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# BIOUPTAKE OF CHLORINATED HYDROCARBONS FROM LABORATORY-SPIKED AND FIELD SEDIMENTS BY OLIGOCHAETE WORMS

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## MANAGEMENT PERSPECTIVE

Oligochaete worms have been shown to be one mechanism of mobilization of contaminants from bottom sediments. The worms accumulate the chemicals in their tissue from the pore water and enhance the diffusion of chemicals from sediments by bioturbation. The chemicals are thus made available to fish or other higher organisms via either consumption of the worms or through bioconcentration from the water. The controlled experiments conducted here on 37 chlorinated chemicals have shown that sediment pore water concentrations of the organic contaminants are the most important driving force for bioaccumulation by the worms. The experiments also demonstrated that new field sampling protocols are required to establish field residues of the less persistent chemicals. Further laboratory and field experiments on population dynamics and interaction kinetics will be required to assess the importance of these organisms and other benthic invertebrates on contaminant movement from sediments.

Il est apparu que les vers oligochètes constituaient l'un des mécanismes de mobilisation des contaminants dans les sédiments de fond. Les vers accumulent les produits chimiques dans leurs tissus à partir de l'eau interstitielle et favorisent leur diffusion à partir des sédiments, par bioturbation. Les produits chimiques deviennent donc ainsi disponibles pour les poissons et autres organismes supérieurs soit par consommation des vers, soit par bioconcentration à partir de l'eau. Des expériences contrôlées effectuées sur place sur 37 produits chimiques chlorés ont montré que les concentrations de contaminants organiques de l'eau interstitielle sédimentaire sont le principal facteur dans la bioaccumulation des produits par les vers. Les expériences ont également démontré la nécessité de mettre au point de nouveaux protocoles d'échantillonnage sur le terrain pour évaluer les résidus des produits chimiques moins persistants. D'autres expériences en laboratoire et sur le terrain portant sur la dynamique des populations et la cinétique des interactions devront être effectuées pour évaluer l'importance de ces organismes et des autres invertébrés benthiques dans le déplacement des contaminants contenus dans les sédiments.

ABSORPTION BIOLOGIQUE PAR LES VERS OLIGOCHETES DES HYDROCARBURES CHLORES CONTENUS DANS LES SEDIMENTS ENRICHIS EN LABORATOIRE ET PRELEVES SUR LE TERRAIN

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## ABSTRACT

The uptake and depuration of 37 chemicals from spiked Lake Ontario sediments by oligochaete worms has been studied at 8° and 20°C in laboratory aquaria. The worms were found to rapidly accumulate the chemicals and reach peak concentrations within two weeks. The concentration of chemicals in the sediment pore water appeared to be the major factor controlling the bioconcentration of chemicals by the worms. The worm bioconcentration factors increased with increasing octanol-water partition coefficient of the chemicals. The worm-mediated fluxes of the chemicals from the sediments have also been estimated. Depuration studies showed the half-lives of the chemicals in the worms ranged from less than five days to several months. Field worms and associated sediments from Lake Ontario near the Niagara River were analyzed and compared to data generated in the laboratory study.

RESUME

L'absorption et la dépuration par les vers oligochètes de trente sept produits chimiques présents dans les sédiments enrichis du lac Ontario ont été étudiées dans des aquariums de laboratoire à 8° et 20°C. Il est apparu que les vers accumulaient rapidement les produits en question et atteignaient des concentrations de pointe en deux semaines. La concentration des produits chimiques dans l'eau interstitielle des sédiments est apparue comme le principal facteur controlant la bioconcentration de ces produits dans les vers. Les facteurs de bioconcentration augmentaient en fonction du coefficient de partage octanol-eau des produits chimiques. Les flux des produits chimiques médiatisés dans le ver à partir des sédiments ont également été évalués. Les études de dépuration ont montré que les demi-vies des produits chimiques dans les vers variaient de moins de cinq jours à plusieurs mois. Des vers prélevés sur le terrain et leurs sediments associés prélevés dans le lac Ontario près de la rivière Niagara ont été analysés et les données recueillies ont été comparées à celles de l'étude en laboratoire.

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## INTRODUCTION

Contaminated sediments are a major problem in the Great Lakes region and in many other industrialized countries throughout the world. Many chlorinated hydrocarbons exhibit a strong tendency for adsorption to suspended and/or bottom sediments when they are discharged to the aquatic environment (1). PCB's (2), chlorobenzenes (3), mirex (4), and chlorostyrenes (5) are some of the chemicals which have been found at high concentrations in Great Lakes sediments. Knowledge of the bioavailability of these sediment-associated chemicals is a critical requirement for assessing their potential hazards in sediments.

Benthic organisms can influence the availability of chemicals in two ways: they can enhance the rate of diffusion of chemicals out of bottom sediments into the water column by the process of bioturbation (6, 7) or they can incorporate the chemicals into their tissue by adsorption from ingested sediments and/or pore water (8, 9). In the first case, the chemicals are then available to higher organisms such as fish through the bioconcentration process (10) and in the second case through the food chain process (11). In a field study Fox *et al.* (12) demonstrated a strong correlation between sediment hexachlorobenzene (HCB) concentration and oligochaete HCB concentration for several Lake Ontario sediments. Polychaete worms in marine systems have been shown to accumulate PCB's from contaminated

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sediments (13, 14). The degree of accumulation by the worms seemed to be inversely correlated with worm size (13) and likely with organic matter content of the sediment (15).

In an earlier laboratory study it was demonstrated that oligochaete worms could become contaminated by feeding on and living in anthropogenically contaminated sediment from Lake Ontario (8). In that study only a limited number of chemicals could be studied because of detection limit problems at the environmentally-encountered concentrations. In the current study spiked sediments were used to obtain a broader compound coverage, and a flow-through (instead of static) system was employed. Two different temperatures 8°C and 20°C were used to assess the effect of this variable. Oligochaetes and associated sediments were collected from several contaminated Lake Ontario field sites to find out whether the laboratory-derived data could be applied in the field.

## EXPERIMENTAL

A large sediment sample (4.6% organic carbon) was collected from the central basin of Lake Ontario for the experiment. A sediment slurry (≈20% solids) was prepared to which the chemicals in acetone were added slowly dropwise over a period of several days with constant stirring. The spiked sediment slurry was then stirred periodically and "aged" for six weeks prior to use. Karichkoff (16) has previously

shown that, depending on the chemical, days to several weeks may be required for diffusion processes within the sediments to achieve equilibrium. Three kilograms of the sediment were then placed in each of four (30 cm x 60 cm x 30 cm deep) aquaria and allowed to settle for three days (sediment depth 5-6 cm). The water supplied to the tanks was carbon filtered tapwater from Lake Ontario. The water was circulated through coils submersed in 8°C or 20°C thermostats prior to entering the aquaria and cooling coils at the appropriate temperature were placed in each aquaria to maintain the temperature at 8±1 and 20±1°C. The two tanks used at each temperature were connected in series and the water flow rates were 110±10 mL/min for the 8°C tanks and 150±15 mL/min for the 20°C tanks.

Approximately 13 grams wet weight of worms (≈7000 worms/$m^2$) from Toronto Harbour (Lake Ontario) were added to each tank to begin the exposure period. The worms, which were mainly Tubifex tubifex and Limnodrilus hoffmeisteri, had an average dry weight of 13% and a lipid content of 1%. In order to made a correction for contaminant present in the gut on ingested sediments, the dry worms were muffled at 500°C to measure the amount of sediment they contained. This sediment accounted for 15% of the dry weight and, in most cases, a negligible amount of the contaminant. Worms and sediments were recovered from the tanks after 4, 11, 39 and 79 days of exposure. At 79 days the remaining worms from the two cold tanks were combined and placed in an 8°C tank containing clean Lake Superior sediments. Similarly worms

from the two warm tanks were combined and added to a 20°C tank containing Lake Superior sediments to begin the depuration phase of the study. Samples were collected after 5, 12, 21, 36 and 84 days of depuration.

Soxhlet extraction with acetone/hexane was used to extract the chemicals from the sdiments and worms as previously described (17). Water samples were pressure filtered through a glass fiber filter (1 μm) prior to extraction with hexane. Pore water samples, collected by submersing a pipette in the sediment and slowly sucking up the water with a rubber bulb, were centrifuged and pressure filtered prior to liquid-liquid extraction with hexane. All procedures were thoroughly tested prior to use and recoveries were excellent, >80% (see also Oliver and Nicol (17)). Quantification was carried out by a dual column capillary gas chromatographic method with 30 m, DB5 and DB17 columns and electron capture detectors.

Field samples of worms and sediments were collected using a box corer (0.25 $m^2$). The sediment was screened on site using a 500 μm plankton net and the benthic organisms and debris were transferred to wide mouth jars on site. The jars were kept cool until return to the laboratory where the organisms were sorted. The sorting was completed within three days of collection and the worm samples and sediments were then frozen until analysis.

## RESULTS AND DISCUSSION

The 37 chemicals used in the study are listed with their abbreviations and octanol-water partition coefficients, $K_{ow}$, in Table I. The chemicals were chosen to span a wide range of physical/chemical properties. With 37 chemicals, four aquaria and nine sampling times for worms, sediments, water and pore water, a large quantity of data has been generated. Only a small fraction of the data will be presented here for brevity.

Samplings of the replicate tanks at each temperature showed excellent agreement to within ±10% for all compartments. Although there were some differences in the uptake and elimination rates for the two temperatures, which will be discussed later, only averaged data for worms and sediments in the 8°C aquaria are shown in Table II. With the exception of αBHC and lindane only minor changes in the sediment concentrations occurred during the 79 day exposure period. αBHC and lindance seemed to be only weakly bound to the sediments and most of these chemicals were lost from the sediments over the course of the study. This observation agrees with field measurements which show these chemicals to be present at fairly high concentrations in water but at very low concentration in sediments (27). The uptake of the chemicals by the worms is shown for HCB and OCS in Figures 1 and 2. The worms at 20°C seem to achieve their peak concentrations faster than the worms at 8°C, probably because of higher metabolic activity, but both worm sets reach about the same maximum concentration.

A plot of maximum concentration factor (CF) versus log octanol/water partition coefficient (Fig. 3) has a shape similar to that found previously by Oliver (8). The CF increases until log $K_{ow}$ reaches about 6 then the CF levels off and shows a decline for the larger molecules with very high $K_{ow}$'s. The chemicals αBHC and lindane plot well above the curve probably because of their low sedment affinity.

For all chemicals at both temperatures the chemicals reached a maximum concentration then the concentrations declined with continuing exposure. These observations can be readily explained by examination of the changes in chemical concentrations in the water and pore water in the aquaria. These concentrations were steady for the first two weeks of the study then declined gradually over time. Thus the worms were exposed to lower water and pore water concentrations as the experiment progressed and reduced residue levels were observed. Decreasing pore water concentrations would be expected in this flow-through system as the more readily desorbable portion of the sediment-associated contaminant is depleted (28).

Although it was not possible to detect all the study chemicals in the pore water, because of the small volume sampled, measurable concentrations were obtained for 17 chemicals. Table III lists the average pore water concentrations at 8°C for the first two samplings and the bioconcentration factors, BCFs, for the worms expressed as chemical concentration in worms dry weight (ng/kg)/pore water

concentration (ng/L). Also shown in the table are BCF values obtained from our earlier studies for rainbow trout. Although the worms have a lipid content of only 1% on a wet weight basis, their lipid content on a dry weight basis is about 8%, very close to that of the rainbow trout. For many of the chemicals the worm BCFs are in good agreement with the fish BCFs. For some of the larger chemicals the fish BCFs are lower than the worm BCFs because equilibrium concentrations were not attained for these chemicals during the time course of the fish experiment. This general agreement between the worm and fish BCFs for chemicals at equilibrium indicates that the worms' body burden of chemicals comes mainly from the pore water rather than from ingestion of contaminated sediment particles.

Thus the measurement of pore water chemical concentrations will likely be an important requirement for prediction of chemical concentrations of worms at contaminated field sites. But such measurements are extremely difficult to perform for organic chemicals. Therefore, conversely, it may be possible to estimate pore water concentrations at various sites using the analysis of oligochaetes (if present) and applying either laboratory-derived worm BCFs or BCF measurements on fish with similar lipid contents or fish BCFs expressed on a lipid basis.

The presence of oligochaete worms has been shown to enhance the flux of contaminants out of the sediments by the process of bioturbation (7). Table IV shows the average chemical concentration

in the aquaria water over the first two weeks of the study together with the estimated chemical flux. Since the chemicals were present at different concentrations in the sediments, the flux was normalized to 1000 ppb by multiplying it by 1000/chemical concentrations in the sediment, so the fluxes of the chemicals could be compared. On average the flux out of the sediments was four times higher at 20°C than at 8°C. Lindane and αBHC are seen to have by far the highest flux at both temperatures. The flux out of the sediments for the various chemicals was consistent with the chemicals' properties - the flux decreased as the chemical $K_{ow}$ increased or as its water solubility decreased. The exception to this rule are lindane and αBHC which have an order of magnitude higher $K_{ow}$ and lower water solubility than the dichlorobenzenes and yet are desorbed more than ten times faster. Most of the chemicals in Table IV are aromatic, whereas αBHC and lindane are cyclic aliphatic compounds.

Although there are very few measurements of this kind in the literature, it is interesting to compare these results to those of Karickhoff and Morris (7). Their fluxes for QCB and HCB from sediments containing 1000 ppb of the chemicals and with about the same worm populations at 20°C were about 220 and 120 $\mu g/m^2$ day in contrast to 9 and 5 $\mu g/m^2$ day in this study. In Karickhoff and Morris' experiment the water was continually purged to remove the chemicals so that diffusion from the sediments was occurring into relatively "clean" water. Also the organic carbon content of their sediment

(0.8%) was much lower than in this study (4.6%). The availability of organics in sediments is considered to be much lower for sediments with higher organic carbon content (1).

After the exposure period the remaining worms were recovered and placed in 8°C and 20°C aquaria containing "clean" Lake Superior sediments. The worms were first sampled from the new aquaria after five days and showed a marked decline in contaminant levels during this period (Table II). This is probably due to the considerable energy and stress expended establishing and building new burrows. After this initial adjustment period the decline in contaminant levels followed normal first order kinetics. For half-life, $T_{1/2}$, calculations the five-day sample was considered the zero point of the depuration phase. Many of the chemicals were not detected in the worms at the first samplings in the new aquaria, so their half-lives must be less than five days. For the other chemicals the $T_{1/2}$ ranged from a few weeks to several months. The $T_{1/2}$'s of the chemicals systematically increased with increasing chlorine content and with increasing $K_{ow}$.

Niimi and Cho (30) have shown that half-lives of chemicals in fish should be corrected for "growth dilution" to obtain accurate values. Since we did not label the worms, such a direct correction was not possible in this experiment. But, if it is assumed that the most recalcitrant substance, mirex, is completely retained by the worms, we can estimate the impact of this growth correction on the

data (Table II, column 14). As expected, this correction increases the $T_{1/2}$ and is particularly significant for compounds with longer half-lives.

The $T_{1/2}$ of the chemicals at 20°C were similar to the 8°C data. The $T_{1/2}$ for PCB's measured in this study is in reasonable agreement with the value of 27 days reported for marine worms by Elder et al. (14).

A limited field sampling of sediments and worms from Lake Ontario sites at 5 km intervals about 10 km off the mouth of the Niagara River was conducted in June, 1985 for comparison with the laboratory tests. The data for a few of the study chemicals is shown in Table V. The sediment samples had a similar organic carbon content to the sediment used in the laboratory study. A range of concentration factors was found in the various samples. The lowest concentration factors were observed in the sediments having the highest organic content indicating a lower bioavailability of contaminants in these sediments. The mean concentration factors for the field data are: QCB, 0.34; HCB, 0.48; HCBD, 0.43; OCS, 4.6; pp-DDE, 3.2; mirex, 4.0; and PCB's, 5.6. The field CF's for QCB, HCB and HCBD are more than an order of magnitude lower than the laboratory CF's, whereas, for OCS, pp-DDE, mirex and PCB's the field CF's are about one half the laboratory values. Thus, the field and laboratory data are in reasonable agreement for the more persistent compounds. The reason for the large discrepancy for the other chemicals is likely due to

differences in sampling methodology. For the field samples the period between sample collection and sorting/freezing is of the order of three days, whereas, for the laboratory experiment this procedure took less than three hours. It can be seen from Table II that when the worms are removed from their normal environment (sieved and transferred to different sediment) a large decrease of about one order of magnitude in the concentration of QCB, HCB and HCBD was observed. A much smaller change in concentration was found for the more persistent chemicals. Thus the data for worms in Table V is probably not a true reflection of residue levels for the less persistent chemicals. Sampling, sorting and freezing must be accomplished within a few hours to obtain accurate data for these compounds.

In summary, oligochaete worms can play an important role in the mobilization of contaminants from bottom sediments by bioconcentration and bioturbation. The pore water concentration of the chemicals was the major driving force for contaminant uptake by the worms. The half-lives of the chemicals ranged from less than five days to several months depending on chemical structure. The laboratory-derived uptake data provided useful information for developing appropriate field sampling protocols and for predicting bioconcentration factors for worms in the environment.

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**REFERENCES**

1. Karickhoff, S.W. Chemosphere 1981, 10, 833.
2. Frank, R.; Thomas, R.L.; Holdrinet, M.; Kemp, A.L.W.; Braun, H.E. 1979, 5, 18.
3. Oliver, B.G.; Nicol, K.D. Environ. Sci. Technol. 1982, 16, 532.
4. Van Hove Holdrinet, M.; Frank, R.; Thomas, R.L.; Hetling, L.J. J. Great Lakes Res. 1978, 4, 69.
5. Kaminsky, R.; Hites, R.A. Environ. Sci. Technol. 1984, 18, 275.
6. Fisher, J.B.; Lick, W.J.; McCall, P.L.; Robbins, J.A. J. Geophys. Res. 1980, 85, 3997.
7. Karickhoff, S.W.; Morris, K.R. Environ. Sci. Technol. 1985, 19, 51.
8. Oliver, B.G. Can. J. Fish Aquat. Sci. 1984, 41, 878.
9. Eadie, B.J.; Faust, W.; Gardner, W.S.; Nalepa, T. Chemosphere 1982, 11, 185.
10. Oliver, B.G.; Niimi, A.J. Environ. Sci. Technol. 1983, 17, 287.
11. Borgmann, U.; Whittle, D.M. Can. J. Fish. Aquat. Sci. 1983, 40, 328.

12. Fox, M.E.; Carey, J.H.; Oliver, B.G. J. Great Lakes Res. 1983, 9, 287.

13. McLeese, D.W.; Metcalfe, C.D.; Pezzack, D.S. Arch. Environ. Contam. Toxicol. 1980, 9, 507.

14. Elder, D.L.; Fowler, S.W.; Polikarpov, G.G. Bull. Environ. Contam. Toxicol. 1979, 21, 448.

15. Lynch, T.R.; Johnson, H.E. In "Aquatic Toxicology and Hazard Assessment: Fifth Conference", Pearson, J.G.; Foster, R.B.; Bishop, W.E. Eds.; American Society for Testing and Materials: Philadelphia, PA, 1982, ASTM STP766, pp 273-287.

16. Karickhoff, S.W. In "Contaminants and Sediments". Baker, R.A. Ed. Ann Arbor Science, Ann Arbor, MI, 1980, Vol. II, pp 193-205.

17. Oliver, B.G.; Nicol, K.D. Chromatographia. 1982, 16, 336.

18. Banerjee, S.; Yalkowsky, S.H.; Valvani, S.C. Environ. Sci. Technol. 1980, 14, 1227.

19. Könеman, H.; Zelle, R.; Busser, F.; Hammers, W.E. J. Chromatogr. 1979, 178, 559.

20. Chiou, C.T.; Schmedding, D.W. Environ. Sci. Technol. 1982, 16, 4.

21. Hansch, C.; Leo, A. "Substituent Constants for Correlation Analysis in Chemistry and Biology", Wiley: New York, 1979.

22. Kaiser, K.L.E. Chemosphere 1983, 12, 1159.

23. Veith, G.D.; DeFoe, D.L.; Bergstedt, B.U. J. Fish. Res. Board Can. 1979, 36, 1040.

24. Kurihara, N.; Uchida, M.; Fujita, T.; Nakajima, M. Pestic. Biochem. Physiol. 1973, 2, 383.

25. O'Brien, R.D. In "Environmental Dynamics of Pesticides", Hague, R.; Freed, V.H., Eds., Plenum Press: New York 1974, pp 331-342.

26. Ballschmiter, K.; Zell, M. Fresenius Z. Anal. Chem. 1980, 302, 20.

27. Oliver, B.G.; Bourbonniere, R.A. J. Great Lakes Res. 1985, 11, 366.

28. Oliver, B.G. Chemosphere. 1985, 14, 1087.

29. Oliver, B.G.; Niimi, A.J. Environ. Sci. Technol. 1985, 19, 842.

30. Niimi, A.J.; Cho, C.Y. Can. J. Fish Aquat. Sci. 1981, 38, 1350.

Table I. Study Chemicals, Abbreviations and log Octanol/Water, log $K_{ow}$, with Literature Source in Brackets.

| Chemical | Abbreviation | log $K_{ow}$ |
|---|---|---|
| 1,3-dichlorobenzene | 1,3-DCB | 3.4 (18) |
| 1,4-dichlorobenzene | 1,4-DCB | 3.4 (18) |
| 1,2-dichlorobenzene | 1,2-DCB | 3.4 (18) |
| 1,3,5-trichlorobenzene | 1,3,5-TCB | 4.2 (19) |
| 1,2,4-trichlorobenzene | 1,2,4-TCB | 4.0 (20) |
| 1,2,3-trichlorobenzene | 1,2,3-TCB | 4.1 (19) |
| 1,2,4,5-tetrachlorobenzene | 1,2,4,5-TeCB | 4.5 (19) |
| 1,2,3,4-tetrachlorobenzene | 1,2,3,4-TeCB | 4.5 (19) |
| Pentachlorobenzene | QCB | 4.9 (18) |
| Hexachlorobenzene | HCB | 5.5 (20) |
| 2,4,5-trichlorotoluene | 2,4,5-TCT | 4.8 (21)[a] |
| 2,3,6-trichlorotoluene | 2,3,6-TCT | 4.8 (21)[a] |
| 2,3,4,5,6-pentachlorotoluene | PCT | 6.2 (21)[a] |
| 3,4-dichlorobenzotrifluoride | 3,4-DCBTF | 4.4 (21)[a] |
| 2,4-dichlorobenzotrifluoride | 2,4-DCBTF | 4.4 (21)[a] |
| Hexachlorobutadiene | HCBD | 4.8 (18) |
| 2,3,4-trichloranisole | 2,3,4-TCA | 4.2 (21)[a] |
| 1,2,3,4-tetrachloronaphthalene | 1,2,3,4-TeCN | 5.5 (22)[b] |
| Octachlorostyrene | OCS | 6.2 (23) |
| α-hexachlorocyclohexane | α-BHC | 3.8 (24) |
| γ-hexachlorcyclohexane | LINDANE | 3.7 (24) |
| γ-chlordane | γ-CHLOR | 6.0 (23) |
| 1,1-dichloro-2,2-bis(4-chlorophenyl)ethylene | pp-DDE | 5.7 (25) |
| 1,1,1-trichloro-2,2-bis(4-chlorophenyl)ethane | pp-DDT | 5.8 (25) |
| Mirex | MIREX | 6.9 (23) |
| 2,5,2'-trichlorobiphenyl | PCB18[c] | 5.6 (22)[b] |
| 2,5,4'-trichlorobiphenyl | PCB31 | 5.6 (22)[b] |
| 2,5,2',6'-tetrachlorobiphenyl | PCB53 | 5.9 (22)[b] |
| 2,5,2',5'-tetrachlorobiphenyl | PCB52 | 5.9 (22)[b] |
| 2,3,2',3'-tetrachlorobiphenyl | PCB40 | 5.9 (22)[b] |
| 2,4,3',4'-tetrachlorobiphenyl | PCB66 | 5.9 (22)[b] |
| 2,4,6,2',4',6'-hexachlorobiphenyl | PCB155 | 6.5 (22)[b] |
| 2,4,5,2',4',5'-hexachlorobiphenyl | PCB153 | 6.5 (22)[b] |
| 2,3,4,2',3',4'-hexachlorobiphenyl | PCB128 | 6.5 (22)[b] |
| 2,3,4,5,3',4'-hexachlorobiphenyl | PCB156 | 6.5 (22)[b] |
| 2,3,4,6,2',3',4'-heptachlorobiphenyl | PCB171 | 6.7 (22)[b] |
| 2,3,4,5,2',3',4',5'-octachlorobiphenyl | PCB194 | 6.9 (22)[b] |

[a]Calculated by the Π method of Hansch and Leo (21).
[b]Calculated by the method of Kaiser (22).
[c]PCB numbering system of Ballschmiter and Zell (26).

Table II. Mean Concentration (ng/g dry weight) in Sediment and Worms from 8°C Aquaria and Estimated Half-Lives.

| | Sediment | | Worms Uptake Phase (CF)* | | | | Worms Depuration Phase | | | | | Half-Life in Days ($r^2$)** | Growth Corrected Half-Life in Days ($r^2$)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4d | 79d | 4d | 11d | 39d | 79d | 5d | 12d | 21d | 36d | 84d | | |
| 1,3-DCB | 830 | 590 | 610(0.7) | 500(0.6) | 350(0.5) | 330(0.6) | ND*** | ND | ND | ND | ND | <5 | <5 |
| 1,4-DCB | 530 | 370 | 200(0.4) | 270(0.5) | 70(0.2) | 60(0.2) | ND | ND | ND | ND | ND | <5 | <5 |
| 1,2-DCB | 280 | 230 | 260(0.9) | 220(0.8) | 140(0.6) | 40(0.2) | ND | ND | ND | ND | ND | <5 | <5 |
| 1,3,5-TCB | 180 | 160 | 150(0.8) | 130(0.7) | 110(0.6) | 90(0.6) | 14 | 5 | ND | ND | ND | <5 | <5 |
| 1,2,4-TCB | 630 | 550 | 180(0.3) | 190(0.3) | 90(0.2) | 100(0.2) | ND | ND | ND | ND | ND | <5 | <5 |
| 1,2,3-TCB | 290 | 230 | 130(0.4) | 190(0.7) | 150(0.6) | 100(0.4) | ND | ND | ND | ND | ND | <5 | <5 |
| 1,2,4,5-TeCB | 250 | 210 | 320(1.3) | 430(1.8) | 210(0.9) | 150(0.7) | ND | ND | ND | ND | ND | <5 | <5 |
| 1,2,3,4-TeCB | 270 | 230 | 400(1.5) | 540(2.1) | 300(1.2) | 150(0.7) | ND | ND | ND | ND | ND | <5 | <5 |
| QCB | 460 | 420 | 1600(3.5) | 2300(5.1) | 1100(2.5) | 800(1.9) | 67 | 31 | 36 | 9 | 19 | <5 | <5 |
| HCB | 900 | 770 | 3500(3.9) | 6100(6.9) | 3500(4.2) | 2400(3.1) | 840 | 410 | 240 | 69 | 66 | 24(0.69) | 27(0.70) |
| 2,4,5-TCT | 340 | 300 | 420(1.2) | 570(1.7) | 320(1.0) | 210(0.7) | 48 | 25 | ND | ND | ND | <5 | <5 |
| 2,3,6-TCT | 250 | 210 | 480(1.9) | 630(2.6) | 350(1.5) | 290(1.4) | ND | ND | ND | ND | ND | <5 | <5 |
| PCT | 690 | 640 | 3000(4.3) | 5300(7.8) | 3000(4.5) | 2000(3.1) | 680 | 670 | 220 | 63 | 57 | 22(0.72) | 26(0.73) |
| 3,4-DCBTF | 220 | 180 | 270(1.2) | 250(1.2) | 120(0.6) | 130(0.7) | ND | ND | ND | ND | ND | <5 | <5 |
| 2,4-DCBTF | 140 | 110 | 130(0.9) | 170(1.2) | 90(0.7) | 70(0.6) | ND | ND | ND | ND | ND | <5 | <5 |
| HCBD | 120 | 88 | 510(4.3) | 930(8.1) | 400(3.8) | 230(2.6) | 26 | 16 | 14 | 9.2 | 5.3 | <5 | <5 |
| 2,3,4-TCA | 710 | 610 | 150(0.2) | 160(0.2) | 290(0.4) | 200(0.3) | 38 | 29 | 120 | 57 | 79 | ? | ? |
| 1,2,3,4-TeCN | 1300 | 1200 | 3200(2.5) | 6400(4.9) | 4000(3.2) | 2800(2.3) | 1100 | 730 | 370 | 110 | 63 | 20(0.83) | 30(0.50) |
| OCS | 560 | 520 | 1900(3.4) | 5000(9.1) | 5000(9.3) | 3300(6.3) | 2800 | 2700 | 2000 | 1400 | 1300 | 71(0.75) | 100(0.84) |
| α-BHC | 310 | 60 | 2400(7.7) | 3400(11) | 1000(5.0) | 610(10) | 68 | 76 | 57 | 37 | 27 | <5 | <5 |
| LINDANE | 740 | 120 | 4800(6.5) | 6600(9.7) | 1600(3.6) | 900(7.5) | 61 | 55 | 32 | 20 | 16 | <5 | <5 |
| γ-CHLOR | 390 | 360 | 1800(4.6) | 3800(9.7) | 2700(7.2) | 1700(4.7) | 1000 | 790 | 680 | 290 | 310 | 46(0.67) | 63(0.66) |
| pp-DDE | 290 | 280 | 860(3.0) | 2200(7.6) | 2000(7.0) | 1200(4.3) | 960 | 890 | 830 | 460 | 500 | 80(0.63) | 130(0.50) |
| pp-DDT | 100 | 92 | 170(1.7) | 540(5.5) | 190(2.0) | 50(0.5) | 47 | 21 | 33 | 9.2 | 14 | 53(0.39) | 74(0.27) |
| MIREX | 600 | 570 | 720(1.2) | 2300(3.8) | 4000(6.8) | 2900(5.1) | 3200 | 3100 | 2600 | 2400 | 2400 | 200(0.60) | ∞(REF) |
| PCB18 | 620 | 600 | 3800(6.1) | 6500(10) | 3400(5.6) | 2200(3.7) | 670 | 450 | 320 | 75 | 66 | 24(0.75) | 26(0.75) |
| PCB31 | 770 | 740 | 2800(3.6) | 5400(7.0) | 3200(4.2) | 2100(2.8) | 1000 | 680 | 470 | 180 | 120 | 26(0.83) | 30(0.85) |
| PCB53 | 770 | 760 | 4500(5.8) | 9000(12) | 5600(7.3) | 3400(4.5) | 1900 | 1300 | 830 | 320 | 210 | 26(0.83) | 30(0.86) |
| PCB52 | 780 | 740 | 3800(4.9) | 8400(11) | 5500(7.2) | 3300(4.5) | 2100 | 1600 | 1000 | 440 | 440 | 36(0.69) | 43(0.70) |
| PCB40 | 720 | 710 | 3300(4.6) | 5900(8.2) | 3800(5.3) | 2500(3.5) | 1300 | 840 | 610 | 230 | 140 | 26(0.86) | 29(0.88) |
| PCB66 | 850 | 840 | 2000(2.4) | 5100(6.0) | 3800(4.5) | 2400(2.9) | 1600 | 1400 | 920 | 360 | 240 | 28(0.85) | 33(0.87) |
| PCB155 | 1000 | 990 | 3100(3.1) | 8500(8.5) | 10000(10) | 6400(6.5) | 6300 | 5800 | 3700 | 2800 | 3800 | 120(0.29) | 310(0.11) |
| PCB153 | 820 | 800 | 2100(2.6) | 5200(6.3) | 6000(7.4) | 3700(4.6) | 3300 | 3000 | 2700 | 2100 | 1800 | 92(0.88) | 170(0.91) |
| PCB128 | 920 | 910 | 1800(2.0) | 5000(5.4) | 4700(5.1) | 2900(3.2) | 2400 | 2300 | 1900 | 1300 | 820 | 50(0.96) | 63(0.97) |
| PCB156 | 430 | 410 | 900(2.1) | 2100(4.9) | 2800(6.7) | 1600(3.9) | 1300 | 1300 | 790 | 510 | 500 | 58(0.67) | 80(0.70) |
| PCB171 | 410 | 370 | 680(1.7) | 1400(3.5) | 2200(5.6) | 1500(4.1) | 1100 | 1200 | 740 | 560 | 690 | 110(0.37) | 260(0.22) |
| PCB194 | 960 | 940 | 750(0.8) | 2100(2.2) | 3200(3.4) | 2400(2.6) | 2300 | 2300 | 2200 | 1900 | 1400 | 100(0.99) | 220(0.54) |

*CF = concentration factor (concentration in worm dry weight/concentration in sediment).
**$r^2$ = square of correlation coefficient for equation.
***ND = not detected.

**Table III. Pore Water Concentrations and Bioconcentration Factors, BCFs, for Worms and Fish**

| Compound | Pore Water (ng/L) | Worm[a] BCF | Fish BCF | Compound | Pore Water (ng/L) | Worm BCF | Fish BCF |
|---|---|---|---|---|---|---|---|
| QCB | 120 | 19,000 | 20,000[b] | pp-DDE | 76 | 29,000 | 14,000[c] |
| HCB | 250 | 24,000 | 20,000[b] | Mirex | 180 | 22,000 | 740[c] |
| PCT | 190 | 28,000 | 6,800[c] | PCB40 | 250 | 24,000 | 17,000[c] |
| HCBD | 32 | 29,000 | 17,000[b] | PCB66 | 180 | 28,000 | - |
| 1,2,3,4-TeCN | 310 | 21,000 | 5,100[c] | PCB155 | 290 | 34,000 | 4,800[c] |
| OCS | 160 | 31,000 | 8,100[c] | PCB153 | 240 | 25,000 | - |
| αBHC | 1400 | 2,400 | 2,400 [c] | PCB128 | 260 | 19,000 | - |
| LINDANE | 3500 | 1,900 | 2,000 [c] | PCB194 | 220 | 15,000 | - |
| γCHLOR | 150 | 25,000 | 22,000 [c] | | | | |

[a] Worm BCF = Chemical Concentration (ng/Kg) in worm dry weight/pore water concentration (ng/L).

[b] From reference (10).

[c] From reference (29).

**Table IV. Average Water Concentrations in Aquaria at 8°C and 20°C for the Frist Two Study Weeks and Normalized Desorption Fluxes.**

| Compound | 8°C | | 20°C | | Compound | 8°C | | 20°C | |
|---|---|---|---|---|---|---|---|---|---|
| | Water Conc. (ng/L) | Normalized Flux * ($\mu g/m^2$ day) | Water Conc. (ng/L) | Normalized Flux ($\mu g/m^2$ day) | | Water Conc. (ng/L) | Normalized Flux * ($\mu g/m^2$ day) | Water Conc. (ng/L) | Normalized Flux ($\mu g/m^2$ day) |
| 1,3-DCB | 6.0 | 6 | 9.3 | 13 | OCS | 0.1 | 0.2 | 0.4 | 0.9 |
| 1,4-DCB | 2.8 | 5 | 5.8 | 13 | α-BHC | 24 | 70 | 75 | 290 |
| 1,2-DCB | 2.4 | 8 | 4.0 | 17 | LINDANE | 61 | 70 | 180 | 290 |
| 1,3,5-TCB | 1.1 | 5 | 1.6 | 11 | γ-CHLOR | 0.6 | 1 | 1.6 | 5 |
| 1,2,4-TCB | 1.8 | 3 | 2.5 | 5 | pp-DDE | 0.05 | 0.2 | 0.2 | 0.8 |
| 1,2,3-TCB | 1.8 | 5 | 2.1 | 9 | pp-DDT | ND | ND | 0.1 | 1 |
| 1,2,4,5-TeCB | 1.2 | 4 | 2.1 | 10 | MIREX | 0.1 | 0.1 | 0.5 | 1 |
| 1,2,3,4-TeCB | 1.5 | 5 | 2.9 | 13 | PCB18 | 0.8 | 1 | 3.6 | 7 |
| QCB | 1.6 | 3 | 3.6 | 9 | PCB31 | 0.8 | 0.9 | 1.9 | 3 |
| HCB | 1.3 | 1 | 3.6 | 5 | PCB53 | 1.6 | 2 | 5.0 | 8 |
| 2,4,5-TCT | 1.2 | 3 | 1.8 | 6 | PCB52 | 1.4 | 2 | 3.8 | 6 |
| 2,3,6-TCT | 1.3 | 5 | 1.7 | 8 | PCB40 | 0.6 | 0.7 | 2.5 | 4 |
| PCT | 0.9 | 1 | 2.5 | 4 | PCB66 | 0.2 | 0.2 | 1.0 | 1 |
| 3,4-DCBTF | 1.1 | 4 | 1.7 | 9 | PCB155 | 0.4 | 0.4 | 1.2 | 1 |
| 2,4-DCBTF | 0.7 | 4 | 1.5 | 13 | PCB153 | 0.3 | 0.3 | 1.0 | 1 |
| HCBD | 0.1 | 0.7 | 0.2 | 2 | PCB128 | 0.2 | 0.2 | 0.7 | 0.9 |
| 2,3,4-TCA | 2.3 | 3 | 9.5 | 16 | PCB156 | 0.1 | 0.2 | 0.5 | 1 |
| 1,2,3,4-TeCN | 0.9 | 0.6 | 7.0 | 6 | PCB171 | 0.1 | 0.2 | 0.4 | 1 |
| | | | | | PCB194 | 0.1 | 0.1 | 0.6 | 0.7 |

*Normalized Flux = Flux x (1000/chemical concentration in sediment).

**Table V. Chemical Concentrations (ng/g dry weight) in Worms and Sediments in Lake Ontario near the Niagara River.**

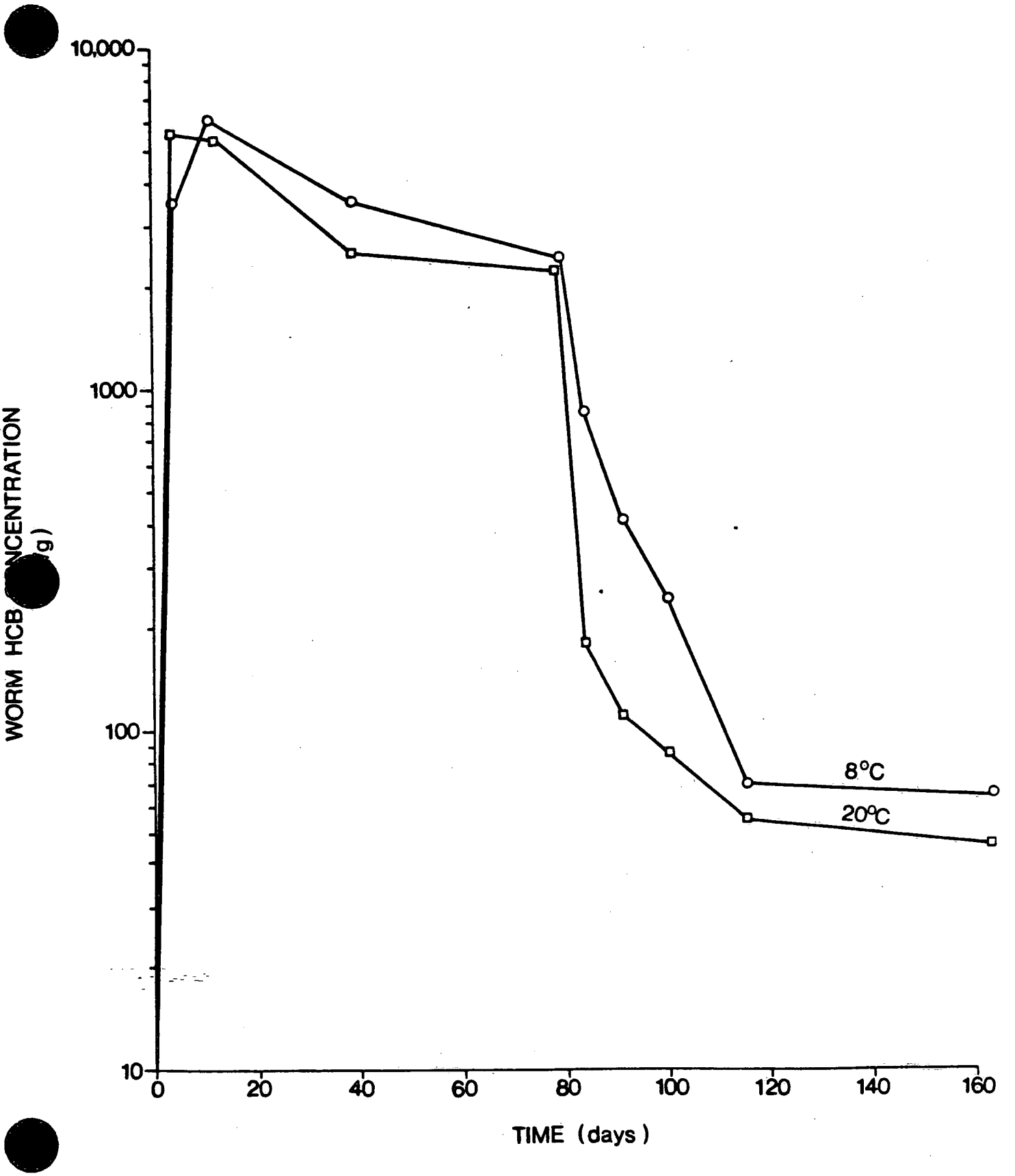
| Chemical | Site 1 Worm/Sed. | Site 2 Worm/Sed. | Site 3 Worm/Sed. | Site 4 Worm/Sed. | Site 5 Worm/Sed. | Site 6 Worm/Sed. |
|---|---|---|---|---|---|---|
| QCB | 3.4/12 | 20/22 | 7.1/15 | 3.9/11 | 3.1/11 | 3.1/15 |
| HCB | 18/43 | 46/60 | 24/39 | 17/36 | 14/56 | 13/40 |
| HCBD | 2.4/9.2 | 8.6/11 | 6.4/8.4 | 3.6/11 | 2.2/11 | 2.0/7.3 |
| OCS | 8.7/2.8 | 31/3.8 | 14/3.5 | 13/2.5 | 21/3.9 | 7.5/4.1 |
| pp-DDE | 33/16 | 69/15 | 34/7.2 | 29/8.4 | 32/11 | 54/38 |
| MIREX | 47/13 | 79/19 | 31/9.3 | 29/6.2 | 35/7.9 | 56/15 |
| Total PCB's | 380/220 | 4300/310 | 1600/270 | 1300/190 | 1200/300 | 460/420 |
| TOC(%) | 4.2 | 3.7 | 2.9 | 3.2 | 2.9 | 5.6 |

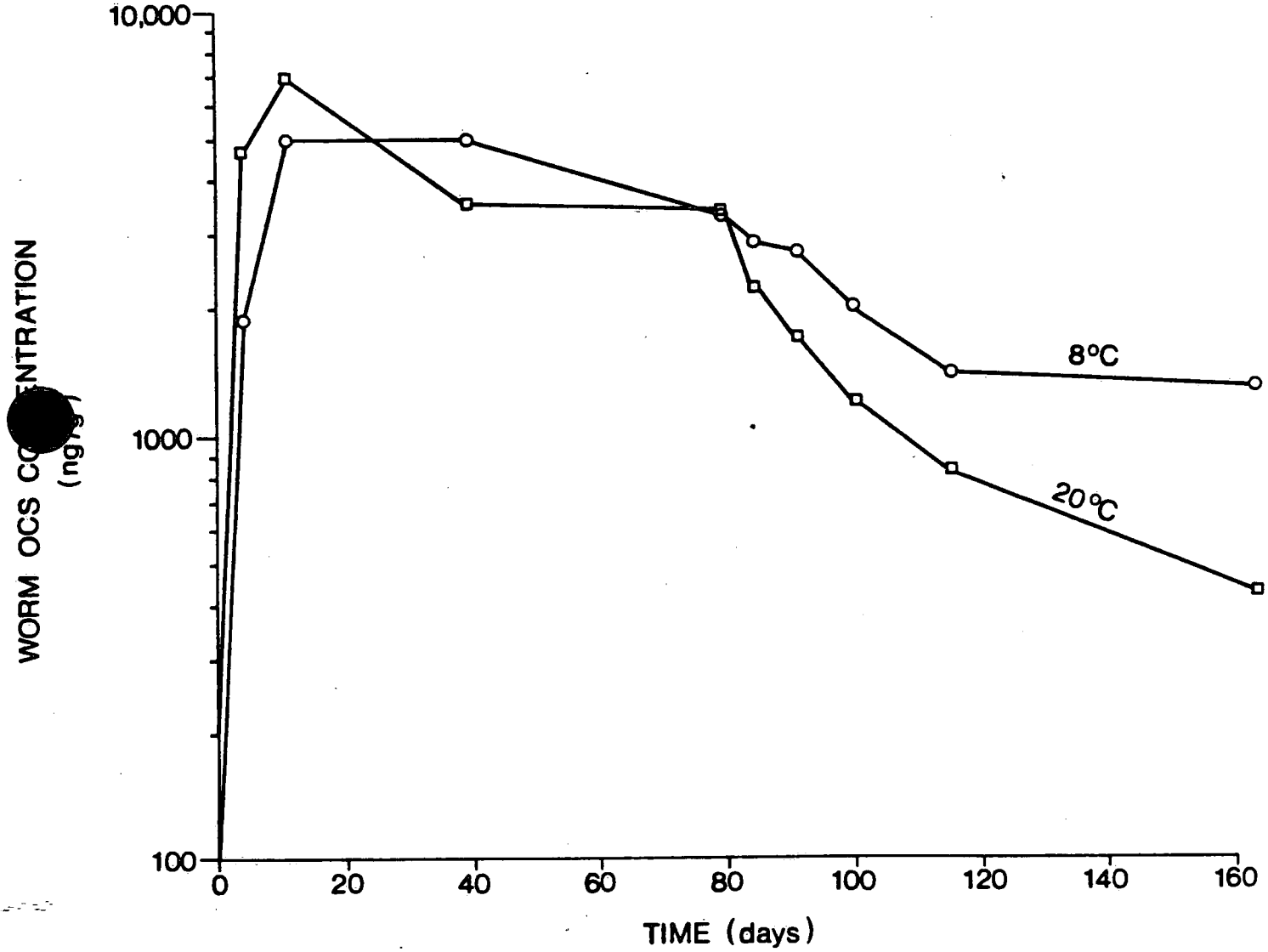
## FIGURE CAPTIONS

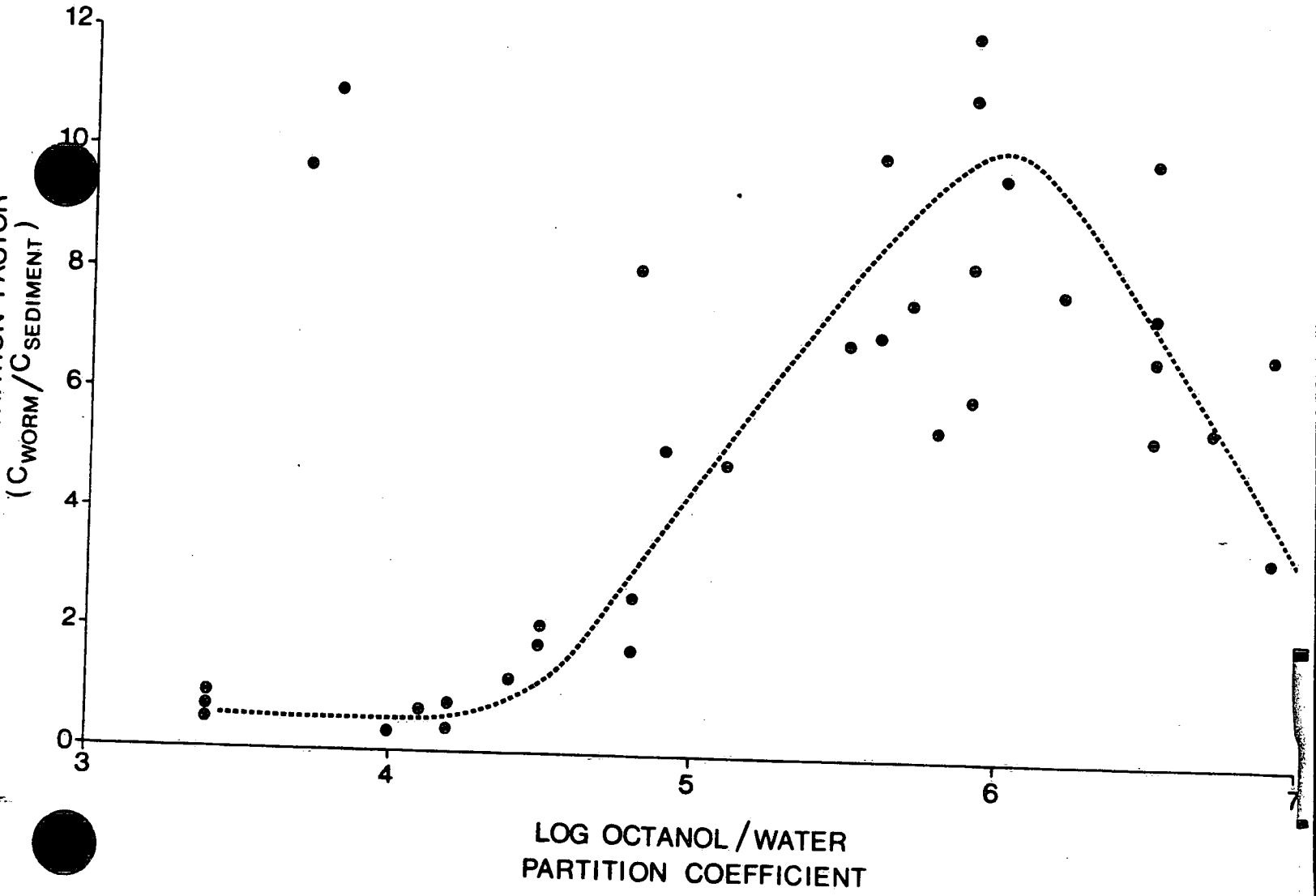
Fig. 1 The uptake of HCB by worms at 8° and 20°C.

Fig. 2 The uptake of OCS by worms at 8° and 20°C.

Fig. 3 Concentration factor (chemical concentration in worm ng/g dry weight/chemical concentration in sediment ng/g dry weight) versus log octanol-water partition coefficient, $K_{ow}$.


10,000
1000
100
10
WORM HCB CONCENTRATION
g)
0
20
40
60
80
100
120
140
160
TIME (days)
8°C
20°C


10,000
1000
100
WORM OCS CONCENTRATION (ng/g)
0
20
40
60
80
100
120
140
160
TIME (days)
8°C
20°C


12
10
8
6
4
2
0
3
4
5
6
7
$(C_{WORM}/C_{SEDIMENT})$
LOG OCTANOL / WATER
PARTITION COEFFICIENT