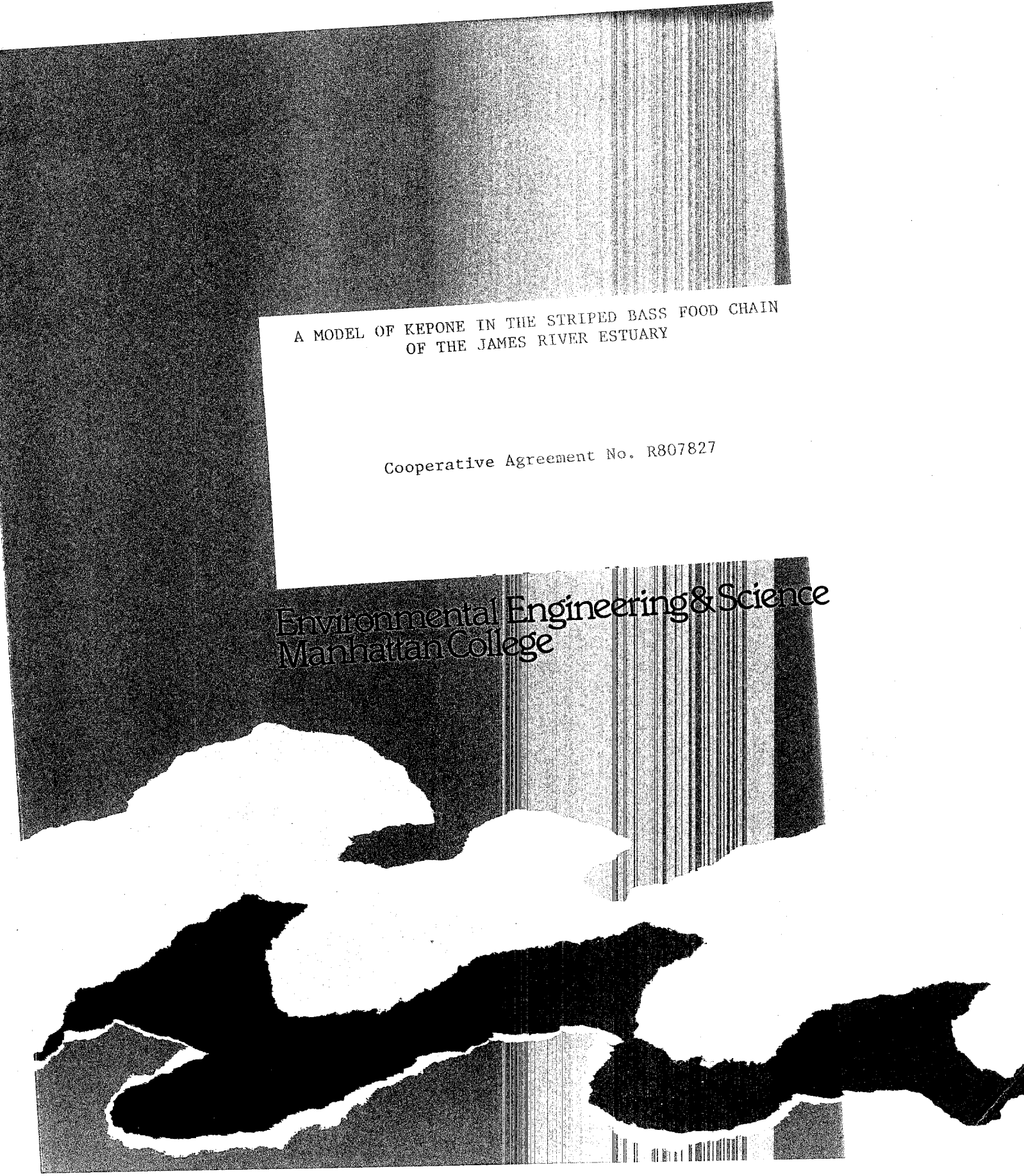
A MODEL OF KEPONE IN THE STRIPED BASS FOOD CHAIN OF THE JAMES RIVER ESTUARY

Cooperative Agreement No. R807827

Environmental Engineering & Science
Manhattan College



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ABSTRACT

A mathematical model that computes the accumulation of Kepone in the striped bass food chain of the James River estuary was developed. The purpose of the model was to help understand the relationship of Kepone levels in important fish species to sediment and water column Kepone concentrations and then to address the question of why these levels still exceed Food and Drug Administration limits 8 years after discharge stopped. The model considers exposure through diet and respiration at rates based on species bioenergetics. It was successfully calibrated to observed 1976 through 1982 striped bass, white perch, and Atlantic croaker Kepone concentrations. The model indicates that for the upper levels of the food chain, diet is the major route of contamination, accounting for 87-88% of the observed concentration in croaker and white perch and 91% of the observed concentration in striped bass. The two Kepone sources; sediment and water column, contribute approximately equally to the croaker and white perch. The water column is more significant for striped bass, being the original source for approxi-

mately 60% of the observed body burdens. It was estimated that a criterion requiring Kepone concentrations in fish to be at or below 0.3 µg/g would require dissolved water column and sediment Kepone concentrations to be reduced to somewhere between 3 and 9 ng/ℓ and 13-39 ng/g, respectively, depending on the species. Striped bass require the greatest reductions in dissolved water column and sediment Kepone concentrations to somewhere between 3 and 5 ng/ℓ and 13 and 24 ng/g respectively.

FIGURES

FIGURES (contd)

FIGURES (contd)

TABLES

ACKNOWLEDGEMENTS

This work was carried out as part of a cooperative agreement (R807827) with the USEPA - Environmental Research Laboratory, Gulf Breeze, Florida. The contents do not necessarily reflect the views and policies of the Environmental Protection Agency. The support of Project Officer Parmely H. Pritchard is gratefully acknowledged.

Charles Lunsford and Gail Walton of the Virginia State Water Control Board provided the Kepone data for the water column, sediment, and fish. They also provided assistance in interpreting and analyzing this data. Their cooperation and support were critical to this work.

Charles Manooch of North Carolina State University kindly supplied us with data on the stomach contents of Albemarle Sound, North Carolina striped bass.

We would also like to acknowledge the participation and cooperation of our colleagues in the Environmental Engineering and Science Program at Manhattan College. Donald J. O'Connor contributed to the analysis of the water and bed data based on his previous work on Kepone in the James River. Robert V. Thomann provided suggestions and critical review. Jeanette M. Samaritan performed the literature review for white perch and calibrated a preliminary model of this species as part of a master's thesis. William Hall compiled data during the early phases of this work.

INTRODUCTION

In December, 1975 the James River was closed to fish and shellfish harvesting from Richmond, Virginia to the Chesapeake Bay because of contamination by the pesticide Kepone. Since that time Kepone concentrations have declined in response to termination of the Kepone discharge to the river. However, in many important species concentrations still exceed the Food and Drug Administration (FDA) action limit of 0.3 ppm and a partial fishing ban remains in effect. From both a management and research standpoint it is important to determine why concentrations have declined so slowly. This requires an understanding of the dynamics of Kepone uptake by the food chain in the James River. It is the purpose of this paper to present an analysis of Kepone accumulation by the food chain leading to the striped bass. This analysis is based on a mathematical framework that describes the uptake and excretion of contaminants in terms of the bioenergetics, or rates of energy uptake and expenditure, of each level of the food chain and the interaction between levels.

SECTION 2

THEORY

The accumulation of toxic chemicals by fish may be described by the following equation (Thomann & Connolly, 1984);

$$\frac{dv_i}{dt} = K_{ui}c + \sum_{j=1}^{n} \alpha_{ij} C_{ij} v_j - K'_i v_i \qquad (1)$$

where $K'_i = K_i + (dw_i/dt)/w_i$

K_j = excretion rate of organism i (d^{-1})

w_i = weight of organism i (g)

t = time (d)

K_{ui} = uptake rate of organism i (L/d-g)

α_{ij} = chemical assimilation efficiency of organism i on organism j

C_{ij} = consumption rate of organism i on organism j (g prey/g pred.-d)

v_i = concentration of chemical in a given organism of age class i (µg/g)

c = dissolved chemical concentration

n = total number of organisms (or age classes) preyed on by organism i

The first term of equation (1) represents the direct uptake of chemical

by the organism from the water. The second term represents the flux of chemical into the organism through feeding. The third term is the loss of chemical due to desorption and excretion from body tissue at a rate K_i plus the change in concentration due to growth of the individual. The values of the coefficients depend on the bioenergetics of the species and the physical and chemical characteristics of the chemical.

The uptake rate constant K_{ui} parameterizes the transport of chemical across the gill to the blood. A diffusive transport mechanism analogous to oxygen transport is generally assumed (Norstrom, et al., 1976; Weininger, 1978; Thomann & Connolly, 1984). The uptake rate constant is calculated as the product of the diffusivity of the chemical relative to oxygen and the respiration rate normalized by the dissolved oxygen concentration. The respiration rate is a function of temperature, organism weight and swim speed which may be specified as (Weininger, 1976):

$$R = \beta w^{\gamma} r^{\rho T} e^{\nu S} \qquad (2)$$

where ν, γ, ρ, β = constants

R = respiration rate (g/g/d)

T = temperature (°C)

S = swimming speed (cm/s)

The food ingestion rate, which controls the uptake of chemical from food, is dependent on metabolism and growth. It is computed as the in-

take necessary to produce the weight change observed in the environment given the metabolic requirement (respiration) and food assimilation efficiency, a, i.e.,

$$C = \frac{R + G}{a} \tag{3}$$

where $G = (dw/dt)/w$ = growth rate

The excretion rate depends on the metabolic rate of the organism as well as the physical and chemical characteristics of the chemical. As a first approximation the dependence on metabolic rate is assumed to be identical to that of the uptake rate from water. This assumption is equivalent to specifying a constant bioconcentration factor for the organism since this factor is equal to the ratio of the rate constants for uptake from water and excretion. The excretion rate constant is therefore calculated as the ratio of the bioconcentration factor to the uptake rate constant K_{ui}.

Each species or level of the food chain is separated into discrete age classes to which equation (1) is applied. This segmentation permits a more accurate representation of the predator-prey relationships that characterize the food chain. Constant assimilation efficiencies and growth rates are specified for each age class. All other bioenergetic parameters vary continually in relation to body weight.

The lower levels of the food chain generally attain equilibrium with the chemical rapidly and exhibit little variation in concentration with age. For example, blue crabs fed Kepone contaminated oysters achieved steady state body burdens by 28 days (Schimmel et al., 1979) and fiddler crabs and lugworms exposed to Kepone in water reached steady

state by 14 days (Bahner et al., 1979). Therefore, it is appropriate to assume a steady-state concentration for these levels in equilibrium with the chemical and independent of size. This is accomplished by setting the left side of equation (1) to zero. The concentration of chemical is then given by the following equation:

$$\nu_i = \frac{K_{ui}c + \sum_{j=1}^{n} \alpha_{i,j} C_{i,j} \nu_j}{K'} \qquad (4)$$

Average values for the species food ingestion, growth, and respiration rates are used. Note that for the phytoplankton-detritus level, equation (4) simplifies further since there is no uptake through feeding.

In estuarine environments many of the important species are anadromous. Consideration of the migration of these species requires specifying the separate food chains with which they interact and the chemical concentrations associated with each. The predator-prey relationships for the migrating species are then specified as a discrete function of time to simulate their movement.

SECTION 3

STRIPED BASS FOOD CHAIN

Determination of the appropriate species to include in the model is based on a review of published stomach content data. From this data a species is chosen to represent the level of the food chain directly below the top predator, striped bass. Representative species are then chosen for each lower trophic level in succession to the phytoplankton-detritus level. At each level a single species is sometimes sufficient because the members of that level generally have similar bioenergetic characteristics and Kepone residues. Additional species from the same trophic level are incorporated if their feeding habits provide a different vector for transfer of Kepone to the predator (i.e., sediment vs. water column) and they are significant food sources for the predator.

Accumulation of Kepone in the striped bass food chain is modeled using four trophic levels (Figure 1). Phytoplankton-detritus is the base of the food chain. The invertebrate level is represented by Neomysis and Nereis, reflecting the importance of both pelagic and benthic species to the higher levels. Atlantic croaker (Micropogan undulatus) and white perch (Morone americana) are the fish species representing the level immediately below the striped bass (Morone saxatilis).

Phytoplankton-detritus, Neomysis, and Nereis are represented by single compartments that are assumed to be in dynamic equilibrium with Kepone in the water column and in their food (equation 4). The white

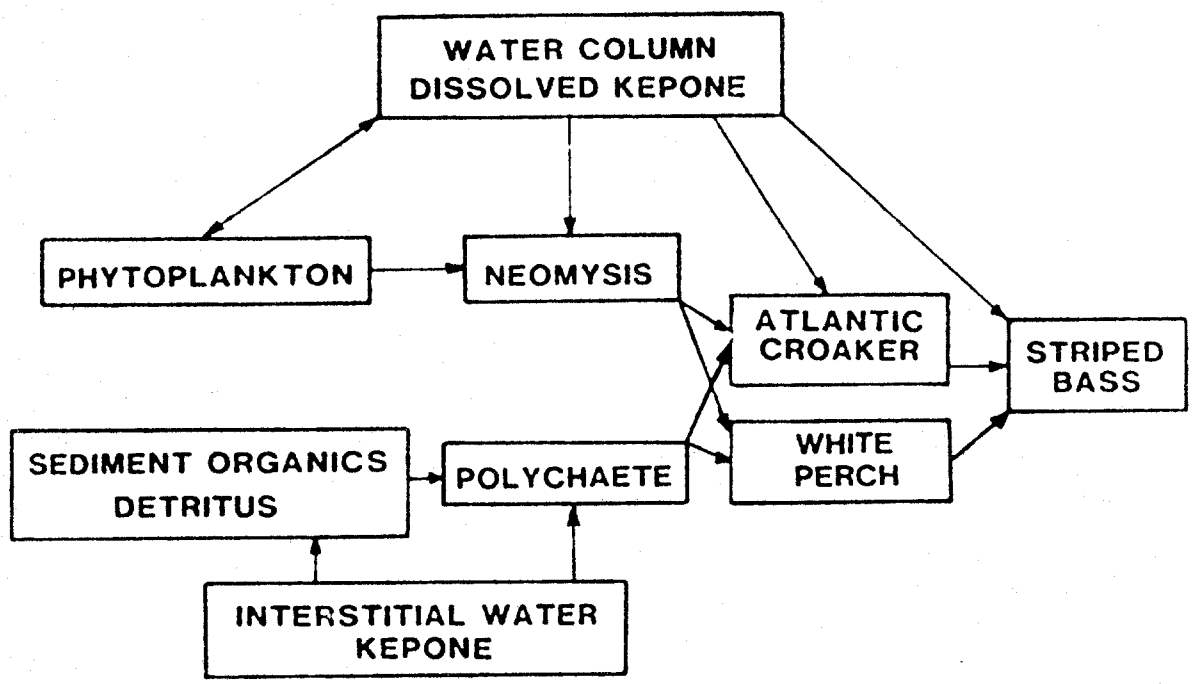

Figure 1. Food chain structure used in the model.

perch, the atlantic croaker and the striped bass are separated into year classes to which equation (1) is applied. Growth rate and predator-prey relationships are assumed to be constant within any age class.

The striped bass is an anadromous species which enters the James River Estuary from Chesapeake Bay in early winter and spawns in the region between the Chickahominy River and Hopewell, Virginia (70-120 km upstream of Chesapeake Bay) from April to early June (Setzler, et al., 1980). Juvenile bass do not migrate, remaining in the estuary for their first two to three years of life (Massman & Pacheco, 1961). A study of stomach contents for young-of-the-year striped bass in the James, York, and Rappahonnock Rivers tributary to lower Chesapeake Bay (Markle & Grant, 1970) indicates that mysids, decapods, insects, and small fish are the dominant food items with the relative contribution of each dependent on salinity and size of the striped bass. Bason (1971) found that Neomysis americana was the basic food of young-of-the-year striped bass in the Delaware River. Small fish, mysids, grass shrimp, and amphipods comprised the diet of one to three year olds. Adult striped bass feed almost exclusively on fish. Hollis (1952) found that atlantic croaker and spot (Leiostomus xanthurus) were the main prey for James River striped bass during the fall and winter with white perch (Morone americana), migrating shad and river herring, and blue crabs (Callinectes sapidus) being significant in the spring and bay anchovy (Anchoa mitchilli) and Atlantic menhaden (Brevoortia tyrranus) also being important during the summer. White perch were also reported in the stomachs of striped bass from Albemarle Sound, North Carolina and were most

significant during the spring (Manooch, 1973). An analysis of stomach content data for striped bass from Albemarle Sound, North Carolina provided by C.S. Manooch (North Carolina State Univ., personal communication) indicates a nearly linear increase in the size of the prey with the size of the striped bass (Connolly & Tonelli, 1984). Eleven single-year age classes of striped bass were considered in the model. The first age class consumed phytoplankton, the next two consumed Neomysis and Nereis, and the older bass consumed the age classes of white perch and atlantic croaker consistent with the prey size distribution mentioned above. The first three age classes were assumed to permanently reside in the James River. Older striped bass were assumed to be migratory and present in the river from November to May. During the period from November to March when the atlantic croaker is not in the estuary the adult striped bass are assumed to prey on white perch only.

The atlantic croaker is a migratory species that spawns in the ocean near the mouth of Chesapeake Bay from late summer through the winter (Haven, 1957). August through September has been reported as the peak spawning period (Welsh & Breder, 1923; Hildebrand & Schroeder, 1928). Newly hatched croakers are carried by currents into the James River and other Chesapeake Bay tributaries and are found further upstream than older members of the population (Haven, 1957). Croakers may remain in the estuary through the summer. They are generally found near the bottom where they prey on epibenthic and infaunal organisms. The most common prey organisms in the York River, Virginia were found to be Neomysis americana, polychaetes, and amphipods (Chao, 1976). Nereis

succinea was the epibenthic species of most importance. In the Patuxent Estuary, Maryland the dominant food items were Neomysis americana and Mya arenaria (Homer, et al., 1980). The average life span of atlantic croakers found north of Cape Hatteras, North Carolina is two to four years (White & Chittenden, 1977). In the model the atlantic croaker component is divided into three single year classes. The first age class consumes phytoplankton, the second age class consumes phytoplankton as well as Neomysis and Nereis, and the third age class consumes only Neomysis and Nereis. All age classes are assumed to enter the James River in March and leave in October.

The white perch is a member of the same genus as the striped bass but is a much smaller fish and is not truly anadromous. White perch over-winter in the deep waters of estuaries and migrate to tidal freshwater in the spring to spawn. Stomach content data indicate that the diet of white perch consists mainly of benthic organisms such as amphipods (Homer, et al., 1980; Whitworth, et al., 1975), polychaetes, and isopods and decapods (Moore, et al., 1975). Neomysis americana was also found to be a significant component of the diet in the Patuxent Estuary (Homer, et al., 1980). Ten single-year age classes are considered in the model. The first two age classes feed on phytoplankton while all others feed equally on Neomysis and Nereis.

Neomysis americana is found in coastal and estuarine waters along the eastern coast of North America from Southern Newfoundland to Northern Florida (Williams, et al., 1974). It is a mysid shrimp of considerable importance in the estuarine food chain linking organic

detritus to fish (Hopkins, 1965). As a filter feeder it collects detritus and algae during diurnal migrations between the bed and surface of the water column. In the model it is assumed to feed on the phytoplankton-detritus level only.

Nereis is an errant polychaete generally found in estuarine environments. The particular species present depends on salinity and the type of sediment. They inhabit the surface sediment and may be found both on top and within the sediment. Errant polychaetes may be classified as deposit-feeders though they prey on other estuarine animals as well as algae and sediment detritus (Price & Warwick, 1980; Shumway, 1979). Sediment particulate material is assumed to be the diet of Nereis in the model.

SECTION 4

PARAMETERS

The parameters that describe the interaction of Kepone and each species include growth rate, respiration rate, the assimilation efficiencies of food and Kepone in food, and the bioconcentration factor for Kepone. For Neomysis and Nereis an average value is used for each parameter consistent with the assumption of steady-state Kepone concentrations for these species. Parameter values are specified for each age class of atlantic croaker, white perch, and striped bass.

The growth rate used in the model is an average value determined from length-age and weight-age data for field populations. Values used for each species are given in Table 1. Because of data limitations the rate applied to Neomysis is based on data for Mysis relicta.

Respiration rate is a function of temperature, body weight, and activity level as described by equation (2). It is similar for species of the same size and general relationships between respiration rate and body weight have been developed for fish (Winberg, 1956) and for poikilotherms and homotherms in general (Schmidt-Nielsen, 1970). Relationships for single species may be developed by regression of respiration data using equation (2), as has been done for lake trout (Weininger, 1978) and salmonid fishes (Stewart, 1980). The respiration rate relationship for striped bass was developed using rates measured at three swimming speeds and two temperatures by Neumann, et al., (1981). Restricting the

TABLE 1. Growth Rates Used For Each Species In The Model

Species	Growth rate (1/d)	System	Reference
Striped bass		Chesapeake Bay	Mansueti, 1961
age class 0-1	0.0069		
age class 2	0.0026		
age class 3-5	0.0014		
age class 6-8	0.00087		
age class 9-10	0.00039		
White perch		James River, Va.	St. Pierre and Davis, 1972
age class 0-1	0.004		
age class 2-4	0.0016		
age class 5-8	0.0007		
Atlantic croaker		York River, Va.	Haven, 1957[1]
age class 0	0.0114		
age class 1	0.0032		
age class 2	0.0026		
Nereis	0.007	Dievengat Pond, Belgium	Heip and Herman, 1979
Neomysis	0.01	Lake Michigan	Morgan and Beeton, 1978[2]

[1] from length-age data using length-weight relationship of White and Chittenden, 1977.

[2] from Mysis relicta length-age data using length-weight relationship of Reynolds and DeGraeve, 1972.

weight exponent in equation (2) to the generally accepted range of -0.2 to -0.3 the relationship is:

$$R = 0.0443w^{-0.3}e^{0.03T}e^{0.0176S} \quad (5)$$

Swimming speed, S, was calculated as a function of weight using an empirical relationship presented by Stewart (1980):

$$S = \omega w^{\delta} e^{\phi T} \quad (6)$$

The coefficients ω, δ, and ϕ were set at 1.19 , 0.32, and 0.0405 respectively based on an analysis of lake trout swimming speed (Weininger, 1978). Sufficient respiration data to determine coefficient values for equation (2) were not available for atlantic croaker or white perch and the general relationship of Winberg (1956) was used.

$$R = 0.038\ w^{-0.2} \quad (7)$$

For Nereis and Neomysis average respiration rates of 0.02 g/g/d (Shumway, 1979) and 0.1 g/g/d (Lasenby & Langford, 1972) respectively, were used. The rate for Neomysis was based on measured rates for Mysis relicta. An annual average temperature of 15°C was assumed in determining the rates.

The assimilation efficiency of food is a function of the type of food eaten and the rate of consumption. In general, efficiencies are near 0.8 for carnivorous species and 0.3 for herbivorous species (Brett & Groves, 1979). Deposit feeders appear to have efficiencies in the range of the herbivorous species (Yingst, 1976). In the model, assimila-

tion efficiencies were assumed to be 0.8 for striped bass, white perch, and atlantic croaker and 0.3 for Neomysis and Neries.

The assimilation efficiency of toxicants in food (Table 2) appears to be related to food assimilation efficiency. Herbivorous species or carnivorous species given an artificial diet such as commercial trout chow have lower efficiencies than carnivorous species on natural diets. Although little data is available to assess the assimilation efficiency of Kepone, it may be assumed to be similar to values reported for other lipophilic chemicals. Values of 0.3 for Neomysis and Nereis, 0.72 for atlantic croaker, 0.8 for white perch and 0.9 for striped bass were assigned based on the information in Table 2 and previous modeling studies of mercury (Norstrom, et al., 1976) and PCB (Weininger, 1978; Thomann & Connolly, 1984).

Observed excretion rates for Kepone and the computed values used in the model are shown in figure 2. The computed values are consistent with bioconcentration factors of 10000 l/kg(w) for striped bass and 6000 l/kg(w) for the lower levels of the food chain. The higher value for striped bass reflects the lower excretion rate needed to reproduce the observed Kepone concentrations. Laboratory equilibrium bioconcentration factors for invertebrates and small fish range from 2300 l/kg(w) to 13500 l/kg(w) (Bell, et al., 1979).

TABLE 2. Assimilation Efficiency Of Various Chemicals In The Diet Of Several Fish And An Invertebrate

Compound	Species	Diet	Assimilation	Reference
Kepone	Channel Catfish (Ictalurus punctatus)	trout chow	0.24**	Van Veld, 1980
Chlordane	Northern Redhorse Suckers (Maxostoma macrolepidotum)	trout chow	0.24-0.57*	Roberts, et al., 1977
Methyl mercury	Northern Redhorse Suckers (Maxostoma macrolepidotum)	trout chow	0.7*	Roberts. et al., 1977
PCB Aroclor 1254	Estuarine Copepod (Acartia tonsa)	phytoplankton	0.2**	Wyman and O'Connors, 1980
PCB Aroclor 1254	Rainbow Trout (Salmo gairdneri)	synthetic organic based food	0.64-0.79*	Lieb, et al., 1974
PCB Aroclor 1254	Striped Bass (Morone saxatilis)	Gammarus tigrinus	0.85*	Pizza and O'Connor, 1983
3,4,2'-trichlorobiphenyl	Cod (Gadus morhua)	squid pieces	0.5**	Mitchell, et al., 1977
2,4,5,2',4',5'-hexachlorobiphenyl	Cod (Gadus morhua)	squid pieces	0.7**	Mitchell, et al., 1977
DDT	Cod (Cadus morhua)	squid pieces	0.5**	Mitchell, et al., 1977

* reported value

** calculated value from reported data

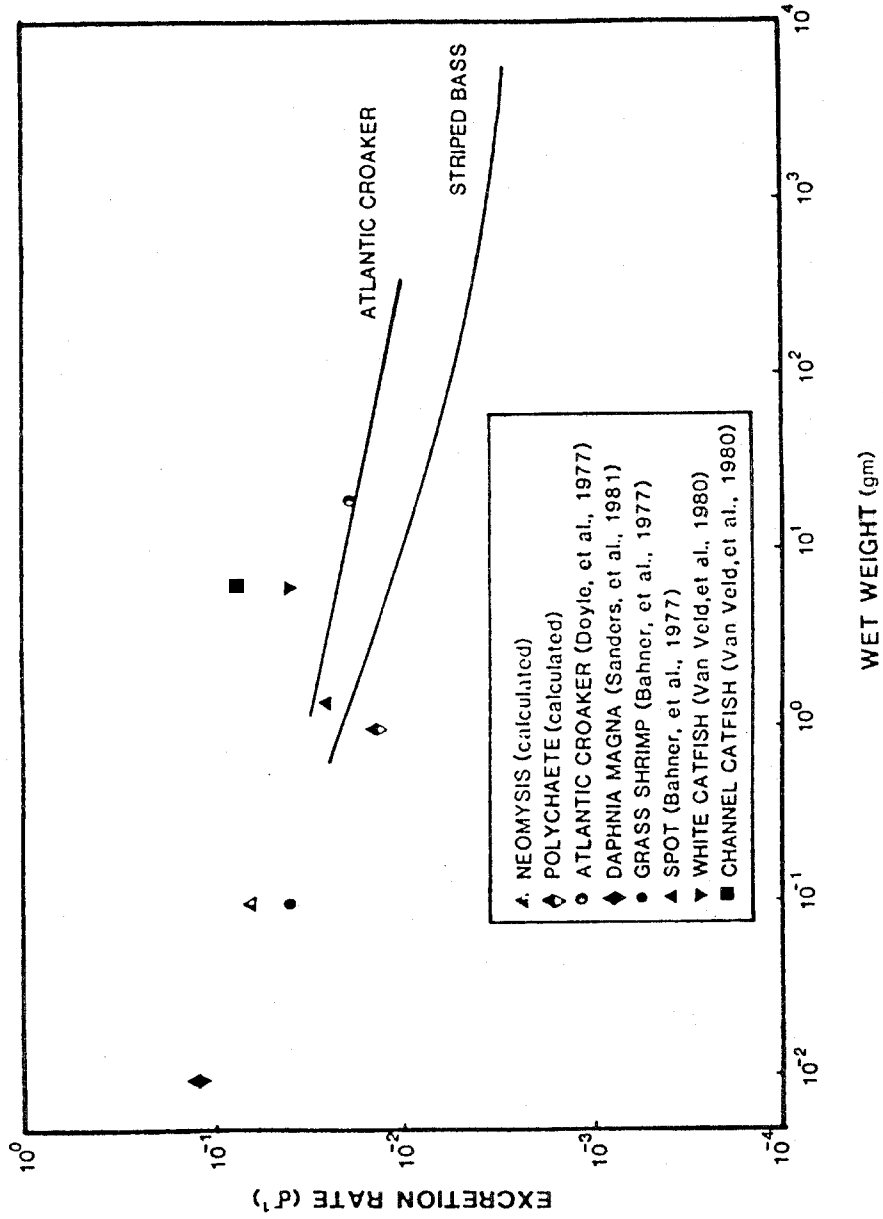

Figure 2. Comparison of observed and computed excretion rates for Kepone

SECTION 5

EXPOSURE CONCENTRATIONS

Kepone concentrations in the water column, sediment and fish of the James River have been routinely monitored by the Virginia State Water Control Board (SWCB) since 1976 (Lunsford, et al., 1980; Lunsford, et al., 1982). These data provide a seven-year time history against which the model may be compared and tested.

The observed median and range of water column total Kepone concentrations and the values for dissolved Kepone used in the model are shown in figure 3a. The data suggest a slow decrease in concentration with time. Concentrations in the water column and sediment increased from 1977 to 1978 suggesting transport to this region of more highly contaminated sediment from upstream. Estimates of the quarterly median total Kepone were obtained from the probability distribution of the data and indicate that concentrations declined from between 0.03 and 0.04 µg/ℓ in 1976 to less than the limit of detection of 0.02 µg/ℓ by 1979. This trend reflects the elimination of the Kepone discharge in 1975 and the subsequent self-cleansing of the river. However, the slowness of the decline indicates that the self cleansing is a slow process with the water column continuing to receive Kepone, most probably from the local sediment and the highly contaminated sediment in the region close to the original discharge (Bailey's Bay). The dissolved Kepone concentrations used in the model were chosen based on the assumption that 70 to 90 per-

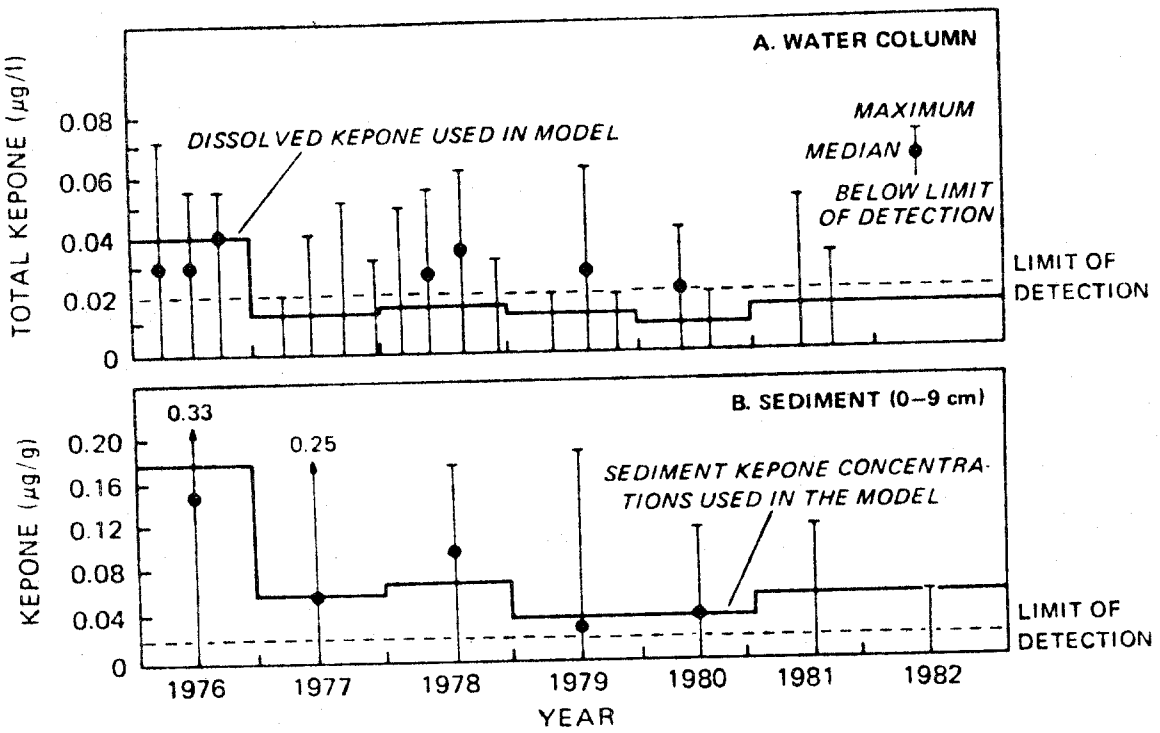

Figure 3. Kepone concentrations observed in the lower James River estuary (0-60 km) and the values used in the model for a) the water column, and b) the surface sediment

cent of the total Kepone is in the dissolved form. These concentrations reflect both the data ranges and the estimates of the median total Kepone. Spatially constant values were used because no consistent spatial gradient is evident in the data. An increase in concentration from 1980 to 1981 was assumed based on an observed increase in Kepone concentration in the fish. A prolonged low flow period in the river from fall 1980 through 1981 may be the reason for the higher concentrations. The only sources of Kepone to the water column are scouring of bed solids and diffusion from interstitial water. Assuming the rate of mass transport of Kepone from the interstitial water to the water column is independent of freshwater flow, the concentration in the water column is related to the water volume. Under the prolonged low flow the lower water volume would then result in higher Kepone concentration. In addition, the further upstream penetration of the salt wedge under low flow would allow anadromous species to migrate to locations where sediment Kepone concentrations were higher in general.

Median surface sediment (0-9 cm) Kepone concentrations in the lower estuary (6-60 km) and the values used in the model are shown in figure 3b. Sediment Kepone concentrations decline slowly in a pattern consistent with the water column. The values used in the model follow the observed values through 1980. In 1981 and 1982 values significantly higher than the observed median values (though still within the range of data) were used to reflect the probable migration of the species further upstream than normal.

SECTION 6

RESULTS AND DISCUSSION

6.1 CALIBRATION

In the calibration procedure the Kepone assimilation efficiency and excretion rate were adjusted within their range of observed values to provide the best comparison of observed and computed Kepone concentrations. SWCB data for atlantic croaker was supplemented by data collected in 1976 by the Virginia Institute of Marine Science (Bender, et al., 1977). Data for the lower levels of the food chain was limited to a study of zooplankton and phytoplankton in 1977 and 1978 (Jordan, et al. 1979). During the portion of the year that atlantic croaker and striped bass were outside the James River they were assumed to be exposed to no Kepone.

The comparison between observed data and calculated Kepone concentrations in atlantic croaker, white perch, and striped bass is shown in figure 4. The data and calculated values are averages over all age classes. The model reproduces the observed within-year and year-to-year concentration profiles for all three species. The oscillation in concentration computed for atlantic croaker and striped bass reflects the migration of these species between the James River and the uncontaminated Chesapeake Bay and Atlantic Ocean. This oscillation indicates that the fish respond rapidly to changes in water and prey Kepone. For atlantic

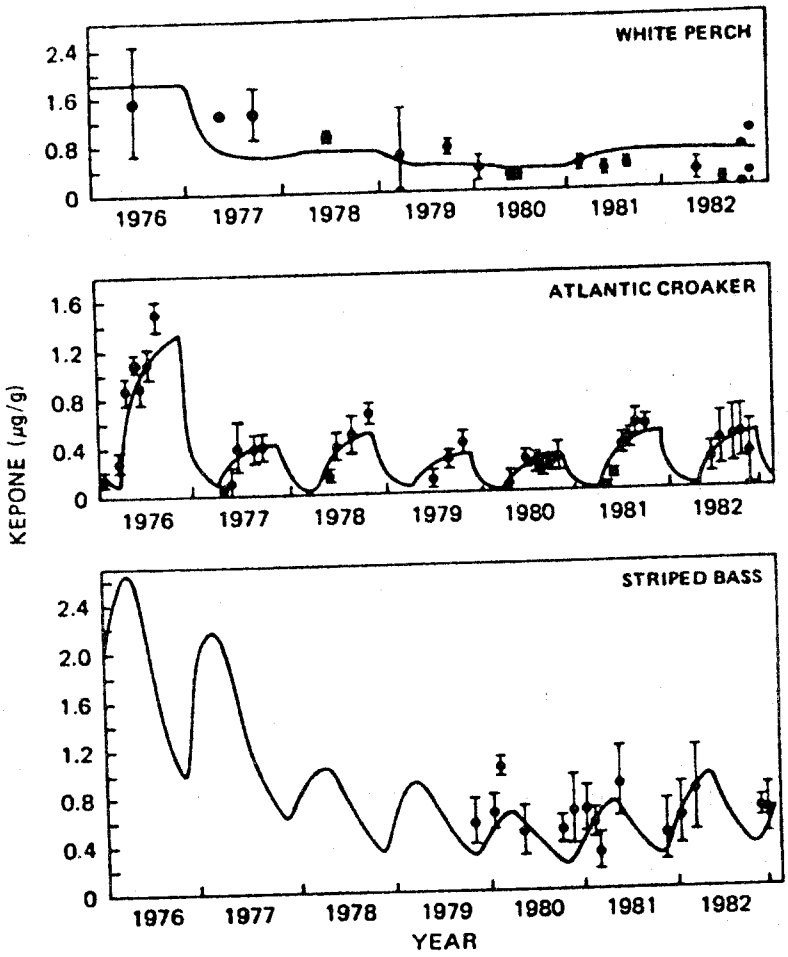

Figure 4. Comparison of observed and calculated Kepone concentrations in the atlantic croaker, white perch, and striped bass.

croaker there is very little carryover of concentration from year-to-year. The average concentration in striped bass reflects previous years more strongly because they have lower excretion rates than the croaker.

Kepone concentrations computed for several age classes of croaker, white perch, and striped bass are presented in figure 5. Each line may be viewed as the concentration of a single fish as it grows throughout the year. Changes over the year reflect migration and changes in food habits as the fish graduates at the birth date to a new age class. Comparing the ages plotted, adult croaker (ages 1 and 2) and white perch (ages 4 and 8) do not significantly increase in concentration as they get older, although they have much higher concentrations than juveniles. This result is consistent with the data which indicate no relationship between Kepone concentration and age (Bender, et al., 1977; Connolly & Tonelli, 1984). It occurs because these species reach equilibrium with Kepone in less than one year and all adult age classes have the same prey and thus the same exposure to Kepone.

The data for striped bass also show no consistent relationship between Kepone concentration and age (Connolly & Tonelli, 1984). Their feeding habits, however, change with age. Figure 5 shows that the non-migrating juvenile bass (ages 0-2) have higher Kepone concentrations than migrating middle age adults. This occurs because their total exposure over the year is greater. The overlap between non-migrating and migratory fish tends to mask any trends in concentration with age. Migration benefits the striped bass by limiting its Kepone concentration. If adults did not migrate they would have much higher body

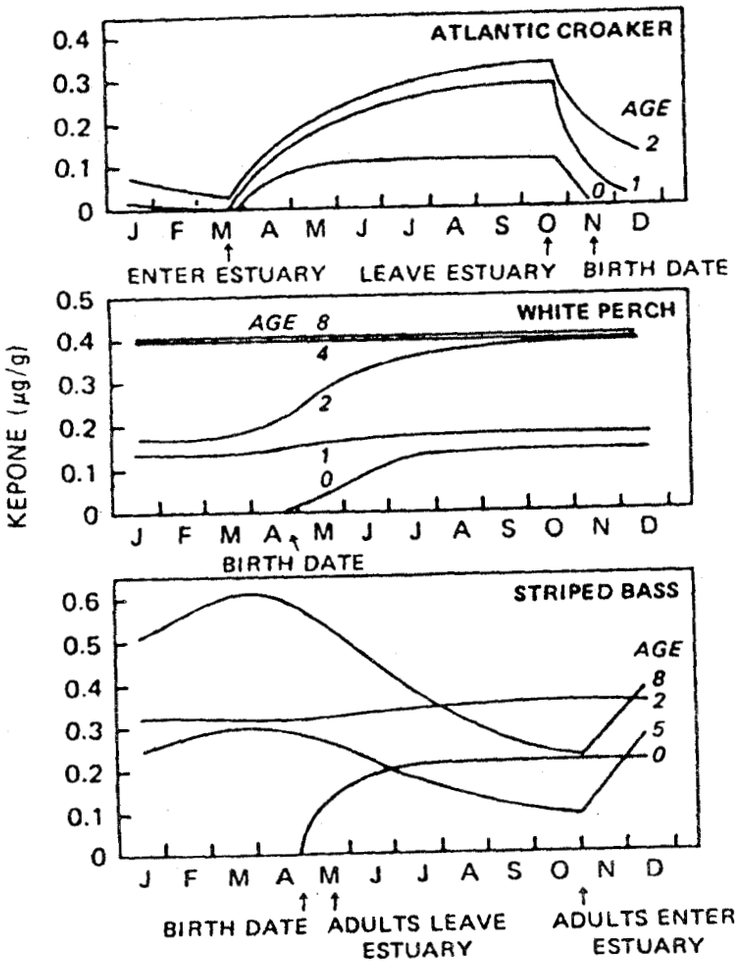

Figure 5. Calculated Kepone concentrations for the year 1980 for various age classes of atlantic croaker, white perch, and striped bass.

burdens.

The main reservoir of Kepone in the James River is the bed sediment. As this sediment is buried by clean sediment from upstream its contribution of Kepone to the water column decreases. Benthic animals, however, will continue to be exposed through ingestion of subsurface sediment. The importance of these animals to direct contamination of fish may be estimated from the computed transfer of Kepone from Nereis to croaker, white perch, and striped bass. Both croaker and white perch feed on Nereis and from 1976 through 1980, as water column and sediment Kepone declined at about the same rate, approximately 50 percent of their Kepone concentrations were obtained from Nereis. Striped bass are indirectly exposed to sediment Kepone through their consumption of white perch and croaker. From 1976 through 1980, approximately 40 percent of their computed Kepone concentration was the result of the ingestion of contaminated sediment by benthic animals (as represented by Nereis).

The computed Kepone concentrations in phytoplankton-detritus and Neomysis are shown in figure 6 along with observed data for phytoplankton and zooplankton. Computed and observed phytoplankton concentrations are nearly identical. The computed Neomysis concentration is lower than the observed zooplankton concentration in 1977 and higher than in 1978. This may be the result of the average water column concentration used in the model which may not reflect conditions during the zooplankton sampling period.

An analysis of the model shows that most of the Kepone in the croaker, white perch, and striped bass was obtained from consumption of

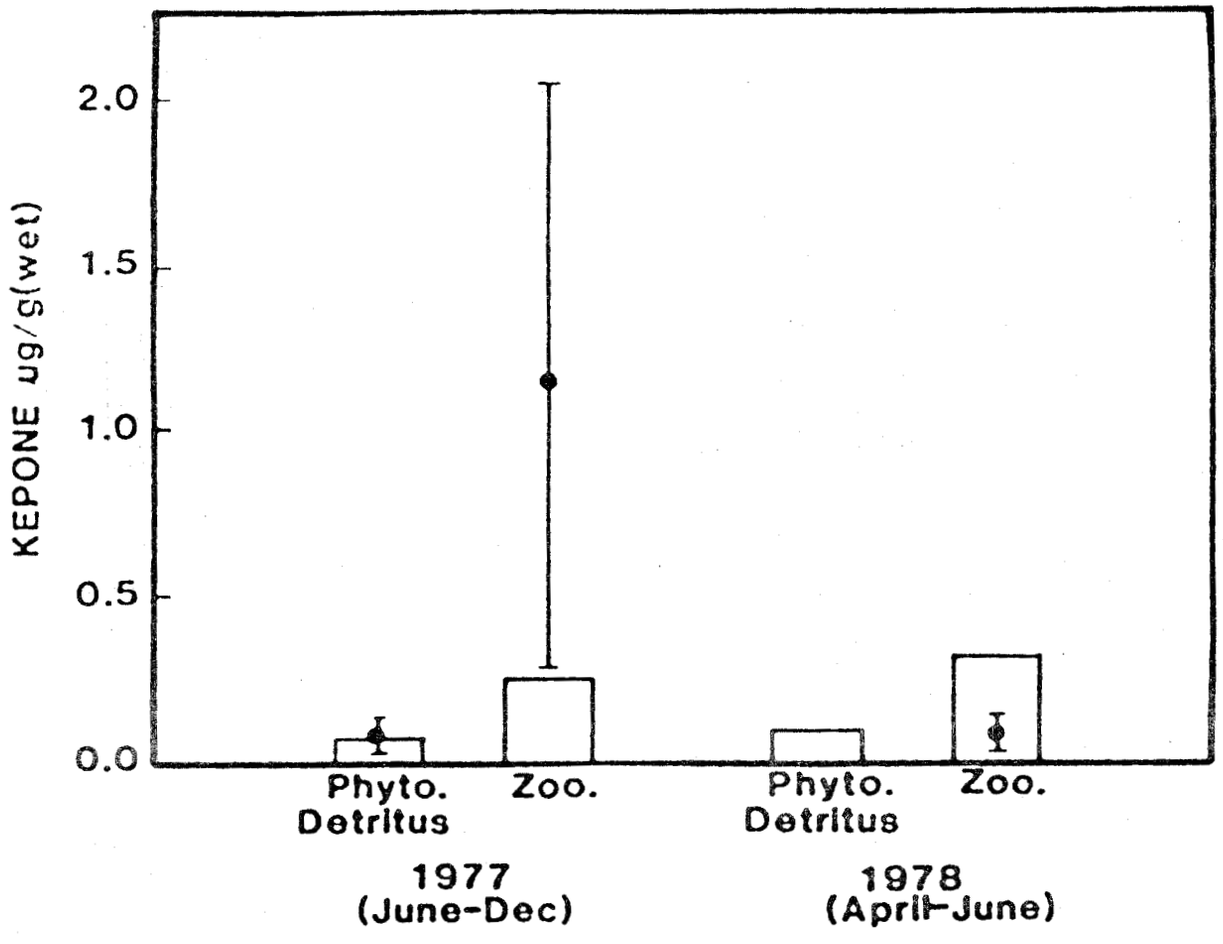

Figure 6. Comparison of observed and calculated Kepone concentrations in phytoplankton and zooplankton (Neomysis)

contaminated prey. Averaging over all age classes, the percentages of Kepone in croaker, white perch, and striped bass obtained from food are 87, 88, and 91, respectively. These high values are consistent with previous studies of mercury (Norstrom, et al., 1976) and PCB (Weininger, 1978; Thomann & Connolly, 1984). They reflect the lipophilic nature of Kepone which results in a high assimilation efficiency from food as well as a high bioconcentration factor. The importance of contaminated food generally causes a significant increase in the concentration achieved by ascending levels of the food chain (Thomann & Connolly, 1984). Although an increase is evident in both the observed and calculated Kepone concentrations (figure 7), it is much less significant than that shown by Thomann & Connolly (1984) for PCB in the Lake Michigan lake trout food chain. The migration of the upper levels of the food chain to regions of zero Kepone concentration results in lower concentrations for these species which mask the significance of the food chain that is indicated by the model.

6.2 PROJECTIONS

The accuracy of any projection or prediction made with the model is limited. Inaccurate information on the parameter values, temporal and spatial averaging, and any incomplete or incorrect formulations of the relevant processes introduce error in the calculations. A rigorous assessment of this error is not possible because the ranges of the model parameters can only be estimated and any errors in the model formulations cannot be determined without further experimental study of the processes

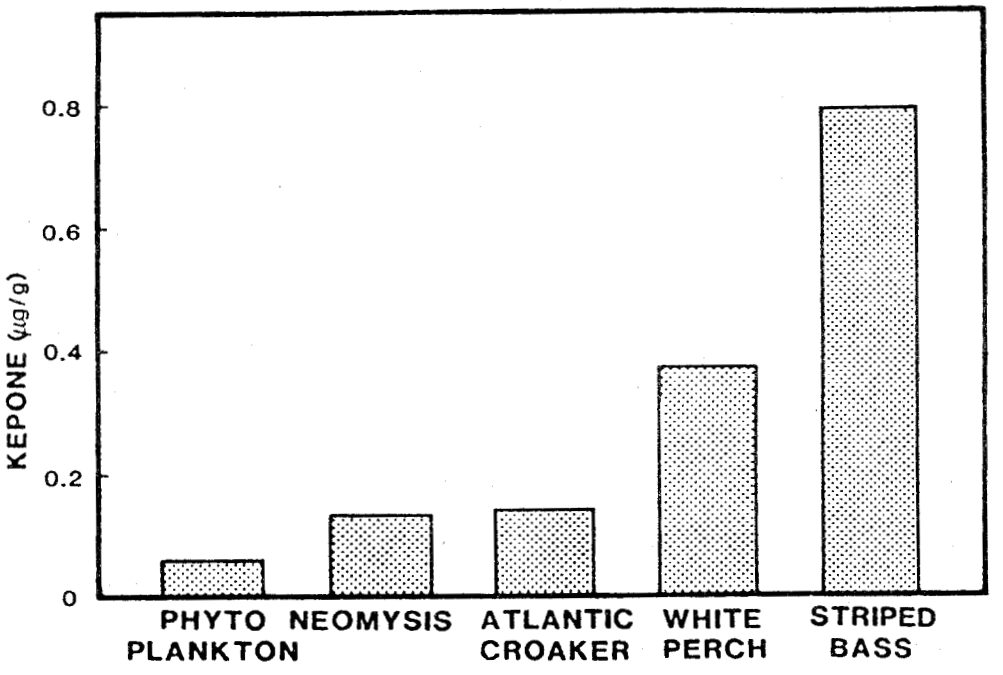

Figure 7. Average observed Kepone concentration at each level of the food chain in May 1978.

TABLE 3. Statistical comparison of observed and calculated Kepone concentration for the calibration

Species	Residual		Median Relative Error*
	Mean (µg/g)	Std. Deviation (µg/g)	(%)
Atlantic Croaker	0.0047	0.129	16.5
White Perch	0.16	0.787	40
Striped Bass	0.13	0.216	30

* Relative Error = $|\text{observed-calculated}|/\text{observed}^2$

involved.

A lower bound for the uncertainty of any prediction is the uncertainty of the calibration. This uncertainty was assessed by analyzing the residuals, that is, the difference between calculated and observed average concentration. The mean and standard deviation of the residuals and the mean relative error of the croaker, white perch, and striped bass calculations for the period 1976-1982 are tabulated in Table 3. For croaker and striped bass the calculations are, on average, within the order of 30 percent of the observed concentrations. The white perch calculation is slightly less accurate possibly due to migration of white perch to upstream areas with higher sediment Kepone concentration than represented in the model.

Possible bias of the calibration relative to the data was assessed by checking if the mean residual error was significantly different than zero. Using the t-test at the 95 percent level of significance, only the striped bass residual error was different than zero. This error, however, was not different from zero at the 99 percent level of significance.

The calibrated model was used to project the relationship between the maximum concentration in each species and the exposure concentration. A constant ratio between water column and sediment Kepone concentration of 0.23 µg/ℓ per µg/g was assumed, based on the values used in the calibration. Prediction uncertainty was assumed to be equal to calibration uncertainty.

Figure 8 shows the range of calculated maximum striped bass, white

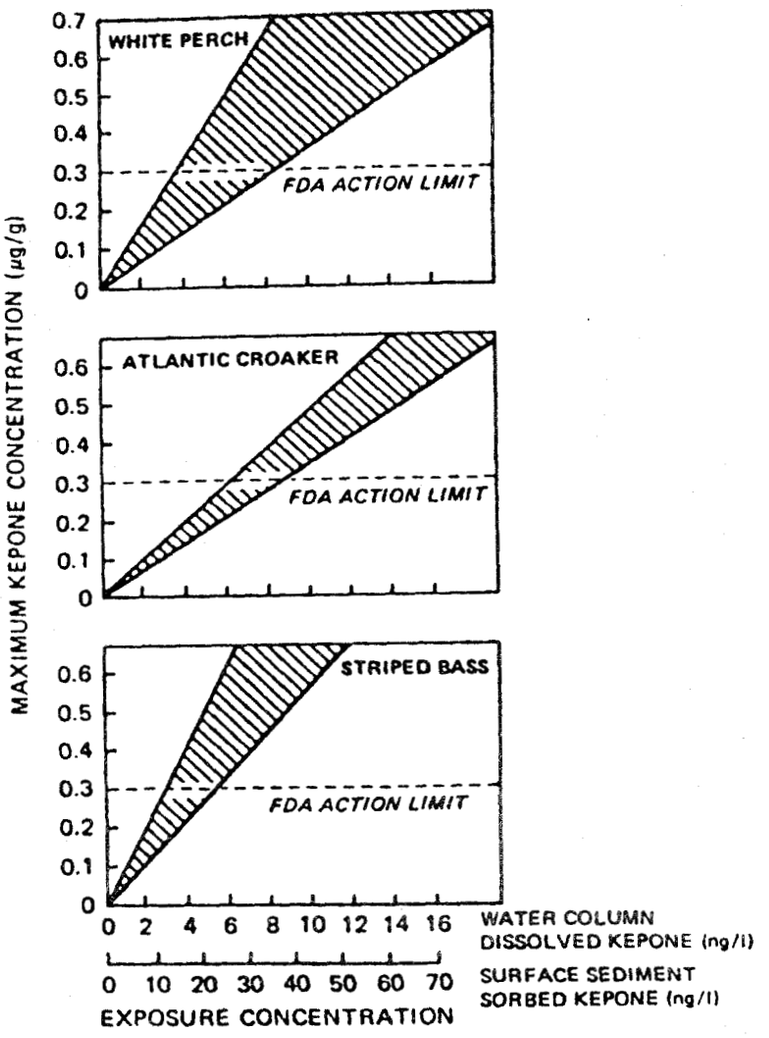

Figure 8. Projected relationship between Kepone exposure concentration and the maximum Kepone concentration in white perch, atlantic croaker and striped bass.

perch, and atlantic croaker Kepone concentrations in relation to sediment and water column exposure concentrations. The FDA action limit of 0.3 μg/g, the level used to determine suitability of the fish for human consumption, is indicated on the plots. Maximum concentrations will be below this level at water column dissolved concentrations in the range of 3-5 ng/ℓ for striped bass, 6-9 ng/ℓ for croaker, and 4-8 ng/ℓ for white perch. The associated sediment concentration ranges are 13-22 ng/g for striped bass, 26-39 ng/g for croaker, and 17-35 ng/g for white perch. Because these ranges reflect the uncertainty of the calibration, which is the lower limit of prediction uncertainty, the actual ranges may be greater.

Based on the 1980-82 data and calibration, current exposure concentrations may be assumed to be in the order of 10 ng/ℓ in the water column and 40 ng/g in the sediment. To achieve the action limit the projection then indicates exposure concentrations must be reduced 50-70% for striped bass, 10-40% for croaker and 20-60% for white perch. These reductions are significant in view of the apparent slow decline in exposure concentration indicated by figure 3. Croaker is the only one of these species likely to reach the action limit in the near future.

SECTION 7

CONCLUSIONS

The analysis of the data and the calibrated model of the striped bass food chain show that:

1. Kepone concentrations in the water, sediment, and fish of the lower James River estuary are slowly declining, although there have been occasional year-to-year increases. The increases are likely caused by hydrodynamic conditions which affect the transport of Kepone contaminated sediment, the location of the salt wedge and thus the migratory range of anadromous species, and the significance of Kepone mass transport from the interstitial water to the water column;

2. the model is capable of reproducing the trends and magnitude of Kepone contamination observed in James River white perch, atlantic croaker, and striped bass;

3. the lack of an observed trend of Kepone concentration with age results from the absence of a diet change with age in adult white perch and atlantic croaker and differences in exposure between non-migrating and migrating striped bass;

4. transfer through the food chain is a greater contributor of Kepone to the fish than direct uptake from water, accounting for 87-88% of the body burden in atlantic croaker and white perch and 91% of the body burden in striped bass;

5. the sediment is a significant source of Kepone for the food chain, accounting for approximately 50% of the body burden in atlantic croaker and white perch and 40% of the body burden in striped bass.

The projections of the response of the food chain to changes in exposure concentration indicate that:

6. to achieve a maximum concentration in striped bass at or below the FDA action limit of 0.3 µg/g the exposure concentrations must be in the range of 3-5 ng/ℓ in the water column and 13-22 ng/g in the sediment, a reduction of 50-70% from the apparent current exposure level;

7. to achieve a maximum concentration in atlantic croaker at or below the FDA action limit of 0.3 µg/g the exposure concentrations must be in the range of 6-9 ng/ℓ in the water column and 26-39 ng/g in the sediment, a reduction of 10-40% from the apparent current exposure level;

8. to achieve a maximum concentration in white perch at or below the FDA action limit of 0.3 µg/g the exposure concentrations must be in the range of 4-8 ng/ℓ in the water column and 17-35 ng/g in the sediment, a reduction of 20-60% from the apparent current exposure level.

9. the significant reductions necessary to reach the FDA action limit will likely not be achieved in the short term because of the apparent slow rate of decline of exposure concentrations.

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APPENDIX 1

KEPONE DATA

Water Column and Sediment

Water column total Kepone data collected over the period, 1976-1981, were obtained from the Virginia State Water Control Board (SWCB). Samples were collected at 56-60 stations in the estuary from above Hopewell to Chesapeake Bay (km 120-0). During 1976 and 1977 bottom and surface samples were collected at all monitoring stations in waters greater than 5 meters in depth. No significant differences were found between surface and bottom concentrations and surface samples were collected in subsequent years. During 1976-1979, samples were collected during winter, spring, summer and fall. From 1980 on, sampling was reduced to spring and summer. These data were compiled and analyzed to elucidate spatial and temporal trends within the estuary. Emphasis was placed on the lower 60 km of the estuary which represents the segment inhabited by the striped bass and Atlantic croaker.

Sediment Kepone data obtained from SWCB were also analyzed both spatially and temporally. Sediment core samples were collected at the same stations at which water samples were taken and Kepone was measured at several depths within the sediment.

The water column data for each sampling station were averaged for each year. Annual spatial profiles (Figure A-1) indicate a slight

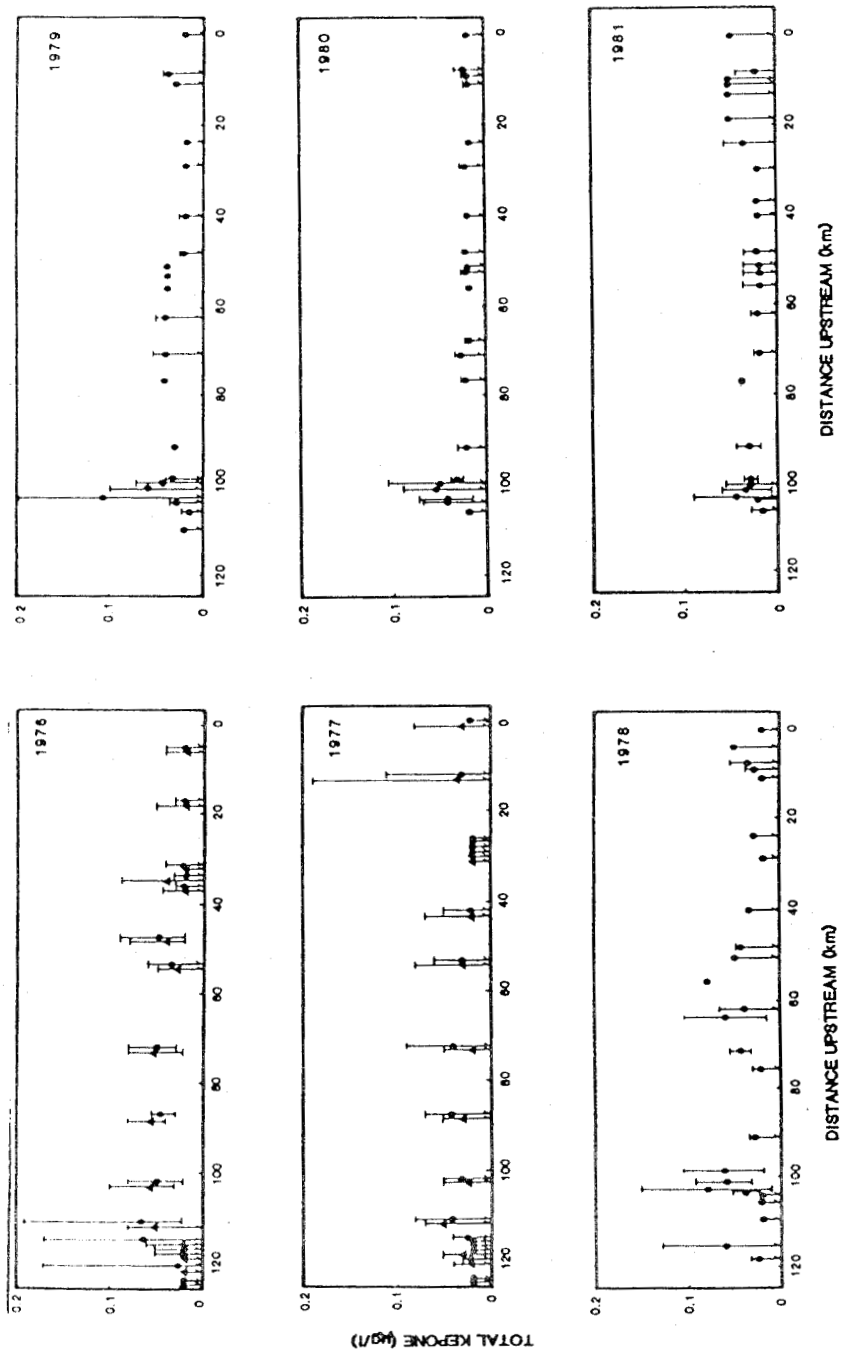

Figure A1. Annual average water column total Kepone in relation to location in the James River.

decline in concentration from Hopewell (km 120) to Chesapeake Bay (km 0). For the lower estuary (0-60 km), Kepone concentration does not change significantly with distance. Annual spatial profiles of surface sediment Kepone (0-9 cm) show a more significant gradient of concentration (Figures A-2 and A-3). Levels were the highest in the Hopewell area and decreased seaward. High Kepone levels were also found in the turbidity maximum zone, from Sturgeon Point to Jamestown Island (km 77-48). From Jamestown Island (km 48) to Chesapeake Bay, levels were usually within the non-detectable range (0.02 µg/g).

For the lower estuary (0-60 km) the data from all stations were combined and the temporal profiles of Kepone concentration in the water column and sediment were determined. Because many concentration values were reported as less than the limit of detection, it is not possible to calculate a valid mean concentration for each sampling period since values below the detection limit must be arbitrarily assigned as zero, the detection limit, or somewhere in between. An alternate method for estimating the central tendency of concentration is to consider the median value which may be obtained if greater than fifty percent of the measured values are above the limit of detection. Therefore, a log-normal probability distribution of concentration was developed for each sampling period (Figures A-4, A-5 and A-6). Median values were interpolated where greater than fifty percent of the concentrations were above the limit of detection. The median, maximum and minimum water column and sediment concentrations for each sampling period are shown in Figure A-7. In the water column, median concentrations decline for 0.03 to

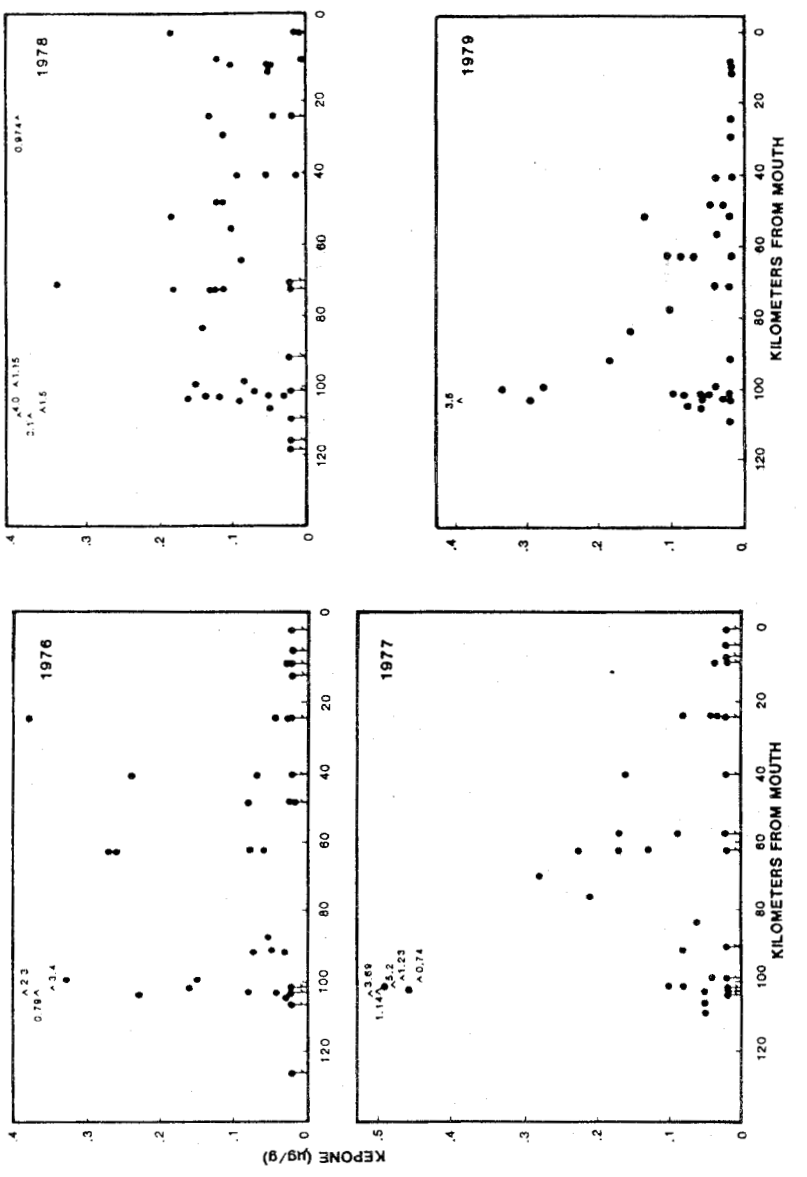

Figure A2. Surface bed sediment (0-9 cm) Kepone for 1976-1979 in relation to location in the James River

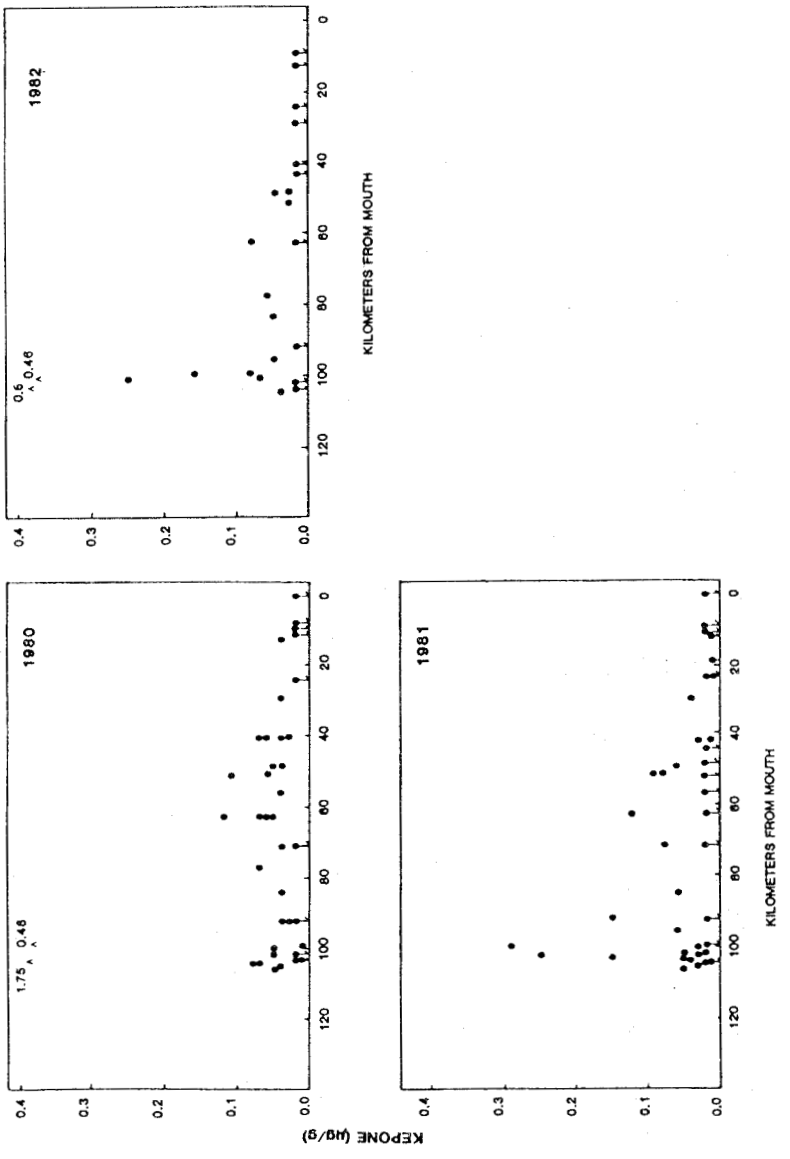

Figure A3. Surface bed sediment (0-9 cm) Kepone for 1980-1982 in relation to location in the James River.

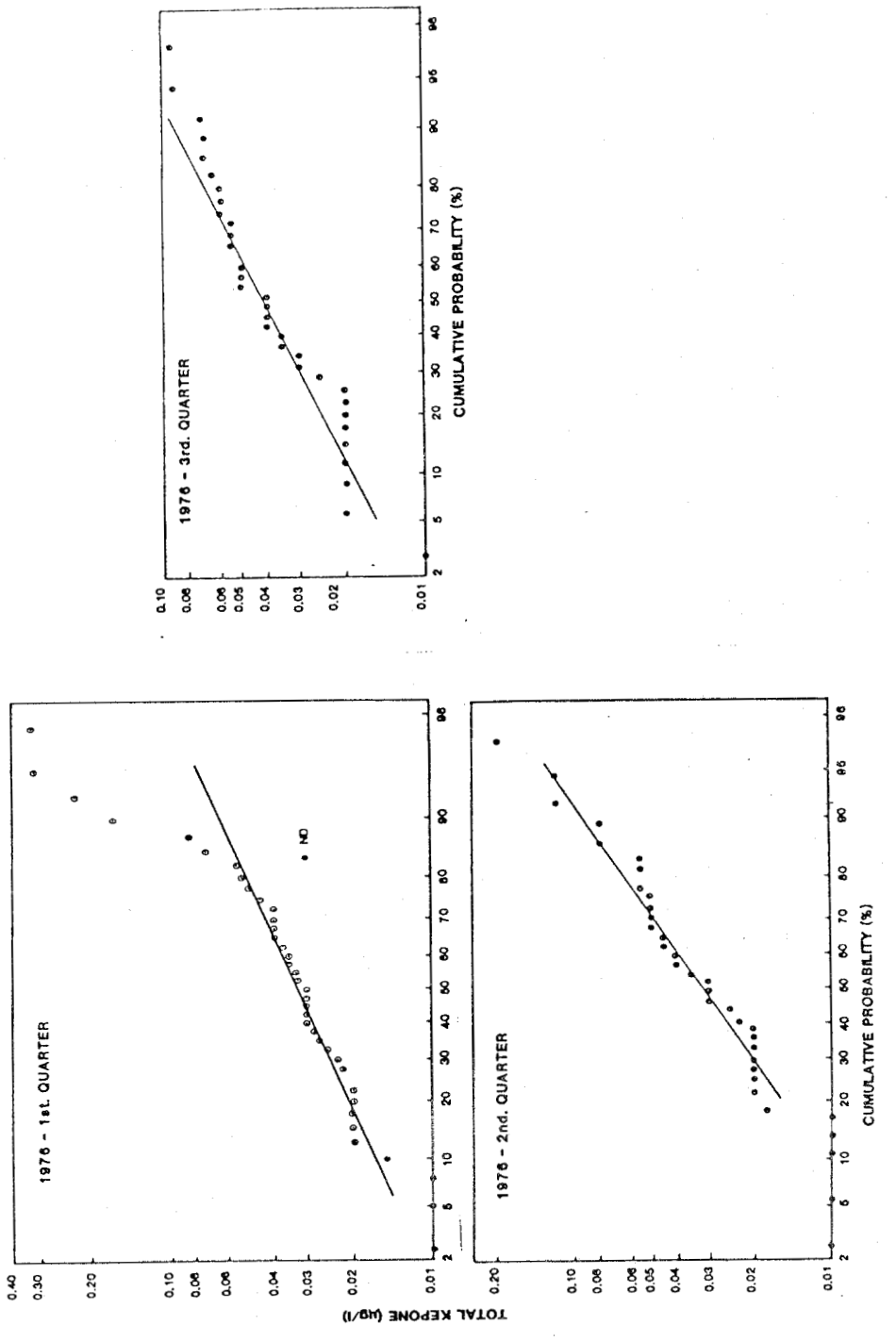

Figure A4. Log-normal probability distributions of water column total Kepone measured in the 0-60 km region of the James River at sampling periods in 1976.

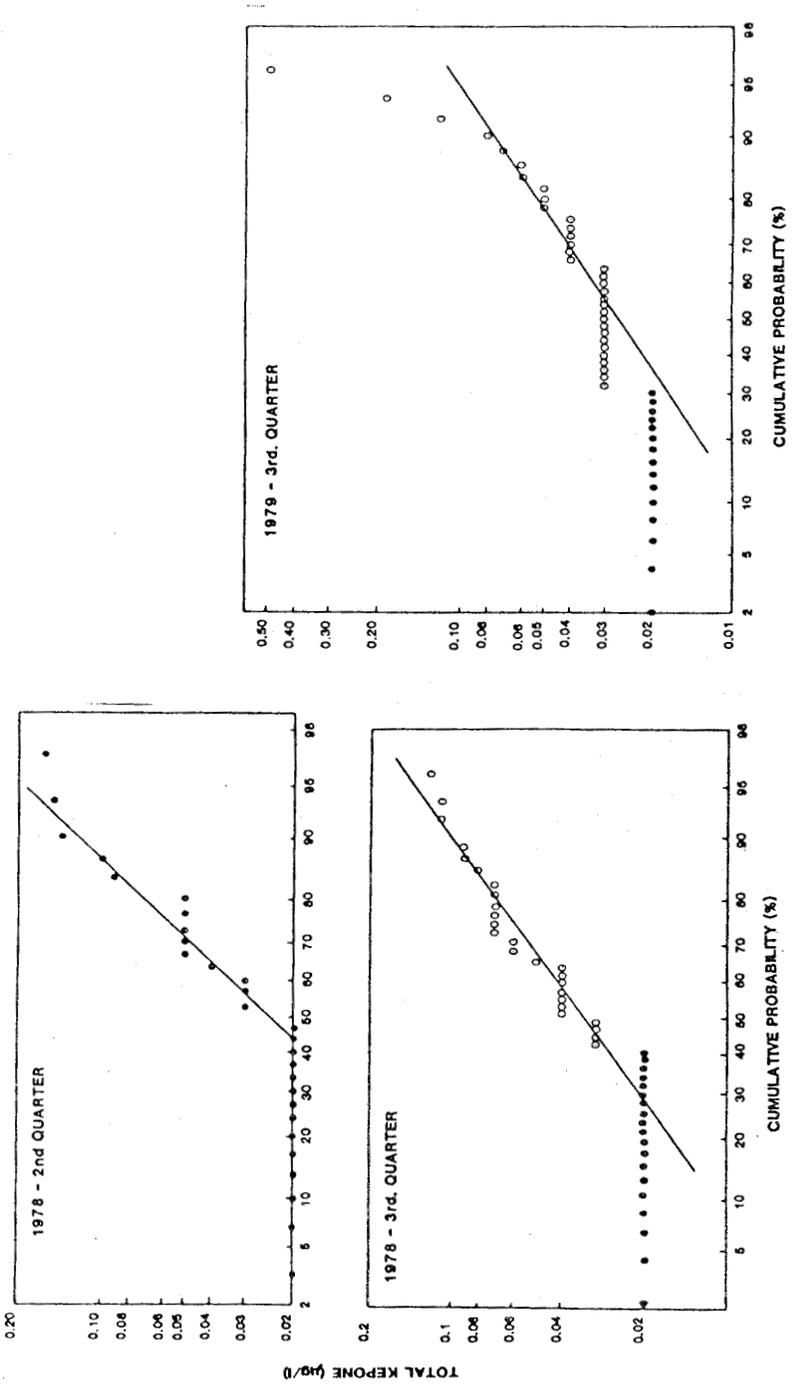

Figure A5. Log-normal probability distributions of water column total Kepone measured in the 0-60 km region of the James River at sampling periods in 1978 and 1979.

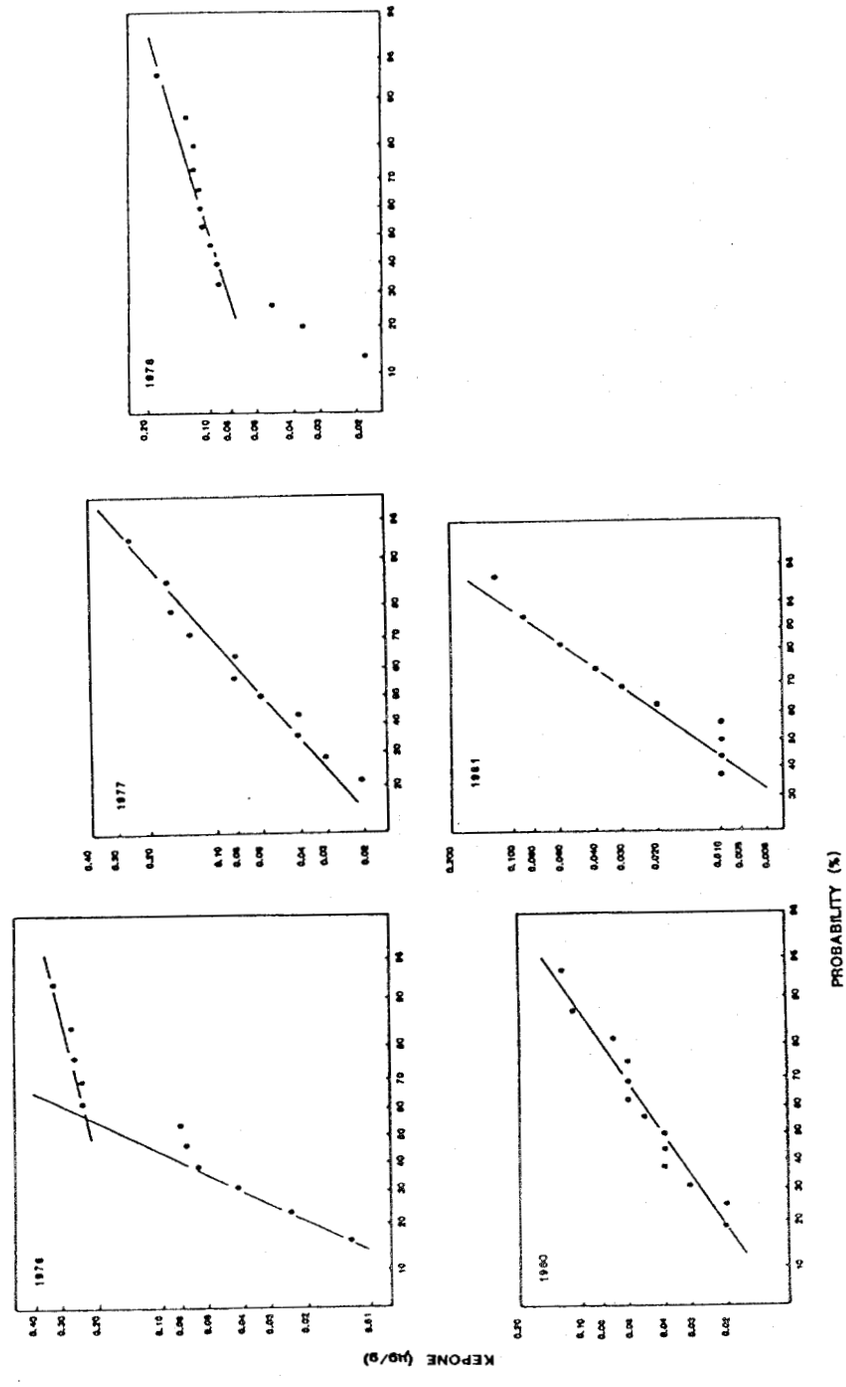

Figure A6. Log-normal probability distributions of surface bed sediment (0-9 cm) Kepone measured in the 0-60 km region of the James River for 1976-1981.

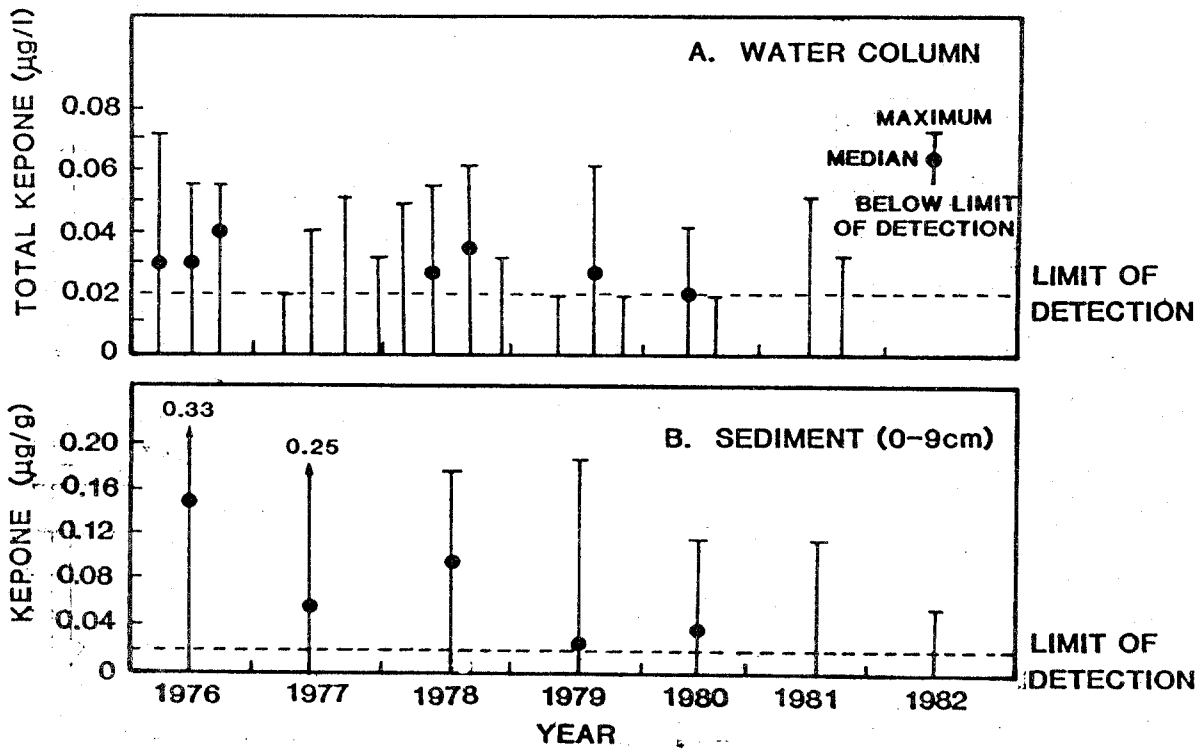

Figure A7. Median, maximum and minimum Kepone concentrations in the water column and surface sediment of the lower (0-60 km) James River over the period 1976-1982.

0.04 µg/ℓ in 1976 to non-detectable levels by 1979. Concentrations decline in similar fashion in the sediment from 0.15 µg/g in 1976 to non-detectable levels by 1981. Note that concentrations in both the water column and surface sediment increase from 1977 to 1978. This may be the result ofthe transport of highly contaminated Kepone from the Hopewell area to the lower estuary during high flows in spring 1978.

Plankton and Crustaceans

Kepone concentrations in plankton were measured at a limited number of locations within the 97 kilometer reach of the James River between Hopewell and Hampton Roads during the period June 1977 to May 1978 (Jordan et al., 1979).

Both direct and indirect methods were used to obtain Kepone levels in plankton. Direct methods consisted of analyzing plankton concentrates obtained from net tows. Indirect estimates were made by determining Kepone concentrations in seston samples taken during sediment cruises. Each sample was divided into two major constituents, phytoplankton and sediment, by centrifugation. The proportions of phytoplankton and sediment and the total Kepone concentration measured in the seston were used to construct two simultaneous equations. The solution of these equations gave the Kepone concentrations in the suspended sediment and phytoplankton.

In 1977, direct and indirect measurements for Kepone levels in phytoplankton were made during September and October. Actual measurements yielded levels ranging from non-detectable to 2.06 ppm and an average of

1.34 : 0.65 ppm. Indirect estimates were in close agreement with measured values and yielded 1.12 ppm. Kepone concentrations in zooplankton were measured during two periods, June to October and November to December. Concentrations during the earlier sampling period ranged from 0.78 to 16.13 ppm, averaging 6.055 ± 4.54 ppm. During the second period, levels declined to between 1.27 and 15.58 ppm with a mean of 4.84 ± 4.58 ppm. For both periods, Kepone concentrations differed within samples collected from the same stations depending upon the taxonomic composition of the samples. The maximum concentrations were measured in copepod samples comprised of the two generas, Acartia and Eurytemora. Since the taxonomic group of plankton sampled was not held constant and because of the large variation in levels among taxonomic groups, spatial analysis of Kepone levels in plankton could not be adequately assessed.

Similar measurements for the year 1978 during April and May indicated a general reduction in both phytoplankton and zooplankton Kepone levels. Concentrations in phytoplankton were at non-detectable levels while zooplankton ranged between 0.16 and 1.12 ppm, averaging 0.425 ± 0.273 ppm.

Collection of grass shrimp, Palaemonetes pugio near the James R. bridge showed that Kepone levels in ovigerous females ranged from 0.005 to 0.63 ppm. Samples taken from areas distant to the James River showed low or undetectable levels of Kepone (Provenzano et al., 1978).

Finfish

Data utilized for Kepone analysis in finfish were obtained from the

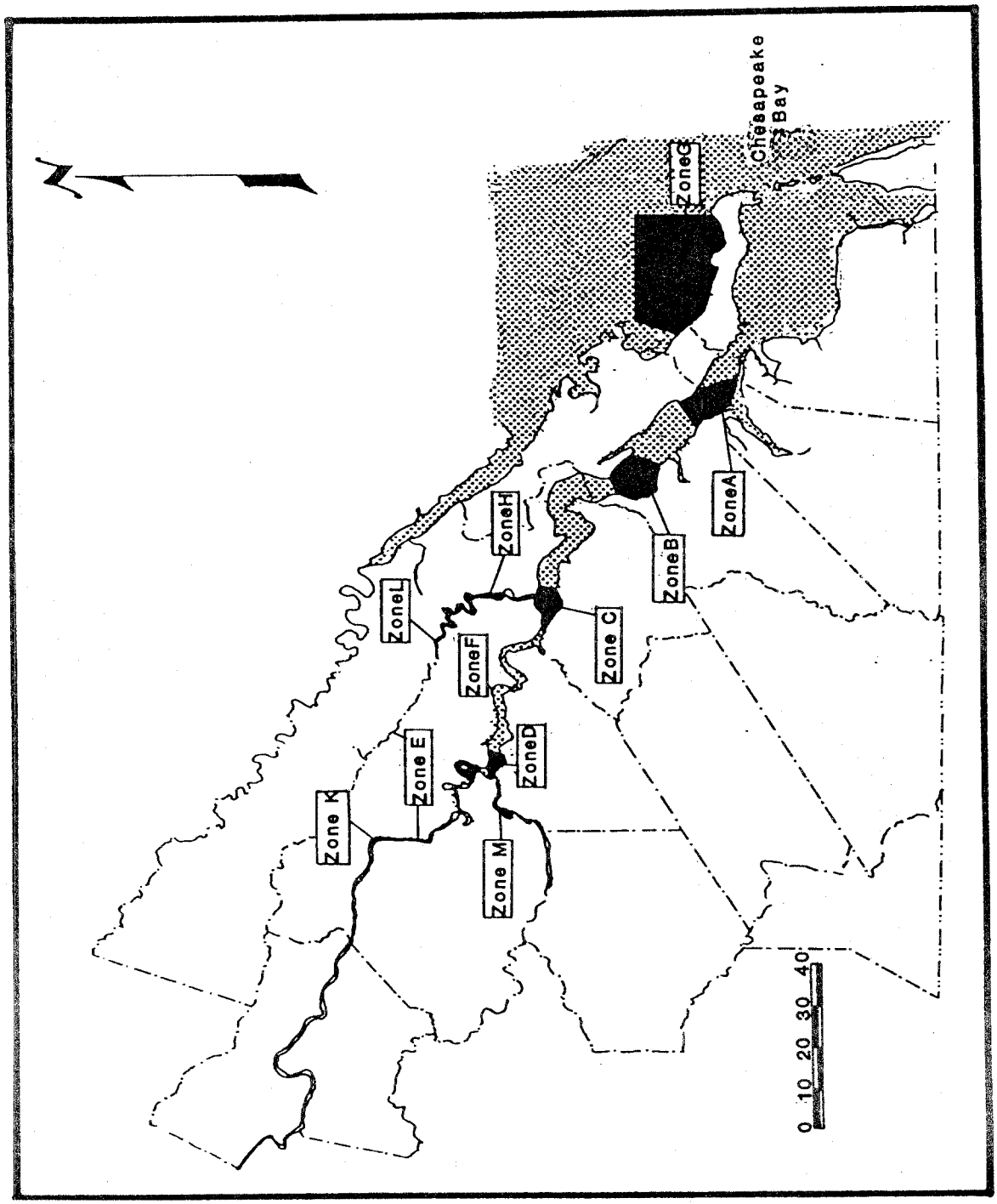

Figure A8. Finfish sampling zones in the James River (Lunsford, et al., 1980)

Virginia Institute of Marine Science (VIMS) for the year 1976, and from (SWCB) for the period 1977-1983. Kepone levels were measured approximately every 15-30 days at the locations shown on the map (Figure A-8). Samples were taken at several locations along the river. For this study, data were utilized from only those locations in which data was available for the three species of fish: Atlantic croaker, white perch and striped bass. These locations are designated as zones A, B and C and correspond to approximately a 60 km stretch beginning in the lower James River at Small Boat Harbor and extending to the mouth of the Chickahominy River. Station A is furthest downstream and proceeds up to the James River Bridge. Located further upstream, is Station B, lying in the Burwell Bay area. Station C, located at the mouth of the Chickahominy River, lies approximately midway in the James River.

Finfish samples were obtained through the use of various collection methods such as electrofishing equipment, gill nets and trawls. For each analysis, an attempt was made to obtain a minimum collection number of 10 samples per species, however, the actual number varied depending on the seasonal availability of the species. Kepone levels utilized for this study are edible meat (muscle) concentrations, but brain and liver samples have also been analyzed. Substantial differences in Kepone residues in muscle and liver samples have been found. For example, for white perch collected in 1976, Kepone concentrations in muscle and liver tissue averaged 1.91 µg/g and 4.18 µg/g, respectively.

In analyzing the finfish data for stations A, B and C, no significant spatial trends were evident. Atlantic croaker did exhibit slightly

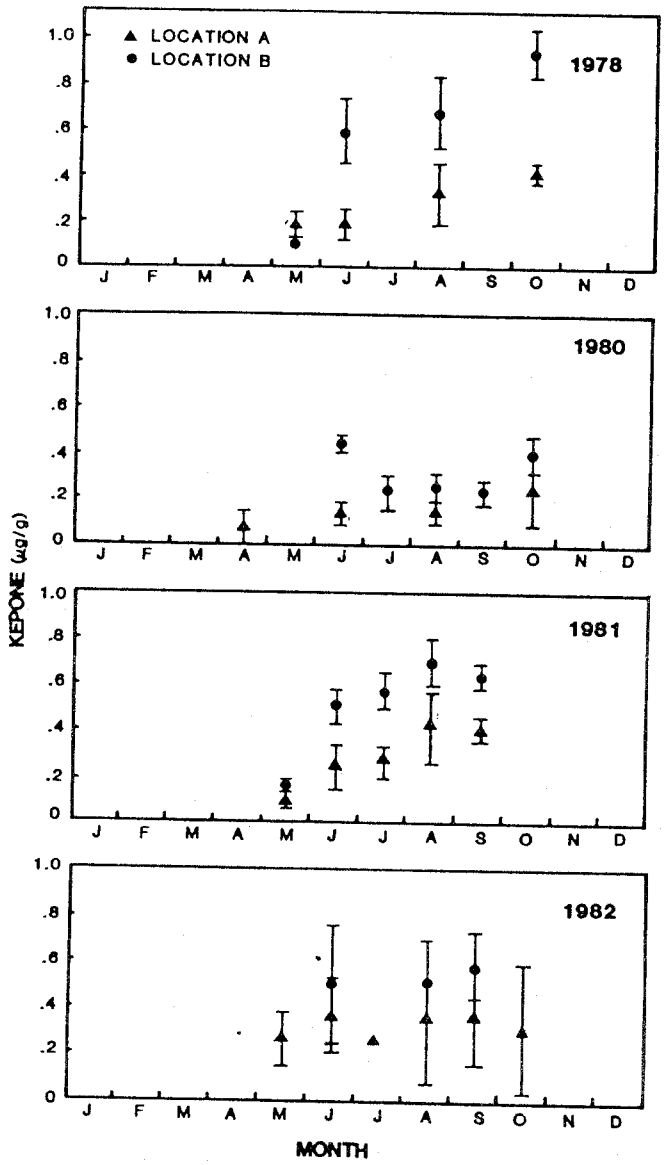

Figure A9. Average (± standard deviation) Kepone concentrations in Atlantic croaker for each sampling time at locations A and B.

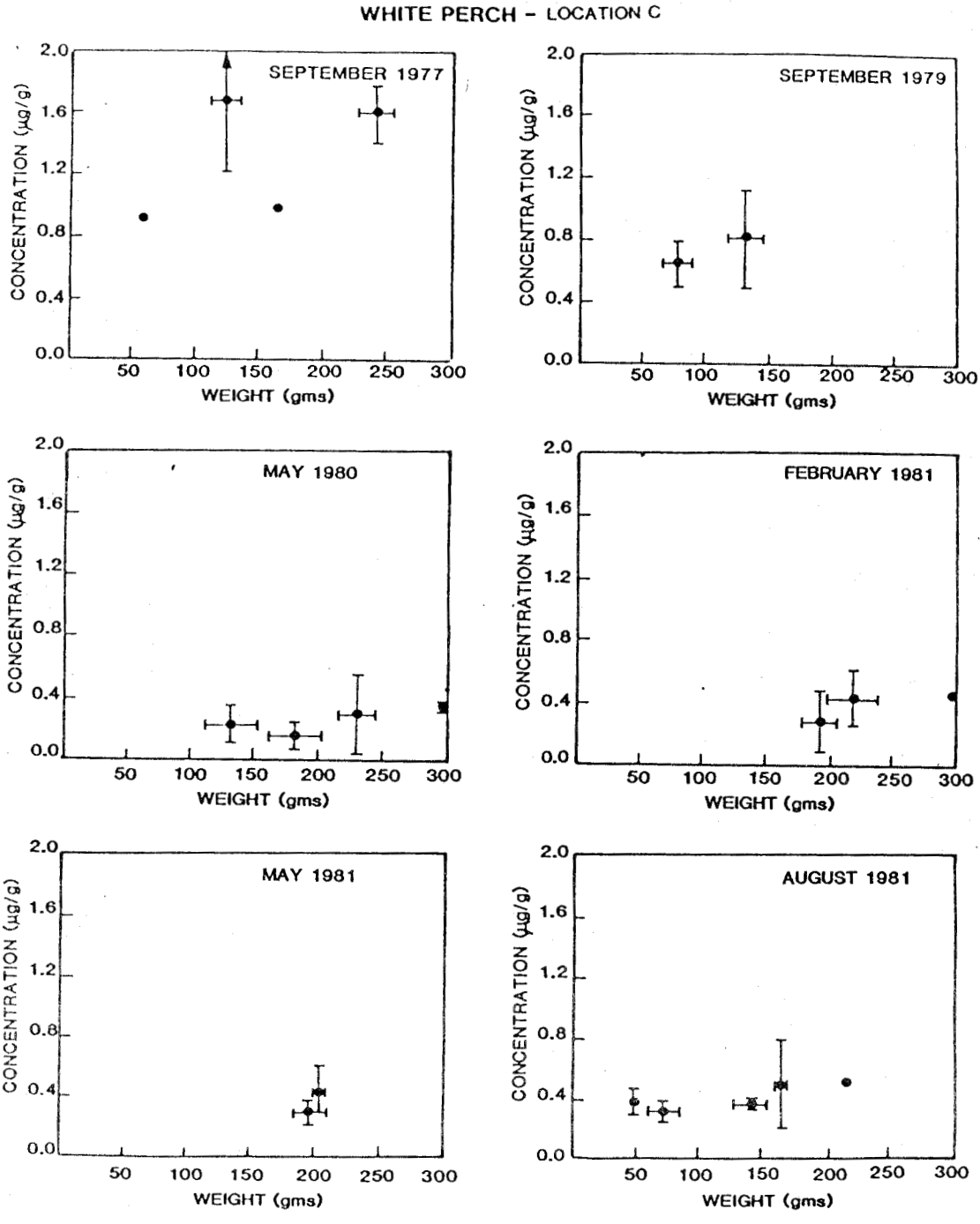

Figure A10. Kepone concentration in white perch from location C in relation to weight of the fish.

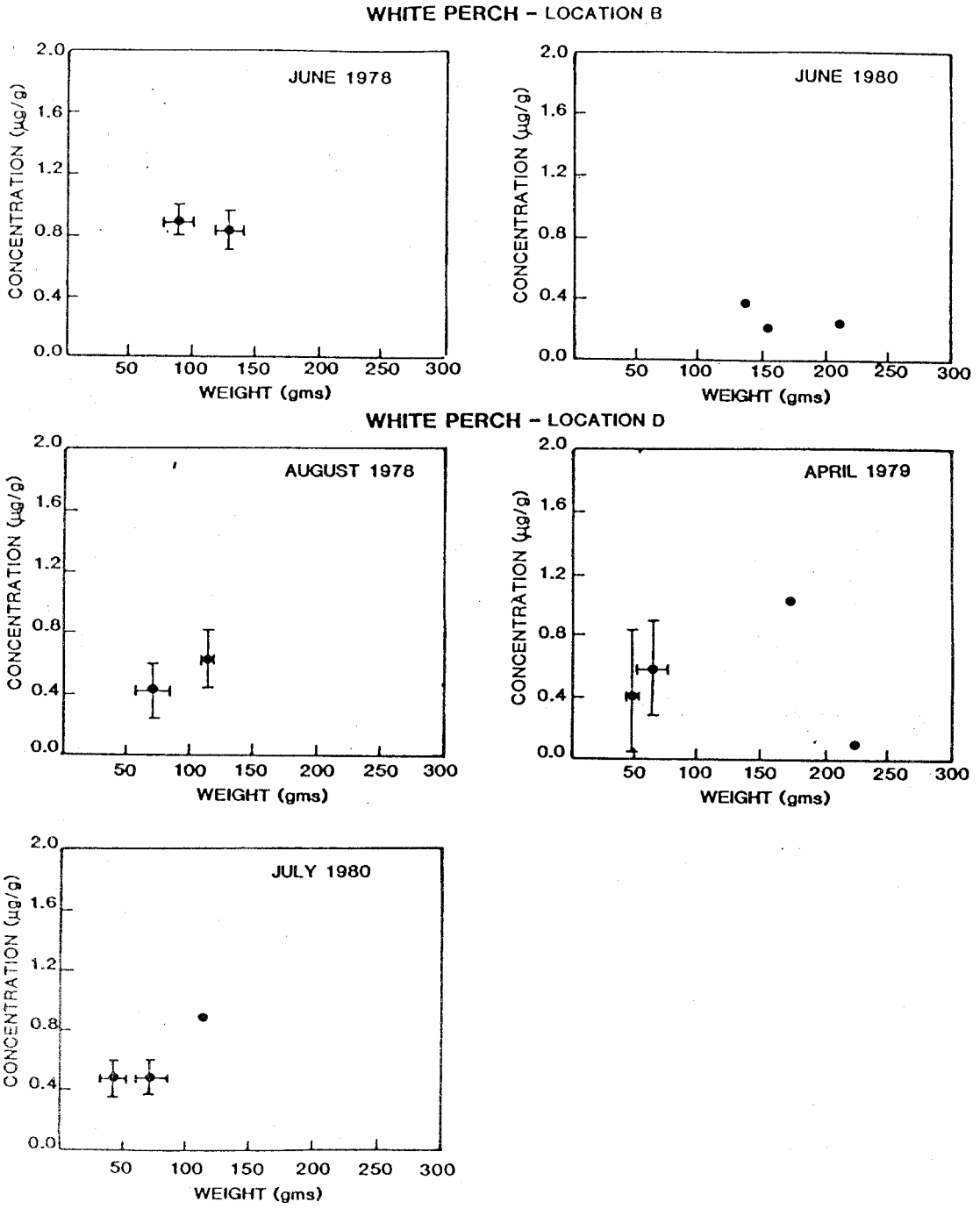

Figure A11. Kepone concentration in white perch from locations B and D in relation to weight of the fish.

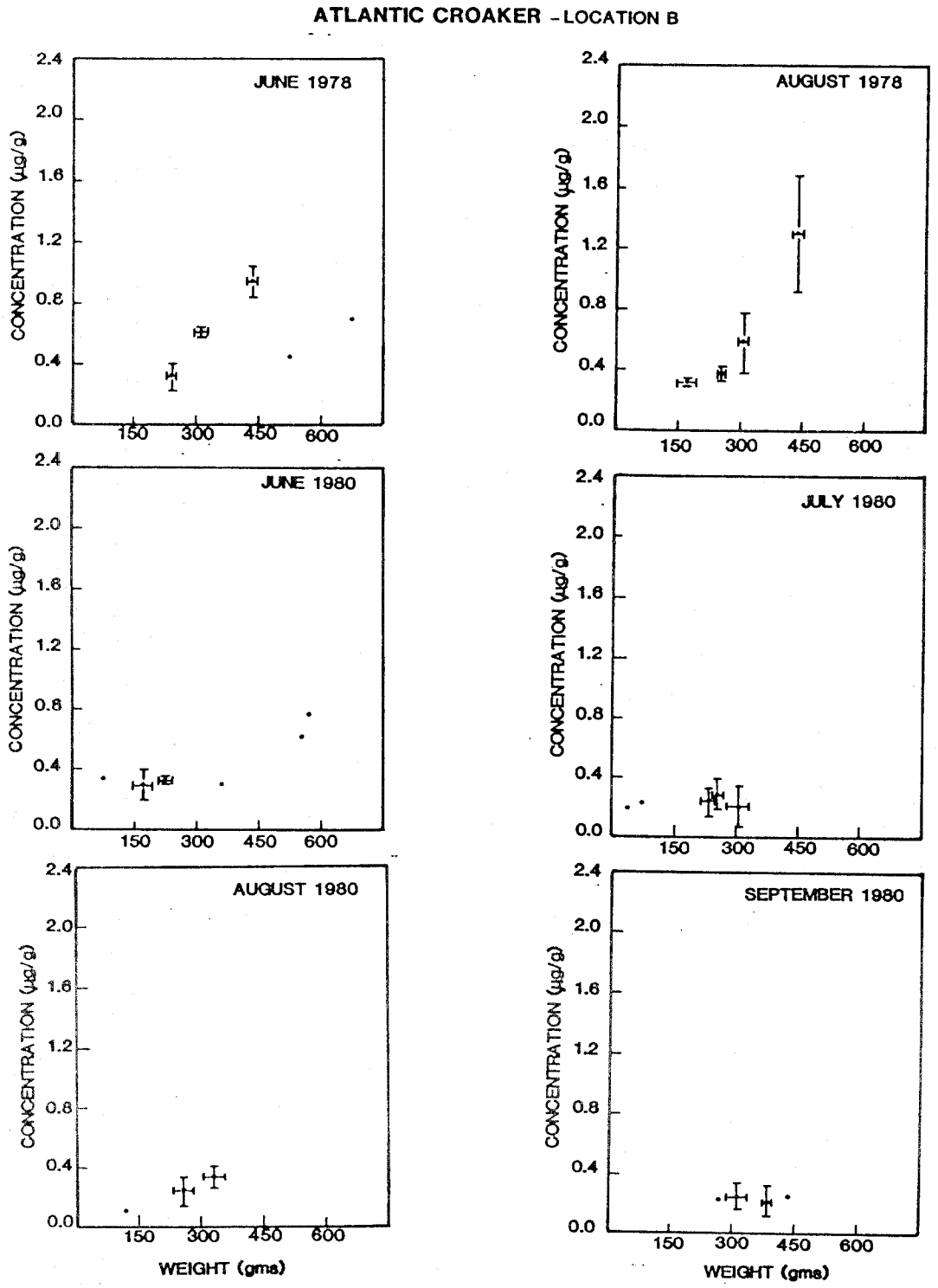

Figure A12. Kepone concentration in Atlantic croaker from location B in relation to weight of the fish.

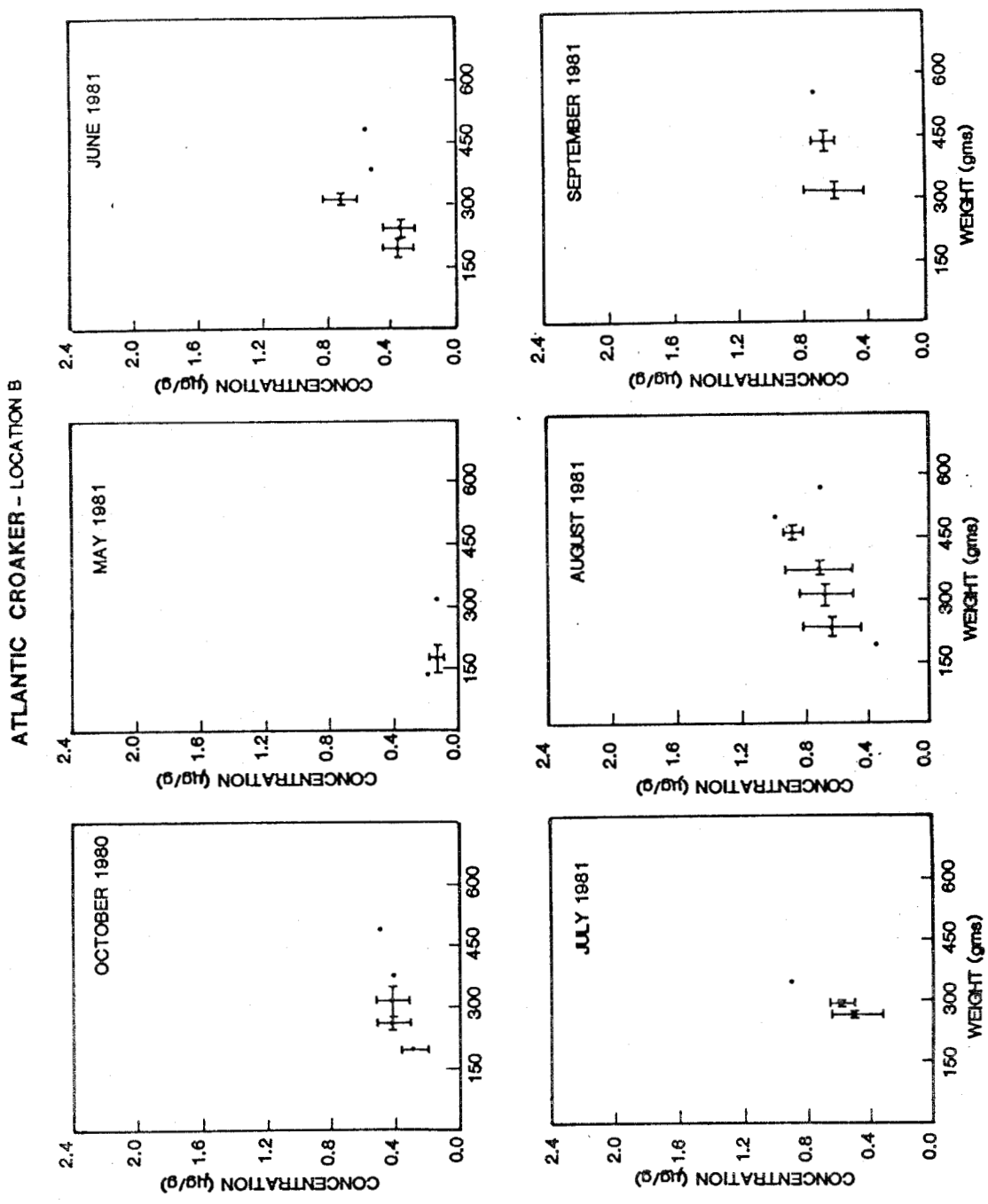

Figure A13. Kepone concentration in Atlantic croaker from location D in relation to weight of the fish.

higher concentrations at station B than at station A (Figure A-9). However, with the exception of 1978, residues were similar at both locations. Bender and colleagues (1977) also found no spatial trends in residue levels for either estuarine or freshwater species.

To determine if significant trends in Kepone concentration with age existed the data were averaged over intervals of 50 grams and plotted as a function of weight and according to month and location. With some exceptions, the Kepone concentrations of white perch and Atlantic croaker increase with weight (Figures A-10 - A-13). This trend is significant for Atlantic croaker in a few sampling periods, however, the increases are generally slight. Only small increases are seen for white perch. Striped bass do not exhibit any consistent trend in Kepone concentration with weight (Figure A-14 - A-16). Differences in migration pattern with age alters the exposure and likely confounds any trends with weight of this species.

For comparison with the model the data were averaged over all weights. The data were not separated by age class because only a limited number of ages were sampled relative to the life span of each species.

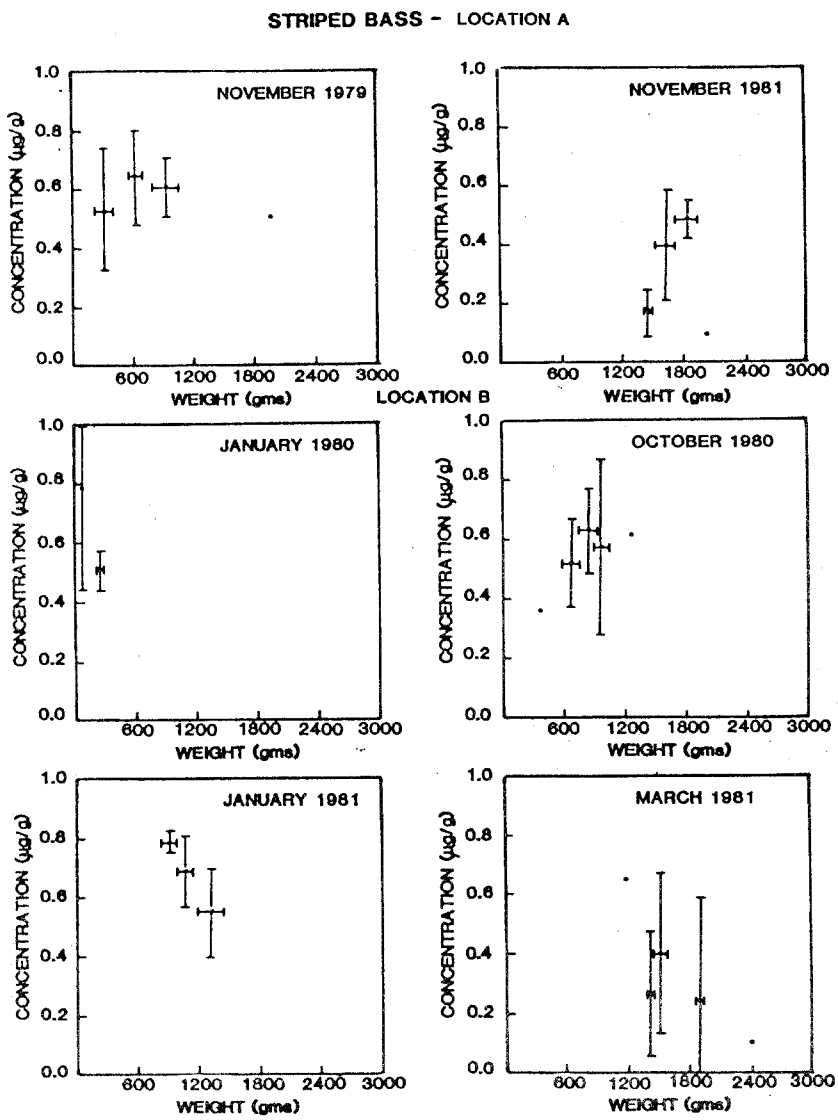

Figure A14. Kepone concentration in striped bass from location A in relation to weight of the fish.

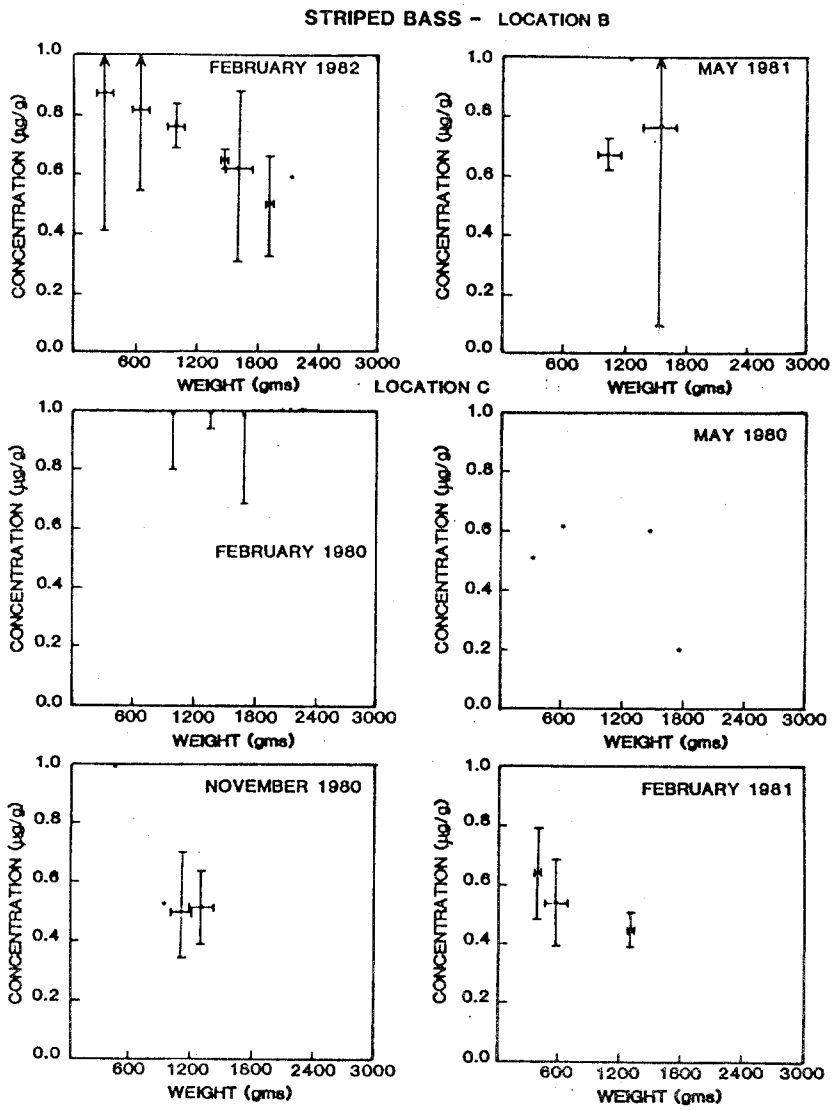

Figure A15. Kepone concentration in striped bass from location B in relation to the weight of the fish.

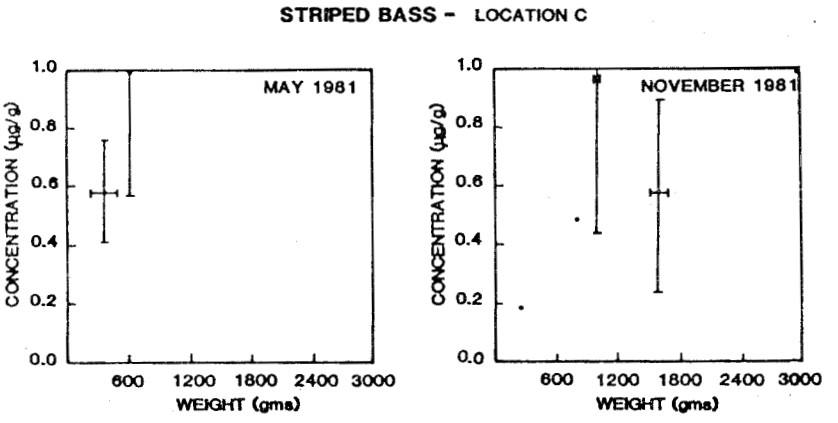

Figure A16. Kepone concentration in striped bass from location A in relation to weight of the fish.

APPENDIX 2

PREDATOR-PREY LENGTH RELATIONSHIP

Stomach content data for 1,069 yearling and adult striped bass from Albemarle Sound, North Carolina obtained from C.S. Manooch (North Carolina State University, personal communication) were used to determine a prey size distribution for striped bass. Striped bass were collected from July 1970 through August 1971. The specimens ranged from 125 to 714 mm in total length. Stomach content analysis indicated that the dominant food items were fish, mainly Atlantic menhaden, alewife, and bay anchovy. Food organisms were grouped according to taxon and total lengths were measured. Partially digested fish were compared to preserved specimens in order to determine a "restored value", or an estimated total length. Manooch provided us with total lengths for striped bass and their respective prey, compiled on a monthly basis. We separated prey lengths by striped bass age class. These values were then averaged to obtain a mean of prey length for each age class of striped bass. Age classes for striped bass were determined using the growth rates presented in Table 1. Figure A-17 shows the mean prey length and standard deviation in relation to striped bass age class. An approximately linear increase in prey size with age of the striped bass is evident. These prey lengths were used to determine the age classes of white perch and atlantic croaker assigned as prey to each age class of

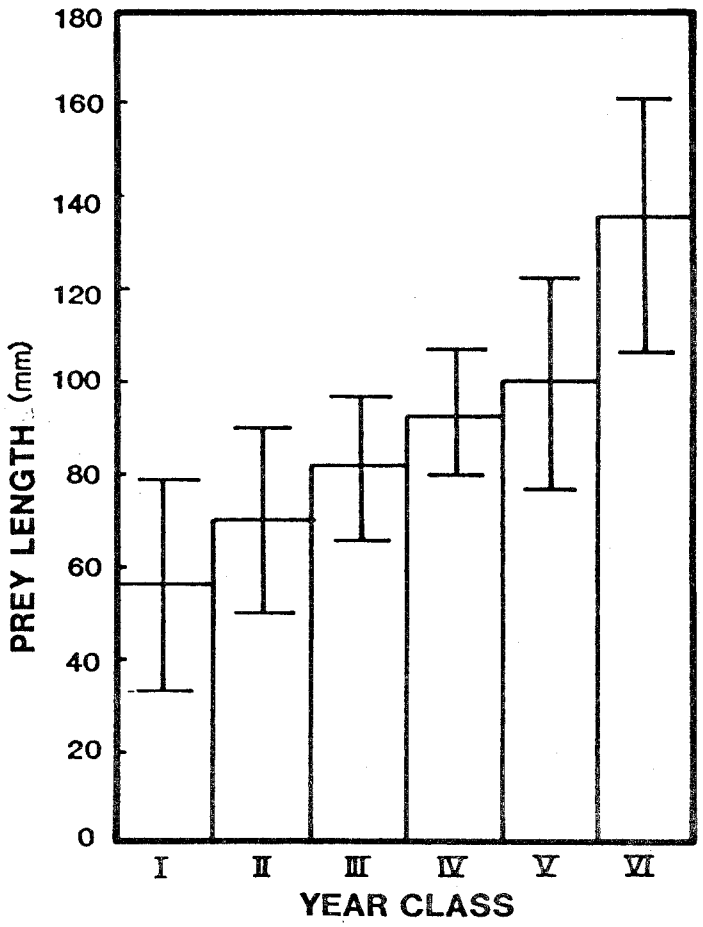

Figure A17. Average (± standard deviation) prey length in relation to striped bass age.

striped bass. Table A-1 presents the predator-prey relationships used in the model.

TABLE A-1. PREDATOR-PREY RELATIONSHIPS USED IN THE MODEL

Species	Age Class	Prey
Striped bass	0	Plankton
	1-2	Neomysis
	3-4	Atlantic croaker (Age class 0)
		White perch (Age class 1)
	5	Atlantic croaker (Age class 0)
		White perch (Age class 1)
	6	Atlantic croaker (Age class 1)
		White perch (Age class 2)
	7-8	Atlantic croaker (Age class 1)
		White perch (Age class 3)
	9-10	Atlantic croaker (Age class 2)
		White perch (Age class 4)
Atlantic croaker	0	Plankton
	1	Plankton
		Neomysis
		Polychaete
	2	Neomysis
		Polychaete
White perch	0	Plankton
	1	Plankton
		Neomysis
	2-7	Neomysis
		Polychaete

APPENDIX 3

RELATIVE CONTRIBUTIONS OF FOOD, WATER AND SEDIMENT TRANSFER TO TOTAL KEPONE BODY BURDEN

Kepone accumulation occurs through exposure from water and consumption of contaminated prey. In addition, benthic invertebrates consume sediment and are in turn consumed by higher trophic animals and therefore provide a mechanism for transfer of sediment Kepone to the food chain. In the model, contaminated sediment is transferred from Nereis, a detritus-consumer, to higher levels of the food chain. The relative amount of Kepone contamination from the bed was determined by eliminating exposure from water. The results obtained are shown in Figure A-18. The shaded area represents the relative amount of Kepone derived from sediment transfer. Approximately 40% of the computed Kepone concentration in striped bass and 50% in Atlantic croaker and white perch is due to sediment transfer.

The amount of Kepone in a particular species resulting from exposure through water was determined by setting the toxicant assimilation efficiency of that species equal to zero. The shaded areas in Figure A-19 represent the fraction of Kepone incorporated in the fish through uptake from water. The difference between the upper curve (i.e. the Kepone concentration due to food and water) and the lower curve (i.e. the Kepone concentration due to water) is the relative amount of Kepone derived from consumption of contaminated prey. This indicates that

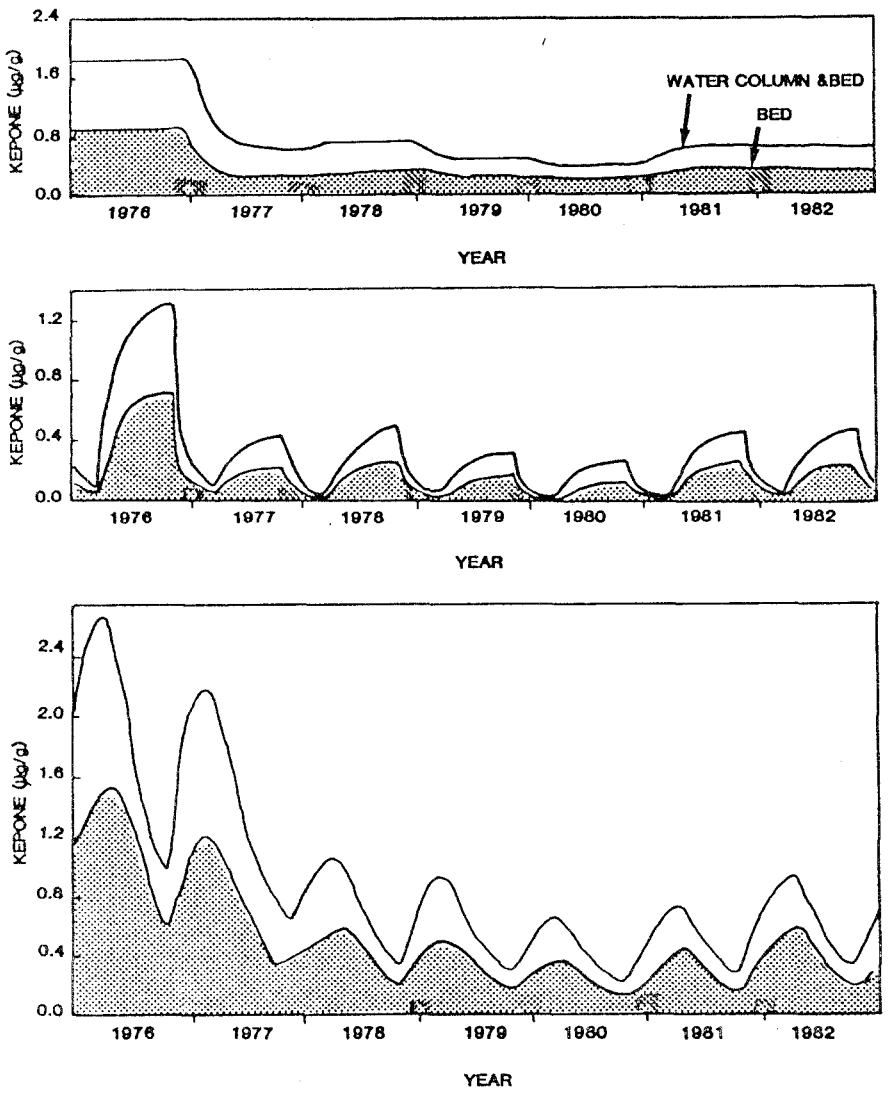

Figure A18. Contribution of bed sediment Kepone to Kepone concentrations computed in a) white perch, b) Atlantic croaker, and c) striped bass.

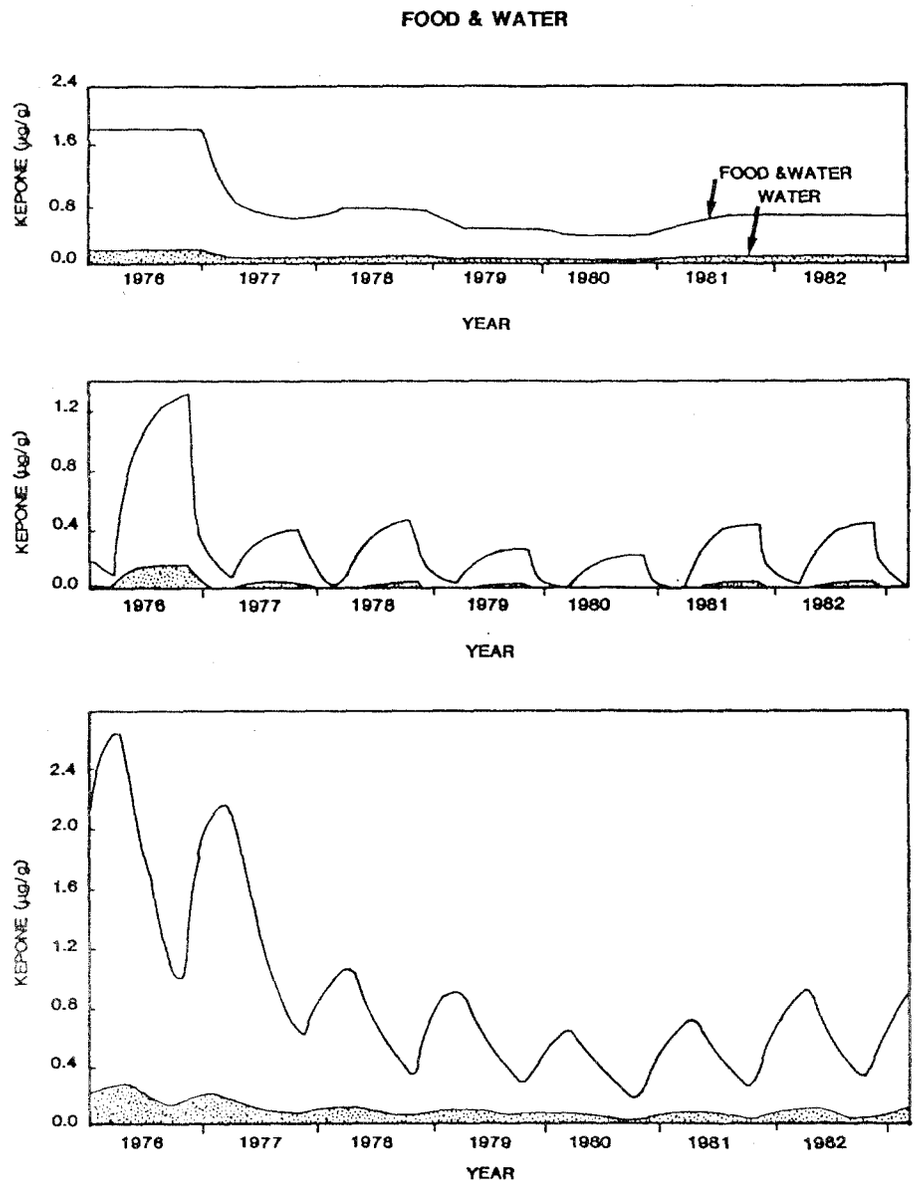

Figure A19. Relative contributions of direct uptake from water and food to Kepone concentrations computed in a) white perch, b) atlantic croaker, and c) striped bass.

transfer through the food chain accounts for the major portion of Kepone incorporated by the three species: 87-88% in Atlantic croaker and white perch and 91% in striped bass.