APPLICATION OF A FOOD CHAIN MODEL OF PCB ACCUMULATION TO THE STRIPED BASS OF THE HUDSON ESTUARY

Year 1
Final Report
to the Hudson River Foundation

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CONTENTS

Page

Figures iii

Tables. v

1. Introduction 1
    Background 1
    Goals and Objectives of Research 3
    Current Status 4

2. Data Analysis 6

    Hudson River Hydrograph 6
    Striped Bass PCB in Relation to Body Weight . . . 6
    Striped Bass PCB in Relation to Lipid Content . . 9
    Short Term Temporal Variations of Striped Bass PCB 9
    Striped Bass PCB in Relation to Location 14
    Water Column PCB Concentrations 19
    Sediment PCB Concentrations. 19

4. Food Chain Model 23

    Review of Previous Work 23
    Determination of the Model Parameters for
      the Striped Bass Food Chain 24
    Development of an Alternative Model 24

References 34

FIGURES

Number Page

1. Annual average PCB Aroclor 1016 and Aroclor 1254 in striped bass from the upper (mp. 40-150) and lower (mp. 0-40) Hudson River 2

2. Hudson River daily flow at Green Island 1975-1982 . . 8

3. Hudson River striped bass - NYSDEC 1978 - total PCB body burden vs. age 10

4. Annual average PCB Aroclor 1016 in Hudson River striped bass in relation to striped bass lipid content, 1975-1978. 11

5. Annual average PCB Aroclor 1016 in Hudson River striped bass in relation to striped bass lipid content, 1979-1982. 12

6. Hudson River striped bass - NYSDEC 1978 - Monthly variation of total PCB body burden for 1978 at four locations 13

7. Hudson River striped bass - NYSDEC 1978 - Monthly variation of weight for 1978 at four locations . . 13

8. Annual average spatial variation of PCB Aroclor 1254 in Hudson River striped bass for 1975-1978. 15

9. Annual average spatial variation of PCB Aroclor 1254 in Hudson River striped bass for 1979-1982. 16

10. Annual average spatial variation of PCB Aroclor 1016 in Hudson River striped bass for 1975-1978. 17

11. Annual average spatial variation of PCB Aroclor 1016 in Hudson River striped bass for 1979-1982. 18

12. Hudson River water column - USGS - yearly variation of total PCB for 1975-1984 at eight locations . . . 20

13. Annual average total PCB in the water column of the Hudson River between mile points 52.5 and 116 . . . 21

14. Spatial profile of surface sediment PCB in the Hudson River 22

15. Schematic of the simplified Hudson River striped bass food chain structure. 25

FIGURES (continued)

Number Page

16. Conceptual description of lipid-non-lipid food chain model 27

17. Variation in total PCB concentration (wet basis) with lipid content of yearling pumpkinseed collected in 1979 at three Hudson River locations: (o), Stillwater; (o) Albany; ( ), Newburgh. (Armstrong and Sloan, 1981) 30

18. Relationship between the depuration rate constant of various organic chemicals and the n-octanol/water partition coefficient 31

19. Relationship between the depuration rate constant of several chlorobiphenyls by goldfish and the n-octanol/water partition coefficient 32

TABLES

Number Page

1 Hudson River Data Sources. 7

SECTION 1

INTRODUCTION

Background

The striped bass, Morone saxatilis (Waldbaum) has been studied for a number of years as an important coastal and estuarine species (Setzler et al., 1980). Striped bass are a significant commercial and recreational resource on all coasts of the United States and especially so in the Hudson estuary. In recent years, the occurrence of trace levels of potentially toxic chemicals in the Hudson River, especially polychlorinated biphenyls (PCBs) has been observed. In particular, concentrations of PCB have been reported in the striped bass ranging up to 90 percentile levels of 65 μg PCB/g(w) (g(w) = grams wet weight) in fillets during the spring of 1978 (NYS, DEC data, 1978 compiled in Hydroscience, 1979).

These elevated concentrations of PCB in the striped bass of the Hudson estuary have thus been a matter of some concern for several years (Hetling et al., 1978 and Armstrong and Sloan, 1981). Concentrations greater than the allowable Food and Drug Administration (FDA) action level of 5 μg PCB/g(w) in the edible portion resulted in the closure of the fishery to commercial use. The action level has recently been lowered to 2 μg PCB/g(w). Dredging of upstream riverine PCB "hot spots" has been proposed to reduce upstream PCB concentrations and also contribute to the reduction of PCB in the striped bass of the estuary. Concern has also been expressed over the disposal of PCB contaminated dredge spoil in the New York Bight and the degree to which such a practice will contribute to the accumulation of PCB by the striped bass.

PCB concentrations appear to be declining in resident Hudson River fish (e.g. yellow perch, see Armstrong and Sloan, 1981), but a decline in the PCB of the striped bass is less clear. Data on striped bass (Figure 1) show a rapid decline of lower chlorinated PCB isomers (measured as Aroclor 1016) but a much smaller drop of the higher chlor-

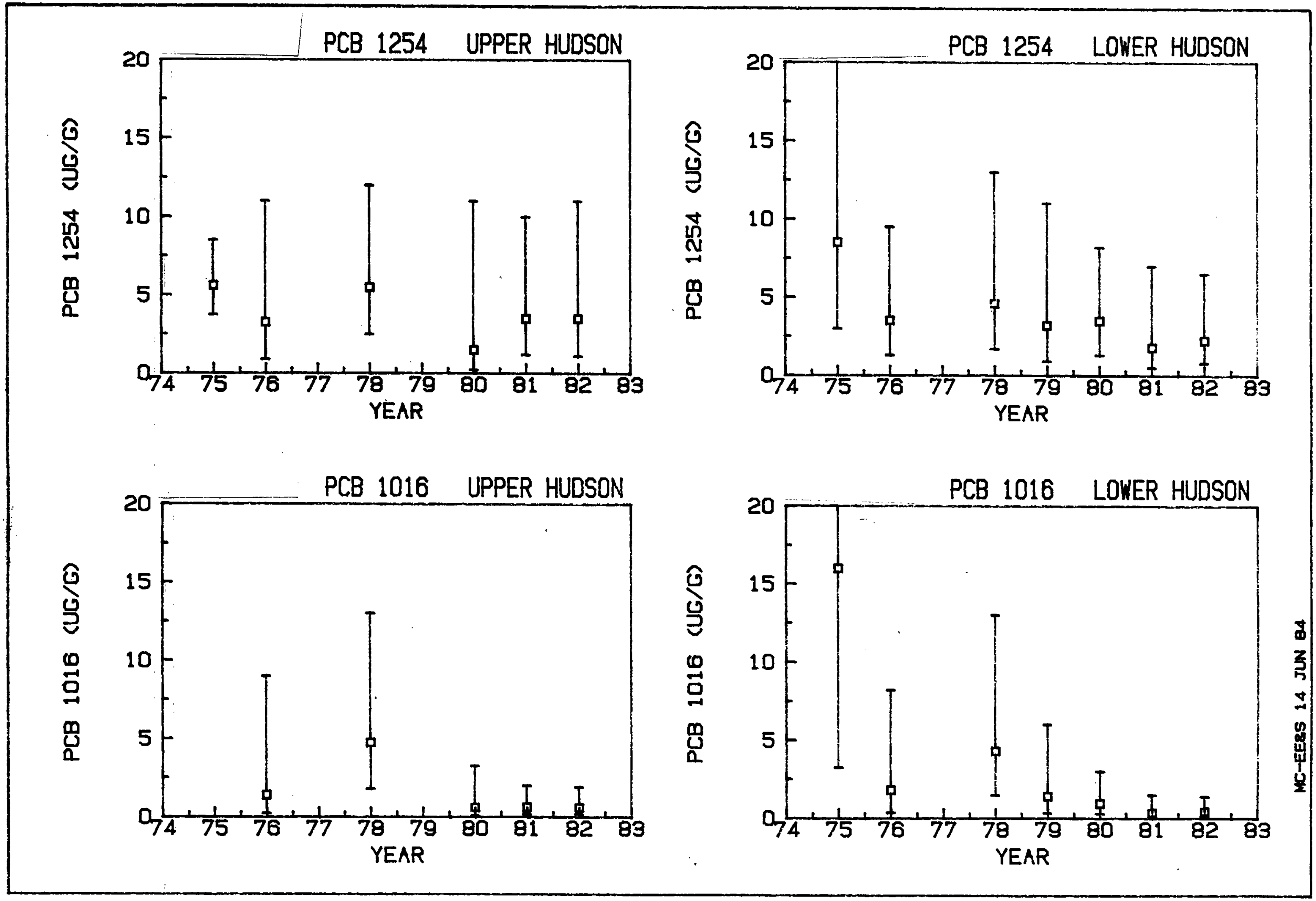


Figure 1. Annual average PCB Aroclor 1016 and Aroclor 1254 in striped bass from the upper (mp. 40-150) and lower (mp. 0-40) Hudson River.

inated isomers (measured as Aroclor 1254). There is considerable uncertainty as to the mechanisms that result in the observed PCB concentrations in the striped bass. Anadromous and resident populations, varying feeding habits and temporal variations in exposure to PCBs contribute to the relative lack of understanding of PCB in striped bass. Furthermore, the impact of observed PCB concentrations in the striped bass on reproduction, behavior and growth of the population is not known. Indeed, the routes by which the striped bass accumulate the PCBs (i.e., water and food) may influence the effect of PCB on the striped bass, both in terms of direct impact on the organism and in terms of the expected concentration of PCB in the striped bass for human consumption.

For example, the importance of food chain routes in the accumulation of PCB in top predators has been demonstrated in a) generalized calculations across diverse food chains (Thomann, 1981), b) detailed age dependent models of PCB in lake trout in Lake Michigan (Thomann and Connolly, 1982) and Kepone in the striped bass food chain of the James River (Connolly and Tonelli, 1984), and c) a preliminary model of PCB in the striped bass of the Hudson (Hydroscience, 1979). The relationships of PCB in the water and sediments of the Hudson estuary and the striped bass therefore have a high degree of relevance in managing this very significant marine resource.

Goals and Objectives of Research

In general, the goal of the research was to utilize the existing data on PCB concentrations in the striped bass, lower levels of the food chain, water column and sediment, apply the previously referenced food chain mathematical model to the accumulation of PCB in the striped bass, calibrate the model to the observed data and estimate resulting PCB concentrations in the striped bass under various assumed reductions in water PCB levels. The earlier work on the PCB model of the striped bass in the Hudson (Hydroscience, 1979) drew on data up through the spring of 1978. In this work, the data obtained since 1978 was to be incorporated and the additional insights from more recent work in food chain modeling of PCB (e.g. Thomann and Connolly, 1982; Connolly and Tonelli, 1984) were also to be included.

The objectives of this project were to:

a) Analyze the existing data base (on PCB concentrations in the striped bass, lower levels of the food chain, water column and sediment);

b) Apply a state of the art food chain toxicant model for the striped bass food chain of the Hudson estuary incorporating:

    i) the principal bioenergetics of the striped bass such as feeding habits, food consumption rates, growth and respiration rates,

    ii) the principal components of the food chain with which the striped bass interacts including the benthic component,

    iii) properties of PCB such as bioconcentration factors, assimilation efficiency and excretion rates;

c) Calibrate the striped bass model to the data base of PCB concentrations in the striped bass using observed sediment and water column concentrations as input;

d) Explore the sensitivity of the model to the various factors affecting the striped bass accumulation of PCB, such factors to include time spent in the estuary and New York Bight, contribution of PCB contaminated benthic organisms to striped bass body burden, and water versus food chain uptake;

e) Project the response of the PCB body burden of the striped bass to various scenarios in sediment and water PCB concentrations representing varying management alternatives, such as dredge spoil disposal, upbasin control and direct source control.

Current Status

The first year of this project was largely devoted to compilation and analysis of data. This effort included the development of a reference library of publications dealing with PCB and the Hudson River fishery and the establishment of a data base containing Hudson River PCB and water quality data.

Three data base systems were utilized to provide maximum capability for data analysis. An HP-86 microcomputer was used to process data obtained in hardcopy form including:

1) USGS water column PCB concentrations
2) Fish PCB concentrations compiled by Hydroscience, Inc.(1979)
3) Sediment PCB concentrations reported by Richard Bopp (1979)

Data obtained on magnetic tape from NYS-DEC was processed on the Manhattan College VAX 11/780 computer using the SPSS-X statistical data base management system. Data in the US EPA STORET system was retrieved in hard copy. All three systems have statistics and graphics capabilities which were utilized for data analysis and presentation.

A majority of the available PCB data has been compiled. Analyses of this data include:

1) relationship between PCB concentration and organism weight
2) relationship between PCB concentration and organism lipid content
3) relationship between organism lipid content and weight
4) relationship between organism PCB concentration and space and time
5) relationship between water column PCB concentration and space and time
6) relationship between surface sediment PCB concentration and space and time

Application of an existing food chain model to the Hudson River striped bass food chain was begun with focus on determination of values for the parameters needed by the model and evaluation of the adequacy of the existing model.

SECTION 2

DATA ANALYSIS

The data analyzed in year 1 of this project consist of; 1) striped bass PCB residues, 2) sediment PCB concentrations, 3) water column PCB concentrations, and 4) USGS Hudson River flows. Plots have been developed to study trends in space and time and to quantify relationships between PCB concentration and various parameters. The data sources are shown in table 1.

Hudson River Hydrograph

Figure 2 presents the annual daily Hudson River flow hydrograph at the USGS Green Island gaging station for 1975 to 1982. This gage which is immediately upstream of the Troy lock and dam and 0.5 miles downstream from the fifth branch of the Mohawk River records the flow from the 8090 square mile upstream drainage area. The average annual flow for the available period of record (1946 to 1982) is 13,715 cubic feet per second (cfs). This translates to an average annual runoff of approximately 1.7 cfs/square mile. The average annual flows for 1975 to 1981 range from a low in 1980 of 9714 cfs to a high in 1977 of 19,160 cfs. For this period the peak flow was over 150,000 cfs in 1977. The seasonal variation of the hydrographs show a classical peak flow period in the spring with low flows in the summer-early fall period. The magnitude of flow effects the water column PCB concentration. From low to medium flows the concentration is diluted whereas at higher flows the scouring of bed material results in an increase in water column concentration.

Striped Bass PCB in Relation to Body Weight

Plots of the 1978 NYSDEC data do not indicate any consistent relationship between PCB concentration and striped bass body weight (Connolly et al., 1984). Because predatory species in other systems

TABLE 1. HUDSON RIVER DATA SOURCES

Parameter	Agency	Time Period	Geographical Extent	No. of Sampling Stations
Flow	USGS	1975-1982	Green Island (mp 154)	1
Fish PCB	NYSDEC	1975-1982	George Washington Bridge (mp 16) to above feeder dam (∿ mp 200)	10
American Shad PCB	NYSDOH	1977	Poughkeepsie (mp 76) to Tappan Zee (mp 34)	2
Striped Bass PCB	NYU	Fall 1982-Spring 1983	Stony Pt. (mp 40) to Canal St. (mp 1.5)	4
Water Column PCB	USGS	1977-1983	mp 198-mp 52.5	10
Water Column PCB	O'Brien & Gere( )	1978-1979	Poughkeepsie NY and Waterford NY water intakes	2
Sediment PCB	NYSDEC	1976-1978	Upper Hudson	
Sediment PCB	Bopp (1977)	1974-1977	Albany-NY Harbor	
Sediment PCB	West & Hatcher(1980)	1973	New York Bight	27
Sediment PCB	Bohm( )		New York Bight	

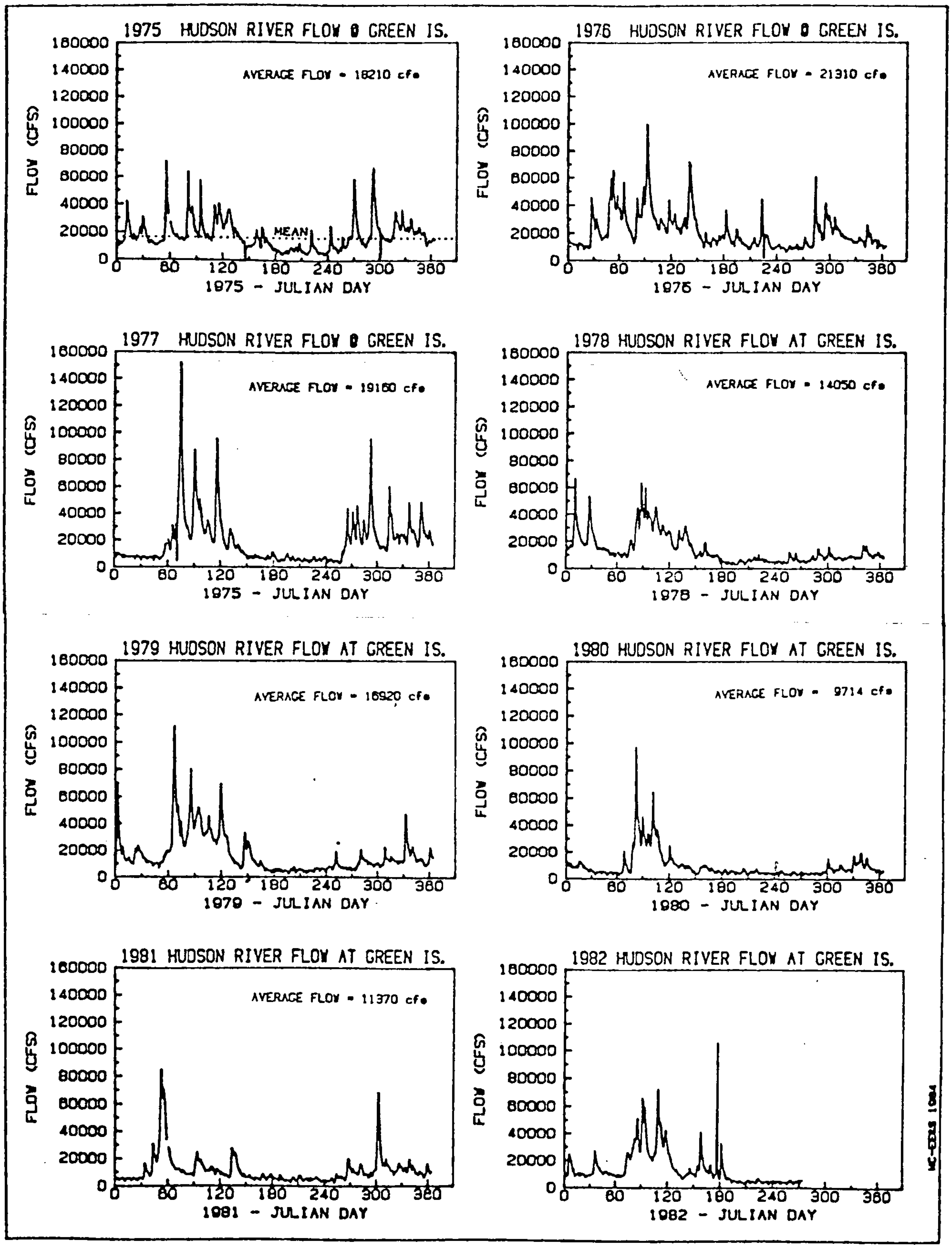


Figure 2. Hudson River daily flow at Green Island 1975-1982

contaminated by PCB exhibit a consistent increase in PCB concentration with weight (e.g. lake trout in Lake Michigan; Thomann and Connolly, 1982), the apparent absence of such a relationship with the striped bass is surprising. Sectioning by age class to examine concentration-weight relationships separately for juvenile and adult fish indicates that PCB concentration does increase with size up to 4 year old fish (Figure 3). This suggests that the annual migration of adult members of the population to the Atlantic Ocean lowers their overall exposure relative to resident members of the population.

Striped Bass PCB in Relation to Lipid Content

A small increase in PCB concentration with increasing % lipid has been shown for striped bass (Hydroscience, 1979). However, the influence of lipid content on PCB concentration is much less than that seen for other species. A strong relationship may not be apparent in the data because of other factors influencing PCB concentration such as body weight and migration. Plots of the NYSDEC data for each year indicate a similar weak relationship to that found by Hydroscience (Figures 4 & 5). Further analysis of this data should be conducted to determine if an underlying relationship between lipid and PCB concentration does exist. PCB concentration should be compared to % lipid to for each individual age class to remove the effects of striped bass size and migration.

Short Term Temporal Variations of Striped Bass PCB

Examination of measured striped bass PCB concentrations at individual sampling locations at several sampling times within the same year indicates significant short term variability. Figure 6 presents striped bass PCB concentrations during Spring 1978 at Hudson River miles 10, 25, 44 and 75. At river mile 10 in the New York Harbor area concentrations decline from approximately 35 μg/g in mid-April to 18 μg/g in mid-May while concentrations at river mile 25 increase from about 7 μg/g to 12 μg/g between late March and early May. At river

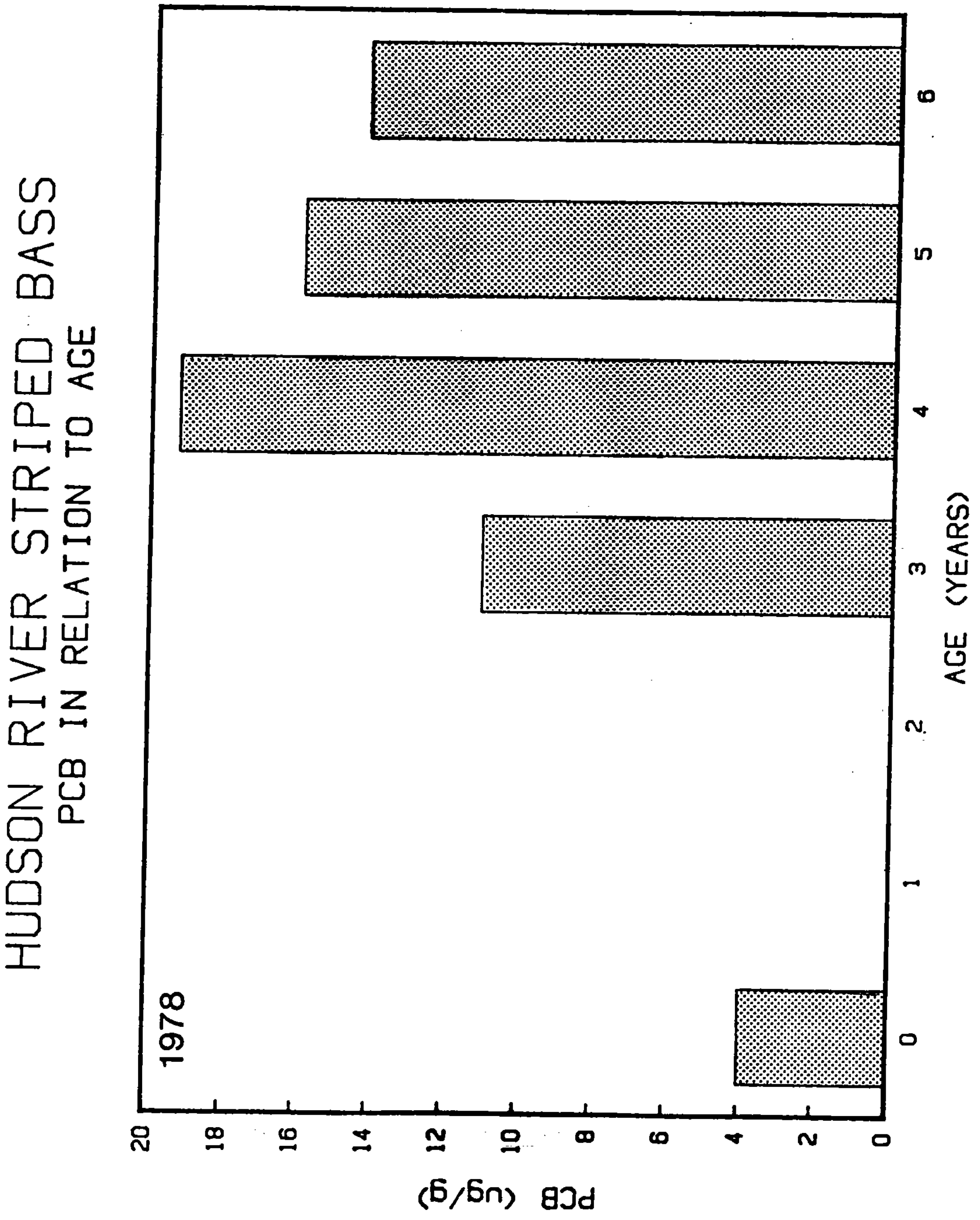


Figure 3. Hudson River striped bass - NYSDEC 1978 - total PCB body burden vs. age.

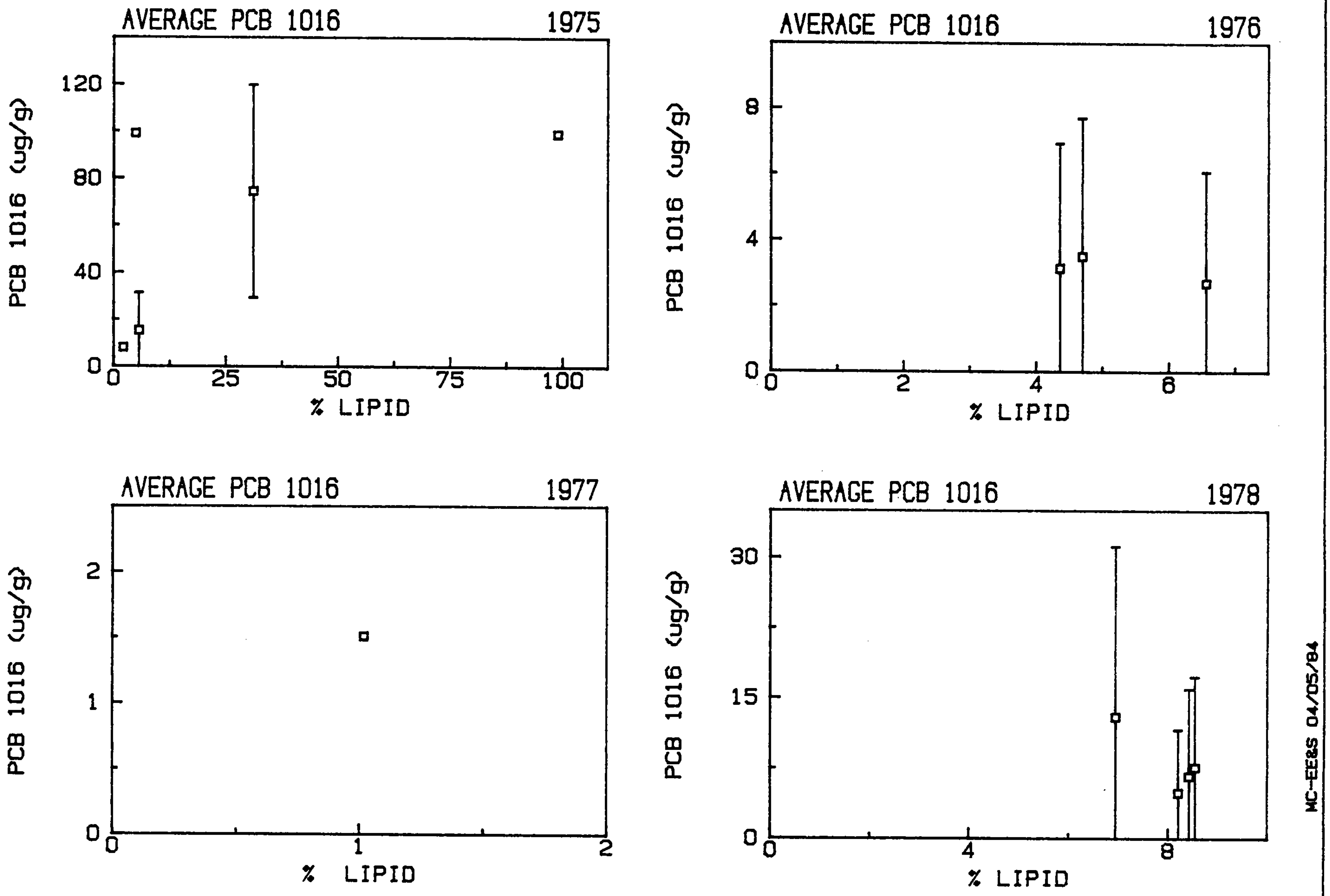


Figure 4. Annual average PCB Aroclor 1016 and Aroclor 1254 in Hudson River striped bass in relation to striped bass lipid content, 1975-1978.

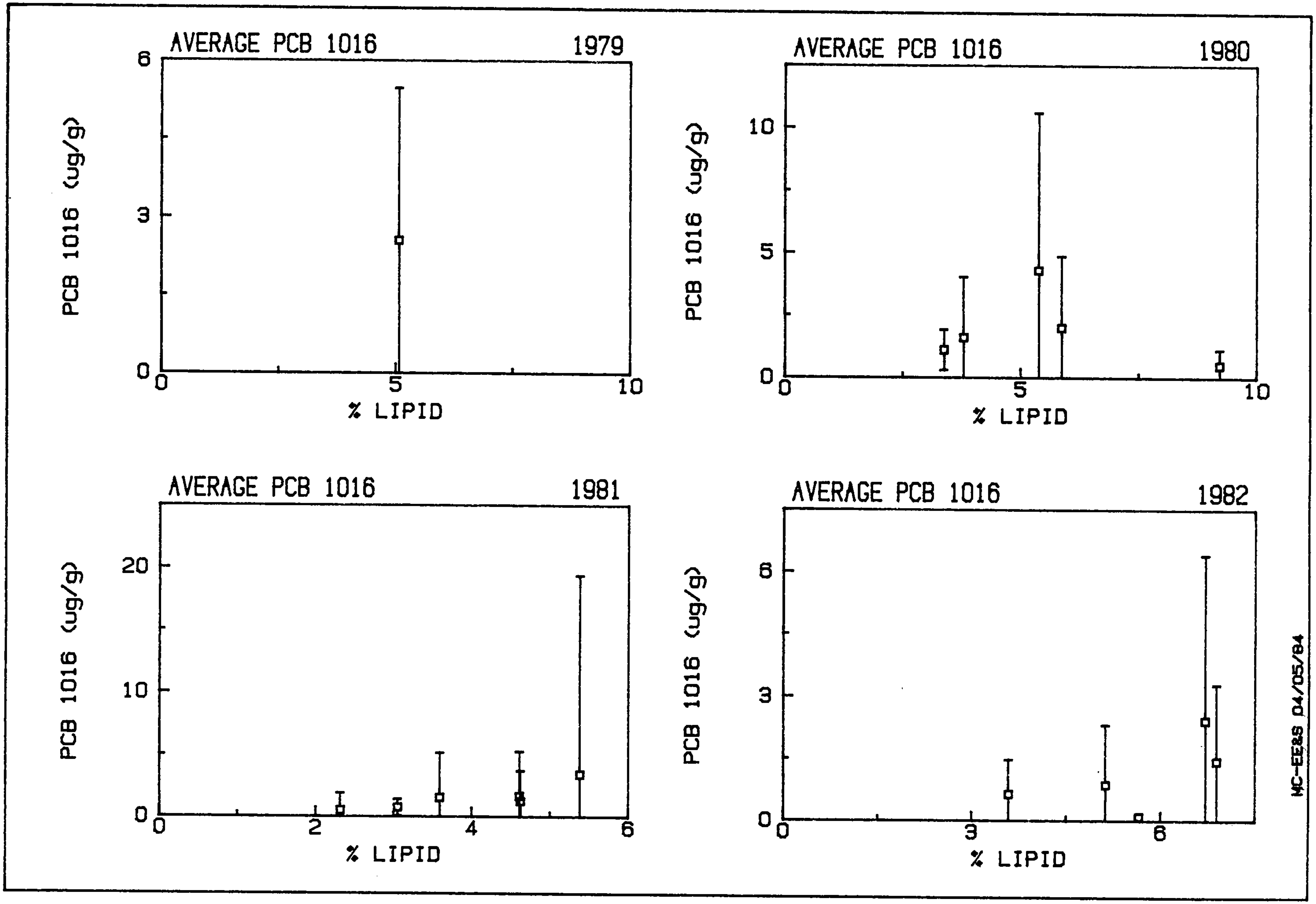


Figure 5. Annual average PCB Aroclor 1016 and Aroclor 1254 in Hudson River striped bass in relation to striped bass lipid content, 1979-1982.

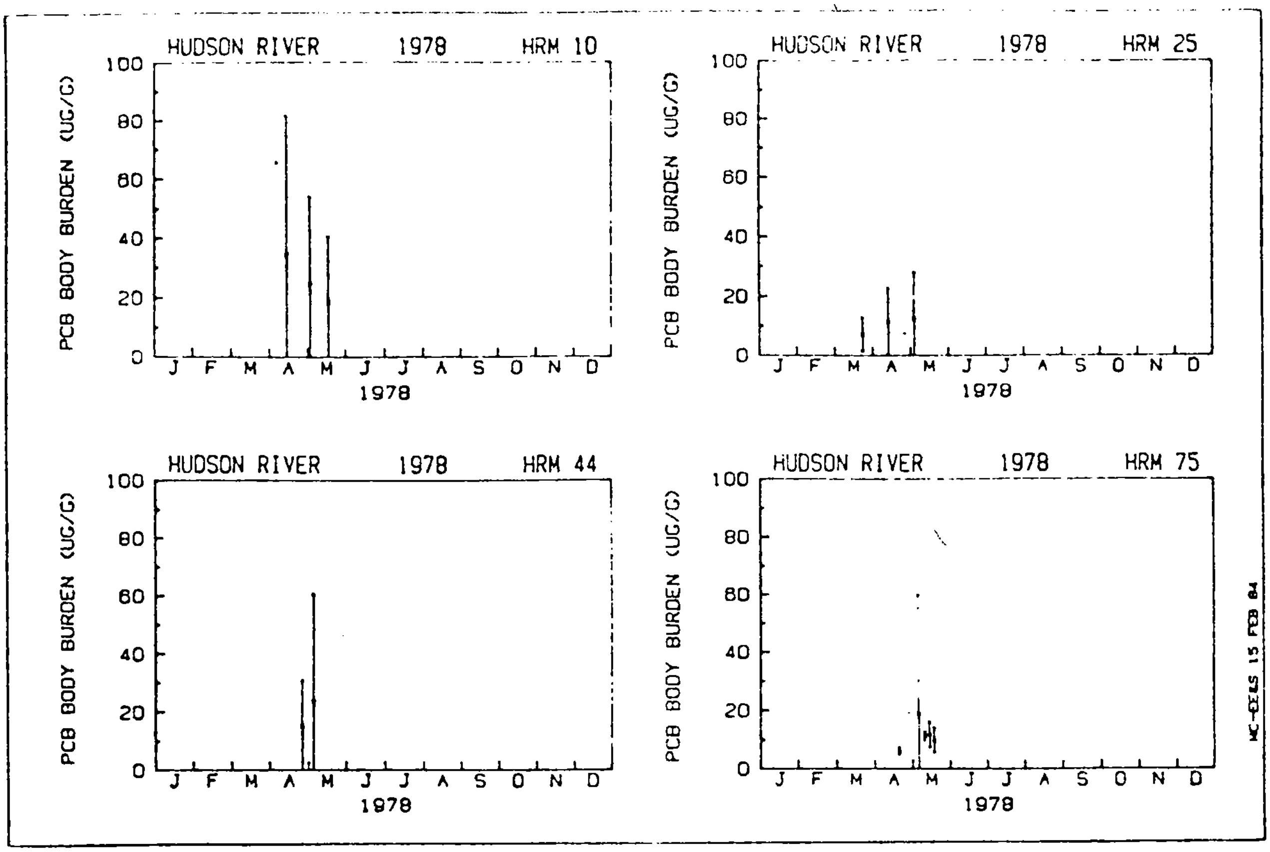


Figure 6. Hudson River striped bass - NYSDEC 1978 - Monthly variation of total PCB body burden for 1978 at four locations

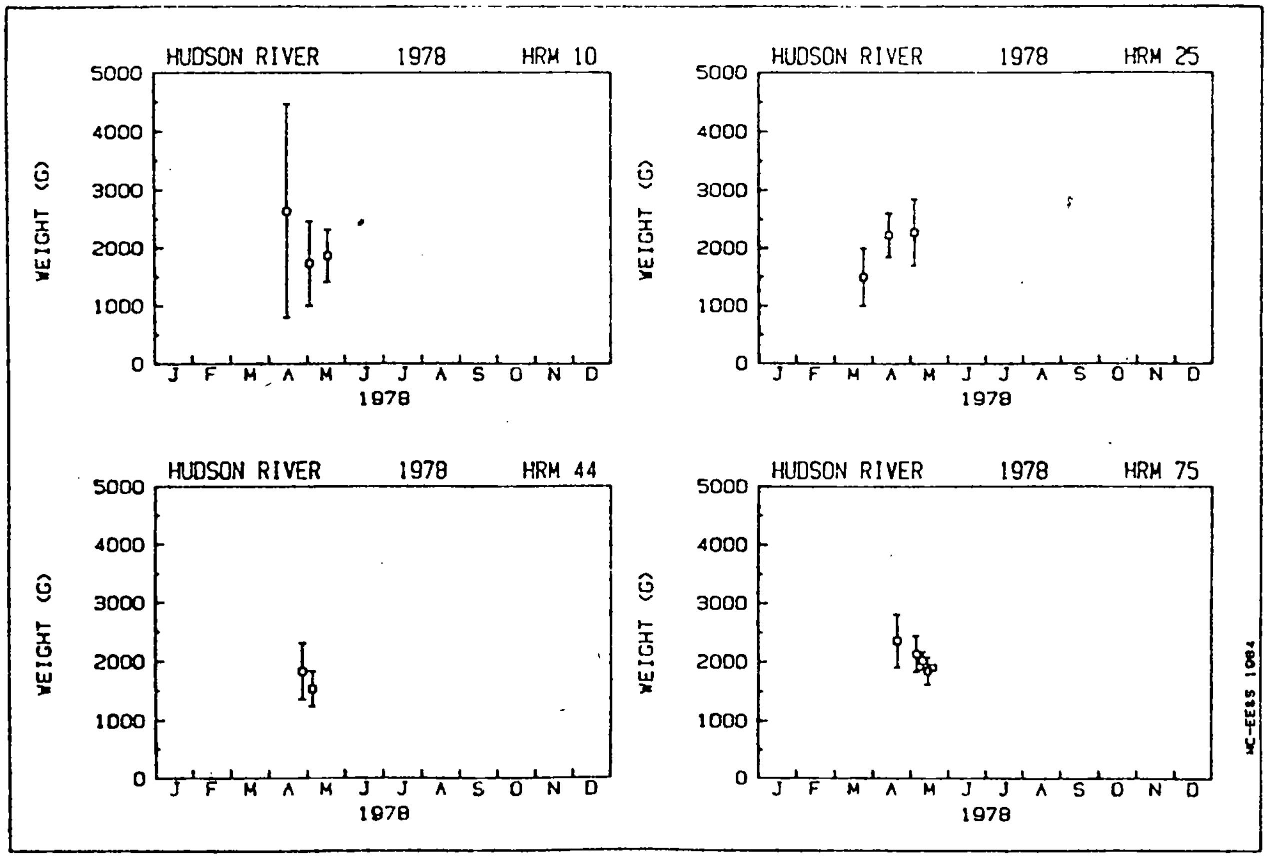


Figure 7. Hudson River striped bass - NYSDEC 1978 - Monthly variation of weight for 1978 at four locations

mile 44 an increase from 15 μg/g to 23 μg/g occurs between late April and early May.

Although statistical variability probably accounts for some of the noted change, the consistent trend apparent at river miles 10 and 25 may be explained by striped bass movements within the river. During spring juvenile bass move downstream while older fish which have overwintered in the deeper waters of the lower estuary and harbor area begin to move upstream to spawning grounds. Assuming adult fish generally have higher PCB concentrations than young fish, this movement would be reflected in changes in measured PCB concentrations at the lower estuary sampling sites. An examination of the weight of fish sampled at each site (Figure 7) indicates a decline in weight at river mile 10 and an increase at river mile 25. These changes are consistent with the expected movement of the striped bass and support the hypothesis for the observed PCB trend.

The apparent significance of striped bass movement with regard to PCB concentration measured at individual sampling sites indicates that the age distribution of the fish sampled at a site must be considered in the use of the data. This factor will be considered further in the analysis of the remaining striped bass data.

Striped Bass PCB in Relation to Location

As indicated in the discussion of short term temporal changes of striped bass PCB at individual sampling points, significant changes occur in time, possibly due to striped bass movements within the estuary. These changes tend to confound any analysis of the spatial variability of striped bass PCB. Figures 8-11 indicate that there is no consistent trend of PCB concentration relative to distance in any of the years sampled. However, 1977 exposure concentrations of PCB, as indicated by surface sediment PCB, increase by a factor of two to four moving upstream from N.Y. Harbor for the same distance. The data do not reflect this exposure variation because of the striped bass movements and the averaging of different age fish which have differing exposure histories.

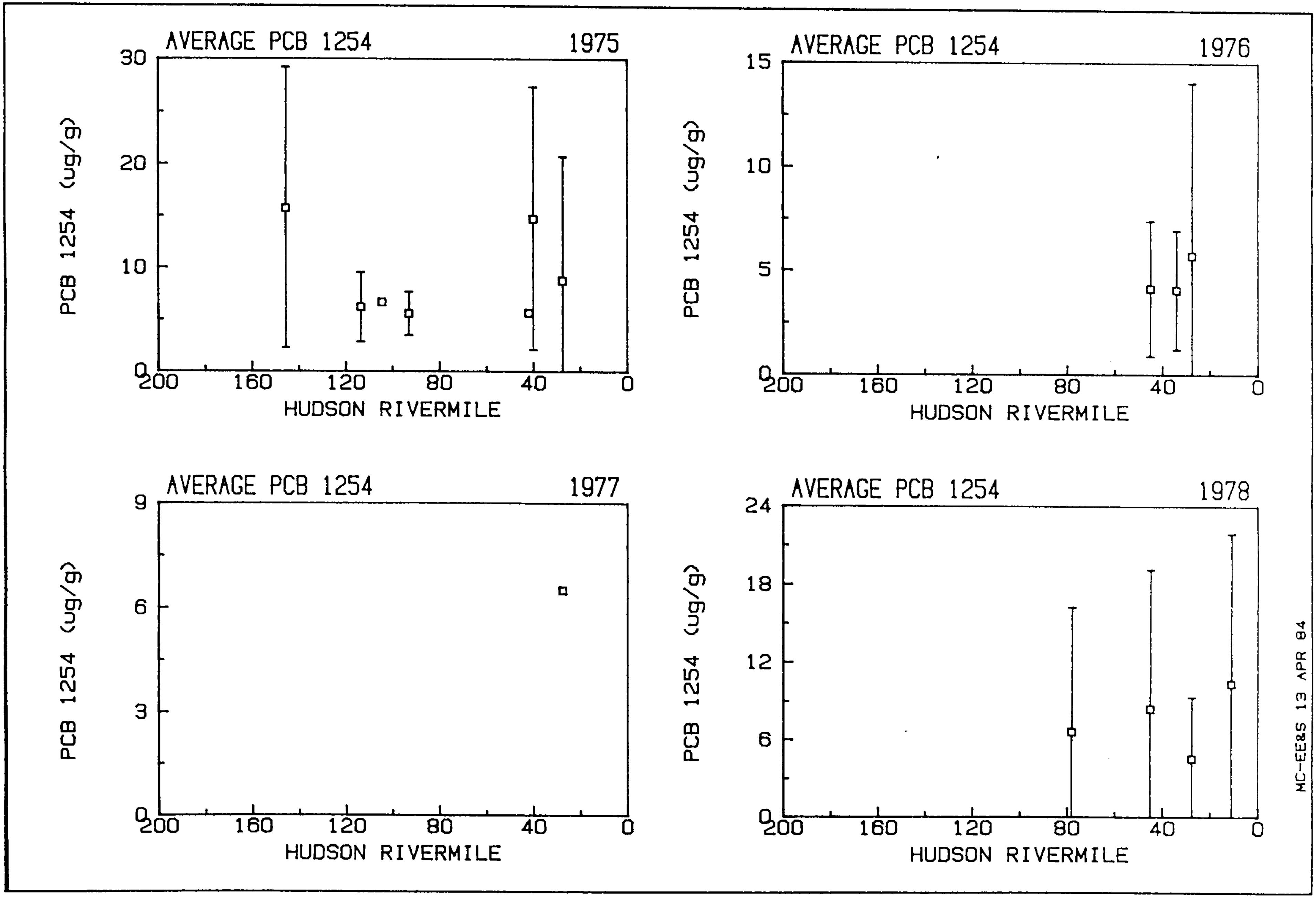


Figure 8. Annual average spatial variation of PCB Aroclor 1254 in Hudson River striped bass for 1975-1978.

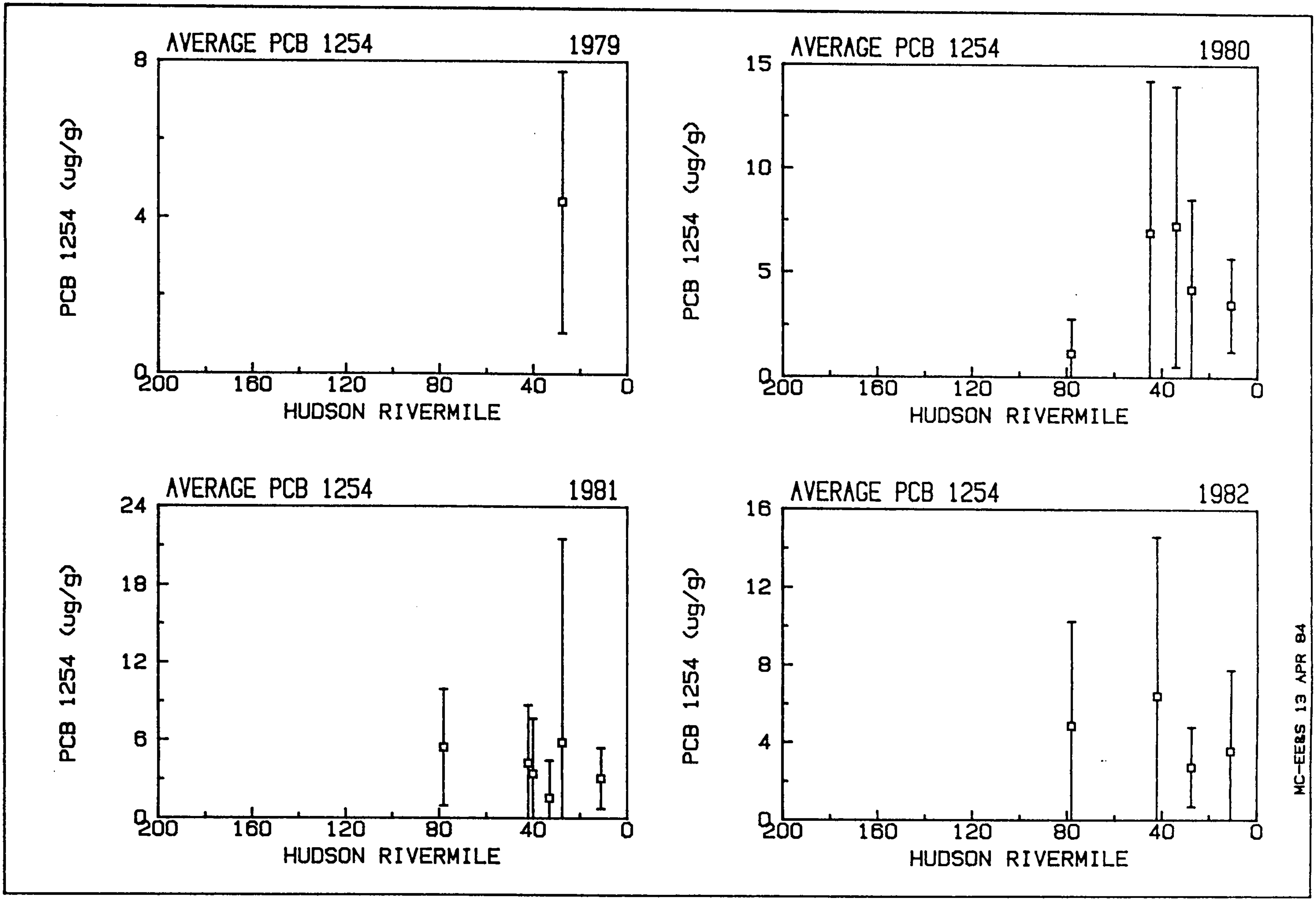


Figure 9. Annual average spatial variation of PCB Aroclor 1254 in Hudson River striped bass for 1979-1982.

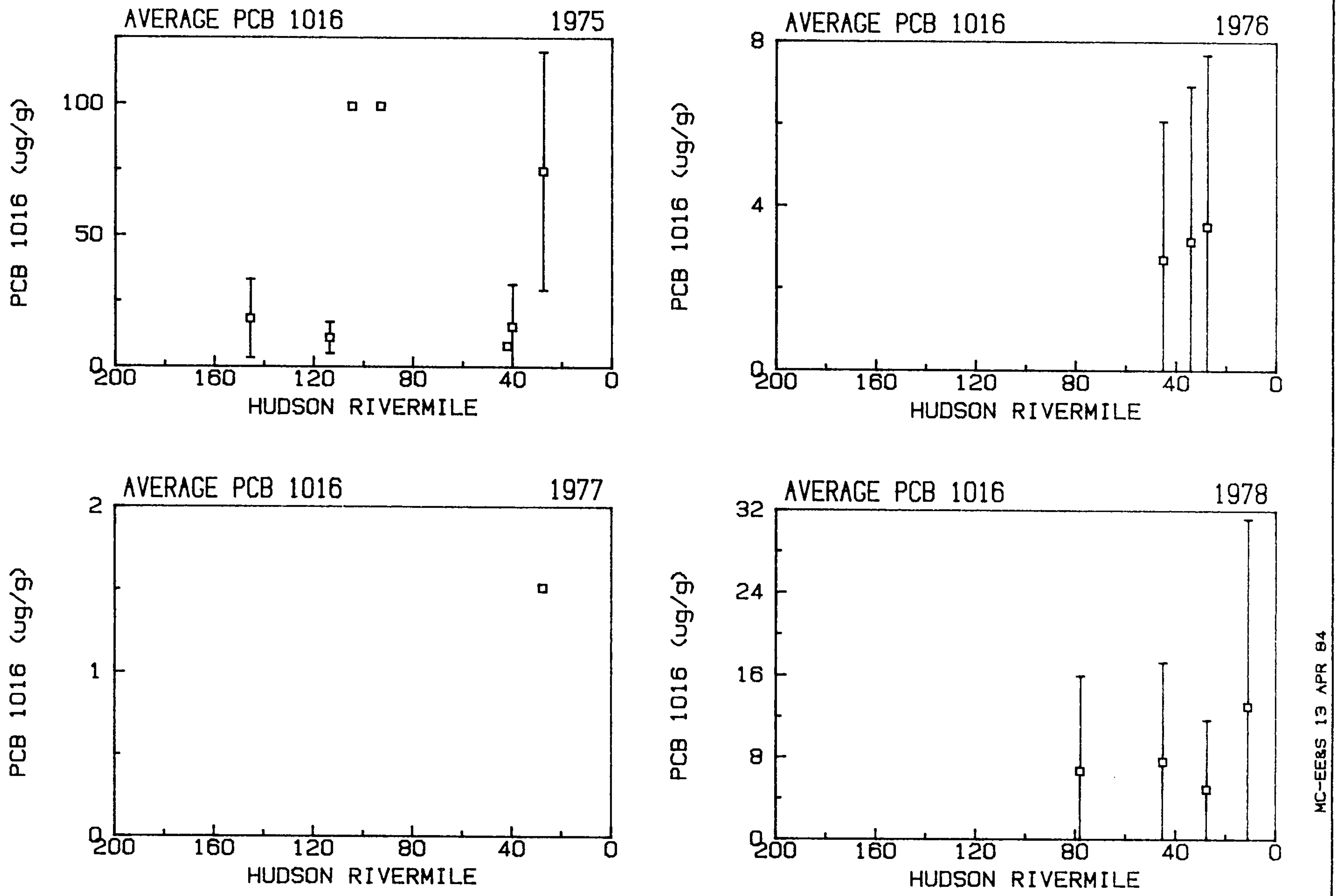


Figure 10. Annual average spatial variation of PCB Aroclor 1016 in Hudson River striped bass for 1975-1978.

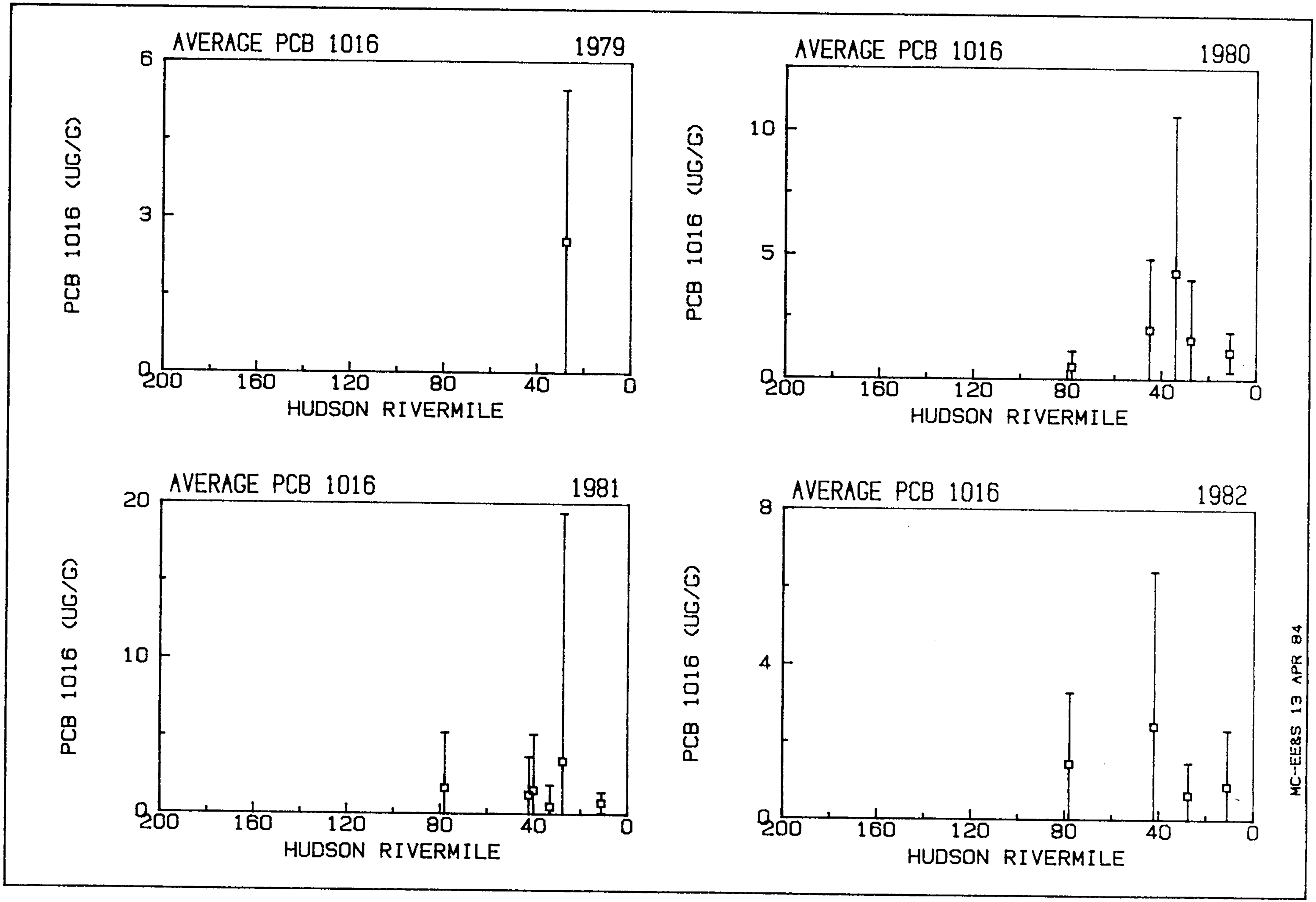


Figure 11. Annual average spatial variation of PCB Aroclor 1016 in Hudson River striped bass for 1979-1982.

Water Column PCB Concentrations

Total PCB concentration in the water column plotted in relation to time for several sampling locations (Figure 12) indicates a general decline over the period of record. Substantial concentration variability is evident reflecting variations in river flow and the associated dilution at low flow and scour of sediment PCB at high flow. From 1978 to 1983 concentrations appear to have declined by a factor of two to ten.

To assess water column PCB concentrations in the lower Hudson the data for the lowest three stations (m.p. 52.5, 96, and 116) were averaged. These averages indicate a rapid decline in concentration over the period 1978 to 1981 from a mean of 0.16 μg/ℓ to 0.05 μg/ℓ (Figure 13).

Sediment PCB Concentrations

In analyzing the sediment PCB data only data for the near surface region (0-10 cm) was considered. This region was operationally chosen as the active zone contributing PCB to benthic infauna. Using data presented by Bopp (1977) a spatial profile of sediment PCB was developed (Figure 14). A general decline in concentration in the seaward direction is evident. However, considering the saline and non-saline regions separately reveals fairly uniform concentrations in each. In the saline zone (mp 0-40) sediment PCB is in the order of 2-3 μg/g. In the non-saline zone, concentrations are in the order of 5-15 μg/g. This separation of sediment PCB into two zones provides a convenient segmentation of the food chain model.

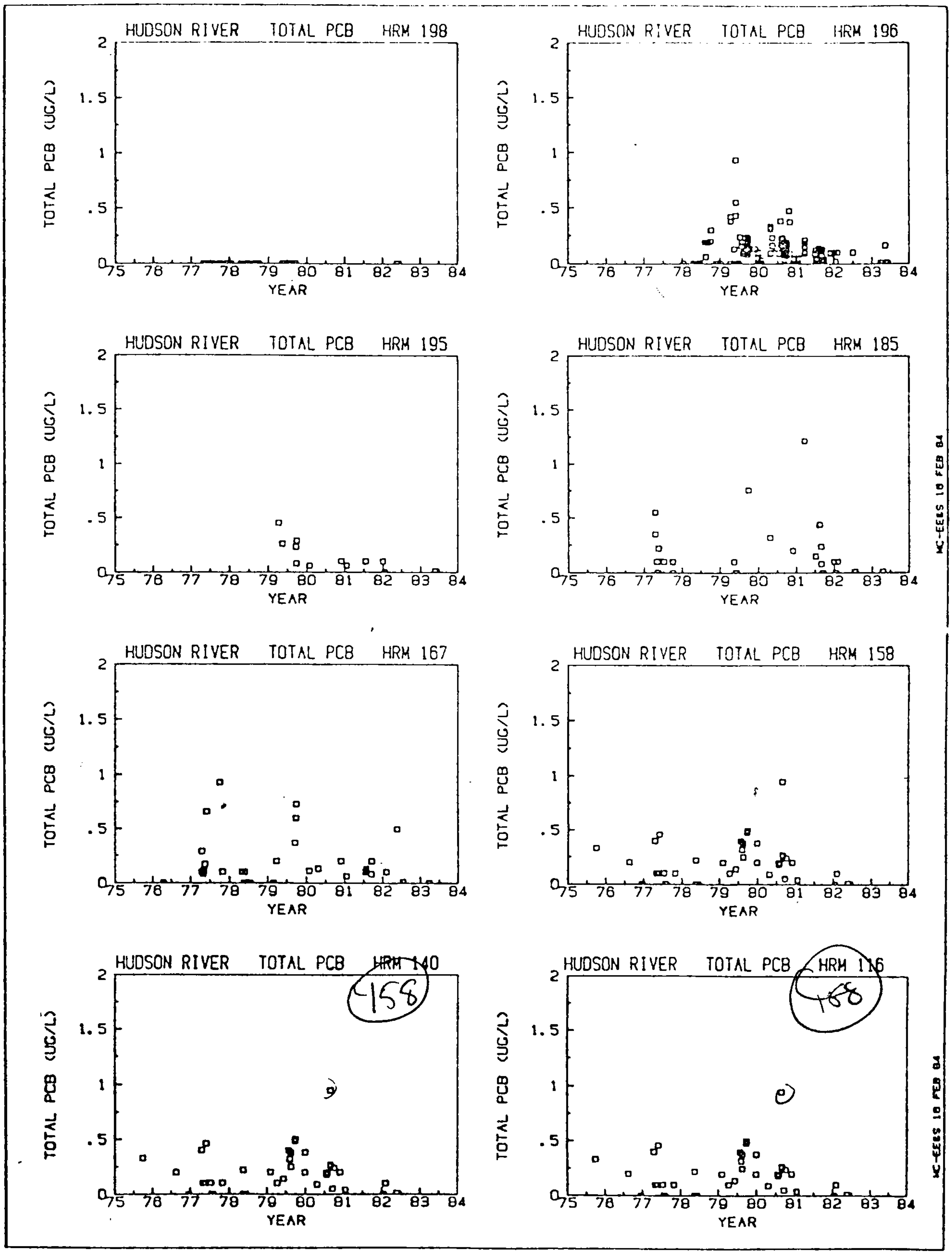


Figure 12. Hudson River water column - USGS - yearly variation of total PCB for 1975-1984 at eight locations

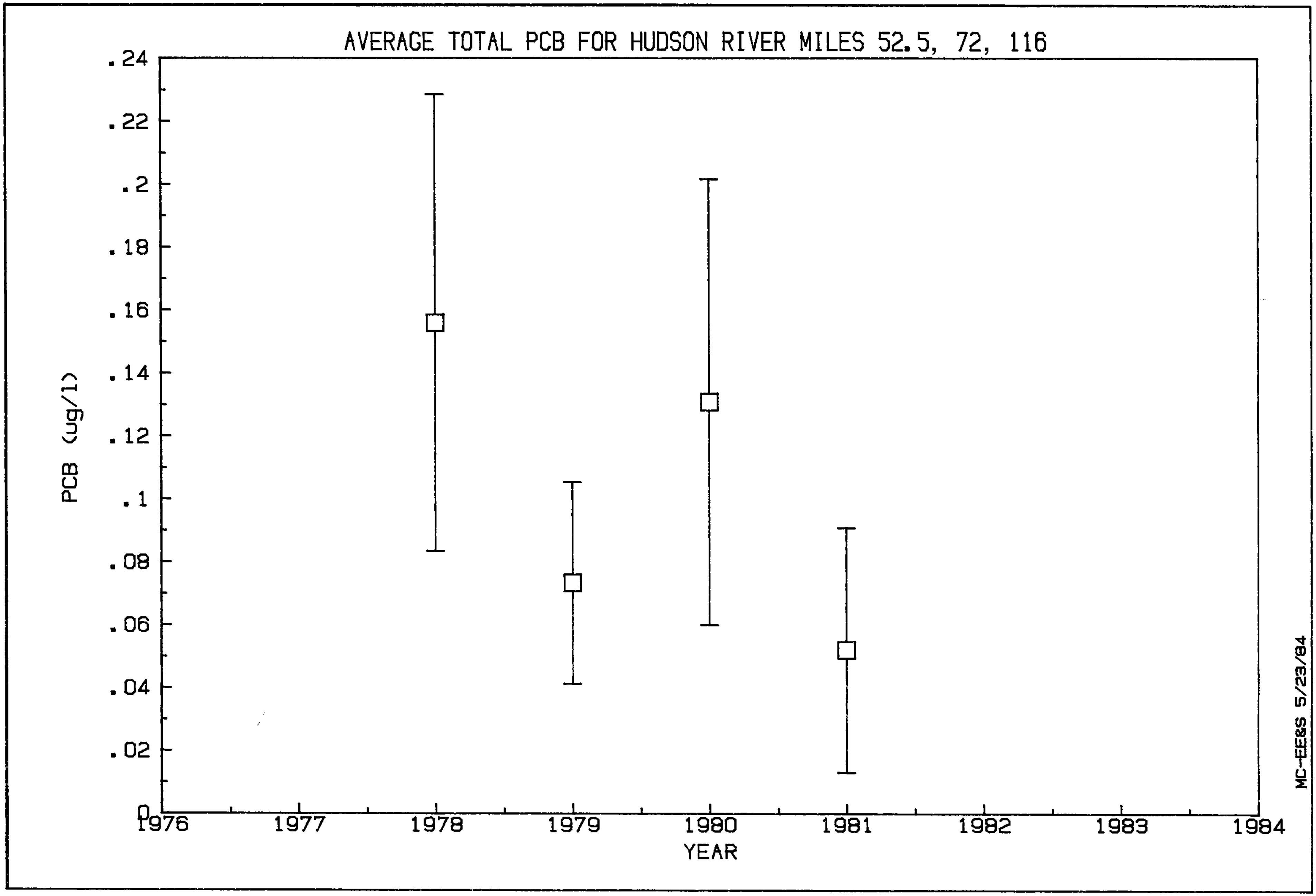


Figure 13. Annual average total PCB in the water column of the Hudson River between mile points 52.5 and 116.

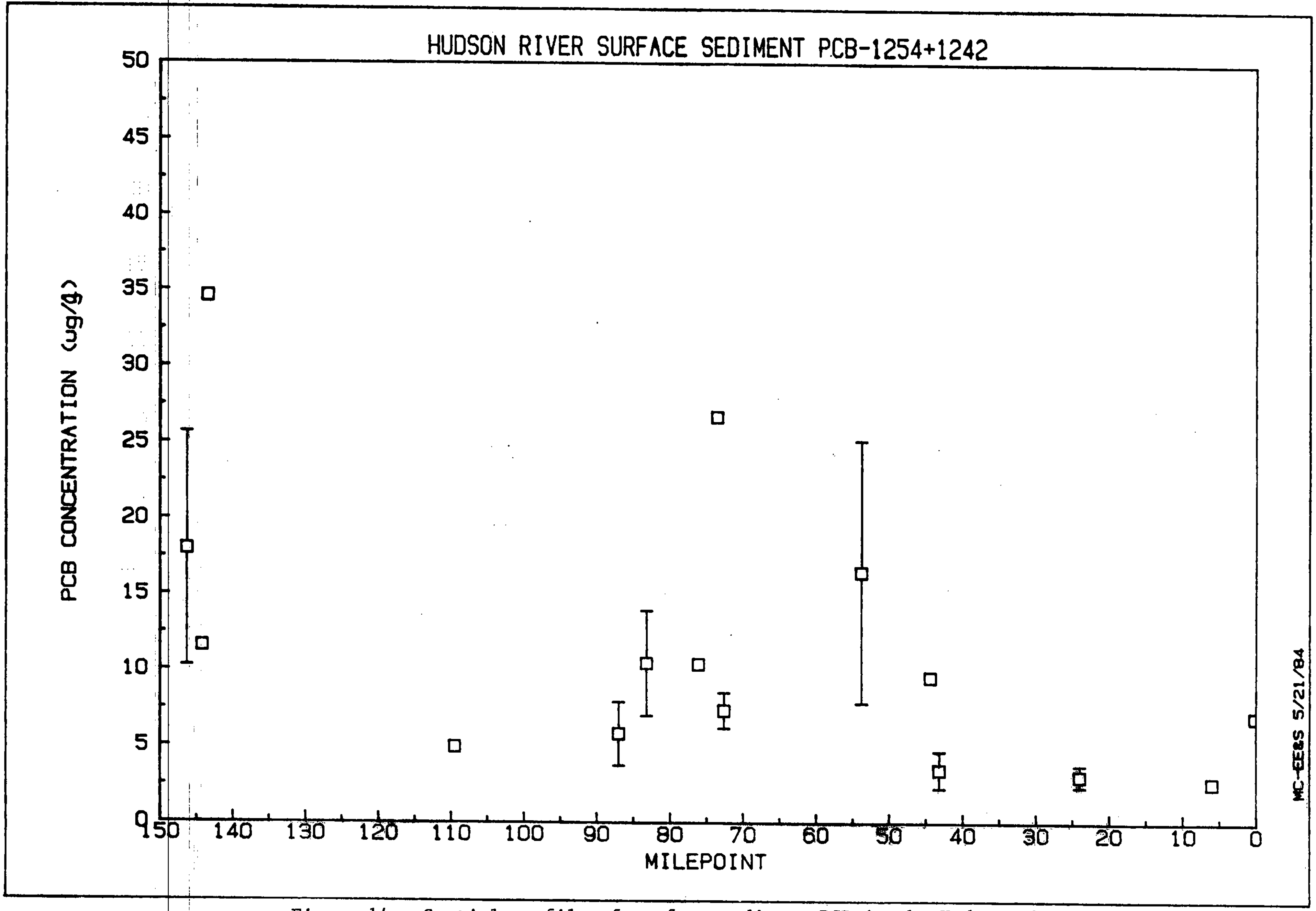


Figure 14. Spatial profile of surface sediment PCB in the Hudson River between mile points 52.5 and 116.

SECTION 3

FOOD CHAIN MODEL

Review of Previous Work

The food chain model being applied in this research builds on an earlier analysis of PCB in Hudson River striped bass (Hydroscience, 1979). A detailed review of that analysis was conducted as a first step in the current work. A major difference between that analysis and the current research is that only striped bass were modeled using bioenergetics rather than all members of the food chain. For the lower levels of the food chain the steady-state concentrations of biomass and PCB were modeled using externally specified rates of food consumption, death, PCB uptake, and PCB excretion. Values used for these parameters reflected available literature data, however the variability of the PCB concentration data and the sparsity of reported parameter values prevented the determination of an optimum parameter set to use in projections. Because the bioenergetic model uses the more highly studied and better known parameters of respiration and growth to internally calculate food consumption, PCB uptake and PCB excretion, a more confident projection is possible.

Several of the parameter values in the Hydroscience analysis are not supported by studies conducted subsequent to that analysis. The assimilation efficiency of PCB in food was assumed to be 0.9 for all species. A review of assimilation efficiencies (Connolly and Tonelli, 1984) indicates that herbivorous species have lower efficiencies than carnivorous species. The reported values for PCB range from 0.2 for the estuarine copepod _Acartia tonsa_ consuming phytoplankton (Wyman and O'Connors, 1980) to 0.85 for striped bass consuming _Gammarus tigrinus_ (Pizza and O'Connor, 1983). The Hydroscience analysis assumed a biomass conversion efficiency (g biomass/g food) of 0.6 for all species. Data on the assimilation efficiency of food (Brett and Groves, 1979) indicates that the biomass conversion efficiency is a function of diet and is higher for carnivors than herbivors. Assimilation efficiencies of carnivorous fish ranged from about 0.75 to 0.9 while values for herbivorous fish ranged from about 0.16 to 0.65.

The modeling in this project will incorporate the improved parameter estimates as well as bioenergetic based equations for all species.

Determination of the Model Parameters for the Striped Bass Food Chain

Application of the model requires that the following bioenergetic and PCB related parameters be specified for each species:

1) growth rate
2) respiration rate
3) food assimilation efficiency
4) predator-prey relationships
5) PCB assimilation efficiency
6) bioconcentration factor for PCB

An extensive literature search has been conducted to provide the data necessary to assign values to these parameters. That literature search has resulted in the compilation of an extensive bibliography. This literature was being thoroughly reviewed at the end of the contract year.

The first phases of that literature review focused on the feeding and migratory habits of the striped bass. The feeding habits were used to establish the food chain below the striped bass that is indicated in Figure 15.

Development of an Alternative Model

The data for PCB concentration in Hudson River fish indicate, for most species, a strong correlation between fish lipid content and PCB concentration. (Armstrong and Sloan, 1981). This relationship has been observed for many lipophilic chemicals and appears to be a dominant factor relative to body burden. The model used in this research implicitly considers the lipophilic nature of the chemical through the values used for assimilation efficiency and bioconcentration factor. However, no

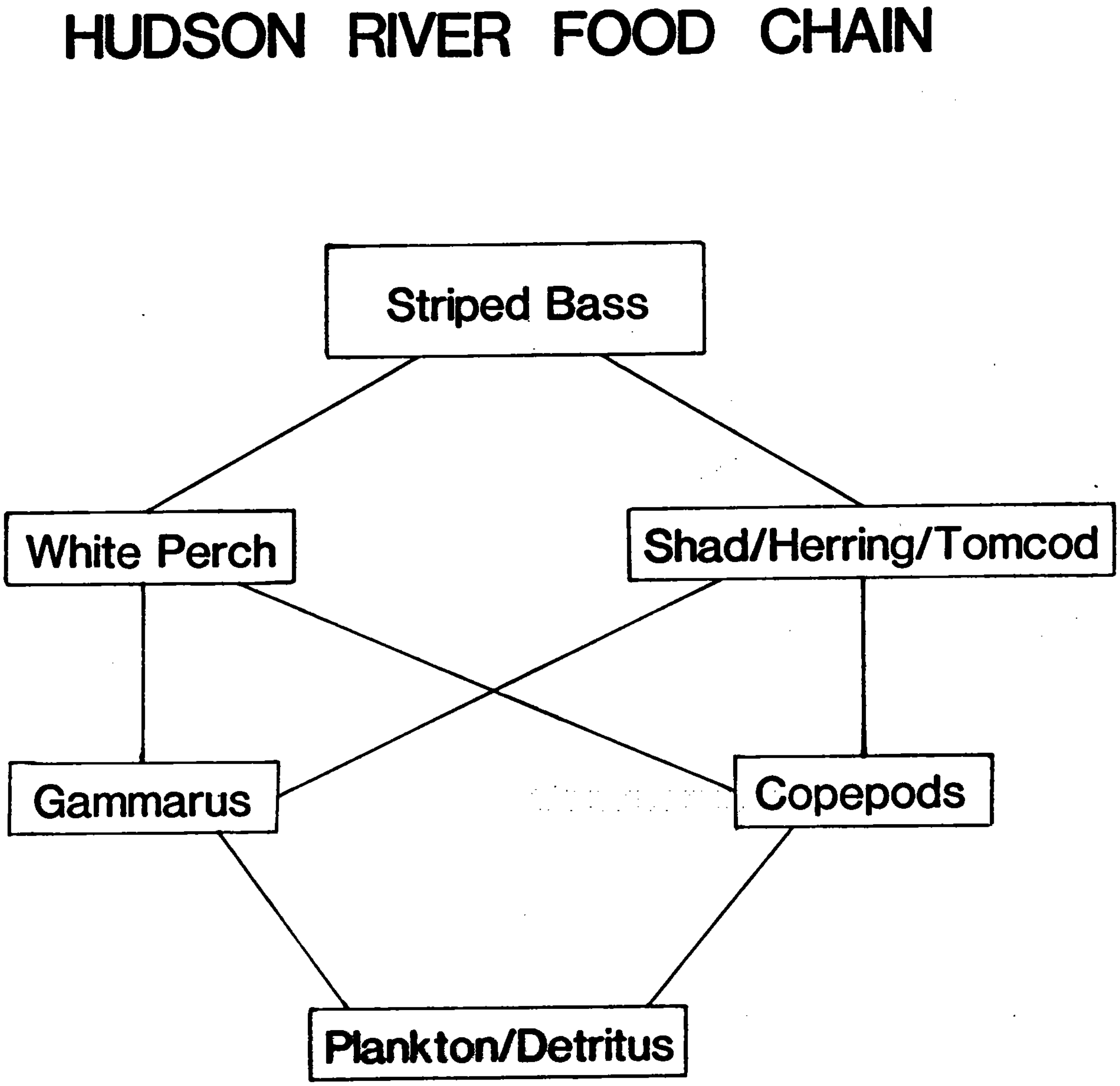


Figure 15. Schematic of the simplified Hudson River striped bass food chain structure.

consideration of lipid within a species and its effect on body burden is considered since single values are used for assimilation efficiency and bioconcentration factor and there is no differentiation between lipid and non-lipid components of the animal. During the first phase of this project the feasibility of incorporating lipid content in the food chain model was investigated. A modeling framework has been developed and is outlined below.

The role of lipid reserves in the accumulation of chemicals by exposed animals may be viewed in simplified fashion as shown in Figure 16. The fish is divided into lipid and non-lipid components. Uptake and excretion occur between the non-lipid component and the environment. Transport of the chemical between the lipid and non-lipid components is assumed to be a reversible reaction. The differential equations for the chemical in each component are:

$$\frac{\partial \nu'_N}{\partial t} = k_u w_c + \alpha C w \nu_p - K\nu'_N - k_1 \nu'_N + k_2 \nu'_L \qquad (1)$$

$$\frac{\partial \nu'_L}{\partial t} = k_1 \nu'_N - k_2 \nu'_L \qquad (2)$$

where ν'_N = mass of chemical in the non-lipid component
ν'_L = mass of chemical in the lipid component
k_u = uptake rate from water (L/d-g fish)
c = dissolved chemical concentration
α = assimilation efficiency for chemical in food
C = consumption rate of the fish (g food/g fish/d)
ν_p = concentration of chemical in thr prey
K = excretion rate
G = growth rate
k_1 = transfer rate from non-lipid to lipid
k_2 = transfer rate from lipid to non-lipid
w = weight of the whole fish

Adding these equations yields:

$$\frac{\partial}{\partial t}(\nu'_N + \nu'_L) = \frac{\partial \nu'}{\partial t} = k_u c w + \alpha C \nu_p w - K\nu'_N \qquad (3)$$

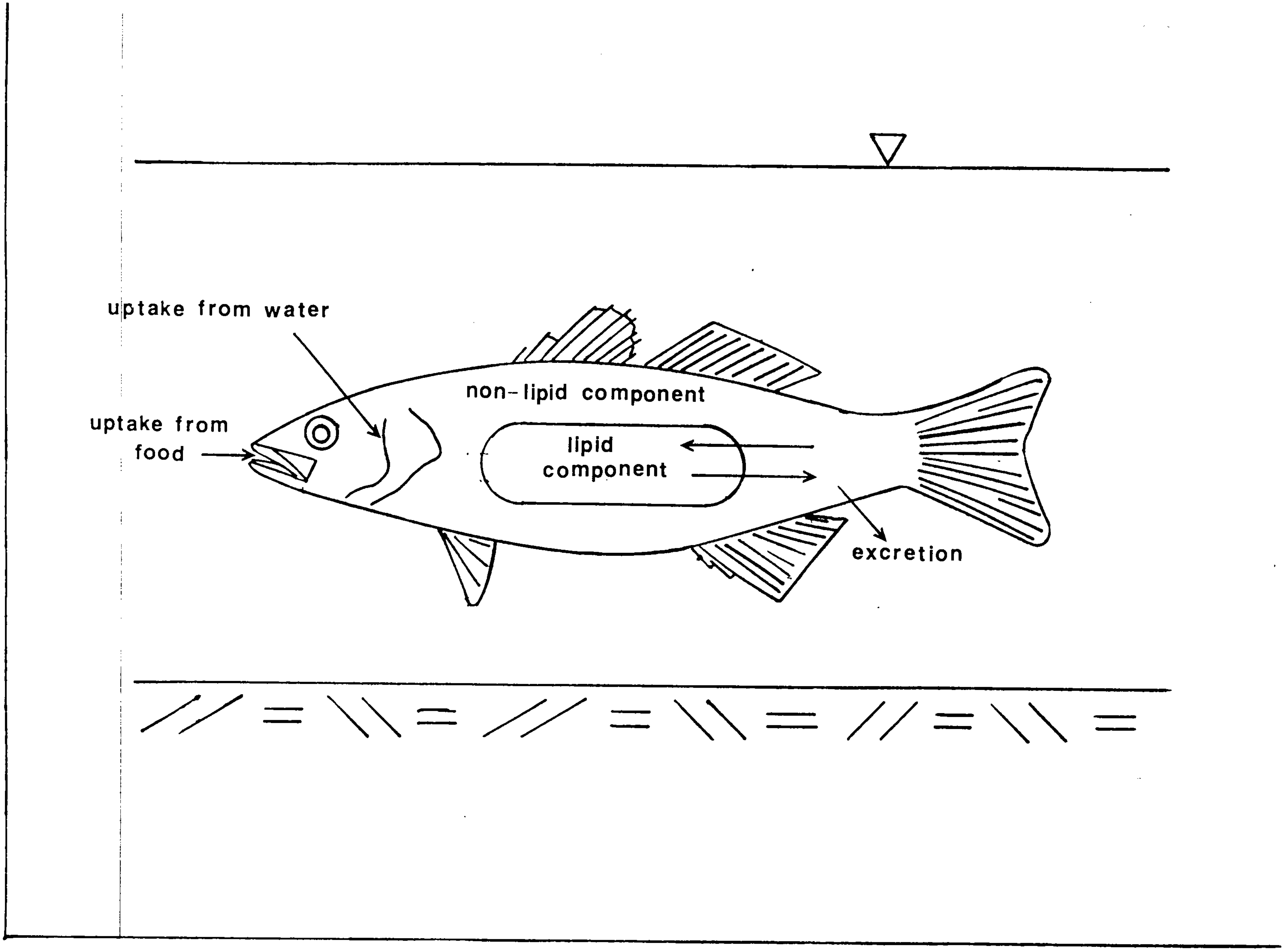


Figure 16. Conceptual description of lipid-non-lipid food chain model.

where ν' = mass of chemical in the whole fish

Since $\nu' = \nu w$ and $\nu'_N = \nu_N w_N$

where ν = concentration of chemical in the whole fish
ν_N = concentration of chemical in the non-lipid component
w_N = weight of the non-lipid component

equation (3) may be rewritten as

$$\frac{d\nu w}{dt} = w\frac{d\nu}{dt} + \nu\frac{dw}{dt} = K_u cw + \alpha C\nu_p w - K\nu_N w_N \tag{4}$$

or

$$\frac{d\nu}{dt} = K_u c + \alpha C\nu_p - Kx_N\nu_N - G\nu \tag{5}$$

where

$$x_N = \frac{w_N}{w} = \text{non-lipid weight fraction of the fish}$$

$$G = \frac{dw/dt}{w} = \text{growth rate of the fish}$$

Equation (5) is similar to the equation for a single compartment fish except that excretion is from the non-lipid component rather than the whole fish. The excretion term may be rewritten in terms of whole fish concentration if instantaneous equilibrium is assumed between the lipid and non-lipid components. Under this assumption a constant ratio or partition coefficient, π, is maintained between the concentrations of chemical in the two compartments, i.e.,

$$\pi = \frac{\nu_L}{\nu_N} \tag{6}$$

The relationship between concentration in each component and whole body concentration is

$$\nu = x_L\nu_L + x_N\nu_N \tag{7}$$

where x_L = lipid weight fraction of the fish = $1 - x_N$.

If equation (6) is substituted into equation (7) the concentration of chemical in the non-lipid component may be expressed in terms of the whole body concentration:

$$\nu_N = \left(\frac{1}{\pi x_L + x_N}\right)\nu = f_N \nu \tag{8}$$

This equation may be substituted into equation (5) to yield

$$\frac{d\nu}{dt} = K_u c + \alpha C \nu_p - K x_N f_N \nu - G\nu \tag{9}$$

Using this equation the lipid component of the fish can be explicitly considered in the food chain model without significantly altering the original model formulation. The only change in the formulation is that the whole body excretion rate, K_{WB}, is calculated from the excretion rate from the non-lipid component, the weight fractions of the lipid and non-lipid components, and the partition coefficient of the chemical between the two components, i.e.,

$$K_{WB} = K\, x_N f_N = K \frac{x_N}{\pi L \;\; + N} = \frac{K}{\pi\left(\frac{x_L}{1-x_L}\right) + 1} \tag{10}$$

From equation (10) it is evident that whole body excretion rate is dependent on the body weight fractioning between the lipid and non-lipid components and the partitioning of the chemical between these components. The former is evident in the relationship between body burden and lipid content observed for individual chemicals (e.g. Figure 17) while the latter indicates that excretion rate should be dependent on the lipophilic character of the chemical. Using the n-octanol/water partition coefficient as a measure of the lipophilic character of the chemical, laboratory measured excretion rates provide evidence of this dependence. Figures 18 and 19 show the relationship between the n-octanol/water partition coefficient of the chemical and the measured excretion rate in catfish, daphnia, and goldfish. The decline of excretion rate with increasing partition coefficient is consistent with equation (10).

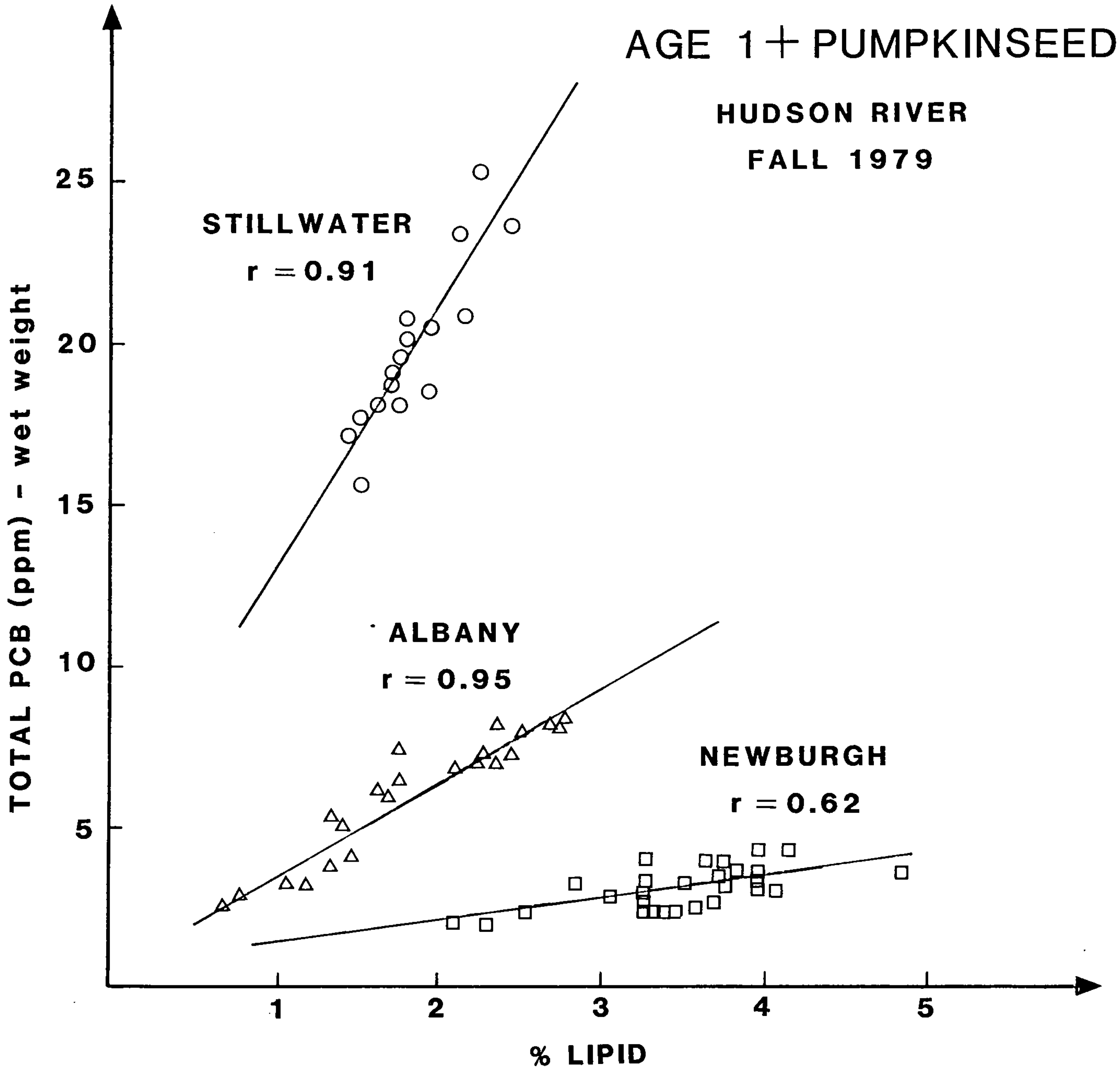


Figure 17. Variation in total PCB concentration (wet basis) with lipid content of yearling pumpkinseed collected in 1979 at three Hudson River locations: (o), Stillwater; (o) Albany; ( ), Newburgh. (Armstrong and Sloan, 1981).

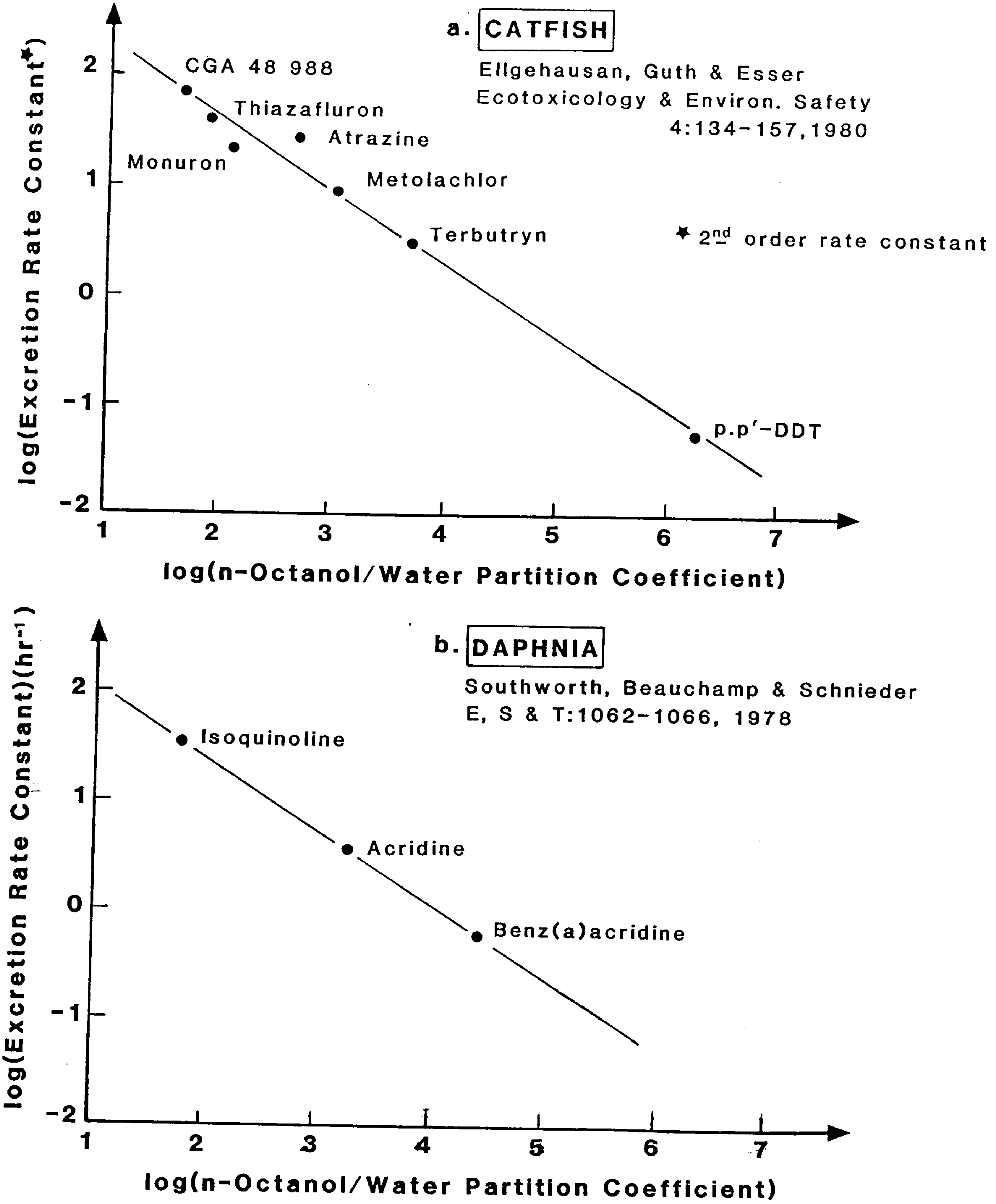
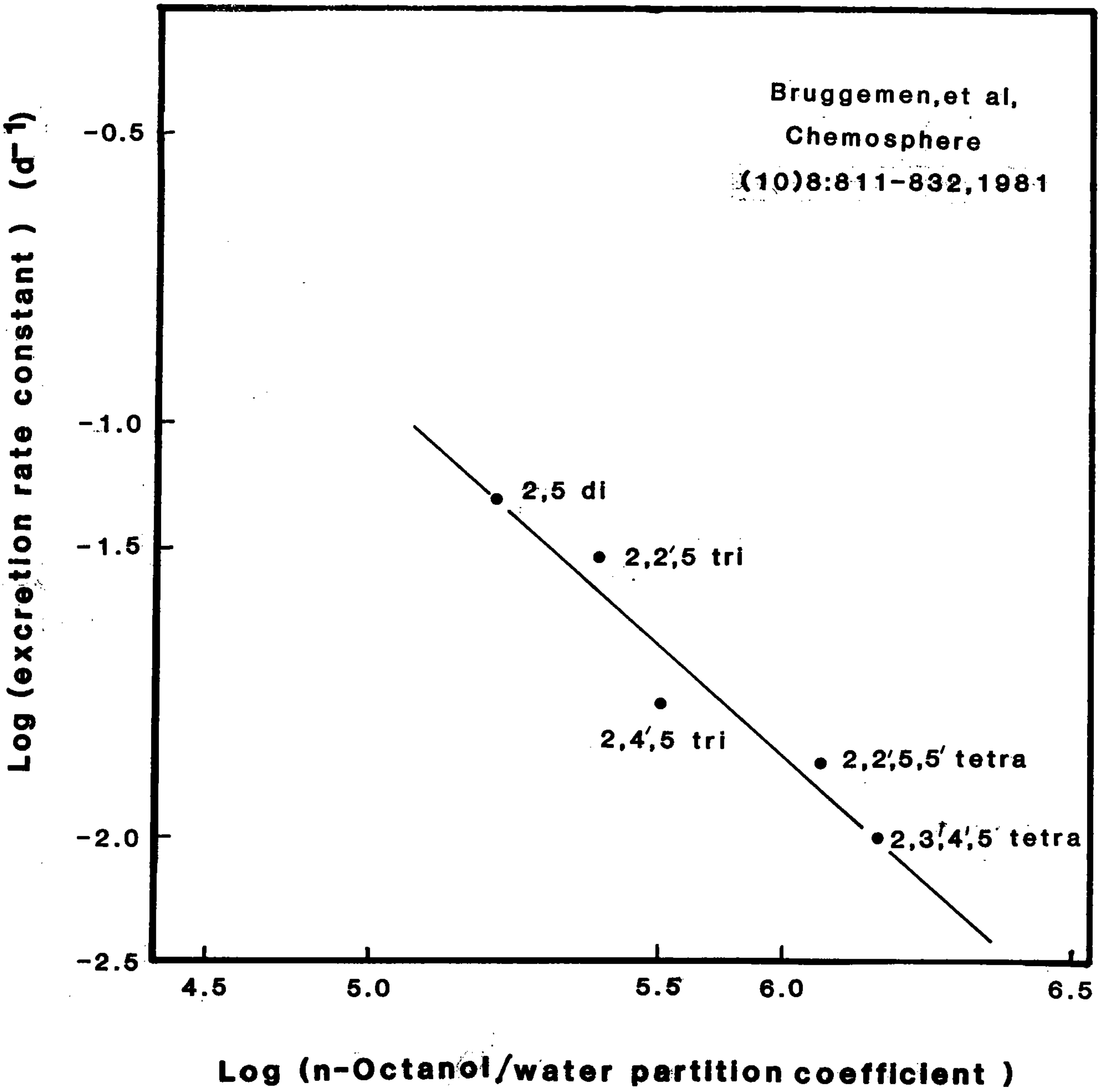


Figure 18. Relationship between the depuration rate constant of various organic chemicals and the n-octanol/water partition coefficient.



RELATION BETWEEN THE DEPURATION RATE CONSTANT OF SEVERAL CHLOROBIPHENYLS BY GOLDFISH AND THE n-OCTANOL/WATER PARTITIONN COFFICIENT

Figure 19. Relationship between the depuration rate constant of several chlorobiphenyls by goldfish and the n-octanol/water partition coefficient.

A rigorous evaluation of the two compartment model is being conducted. Assuming blood as the non-lipid component, literature data is being used to compare observed whole body and blood excretion rates with values computed using equation (10). Observed and computed variations of body burden with lipid content are also being compared. From these comparisons a decision will be made regarding incorporation of the two compartment model in the modeling framework for the Hudson River striped bass food chain.

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