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Recovery of a sewage sludge dumping ground. I. Trace metal concentrations in the sediment

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ABSTRACT: Sewage sludge has been dumped at sea in the Firth of Clyde, Scotland, for almost 90 yr. Prior to implementation of the Dumping at Sea Act (1974) it was dumped ca 2 km south of the Isle of Bute. Surveys at this site before 1974 showed the accumulation of organic material and metallic contaminants in the sediments. The present study describes the geographical distribution of trace metal concentrations in both surface and subsurface sediments in 1985. Trace metal concentrations in surface sediments were much lower than those reported while dumping was in progress. Marked elevations in trace metal concentrations were found with depth in the sediments. A tentative trace metal budget for this disused disposal site is presented. About a quarter to a half of the input metals were retained in the sediment.

INTRODUCTION

Sewage sludge has been dumped in the Firth of Clyde, Scotland, for almost 90 yr (Harper & Greer 1988). Before 1974 the centre of dumping operations was ca 2 km south of Garroch Head on the Isle of Bute (Fig. 1), but in 1974 the disposal operation was moved to a new licensed area 4 km further south.

When the original site was still in use, several workers (MacKay & Topping 1970, MacKay et al. 1972, Topping & McIntyre 1972, Steele et al. 1973) reported strongly altered benthic communities and elevated trace metal concentrations over an area of ca 20 km^2 of seabed (Halcrow et al. 1973). The present study reports the changes in metal concentrations in both surface and subsurface sediments which had occurred by 1985, with a view to assessing the recovery of the abandoned sludge disposal site. The improvements in the condition of the benthic communities are described in the companion article (Moore & Rodger 1991).

METHODS

In 1985, 2 short (10 to 14 cm) undisturbed Craib cores (Craib 1965) and one long (up to 90 cm) gravity core were obtained at 10 stations in the vicinity of the pre-1974 disposal area (Fig. 1). Stns 1 to 5 corresponded to those sampled for the macrobenthic community (Moore & Rodger 1991).

At each station, one short core was sectioned at 1 cm

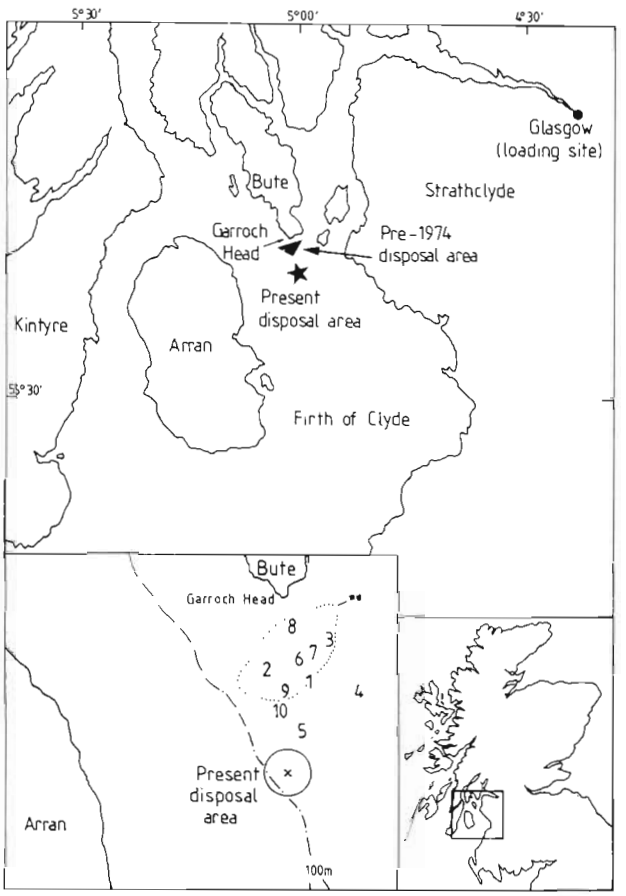

Fig. 1. Position of sewage sludge disposal sites and sampling stations 1 to 10 in the Firth of Clyde, Scotland. **Estimated area of sediment contamination present in the early 1970s from data reported by MacKay et al. (1972)

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intervals to a depth of 8 cm, and the long core was sectioned at 5 cm intervals for its full length. All core sections were stored frozen (−20 ° C) and then freeze-dried. Subsamples of 1 to 2 g were digested with hot concentrated nitric acid and the resultant extracts were analysed for cadmium, copper, lead, zinc, mercury and manganese by flame and cold vapour atomic absorption spectrophotometry as described by Clark & Davies (1989). The long core samples were analysed only for cadmium, copper, lead and zinc. All concentrations are given in mg metal per kg dry sediment.

RESULTS

Trace metal concentrations in surface (0 to 1 cm) sediments in 1985

Generally, Cd, Cu, Pb, Zn and Hg concentrations were higher in surface sediments at Stns 2, 6, 8 and 9 in the western part of the study area (< 0.2 to 0.7 mg kg^{-1} Cd, 81.5 to 87.5 mg kg^{-1} Cu, 133 to 163 mg kg^{-1} Pb, 272 to 294 mg kg^{-1} Zn and 0.63 to 0.97 mg kg^{-1} Hg) than at the easterly Stns 1, 3, 4 and 7 (Fig. 2).

At the southerly Stns 5 and 10, Cu concentrations (and Cd concentrations at Stn 10) were similar to those at the westerly Stns 2, 6, 8 and 9, whilst Pb and Zn levels were relatively low.

Concentrations of manganese in the surface (0 to 1 cm) of the sediments varied from 430 mg kg^{-1} at Stn 5 to 2420 mg kg^{-1} at Stn 4, and, in contrast to the other elements, showed no clear pattern of distribution.

Trace metal concentrations in subsurface sediment

At all stations, except Stn 5, concentrations of Cd, Cu, Pb, Zn and Hg were higher in subsurface (ca 10 to 30 cm depth) than in surface (0 to 5 cm) sediment (Figs.

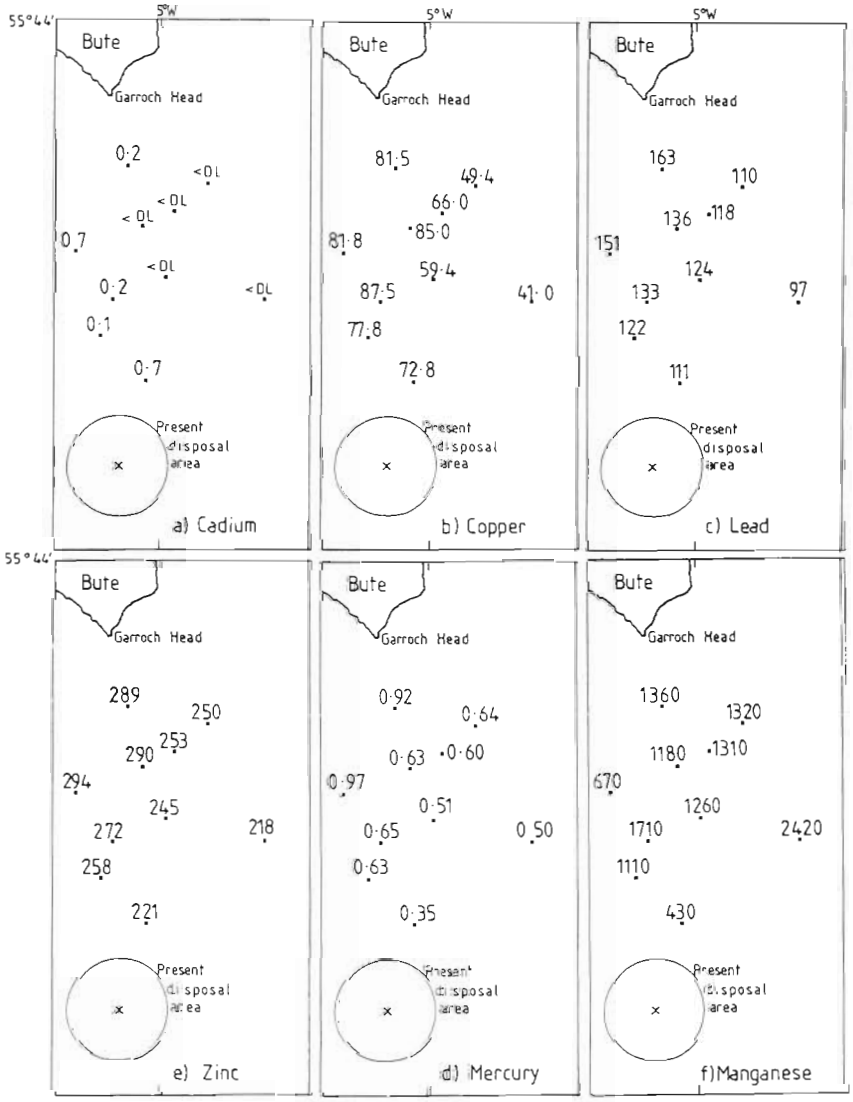

Fig. 2. Trace metal concentrations (mg kg^{-1} dry wt) in the surface (0 to 1 cm) of the sediment from Stn 1 to 10 around the pre-1974 disposal area

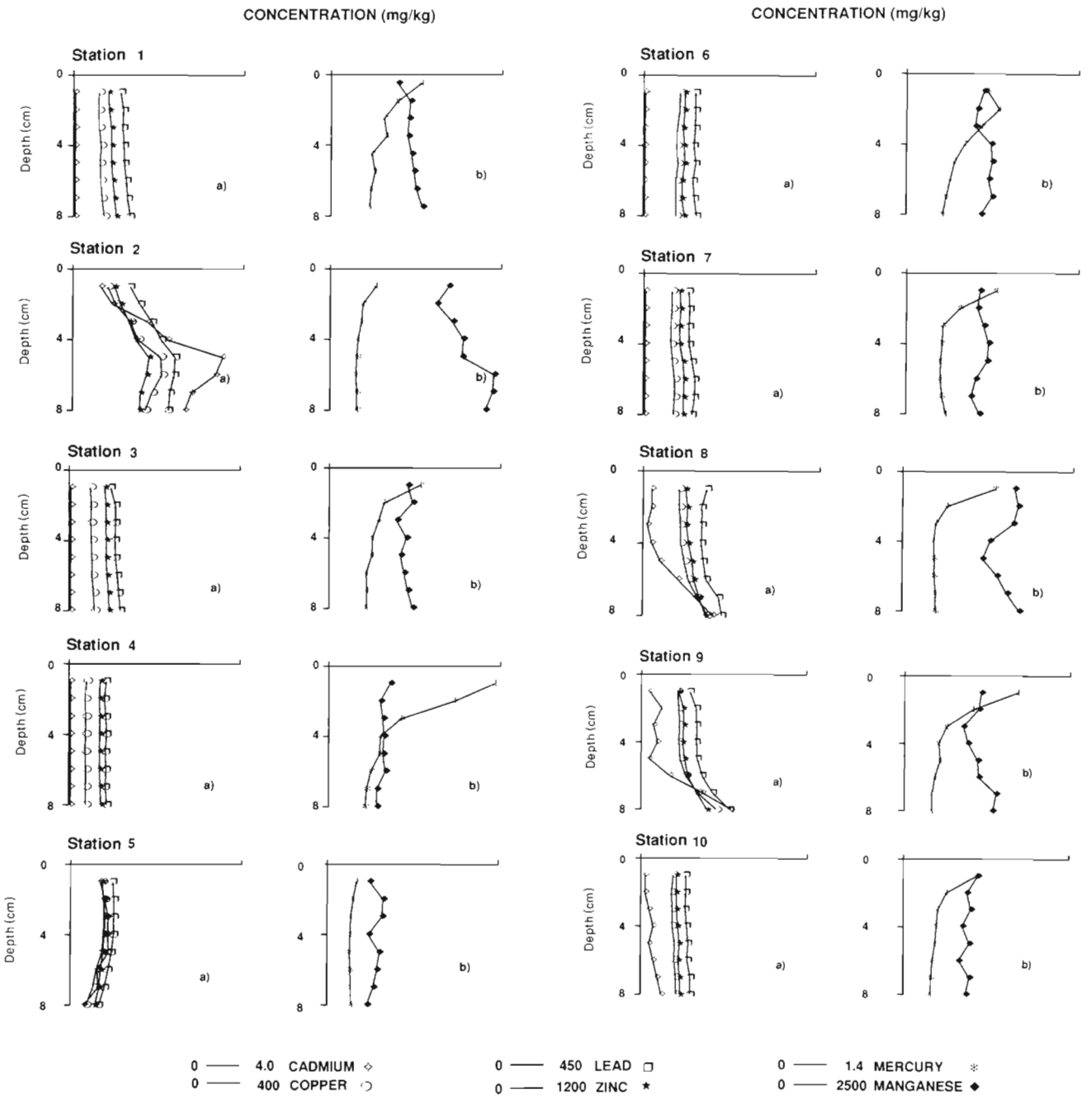

Fig. 3. Depth profiles (0 to 8 cm) of trace metal concentrations (mg kg^{-1} dry wt) in the sediment from Stns 1 to 10. (a) cadmium, copper, lead and zinc; (b) mercury, manganese. The scales for each metal are shown at the foot of the figure. They extend to the full extent of the *x*-axis and differ between the metals

3 & 4). At some stations (e.g. 1, 3, 4, 6 and 7) the increases with depth were not evident in the short cores, whilst at other stations (e.g. 2, 8 and 9) marked increases were found below 2 to 5 cm depth.

The greatest increases in subsurface metal concentrations occurred at Stns 2, 6, 8 and 9, with slightly less marked elevations at Stn 7. At Stns 6 and 9, peak values of ca 3.0 mg kg^{-1} Cd, 220 mg kg^{-1} Cu, 315 mg kg^{-1} Pb and 650 mg kg^{-1} Zn were found at a depth of 16 to 25 cm, and elevated concentrations extended over a depth range from ca 6 to 30 cm. Although concentrations of Cd, Cu, Pb and Zn decreased further down the core at Stn 6, they did not return to those found in the surface (0 to 0.5 cm) sediment.

Stn 7 showed a gradual elevation in concentrations of Cd, Cu, Pb and Zn extending from 11 to 15 cm down

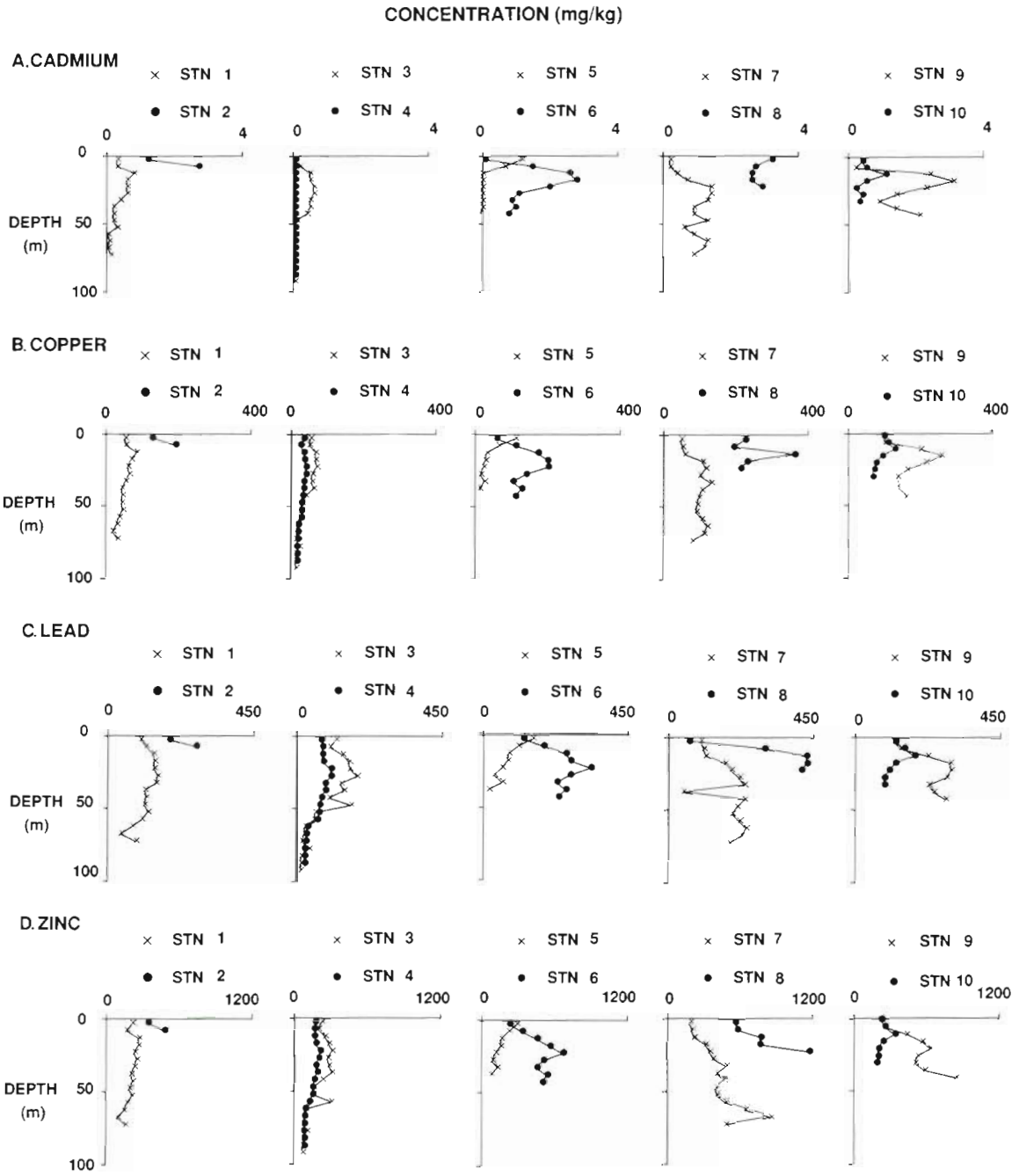

Fig. 4. Depth profiles of trace metal concentrations (mg kg^{-1} dry wt) in the sediment from Stns 1 to 10 obtained by the long cores

to 65 to 70 cm. The last segment of the core at 71 to 75 cm had slightly lower concentrations than the shallower depths, although not as low as those at the surface (0 to 5 cm). Although the maximum metal concentrations at Stn 7 were not as high as those found at Stns 6 and 9, they extended over a much greater depth range within the sediment, and maximum concentrations of individual metals occurred at various depths from 21 to 45 cm.

Stn 10 showed slightly elevated concentrations (1.1 mg kg^{-1} Cd, 97.7 mg kg^{-1} Cu, 183 mg kg^{-1} Pb and 338 mg kg^{-1} Zn) at a depth of 11 to 15 cm. The concentrations subsequently decreased with depth to values similar to those found at the surface (0 to 1 cm) by 21 to 25 cm depth.

At Stns 1, 3 and 4 the concentrations of Cd, Cu, Pb, Zn and Hg varied very little in the upper 8 cm of the sediment. However, slight elevations in the Cd, Cu, Pb

and Zn concentrations (of much less magnitude than those at Stns 2, 6, 7, 8 and 9 to the west) were found between 10 and 50 to 60 cm at all 3 of the above stations. Below 60 cm, the sediment was a stiff grey clay, and showed uniformly low metal concentrations. At other sample stations elevations in trace metal concentrations coincided with darker sediments.

Stn 5 showed a different pattern of trace metal concentrations from that of the other stations, in that the highest levels were found in the surface sediments of both long and short cores. The concentrations of Cd, Cu, Pb and Zn decreased with depth to values at 11 to 15 cm similar to those in near-surface sediment at Stn 4.

At all stations the manganese concentrations increased towards the surface in the upper 4 cm of the short core. Large increases were shown at Stns 4 and 9, with much smaller increases at Stns 1 and 10 and only slight increases at Stns 2 and 5.

DISCUSSION

The position of the sampling stations in the present survey in relation to the approximate area which showed elevated trace metal concentrations in the sediment during the early 1970s (MacKay et al. 1972) is shown in Fig. 1. In 1985 the concentrations of trace metals in the surface (0 to 1 cm) of the sediment at all the stations sampled were below the values reported for the sediment in this area in the early 1970s (ca 100 to 150 mg kg^{-1} copper, 200 to 250 mg kg^{-1} lead and 300 to 500 mg kg^{-1} zinc; MacKay et al. 1972, Figs. 3, 4 & 5). The concentrations in the surface (0 to 1 cm) sediment at Stns 2, 6, 8 and 9 were slightly higher than reported for stations outside the disposal area in the early 1970s. Stns 1, 3 and 7 were situated on the periphery of the pre-1974 disposal area, and in 1985 the trace metal concentrations were well below those reported for that area in the early 1970s. The trace metal concentrations in the surface sediments, although considerably reduced, showed a similar pattern of distribution to that found in the early 1970s, in that surface sediments in the west of the study area contained higher concentrations of trace metals than sediments in the east.

The lower concentrations of metals in the surface sediments in 1985 than in the early 1970s suggest that metals accumulated from the original dumping operation had either been released from the sediments through bioturbation or other processes, or become buried by post-1974 sedimentation. The marked subsurface elevations in trace metal concentrations in the short or long cores at Stns 2, 6, 7, 8, 9 and 10 suggest that the latter case is more likely. These stations are positioned to the west of the study area in the region of highest concentrations in surface sediment in the early 1970s. It therefore appears that some of the metals input with sewage sludge during the pre-1974 disposal operation have been retained in the sediments, and could be detected in 1985 at generally similar concentrations to those found in surface sediments whilst dumping was taking place. Some mixing of deeper sediments contaminated by sludge with more recently deposited material has probably occurred, and caused the slightly raised metal concentrations in areas which were previously heavily contaminated by sludge.

The profiles of trace metal concentration with depth illustrate 3 sediment types. A grey clay with very low trace metal concentrations found at depths greater than 60 cm at Stns 3 and 4 probably represents glacial sediment (Deegan et al. 1973). The sediment above 60 cm depth at Stn 4 showed slightly elevated trace metal concentrations similar to those in other parts of the Clyde not affected by direct waste disposal, and is typical of recent deposits from the Clyde. Superimposed on the above is the sludge-amended sediment resulting from the disposal operation, which forms a layer of varying thickness within the Recent deposits. The effect of the sludge is clearly seen as marked elevations in trace metal concentrations, e.g. at Stns 6 and 9 (centre of the pre-1974 disposal area), and as smaller elevations at Stns 1 and 3 (periphery of the pre-1974 disposal area). The depth of the sludge-amended layer varied across the study area, from ca 25 cm at Stns 6 and 9, to ca 60 cm at Stn 7. The sludge-amended layer had previously been estimated by Halcrow et al. (1973) to be 40 to 50 cm deep and by Baxter & Harkness (1975) to be 40 to 65 cm deep.

The profiles of trace metal concentrations at Stns 6 and 9 did not show the concentrations decreasing at depth to the typical levels of Recent sediments shown at Stns 1, 3 and 4, indicating that the cores obtained at Stns 6 and 9 did not extend to the full depth of the sludge-amended sediment layer. None of the stations with greatly elevated trace metal concentrations (2, 6, 7, 8 and 9) showed a reduction in trace metal concentrations at depth to values as as low as those in the glacial sediments.

The situation at Stn 5 is dissimilar to all the other stations in the present study. The elevated trace metal concentrations towards the surface of the sediment, the macrobenthic community structure (Moore & Rodger 1991), and its proximity to the current dump site, suggest that this station has been affected by the post-1974 disposal operation.

A conservative estimate of the area of seabed showing elevated trace metal concentrations from the pre-1974 disposal operation would be that delineated by

Table 1. Metal content of sediment and sludge input, and percentage of metals retained in the sediments, of the pre-1974 Garroch head disposal area

Metal	Sediment content (tonnes)	Sludge input (tonnes)	Metal dumped retained in sediment
Cadmium	2.6	12	22
Copper	225	875	26
Lead	459	848	54
Zinc	1,026	2,213	46

the positions of Stns 1, 2, 3, 8 and 10, which includes all the stations found to have elevated trace metal concentrations in subsurface sediments in 1985. This area is ca 7.5 km^2, but it must be viewed as a minimum, as the full extent of metal accumulation in sediment to the west of the study area is unclear. If a layer of 60 cm depth is taken as containing trace metal concentrations above control levels (0.04 mg kg^{-1} Cd; 50 mg kg^{-1} Cu; 90 mg kg^{-1} Pb; and 200 mg kg^{-1} Zn: from Clark 1989), the volume of contaminated sediment may be estimated as 4.5×10^{12} cm^3.

The total metal content of the contaminated sediment can be calculated from this volume and the trace metal concentrations, if allowance is made for the water content (40 % dried solids) and bulk density (1.2 g cm^{-3}) of the sediment. The mean trace metal concentrations of the sludge affected sediment at Stn 7 were used for these calculations, as they were between the high values of Stns 2, 6, 8 and 9 and the lower values at Stns 1, 3 and 10. These values (Table 1) are uncorrected for natural sedimentation.

The trace metal content of the sediment can be compared to the estimated amount of trace metals input with the sewage sludge during the period of dumping, to produce an estimate of the degree to which the sediments have retained the dumped metals. The amounts of Cd, Cu, Pb and Zn dumped with the sludge (Table 1) were calculated from the reported composition of the sludge in the period that the site was operational (MacKay & Topping 1970), and the quantities dumped, allowing for short periods when sludge was dumped elsewhere (Harper & Greer 1988).

The preliminary calculations, making no allowance for natural sedimentation, suggest that about half of the lead and zinc dumped, and a quarter of the cadmium and copper, have been retained in the sediments. Baxter & Harkness (1975) however calculated that only 15 % of the carbon from the sludge could be accounted for in the sediments of the disposal area. This may suggest that the large benthic biomass present at that time caused preferential mineralisation and loss of organic material from the sediments, while retaining the trace metals.

The likely underestimate of the area of affected sediment would lead to an underestimate of the degree of retention, although this would to some extent be offset by the lack of correction for the contribution from natural sedimentation. The metals input to the sludge has been calculated from the sludge composition in 1970 (MacKay & Topping 1970), and may therefore have been overestimated as domestic and industrial inputs grew in the first 70 yr of this century. The estimates presented above of the percentage of trace metals dumped which have been retained in the sediment are, however, considered to be a realistic reflection of the accumulative capacity of the sediment at the pre-1974 disposal site at Garroch Head.

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