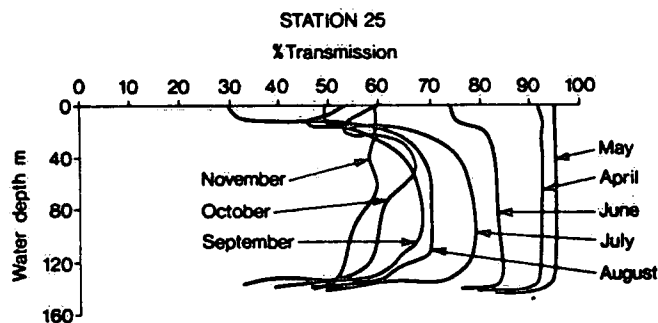
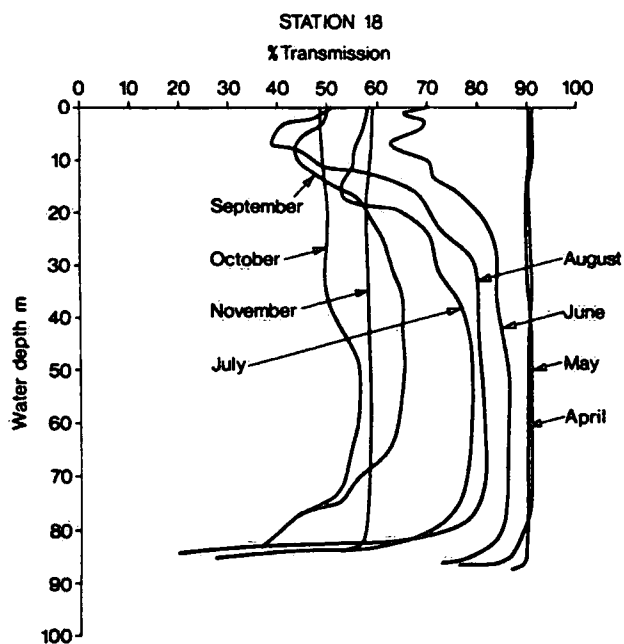


Fig. 2.

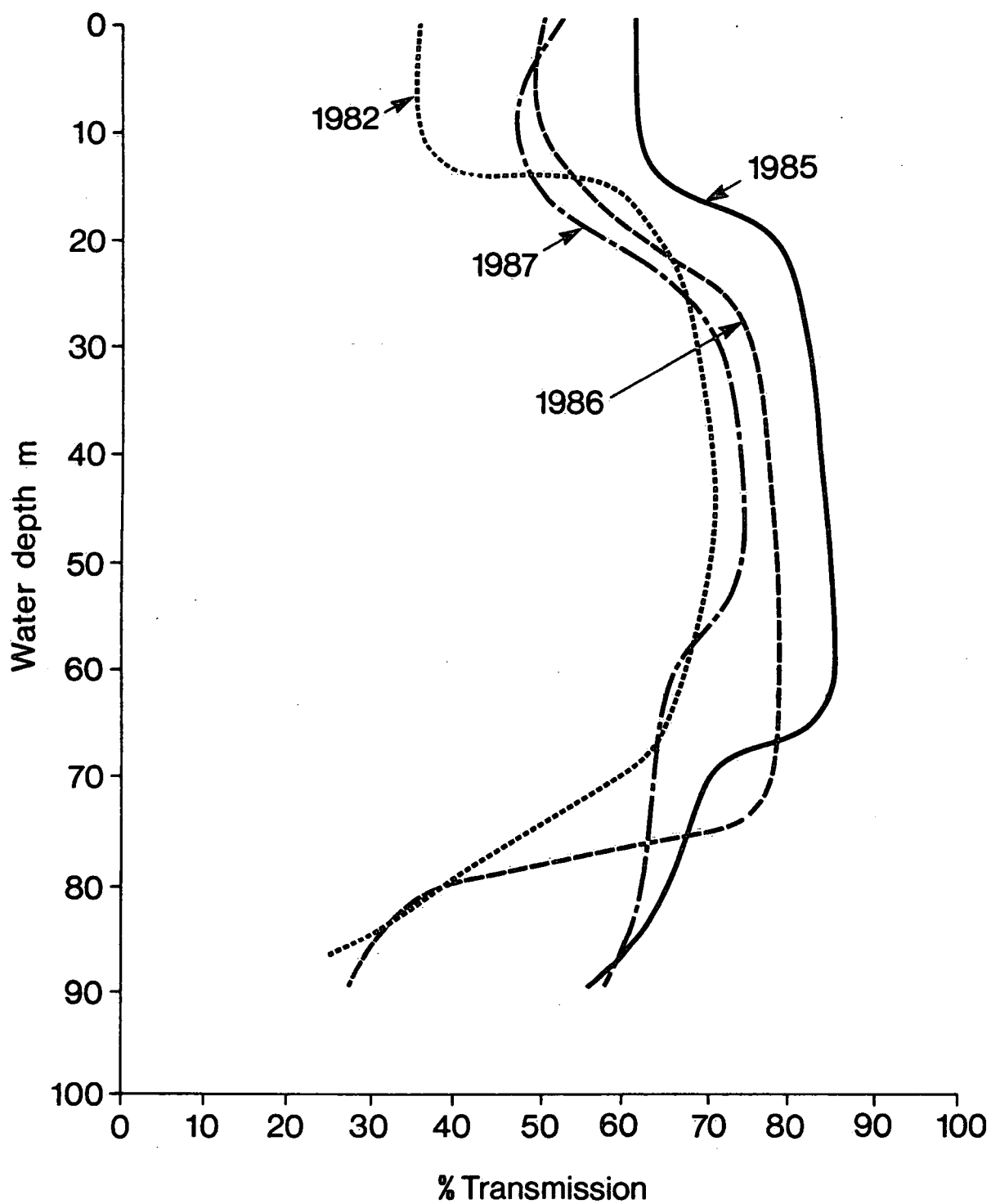


Fig. 3.

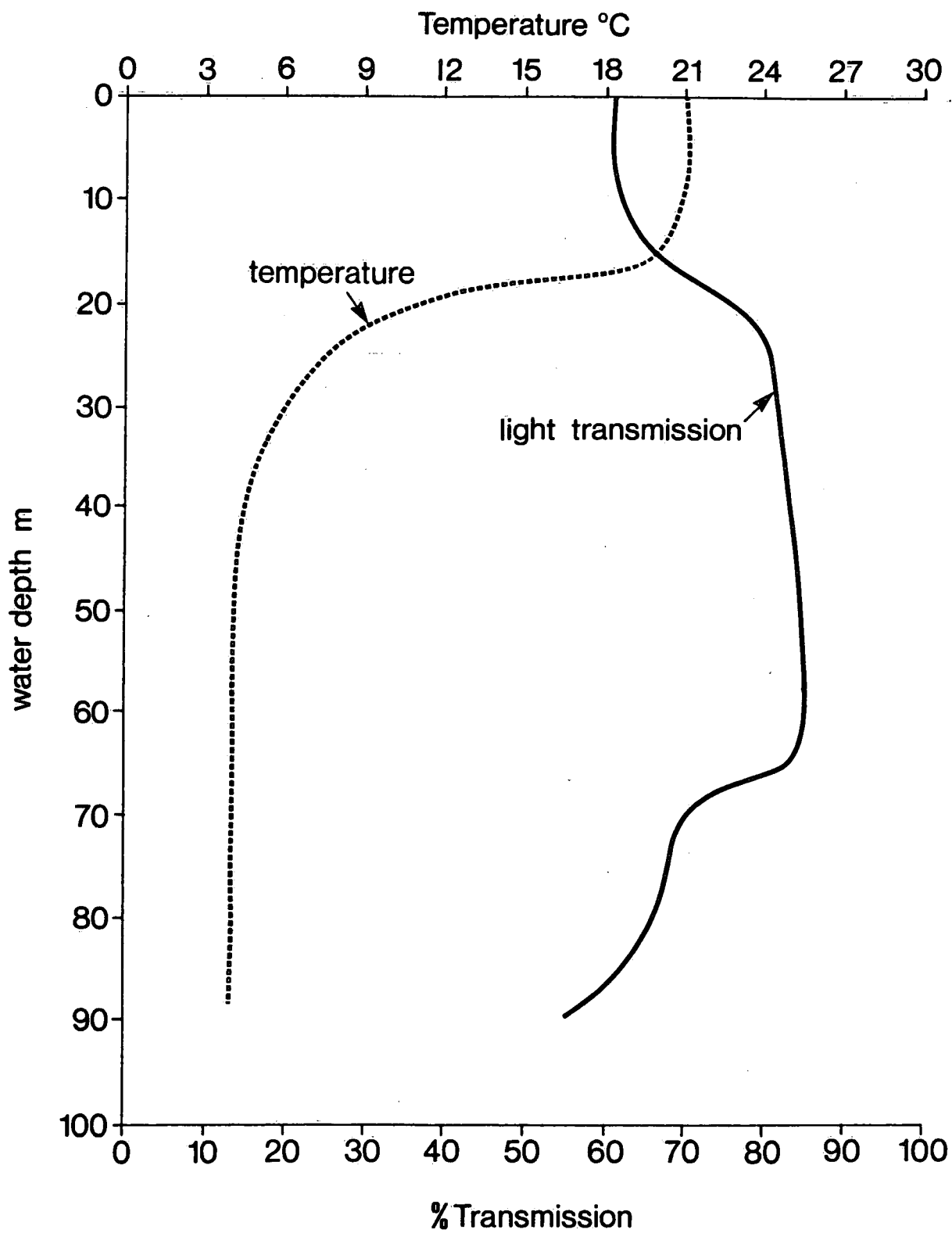
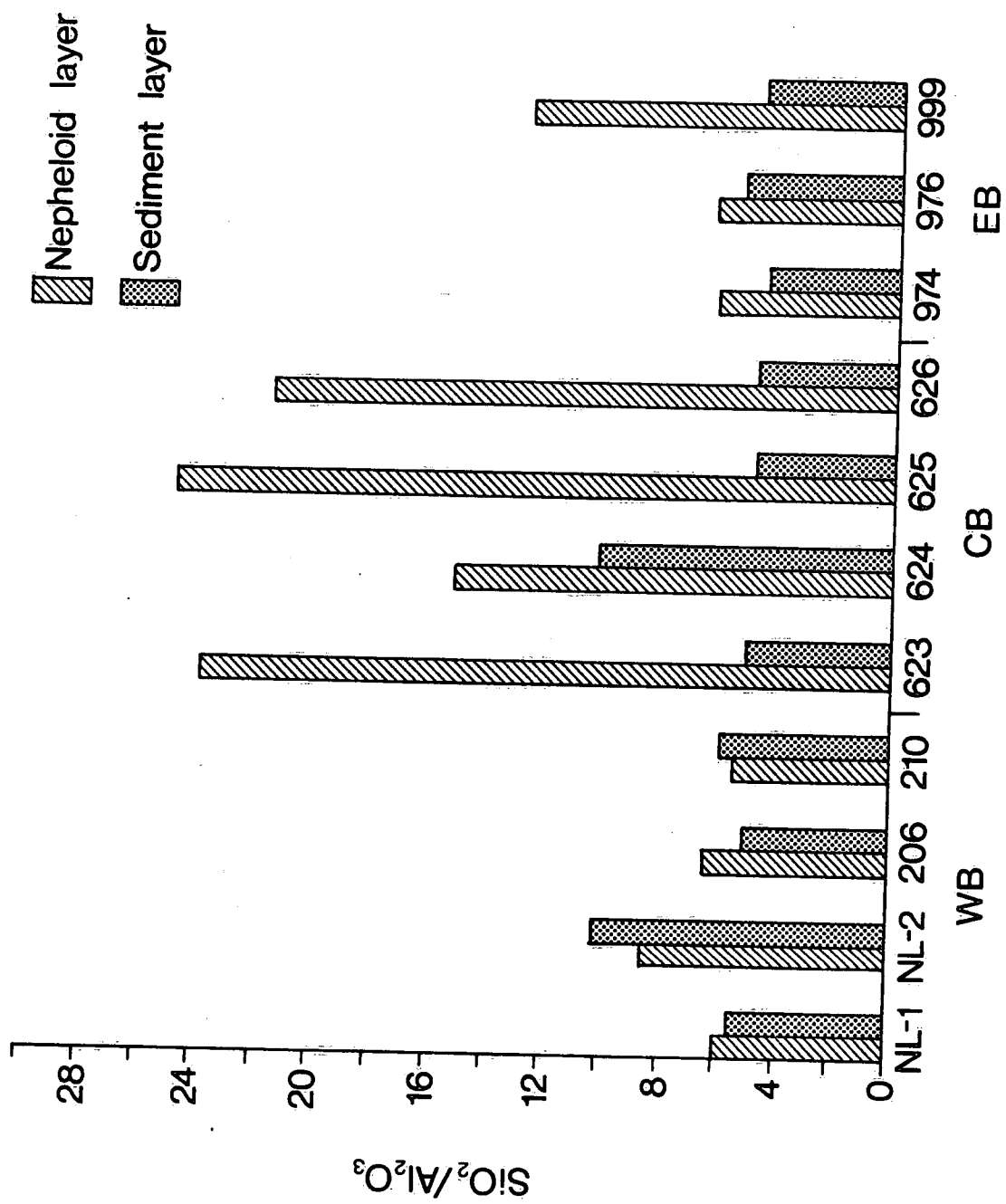


Fig. 4.



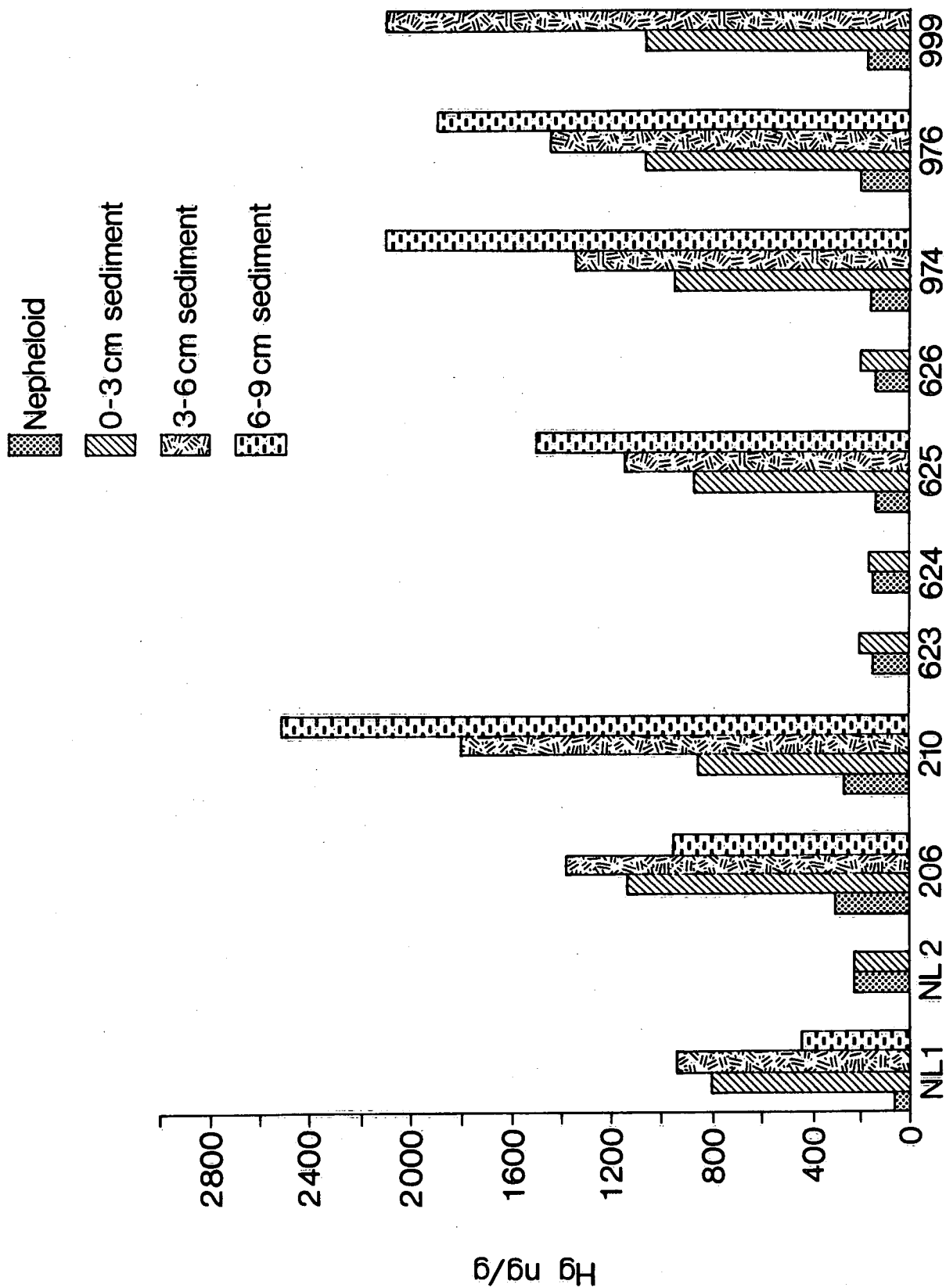
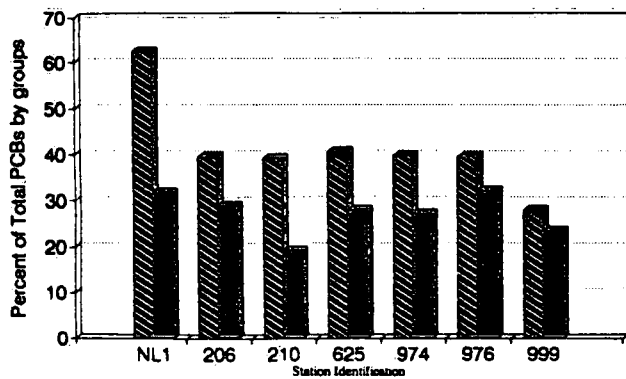
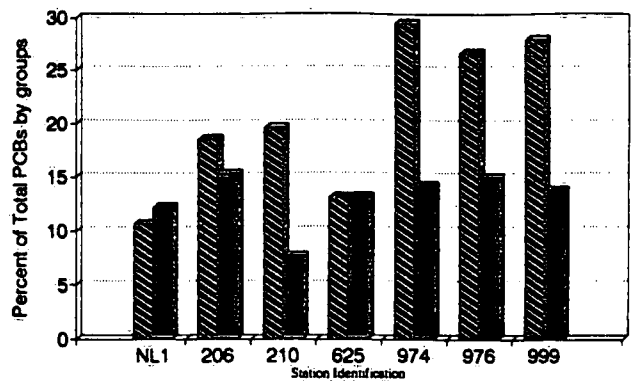


Fig. 6.

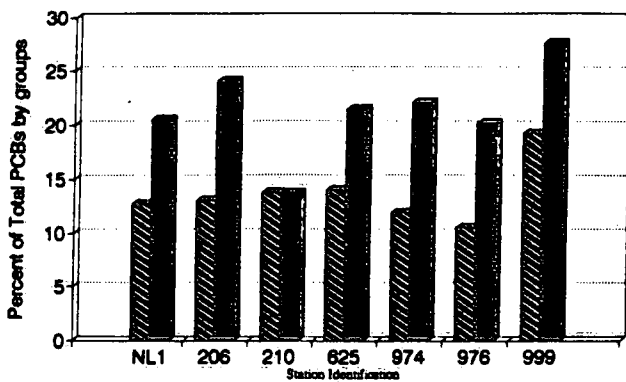
Tetrachlorobiphenyls



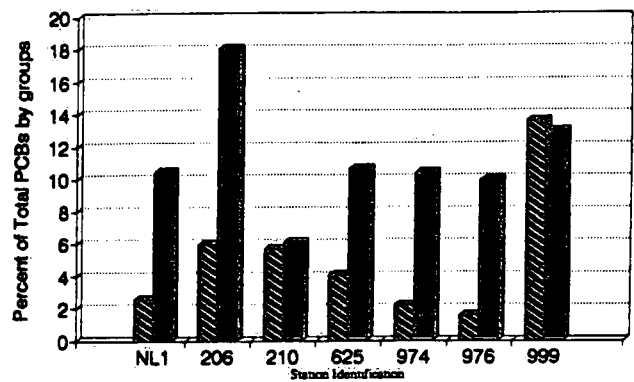
Pentachlorobiphenyls



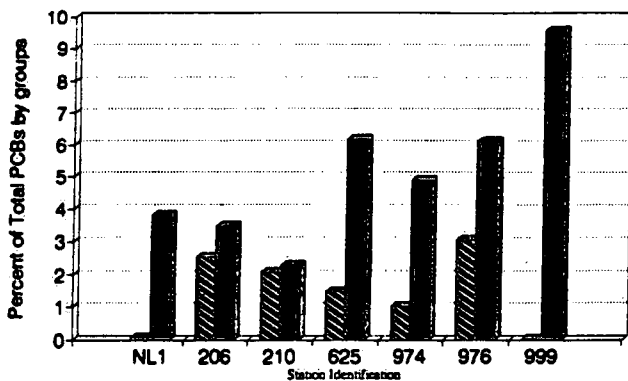
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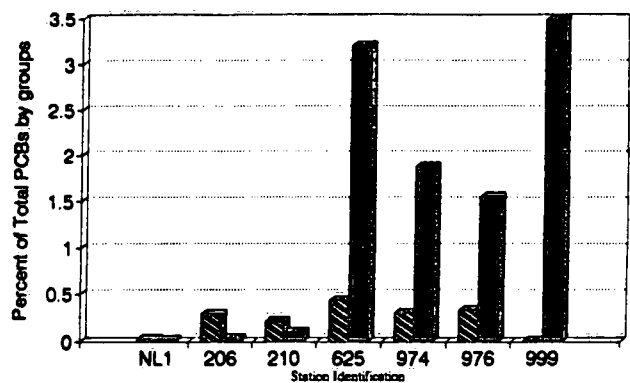
Heptachlorobiphenyls



Octachlorobiphenyls



Nonachlorobiphenyls



 nepheloid
  sediment

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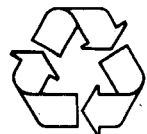
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