

## Specific organic components as tracers of contaminated fine sediment dispersal in Lake Ontario near Toronto

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### Abstract

Bottom sediments around the outfall of the Humber Sewage Treatment Plant (STP), which, with the Humber River, comprises the major contaminant point source emptying into Humber Bay, Lake Ontario, were analyzed for a number of cultural and industrial organic contaminants, including sewage-related compounds such as the faecal sterol coprostanol,  $\alpha$ -tocopheryl acetate ( $\alpha$ -TA), linear-chain n-alkane hydrocarbons, and carbon and nitrogen isotope ratios of refractory sediment organic matter. The goal was to test these chemical markers as tracers of contaminated fine sediment transport. Although these chemical species are not all conservative (some decompose at fairly rapid rates), they are believed to be good 'natural' tags for fine sediment and should nonetheless exhibit clear dispersal plumes from a presumed source. Their plumes can thus provide an effective way to obtain qualitative, intermediate- and long-term transport pathway indicators for contaminated sediments discharged on a continuing basis. The contoured plots for coprostanol, alpha-tocopheryl acetate, and n-alkane distribution were characterized by high values near the STP outfall, and these tracers were detectable at distances of 1 km or more. Interpretation of the net transport patterns indicates a primary transport toward the south and southwest, with a secondary trend northward, curving eastward. The carbon and nitrogen ratios, while showing a slightly different pattern, served to differentiate STP-source materials from those coming from the river and the open lake. Thus, transport from these sources, sometimes in the opposite direction to that from the main source, were resolved. Systematic variations in the interpreted transport patterns are explained by the presence of different pathways taken by the sediments, i.e. whether bedload or suspended load in a stratified water column.

### Introduction

#### *Background*

Nearshore aquatic systems adjacent to urban centres are generally characterized by contaminated fine sediment deposits brought in from a variety of point sources, such as streams and storm/sanitary sewer outfalls. The large and reactive surface areas of such fine-grained sedi-

ments make them extremely effective as adsorption and transport platforms for a variety of contaminants. Because such contaminated sediments can also be readily resuspended and dispersed over considerable areas through this medium and thus pose a threat to nearby clean-water activities, understanding the transport pathways of such sediment is important in water management programs.

Most of the field studies of fine sediment trans-

port published to date have relied on radioactive tracer techniques (Coakley & Long, 1990; Sauzay & Courtois, 1973; Etcheber *et al.*, 1980; Tola, 1982). Although such tracers are effective for resolving short-term sediment responses, e.g. to specific time-dependent process events such as tidal cycles or storms, they are complicated to manage and are not well suited for investigations into more long-term, time-integrated transport. Increasing interest is being focused on research using certain sediment chemical properties as tracers, e.g. incidentally-introduced anthropogenic chemical contaminants stably adsorbed or precipitated onto the fine sediments themselves. Examples of this approach are found in de Groot *et al.* (1970), Olsen *et al.* (1980), Hatcher & McGillivray (1979), Salomons & Mook (1987), Holm & Windsor (1990), Coakley & Poulton (1991), Brown & Wade (1984) and Eaganhouse & Kaplan (1985). The above studies conclude that fine sediments can be effectively traced by analysis of the spatial concentration patterns observed in the more conservative and source-specific of the contaminants present in the sediments.

A newer approach involves the use of ratios of key stable isotopes found in sediment organic matter, especially  $^{13}\text{C}$  and  $^{15}\text{N}$ . Stable isotope ratios have been used previously to identify the contribution of various sources of material in marine systems (Peters *et al.*, 1978; Sweeney *et al.*, 1980; Cifuentes *et al.*, 1988; Lucotte, 1989). Although organic matter itself is not conservative in aquatic systems, and its isotopic composition is known to be altered by diagenesis (Eadie & Jeffrey, 1973), ratios between these isotopes, especially in the refractory organic carbon fraction, can be regarded as conservative and related to specific broad source groupings. Because of the distinct isotopic signatures of terrestrial, aquatic, and anthropogenic sources, these ratios can be used to identify isotopically well-defined source end-members and thus interpretable transport gradients.

The prime objective of this study is to test and evaluate the use of selected organic components as indicators of intermediate- to long-term

sources and transport patterns of contaminated sediments. The chemical markers tested are the faecal sterol, coprostanol;  $\alpha$ -tocopheryl acetate ( $\alpha$ -TA); selected hydrocarbon species (n-alkanes); and ratios of stable isotopes of carbon and nitrogen. Initial test results are presented with respect to two known contaminant sources in Humber Bay, Lake Ontario, near Toronto: the Humber River and the Humber Sewage Treatment Plant (STP) (Fig. 1). Investigations by the Ontario Ministry of the Environment (Persaud *et al.*, 1985) showed that considerable areas of the bottom sediments in this area were contaminated to a greater or lesser degree by heavy metals, nutrients, bacteria, and solvent-extractable organics. Sediment-water dynamics in Humber Bay are complex and attempts at mathematical modelling of sediment transport have had little success. It was hoped that the tracers described below would provide a useful, though qualitative, insight into contaminated sediment transport.

#### *Study area*

Humber Bay forms a large embayment of north-western Lake Ontario immediately west of Toronto Harbour (Fig. 1). It receives water and sediments primarily from the Humber River (average daily discharge for 1987:  $1287 \text{ m}^3 \text{ s}^{-1}$  (Environment Canada, 1988); average annual suspended load  $87000 \text{ tonnes } \text{y}^{-1}$ ), which drains a  $900 \text{ km}^2$  watershed with a large urban, industrialized component. In addition, it is the site of the submerged outfall from the Humber STP which has an average discharge volume of  $5 \text{ m}^3 \text{ s}^{-1}$ , and carries a total of  $3700 \text{ tonnes } \text{y}^{-1}$  of suspended sediments into the Bay (W. Salib, Metropolitan Toronto Department of Works, pers. comm., 1990). Other relatively minor drainage inputs are via Mimico Creek to the west, the Western Gap of Toronto Harbour, and a number of storm sewer outfalls along the intervening shoreline. The surficial bottom sediments of Humber Bay, mapped using a combination of bottom sampling and echo-sounding, are presented in Fig. 2), and consist of the following general types:

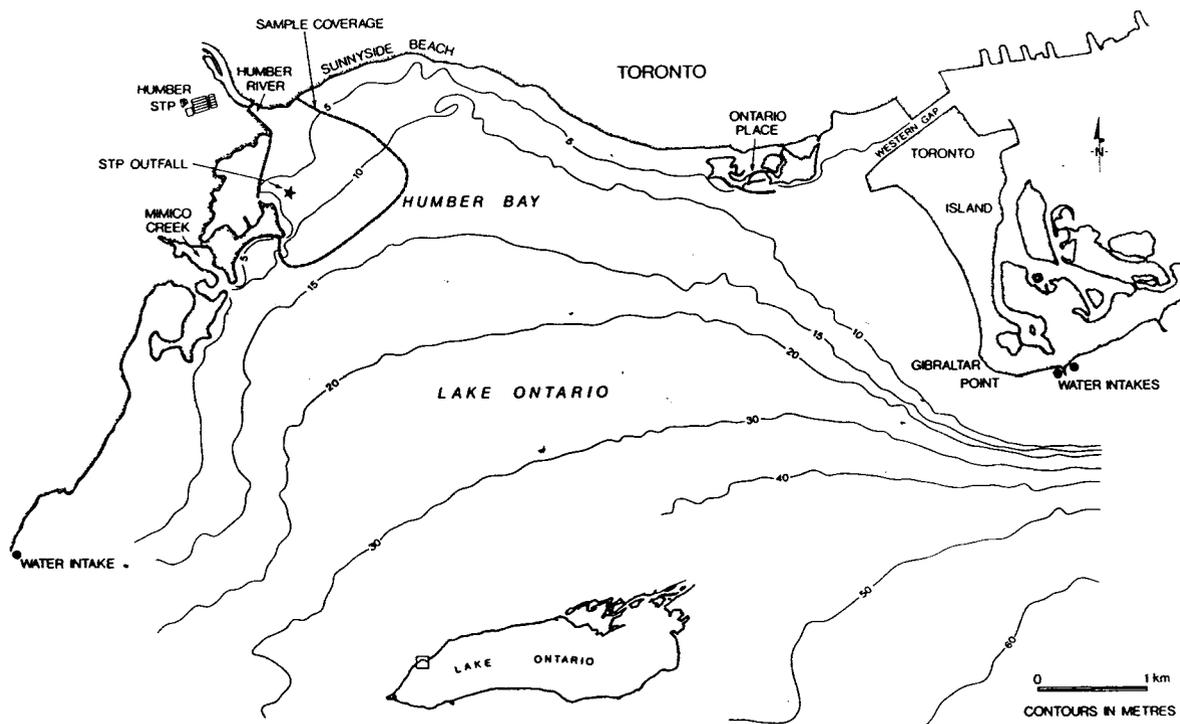


Fig. 1. Humber Bay area, just west of Toronto Harbour, showing mouth of the Humber River and the Humber Sewage Treatment Plant (STP), two major contamination sources. Nearby clean-water areas are the Sunnyside Beach and water intakes shown on the map. Study area around STP outfall is shown enclosed in heavy dashed line.

**Modern sediments.** These sediments comprise two main types: soft clayey silts in the central and offshore Bay areas, including most of the study area, and a narrow border of better-sorted sandy materials along the shore. Well-sorted sands are also found occasionally as lag deposits on the till in the offshore areas.

**Glacial and older deposits.** These deposits occur below the modern sediments and comprise glaciogenic sediments (dense-clay-rich glaciolacustrine sediments or till) and bedrock (dark grey Dundas shale). The glaciogenic deposits overlie the bedrock, and outcrop primarily in the western and central portions of the area, and in a small area west of Toronto Harbour.

### Experimental details

The sediment samples used in this investigation formed a part of two surveys (carried out in June

and September of 1987) along radial grids centred on the mouth of the Humber River and covering also the area around the Humber STP outfall (Fig. 1). To ensure only the modern sediment was analyzed, the sediment collected was limited to the top 1 to 2 cm, and to minimize the effect of the relatively inert, quartz-rich fraction, the samples were passed through an 88  $\mu\text{m}$  sieve prior to analysis. Twenty-three samples from the June survey, all collected within a radius of approximately 1 km of the outfall (Fig. 3), were submitted for determination of sewage-related organic compounds. The specific organic compounds determined were those associated in the literature with sewage-contaminated sediments: coprostanol (Hatcher & McGillivray, 1979; Holm & Windsor, 1990),  $\alpha$ -TA (Eganhouse & Kaplan, 1985), and the n-alkane hydrocarbon fraction (Brown & Wade, 1984).

After freeze-drying, the samples were Soxhlet-extracted with dichloromethane (DCM). The

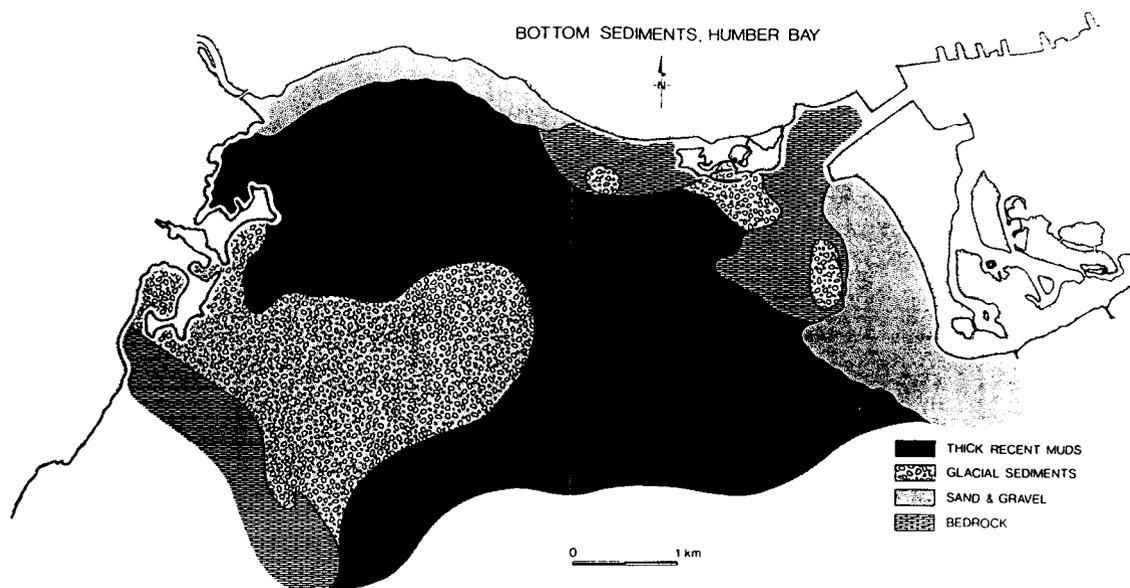


Fig. 2. Bottom sediment types, Humber Bay.

extracts were then reduced in volume and transferred to iso-octane by repetitive evaporation, followed by fractionation using a silica gel column and consecutive elution by four solvent mixtures (Nagy *et al.*, 1986). Fraction 1, analyzed for the n-alkanes, was produced by elution of the column with hexane. Fraction 2 was obtained by elution with 30% DCM in hexane; this fraction was analyzed for coprostanol and  $\alpha$ -TA. The analysis was done using capillary gas chromatography and flame ionization detectors. Confirmation of selected extracts was carried out later by mass spectrometry.

Another suite of 30 samples from the September survey, covering the area around the outfall, were selected for determination of carbon and nitrogen stable isotopic composition. Sediment samples were prepared for isotope analysis by a modified Dumas high temperature combustion. The sediments were ground and  $\text{CaCO}_3$  removed by adding 1 N HCl, shaking overnight, and drying in an oven at  $60^\circ$ . Dried samples were placed in 9 mm Vycor tubes (pre-combusted at  $900^\circ\text{C}$  with CuO) and Cu wire was added. The tubes were evacuated and flame-sealed, then combusted at  $900^\circ\text{C}$  for 2 hours, then cooled to

$600^\circ\text{C}$  for 2 hours. The latter step was included to reduce the oxides of nitrogen to  $\text{N}_2$ .

Stable isotope ratios were calculated as follows:

$$\delta\text{C}^{13}(\text{‰}) = \left( \frac{\text{C}^{13}/\text{C}^{12}\text{ sample}}{\text{C}^{13}/\text{C}^{12}\text{ standard}} - 1 \right) * 1000$$

with an analogous formula for nitrogen. Standards are PDB for carbon and air for nitrogen. Precision (1 standard deviation) for triplicate analysis of split samples was 0.1 per mil for C and 0.2 per mil for N.

To evaluate the effect of grain size on the above contaminant concentrations, 36 of the September samples were analyzed for grain-size at 0.5 phi intervals, using a combined SediGraph/sieve technique.

## Results

### *Data treatment and analysis*

The results of the analyses were expressed in concentrations per unit dry sediment, in the form of either  $\mu\text{g g}^{-1}$  (organic compounds) or per mil

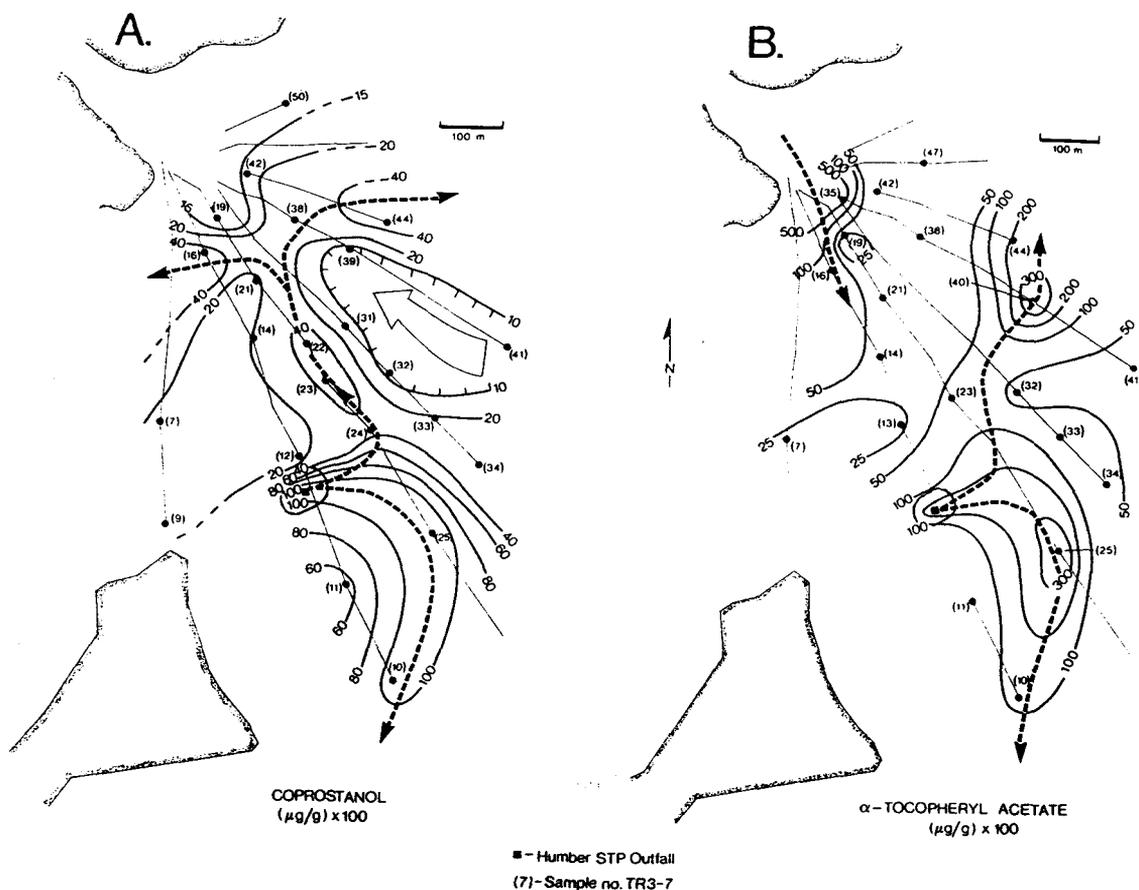


Fig. 3. Transport trends interpreted from distribution of (A) coprostanol and (B)  $\alpha$ -tocopheryl acetate ( $\alpha$ -TA). High  $\alpha$ -TA values near Humber River suggest a possible secondary source there. June 1987 radial sampling grid and locations of samples analyzed are also indicated. Sample numbers shown in brackets are cross-referenced to Table 1.

(isotopic ratios). The spatial distribution of these values was analyzed by plotting their position on a map of the study area followed by careful hand-contouring. Transport directions of the marker chemicals were then inferred based on the assumption that the source coincided with the location of maximum values. The inferred net transport directions (shown as dashed lines) were drawn along identifiable plumes of higher values extending from the source in a coherent fashion. Although the approach is qualitative, and does not take into account perturbations in the sediment concentrations due to processes such as mixing or uptake and transformations by benthic organisms, it should be sufficient to resolve net transport trends.

#### *Faecal matter indicators (June 1987)*

The distribution of concentrations of coprostanol and  $\alpha$ -TA in the local sediments is listed in Table 1 and plotted in Fig. 3. The peak value for coprostanol ( $1.13 \mu\text{g g}^{-1}$ ) occurs less than 200 m southeast of the STP outfall. These values are of the same magnitude as those reported by Brown & Wade (1984) and Holm & Windsor (1990), but far less than those obtained by Dureth *et al.* (1986). For  $\alpha$ -TA, although values near the STP outfall were relatively high ( $3.2 \mu\text{g g}^{-1}$ ), the maximum values (up to  $6 \mu\text{g g}^{-1}$ ) were near the Humber River mouth.

Interpreted transport patterns with respect to presumed sources are indicated in Fig. 3. The

Table 1. Concentrations of coprostanol, alpha-tocopheryl acetate, and n-alkanes in bottom sediments from Humber Bay, Lake Ontario (June 1987 survey). Units are in  $\mu\text{g g}^{-1}$  dry sediment. The modified Carbon Preference Index (CPI) is also shown. Transformed values are plotted in Figs 3 and 4.

Sample	Coprostanol	$\alpha$ -TA	n-alkanes		
			Total	n-16 to n-21	CPI (mod)
TR3-6			4.4	2.16	1.2
TR3-7	0.17	0.24	4.6	1.82	1.2
TR3-8			2.8	1.02	0.9
TR3-9	0.15		19.2	3.33	1.1
TR3-10	1.12	1.54	46.6	19.31	1.1
TR3-11	0.61	0.71	87.1	30.54	0.5
TR3-12	0.12		39.6	17.23	1.2
TR3-13		0.21	11.3	2.69	1.0
TR3-14	0.20	0.47	14.4	4.61	1.0
TR3-16	0.46	0.67	4.7	1.70	1.1
TR3-17			2.7	1.03	1.7
TR3-19	0.14	0.16	10.4	2.07	0.9
TR3-21	0.19	0.37	14.4	3.66	1.3
TR3-22	0.47		6.8	2.90	1.1
TR3-23	0.44	0.56	15.0	5.21	1.1
TR3-24	0.38		18.7	6.49	1.2
TR3-25	1.13	3.21	23.6	6.75	1.1
TR3-31	0.11		8.2	2.94	1.1
TR3-32	0.08	0.45	4.4	1.85	1.3
TR3-33	0.21	0.75	16.1	7.01	1.1
TR3-34	0.29	0.53	15.2	4.35	1.1
TR3-35		6.03	2.0	0.77	0.5
TR3-38	0.27	0.33	10.0	3.64	1.0
TR3-39	0.09		6.7	2.80	1.2
TR3-40		3.59	5.3	2.26	1.1
TR3-41	0.06	0.22	6.80	2.13	1.2
TR3-42	0.18	0.34	4.3	1.88	1.2
TR3-44	0.48	2.09	10.6	3.16	1.0
TR3-47		0.38	2.8	1.28	1.60
TR3-50	0.14		9.90	7.13	1.10

pattern for coprostanol is characterized by a main trend (high values) eastward from the STP outfall, then southward and parallel to the west side of the Bay. A secondary trend is noted in the opposite direction, i.e. toward the north and curving both west and east. For  $\alpha$ -TA, assuming the STP outfall as the main source, the interpreted main trend is similar to that inferred from the coprostanol data, but the secondary northward trend shows no westward transport. The high values near the river mouth could indicate a second-

ary source in the Humber River area; thus a southwardly directed local transport from that source can be interpreted.

#### *N-alkanes and PAH's (June 1987)*

Total alkane concentration and that of the particle-associated n-16 to n-21 fraction are also presented in Table 1. Also shown is the Carbon Preference Index (CPI), the ratio of the amount of odd- to even-hydrocarbons present in the sample, used to indicate the source of the organic matter (whether terrestrial, or aquatic) (Holm & Windsor, 1990). Values for total and partial (n-16 to n-21) alkanes reach 87 and  $30 \mu\text{g g}^{-1}$ , respectively, 100 m south of the STP outfall. One high outlier value is located just east of the Humber River mouth. In general, the analysis results do not allow a clear identification of a terrestrial-source signature based on the CPI. However, relative abundance of the n-alkane fractions shows that petroleum-related alkane fractions were dominant, suggesting inputs from internal combustion vehicles, either directly by boat motors, or indirectly by road run-off into the storm sewers and to the STP outfall. Therefore, because of the large number of storm sewer outfalls along the shore, and the importance of surface runoff in the Humber River watershed, there is no way of unequivocally identifying a point source for these contaminants.

The partial n-alkane distribution (Fig. 4), however, produces interpreted transport trends that are in good agreement with those resulting from the faecal indicators. Assuming the STP outfall as the main source, the patterns are characterized by a dominant southern transport, with a secondary northward trend which curves east in the central section of the area.

#### *Carbon and nitrogen ratios (September 1987)*

The results of the isotope ratio determinations are summarized in Table 2. Values range between  $-23.50$  and  $-26.60$  per mil for  $\delta^{13}\text{C}$ , and between

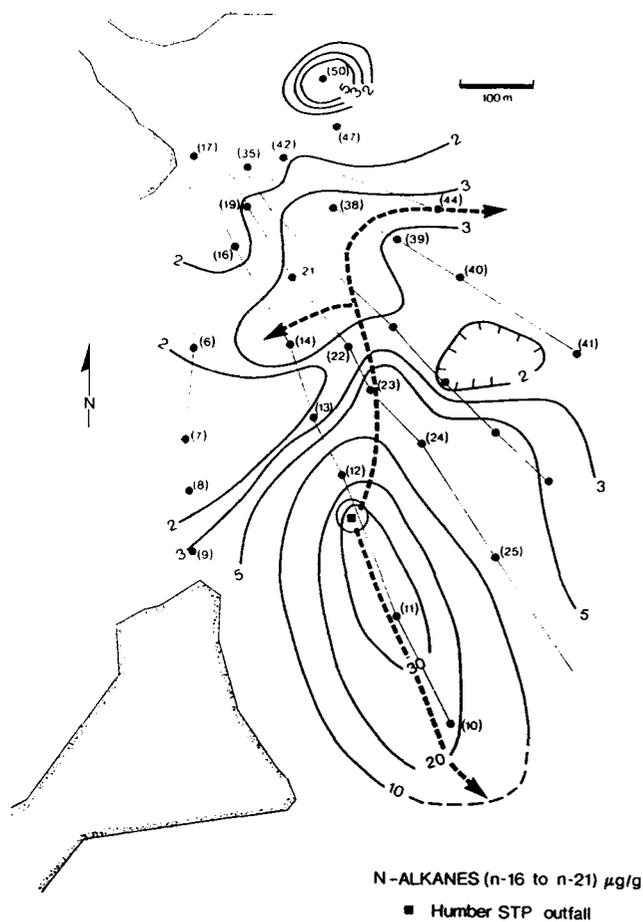


Fig. 4. Net transport patterns interpreted from the partial n-alkanes data. June 1987 sample points are shown as solid dots, and the bracketed sample numbers cross-referenced to Table 1.

+0.6 and 7.9 per mil for  $\delta^{15}\text{N}$ . Total organic carbon contents are also shown, and range as high as 2.28%. In order to enhance the visual contrast of the contour plots, especially those for  $\delta^{13}\text{C}$ , the results were first transformed as follows: the average ratio value was subtracted and the residual was multiplied by 10. This transformation using a constant clearly had no effect on the relationship between the values. The plots of the spatial distribution of the transformed data (Fig. 5) indicate that the sewage outfall is a clear source of heavy ( $^{13}\text{C}$  and  $^{15}\text{N}$  enriched) carbon and nitrogen). The open lake has a C isotopic signature that is considerably lighter (more negative) than the sewage outfall. The same holds

Table 2. Determinations of stable isotope ratios for carbon and nitrogen in bottom sediments, Humber Bay. Organic carbon and median phi size also shown (September 1987 survey). Transformed values are plotted in Figs 5 and 6.

Sample	$\delta^{13}\text{C}$ per mil	$\delta^{15}\text{N}$ per mil	Organic carbon %	Median phi. $\emptyset$
TR4 1-3	-25.90	0.60	0.93	3.64
TR4 1-4	-25.10		1.03	6.37
TR4 1-5	-24.75	1.90	1.39	6.89
TR4 2-1				7.01
TR4 2-3	-24.60	4.90		5.87
TR4 2-4	-23.50	7.80	2.10	7.29
TR4 2-5	-24.30	6.30	1.36	7.17
TR4 2-6	-24.80	3.30	2.28	6.72
TR4 2-7	-25.40		0.99	3.41
TR4 2-8	-26.10	2.60	0.57	3.48
TR4 3-1	-26.10	4.00		7.01
TR4 3-3	-25.60	1.80	0.76	6.39
TR4 3-4	-25.80		1.30	6.69
TR4 3-5	-25.80	2.20	1.50	6.47
TR4 3-6	-25.70		1.90	6.80
TR4 4-3	-25.60		0.81	6.45
TR4 4-4	-26.30		0.99	5.77
TR4 4-6	-25.40		0.91	6.09
TR4 4-7	-24.40		0.38	2.96
TR4 4-8	-25.90	2.60	0.19	2.91
TR4 5-1	-25.90			6.99
TR4 5-2	-26.11	2.70		6.93
TR4 5-3	-26.30	4.20	0.81	5.90
TR4 5-4	-26.60		0.38	3.07
TR4 5-6	-24.80	2.00	0.52	5.28
TR4 5-7				6.10
TR4 6-1				6.79
TR4 6-2	-25.40	1.90		6.55
TR4 6-4	-24.70	2.30		6.34
TR4 7-1	-26.30	2.60		6.64
TR4 7-2	-26.10	2.60		6.57
TR4 7-3		2.00		5.02
TR4 7-5	-25.93			2.36
TR4 8-1	-26.30	1.80		5.70
TR4 8-2	-24.20	1.80	2.11	6.41
TR4 8-3	-24.00		2.23	6.88

true for the N isotope ratios, although in this case the lightest values are associated with the Humber River. Runoff of common fertilizers, characterized by N-isotope values of 0 per mil could explain this association.

The differences between sewage outfall and offshore/river sediments (2 per mil for C and 8 per mil for N) provides a clear and distinct separation

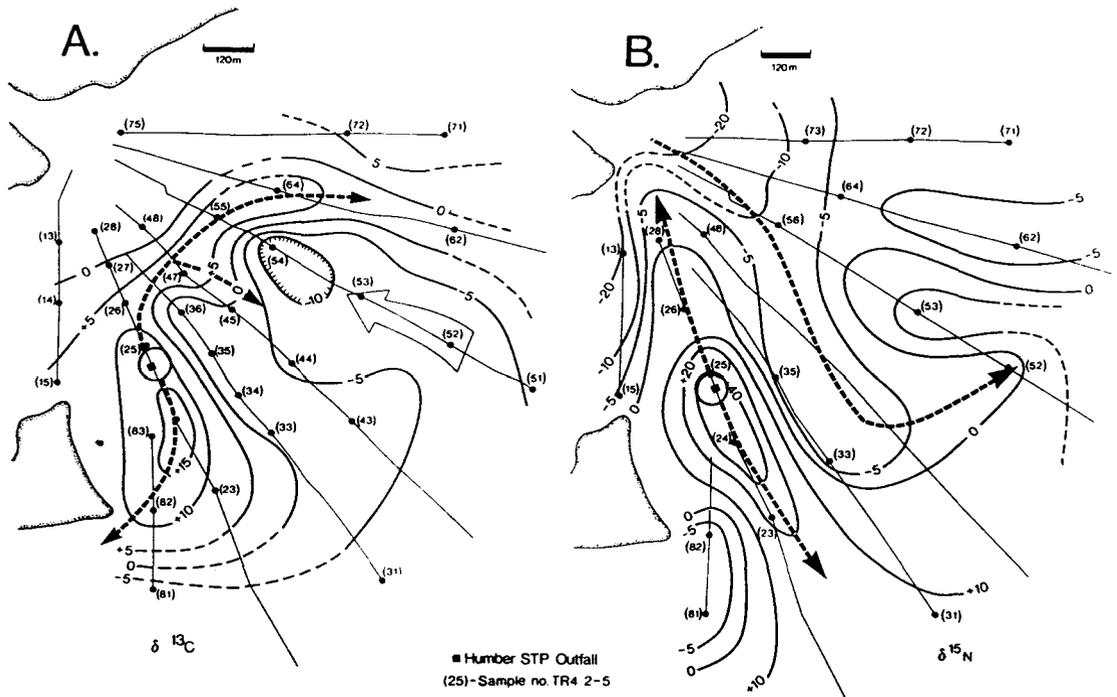


Fig. 5. Distribution and interpreted transport patterns using transformed residual values of  $\delta^{13}\text{C}$  (A); and of  $\delta^{15}\text{N}$  ratios (B). September 1987 sampling points are shown as solid dots. Sample numbers shown in brackets are cross-referenced to Table 2.

that can be used to infer the mixing and qualitative dispersal patterns of these sediment pools (Fig. 5). The main trend inferred from the  $\delta^{13}\text{C}$  values is toward the south, with an apparent swing toward the west. Also apparent is a more secondary trend northward which also eventually curves eastward. The northward-trending trough of low values (associated with open-lake organic carbon inputs), located in the east-central part of the figure, is interpreted as indicating a landward return flow, most likely in the epilimnion. The  $\delta^{15}\text{N}$  ratio distribution is markedly different from that for carbon, and shows a distinct southward plume of isotopically lighter values apparently linked to the Humber River. The heavier outfall-related nitrogen defines a plume trending both southward and northward from the outfall.

#### *Median grain-size (September survey)*

Median phi ( $\phi$ ) grain size values of the surficial bottom sediments based on the September survey

are listed in Table 2, and the distribution is plotted in Fig. 6. There is no apparent association with the STP outfall; rather the Humber River is indicated as the major source of the relatively coarse (fine sand to coarse silt) sediments. This result indicates that grain-size was not an important factor in the distribution of the STP-source tracer components. The plotted and contoured size data provide, however, another good transport pathway indicator (dashed line) for sediments emanating from the Humber River and passing to the east of the STP outfall.

#### *Synthesis of net transport patterns*

The spatial distributions and the inferred net transport patterns described above are characterized by considerable variability in direction. This is to be expected in that the transport responds to a variety of transient process regimes, and thus transport pathways vary with time. Also, the various tracers used might have undetermined

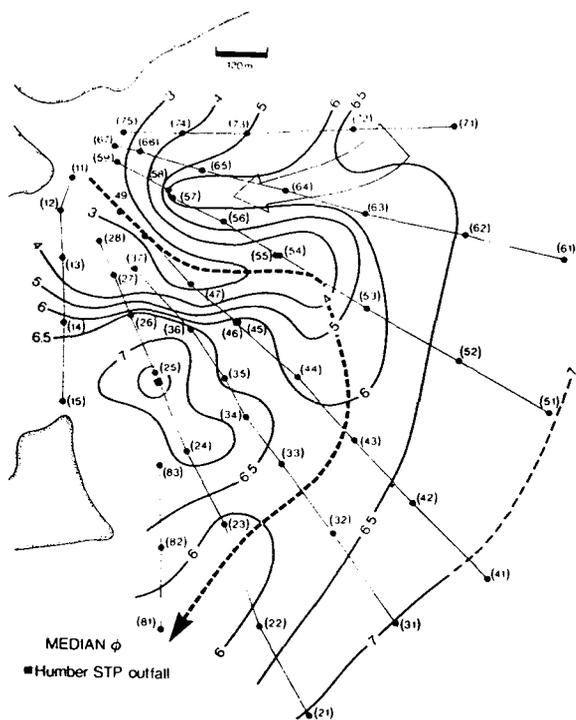


Fig. 6. Median particle size (phi units) of bottom sediments in the study area (September survey). September 1987 sampling points are shown as solid dots. Sample numbers shown in brackets are cross-referenced to Table 2.

fractionation characteristics, associated with sediment size, density, or nature of organic matter, to name a few. Despite the variability inherent in the multi-tracer approach used, there is enough consistency in the interpreted patterns to draw some reliable conclusions on net fine sediment transport. Fig. 7 presents the combined directions inferred from the five different tracers used. The dominant transport direction from the STP outfall, based on defined plumes of higher values, is toward the south, down the nearshore slope. The concordance with the major direction of silt from the Humber River (see below) indicates that this southward trend corresponds to transport in the hypolimnion near the bed, possibly during stratified conditions. A secondary trend is directed toward the north, consistently showing a curving toward the east, and (in the case of coprostanol), toward the west. The distribution patterns also suggest a landward (northwestward) transport in

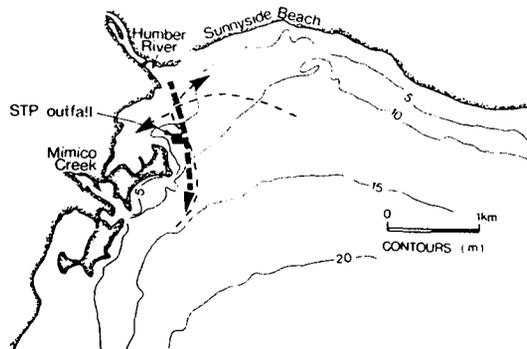


Fig. 7. Synthesis of sediment transport patterns based on the combined tracer results. Heavy dashed lines denote likely near-bottom transport mode (bedload); lighter lines denote likely directions of transport in upper water column (suspended load).

the area northeast of the STP outfall, characterized by the predominance of isotopically light organic matter and minimum values for the two faecal contaminants. This opposition of inferred transport directions is concluded too consistent to be an artifact of the tracer approach itself, and is believed to be caused by sediment inputs from less-contaminated, compensating epilimnetic flows during periods of thermal stratification. The variable direction of the flows closer to shore is not surprising, as they are known to be highly responsive to wind direction.

The net transport patterns can be tested further against the results of another study in the area using an artificial cesium-based tracer (Coakley & Poulton, 1991), in addition to the above-mentioned median grain-size indicator (Fig. 7). Figure 8 shows transport directions interpreted from distribution patterns of the cesium tracer, corresponding to the June and September surveys. These tracers were focused on the Humber River as principal source, and like the grain-size tracer pattern, they also indicate a dominant southward transport, eventually curving west. The absence of a northward component in these data is most likely due to the fact that the transport mode favoured by these relatively coarse sediments is bedload, in contrast to the largely suspended load pathway most characteristic of the highly organic STP outfall sediments.

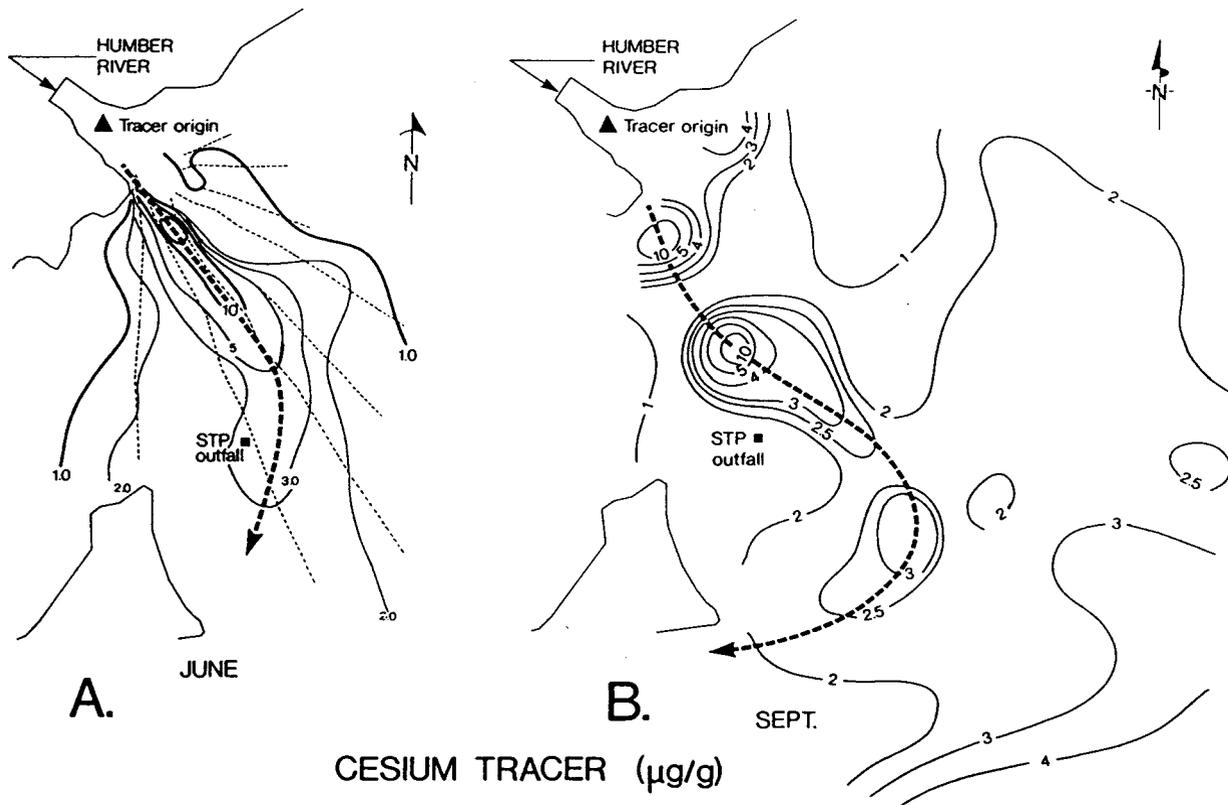


Fig. 8. A. Cesium-tracer dispersal pattern for the June/87 survey. B. Cesium-tracer results for September survey. Breakup of the tracer pattern is due to sediment concentrations approaching detection limits.

## Conclusions

Although the marker chemicals analyzed are not all conservative (some decompose at fairly rapid rates), their relative concentrations in the bottom sediments appear to be controlled primarily by dilution and distance from the source. This report confirms their effectiveness as indicators of dispersal patterns of sewage-contaminated sediments discharged on a continuing basis.

The clearest transport patterns were obtained from coprostanol, which showed a primary transport direction from the STP outfall southward and parallel to the west side of the Bay. However, the plume also showed a secondary trend in the opposite direction, i.e. toward the north and curving northwest and northeast. This result thus indicates that effluents from the STP do, in fact, move northward under undefined process re-

gimes. A similar trend was obtained for  $\alpha$ -TA, but without the northwest extension. The high values for  $\alpha$ -TA near the Humber River mouth suggest that the river could also be an important source of  $\alpha$ -TA (and probably associated faecal contamination), and raises questions as to the assumption of a sole source (the STP outfall) for this constituent. A similar problem of ambiguous source affected the use of the n-alkanes as STP outfall tracers; the CPI was not conclusive as to whether the hydrocarbons were terrestrial or aquatic in origin. In any event, the distribution of the values does suggest that the STP is the dominant source for the n-alkanes, and the interpreted net transport patterns indicate a similar overall trend to that of coprostanol. The isotope ratios, though based on organic matter that is subject to diagenesis and degradation, appear to retain their source isotopic signatures, and serve as effective

sediment tracers. Spatial distribution patterns differed considerably between the C and N ratios, indicating the importance, once again, of the Humber River in the nitrogen ratio distribution. However, inferred net transport directions were compatible.

Comparison of these results with those of a tracer study on the Humber River sediment plume (carried out concurrently) shows that the STP-source tracers exhibit a greater variability in dispersal trends. Given the coarser, inorganic, and denser sediments in the river effluent compared to the more organic STP sediments, this variability can be explained by sediment transport via different modes: primarily bedload for the southward-directed Humber River silts and coarser fractions of the STP sediments, suspended load for the lighter STP fractions. Although the study did not investigate actual hydrodynamic processes near the STP outfall, a hypothesis explaining the variable directions of the trends is that, depending on effluent temperature and relative density, the included sediment could be either transported in the epilimnion (buoyant plume) or in the hypolimnion (sinking plume). The end result would be that material from the same source might be advected along with either of two vertically separate water masses, depending on conditions of outflow, and thus may sometimes travel in widely divergent directions. Although further testing is necessary to confirm this model, it serves also to explain the clearly opposite main transport direction (southward) indicated for the Humber River tracers.

The above results, though qualitative and integrated over a fairly long time-frame, indicate the complexity of the sediment transport processes in the study area. They suggest that any attempt to quantify the transport of contaminated fine sediment there must take into account factors such as thermal stratification and seasonal changes in the circulation-forcing processes.

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