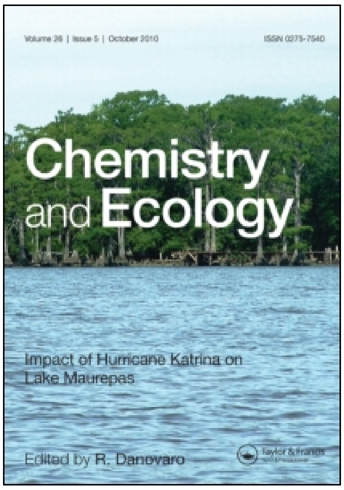

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Environmental Impact on Coastal Waters off Rio De Janeiro Due to Sewage Discharge via Submarine Outfall

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ENVIRONMENTAL IMPACT ON COASTAL WATERS OFF RIO DE JANEIRO DUE TO SEWAGE DISCHARGE VIA SUBMARINE OUTFALL

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(10 May 1991)

A survey was made in an area of 28 km^2 around the outlest of Ipanema's submarine outfall in order to evaluate the impact of the raw domestic sewage effluent on coastal waters. Nutrient concentrations, dissolved oxygen, particulate matter and other physico-chemical parameters were measured monthly for 15 months. Copper and lead concentrations were also determined for two of the samplings.

The outfall has been in operation for 18 years, and the parameters measured within the observation area appear to be in steady state. From the observed radial concentration gradients within the survey area, a real extension of the steady state distribution of particulate matter and of sewage-derived nitrogen was estimated. The stationary cloud of particulate organic matter was about 150 km^2. From its total inventory and the discharge rate, a mean residence time of the particles in the sea of 56 days is estimated, prior to their being decomposed by bacterial action or settling to the bottom. For sewage derived N (as ammonia or nitrate), the steady state amount (above background) covers an area of about 60 km^2 and leads to a mean residence time of 5 ± 1 days in the ocean. Phosphorus is readily absorbed by the phytoplankton.

The presence of temperature gradients established by cold upwelling waters controls the dispersion of the sewage material and the rising of the sewage plume to the surface waters.

KEY WORDS: Sewage, sub-marine outfall, Rio de Janiero, particulates, nitrogen.

INTRODUCTION

The health of many marine ecosystems, especially those located in coastal areas, has been endangered through the disposal of domestic and industrial wastes.

In the developed countries, an awareness for the need of a better environment has arisen over the last several decades. This has resulted in the reduction of waste disposal in the ocean, an improvement in effluent quality and in more intensive use of costly but efficient technologies for waste treatment.

However, in the developing countries, problems arising from rapid population growth and public deficits have led to an increasing tendency to use the marine environment as a sink for untreated wastes.

The submarine outfall of Ipanema (SOI) in Rio de Janeiro has been taken as a case study of impact derived from untreated domestic sewage released in coastal waters. Although sewage disposal via submarine outfalls is a common practice all over the world, few environmental impact data are found in the literature and most refer to the outfall system of Los Angeles (Galloway, 1979; Morel *et al.*, 1975; Bruland *et al.*, 1974 and others).

The submarine outfall of Ipanema (SOI) (Figure 1a) is a 2325 m long concrete pipe with a 2.4 m diameter. The sewage is released through 180 diffusers of 0.17 m diameter located along the last 448 m of the pipe. The diffusers are at 27 m depth and 3300 m distant from the beach line of Ipanema and Leblon (see Figure 1b) (Britto *et al.*, 1978). Figure 2 shows the outfall positioning and the bottom topography of the region. As can be seen, the pipe lies between the continent and an arc of islands.

The projected average and maximum outfall discharges are 8 and 12 $m^3.s^{-1}$, respectively, with an initial dilution factor of 100:1 and a jet velocity of 2 $m.s^{-1}$. The SOI collects sewage from a population of about 1.2×10^6 inhabitants (IBGE, 1983) and operates at a discharge rate of 6 $m^3.s^{-1}$.

A few studies on faecal coliform distribution, oxygen concentration (Britto *et al.*, 1986) and plankton taxonomy (Semeraro, 1979) are reported for the period after the inauguration of the plant in 1975.

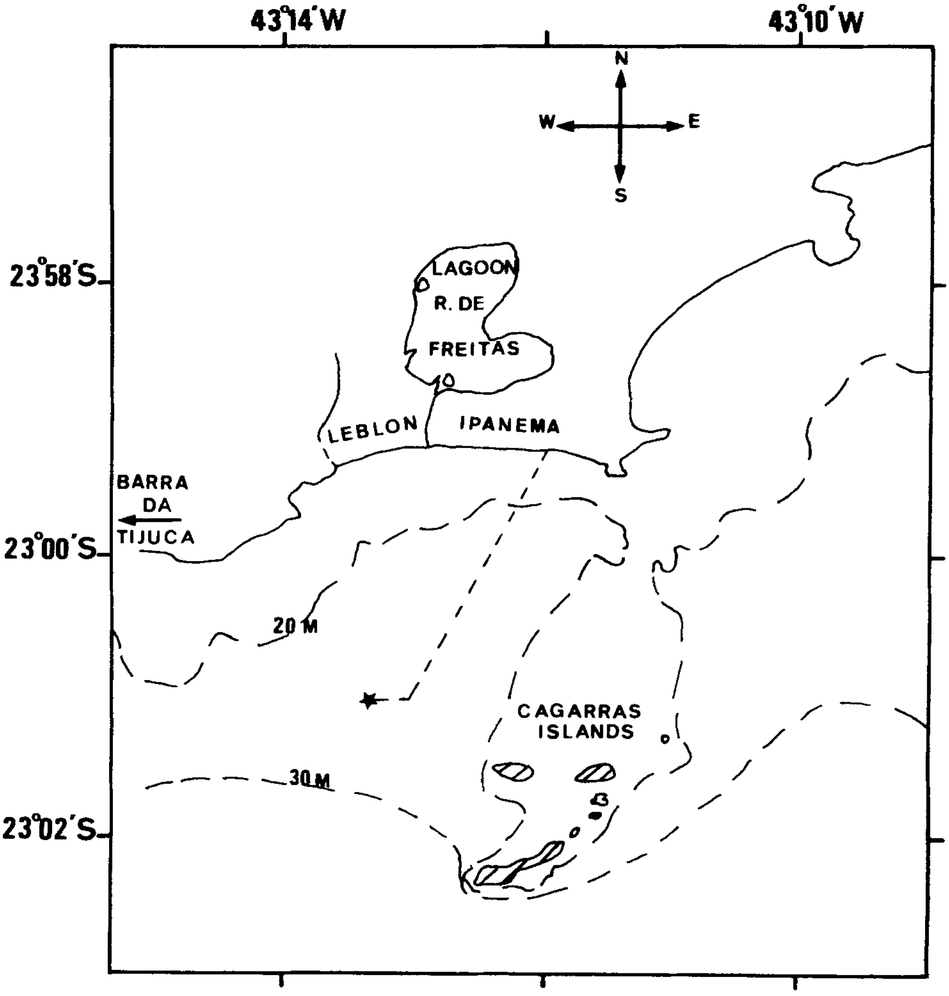

Figure 1a Map showing part of the south coast of Rio de Janeiro and the location of the outfall.

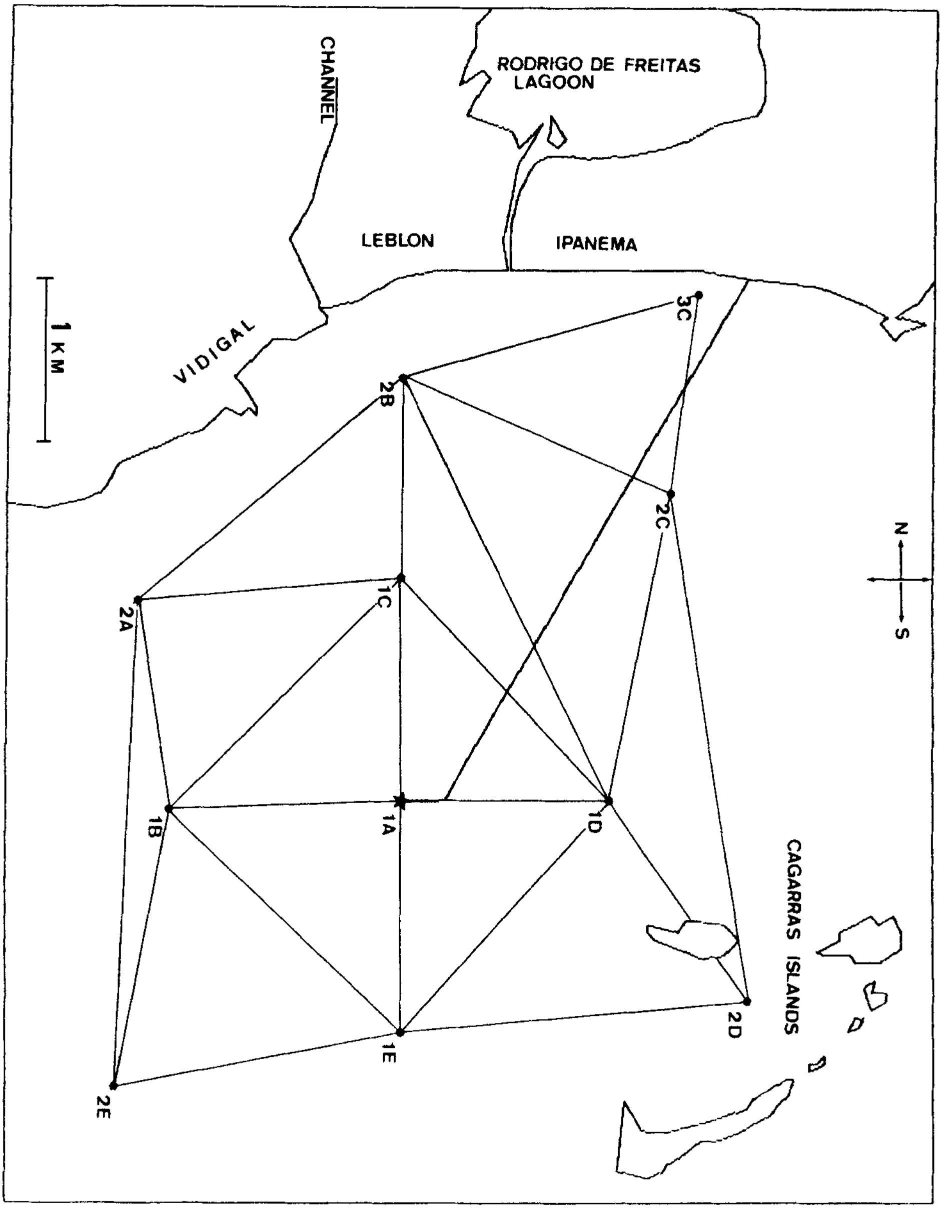

Figure 1b Survey area and sampling stations; the sewage outlet is at station 1A.

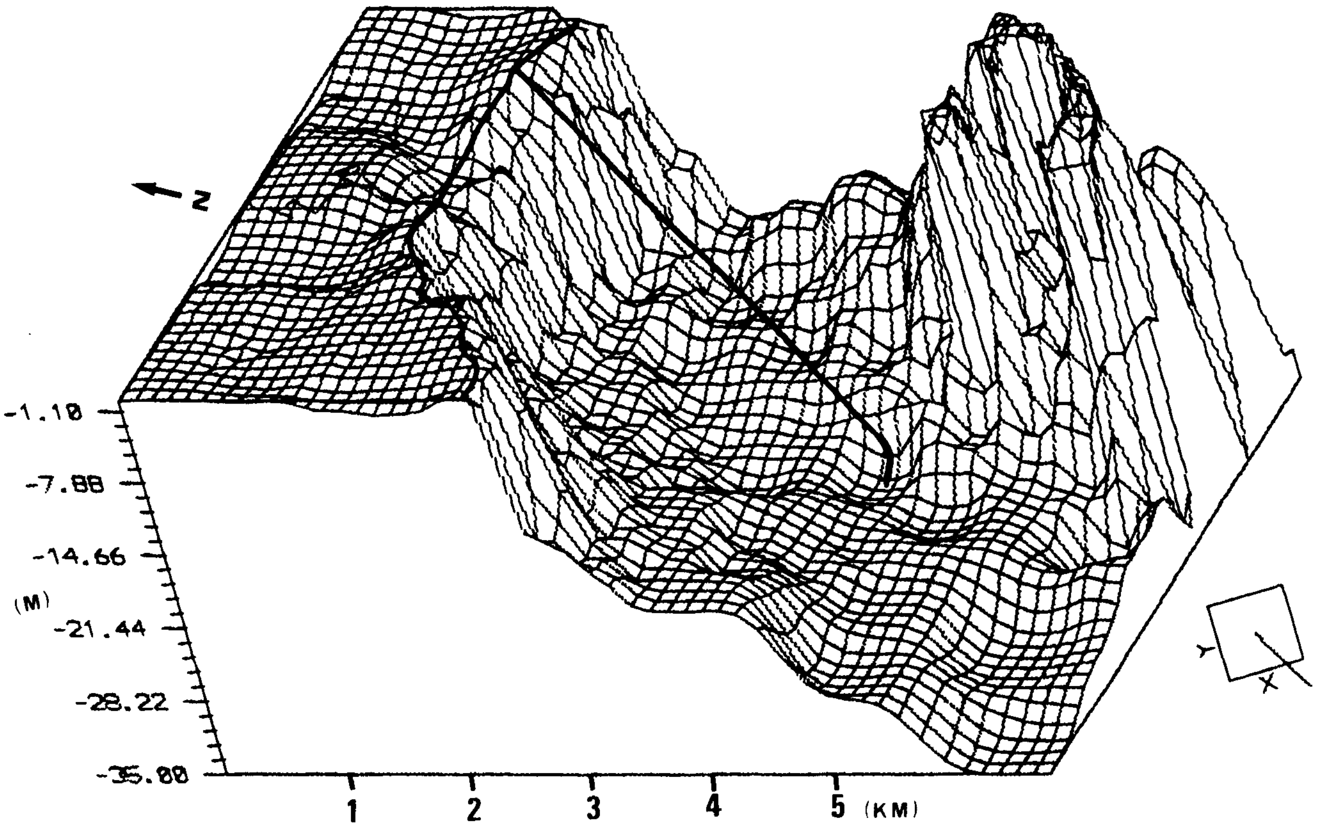

Figure 2 Bottom topography of the survey area. The vertical solid line represents the sewage discharge pipe.

Moreira *et al.* (1963) obtained some oceanographic data for the area under study: prevailing winds are NE and ESE (5 m s^{-1}) changing to SE during the approach of cold fronts; tidal currents move tangentially to the coast towards the NE (35 cm s^{-1}) on high tide and towards the SW (25 cm s^{-1}) on low tide. A well defined thermocline is established over the summer period when cold upwelling waters reach the coast. Similar conditions are found in a study by Roberts (1987) executed on behalf of the State Environmental Control Agency (FEEMA) about 15 km west of our observation area. The government is planning to install an ocean outfall there at 41 m depth and 5 km off the coast. Physical oceanographic measurements showed the local currents are usually in the range 10 to 40 cm s^{-1}, with no strongly preferred direction.

The SOI is not the only source of sewage to the area; contributions are also derived from the channels of Lagoa Rodrigo de Freitas and of Leblon and from an outlet at Vidigal (see Figure 1b).

EXPERIMENTAL DETAILS

Figures 1a and 1b show the studied area and the sampling stations where water was collected monthly from three different depths (5 m, mid-depth and bottom) over a period of 15 months (April 1988 to July 1989). The samples were analysed for the content of particulate matter, dissolved oxygen, ammonia, nitrate, nitrite, inorganic phosphate, dissolved silica, lead (only in one sampling) and copper (only in two samplings). Temperature, conductivity and pH were also measured.

Sampling for nutrient determination was made with the help of a Van Dorn sampler. Ammonia and dissolved oxygen were fixed 'in situ'. The water samples were refrigerated in clean polyethylene bottles for less than 24 h until the analyses were performed. Particulate matter was determined by filtration through 0.45 μm Millipore membranes. The analytical methods applied for nutrient determination were those described by Grasshoff *et al.* (1983). Dissolved oxygen was determined following the modified Winkler method (Grasshoff *et al.*, 1983), and pH was measured 'in situ' by means of a Schott combined glass electrode.

The precision of the results presented here are as follows: ± 0.05 μmol Pl^{-1} for phosphate, ± 0.44 μmol Nl^{-1} for nitrate, ± 0.12 μmol Nl^{-1} for nitrite, ± 0.26 μmol Nl^{-1} for ammonia, ± 0.48 μmol Si^{-1} for dissolved silica and ± 0.02 ml O_2l^{-1} for dissolved oxygen. Temperature measurements are within ± 0.1°C and salinities calculated from conductivity data have an accuracy of ± $0.01gl^{-1}$.

Lead and copper samples were collected with a Teflon go-flo type bottle. The samples were acidified 'in situ' to a pH of approximately 2 with Merck Supra-pur nitric acid and stored at -20°C in low density polyethylene bottles. All bottles, containers and other devices used were carefully pre-cleaned as advised by Patterson *et al.* (1976a, 1976b). Lead and copper determinations were carried out in the acidified samples (pH adjusted to 1.3) using Differential Pulse Anodic Stripping Voltammetry (PAR 384–B Polarographer) and the Hanging Mercury Electrode (PAR 303A) equipped with Teflon cells.

The procedures of sample transfer and the voltammetric measurement were performed under a horizontal laminar flow hood. The concentrations were determined after three standard additions of 10–20 μl of solutions freshly prepared from a 1000 ppm standard solution (Titrisol Merck).

The optimized instrumental parameters were: deposition potential, -0.580

V(AgCl); deposition time, 1200 s; deoxygenation time, 600 s; scan rate, 2 mV s^{-1}; pulse modulation, 50 mV; number of replicates, 3.

The sensitivity of the method, calculated according to Arras and Rebello (1980), was 0.44 ± 0.06 nA nmol^{-1}. min^{-1} for lead and 0.45 ± 0.07 nA nmol^{-1}. min^{-1} for copper. The limits of detection were 0.09 ± 0.01 nmol l^{-1} for lead and 0.47 ± 0.07 nmol l^{-1} for copper and the relative standard deviation for five replicates was smaller than 12% for lead and 17% for copper.

RESULTS AND DISCUSSION

Due to the impossibility of listing in this paper all the data collected (the complete set of data can be found in Bouch, 1990), the results will be presented according to a concentration range and a mass inventory. The concentration ranges of the measured variables are shown in Table 1.

A mass inventory was estimated for the whole survey area by first dividing it by interconnecting the points of sampling, as shown in Figure 1b. The mass of a certain constituent in each triangle was calculated by multiplying the volume of each triangle by the average concentration in the triangle (average of the data at the three stations at the vertices). The 'depth' of the triangle is the average of the three depths at the sampling stations. The results for the total inventories are given in Table 3 as well as the average concentration of each constituent for the whole period of observations. The results for copper and lead are listed in Table 2. For copper and lead the total inventory gave 2373 moles and 420 moles, respectively.

The variation of mass in the survey area over time is given also in Table 3. As can be seen, the variations around the average mass are relatively small with the exception of nitrate. The scatter of the nitrate data is largely due to the high values encountered during the period when a secondary sewage pipe buried in the sand at the beach was broken by strong waves. On this occasion, the highest nitrate values were found in the stations nearest to the beach. In one of the samplings under normal conditions, high values of nitrate were evidently associated with the sewage outlet. As nitrate is not expected under the anaerobic conditions prevailing in sewage, a plausible explanation for the observed values is that oxidants were added to the sewage in order to reduce the unpleasant smell at the beach. Unfortunately, no official information about this was released by the authorities. The nitrate is then formed in part by the oxidation of ammonia or of organic matter.

The highest values of phosphate were usually associated with the appearance of cold upwelling waters. However, on some occasions, especially after heavy rain, there was a strong contribution of phosphate from the channels of Lagoa Rodrigo de

Table 1 Concentration ranges for some of the measured variables from April 1988 to July 1989

pH		*Part.* (*mgl*$^{-1}$)	*NH_3* (μm N)	*NO_3* (μm N)	*NO_2* (μm N)	*SiO_2* (μm Si)	*PO_4* (μm P)
S	8.03–8.34	4.3–18.5	1.8–12.8	<dl–8.8	<dl–1.2	1.5–12.1	<dl–3.0
M	8.04–8.30	4.9–25.4	1.5–21.1	<dl–18.8	<dl–1.5	1.5– 9.9	0.05–3.3
B	7.80–8.24	2.1–78.4	1.7–19.9	<dl–20.2	0.1–2.4	1.7–10.7	0.12–2.4

S, M and B stand for surface (5 m), mid-depth and bottom samples, respectively; dl is the detection limit.

Table 2 Copper and lead concentrations (nmoll^{-1}).

Sampling stations	*Depth (m)*	*Cu (April/88)*	*Cu (July/89)*	*Pb (April/88)*
1AS	5.0	2.2	4.4	0.4
1AM	14.0	5.0	4.1	1.2
1AB	27.0	3.6	4.6	1.5
1BS	5.0	2.8	6.3	0.4
1BM	16.0	6.5	8.5	2.1
1BB	32.0	3.1	3.3	0.5
1CS	5.0	2.5	6.9	0.8
1CM	14.0	6.3	6.8	0.5
1CB	28.0	5.7	5.2	0.5
1DS	5.0	5.5	3.6	0.7
1DM	10.5	6.1	5.5	0.6
1DB	21.0	6.8	5.8	0.8
1ES	5.0	4.4	2.2	0.4
1EM	16.5	5.8	3.9	0.8
1EB	33.0	4.1	3.1	0.7
2DS	5.0	2.8	3.0	0.7
2AM	11.5	4.4	3.8	1.9
2AB	23.0	1.4	1.7	0.5
2BS	5.0	3.9	6.6	1.3
2BM	9.0	5.7	7.9	0.3
2BB	18.0	4.7	3.1	0.7
2CS	5.0	4.4	3.8	0.5
2CM	13.0	2.8	2.4	0.7
2CB	26.0	2.5	1.9	1.0
2DS	5.0	3.6	3.1	0.4
2DM	10.0	5.5	3.0	0.4
2DB	20.0	1.7	5.5	0.4
2ES	5.0	2.4	2.8	0.4
2EM	20.0	4.4	3.6	0.9
2EB	40.0	1.6	2.2	0.4

S, M and B stand for surface, mid-depth and bottom samples, respectively.

Table 3 Calculated inventories (average mass) and concentration average values over 15 months (basis: volume of survey area = 0.56 km^3)

	Particulate (tonnes)	*O_2 (tonnes)*	*NH_3 (kmol)*	*NO_3 (kmol)*	*N_{total} (kmol)*	*PO_4 (kmol)*
Mass av.	7827	3835	3241	2066	5223	345
SD (%)	± 20	± 11	± 31	± 74	± 21	± 31
	mgl^{-1}	mgl^{-1}	(μM N)	(μM N)	(μM N)	(μM P)
Conc. av.	14	6.8	5.8	3.7	9.3	0.6

SD (%) is the standard deviation in percent

Freitas and from the outlet of Vidigal (near station 2A). The highest concentrations of ammonia were always in the vicinity of the SOI outlet. The presence of cold water masses also affected the average concentration of ammonia: the lowest values were detected when the water below 5 m depth were around 12–16°C. This effect, as will be discussed later, is related to the behaviour of the sewage plume during the upwelling season and in the presence of stratification. The oxygen concentrations for the surface layer were in general slightly super-saturated, except for the periods of leakage in the sewage system at the beach. Values as low as 2.9 mgl^{-1} were measured at stations 2A and 2B.

Particulate matter concentration was higher in periods of heavy rain near the SOI outfall. The SOI system, in addition to sewage, collects surface runoff with a considerable sediment load derived from weathering of Rio's catchment.

Figures 3 and 4 characterize the SOI as a source of copper and lead to the coastal waters. The influence of the urban runoff is evident from the value of 1.3 $nmolPbl^{-1}$ for surface waters of station 2B. Lagoa de Freitas is an additional source of copper especially following heavy rain (as for instance shown in Figure 3b). The Figures 3a and 4 also show differences in the distribution of copper and lead. This may be ascribed to the diversity in nature and size of the particles carrying the metals and to differences in their reactivity. However, no speciation was performed in the present work and any assumption would be highly speculative. Lead, which appears in higher concentrations close to the sewage outfall, seems to be bound preferentially to heavier particles. Copper, on the other hand, shows a distribution resembling that of the bulk particulate material.

The concentration values for lead are in general comparable to those reported by Patterson (1976b) for polluted surface waters. A survey of the region of the Los Angeles submarine outfall (JWPCP) reported by Morel *et al.* (1975) gave average copper values of 50 nmol Cu l^{-1} which are an order of magnitude above the average of 4.5 nmol Cu l^{-1} of this work. This difference could be ascribed to the proximity of a more intensely industrialized area in the case of Los Angeles.

Figures 5, 6 and 7 give a graphic view of the areal inventories expressed in μmol m^{-1} (summed over the whole water column) for lead and copper and show lead distribution in the expected direction for the sewage plume (Figure 6) and the even distribution of copper around the outlet.

There was only a weak correlation between actual concentration values of different species measured in the same places (stations) (e.g. between particulate matter and ammonia, heavy metals and phosphate). From these results, it can be concluded that their spatial and chemical pathways are significantly different. In spite of this, a consistent behaviour of all outfall-derived components could be observed, and related to the presence or absence of upwelling and to the stratification of the water column. During the upwelling season (October to April), cold water masses enter the survey area at the bottom, establishing a well defined pycnocline. In this condition the outfall derived components are retained between the bottom to mid-depth, and their horizontal distribution stretches out rather evenly over the whole observation area. In the absence of upwelling and consequently of a temperature gradient, the sewage discharge ascends immediately above the outfall and a better definition of the sewage plume can be observed. In this situation the highest concentration of all outfall-derived components were found at the surface, gradually decreasing to the bottom. In this condition the centres of higher concentration were determined primarily by wind speed and direction and surface currents. As examples for these two situations Figures 3, 4, 8, 9 and 10 show

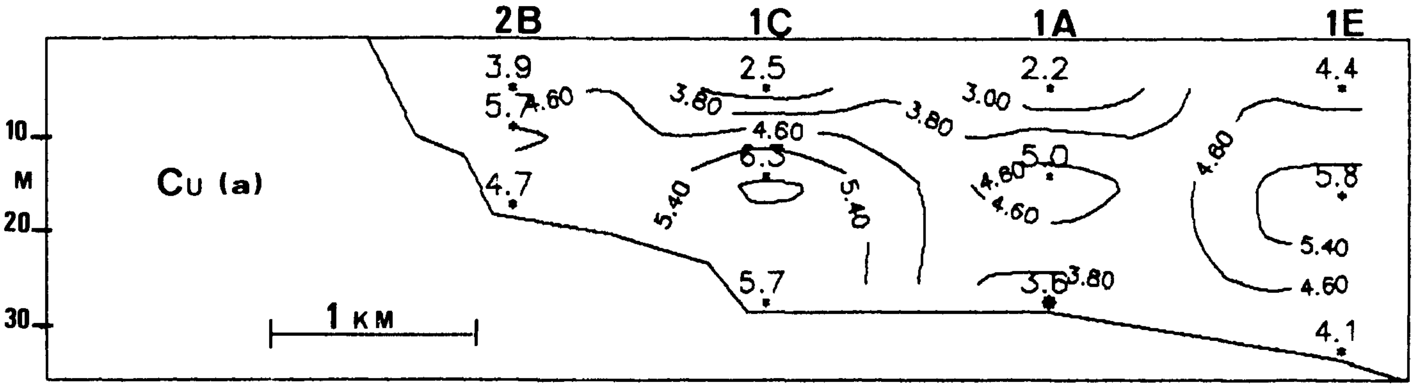

Figure 3a Copper concentration (nmolel^{-1}) along a profile perpendicular to the coast; data for sampling in April 1988 when there was stratification.

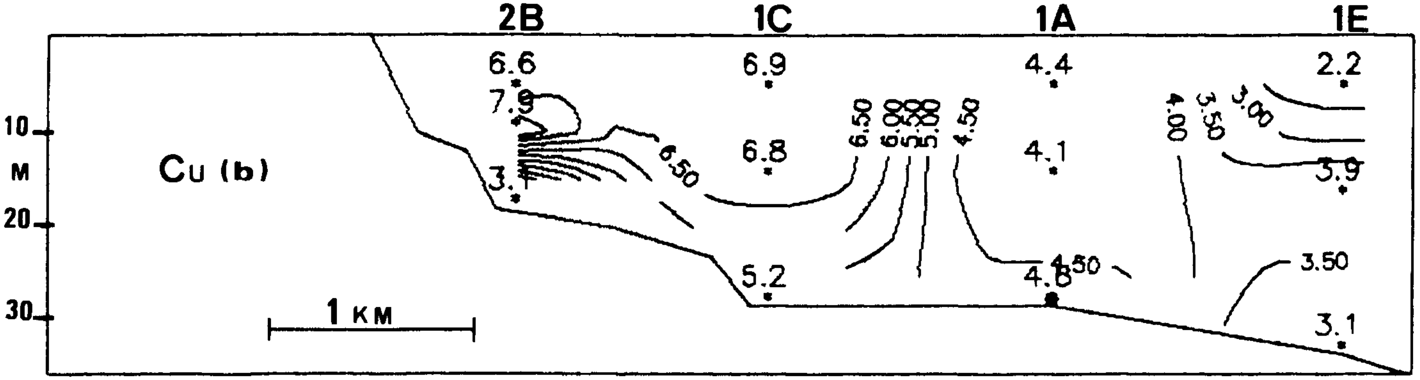

Figure 3b (b) as for (a), sampling in July 1989 with no stratification in the survey area. Sampling points are indicated by dots and numerals.

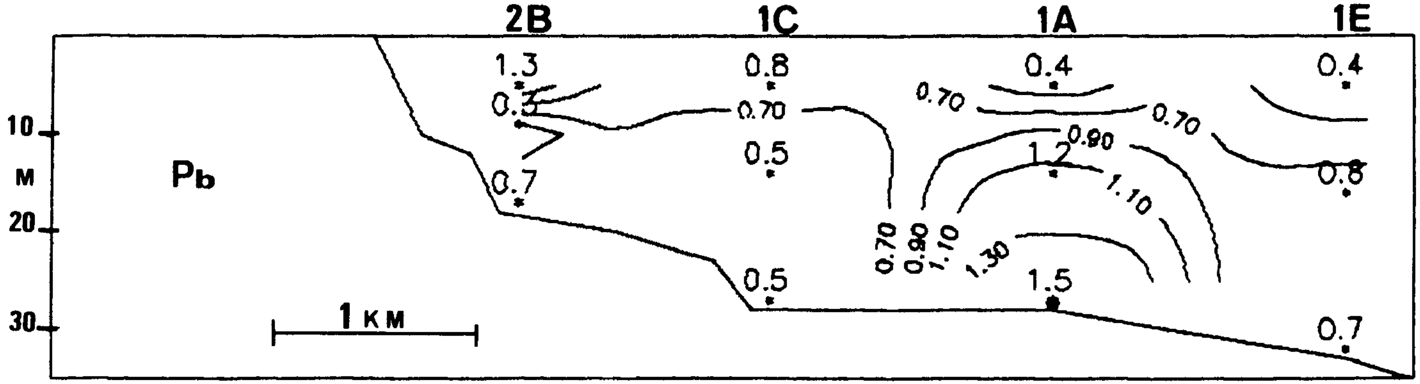

Figure 4 Lead concentration (nmoll^{-1}) along a profile perpendicular to the coast for sampling in April 1988 with stratification of the water column. Sampling points are indicated by dots and numerals.

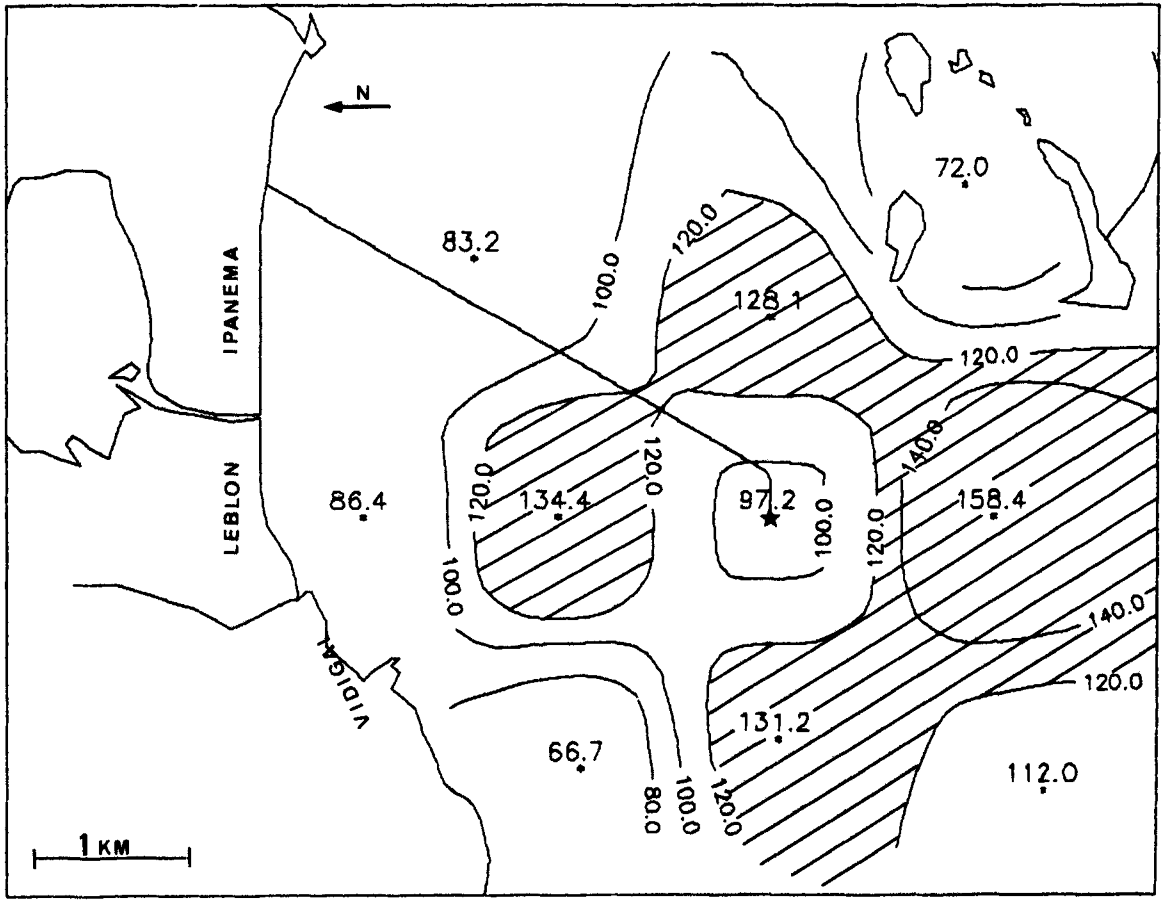

Figure 5 Distribution of copper in the sampled area (μmol m^{-2}) for sampling in April 1988 with stratification of the water columm. The highest concentrations are indicated by the shaded areas. Sampling points are indicated by dots and numerals.

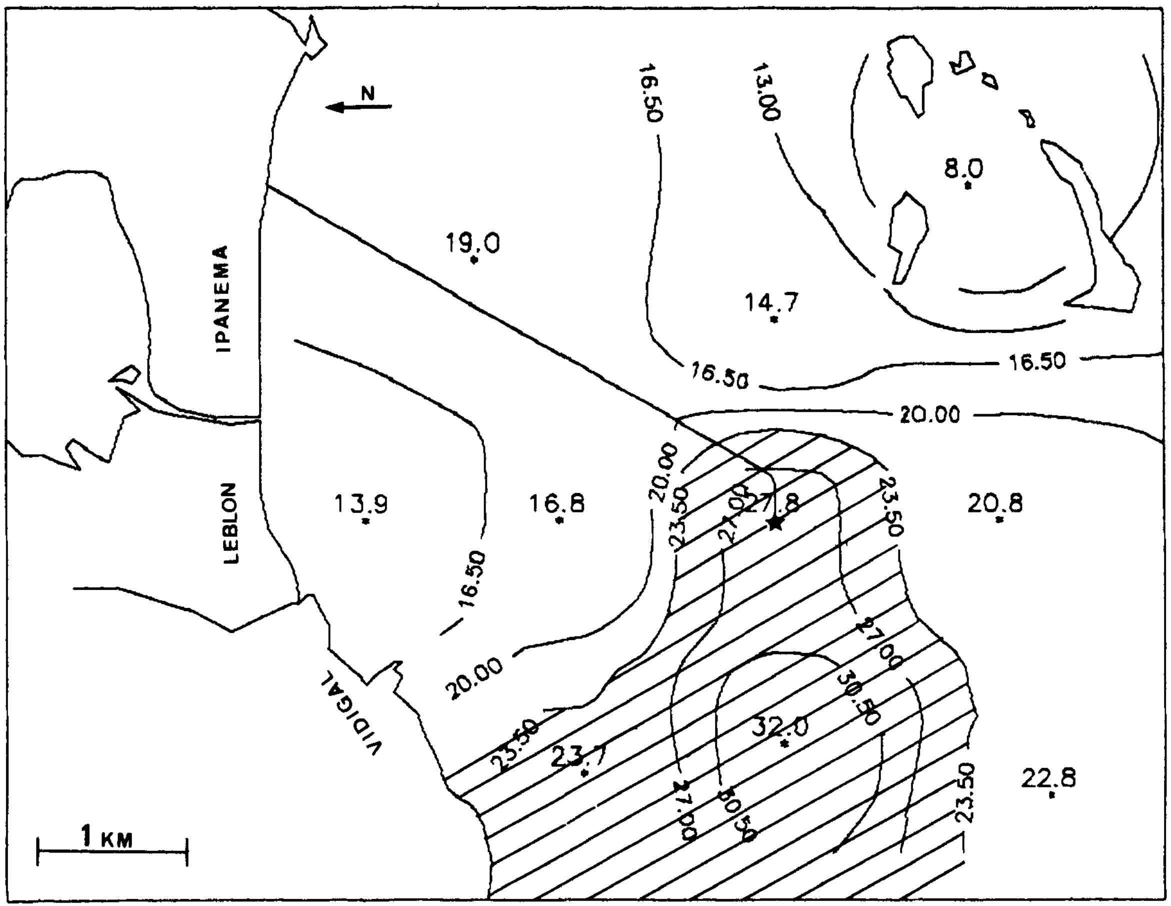

Figure 6 Distribution of lead in the sampled area (μmol m^{-2}) for sampling in April 1988 with stratification of the water column. The highest concentrations are indicated by the shaded areas. Sampling points are indicated by dots and numerals.

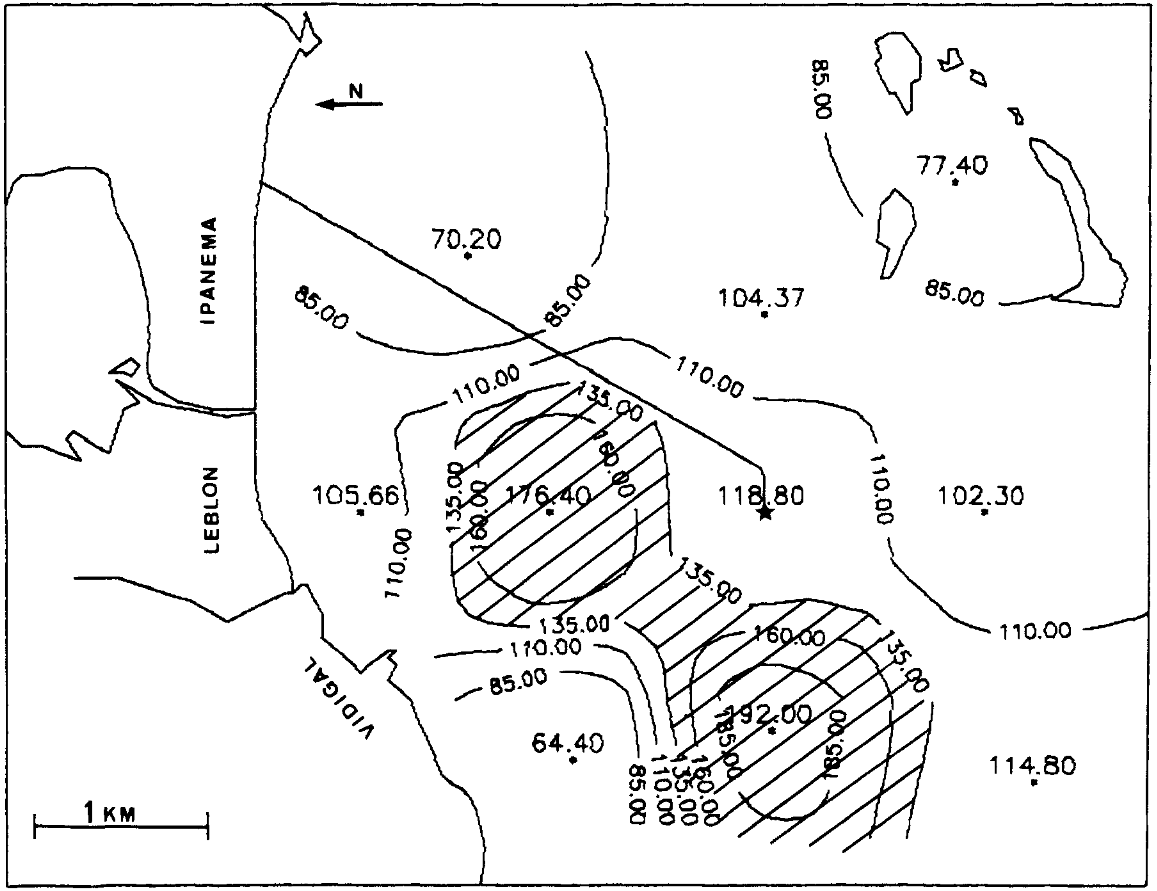

Figure 7 Distribution of copper in the sampled area (μmol m^{-2}) for sampling in July 1989 with no stratification of the water column. The highest concentrations are indicated by the shaded areas. Sampling points are indicated by dots and numberals.

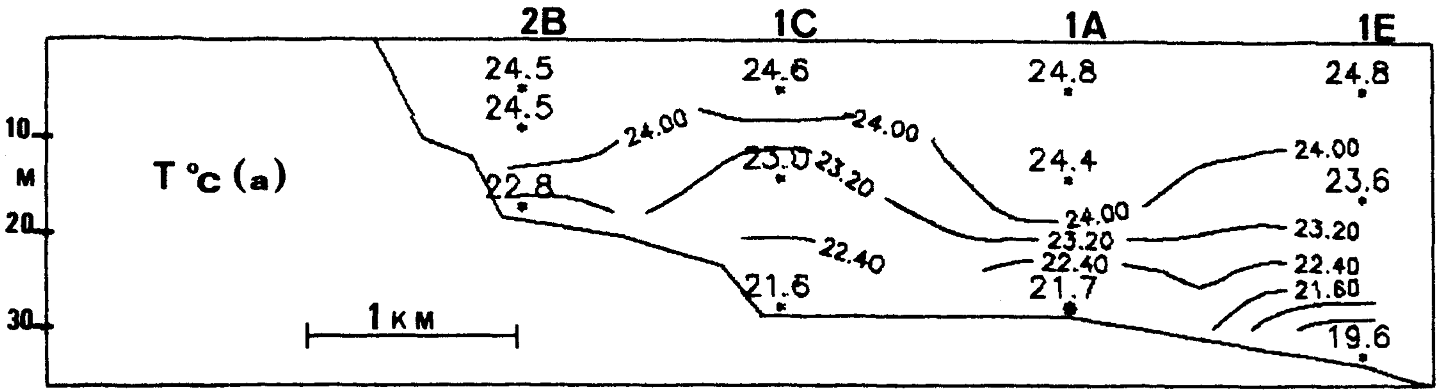

Figure 8a Temperature profile perpendicular to the coast for sampling in April 1988 showing the stratification in the survey area.

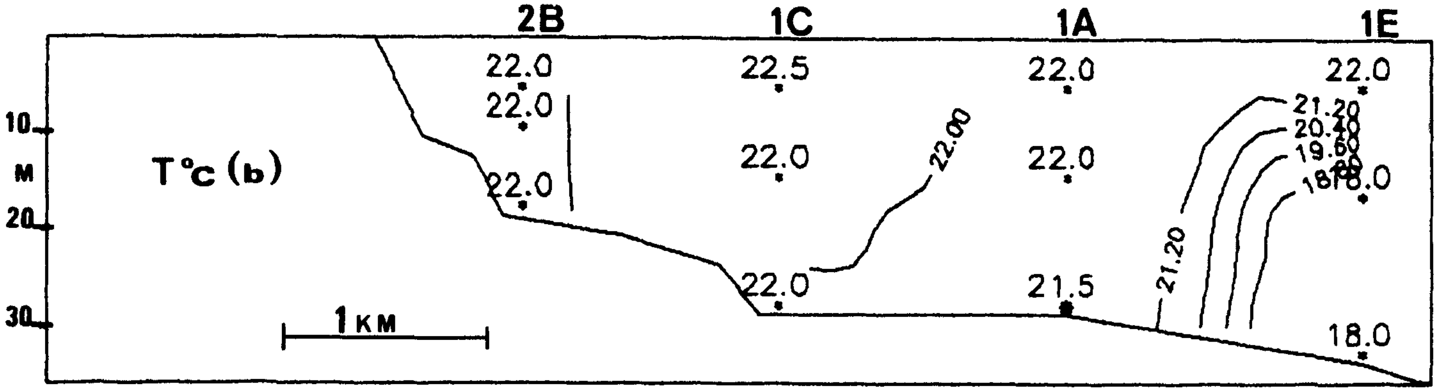

Figure 8b As for (a) for sampling in July 1989 showing no stratification. Sampling points are indicated by dots and numerals.

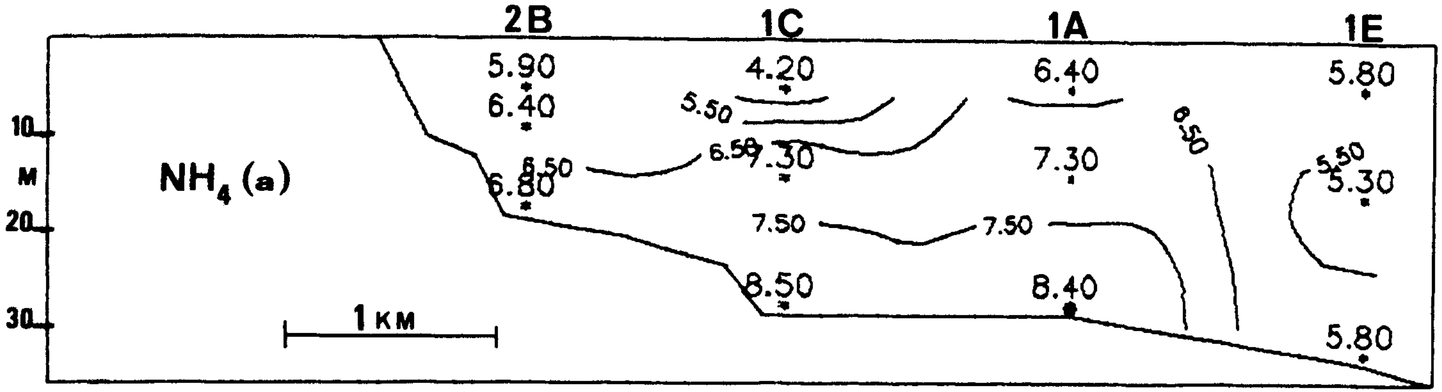

Figure 9a Ammonia concentration (μmol N) profile perpendicular to the coast for sampling in April 1988 with stratification of the water column.

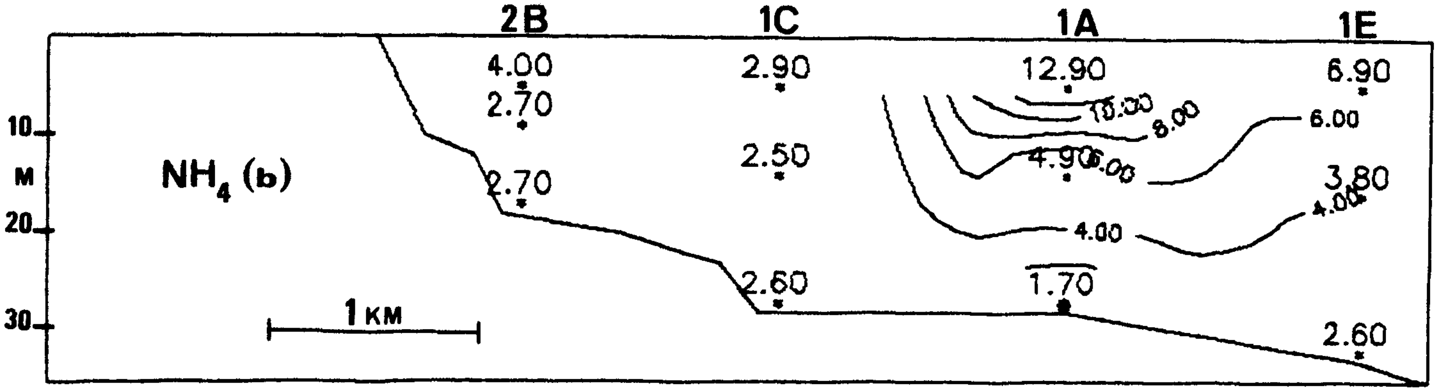

Figure 9b as for (a) sampling in July 1989 with no stratification. Sampling points are indicated by dots and numerals.

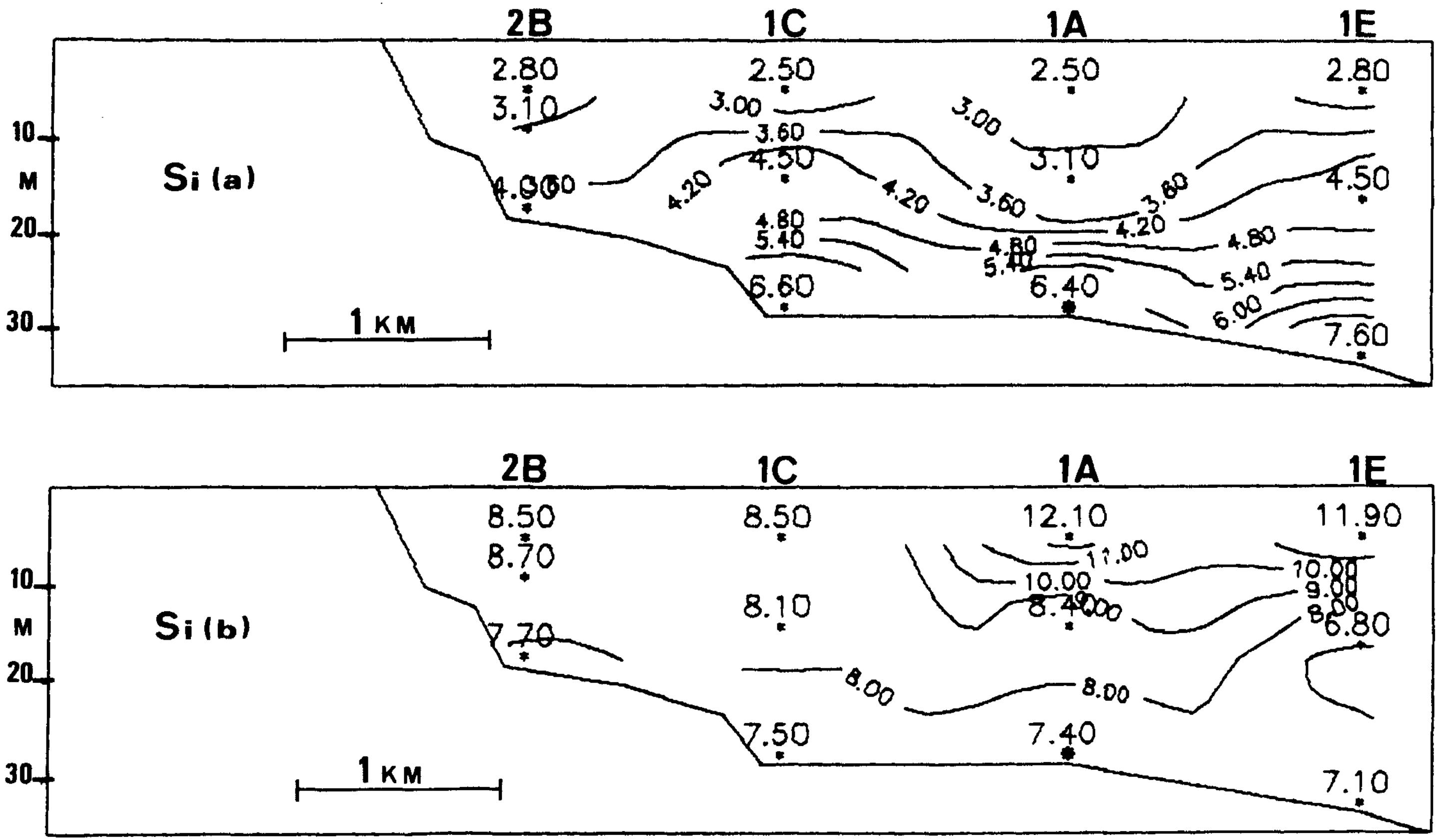

Figure 10a and **b** Dissolved silica (μmol Si) profiles for sampling in April 1988 with stratified water column and in July 1989 with no stratification. Sampling points are indicated by dots and numerals.

the distributions of copper, lead, temperature, ammonia and silica.

The centre of gravity of the mass distribution for all components and all samplings was calculated. The results indicate a slight shift away from the discharge point: about 600 m toward the land (north) and 70 m parallel to the west with no difference for short-lived components (such as sewage-derived N, see below) and long-lived components (such as particulate matter, see below). This indicates that there is no persistent current advecting sewage, and the obviously stationary centre of gravity may simply represent a 'dead point' in the periodic water movement caused by the tides.

The Fate of Particulate Sewage Matter in the Ocean

From the actual inventories for each sampling, it was found that the amount of particulate material in the observation area was variable, an average of 7,825 ± 1,578 tonnes. There was a slight increasing trend (255 tonnes/ month) which is 79.5% significant and attributed to an increasing discharge rate. The average value of 7,827 tonnes will be used. The measured particulate matter can be taken as 'outfall-derived particulate matter', because inorganic particulate matter from catchment runoff is discharged via the same outfall, and the mass of algae cells (except during blooms) is insignificant.

Assuming steady state conditions with a discharge rate taken as constant, the mean residence time of the sewage particles within the sampling area is:

$$\begin{aligned}\text{(mass value) / (discharge rate)} &= (7{,}827 \pm 1{,}578\ \text{t}) / (336\ \text{tday}^{-1})\\ &= 23 \pm 5\ \text{days}\end{aligned}$$

What happens to the particles after the 23 days? They may have been decomposed or escaped from the observation area. There is strong evidence for the latter. The profile of total particulate concentration through the north-south section 2B, 1C, 1A, 1E was calculated by linear regression for each sampling. The average of all slopes gives -1.21 ± 0.73 gm^{-3} per kilometre from the coast. With the mean value 1.66 standard deviations below zero, there is an 81% confidence level that the gradient is indeed negative. Extrapolating this profile would lead to zero concentration about 10 km outside the area. This provides only a very rough estimate, but it shows the order of magnitude of the real extension of influence of sewage material. An area of this size, i.e. of the order of 150 km^2, may be assumed at steady state with the present discharge rate, taken as constant, of 336 tonnes of particulate organic matter per day. With the discharge point about 3 km off the coast, this would give a distribution with the shape of half a disc and a radius of 10 km. The radial diffusion flux of particles would then compensate for the discharge rate at the centre.

Using this hypothetical model, we can estimate the mean life-time of sewage particles in the sea, until they are decomposed (or have settled). The distribution of particles, representing their local concentration as the vertical ordinate, has the shape of half a cone with the height (= concentration) at the discharge (= centre) point and the basal diameter of 20 km (see Figure 11). The total inventory then is:

$$\begin{aligned}\text{total steady state part.mat.} &= \text{vol.} \times \text{conc. at the centre point}\\ &= 1/2 \times 1/3 \times \pi/4 \times (20{,}000\text{m})^2 \times 27\text{m} \times 13.4\text{gm}^{-3}\\ &= 1.9 \times 10^4\ \text{tonnes}\end{aligned}$$

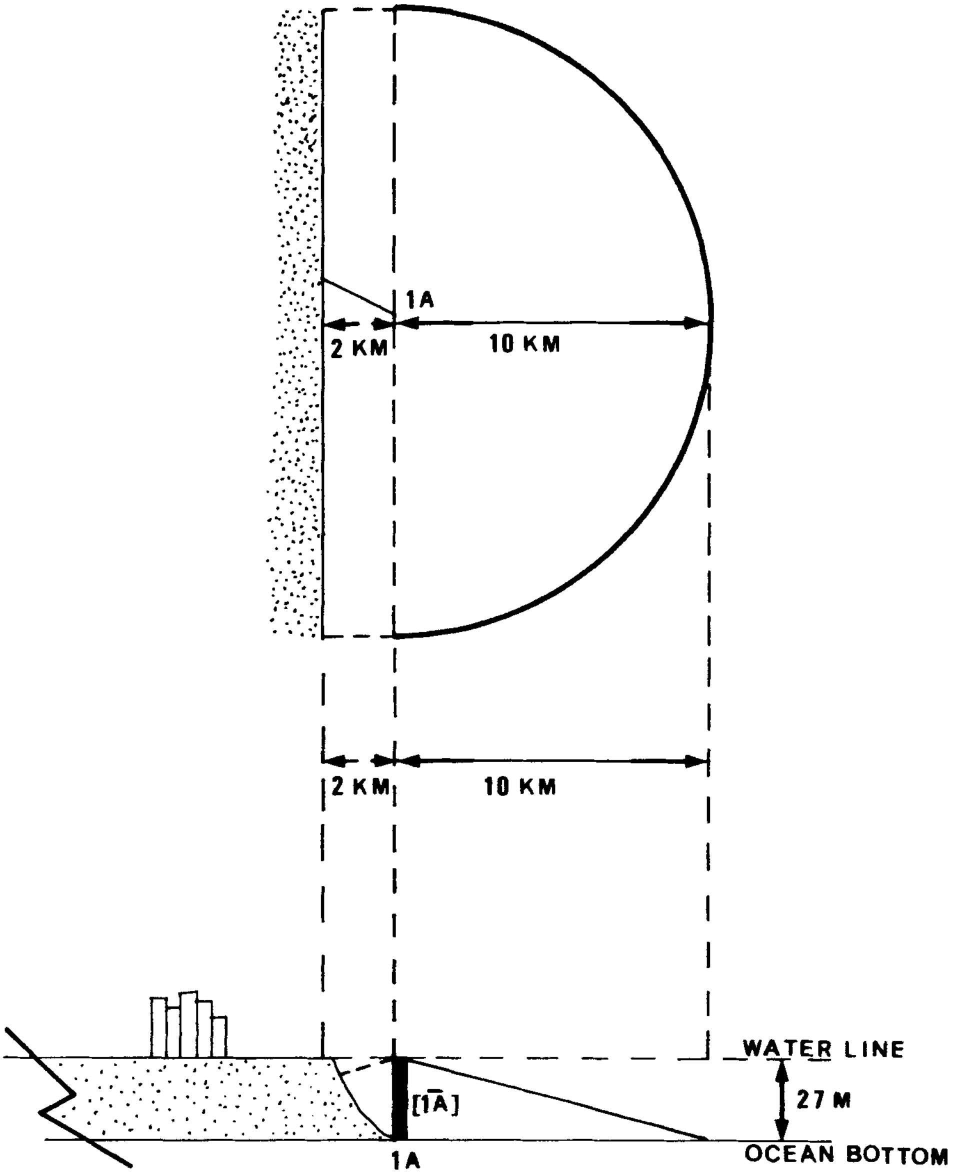

Figure 11 Graphic representation for the distribution of particles. Using their local concentration as the ordinate gives their distribution the shape of half a cone with the highest concentration at the discharge centre and a basal radius of 10 km.

Taking this as the steady state mass gives a mean life-time of the sewage particles in the sea:

$$\begin{aligned}\tau &= 1.9 \times 10^4 \text{ tonnes/ } (336 \text{ tonnes day}^{-1})\\ &= 56 \text{ days}\end{aligned}$$

until they are decomposed or settled, respectively.

The Fate of Sewage Derived Nitrogen and Phosphorus in the Sea

The presence of nitrogen in the form of nitrate is probably an artefact resulting from the pre-treatment of the sewage with an oxidant. This is also suggested by the extreme variability of the amount of nitrate within the observation area (between 1.6 and 63 tonnes). However, the sum of ammonia and nitrate, expressed as total N, is remarkably constant at 73 ± 15 tonnes, with no trend; we consider this to be derived from sewage.

The total steady state mass in the sea is greater. This can be inferred from the concentration profile across the sampling area. The north-south profile (i.e. perpendicular to the coast) has a pronounced peak at the discharge point and a steep gradient to lower values from this point to the open ocean. Extrapolation leads to zero concentration at about 2.4 km distant. In turn, this provides an estimate of sewage-derived N from the Ipanema outlet of about 100 ± 20 tonnes (as NH_3 or NO_{-3}).

The discharge rate of nitrogen at the outlet can be estimated from the values given above for the sewage discharge as follows. Discharged volume of sewage is $4.8.10^5$ m^3 day^{-1}. A fraction (7.10^{-4}) is organic solids with about 30% of protein. This gives discharged organic nitrogen of about 16 tonnes per day. An additional 17% of this value is usually present in the form of urea or uric acid, giving a total discharge of nitrogen of about 19 tonnes/day. The mean life-time of this sewage-derived nitrogen (in an assimilable form) is then:

$$\begin{aligned}&(\text{steady state mass of N in the ocean}) / (\text{daily discharge rate}) = (100 \pm 20) \text{ tonnes/ } (19 \text{ tonnes/day}^{-1})\\ &= 5 \pm 1 \text{ days.}\end{aligned}$$

Phosphorus, as the rate-controlling minimum component, is immediately absorbed by the phytoplankton. The steady state concentration within the observation area is (0.5 ± 0.3) $\mu mol l^{-1}$, and thus only slightly above the presumed natural level.

CONCLUSIONS

1) Observations of a number of indicator variables over 15 months in an area of 28 km^2 around the sewage outfall at Ipanema indicated steady state conditions, as was to be expected after 18 years of operation.
2) The extent of the steady state distribution of sewage derived products in the ocean is considerably larger than the area of observation. Its total extent can be estimated from concentration gradients observed within the sampling area.
3) A cloud of suspended particulate organic matter covers an estimated area of about 150 km^2, and from an estimated total inventory and the known discharge rate, residence of these particles in the ocean is calculated as about 56 days.
4) In the same way, sewage-derived nitrogen (ammonia or nitrate) has a mean residence of about 5 days.

5) Nitrate in the sewage seems, almost certainly, to be caused by pre-treatment of the sewage with oxidants before release.
6) In the absence of any persistent current, the centre of gravity (maximum concentrations) of all discharged components is coincident with the point of discharge.
7) The discharged sewage is a significant source of lead to the area.
8) The vertical and horizontal transport of the discharged material is governed by the presence or absence of the upwelling conditions and stratification of the water body. If cold upwelled waters enter the observation area and pass over the discharge outlet, most of the discharged material is trapped below the pycnocline, resulting in horizontal spreading over a large area. In these conditions, the concentrations of outfall derived components in the surface waters are low. In the absence of upwelling, or during stormy weather conditions that break down stratification, the plume ascends to the surface, close to the outfall. The plume can easily be driven towards the shore by prevailing onshore winds.

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