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A Basis for Modelling of Radionuclide Flow in the Forsmark Biotest Basin

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A BASIS FOR MODELLING OF RADIONUCLIDE FLOW IN THE FORSMARK BIOTEST BASIN

1. INTRODUCTION

The Forsmark Nuclear Power Plant is situated on the Swedish east coast in the southern part of the Bothnian Sea, 70 km north of Uppsala. It consists of three boiling water reactors. Unit 1 (900 MW) has been operating since 1980, unit 2 (900 MW) since 1981, and unit 3 (1050 MW) since 1985.

The Biotest Basin is the primary recipient for the cooling water from units 1 and 2. Chemical, physical and biological parameters have been studied in the environment since the beginning of construction of the power plant. The investigation programs are mainly concentrated on the Biotest Basin. Environmental and hydrological conditions have been studied by SNV (the National Swedish Environment Protection Board) and SMHI (the Swedish Meteorological and Hydrological Institute), with the aim of recording ecological effects and how heated cooling water and radioactive discharge are spread in the local aquatic environment.

The water from the reactor tanks still contains some radioactivity after the waste water treatment when discharged with the cooling water, and is the main radioactive input into the basin. The radionuclides are included in the biological circulation by adsorption, absorption or intake of food and water. The Biotest Basin is an ecosystem with relatively high radionuclide concentrations in biota from different levels of the food chain, environmental conditions are well documented, and thus it is a suitable system for developing a model describing the behaviour of radionuclides in the environment.

This report presents a rough estimate of the flow of radionuclides within the Biotest Basin. The pathways that are most important for transport and accumulation of radionuclides are determined, providing a basis for further quantitative calculations of the radioactive flow. Some subsystems are pointed out as suitable for more detailed modelling, where dynamic flows can be simulated and studied. A separate issue was a compilation of investigations and/or research that have been performed in the Biotest Basin until 1986, which is given in appendix 1.

2. THE BIOTEST BASIN

2.1 DESCRIPTION OF THE AREA

The Biotest Basin is an artifical closed waterbody receiving cooling water from the Forsmark Nuclear Power Plant. It was built for investigation of the effects of radioactivity and heat on a brackish coastal ecosystem. The cooling water for the power station is taken from Asphällsfjärden, a bay connected to Öregrundsgrepen, with a salinity of 5-6 ^{o}/oo. The water is taken into the units 1 and 2 via inlet conduits, and is heated up as it passes through the reactor cooling system. A tunnel under the sea-bed carries the heated water out into the Biotest Basin (see Fig. 1), from where it is released into the sea. The construction, connecting five small islands with dams, was finished in 1977, and the supply of cooling water was started during the second half of 1980.

Öregrundsgrepen is an area of little organic sediments, only at less exposed, deeper sites, organic material is accumulating. The bottom of the Biotest Basin consists of solid rock, sand and stones. Less than 5 % of the bottom area in the Biotest Basin has accumulating conditions. The water is heated 8-10^{o}C as it passes through the reactor condensors; this is also the temperature elevation in the largest part of the basin, as compared to natural waters in its surroundings. The different parts of the Biotest Basin have varying water exchange. The lagoon, an area partly separated from the rest of the basin by a ca 400 m long pier (see Fig. 1), has a lower temperature than the rest of the basin. The vertical temperature variation is generally only a few tenths of a degree Celsius, and seldom greater than 1^{o}C (Andersson, 1983). No chemicals are used to diminish fouling organisms in the cooling water tunnels; mechanical cleaning with small rubber balls is applied.

Most of the water (70-90%) is transported between the intake channel of the power station and the outflow channel from the Biotest Basin within 3-6 hours. In the lagoon the retention time is up to a few days; here the water is quiescent. There is a stand-by outlet where part of the cooling water can be released directly from the tunnel into the sea when manipulation of the flow through the Biotest Basin is needed. When the stand-by outlet is opened the flow through the Biotest Basin depends on how much the lock of the outlet is opened and to what extent the inlet to the basin is closed. Between 25-50% of the cooling water flows

through the Biotest Basin when the stand-by outlet is open (Sandström (SNV), Wahlström (Forsmark, pers. comm.). Exactly how much activity that passes the stand-by outlet when it is used is not documented. In the calculations 25% water flow through the basin is used.
For additional information about the Biotest Basin see Forsmarks Kraftgrupp and SNV (1982), Grimås (1979) and Statens Vattenfall (1972).

2.2 BASIC INFORMATION

Basic information on the reactor units 1 and 2, and the Biotest Basin, is given in Table 1.

TABLE 1: BASIC INFORMATION

NUCLEAR POWER PLANT (UNITS 1+2):		SOURCE
TOTAL THERMAL OUTPUT	5400 MW	F
TOTAL ELECTRICAL OUTPUT	1800 MW	F
COOLING WATER (AT FULL OPERATION):		
DISCHARGE TUNNEL LENGTH	2350 m	F
COOLING WATER FLOW	86m^3/s	A,F
FLOW RATE AT THE OUTLET (site E)	2 m/s	A,F
FLOW RATE MAIN STREAM THROUGH BASIN	0.1-0.3 m/s	A
LEAKAGE THROUGH DAMS	5-6% of flow	A,F
TEMPERATURE ANOMALY	8-10°C	A,F
RETENTION TIME MAIN STREAM (70-90%)	3-6 h	A
RETENTION TIME BACKWATERS	a few days	A
BIOTEST BASIN:		
MAXIMUM DEPTH	5 m	A,F
AVERAGE DEPTH	2.5 m	F
SURFACE AREA	0.9 km^2	A,F
TOTAL VOLUME	2.3 10^6 m^3	A

A = Andersson, 1983
F = Forsmarks Kraftgrupp AB and SNV, 1982

2.3 THE CONTROL PROGRAMS

An overall monitoring program for the power plant is organised and performed by the authorities. As a part of this program hydrological and meterological parameters are continuously measured by the Swedish Meteorological and Hydrological Institute (SMHI). A number of sensors situated both in- and outside the Biotest Basin give the mean value per hour of: water temperature, turbidity, light intensity (PAR=Photosynthetic Active Radiation), global radiation, cooling water input, water level, air temperature, wind direction and wind speed. The information is then sent by telephone to the SMHI computer in Norrköping for further processing.

The biological monitoring program is carried out by the National Swedish Environmental Protection Board (SNV) also responsible for more specialized research on the effects of the cooling-water release. Studies have been, or are being done in the following fields: radio-ecology, heavy metals, nutrients, oxygen concentration and salinity in water, plankton, benthic algae, bottom vegetation, bottom fauna and fishery biology. For overviews of publications on the Biotest Basin see Appendix I in this report and Sandström (1985).

3. DISCHARGE OF RADIONUCLIDES TO THE BIOTEST BASIN.

The greater part of the radionuclides in the liquid discharge from the Forsmark Nuclear Power Plant originates from fission products leaking from the fuel rods, and neutron activated corrosion products from the reactor vessel, turbin plumbs and tube systems. Most radionuclides are removed from the system via continuously operating ion exchange filters. Used process water and ion-exchanger are transported to the active waste treatment processing building within the power plant, where the water is cleaned in several steps with different methods. After that, most of the water is re-used, and a minor part is discharged into the waste water tanks; this water still contains small amounts of radioactive substances. The waste water tanks have a volume of 250 m^3. When a tank is full, the total gamma radiation (in cps) is measured, and if the concentration is below the prescribed limit (by NIRP), it is emptied into the cooling water channel with a rate of ca. 1 m^3/min. It takes about four hours to empty one tank.
The cooling water flow at full operation is 86 m^3/s, and is discharged through the Biotest Basin. If necessary, some of the water goes directly into the sea through the stand-by outlet.
At normal operation 30 tanks are emptied per month from units 1 and 2; during overhaul of the power plant, the number of tanks emptied can be more than the double. In general overhaul of the power station takes place in summer, during which each unit is turned off for a period.
During the emptying of a tank a representative sample (about 0.01 % of the whole tank) is taken. Two litres of all representative samples from tanks discharged during one month are pooled before a subsample is analysed. The gamma spectrum is determined for the filtered fraction and for the particulate fraction (>0.45 µm). The results of these measurements are reported to the authorities.

The reported activity from the proportional samples, with consideration taken to the stand-by outlet, gives the activity in Becquerel released into the Biotest Basin. The discharge procedure results in pulses of increased concentration of radionuclides when the waste water tanks are emptied. Such a pulse has been studied by Notter (1986b); frequently during the discharge, water samples were collected in the main stream of the Biotest Basin at station 1. The concentration of both Co-60 and

Zn-65 increased 10-500 times within one hour as shown in Fig. 2. After five years of operation the background level of radioactive nuclides in the Biotest Basin has been enhanced by accumulation e.g. in sediments.

4. THE CONCEPTUAL MODEL.

A conceptual model describing plausible transport paths for radionuclides in the environment is needed as a basis for mathematical modelling. In Fig. 3, a schematic description of the possible reservoirs for the radionuclides and the transport paths between them are shown.

The radionuclides from the power plant enter the Biotest Basin together with the cooling water. The mixing of the fresh water containing radionuclides and the brackish cooling water, preceeding the release into the basin, will affect the chemical form and oxidation state of the radionuclides. Chemical form and oxidation state will in turn influence the behaviour of the radionuclides in the Biotest Basin. Radionuclides can aggregate with, or adsorb to, particulate organic material and minerals. These processes can be reversible, and may be followed by desorption and dissolution. The large water flow through the small volume of the Biotest Basin results in a short turn-over time and a large proportion of the radionuclides are transported straight out of the Biotest Basin with the cooling water flow.

Part of the radionuclides, however, are expected to be retarded in the basin by various processes, and to circulate within the system. Dissolved radionuclides can sorb to e.g. algae, by ion exchange. Radionuclides are also taken up actively as nutrients, or swollowed by organisms with water or food, and thus transported in the food chain. The reverse processes from the reservoirs in the conceptual model are secretion and chemical desorption, directly or delayed by accumulation. The radionuclides released in this way can be taken up again and thus keep on circulating.

Another delay of transport out of the Biotest Basin is sedimentation of particles. However, only a small part of the bottom of the Biotest Basin functions as accumulation areas for sediments. The sediment can later be removed by resuspension and be retransfered to the circulation within the basin. In the accumulation areas radionuclides can be buried by new sediment, and be taken up by organisms living in the sediment.

This chemical and biological circulation, will give a distribution of radionuclides in the different organism-reservoirs of the basin (see

Fig. 3). As many of the reservoirs vary in biological importance throughout the year, so will the distribution of radionuclides.

5. CONCENTRATIONS, AMOUNTS AND FLUXES OF RADIOACTIVITY IN THE BIOTEST BASIN.

In this section the available data on concentrations, amounts and fluxes of radioactivity in the Biotest Basin are used to give a rough idea of the distribution of radionuclides over the different reservoirs and the flows between them. The main radionuclides studied are Co-60 and Zn-65, and in some cases also Co-58, Ag-110m and Mn-54. The method and input data used to estimate the activity is described for each reservoir. The necessary information for the biota is a list of major constituent species, their quantitative occurrences and measurements of radionuclide concentrations for each of the important species from different parts of the basin. For some reservoirs only very rough estimates can be made due to the lack of data. Primary data are given if not previous published or if only fragmentarily reported.

5.1 WATER

Introduction

The radionuclides enter, and are released from the Biotest Basin with the cooling water. The flow of water within the Biotest Basin is comparatively simple but may depend on the direction of the wind and the amount of cooling water. Most of the cooling water is transported rather rapidly northwards through the basin. In the central part the flow velocity is 10-30 cm per second (Andersson, 1983). Measurements over longer periods indicate varying flow directions depending on wind directions. In some occasions the main stream was found to be southwards (Evans, unpublished).

A calculation of the balance between inflow and outflow of radionuclides to and from the Biotest Basin was made by comparing the activity discharged into and the activity measured in water out from the basin during the years 1984 and 1985.

Little is known about the form of the radionuclides when they enter the Biotest Basin. In experimental work done by Salbu (1986) the size of the radionuclide complexes in the tanks was determined for Co-60, Co-58, Zn-65 and Mn-54. The radionuclides are to a certain extent associated with colloids, pseudocolloids and particles. Only a small fraction (<20%)

is present in low molecular weight forms; e.g. simple ions. However, it is not clear if this represents the orginal size distribution of the nuclides or if it is caused by sorption to colloids already present in the waste water. Salbu is also studying form and oxidation state of the different radionuclides in the water one hour after their entry into the basin (Salbu, unpublished).

Method and input data

The monthly discharge of radionuclides from the power plant is calculated as follows (see also 5.3): Information is available on the total gamma radiation (in cps) for each tank, the date of discharge, and whether the stand-by outlet was used that day. Thus for each month the total discharge in cps can be calculated, both to the basin and to the stand-by outlet (we assumed that 25% of the cooling water enters the basin if the stand-by outlet is open). The total discharge per tank of each radionuclide (**D**) can be calculated as follows: **D** (Bq)=total monthly discharge (Bq) x total gamma per tank (cps)/total gamma per month (cps).

At the outlet of the Biotest Basin 400 litres per month of the by-passing water is continuously pumped into a tank. The Co-58, Co-60 and Zn-65 in the water is precipitated and measured. The yield of the cobalt precipitation is measured by adding a known amount of Co-57 (H. Dahlgaard, pers. comm.). Outlet concentration data are available for one month in 1983, six months in 1984 and eight months in 1985, see table 2.

TABLE 2: CONCENTRATION OF Co-58, Co-60 AND Zn-65 IN WATER AT THE OUTLET FROM THE BIOTEST BASIN; OCTOBER 1983 - OCTOBER 1985. (DATA: H. DAHLGAARD) in Bq/m^3. (- = below detection limit)

MONTH	Co-58	Co-60	Zn-65
OCT 83	7.47	27.58	11.67
JAN 84	2.67	23.76	9.84
FEB 84	10.93	19.90	8.50
MAR 84	8.35	20.25	6.90
JUL 84	39.9	109.0	53.8
AUG 84	-	33.7	10.6
DEC 84	3.5	21.3	5.95
FEB 85	5.0	11.85	-
MAR 85	-	26.3	-
APR 85	-	21.6	5.41
MAY 85	3.9	16.73	2.22

table 2 cont.

MONTH	Co-58	Co-60	Zn-65
JUN 85	111.0	373.8	60.1
AUG 85	32.41	242.7	36.8
SEP 85	9.7	145.0	17.8
OCT 85	6.46	79.5	15.6

The amount of radionuclides released from the Biotest Basin is calculated by multiplying the measured outlet concentration with the cooling water flow through the Biotest Basin during that month.

The total amount of radionuclides in the water phase in the basin was estimated by multiplying the outlet concentration with the total volume of water in the basin. This can lead to an overestimation of the activity since the concentration probably is lower in some parts of the Biotest Basin, e.g. the lagoon.

Results and discussion

Comparisons were made between the amount of Co-60 and Zn-65 entering and leaving the Biotest Basin. Both the total and particulate fractions were considered (see Fig. 4 and 5). Table 3 gives the values for the total activity.

TABLE 3: COMPARISON OF TOTAL AMOUNT OF Co-60 AND Zn-65 IN AND OUT FROM THE BIOTEST BASIN. 10^7 x Bq. (- = below detection limit, * = not measured)

Period	Co-60 in	Co-60 out	Zn-65 in	Zn-65 out
8401	359	468	120	194
8402	375	372	140	159
8403	265	281	104	96
8404	230	*	81	*
8405	97	*	34	*
8406	1420	*	196	*
8407	1800	859	524	424
8408	612	415	76	130
8409	110	*	25	*
8410	228	*	97	*
8411	490	*	110	*
8412	540	498	120	139
8501	469	*	107	*
8502	280	251	41	-
8503	290	539	67	-
8504	170	320	47	80
8505	190	331	31	44

table 3 cont.

Period	Co-60 in	Co-60 out	Zn-65 in	Zn-65 out
8506	5990	4560	939	733
8507	3070	*	598	*
8508	2490	5680	469	861
8509	949	3320	160	408
8510	1930	1700	211	334
8511	1200	*	200	*
8512	700	*	98	*

Since few values are available for the outlet of the Biotest Basin it is difficult to draw any definite conclusions. However, the total activity in water into the basin is of the same level as the activity in water released from the basin. At some occasions the activity out of the basin is larger than the activity discharged into it. This is especially noticeable for Zn-65. Uncertainties in the calculations of the content of radionuclides in the water might be caused by:

a) An error in the estimation of the amount of cooling water that enters the basin when the stand-by outlet is opened. This amount was estimated to 25 % by O. Sandström, (pers. comm.).

b) During these years there was occasionally minor sedimentation in the subsampling cans which would result in an underestimation of the radionuclides discharged from the nuclear power plant. The sampling procedure is now changed.

c) A discrepancy between the two kinds of activity measurements made on the radionuclides in the discharge (total gamma and nuclide-specific spectrum).

d) The sampling at the outlet is done by pumping up water through a thin plastic hose (Ø = 7 mm); radionuclides attached to larger particles were not sampled. However this would lead to an underestimation of release from the Biotest Basin, which is the opposite to what was found in the comparison.

e) The efficiency of the precipitation is determined by adding Co-57. The chemical form of cobalt in the added solution might be different from that of the Co-60 and Co-58 in the discharge. It is most probable that cobalt in the added solution precipitates to a greater extent than cobalt in the discharge: the result would again be an underestimation of the release from the Biotest Basin.

f) Some months of the year cobalt-57 is reported to be discharged from the nuclear power plant. This would also lead to an underestimation of the release from the basin.

g) No efficiency determination is made for Zn-65. The same values as for Co-57 are used.

h) Water can flow from the outlet of the basin to the cooling water intake and re-enter the nuclear power plant. The concentration of radionuclides in the cooling water is low, but because of the large amounts of cooling water this could have an effect on the total amount. The power plant is, however, designed to minimize this recirculation. Based on temperature measurements no recirculation was found (Andersson, 1983). Estimates based on the radionuclide concentration in benthic diatoms indicate a recirculation of radionuclides of 10 % (Notter and Snoeijs, 1986). The power board has through the efficiency of the power plant estimated the recirculation to a maximum value of 10% at some occasions (Wahlström, pers. comm.). The latter values would give an overestimation of the release from the basin.

i) Leakage through the walls of the basin, has been estimated to be about 6 % of the flow (Andersson, 1983). However, as the radionuclide concentration in the leakage water is probably not substantially lower than at the outlet, this would only have a minor effect on the estimation of the release from the basin.

The different causes of uncertainties in the calculations point mainly to an underestimation of the amount of radionuclides that leave the Biotest Basin in the water phase. It is likely that the very different sampling procedures for determine the amount of radionuclides entering and leaving the basin are not compatible.

5.2 SEDIMENT

Introduction

Although there are only a few areas within the Biotest Basin where sediment accumulates, an appreciable amount of the discharged radionuclides are stored in the sediment. In this section an estimate is made of the amount of activity stored in the sediment and the transfer to the sediment from the water.

Method.

In the autumn of 1983 a survey was made of the radionuclide concentration in sediments at different locations in the Biotest Basin and its surroundings. From the radionuclide concentration in sediments from different locations inside the basin, the total amount of activity accumulated in the sediment was estimated. About 4 % of the Co-60 that was released from the nuclear power plant during 1980 - 1983 was detected in the sediment of the Biotest Basin. An additional 5 % was found in sediments outside the basin (Notter, 1985).

After the 1983 survey, sediment samples have been included in the monitoring program. These samples are only taken at one point, station 3, (see Fig. 1), located in the periphery of the main stream through the Biotest Basin. For 1984 and 1985 the amount of radioactivity in the sediment of the basin was estimated by a transfer factor. This is the fraction of the release transfered to the sediment in the 1983 survey, taking the radioactive decay into consideration.

During 1984, sediment traps were placed at the stations N and S (see Fig. 1) in the Biotest Basin for the collection of sedimenting material (Notter, 1986c). The amount of sedimenting material, its organic matter content (ash-free dry weight) and the radionuclide concentration were measured in two-weeks intervals. The traps were placed one metre above the sediment surface.

A comparison has been made between the sedimentation rate with data from the 1983 survey and the sedimentation rate measured by the sediment traps. Station N was used since it is situated close to the sediment sampling station 13 of the 1983 survey. Station S showed very fluctuating results probably caused by irregular currents.

The data from the sediment traps have also been used to study the correlation between the discharge of radionuclides into the Biotest Basin and the sedimenting radioactivity in the traps. In order to evaluate the effect of the amount of particles available for sedimenting, correlations have also been performed by multiplying the discharge into the basin with the turbidity and the diatom biomass, respectively; turbidity being a measure of the amount of particles in the water, and the biomass of diatoms being an index of the total amount of microphytobenthos in the basin.

Results and discussion

Figure 6 shows the total activity of Co-60 accumulated in the sediment in the period 1984 - 1985 as calculated with the transfer factor. The activity in the sediment increases from spring to autumn, and is rather constant during the winter. The measurements made in the monitoring program show an increasing trend for the concentration of Co-60, but the values show a great deal of fluctuation. There are no accumulating conditions for sediments at the single point (station 3) where the sampling is done and the fluctuations may be caused by contaminated sediment which is moved along the bottom by currents. However, the model used for the calculation is rather rough and does not handle seasonal variations of sedimentation rate or removal rate.

In Table 4 the sedimentation rates calculated from the 1983 survey are compared with the sedimentation rates calculated from the sediment traps.

TABLE 4: THE SEDIMENTATION RATES CALCULATED FROM THE 1983 SURVEY COMPARED WITH THE RATES CALCULATED FROM THE RESULTS OF THE SEDIMENT TRAPS.

Radionuclide	Sedimentation rate from 1983 survey	Sedimentation rate from traps
	Bq $m^{-2}a^{-1}$	Bq $m^{-2}a^{-1}$
Co-60	1240	19200
Co-58	220	7300
Zn-65	530	7400
Ag-110m	1000	3700

The sedimentation rates calculated from the 1983 survey data are considerably lower than the sedimentation rates measured in the sediment traps. The survey-based values are, however, net rates also taking the removal of activity from the sediment into consideration. The large difference may then indicate that a large fraction of the activity bound to sedimenting particles are transported out of the basin along the bottom surface or released by the decomposition process.

The correlations made between discharge and sedimenting activity in the traps are shown in Fig. 7 for Co-60 and Zn-65, respectively. Discharge and concentration in sedimenting material are well correlated for both Co-60 and Zn-65. If compensation is made for the amount of sedimenting material available, either by using turbidity (see Fig. 8) or the diatom biomass (see Fig. 9), the correlation is not improved. This gives an indication that the sedimenting process is quite complicated; it might also depend on flow conditions in the Biotest Basin (see Fig. 13).

5.3 PRIMARY PRODUCERS

5.3.1 PHYTOPLANKTON

The phytoplankton in the area was studied by Eriksson et al. (1977) in Öregrundsgrepen, and by Willén (1985) in the Biotest Basin after the units 1 and 2 were taken into operation. Fragile diatoms and flagellates (mainly Chrysophyceae and Volvocales) are chocked or destroyed by the passage through the power plant. Cryptomonads are not damaged to such extent. In the lagoon large populations of Chaetoceros simplex Ostenfeld, Diatoma elongatum (Lyngbye) Agardh and Pedinella tricostata (Rouchijainen) often develop (Willén, 1985).

Phytoplankton primary productivity was calculated to be 17 gCm^{-2} $year^{-1}$ for a reference site outside the Biotest Basin, 21 gC m^{-2} $year^{-1}$ in the main flow of the cooling water through the basin, and 24 gC m^{-2} $year^{-1}$ in the lagoon (values for the upper two meters of the water column). Maximum biomass measured was 0.9 mm^3 l^{-1} (chlorophyl ca. 7 mg m^{-3}) (Willén, 1985).

In comparison with microphytobenthos, primary production of phytoplankton is very low; comparison showed that yearly microphytobenthic standing crop was about 1000 times greater than that of phytoplankton (Snoeijs, 1986). In the free water column also many benthic diatoms occur in dead, decaying or living condition. No acceptable plankton samples for radionuclide analysis using a plankton net could be taken in the basin, as the samples contained mainly other things (benthic diatoms and detritus).

It may be concluded that phytoplankton plays a small role as primary producer compared with other plants in the Biotest Basin, and can as such be considered of minor importance for a model of radionuclide flow through the basin.

5.3.2 MICROPHYTOBENTHOS (including blue-green algae)

Introduction

The algal group that seems to be most favoured by the temperture anomaly and water flow conditions in the Biotest Basin is the benthic Diatomophyceae (diatoms). The diatoms occur mainly epilithic, epiphytic on macrophytes, epipsammic and epipelic, loose-lying on soft bottoms and (at times of major blooms) also in free-floating clumps all over the basin. The most important diatom species in the Biotest Basin are: Melosira spp., Amphipleura rutilans (Trentepohl) Cleve, Nitzschia filiformis (W.Smith) Hustedt, Diatoma elongatum (Lyngbye) Agardh, Gomphonema olivaceum (Hornemann) Brebisson, Rhoicosphenia abbreviata (C.Agardh) Lange-Bertalot, Synedra tabulata (Agardh) Kützing, and Cocconeis pediculus Ehrenberg. Diatoms are consumed by chironomids, snails and some fish.

Diatom biomass on rocky substrates is higher (up to four times) throughout the year inside the Biotest Basin compared with outside. The seasonal biomass pattern, which under normal conditions shows peaks in spring and autumn, is also altered by an extension of the growing season, resulting in exceptionally high biomass during winter (Snoeijs, 1985). Biomass of soft bottom diatoms (epipsammic and epipelic) has not been studied. For the diatoms that are loose-lying on soft bottoms (dm thick layers) only rough biomass estimations are available (Snoeijs, 1986).

Method

During one year (February 1984 - March 1985), diatom samples for radionuclide analysis were taken from stones every three weeks at four sites in the discharge area of the power plant: site F (inlet), site E (outlet), site A (stand-by outlet), site K (lagoon) (see Fig. 1). Simultaneously samples were taken at a reference site at the cooling water intake of the power plant (site G) (Notter and Snoeijs, 1986). Radionuclide concentrations in diatoms from stones are also available for July and August 1985 during and after overhaul of the nuclear power plant (see Table 5).

Results and discussion

Good correlations were found between the total discharge of radionuclides from the power plant and the concentration in the benthic diatoms for sites which are directly passed by the cooling water flow. In Fig. 10 the total amounts of Co-60, Zn-65, Ag-110m and Mn-54 in diatoms are shown for the year 1984. Stable and unstable heavy metals are probably mainly chemically bound to the silica skeletons of the diatoms, and only a small portion is absorbed into the cells (Cushing, 1967; Lindahl et al., 1983). Therefore diatoms might respond fast to discharge of radionuclides. The situation of the sampling sites in the basin influences the radionuclide concentration in the algae: the one year study in 1984 showed higher concentration at sites with fast flowing water than at sites with more quiescent water. This was not found for the two sampling occasions in 1985 (see Table 5). The latter two samples were taken at the period of overhaul of the power plant when there are big fluctuations in the discharge. There are indications that there is considerable recirculation of the radionuclides within the algal assemblages.

Because diatoms play such an important role as primary producers in the Biotest Basin, also the amount of dead and decaying diatoms is high. No studies have been performed on decomposition in the Biotest Basin but microscopic investigation of sedimenting material (see 5.2) has shown that this contained many dead decaying, and also living diatoms. Blooms of benthic diatoms in February-March were followed by high ash-free dry weight of sedimenting material in May-June (see Fig. 11). The pattern of concentrations Co-60 and Zn-65 throughout the year is quite similar for benthic diatoms and sedimenting material although the actual concentration may be different as in the case of Zn-65 (see Fig. 12). For Ag-110m and Mn-54 these patterns are less similar.

For making a model of radionuclide flow through the Biotest Basin enough information is available on epilithic diatoms. The diatoms living in soft bottoms are covered by the sediment samples. The biomass of diatoms loose lying on soft bottoms has been roughly estimated by Snoeijs (1986), and for this group thus estimations of radionuclide content can be made. The amount of loss of diatoms which are stirred up by the winds and in floating masses leaving the Biotest Basin needs more investigation.

TABLE 5: RADIONUCLIDE CONCENTRATION IN BENTHIC DIATOMS SUMMER 1985.
in Bq/kg dry weight ± sd%

DATE	SITE	Co-60	Zn-65	Ag-110m	Mn-54
850724	A	24400±1	4510± 3	500±18	1590± 3
850827	A	3980±2	480±14	130±26	220±11
850724	C	18420±1	2170± 6	410±21	980± 5
850827	C	6780±1	970± 6	180±32	250± 9
850724	D	1040±3	120±31	-	130±16
850724	E	19690±1	2700± 2	560±14	1000± 4
850827	E	6920±1	510±13	210±33	300± 8
850724	F	21500±1	3500± 3	750±18	1370± 3
850827	F	7170±1	670± 9	110±39	-
850724	G	1250±2	180±15	100±33	80±13
850827	G	410±1	60±14	-	20±21
850724	K	23490±1	1970± 6	-	1060± 4
850827	K	4910±1	720±13	-	300±13

- = below detection limit

Microscopic blue-green algae, which often form macroscopic crusts on rocky substrates, are favoured by the higher temperature in the Biotest Basin, especially in the backwaters (Snoeijs, 1987). These are e.g. species belonging to the Calothrix scopulorum community, Lyngbya spp. and Phormidium spp. No biomass and no radionuclide concentrations have been measured in blue-green algae from the basin, but from field observations it is clear that blue-green algae do not reach such enormous blooms as diatoms, and they are only important in the hydrolittoral.

5.3.3 MACROPHYTES

Introduction

Macro-algae on rocky substrates and submerged phanerogams on soft bottoms play an important role as primary producers in the Biotest Basin, especially in summer; maximum standing crop is reached in August - September. About 60% of the bottom of the Biotest Basin consists of rocky substrates and about 40% of soft bottoms (Snoeijs, 1986). In the lagoon the vegetation has less cover than in the rest of the basin (Widahl, 1985).

The most important macro-algae are the green algae: *Cladophora glomerata* (Linnaeus) Kützing, *Enteromorpha ahlneriana* Bliding, *Enteromorpha flexuosa* (Wulfen) J.Agardh, *Enteromorpha intestinalis* (Linnaeus) Link, *Enteromorpha compressa* (Linnaeus) Greville, the brown algae: *Pilayella littoralis* (Linnaeus) Kjellman, *Ectocarpus siliculosus* (Dillwyn) Lyngbye, the red alga: *Ceramium tenuicorne* (Kützing) Waern, and the Charophyte: *Chara fragilis* Desvaux. *Enteromorpha intestinalis* and *E. compressa* are macroscopically hard to distinguish from each other, and will therefore here be treated as a combined group *E. intestinalis+compressa*. *Enteromorpha flexuosa* and *Enteromorpha ahlneriana* often grow in mixed stands, they are only microscopically distinguishable from each other, and thus it was impossible to separate the samples, therefore the two species will here be treated as one group: *E.flexuosa+ahlneriana*. Filamentous green algae (*Spirogyra spp*., *Rhizoclonium spp*., *Ulothrix spp*. etc.) also play a considerable role, and some of them are favoured by the cooling water discharge, especially in the backwaters of the Biotest Basin (Snoeijs, 1987).

The most important submerged phanerogams in the Biotest Basin are: *Callitriche hermaphroditica* L., *Myriophyllum spicatum* L. and *Potamogeton pecitinatus* L. (Widahl, 1985; Renström et al., 1985b).

Method A.

Biomass determinations of macrophytes were made by Renström et al. (1986) for summer 1985 for five common vegetation types in the Biotest Basin (see Table 6). The results of radionuclide analysis of samples of these vegetation types are given in Table 7.

TABLE 6: BIOMASS OF FIVE VEGETATION TYPES IN THE BIOTEST BASIN

VEGETATION TYPE	SITUATION	dry weight g/m^2	 basin(tons)
1. CLADOPHORA GLOMERATA dominating	backwaters	21.8	5.0
2. POTAMOGETON PECTINATUS dominating	main flow	419.1	47.9
3. MYRIOPHYLLUM SPICATUM dominating	main flow	312.0	28.7
4. CLADOPHORA GLOMERATA with exposure-sensitive phanerogams	lagoon	53.8	16.1
5. CLADOPHORA GLOMERATA with exposure-tolerant phanerogams	main flow	*	*
TOTAL			97.7

* = included in vegetation type 4 (data from Renström et al., 1986)

TABLE 7: RADIONUCLIDE CONCENTRATION OF FIVE VEGETATION TYPES IN THE BIOTEST BASIN in Bq/kg dry weight ± sd%

Date	VT	Co-60	Zn-65	Ag-110m	Mn-54	Co-58	K-40
850819	1 *	30000±1	1900±19	230±72	1650±7	7000±22	350±30
850819	1 **	13000±1	830±13	-	560±7	3300±17	420±7
850819	2 *	33300±1	2300±4	50±54	1230±3	8000±7	870±7
850819	2 **	14700±6	1600±6	100±55	580±6	3400±14	540±10
850819	3 *	10000±1	720±7	190±22	460±4	1800±12	570±5
850819	3 *	13800±1	1080±4	170±20	590±3	3400±7	570±5
850819	3 **	10500±1	1500±11	-	460±10	-	690±9
850819	4 *	8600±2	750±51	950±60	280±40	-	230±36
850819	4 **	11300±1	1640±10	80±50	350±18	1800±42	440±21
850819	5 *	34200±1	2200±15	230±60	1860±5	4650±31	980±5
850819	5 **	23700±1	600±44	-	1420±9	12700±14	950±15

VT = vegetation type (see Table 6)
* = one sample only containing the dominant species (but in vegetation types 4 and 5 a mixture of several species)
** = subsample from a mixture of 9 samples
- = below detection limit

Renström et al. (1986) combined the vegetation types 4 and 5 in their biomass calculations because the species composition of both types was very similar. In radionuclide concentration however there is a big difference between 4 and 5, which is probably due to the different situation of the sampling sites: vegetation type 4 was sampled in the lagoon and has much lower radionuclide concentrations than vegetation type 5, which was sampled in the main flow of the cooling water through the Biotest Basin. There is also a big difference in radionuclide concentration between individual samples (* in Table 7) and a combination of 9 samples (** in Table 7), which may indicate rather large differences within patches and/or between different species.

Results and discussion

For a rough estimation of total amounts of radionuclides in macrophytes in the basin in August 1985, (at time of maximum standing crop) see Table 8. We used the measurements of the subsamples adressed to as ** in Table 7 for these calculations, and we assumed that 50% of the combined vegetation types 4 and 5 were situated in the main cooling water flow area and 50% in the lagoon and in the backwaters of the basin.

TABLE 8: TOTAL AMOUNT OF RADIONUCLIDES IN MACROPHYTES IN THE BIOTEST BASIN 19 AUGUST 1985 in 10^6 Bq.

VEGETATION TYPE	Co-60	Zn-65	Ag-110m	Mn-54	Co-58	K-40
1	65	4	-	3	17	2
2	702	75	5	28	165	26
3	302	44	-	13	-	20
4	91	13	1	3	15	4
5	191	5	-	11	100	8
WHOLE BASIN	1351	141	6	58	297	60

- = below detection limit

Method B.

Analyses of radionuclide concentration in macropytes were also done per species. From 1980 to 1984 six samples of the green alga <u>Cladophora glomerata</u> were analysed for radionuclides (Notter and Kukulska, 1983; Notter, 1984a; Notter, 1986a, Notter, 1986d); in 1980 concentrations were below detection limit, in 1981 concentrations were hardly detectable and with more constant operation of the nuclear power plant from 1982 onwards, concentrations became higher (see Table 9).

TABLE 9: RADIONUCLIDE CONCENTRATION IN CLADOPHORA GLOMERATA 1980-1984 in Bq/kg dry weight ± sd%.

DATE	SITE	Co-60	Zn-65	Ag-110m	Mn-54	Co-58	K-40
800607	101	-	-	-	-		
810503	101	<17	-	-	<16		
811030	F	12	12	1	9	25	880
811030	101	8	6	6	8	21	800
820528	101	29±2	31±4	19±7	12±4	100±4	97±1
830629	101	620±3	200±9	-	-	<370	84±20
840515	101	130±1	42±3	24±7	10±5	96±1	120±3
850917	101	3400±1	370±3	250±6	130±3	200±4	650±3
861024	101	130000±1	17000±1	-	1600±4	8400±1	-

- = below detection limit

In summer 1985 radionuclide concentrations were measured in <u>Cladophora glomerata</u> from 13 dates between 17 July and 29 August, during overhaul of the nuclear power plant (see Table 10 and Fig. 13). Samples were always taken at Station 1 (see Fig. 1).

TABLE 10: RADIONUCLIDE CONCENTRATION IN CLADOPHORA GLOMERATA IN 1985 AT STATION 1 in Bq/kg dry weight ± sd%.

DATE	Co-60	Zn-65	Ag-110m	Mn-54	Co-58	K-40
850717	9900±1	1300±4	360±16	580±4	1450±11	1050±7
850719	7900±1	1170±3	330±7	570±3	690±13	880±7
850722	11400±1	1080±5	190±22	670±3	300±34	1050±6
850729	14700±1	1210±2	220±16	760±2	3910±1	870±3
850802	21300±1	1300±10	300±25	1220±4	5280±2	1310±7
850807	30200±1	2040±6	610±10	1190±4	7210±1	880±10
850809	20200±1	1250±7	310±36	930±4	5080±2	1060±8
850813	25400±1	1650±5	540±19	1220±3	5560±2	850±8
850815	19200±1	1520±6	450±33	910±4	4090±2	1000±8
850819	19000±1	1470±9	380±26	720±8	-	760±13
850822	19700±1	1110±8	250±35	930±4	3900±2	720±11
850827	23500±1	1120±9	360±21	870±5	4370±2	620±13
850829	21960±1	1450±10	670±25	810±8	3890±4	490±24

- = below detection limit

Radionuclide concentrations were determined in samples of Cladophora glomerata, taken at different sites in the Biotest Basin 24 July 1985 and 27 August 1985, during and after overhaul of the nuclear power plant (see Table 11).

TABLE 11: RADIONUCLIDE CONCENTRATION IN CLADOPHORA GLOMERATA AT DIFFERENT SITES IN SUMMER 1985 in Bq/kg dry weight ± sd%.

DATE	SITE	Co-60	Zn-65	Ag-110m	Mn-54	Co-58	K-40
850724	A	1510±2	550±5	120±25	80±11	440±3	1020±6
850724	C	5970±1	1280±3	150±12	340±4	1860±1	1520±4
850724	E	11280±1	1390±4	230±51	660±4	3260±1	1840±5
850827	A	5930±1	400±9	60±70	220±8	1200±2	470±10
850827	C	4320±2	470±16	140±31	310±12	840±4	1210±9
850827	E	8260±1	1070±3	150±28	290±5	1450±1	600±4
850827	I	8300±1	280±19	100±30	370±7	1500±2	850±10
850827	K	3420±2	780±12	90±100	110±30	520±10	440±18

- = below detection limit

Cladophora glomerata is a branched, uniseriate green alga that often is overgrown by many epiphytes (mainly diatom species and the blue-green alga Lyngbya Kützingii Schmidle). Epiphytes may influence the radionuclide concentration in the Cladophora glomerata samples.

From comparison of radionuclide concentrations in Cladophora glomerata and the discharge of the power plant (see Fig. 13) it may be concluded that the effect of discharge is already recognizable in the first week after discharge, the maximum effect is reached in the second week after discharge. Radionuclide concentration in the alga decreases only slightly after the maximum discharge.

Radionuclide concentration in Cladophora glomerata differs at different sites within the Biotest Basin (see Table 11); it is highest at site E with fast flowing heated water and lower in the backwaters of the basin and the lagoon (sites C, I and K). The stand-by outlet was opened 23-30 July 1985, this effect can be seen in the difference in radionuclide concentration in Cladophora glomerata between 24 July and 27 August at site A.

Radionuclide concentration in Cladophora glomerata from 27 August 1985 in Table 11 is low compared with those from the same date in Table 10, probably due to the different situation of the sampling sites.

Radionuclide concentration was determined in samples of Enteromorpha spp., taken at different sites in the Biotest Basin 24 July 1985 and 27 August 1985 (see Table 12).

TABLE 12: RADIONUCLIDE CONCENTRATION IN ENTEROMORPHA SPP., AT DIFFERENT SITES IN SUMMER 1985 in Bq/kg dry weight ± sd%.

DATE	SITE	Co-60	Zn-65	Ag-110m	Mn-54	Co-58	K-40
ENTEROMORPHA INTESTINALIS+COMPRESSA:							
850724	C	1660±1	2050±2	280±9	80±11	540±3	480±7
850827	A	720±2	230±15	80±29	30±33	-	320±10
850827	C	620±3	650±7	120±78	-	190±39	560±9
850827	H*	60±14	110±21	-	9±77	10±114	320±9
850827	J*	110±11	60±45	-	20±38	-	560±10
850827	K	310±10	930±8	260±31	10±132	-	570±11
ENTEROMORPHA FLEXUOSA+AHLNERIANA:							
850724	C	930±4	620±9	100±35	60±29	180±9	1380±8
850724	D**	140±2	60±9	20±12	10±16	80±3	1270±2
850724	K	7840±1	1650±3	290±17	710±3	2000±1	840±6
850827	C	170±26	-	50±42	-	90±29	1190±14
850827	E	580±2	400±6	-	-	110±9	1370±4
850827	F	630±3	110±24	20±39	-	30±43	1330±7
850827	K	380±5	280±10	-	-	-	1360±7

- = below detection limit
* = reference sites outside the Biotest Basin
** = situated in the discharge channel of unit 3

Enteromorpha spp. are branched or unbranched, tube-shaped green algae, never overgrown with epiphytes if in healthy condition; Enteromorpha spp., have a very smooth surface, hard for epiphytes to attach to. Radionuclide concentrations are generally lower in Enteromorpha spp., than in Cladophora glomerata, probably due to different morphology of the algae and the occurrence of many epiphytes on Cladophora glomerata, but not on Enteromorpha spp..

Radionuclide concentrations were determined in three samples of Spirogyra spp. taken at site I (in a sheltered part of the Biotest Basin) and site K (lagoon). The samples were taken in summer 1985 (see Table 13.

TABLE 13: RADIONUCLIDE CONCENTRATION IN SPIROGYRA SPP. AT SITE I AND K IN SUMMER 1985 in Bq/kg dry weight ± sd%.

DATE	SITE	Co-60	Zn-65	Ag-110m	Mn-54	Co-58	K-40
850724	I	14090±1	1910±4	60±52	210±13	3800±1	330±17
850724	K	7960±1	1650±4	60±33	160±10	2150±2	290±14
850827	I	4660±3	1980±8	-	100±38	890±8	-

- = below detection limit

Spirogyra spp. is a uniseriate green alga which is favoured by the temperature anomaly in the Biotest Basin. The alga mainly occurs in floating masses in the backwaters of the basin. Radionuclide concentration in Spirogyra spp. is rather high compared to Enteromorpha spp. (see Table 12) which might be due to morphology and faster growth rate of Spirogyra spp..

Radionuclide concentrations were determined in two samples of Ceramium tenuicorne, taken at site F in the Biotest Basin 28 February 1984 and 20 March 1984 (see Table 14).

TABLE 14: RADIONUCLIDE CONCENTRATION IN CERAMIUM TENUICORNE IN 1984 in Bq/kg dry weight ± sd%.

DATE	SITE	Co-60	Zn-65	Ag-110m	Mn-54	Co-58	K-40
840228	F	4040±1	1300±5	1020±5	290±6	2310±2	-
840320	F	5010±3	2250±40	1300±20	440±21	2010±9	230±15

- = below detection limit

Ceramium tenuicorne is a branched red alga, radionuclide concentrations are comparable with those in diatoms taken at the same place and time.

Renström et al. (1985a and b) made semi- quantitative measurements of macrophytic vegetation in the Biotest basin by using a 0-4 cover scale, each unit on the scale roughly representing a certain biomass. From these results the percentage biomass of the most important species was calculated for the years 1983 and 1984 (see Table 15).

TABLE 15: PERCENTAGE OF TOTAL BIOMASS FOR THE MAIN MACROPHYTES IN THE BIOTEST BASIN

SPECIES	% 1983	% 1984	
ALGAE:			
CHARA ASPERA	2	3	
CHARA BALTICA	1	3	
CHARA FRAGILIS	11	8	
CLADOPHORA GLOMERATA	32	6	**
CLADOPHORA RUPESTRIS	4	1	
CERAMIUM TENUICORNE	2	2	*
ETEROMORPHA AHLNERIANA	-	1	*
VAUCHERIA SP.	4	3	
PHANEROGAMS:			
CALLITRICHE HERMAPHRODITICA	7	1	
MYRIOPHYLLUM SPICATUM	7	18	*
POTAMOGETON FILIFORMIS	1	3	
POTAMOGETON PECTINATUS	22	43	*
POTAMOGETON PERFOLIATUS	2	4	
RUPPIA MARITIMA	1	2	
ZANNICHELLIA PALUSTRIS	3	1	
REST GROUP:	1	1	

- = less than 1%; species with in both years less than 1% have been left out
* = some information available, but not enough
** = enough information available

5.3.4 SHORE VEGETATION

Helophytes are favoured by the embankment of the Biotest Basin because of reduced exposure (Renström et al., 1985b); the area covered by helophytes increased from 720 m^2 in 1974 to 11057 m^2 in 1985 (Renström et al., 1986). The main species occurring at the shores of the basin are: Phragmites communis Trin., Scirpus maritimus L. and Scirpus tabernaemontani C.C.Gmel. (see Table 16).

TABLE 16: AREA COVERED BY SHORE VEGETATION (HELOPHYTES)

	SURFACE AREA COVERED (in m^2)				
SPECIES	1974	1980	1982	1984	1985
PHRAGMITES COMMUNIS	710	2960	5420	8960	10237
SCIRPUS MARITIMUS	5	229	351	390	333
SCIRPUS TABERNAEMONTANI	5	236	373	390	404
OTHER (MIXED SPECIES)	0	0	28	114	83
TOTAL AREAL	720	3210	6170	9850	11057

(data from Renström et al., 1985b and Renström et al., 1986)

No radionuclide concentrations have been analysed for shore vegetation.

5.4. CONSUMERS

5.4.1 MICRO- AND MEIOFAUNA.

Microfauna (<0.06 mm, e.g. zooplankton and benthic ciliates) and meiofauna (<0.06 - 1 mm , e.g. Nematoda and Ostracoda), have not been investigated to a large extent in the Forsmark Biotest Basin. From microscopic investigation it was concluded that benthic microfauna only plays a small role on rocky substrates; Nematoda and Ostracoda however occur more abundantly on rocky substrates. To be able to detect radionuclides at this low concentrations within a realistic analysing time, samples of about at least 3 g dry weight are necessary. It is extremely difficult to gather micro- and meiofauna samples in that amount in the basin. For making a model of radionuclide flow through the Biotest Basin we cannot take micro- and meiofauna into account because of sampling difficulties.

5.4.2. INVERTEBRATE MACROFAUNA

Invertebrate macrofauna (>1 mm) in soft bottoms was studied by Mo (1984). The most important animals occurring are: Oligochaeta, Gammarus spp., Corophium volutator (Pallas), Chironomidae, Theodoxus fluviatilis (L.), Paludestrina jenkinsi (Smith), Cardium spp. and Macoma baltica (L.). Species abundance (numbers) are available from five sites in the Biotest Basin for the years 1978-1983, with one or two samplings per year. Macrofauna on rocky substrates was studied by Snoeijs and Mo (1987). The most important animals occurring are: Hydrozoa, Balanus improvisus

Darwin, *Electra crustulenta* (Pallas), *Chironomidae*, *Theodoxus fluviatilis* (L.), *Paludestrina jenkinsi* (Smith), *Lymnaea palustris* (Müller), *Gammarus spp*., and *Trichoptera*.

There are also macrofauna species, like Mysidae living in the free water column. In the 2350 m long tunnel under the sea-bed through which the cooling water is led to the Biotest Basin, there live balanoids and hydroids. Because of the difficulty of access to the tunnel, studies are difficult to perform here. It may be assumed that also these animals take up a certain amount of radionuclides.

Radionuclide concentrations were measured in snails belonging to the genus *Lymnaea* (Notter and Kukulska, 1983; Notter, 1984a; Notter, 1984b; Notter, 1986a). Four species of *Lymnaea* are known to occur in the Biotest Basin: *L. palustris* (Müller), *L. peregra* (Müller), *L. stagnalis* (L.) and *L. truncatula* (Müller). As they are macroscopically hard to distinguish from each other all *Lymnaea* species were treated here as one group: *Lymnaea spp*.. Whole snails (with their shells) were homogenized. In Table 17 the radionuclide concentrations are given for *Lymnaea spp*. sampled 1980-1984. In 1980 and 1981 concentrations were below detection limit, and with more constant operation of the nuclear power plant from 1982 onwards, concentrations became higher.

TABLE 17: RADIONUCLIDE CONCENTRATION IN LYMNAEA SPP. 1980-1984
in Bq/kg dry weight ± sd%.

Date		Co-60	Zn-65	Ag-110m	Mn-54	Co-58	K-40
800607	BT	-	-	-	-	-	100
801011	BT	-	-	-	<6	26	140
810617	BT	-	-	-	-	-	<620
810923	BT	-	-	-	-	<6	64
820526	BT	<10	<20	40±16	-	14±12	260±9
820927	BT	43±8	20±19	220±5	-	34±8	<97
830629	BT	220±3	30±22	140±9	13±21	22±18	<120
840515	BT	200±3	52±11	190±6	14±22	26±12	62±41
850917	BT	1300±1	220±6	220±8	40±12	130±10	100±21
861001	BT	1500±1	200±6	770±2	-	110±6	-

\- = below detection limit
BT = Biotest Basin

Data are available on radionuclide concentrations in different macrofauna species for July-October 1985 (see Table 18). Compared with primary producers from summer 1985, the macrofauna has relatively high concentrations of Ag-110m and relatively low concentrations of Mn-54.

TABLE 18: RADIONUCLIDE CONCENTRATION IN MACROFAUNA 1985 in Bq/kg dry weight ± sd%.

Date	Site	Co-60	Zn-65	Ag-110m	Mn-54	Co-58	K-40
GAMMARUS SPP.:							
850724	BT *	1480±110	1830±440	2070±100	-	680±170	<2400
850828	BT	1140±2	480±9	1140±4	20±49	240±6	-
851029	BT	1070±5	300±43	660±13	-	210±25	-
850828	OUT	160±37	190±32	90±100	-	120±30	640±13
MYSIDAE:							
850724	BT *	300±23	850±80	890±30	-	-	700±450
850828	BT	580±9	900±12	550±52	-	170±29	860±12
851030	BT	300±3	140±11	280±10	-	-	210±10
850828	OUT	80±19	200±17	70±88	-	-	3±19
BITHYNIA TENTACULATA:							
850724	BT *	620±8	580±17	530±6	40±5	180±7	<70
850828	BT	830±2	490±5	560±7	-	110±14	520±7
LYMNAEA SPP.:							
850724	BT *	2000±50	440±18	720±21	60±6	530±12	40±42
850828	BT	1070±2	180±14	130±15	-	110±9	110±15
851029	BT	1120±2	-	360±11	80±13	100±15	40±14
851029	OUT	260±4	130±15	100±42	4±107	40±17	-
PALUDESTRINA JENKINSI:							
850828	BT	2902±2	260±16	620±13	90±19	530±6	-
THEODOXUS FLUVIATILIS:							
850725	BT *	200±6	740±8	50±2	200±10	70±4	10±20
850828	BT	270±4	90±17	30±36	60±10	-	30±17
851029	BT	320±4	70±22	30±27	30±19	80±18	80±13
CHIRONOMIDAE:							
850726	BT *	770±60	790±180	-	-	-	<200

- = below detection limit
* = unpublished data Sverker Evans (Studsvik Energiteknik AB, Nyköping)
BT = Biotest Basin
OUT = Outside Biotest Basin

5.4.3 FISH

Introduction

When the dose to humans, corresponding to a certain amount of radioactivity, is to be calculated, the concentration in fish is of special interest. Fish represent the most important component in the pathways of radionuclides from the aquatic system to humans.

Method

For a rough estimate of the total activity bound to the fish biomass we must know the sizes of the populations of various species and their fluctuations between and within years. Some idea of the result of uptake and excretion of different radionuclides in different fish species is also needed. Research in this field is being performed by SNV.
Population studies and biological research concerning fish in the Biotest Basin have been made since some years before the power plant was taken into operation. Most of this work has been reported (see appendix I).
Perch is the most closely examined fish species. Uptake and excretion of stable metals and radionuclides have been studied since 1985. Samples of about 20 female perch (17-20 cm) were taken monthly. During 1985 the fishes were dissected in muscle, liver, stomach and gonades, and analysed. Since 1986 the remaining parts of the fish were also analysed. This investigation will continue during 1987 and is to be reported in 1988.
Parallel studies on other fish species (pike, roach and silver bream) is done by Sverker Evans (Studsvik Energiteknik, unpublished). The concentration of radionuclides in different species of fish is also reported yearly in the environmental monitoring program performed by the power board.

Results

The most frequently detected nuclides are Co-60 and Zn-65. For perch the total "body burden" was calculated monthly for 1986 as all parts of the fish were then analysed. Estimation of total nuclide concentrations in 1985 were based on the ratio in muscle and remaining part of the fish in 1986. The results are given in Fig 14 and 15. In 1986 there were large fluctuations in the ratio between the radionuclide concentration in muscle and the remaining parts, specially for Zn-65. This led to an uncertainty in the calculated values for 1985 estimated to ±60% for Zn-65 and about ±30% for Co-60.

From July to December the total body burden was larger than in the beginning of the year. This was expected, as about 90% of the radionuclide discharge takes place during the overhaul period (June-July). After spawning in spring, the fish start to eat and reach a period of growth in summer, including fat storage, which is followed by the gonad growth period in autumn.

As the two first units have been operating continuously for some years, the radioactive discharge to the Biotest Basin is stabilized. During the samplings 1985 and 1986 we could not find evidence for any accumulation between years of radionuclides in fish. It seems that the increase of Zn-65 and Co-60 after the overhaul period to the major part is excreted before summer next year. The concentrations of Co-60 and Zn-65 increase with one months delay after the overhaul period. Zinc is taken up to a larger extent than cobalt. Although the discharge of Co-60 is about ten times greater than that of Zn-65 the concentration in fish muscle is 20 Bq/kg dry weight Co-60, and 100 Bq/kg dry weight Zn-65. This agrees with other investigations (G. Neumann, 1985). Zinc is essential for organisms and biologically more mobile than many other metals. The biological half time for both Co-60 and Zn-65 in fish is 50-200 days and depends on temperature and uptake path.
Except in pike, there were no big differences in the concentrations of Co-60 and Zn-65 between various species of fish in the Biotest Basin (S.Evans, pers. comm.). Pike mainly feeds on other fish, and has a very fast growth rate in the Biotest Basin, probably its metabolism is thus not comparable with the other fish species. (see Table 19). The same results are shown by the monitoring program (see Table 20).

TABLE 19: CONCENTRATIONS OF Co-60 AND Zn-65 IN MUSCLE FROM DIFFERENT SPECIES OF FISH FROM THE BIOTEST BASIN, JULY 1985. THE MEAN VALUE OF (n) SPECIMEN in Bq/kg dry weight (pers.comm. Sverker Evans).

NUCLIDE	ROACH	PERCH	SILVER BREAM	PIKE
Co-60	23(20)	25(20)	57(16)	6(10)
Zn-65	87(20)	134(20)	104(16)	37(10)

TABLE 20: CONCENTRATION OF Co-60 AND Zn-65 REPORTED IN THE ENVIRONMENTAL MONITORING PROGRAM FOR THE POWER PLANT in Bq/kg dry weight.

PERCH	831001	840927	850918	860911
Co-60	-	3	27	30
Zn-65	15	29	120	38
PIKE	831001	840920	850920	861008
Co-60	-	3	9	16
Zn-65	45	15	72	47
EEL	831001	840920	850920	no
Co-60	-	23	49	sample
Zn-65	-	42	53	

The dominating fish species in the Biotest Basin are perch and roach (O. Sandström, 1984).

Although no direct investigations have been made on the total biomass of fish in the Biotest Basin, fish populations have been studied all year round by fyke and gillnet fishing and may be estimated to be about 40-50 10^3 kg. (E. Neuman, pers. comm.) Based on these data we calculated the amount of radioactivity (Co-60 and Zn-65) bound to fish monthly from March 1985 to June 1986 (see Table 21).

The monthly discharge and the percentage measured in fish is presented in Table 21.

TABLE 21: MONTHLY DISCHARGE, AMOUNT OF Co-60 AND Zn-65 BOUND TO THE FISH POPULATION AND THE PERCENTAGE OF THE DISCHARGE BOUND IN FISH IN THE BIOTEST BASIN.

	Co-60 Bq x 10^5			Zn-65 Bq x 10^5		
DATE	DISCHARGE	FISH	%	DISCHARGE	FISH	%
850306	29000	3.0	0.010	6700	16.2	0.24
850627	600000	2.7	0.000	94000	10.4	0.01
850724	380000	8.0	0.002	74000	45.1	0.06
850828	250000	3.8	0.002	47000	16.2	0.03
850930	95000	9.3	0.010	16000	41.4	0.26
851030	220000	6.1	0.028	24000	29.6	0.12
851127	120000	8.7	0.007	20000	36.4	0.18
851218	70000	8.8	0.013	9800	38.9	0.40
860128	210000	7.5	0.004	16000	21.5	0.13
860413	150000	2.4	0.002	16000	4.3	0.03
860522	160000	6.2	0.004	14000	6.2	0.12
860807	710000	4.7	0.001	69000	11.1	0.02

Cobalt-60 bound to the fish population is below 0.3 ^{o}/oo of a monthly discharge and for Zn-65 below 4 ^{o}/oo. These figures are probably overestimated as the nuclide concentrations in perch, used in the calculations, were some what higher than in other fish species.
The concentrations of radionuclides in fish are, for these nuclides, dependent on the concentrations in the food organisms. The daily food consumption depends to a large extent on temperature. P. Karås (1984) has since 1983 made stomach analyses on perch and found that perches of 17-20 cm length prefer amphipods, fish and chironomids, somewhat dependent upon the amounts present at a certain time.
Perch stomach contents were also analysed as the radionuclides there are potentially available for metabolism. Another reason for sampling stomach contents is the difficulty of sampling food organisms in sufficient quantities.

TABLE 22: THE RADIONUCLIDE CONCENTRATION IN STOMACH AND STOMACH CONTENT OF PERCH IN THE BIOTEST BASIN in Bq/kg dry weight.

Date	Co-60 Stomach	Co-60 Stomach content	Co-60 Ratio	Zn-65 Stomach	Zn-65 Stomach content	Zn-65 Ratio
850306	52	27	0.52	245	354	1.44
850627	71	399	5.62	95	465	4.90
850724	119	426	3.58	408	531	1.30
850828	89	224	2.51	333	499	1.50
850930	129	765	5.93	537	570	1.06
851027	191	225	1.18	274	349	1.27
851127	198	390	1.97	345	185	0.54
851218	215	311	1.45	284	496	1.75
860128	207	1006	4.86	111	1162	10.5
860413	56	178	3.18	81	103	1.27
860522	94	533	5.67	144	162	1.26
860807	138	317	2.30	122	202	1.66
860828	86	225	2.62	125	234	1.87

Table 22 shows the concentrations in stomach content and in stomach ventricular and intestine. The concentration of radionuclides in the stomach contents are somewhat lower than those found in food organisms in the basin (compare Table 22 with Table 18 in chapter 5.4.3). This might depend on the mixture of organisms in the diet or on the degradation process in the stomach. The epithelia of the stomach tissue functions as a filter and the concentrations in the stomach itself is somewhat lower than in the stomach contents but higher than in other tissues, e.g. muscle.

P. Karås and E. Neuman (SNV) have applied the energetic model of Kitchell and Stewart (1977) to the perch population in the Biotest Basin after some adjustments. The total food intake for 1984 for a perch (of 40 g) can be calculated to about 220 g fresh weight. If we approximate the fish biomass to perches of this size and the concentration in the food to 1000 Bq kg^{-1} dry weight for Co-60 and 400 Bq kg^{-1} dry weight for Zn-65 (see 5.4.2), the total flux into fish of these nuclides 1985 can be estimated to 50 10^6 Bq Co-60 and 20 10^6 Bq Zn-65. The total discharge 1985 to the Biotest Basin was 2 10^{11} Co-60 and 3.2 10^{10} Zn-65, consequently the amount bound to the fish population and the yearly flux trough the fish biomass is insignificant.

5.4.4 BIRDS AND MAMMALS

Waterfowl were studied by Sandström (1986); seventeen species were observed 1981-1984.

Only the goosander showed an increased population in the Biotest Basin and its surroundings with a maximum during winter 1983-1984.

No radionuclides have been measured in birds on mammals. It may be recommended to make some measurements on fish- and plant- eating birds, and mink.

5.5 QUANTIFICATION OF THE CONCEPTUAL MODEL

The amount of radionuclides in the different reservoirs of the conceptual model was estimated. In fig. 16 the activity of Co-60 in the different reservoirs during spring, summer, autumn and winter is shown. For some of the reservoirs only one or few values are available. In those cases where they are based on rough estimates (e.g. macrophytes) the estimates have a high degree of uncertainty. Anyhow, Fig. 16 gives an idea of the level of radionuclide concentration in the different reservoirs and allows also comparison of the radionuclide amounts in the different reservoirs. The calculations are made for a certain moment and do not reflect the flow of radionuclides between the different reservoirs.

6. DISCUSSION AND CONCLUSIONS

The five reservoirs in the conceptual model "water", "shore", "pelagic", "sediment" and "benthic" together represent the Biotest Basin. In some of the reservoirs transport of radionuclides from the Forsmark Nuclear Power Plant into the Baltic Sea may be delayed. The "water" reservoir in the conceptual model functions as the main transport medium for radionuclides to and from the other four reservoirs.
Due to the short retention time of the cooling water in the Biotest Basin, most of the discharged radionuclides flow straight through and out of the basin. The occurrence of delay could not be confirmed by comparing in- and outflow of radionuclides to and from the basin in the water; this is probably caused by the great uncertainties in the available data.

The reservoirs in the conceptual model that contain the highest amounts of radioactivity are: "water, "sediment" and "benthic", where the consumer components within the reservoirs play a minor role. Some of the reservoirs show a considerable variation in radionuclide content throughout the year, based on both biological seasonal cycles, and irregular discharge of activity from the power plant. Especially diatoms and sedimenting material (the latter largely consists of dead, decaying and even living diatoms) show a large and rapid variations; it may be concluded that the flow of radionuclides between water, sediment and benthic diatoms is relatively fast. There might also be considerable recirculation of radionuclides within benthic diatom assemblages. The flow to and from macrophytes is probably of great importance too, but lack of data prevents us from quantifying this component satisfactorily for the moment.

In general, the available data are insufficient for making a budget of the radionuclide flow in the Biotest Basin.
Missing data are:

- Good measurements of the amounts of radionuclides to and from the basin in the water. As most radionuclides are transported straight through the Biotest Basin, the difference between the amount of radionuclides entering and leaving the basin will always be very small. Even a very small discrepancy in the data can give misleading results. This implies that sampling must be the same procedure at inlet and outlet to and from the basin, and a calculating procedure must be based on very accurate measurements if a total budget for the Biotest Basin is considered.

- Reliable information on the amount of radionuclides that is lost via the stand-by outlet. As no nuclide - specific analyses are done for each seperate discharge tank it will still be impossible to correctly divide the discharge between the stand-by outlet and the Biotest Basin, even if the correct amount of water through the stand-by outlet is known. It may also be recommended to continuously sample water at the stand-by outlet, in the same way as it is being done at the outlet, and as it should be done at the inlet to the basin.

- Information on the physical-chemical form of the different radionuclides in the water; what happens to the radionuclides when the fresh water from the tanks mixes with the brackish cooling water? (Do they get more or less biologically accessible?)

- More measurements of radionuclide concentration in macrophytes. For making a model of the radionuclide flow through the Biotest Basin, the data on which the results in Table 8 are based are not sufficient. Where the sampling sites are situated seems to determine the radionuclide concentrations in macrophytes (as in the diatoms); more samples should be taken of all vegetation types at different sites within the basin. Radionuclide concentrations should be measured in some of the species that account for the larger part of the total macrophytic biomass (<u>Chara fragilis</u>, <u>Myriophyllum spicatum</u>, and <u>Potamogeton pectinatus)</u> from different parts of the basin. For most of the species occurring in the hydrolittoral and upper sublittoral enough measurements on green algae, but not on brown and red algae are available; good biomass determinations are not available for these parts of the littoral (e.g. <u>Enteromorpha spp</u>., benthic thread-like green algae and free-floating algae such as <u>Spirogyra spp.</u> are underestimated or even absent in Table 15).

- Some quantitative samples of blue-green algae (<u>Rivularia atra</u> (Roth) and the <u>Calothrix scopulorum</u> (Weber and Mohr) C.A.Agardh -community) should be taken for radionuclide analysis.

- Biological information on loss rates of primary producers: decomposition within the basin, consumption by faunal organisms, and transport out of the basin.

- Measurements of radionuclide concentration in different components of the "shore" reservoir. Samples should be taken for such analysis of the three most important helophytes at different sites around the basin. Also the effect of spray (aerosol) from the basin on the terrestrial vegetation (e.g. pine trees) should be investigated for radionuclides. to get some idea of its degree of importance in the whole system.

- More measurements of radionuclide concentration in invertebrate macrofauna organisms, including temporal and spatial variation.

- Information on the biological accessability of radionuclides, if bound to algae and eaten by consumers or if bound to the sediment passing through consumers.

- The radionuclide concentration in fish is of great importance for dose calculations to humans. The progress of model research concerning uptake and excretion of radionuclides in the fish population in the Biotest Basin should be reported before further research in this field is initiated. It is also of great importance to do a more accurate calculation of the total biomass of the different fish species in the Biotest Basin.

SNV has already initiated special studies to cover missing data in some of these fields.

In this report a static description is given of the distribution of radionuclides over the different components in the Biotest Basin - ecosystem for as far as data are available. A dynamic approach by mathematical modelling can be done when the now identified missing data have been gathered. A model is proposed, describing uptake of radionuclides on/in diatoms from the water, release from living, decaying and dead diatoms, including description of pathways of loss of diatom biomass to other systems (e.g. consumption, fixation in sediment). Such a model could be used as input to other models, describing transfer of radionuclides to fish, which are at the moment being developed under the authority of NIRP. A coupling of these models into a larger dynamic model will give a better understanding of the pathway of radionuclides from the discharge of nuclear power plants to humans.

For further studies we suggest selection of the subsystem water-sediment-primary producers. This project shows that the greatest radionuclide flow in the Biotest Basin takes place between these components. This subsystem has not received as much attention in the past as e.g. transfer to fish, and transfer between water and sediment. As the primary producers are in the beginning of the food chain, investigations in the subsystem water, sediment, primary producers are of great importance. The Forsmark Biotest Basin offers an excellent opportunity for studying transfer to and from primary producers, partly because their growth is enhanced and their growing season extended, due to the temperature anomaly of the cooling water, partly because radionuclides are supplied in fairly precisely known amounts. Many important data are already available.

7. SUMMARY

The Forsmark Biotest Basin is an artificial offshore brackish lake, through which the cooling water is led from the Forsmark power Station on the Swedish east coast. Certain radionuclides are discharged together with the cooling water. Of these, Mn-54, Co-60, Zn-65 and Ag-110m are easily detectable in the environment because of the amounts that are discharged and because of their physical half-lives of between 0.7 and 5.2 years.

This report gives a conceptual five-compartment model for the flows of radionuclides within the basin ecosystem. The "water" reservoir is the main means of transport of radionuclides through the basin. Most radioactivity flows with the cooling water straight out into the Baltic Sea. A part of the input of radionuclides, however, is delayed in the Biotest Basin. Radionuclides may be retained in/on living organisms, or may become chemically attached to nonliving particles, in the other four reservoirs: "sediment", "benthic", "pelagic" and "shore".

The available data from biological and radio-ecological investigations in the Biotest Basin were used in this study to quantify the amounts of radionuclides in each of the reservoirs. The subsystem water-sediment-primary producers was pointed out to be the most interesting part of the ecosystem for studying radionuclides with mathematical modelling in the future. However, some data are missing for modelling, especially important are: good measurements of radionuclides in the water phase entering and leaving the Biotest Basin, measurements of radionuclide concentration in some important macrophyte species from different parts of the basin, annual variation of radionuclides in invertebrates, and a reliable estimation of the total fish biomass within the basin.

This report also presents an overview of studies that have been, or are being performed in the Biotest Basin, both within the monitoring program and in special projects.

7. SAMMANFATTNING

Biotestsjön är en inneslutning av Öregrundsgrepen på ca 0.9 km^2 och utgör primär recipient för kylvattnet från Forsmarks kärnkraftverk. Kylvattnet innehåller små mängder av radioaktiva nuklider, främst Co-60, Zn-65, Mn-54 och Ag-110m. I anslutning till Biotestsjön bedrivs biologisk och radioekologisk forskning. En gång årligen genomförs dessutom rutinmässigt kontroll av eventuell ackumulation av radionuklider i biota. Framförallt Co-60 och Zn-65 kan mer kontinuerligt följas i olika typer av omgivningsprover.

I denna rapport ges exempel på en "compartment modell", bestående av fem delar, för flödet av radionuklider i Biotestsjön. Vattenreservoaren är det huvudsakliga transportmediet för radionuklider i biotestsjöns ekosystem. Största delen av radioaktiviteten fraktas med kylvattnet rakt igenom Biotestsjön ut i Öregrundsgrepen. Till viss del fördröjs radionukliderna i Biotestsjön i någon av modellens övriga delar: "sediment", "bentisk", "pelagisk" och "strand". Detta kan ske genom upptag och/eller adsorption på levande organismer eller genom kemisk bindning till partiklar av annat slag.

Data från tidigare biologiska och radioekologiska undersökningar i Biotestsjön har nu utnyttjats för att beräkna mängden radionuklid (Co-60 och Zn-65) i modellens olika delar vid olika tidpunkter på året. I första hand bedöms delsystemet vatten-sediment-primär producenter vara ett lämpligt område att studera vidare med matematiska modeller som utgångspunkt. Delsystemt innehåller relativt stor del av de radionuklider som finns i Biotestsjön. En del data saknas dock inför fortsatta modellstudier såsom: flödesmätning och koncentration av radionuklider i vatten vid utloppet, koncentrationen av radionuklider i olika arter av macrophyter från olika stationer i Biotestsjön, årsvariation av koncentrationen av radionuklider i evertebrater samt en noggrannare beräkning av fisk- biomassan. Rapporten innehåller också (Appendix 1) en förteckning över forskning och undersökningar som bedrivits i Biotestsjön.

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Fig. 1. The Forsmark Nuclear Power Station and the Biotest Basin, showing the different sampling sites.

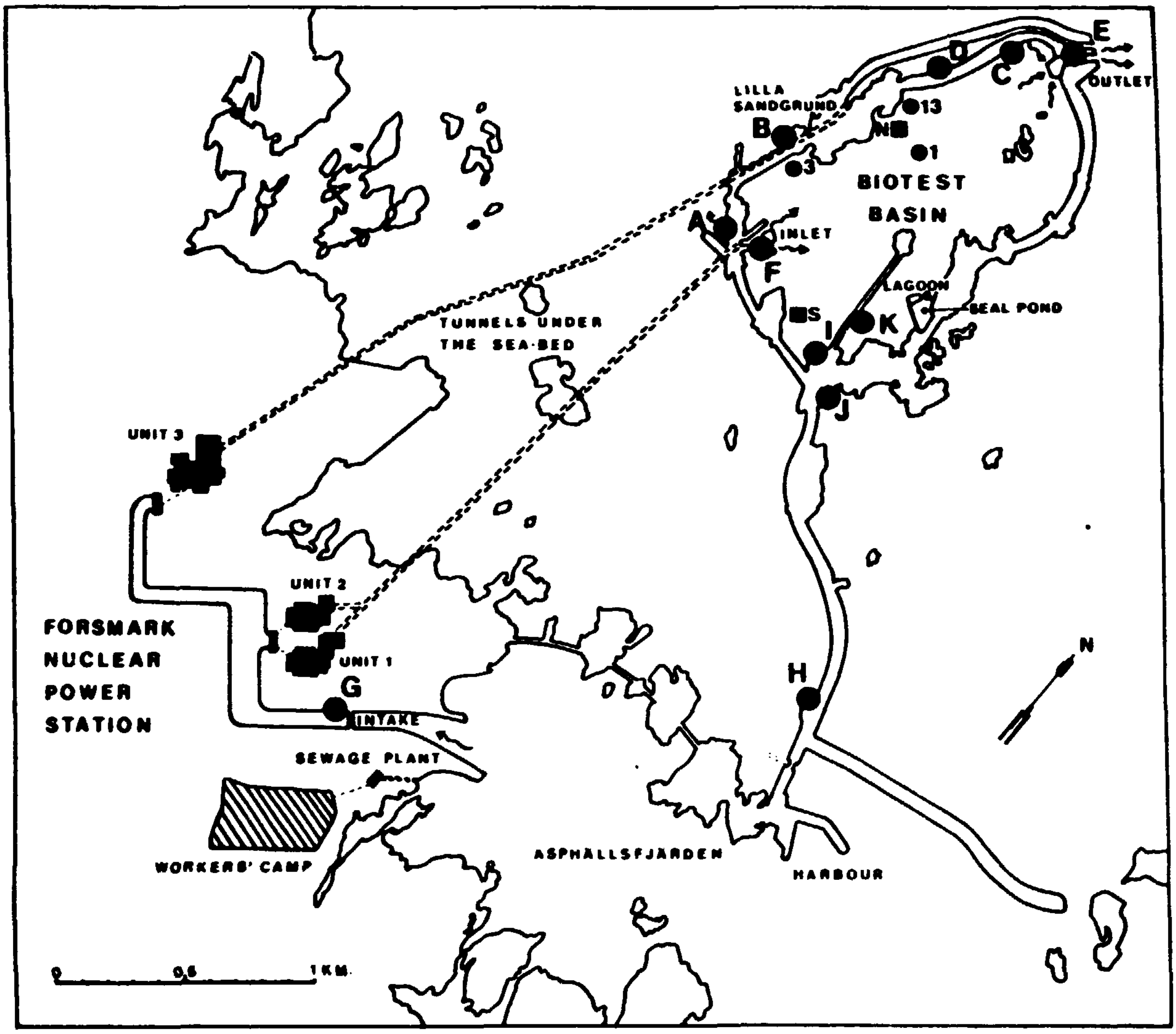
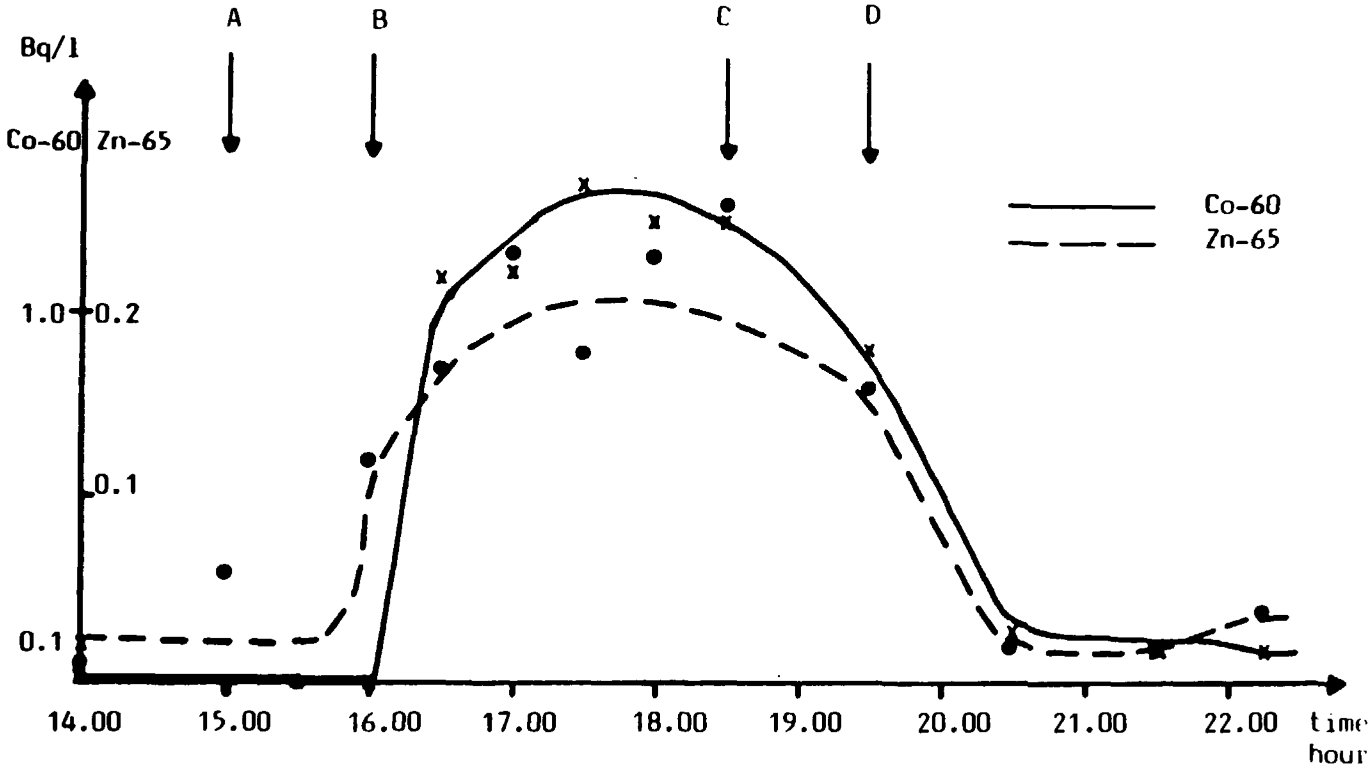


Fig. 2. The variation in Co-60 and Zn-65 concentrations in water from the Biotest Basin (main stream), during the discharge of a tank.



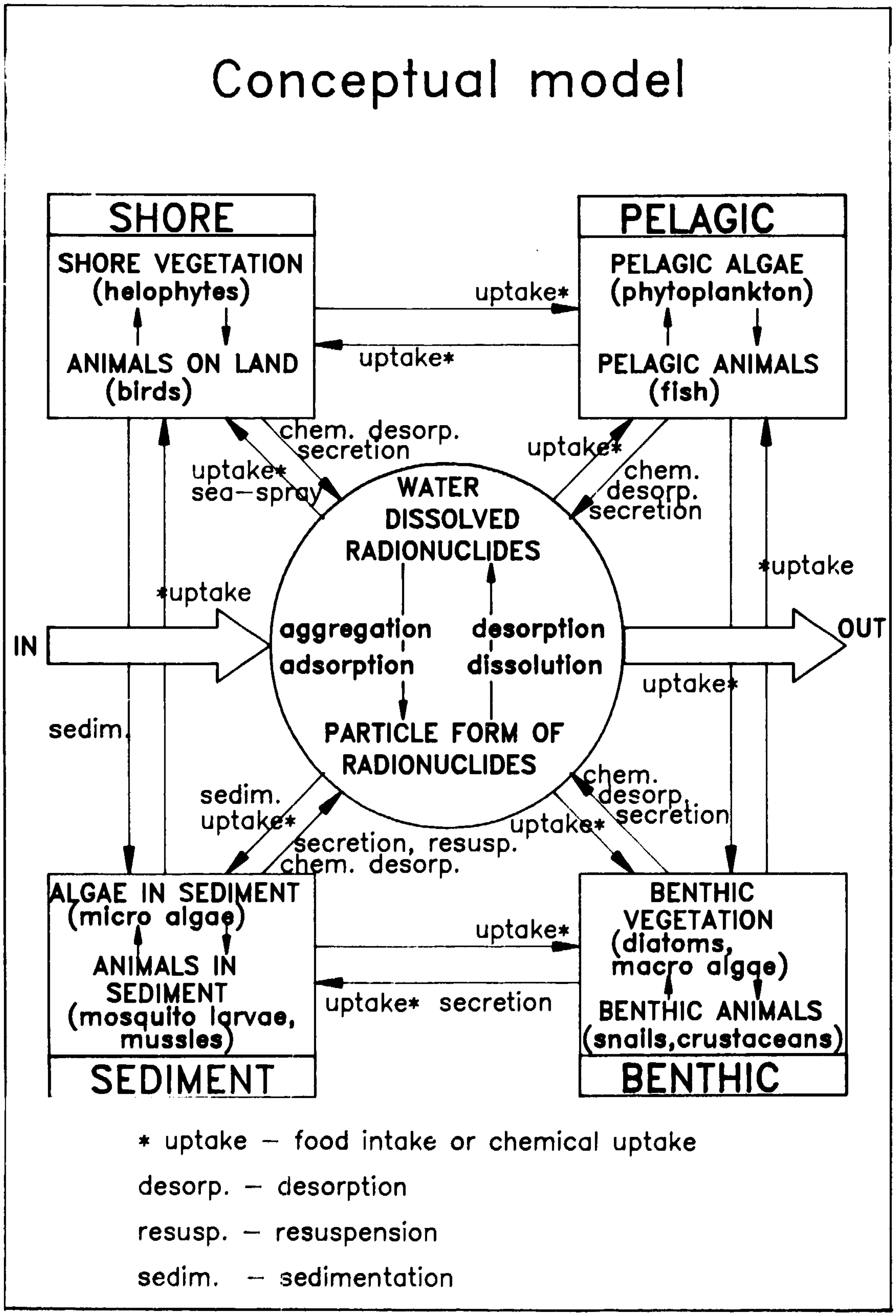
A Starting point for pumping the contents of the waste water tanks into the cooling water.

B The radionuclide concentration in the water at station 1, begins to rise.

C Pumping stops.

D The radionuclide concentration in the water at station 1, begins to decrease.

Fig. 3. The conceptual compartment model.



* uptake – food intake or chemical uptake

desorp. – desorption

resusp. – resuspension

sedim. – sedimentation

Fig. 4. The total amount of Co-60 into and out of the Biotest Basin, 1984 and 1985.

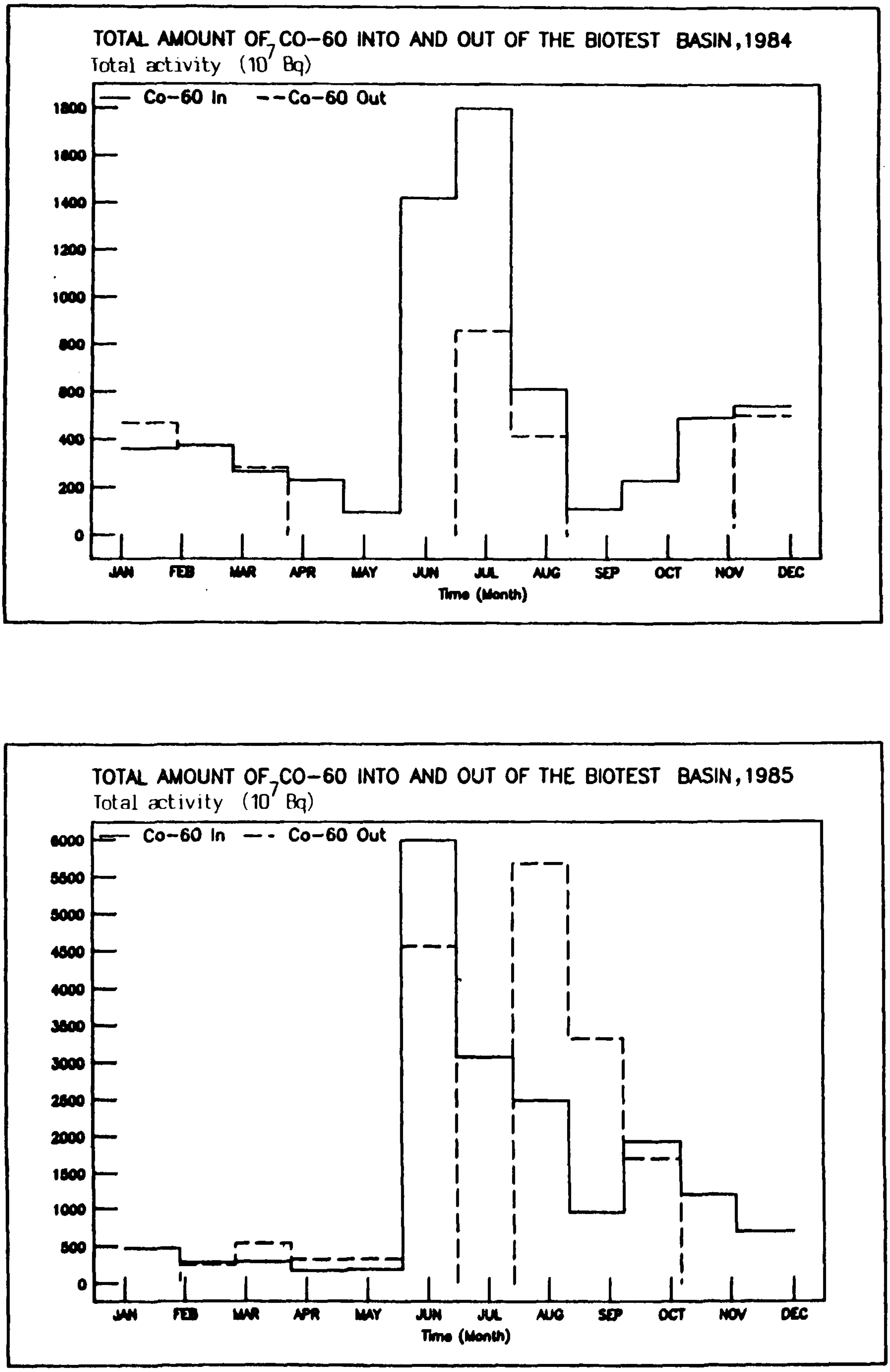
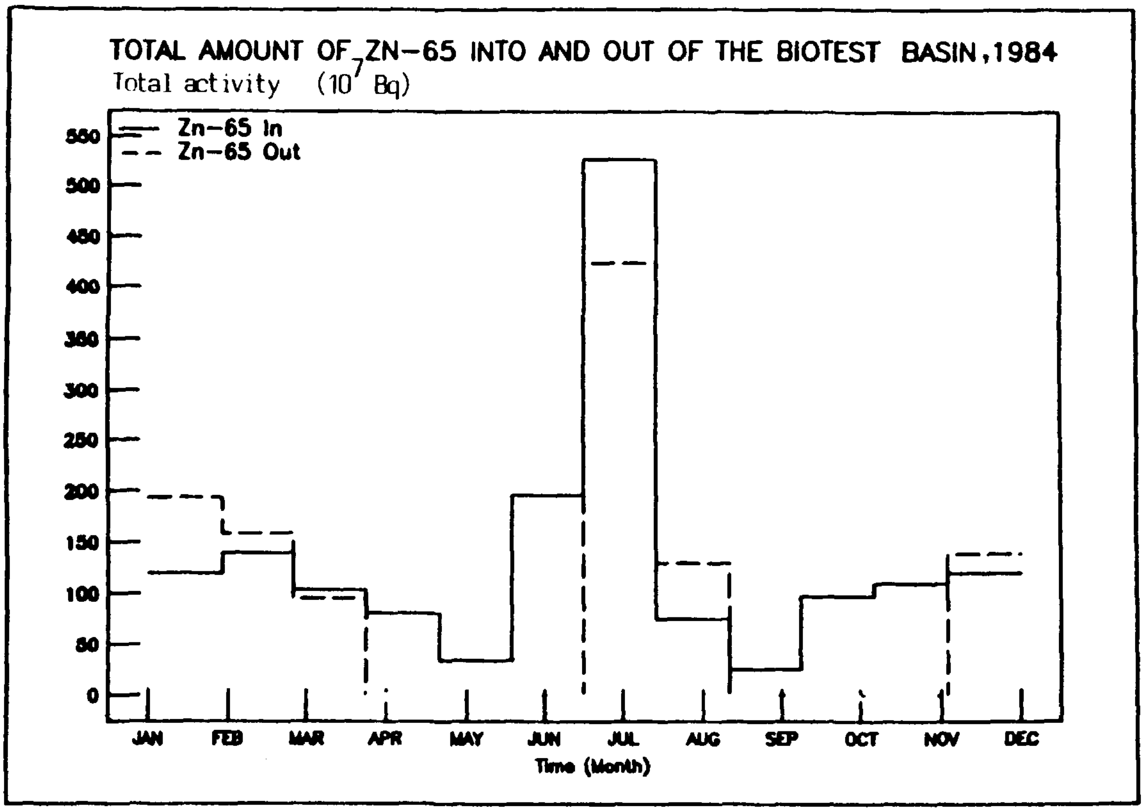


Fig. 5. The total amount of Zn-65 into and out of the Biotest Basin, 1984 and 1985.



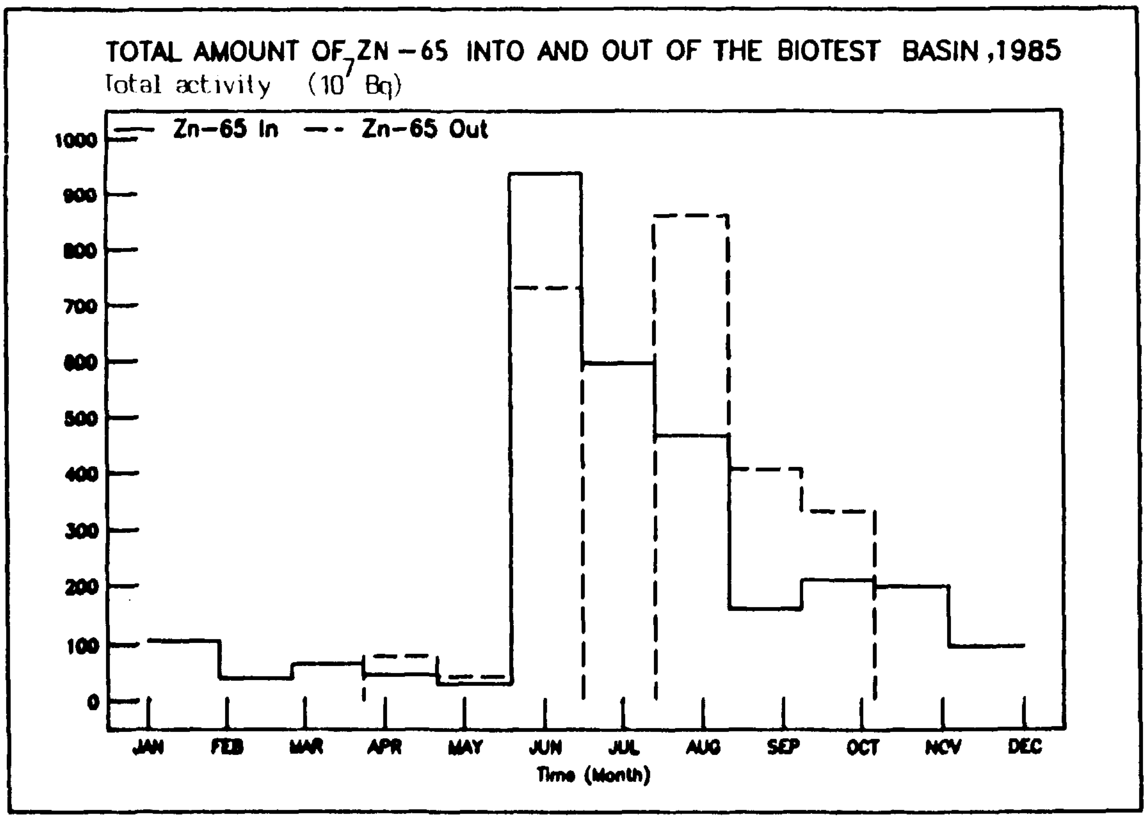


Fig. 6. Estimated total activity of Co-60 in the sediments of the Biotest Basin.

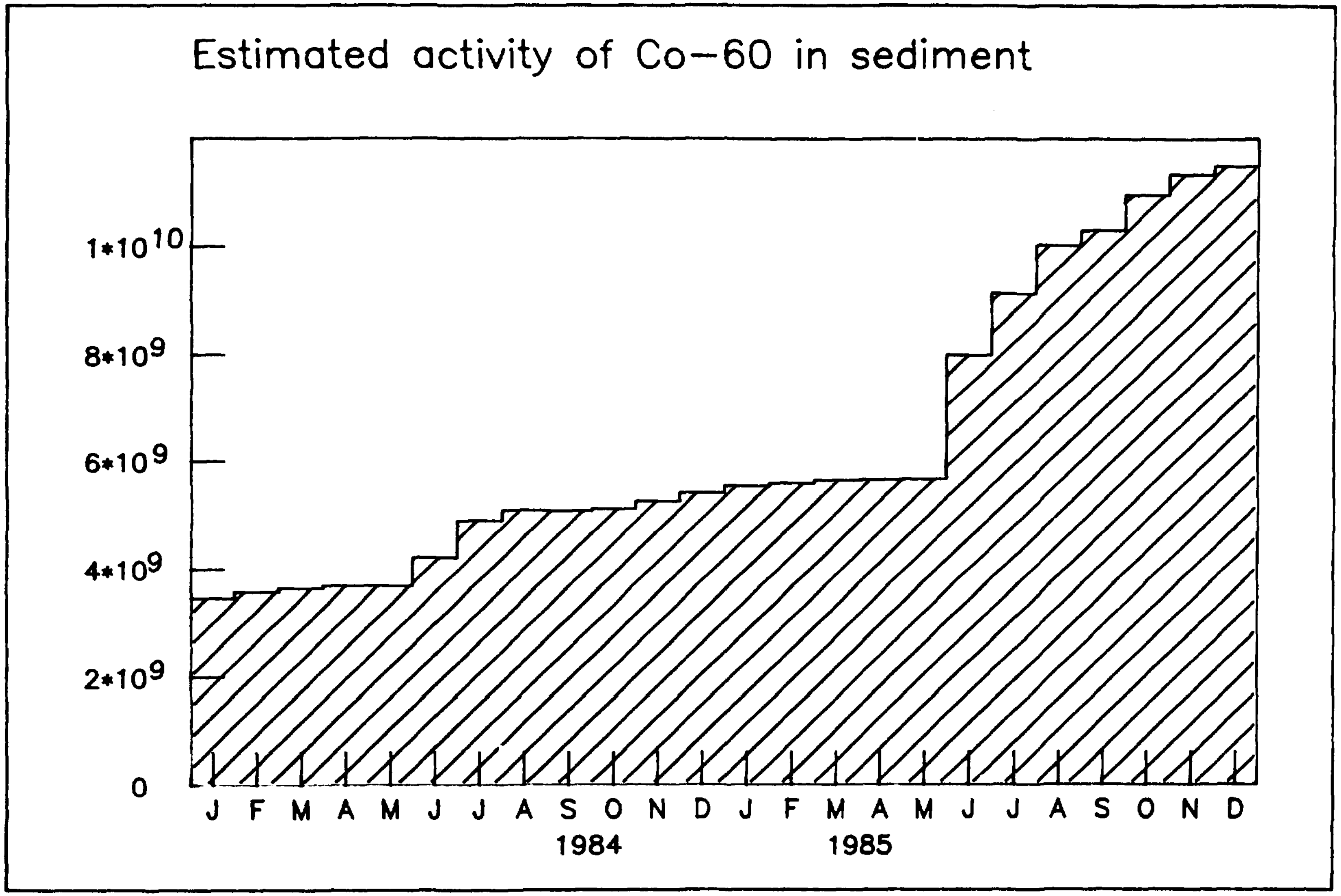
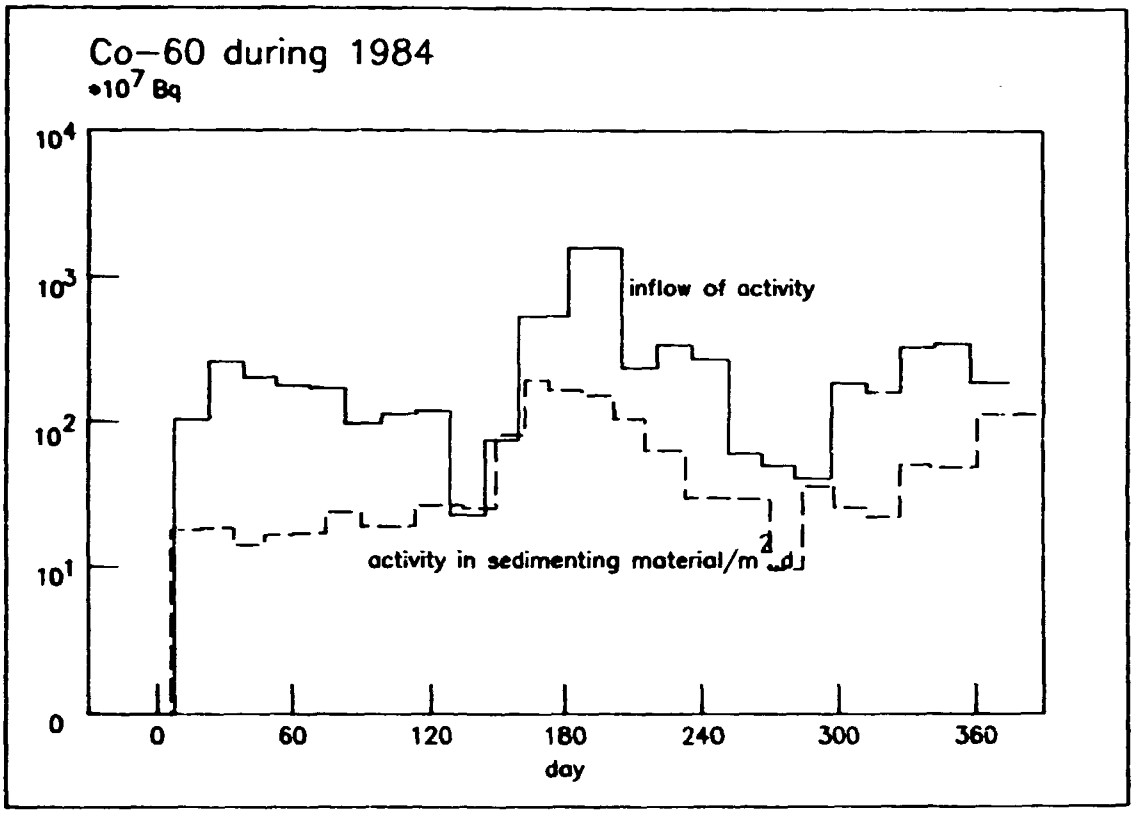


Fig. 7. Sedimenting activity (Bq m^{-2} Day^{-1})of Co-60 and Zn-65, during 1984, compared with the total discharge to the Biotest Basin.



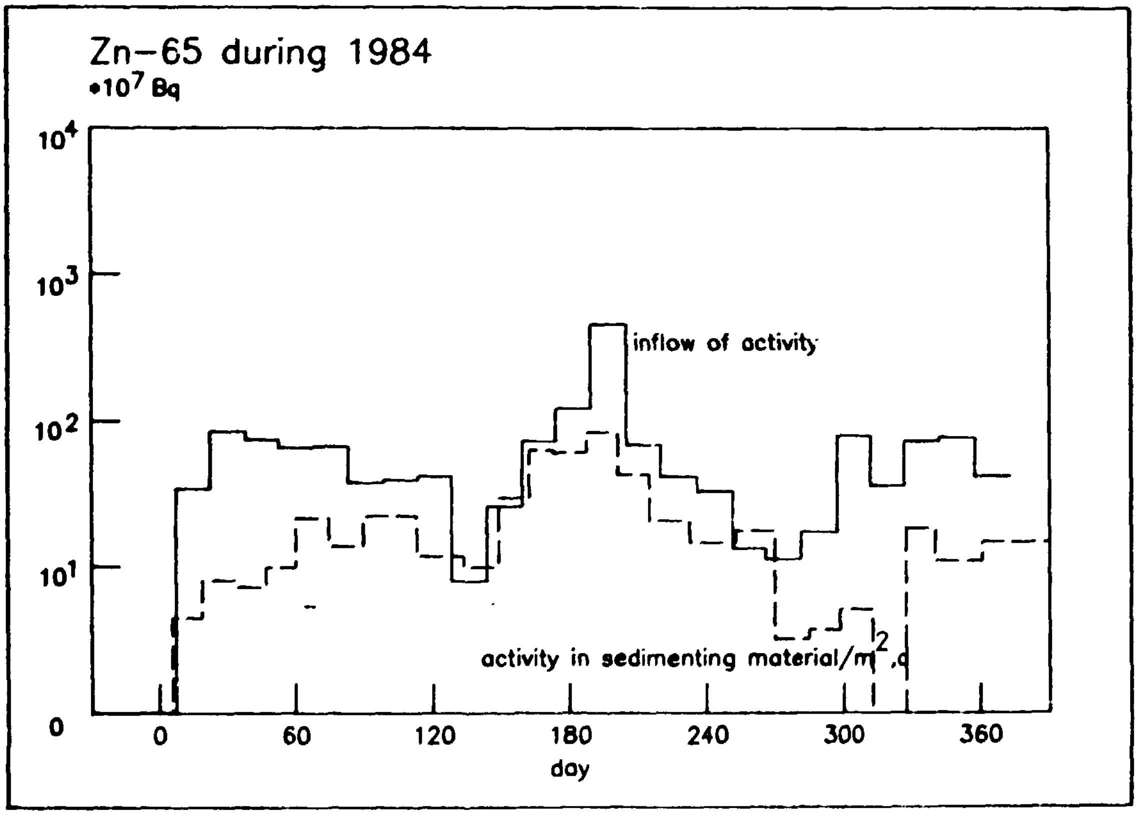


Fig. 8. Sedimenting activity (Bq m^{-2} Day^{-1}) of Co-60 and Zn-65, during 1984, compared with the total discharge to the Biotest Basin multiplied with turbidity. (NTU).

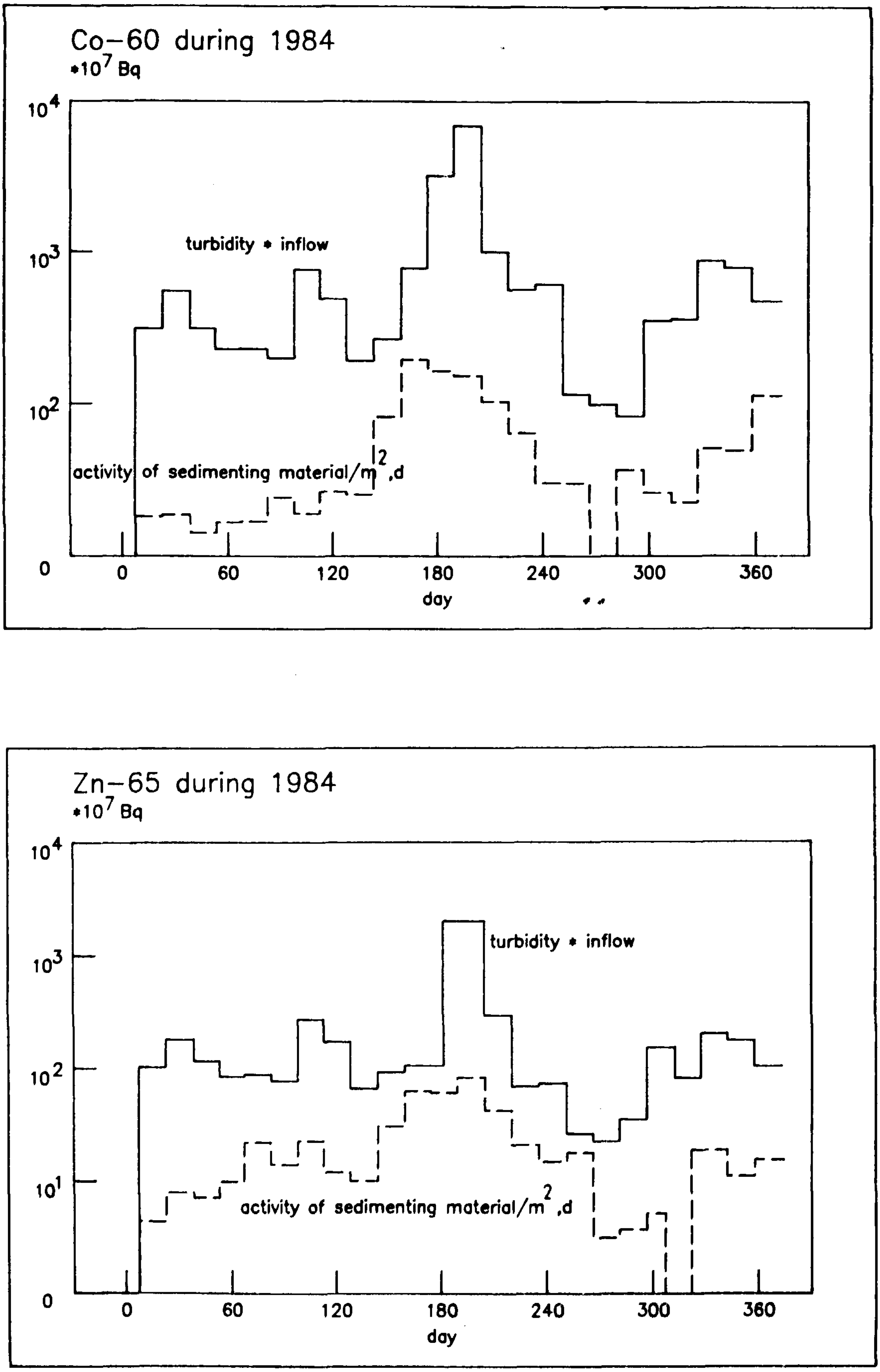
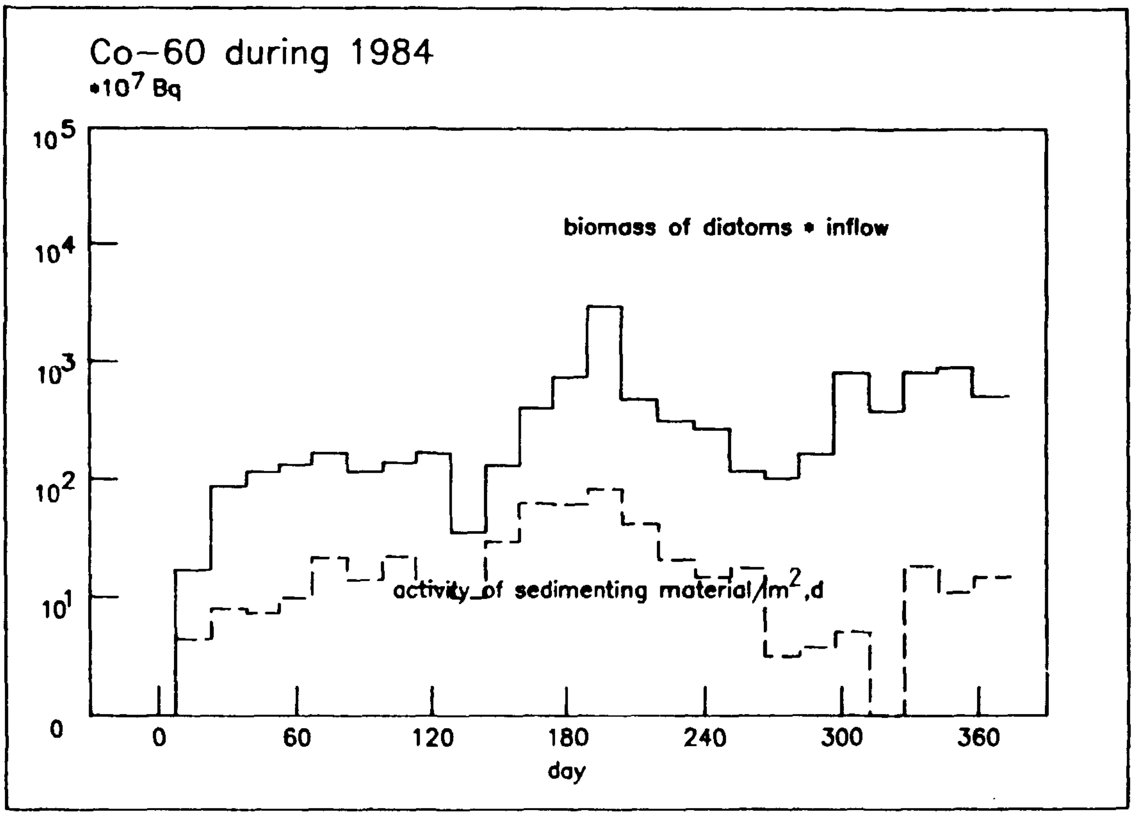


Fig. 9. Sedimenting activity (Bq m^{-2} Day^{-1}) of Co-60 and Zn-65, during 1984, compared with the total discharge to the Biotest Basin multiplied with ashfree dry weight of the diatoms (gm^{-2}).



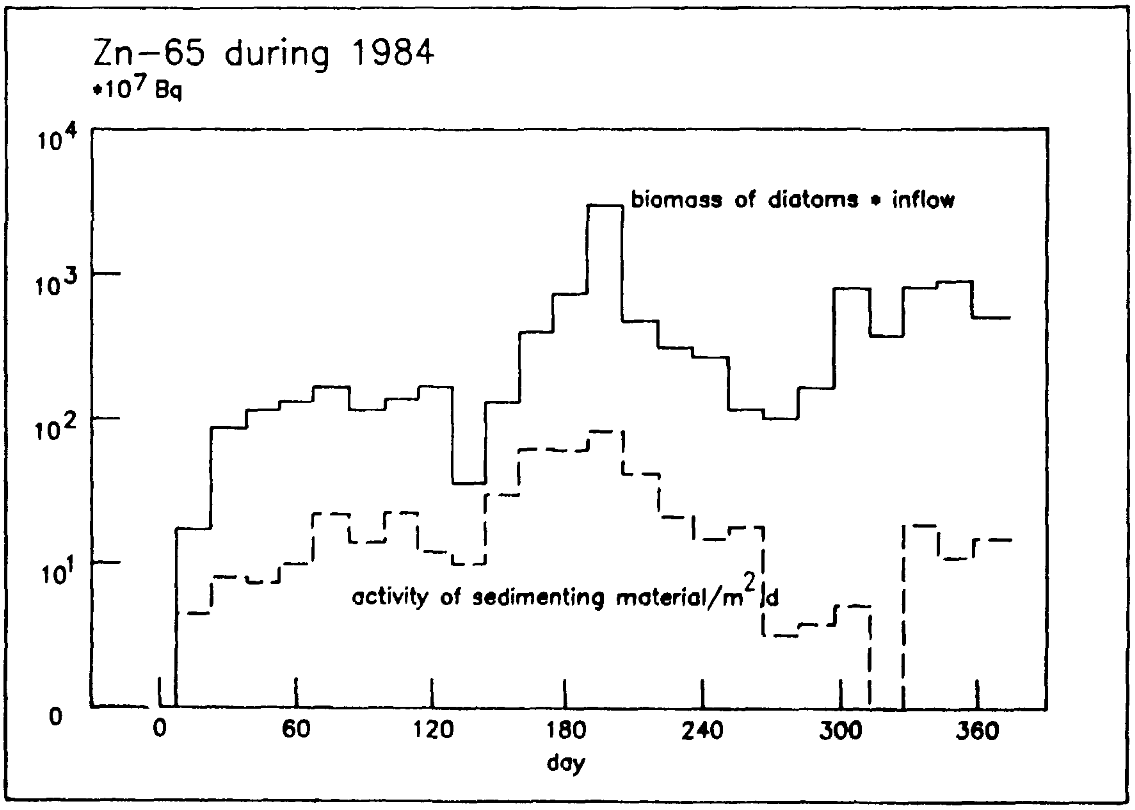


Fig. 10. The total amounts of Co-60, Zn-65, Ag-110m and Mn-54 in diatoms, throughout the year 1984 (from Notter and Snoeijs SNV PM 3213).

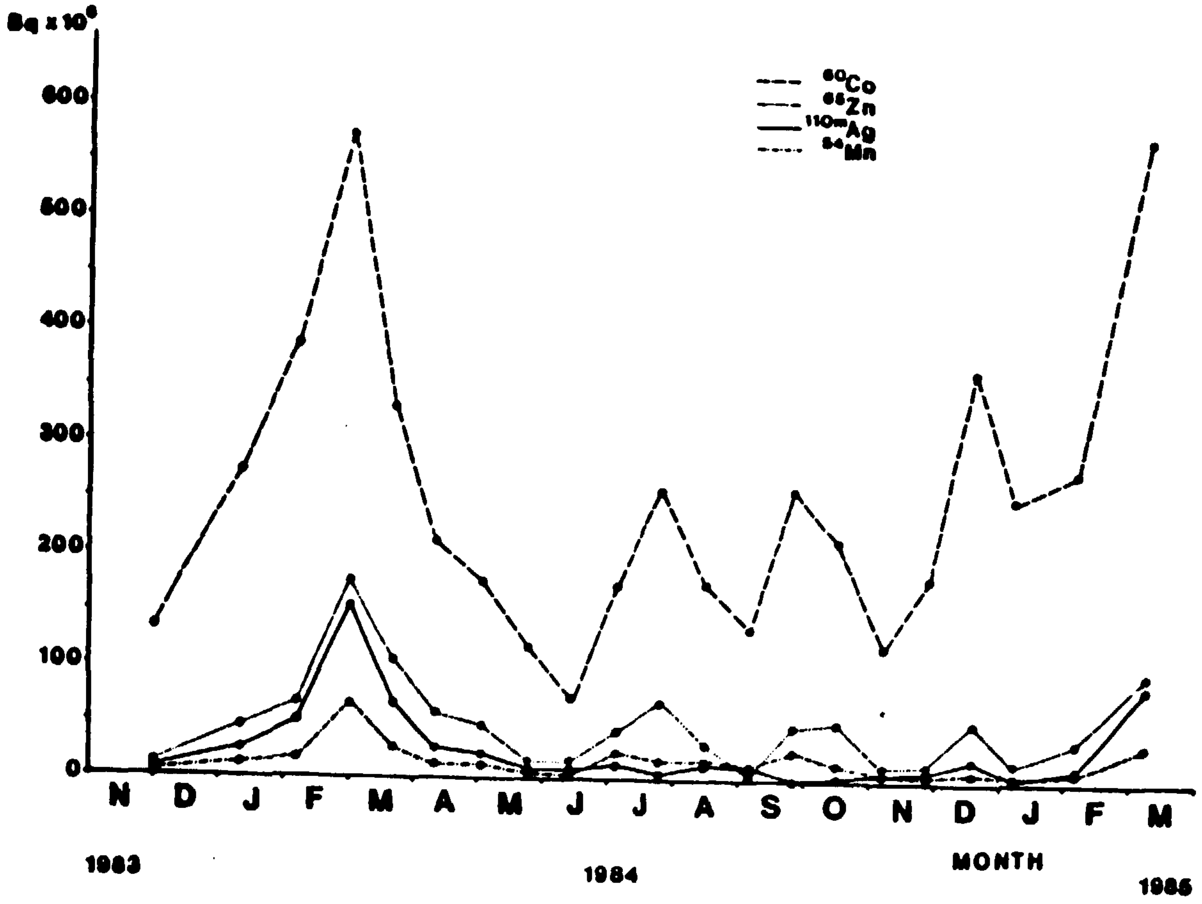


Fig. 11. Ash-free dry weights of diatoms (site E) and sedimenting material (site N), throughout the year 1984.

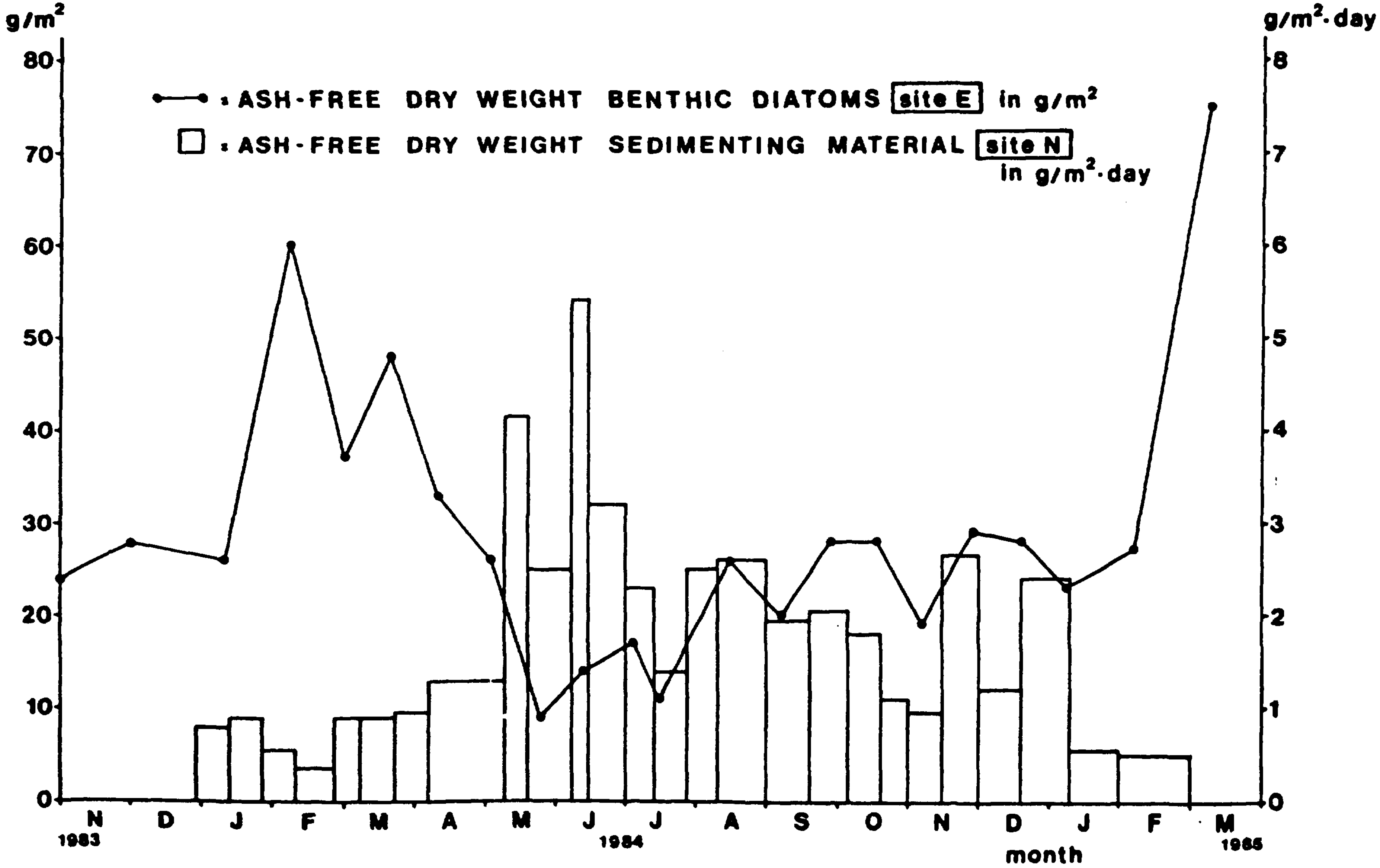


Fig. 12. The concentration of Co-60 and Zn-65 in benthic diatoms and sedimenting material. throughout the year 1984.

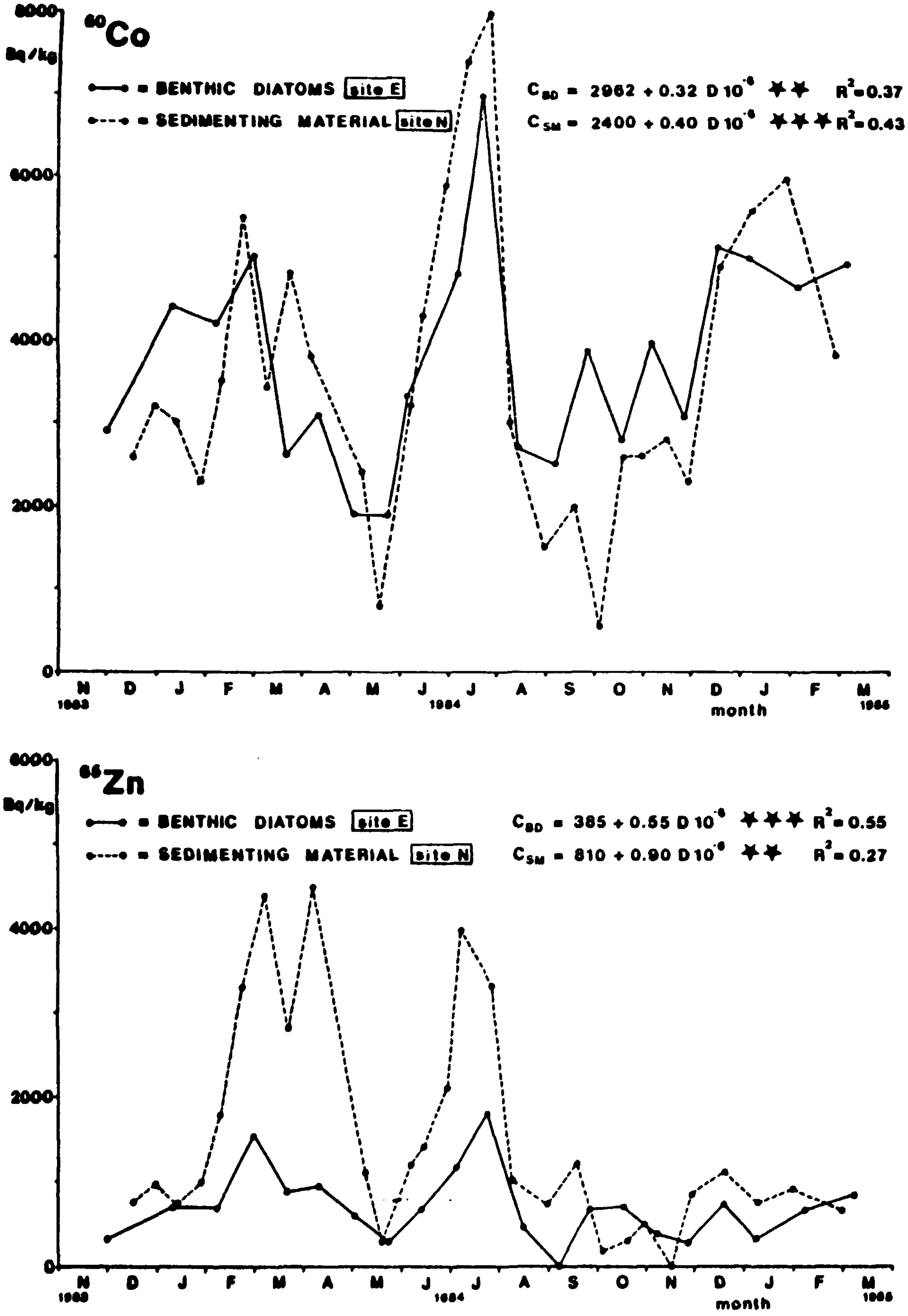


Fig. 13. The concentration (Bq/kg dry weight) of radionuclides in Cladophora from stie 1 in the Biotest Basin, during overhaul of the power plant in summer 1985.

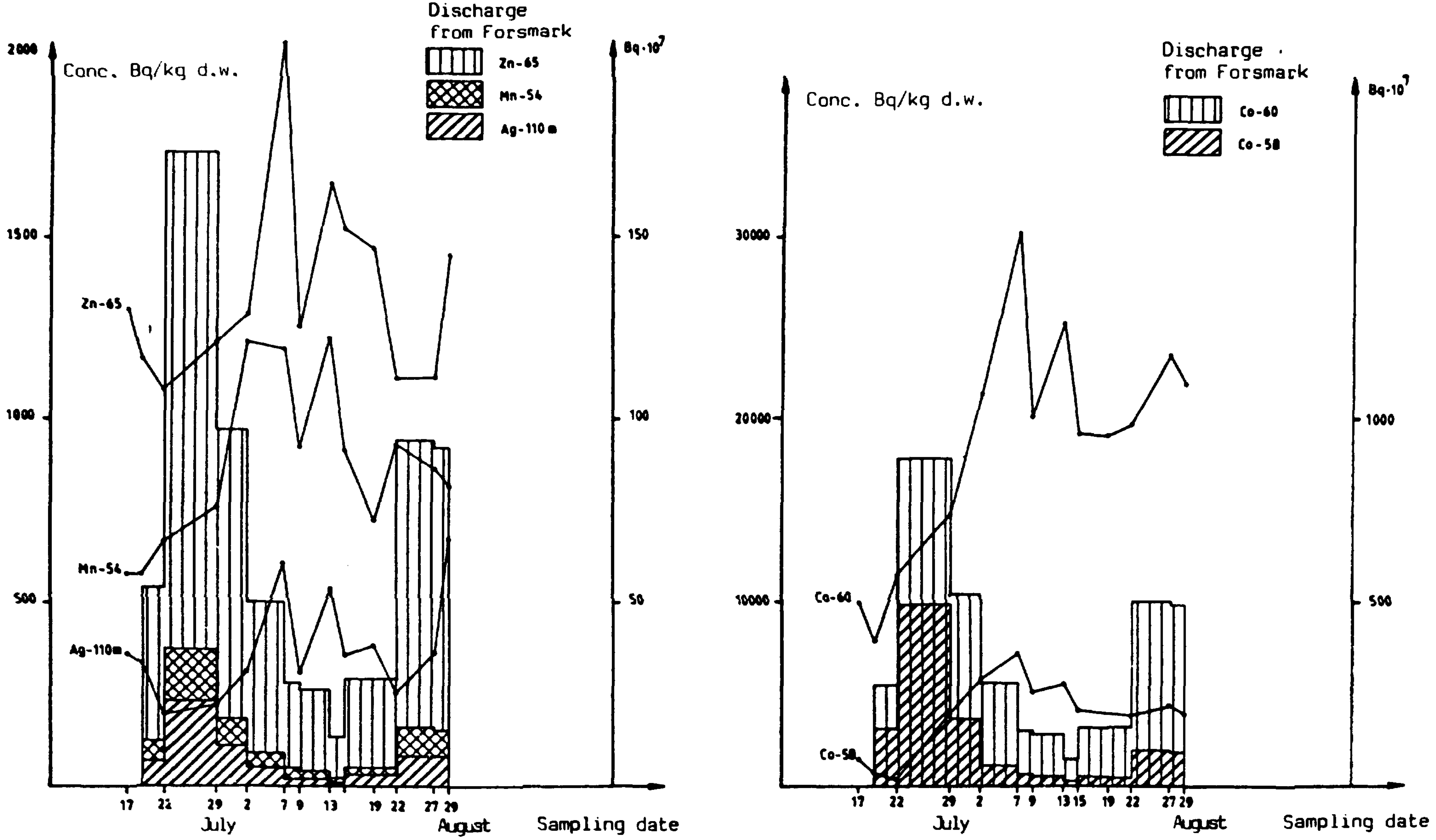


Fig. 14. The concentration of Co-60 in Perch from the Biotest Basin, 1985 and 1986.

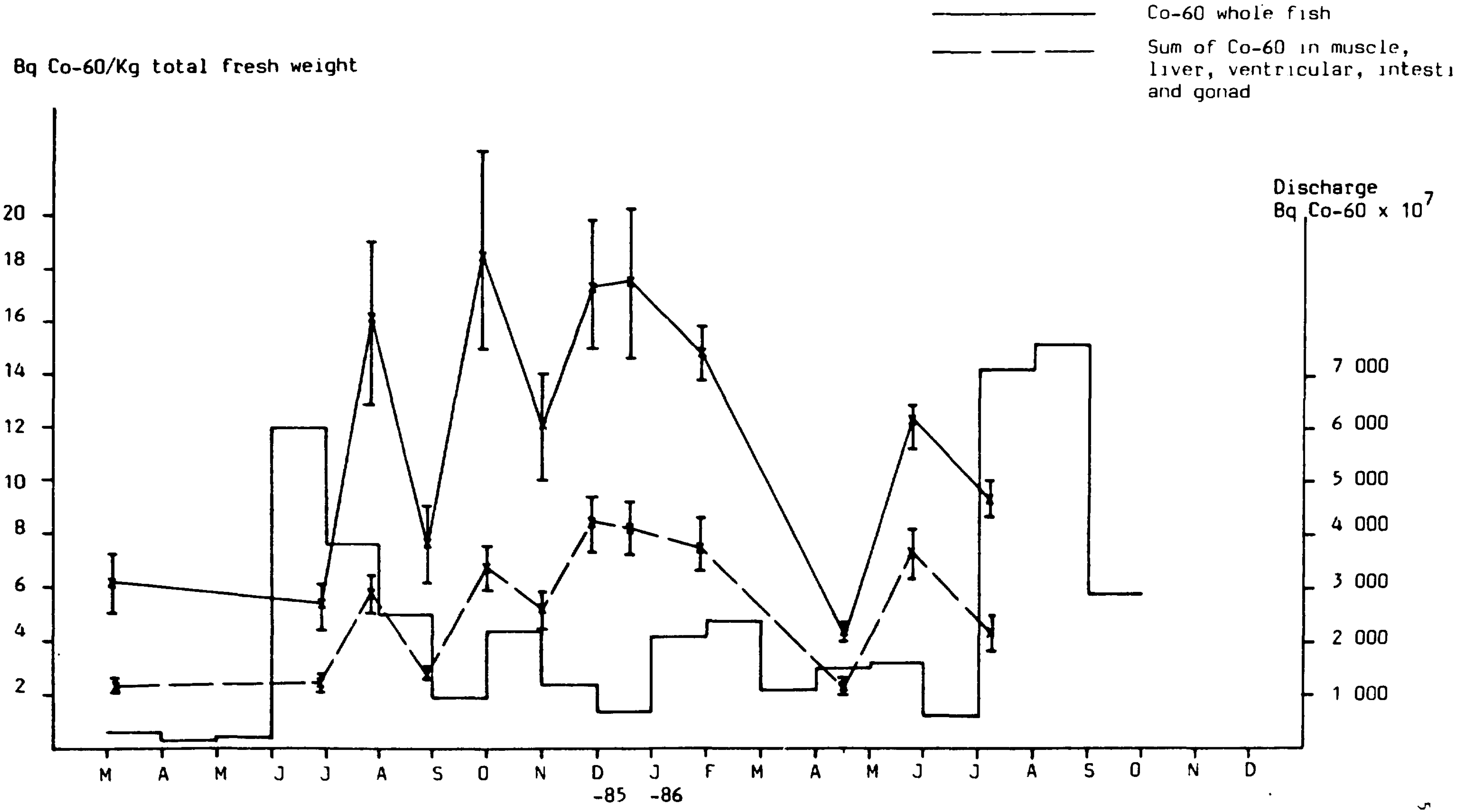


Fig. 15. The concentration of Zn-65 in Perch from the Biotest Basin, 1985 and 1986.

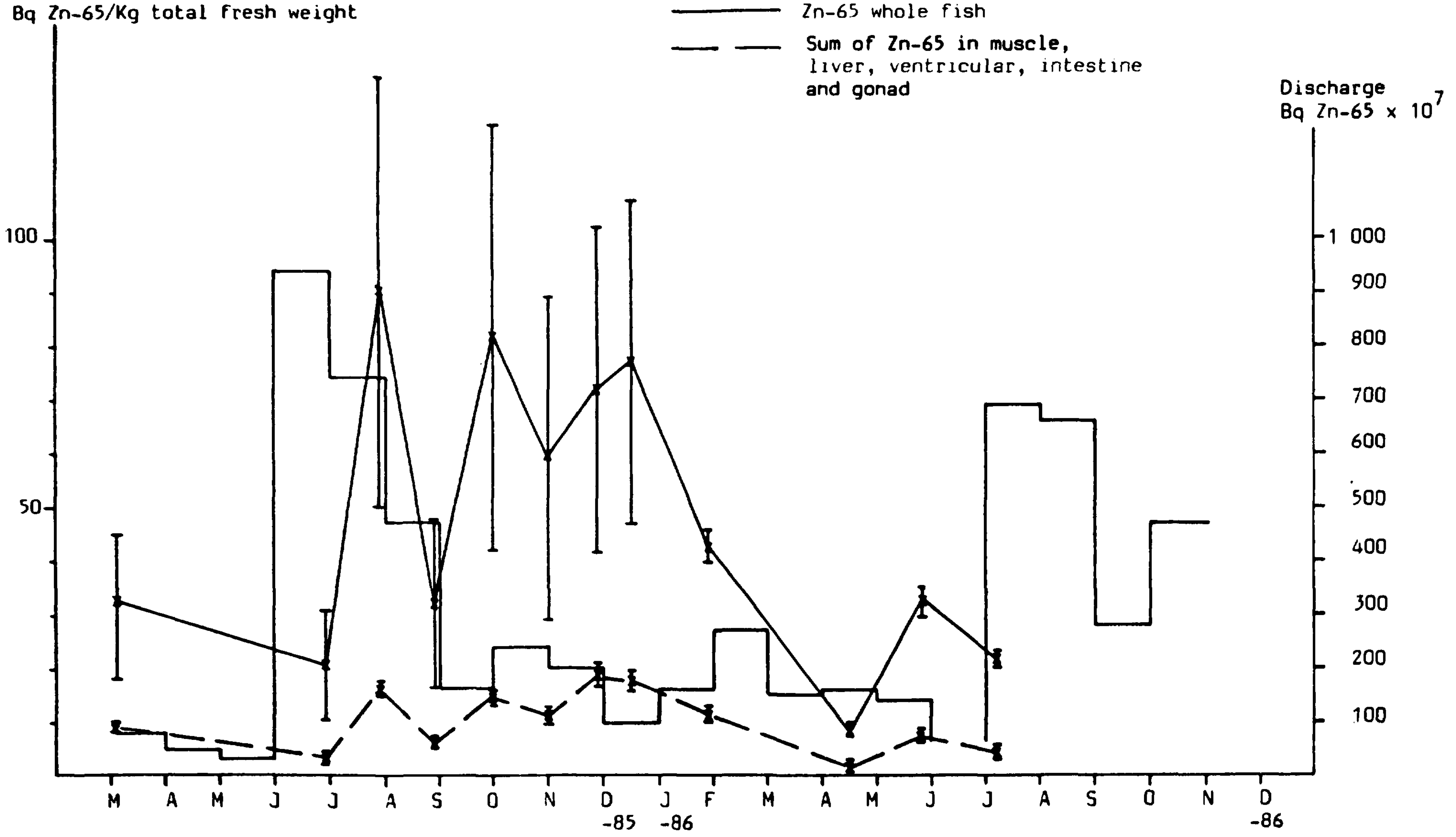
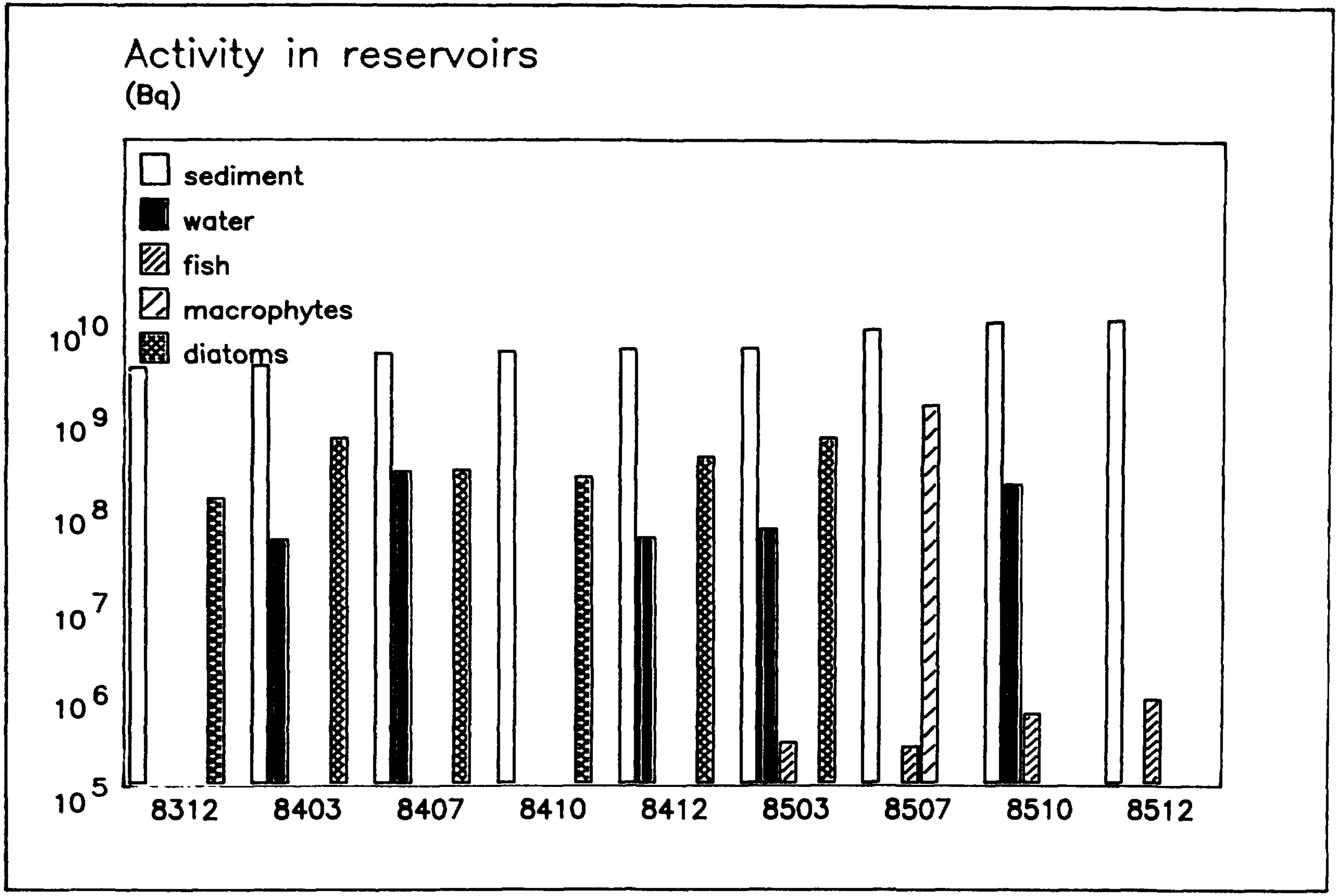


Fig. 16. Calculated amount of Co-60 in some reservoirs at different seasons from December 1983 to December 1985 (if no histogram occurs, no calculation has been made).



APPENDIX I.
RESEARCH DONE IN THE BIOTEST BASIN

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Energifördelning hos Abborre (The energy distribution in perch). Neuman, E./SNV -Öregrund.

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Zooplanktonförluster i kylvattenvägar (Zooplankton losses in cooling water). Karås P./SNV - Öregrund.

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