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NWRI Contribution No. 90-03

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## MANAGEMENT PERSPECTIVE

Fine-grained sediments comprise the bulk of the sediment entering the Great Lakes and St.Lawrence River ecosystem. Because of industrial and agricultural activities, especially in the more downstream parts of the above system, these sediments have become contaminated to a greater or lesser degree by man-introduced chemicals. Although contaminated sediments are gradually removed from the system by final burial, they first pass through a dynamic cycle of interim deposition and resuspension during which they could release their contaminant burden and thus cause concern for water management. An important issue, therefore, is their net pathway through the physical environment, and the rate at which they are transported and buried. As a first step in developing techniques to address this problem, a variety of different tracer approaches was tested to determine patterns of transport for sediment entering Humber Bay (immediately west of Toronto Harbour) from the harbour and several other sources. The results of the study are thus especially relevant to eventual Remedial Action Plans for Toronto Harbour, one of the IJC-designated areas of concern for contaminated sediments in the Great Lakes, as well as to the Lake Ontario Management Plan.

Of the techniques used, the best resolution was obtained using the chemical tracers: artificially-injected into the system, or incidentally introduced by industrial processes and adsorbed onto the particles in the water column. For sediments entering from the Humber River, the main tributary stream, distinct transport patterns were obtained using an artificial silt-sized tracer containing cesium, and also using the existing distribution pattern of cobalt around the river mouth. Both these techniques indicated a predominant direction initially toward the south, then turning southwest. The sediments derived from the outfall of the Humber Sewage Treatment Plant (STP) in the western part of the Bay were effectively traced using the concentrations of coprostanol and $\alpha$-tocopheryl acetate. These tracers indicated a more variable transport, with an important northward and northeast, in addition to the dominant south-to-southwest trend. The data are insufficient, however, to determine whether this northward trend poses a problem to Sunnyside Beach to the north. A multivariate statistical technique (cluster analysis of a number of routinely collected sediment chemical parameters) supported the above dominant trend to the south and southwest in the western part of the Bay, but was more equivocal in the eastern part near the Western Gap entrance to Toronto Harbour. The other techniques tested, namely the grain-size-related parameters, showed a lower resolution, mainly because of the obscuring effect of glacial sediments on the size trends. The relatively high level of variability noted in all the transport directions deduced could be a reflection of both the need for denser sample coverage, as well as of the inherent complexity of the transport processes, where seasonal wave and current patterns, thermal lake stratification, and variability of particle grain-size all are important factors.

# PERSPECTIVE DE GESTION

Les sédiments pénétrant dans l'écosystème des Grands Lacs et du fleuve Saint-Laurent sont principalement des sédiments à grains fins. En raison des activités industrielles et agricoles, surtout dans les parties aval de cet écosystème, ces sédiments ont été plus ou moins contaminés par des produits chimiques introduits par l'homme. Bien que les sédiments contaminés soient progressivement retirés du système par enfouissement final, ils passent d'abord par un cycle dynamique de dépôt provisoire et de remise en suspension pendant lequel ils pourraient libérer leur charge de contaminants et ainsi être préoccupants pour la gestion des eaux. Il est par conséquent important de connaître leur cheminement net dans le milieu physique et les taux auxquels ils sont transportés et enfouis. À titre de première étape de la mise au point de méthodes permettant de ce faire, une gamme d'approches utilisant des traceurs ont été éprouvées afin de déterminer les configurations du transport des sédiments pénétrant dans la baie Humber (immédiatement à l'ouest du port de Toronto) et provenant de plusieurs autres sources. Les résultats de l'étude sont particulièrement pertinents pour d'éventuels plans de dépollution du port de Toronto, l'une des zones des

Grands Lacs désignées préoccupantes par la CMI quant aux sédiments contaminés, ainsi que pour le Plan de gestion du lac Ontario.

Parmi les méthodes utilisées, celle qui a fourni la meilleure résolution a été l'utilisation detraceurs chimiques injectés artificiellement dans le système ou introduits d'une manière incidente par des procédés industriels et adsorbés sur les particules présentes dans la colonne d'eau. Dans le cas des sédiments pénétrant par la rivière Humber, le principal cours d'eau tributaire, des configurations distinctes du transport ont été obtenues par l'utilisation d'un traceur artificiel de la granulométrie du limon et renfermant du césium ainsi qu'à l'aide de la configuration de la répartition existante du cobalt autour de l'embouchure de la rivière. Ces deux méthodes ont indiqué un transport dont la direction prédominante était initialement vers le sud pour ensuite s'incurver vers le sud-ouest. Les sédiments provenant du point de déversement de la station Humber d'épuration ndes eaux usées, dans la partie opuest de la baie, ont été efficacement suivis au moyen des concentrations de coprostanol et d'acétate d'alpha-tocophéryle. Ces traceurs indiquent un transport plus variable, avec une importante composante vers le nord et le nord-est, en plus de la tendance dominante vers le sud ou le sud-ouest. Les données sont toutefois insuffisantes pour permettre de déterminer si cette tendance vers le nord du transport constitue une menace pour la plage Sunnyside située au nord. Une méthode statistique à plusieurs variables (analyse typologique d'un certain nombre de paramètres chimiques couramment relevés des sédiments) confirme la tendance dominante ci-haut mentionnée du transport vers le sud et le sud-ouest dans la partie ouest de la baie, mais a fourni des résultats plus ambigus pour la partie est, près de l'entrée Western Gap du port de Toronto. Les autres méthodes éprouvées, soient celles associées aux paramètres granulométriques, ont fourni une résolution moindre, principalement en raison de l'effet obscurcissant des sédiments glaciaires sur les tendances dérivées de la dimension des grains. Le degré relativement élevé de variabilité observé pour toutes les directions de transport déduites pourrait refléter la nécessité d'un échantilolonnage plus dense ainsi que la complexité inhérente des processus de transport influencés par d'importants facteurs comme les configurations saisonnières de l'action des vagues et des courants, la stratification thermique du lac et la variabilité de la granulométrie des particules.

## ABSTRACT

Several physical and chemical attributes of bottom sediments in Humber Bay, Lake Ontario were investigated as tracers of medium- and long-term transport patterns for fine-grained contaminated sediments entering the Bay. These are: concentrations of trace pollutants and their ratios; the spatial distribution of an artificial cesium-containing tracer material, introduced in 1987; and selected grain-size statistics. The investigation was focused on three possible point sources: Humber River, the Humber Sewage Treatment Plant (STP) outfall, and the Western Gap outlet from Toronto Harbour.

Interpretable sediment transport patterns related to Humber River were obtained for the cesium tracer, as well as for cobalt originating upstream in the Humber River watershed. Transport patterns related to the outfall of the Humber STP were obtained for sewage-related organic substances: coprostanol and $\alpha$-tocopheryl acetate. Spatial zonation based on cluster analysis of chemical data from the Ontario Ministry of the Environment sediment survey of 1979 resulted in distribution patterns which appeared to be related both to the STP outfall and the outflow from the Western Gap. Grain-size parameters, primarily mean size, also showed well-defined patterns that are apparently related to the long-term net physical processes acting on the mobile sediments in Humber Bay.

# RÉSUMÉ

Plusieurs attributs physiques et chimiques des sédiments du fond de la baie Humber du lac Ontario ont été étudiés à titre de traceurs permettant de déterminer les configurations à moyen et à long termes du transport des sédiments de granulométrie fine pénétrant dans la baie. Ce sont: les concentrations de polluants présents à l'état de traces et les rapports de ces concentrations; la répartition spatiale d'un traceur artificiel renfermant du césium introduit en 1987; et des statistiques choisies sur la granulométrie. L'étude a porté sur trois sources ponctuelles possibles: la rivière Humber, le point de déversement de la station Humber d'épuration des eaux usées et la sortie Western Gap du port de Toronto.

Des configurations interprétables du transport des sédiments associés à la rivière Humber ont été obtenues à l'aide du traceur au césium ainsi que du cobalt provenant de l'amont dans le bassin versant de la rivière Humber. Des configurations du transport associé au point de déversement de la station Humber d'épuration des eaux usées ont été dérivées de substances organiques associées aux eaux usées, le coprostanol et l'acétate

d'*alpha*-tocophéryle. Une zonation spatiale basée sur l'analyse typologique de données chimiques du relevé des sédiments effectué en 1979 par le ministère de l'Environnement de l'Ontario a produit des configurations de la répartition qui semblaient reliées au point de déversement de la station d'épuration et à l'écoulement sortant du Western Gap. Les paramètres granulométriques, principalement la dimension moyenne des grains, indiquaient également des configurations bien définies qui sont apparemment reliées aux processus physiques nets agissant à long terme sur les sédiments mobiles dans la baie Humber.

# INTRODUCTION

Most of the studies of fine-grained sediment transport published to date have relied on radioactive tracer techniques (Coakley and Long 1989, in press; Sauzay and Courtois 1973; Etcheber et al. 1980; Tola 1982). This is primarily because of the relative ease of tagging the large volumes required in such studies, as well as the ease of monitoring the tracer dispersal in real time through the use of a suitable towed detector. However such techniques have severe limitations when the goal is long-term sediment tracing, the major weakness being their relatively short duration. The tracer is selected either to decay to background (safe) levels, or to be diluted to non-hazardous levels, within a limited time. Although such tracers are effective for resolving short-term sediment responses, e.g. to a specific time-dependent process event such as tidal cycles or storms, they are not well suited for investigations into long-term, time-integrated transport. Furthermore, radioactive tracers generally require specialist intervention to tag and inject the tracer safely. Other less demanding techniques, especially those making use of parameters that are routinely collected in contaminant surveys, or can be readily collected or compiled from existing data bases, might offer advantages in such studies. A promising approach, therefore, involves the use of spatial patterns in the magnitude of physical and chemical properties of the bottom sediments as tracers of long-term sediment transport. The chemical properties may pertain either to naturally-occurring or artificially-introduced substances.

Physical sediment properties, especially those related to granulometry, have been used before as indicators of net transport patterns over extended time periods (Pettijohn and Ridge 1932, 1933; Visher 1969; McLaren and Bowles 1985). The main advantage of such an approach is that these properties are the time-integrated result of many random transport events. Grain-size parameters are used because they are closely linked to the source of the sediments and the energy of the transporting medium. Simply put, the coarser, poorer-sorted materials are usually deposited closer to the presumed source than the finer, better-sorted materials. Thus, materials entering Humber Bay from a clearly defined source such as the Humber River or the Toronto Island might show a systematic and interpretable pattern or plume with respect to that source. This approach is complicated in many parts of the Great Lakes by the mixing of sediments derived from multiple sources, and by the presence of relict, glacially-derived bottom sediments.

Chemical sediment properties, such as incidentally-introduced anthropogenic chemical contaminants, adsorbed or precipitated onto the fine sediments, have also been used successfully by various researchers (de Groot et al. 1970; Olsen et al. 1980; Hatcher and McGillivary 1979; Salomons and Mook 1987) to classify sediment deposits as to their origin. Analysis of their spatial distribution may thus allow them to be used as indirect sediment tracers because these contaminants are distributed by the same physical processes as the sediment itself. The major requirement for such an application is that the elements chosen have a predominant point source, and that they be conservative, i.e., their concentrations should not change appreciably with time because of factors other than dilution. However, because these contaminants generally vary spatially in subtle and complex ways, and because precise source definition is not always possible, sophisticated statistical techniques are often required to resolve and interpret the resulting distribution patterns. Poulton (1989) used a combination of two statistical techniques to systematically define groups of sediment samples affected by similar factors, such as transport processes or proximity to specific sources.

Finally, non-radioactive artificial tracers, either simulating, or attached to, the natural fine-grained sediment, may be used for intermediate-term studies. The study duration is limited by the length of time that the concentration of the tracer element remains above detection limits, and this depends on the dispersion intensity of the environment, the analytical resolution, and the amount of tracer injected. For maximum resolution, procedures such as Neutron Activation Analysis (NAA) are generally used for tracer concentration determination in the sediment samples, making those elements having good neutron-capture cross-sections (rare-earth elements, lanthanides) most attractive. The technique has been described in the literature by Attas (1987) and Krezoski (1989).

This report describes the use of some routinely-collected physical and chemical parameters as tracers of medium- and long-term, fine sediment dispersal in Humber Bay, Lake Ontario. Also discussed are artificial and incidental tracers aimed at resolving transport patterns related to two point sources of contaminated sediments: Humber River and the Humber Sewage Treatment Plant (STP) submerged outfall.

## PHYSICAL SETTING

Humber Bay forms a large embayment of northwestern Lake Ontario, and is located immediately west of Toronto Harbour (Figure 1). It receives water and sediments primarily from the Humber River (average daily discharge for 1987: 1287 $m^3/s$ (Environment Canada 1988); average annual suspended load 87,000 tonnes/y), which drains a 900 $km^2$ watershed with a large urban, industrialized component. In addition, it is the site of the submerged outfall from the Humber STP and a number of storm and combined storm overflow sewer outfalls. Other drainage inputs into the Bay are Mimico Creek, to the west, and the Western Gap of Toronto Harbour, to the east. A large (45 ha) shore-armoured landfill, Humber Bay Park, composed mainly of construction-derived materials, is also located immediately west of the Humber River mouth.

Investigations by the Ontario Ministry of the Environment (Persaud et al. 1985) showed that considerable areas of the bottom sediments were contaminated to a greater or lesser degree with heavy metals, nutrients, bacteria, and solvent-extractable organics from these sources, especially Humber River and the Humber STP outfall. Undetermined quantities of sediment are also supplied by dredged material disposal from the harbour entrances, as well as the erosion of the adjacent shoreline and nearshore bottom materials.

## METHODS

### Sediment types and grain-size properties

The sediment-related field data used in this study is presented in Figure 1, and consists of the following:

- 50 Shipek grab samples collected over the area in 1988, positioned using a Motorola Mini-Ranger system;

- More than 40 km of echo-sounder lines, using a Kelvin-Hughes MS26A sounder (frequency: 30 kHz).

The individual sediment samples collected in the field were taken from the ships in plastic bags to the laboratory where they were freeze-dried and subjected to particle-size analysis using the sieve/SediGraph combined technique (Duncan and Lahaie 1979). These analyses were carried out only on approximately the topmost 2 cm of the Shipek sample, in an effort to focus mainly on the modern sediment deposits and to avoid as much as possible the inclusion of the glacial sediments or bedrock below. In any event, even the surface materials at some of the offshore sites are probably residual or lag, rather than transported, deposits. These were not differentiated.

Grain-size analyses for 63 of the Humber Bay bottom sediment samples (the above 50 plus fill-in samples from previous surveys) were sent to Dr. Patrick McLaren of GeoSea Consultants of Victoria, B.C. for analysis of transport patterns. The technique used is described in the consultant's report (GeoSea Consultants 1989) and, in its original, more expanded form, in McLaren and Bowles (1985). In brief, the interpretations are based on a statistical analysis of an array of ratios generated from the grain-size frequencies, using the first three moment measures (mean, standard deviation and skewness), and results in the identification of transport-related gradients over the area of coverage.

## Cluster analysis of chemical data

Figure 2 shows the grid of bottom samples collected by the Ontario Ministry of the Environment (Persaud et al. 1985), and used here for cluster analysis. The chemical parameters compared were: total phosphorus, total Kjeldahl nitrogen (TKN), loss-on-ignition, solvent-extractable organics, and trace metals (Hg, Cd, Cr, Cu, Pb, and Zn).

The first procedure used on the data array is called "ratio matching", and was originally developed by Anders (1972). It is based on the fact that sediments of common origin will tend to have similar ratios of concentrations of trace pollutants (heavy metals, organics, etc.), whereas absolute values of these pollutants may vary widely because of dilution with cleaner or more inert materials. Comparison of these ratios between all possible pairs of individual samples yields a matrix of "similarity coefficients". These coefficients range in value downward from one for complete similarity, to near zero for highly dissimilar sample pairs; thus the similarity coefficient matrix can be regarded as a correlation matrix. The second technique used is cluster analysis. This is performed on the similarity coefficient matrix in order to discern groupings for interpreting the extremely large similarity coefficient matrix. The analysis is performed on an IBM PC microcomputer, using the SPSS-PC statistical package (SPSS 1988). In addition to visual evaluation of the distinctness of the clustering by plots of dendrograms, the level of statistical similarity or difference between the various clusters is determined afterward by a BASIC program which calculates the maximum, average, minimum, and standard deviation of the similarity coefficients for all possible cluster combinations. This technique was used to determine the most distinct clusters. Further details of the combined techniques are given by Poulton (1989). Two separate computer runs were made: one for all chemical parameters, and the other for metals plus solvent-extractable organics.

## Artificial and incidental sediment tracers

Sediment transport patterns related to two known sources of contaminated fine-grained sediment located in the western part of Humber Bay were investigated during the period May - September 1987. These sources (Figure 1) are:

- the Humber River,
- the Humber Sewage Treatment Plant (STP) outfall.

Humber River. A large quantity (230 kg) of cesium tracer was placed at the mouth of the Humber River and its spread was monitored over the next several months by three separate bottom sediment sampling surveys. The surveys consisted of taking 50 bottom samples using a Shipek grab along a radial grid centred on the Humber River mouth, and extending 1 to 2 km into the lake (Figure 1); positioning was by Mini-Ranger. In order to sample only the modern, transported, sediment fraction, only the top 2 cm of the sample was collected. Also, prior to analysis, the sample was passed through an 80 micrometer (3.5 phi) sieve in order to improve the resolution (the artificial Cs tracer was pre-sized to finer than 80 micrometers). In addition to cesium (Cs), the samples collected were analyzed for Fe, Ba, Co, Th, Cr, and Sc, using Neutron Activation Analysis (at Nordion International, Kanata, Ontario).

Humber STP. Because of the location of the STP outfall within the radial grid used for the artificial tracer study, a suite of samples was selected within a radius of approximately 1 km of the outfall and analyzed for organic compounds associated with sewage-contaminated sediments. The three organic substances selected were: coprostanol (Hatcher and McGillivary 1979), $\alpha$-tocopheryl acetate (Eganhouse and Kaplan 1985), and the n-alkene fraction (Brown and Wade 1984). The samples were prepared using the extraction procedure outlined in Carey and Hart (1986) and were analyzed by capilliary gas chromatography with flame ionization detectors. External standards were used for all components identified, and identification was confirmed by gas chromatography / mass spectrometry (GC/MS). The n-alkenes were found in fraction one and coprostanol and $\alpha$-tocopheryl acetate were found in fraction two.

## RESULTS AND DISCUSSION

### Spatial distribution of bottom sediment types

In addition to characterizing the bottom sediment distribution of an area, spatial patterns of bottom sediments can provide a preliminary indication of the general trends of sediment transport. Figure 3 shows the distribution of bottom sediment types based on the bottom-sampling and echo-sounding coverage shown in Figure 1. The sediments of the area may be sub-divided into the following general types, presented in order of decreasing area.

Modern sediments. These sediments were deposited under conditions similar to those of today, and comprise two main types: the muddy sands and sandy muds in the more offshore areas, and the narrow zones of better-sorted sandy materials bordering the shore. The areas of fine, muddy sediments are especially important because they tend to be associated with contaminant exchanges to and from the water column. The areas where mud deposition exceeds 1 m in thickness were identified by coring (Figure 1) and were found to occur primarily within an east-west band around the 10 to 15 m depth contour. Deposits in this zone may reach more than 3 m in thickness, and could define the location of a topographic low in the pre-modern nearshore surface, probably associated with the ancestral Humber River (Lewis and Sly 1971). It appears also that the thickness of these highly mobile fine sediments may vary considerably according to season, time elapsed since the last major storm, etc. Comparison with earlier surveys indicates that the mud cover periodically disappears over large areas, leaving exposed glacial sediments. This behaviour might explain some of the wide discrepancy between the distribution in Figure 3 and that of prior surveys Kindle (1925), Rukavina (1969), Coakley (1970), Lewis and Sly (1971), and Persaud et al. (1985). For instance, an area of fine sediments close to the Toronto Island sand body mapped in 1985 was not evident in 1988. This area is used as a dump site for dredged material from the Western Gap (Lewis and Sly 1971), and might be characterized by rapid export of muddy sediments. Another likely reason could be the much higher spatial resolution of the present survey.

The well-sorted sands are found primarily in a narrow inshore band east of Humber River and around the Toronto Island, although they occur occasionally in the offshore areas. However, these offshore sands could represent accumulations of lag materials derived from underlying glacial deposits.

Glacial and older deposits. These deposits were formed during earlier periods prior to modern Lake Ontario, and comprise glacial sediments (dense, clay-rich glaciolacustrine sediments or till) and bedrock (dark grey Dundas shale). The glacial deposits overlie the bedrock, and outcrop primarily in the western and central portions of the area, and in a small area west of the Western Gap (Figure 3). Bedrock also outcrops along the fringes of the glacial deposits in these areas. The distribution of the bedrock and glacial sediments appear to define topographic highs on both sides of the Bay, existing prior to modern Lake Ontario (Lewis and Sly 1971).

Interpretation of transport from sediment distributions. The direction of asymmetry in the distribution of the sandy sediments along the shore with respect to their presumed sources (Humber River, and the Toronto Island littoral drift system) suggests that the main plume for sandy sediments derived from the Humber River and shorelines to the west stays close to shore and is directed toward the east, then is transported southeastward beyond the Western Gap. It is likely that under different wave conditions, such as during occasional easterly storms, the pattern could be reversed, i.e., northwestward toward the Western Gap, and westward from that point. This view is supported by the excellent sorting measured at Stn. 41 near Toronto Island (Figure 1), indicating predominant back-and-forth transport. However, it does not appear that the latter pattern of transport is as important as the former, mainly because the abundant bedrock and glacial sediment exposure near the Western Gap, and the low dredging required to keep this passage navigable (Ken Gilbert, Toronto Harbour Commissioners, personal communication, 1989). Both factors point to low sediment accumulation in the northeastern corner of Humber Bay.

The areas of mud deposition and accumulation indicate areas where low-energy conditions predominate, thus allowing slow gravity-settling of fines from suspension. Their distribution, which is not consistently related to water depth, can thus be interpreted as corresponding to areas where currents are retarded due to the presence of features such as gyres or shear zones between water masses flowing in opposite directions.

As for the glacial sediment and bedrock areas, their distribution points to areas where resuspension and export of loose sediment (or at least non-deposition) is predominant. Therefore, these exposures are likely associated with relatively strong currents, with the net direction of sediment transport being <u>away</u> from these areas.

## Grain-size properties

Median grain size. Figure 4 shows the contour plot of median phi-scale diameters for the 50 surface bulk samples evenly distributed over Humber Bay. The main feature of the contour pattern is the large zone of fine-grained sediments (higher median values) covering most of the west-central area, and extending almost to the nearshore zone east of the Humber River mouth. This fine-grained zone is bordered to the east by a closed zone of coarser values which bifurcates in a shoreward direction toward the west (Sunnyside Beach area) and to the east (toward the Western Gap). Another noteworthy feature is the salient of coarser material extending westward from both the Western Gap entrance to the harbour, and from Gibraltar Point on Toronto Island.

In interpreting sediment textural patterns as transport indicators, the basic assumption is that the particles become finer away from the source. Thus, the inferred transport gradient is from areas of high median values toward those with lower values. Although this assumption requires a knowledge of the source of the sediments, and such information is not fully known for this area, the tentative interpretation can be made that the major source of the transported sediments is in the wave-eroded nearshore zone, either as point sources (Humber River or the Western Gap), or as diffuse sources (shore and bottom erosion).

Thus, the coarser materials in the areas mentioned above are being transported alongshore and eventually offshore. The patterns made by the contours of the median size values show salients and depressions whose orientation can be used to infer direction of offshore transport. These patterns are shown as dashed arrows in Figure 4 and 5, and indicate that offshore transport proceeds mainly from the central portion of the Humber Bay inshore zone, and near the Western Gap. The distribution of the fines is more difficult to integrate into an overall transport pattern. These areas show closed contours and are not linked with salients indicating nearshore sources. This prompts the conclusion that the areas of finer median values indicate deposition of materials transported to those locations in a manner different from that of the coarser-median deposits, probably as suspended load within the water column, and that these materials are deposited only in areas where transport conditions stagnate or flocculation occurs. The larger closed fine-median areas thus support the view stated earlier that they could be related to features such as gyres or shear-zones in the nearshore circulation system.

<u>Sand and gravel percentages</u>. The picture presented by the plotted distribution of sand+gravel percentages (Figure 5) reflects the overall trends visible in the coarser median grain-size values.

The close resemblance of the sand+gravel plot to that of the median size is not unexpected, as both are directly related to the nature of the source of the sediments and to the intensity and directions of bottom currents. There are several major highs located offshore in the central and extreme southwestern sections of the Bay, and off Gibraltar Point. The salient patterns formed thus suggest a connection between assumed nearshore point-sources and these offshore areas, and thus, an interpreted direction (shown as dashed arrows in Figure 5). The interpretation of these patterns, however, suffers from the fact that the source of the coarser material (sand+gravel) can be offshore (the subaqueous erosion of the exposed till and the release of lag coarse materials) or littoral (shore erosion and point-sources). Until we determine which source is predominant, the arrows shown can easily be drawn in the opposite direction, i.e., showing shoreward transport. However, the evidence from the median-size plot supports the former interpretation.

Higher grain-size statistics as transport indicators. The estimated transport pattern provided by GeoSea Consultants (1989) is reproduced in Figure 6. The dominant trend noted was east-to-west in the inshore areas (sand transport), and a reversed east-to-west trend offshore (mud transport). However, the amount of samples used were judged to be "inadequate to establish sediment trends that follow strict statistical criteria" (GeoSea Consultants 1989), and caution was advised in applying the transport patterns. Normally, 50 samples would have been adequate, so the need for more samples must be due to the common presence of glacially-derived sediments, which tended to obscure the transport trends. Nevertheless, the interpreted transport patterns (Figure 6) are included mainly to illustrate another approach using grain-size parameters as transport tracers.

Cluster analysis of chemical data. Of the two types of comparison used (all chemical parameters, and metals plus solvent-extractable organics), the one for all chemical parameters, and using the complete linkage technique, showed better definition. The dendrogram for this run is shown in Figure 7, and the four best-defined clusters are shown coded and plotted in Figure 8.

The plot of the main cluster groupings shown in Figure 8 could also have been improved by more samples. Another factor making interpretation difficult is the uncertainty in identifying the sources of the clustering factors. However, assuming that the sources of the properties most instrumental in the clustering of these samples are the Humber STP (Group 1) and the Western Gap (Group 2) the patterns deduced can be interpreted and compared with those from the other lines of evidence.

The clearest transport pattern inferred from the cluster analysis is that of Group 1, apparently related to the Humber STP outfall. The pattern shows a definite southward trend initially, gradually curving toward the west in the offshore areas. This trend is in good agreement with that deduced by GeoSea Consultants (Figure 5).

The distribution of Group 2 (Western Gap) sediments is not as well defined as that of Group 1. The dominant trend, however is toward the east, but the pattern is apparently restricted to the western side of Toronto Island. The location of the single Group 2 sample several kilometres to the west could be interpreted as indicative of a secondary westward transport trend, however this interpretation needs further verification. To a certain extent, the bi-directional transport inferred for Western Gap (Group 2) sediments is consistent with that interpreted by GeoSea Consultants for inshore sediments (eastward), and for fine-grained sediment in the offshore areas (westward). The transport patterns interpreted could be explained by current reversals which have been documented in this area (Kohli 1986). The clustering of Group 2 samples west of Toronto Island suggests the presence of restricted circulation (gyres?) in the leeside of the Island.

Interpretation of source-specific tracers.

These patterns were derived from the artificial and incidentally-tagged tracer studies related to the Humber River and the Humber STP outfall.

Humber River transport pattern. Of the seven potential tracer elements analyzed by NAA, only Cs and Co produced distribution patterns that were visibly related to the Humber River mouth. The concentration contour plots for the three separate surveys are presented in Figures 9 and 10.

The Cs tracer plume was readily detectable, even at the time of the last survey in September, i.e, over a period of more than four months. The first survey showed a southeast flow pattern aligned with the trajectory of the river outflow. Later surveys were characterized by a noticeable shift of the centroid of the contoured plume toward the west, and a re-orientation of the plume as a whole toward the western side of the Bay. It appears that the plume direction was influenced at first by advection with the outflow of the river, but later it was more and more influenced by diffusion and advection related to the general circulation patterns within Humber Bay. Another noteworthy feature that has bearing on the duration of the tracer is the clear effect of dilution of the tracer injection site by "clean" river sediments. This is clearly visible in the distribution patterns near the mouth of the Humber River, which are characterized by highs on both sides, with a low in between, corresponding to the main river outflow.

The Co plume shows a similar overall trend as that of the Cs tracer with one interesting exception in that it bifurcates noticeably: one trend extending in a straight line southeast from the river mouth, the other shifted toward the western side like that of the Cs tracer. It is tempting to speculate that this division is due to some of the Co being transported both along the bottom as near-bed load (in the heavy mineral fraction of the coarse silt) directly out from the river, and adsorbed onto the suspended load being transported in the upper layers.

The above patterns are in general agreement with Lagrangian water motions monitored at the mouth of Humber River over periods of four months and two days, respectively, by Hunter and Associates (1985) and Gore and Storrie (1985). Both studies noted the variability in direction of the turbidity plume exiting the river. For instance, it was noted that the plume turned eastward or southeastward 52% of the time, and southward (i.e., along the west shore of Humber Bay), 30%. It should be emphasized that these observations were made from the shore and cover only the inshore and shore-adjacent water motions. As such, they support the evidence of the sediment distribution that inshore sediments generally are transported eastward. Observations made by one of the authors (JPC) and others (M. Mawhinney, NWRI, personal communication 1987) from aircraft and surface vessels on three occasions confirmed the variable plume behavior in offshore waters as well. On most occasions, however, the plume was seen to follow the western shore, and on occasion veer sharply toward the east after reaching the extremity of the Humber Bay Park. Unfortunately, concurrent measurement of waves and currents were not made, so the relationship between the hydrodynamic regime and the plume behavior is still not fully understood. In general, however, westward movement of the plume appeared to correspond with southwest-to-northwest winds and waves. It appears that off promontories, such as the Humber Bay Park, the plume then is often deflected eastward. The observations do indicate that a key process in the plume variability might be the strength and direction of the wind and wind-driven waves.

<u>Humber STP outfall pattern</u>. Of the organic species analyzed, the clearest transport patterns were obtained from coprostanol and $\alpha$-tocopheryl acetate. While all showed contour patterns compatible with dispersal from the outfall source, some high values near the Humber River suggest that it might also be a secondary source. The results for each of these two are presented in Figure 11. The most noteworthy result was that in addition to the transport direction southward and parallel to the west side of the Bay, as was noted in the Humber River tracer results, a plume in the opposite direction was evident in all the

substances, i.e., toward the north and curving northeast. There is every indication that the former plume is the dominant one; however, it appears that effluents from the STP do, in fact, move northward under undefined process regimes. This trend is important in view of the implications on clean water for swimming at the popular Sunnyside Beach (Figure 1).

In looking for an explanation for the variation in transport pattern at this site one should not overlook seasonal changes in the temperature and solids concentration (and thus the relative density) of sediment-carrying effluents with respect to the lake water. This could lead to variations in transport pathways, either in the epilimnion (buoyant plume) or in the hypolimnion (sinking plume). In the case of the STP effluent, occasional sinking plumes could also result from density increases caused by elevated concentrations of suspended particulate matter released during occasional heavy rain-storms when the STP may be largely bypassed because of excessive inflows. The end result would be that material from the same source might be advected along with either of two water masses, depending on the time of outflow, sometimes travelling in widely divergent directions.

## Synthesis of sediment transport patterns in Humber Bay.

Despite the clear limitations of the individual approaches, when used together they can contribute to identifying long-term trends in sediment transport that relate to the net effect of the transport regime over many randomly occurring events. The utility of the combined chemical tracer results is best demonstrated in the western side of Humber Bay, where the transport patterns for sediments exiting Humber River were found to show a consistent, strong net southeastward and southward trend. At the Humber STP outfall, in addition to the main southward plume, the organic compounds used as tracers indicated an important plume directed toward the north which eventually veered toward the east. This indicates clearly that the plume from the STP outfall flows northward toward the Sunnyside Beach area at times, but whether it actually reaches this popular beach area in any significant concentration could not be determined on the basis of the existing data.

The transport patterns in the other parts of the Bay are less clearly defined, due to the lack of definite point-sources of identifiable chemical tracers, as well as the lack of resolution in the other, more general techniques used. By adding to the data base some documented general observations regarding circulation patterns in the Bay, the picture is improved considerably. Examples of such observations are:

- Surface water masses enter Toronto Harbour via the Western Gap and exit through the Eastern Gap (Persaud <u>et al.</u> 1985);

- Dredging requirements for the Western Gap are low, indicating that only small amounts of sediments are deposited there, or any significant sedimentation is rapidly flushed out, presumably along the bottom.

When all the above data are considered in combination, they can be synthesized into an apparently reasonable qualitative model of net sediment transport in Humber Bay (Figure 12). In brief, the dominant net pattern for inshore sediment transport is from west to east. The coarser sediments from the Humber River are generally transported by westerly waves toward the Western Gap, where some are advected offshore with the bottom flow from Toronto Harbour. The rest continues on to the Toronto Islands where they are either deposited near the end (Gibraltar Point), or are advected offshore. This pattern reverses for winds and waves from the east, but it appears that the former model is prevalent.

The fine sediments enter the Bay from a variety of sources: shore and bottom erosion in the nearshore and shallow-water zones, and from Humber River and the Western Gap. They are carried in the upper water column and first travel parallel to the shore. Some of this suspended load is advected into Toronto Harbour. Eventually they are transported offshore and are carried along in suspension with the offshore circulation. The direction of this circulation is generally clockwise in Lake Ontario, i.e., opposite to the prevalent wave-generated longshore drift direction in Humber Bay. The presence of relatively thick deposits of fine material in close association with exposed glacial materials in the offshore areas indicates that deposition only occurs in sharply defined stagnant zones where the lake currents allow flocculation and settling-out of fines. This prompts the conclusion that gyres are important in the location of such deposition zones.

The above represents only an initial attempt to identify the net sediment transport regime in Humber Bay. Its further development must await more comprehensive studies of the physical processes driving sediment transport and deposition in Humber Bay.

## SUMMARY AND CONCLUSIONS

The various techniques applied to the problem of determining transport patterns of fine-grained sediment in Humber Bay, especially the artificial and incidental tracers, produced spatial patterns that appear credible given what is presently known about the sediment transport processes in Humber Bay. Nevertheless, many show limitations which make conclusive interpretations difficult. The grain-size-related approaches, while having the advantage of using data that are relatively easy to obtain, show rather poor resolution of patterns in areas where glacial sediments occur in close association with modern lacustrine sediments. In such cases, actively-transported sediments become mixed with relict lag sediments released by erosion of the glacial materials and thus hinder reliable transport interpretation. Even though the use of ratios of grain-size moment measures produced some statistically significant results, they must be regarded with some caution if the number of samples is low. In any event, it appears that grain-size parameters work best for the coarser materials, where a spatial relationship between deposit and source is maintained. The other general technique, namely the application of cluster analysis to routine sediment quality parameters, allowed interpretation of affinity groups of samples based on a multivariate approach, so the clusters identified are probably very reliable. However, but sources cannot be precisely defined, and so the inferred transport patterns rely heavily on corroboration by other evidence.

Individual chemical tracers apparently are more effective in dealing with fine sediments whose grain-size properties are often obscured by flocculation, and where suspended load transport takes them far from the source. The spatial distribution of incidentally-introduced chemical tracers with respect to a presumed source (Humber River and Humber STP outfall) proved to be more useful in identifying relatively long-term transport patterns, although a comprehensive knowledge of their sources and of how conservative they are is essential. The use of the artificial cesium tracer eliminates many of the above limitations and results in improved resolution. However, because of dilution and burial, it represents only a temporary source (approximately four summer months, in this case) and thus gives only a relatively short-term picture of local transport. Whether the results truly reflect year-round transport patterns remains an important question in the use of this technique. The sewage-related organic compounds proved to be excellent tracers of net long-term transport patterns of fine sediments near these STP outfalls. One major drawback would be their relatively high cost per analysis.

In summary, we believe that the variability in transport directions, indicated by the physical and chemical tracers, especially in the eastern part of the bay, is a reflection more of the complexity of the phenomenon, than an indictment of the reliability of the techniques described. Much of this variability could be due to a number of factors, such as:

- Different grain-size fractions being transported by different processes and in different positions in the water column, e.g., bedload for the sand and coarse silt, suspended load for the finer clays and organics.

- Seasonal differences in wind and wave directions, combined with shoreline irregularities, leading to variability in longshore drift or lake circulation processes. These seasonal effects should be minimized in the net transport results, however, as all the techniques used integrated samples covering the top 2 cm (several years' accumulation). However in some sheltered areas such seasonal differences could persist over relatively long time-periods.

The conceptual model of net transport patterns discussed here represents a preliminary approach to understanding sediment dynamics in Humber Bay. A better understanding of the driving physical processes is necessary in order to test and refine this concept further.

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## FIGURE CAPTIONS

Figure 1: (Top) Location map of Humber Bay showing physiographic features. (Bottom) Location of samples and survey instrumentation.

Figure 2: Location of samples used for cluster analysis location.

Figure 3: Bottom sediment types, Humber Bay.

Figure 4: Contour plot of median phi diameters of surface sediment samples.

Figure 5: Contour plot of sand+gravel percentages in surface samples.

Figure 6: Transport patterns in Humber Bay, reproduced from GeoSea Consultants (1989).

Figure 7: Dendrogram and identification of cluster groupings among surface samples collected by Ontario Ministry of the Environment.

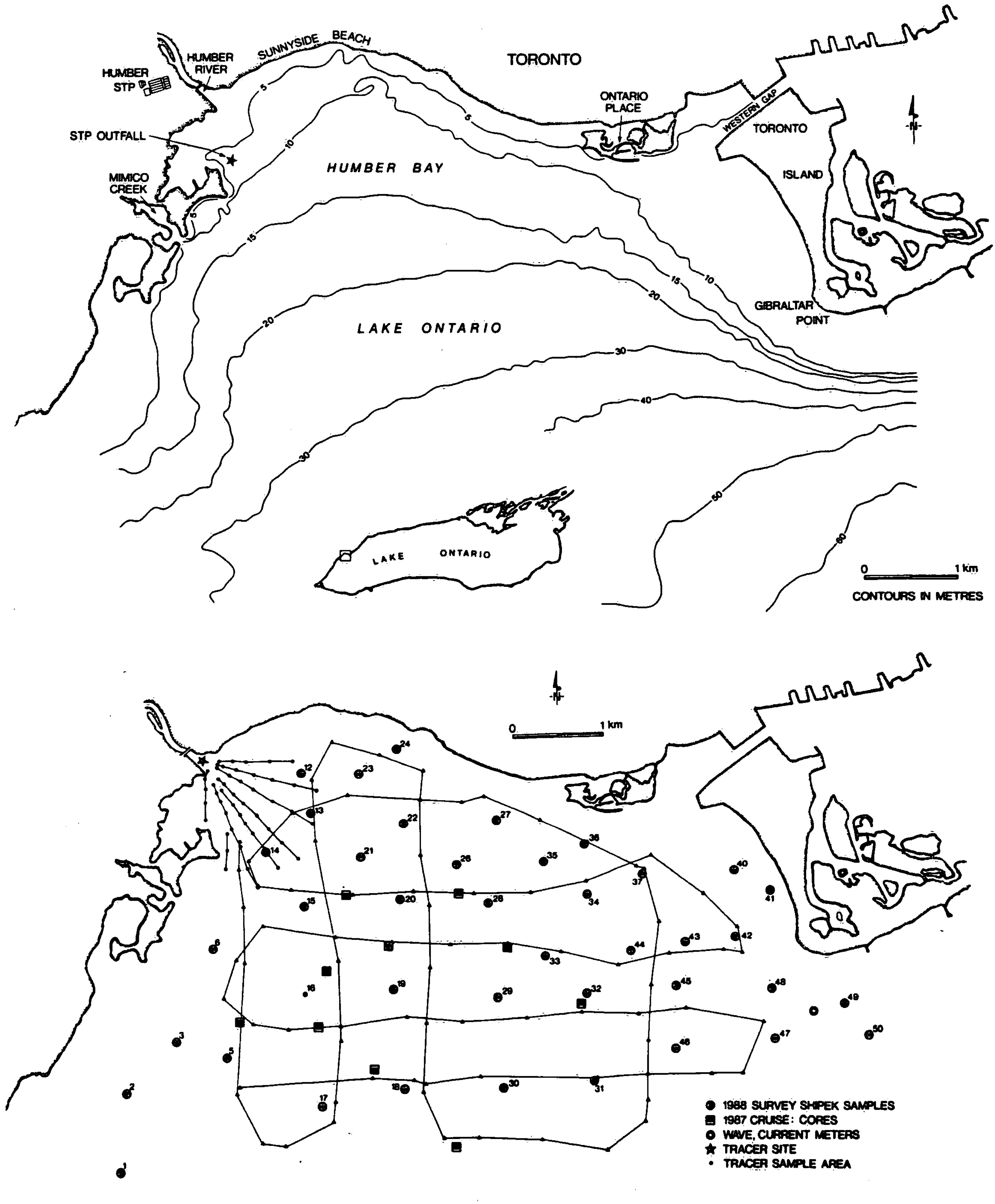
Figure 8: Transport pattern deduced from cluster analysis. Wider-spaced dashed line denotes lower transport possibility.

Figure 9: Contoured plot of concentration (ppm) of the artificial tracer (cesium). Samples were collected over three surveys.

Figure 10: Contoured plot of concentrations of naturally-occurring cobalt, collected over two surveys.

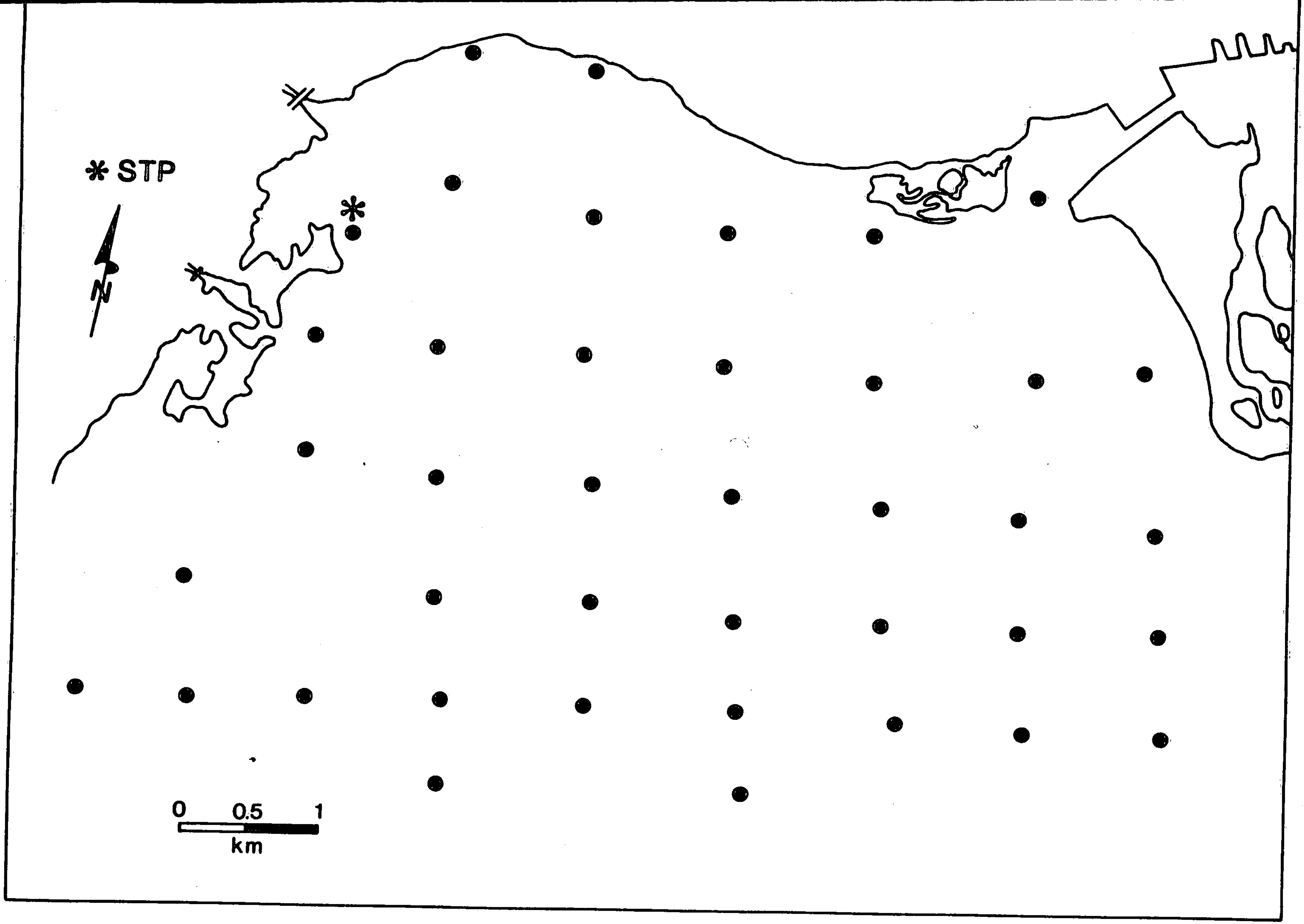
Figure 11: Contoured plot of concentrations (ppm) of coprostanol and $\alpha$-tocopheryl acetate.

Figure 12: Synthesis of data into a schematic conceptual model of Humber Bay net sediment transport patterns.



HUMBER STP
HUMBER RIVER
SUNNYSIDE BEACH
TORONTO
ONTARIO PLACE
WESTERN GAP
TORONTO ISLAND
STP OUTFALL
MIMICO CREEK
HUMBER BAY
LAKE ONTARIO
GIBRALTAR POINT
0 1 km
CONTOURS IN METRES
1988 SURVEY SHIPEK SAMPLES
1987 CRUISE: CORES
WAVE, CURRENT METERS
TRACER SITE
TRACER SAMPLE AREA


FIGURE 1


* STP
N
0
0.5
1
km

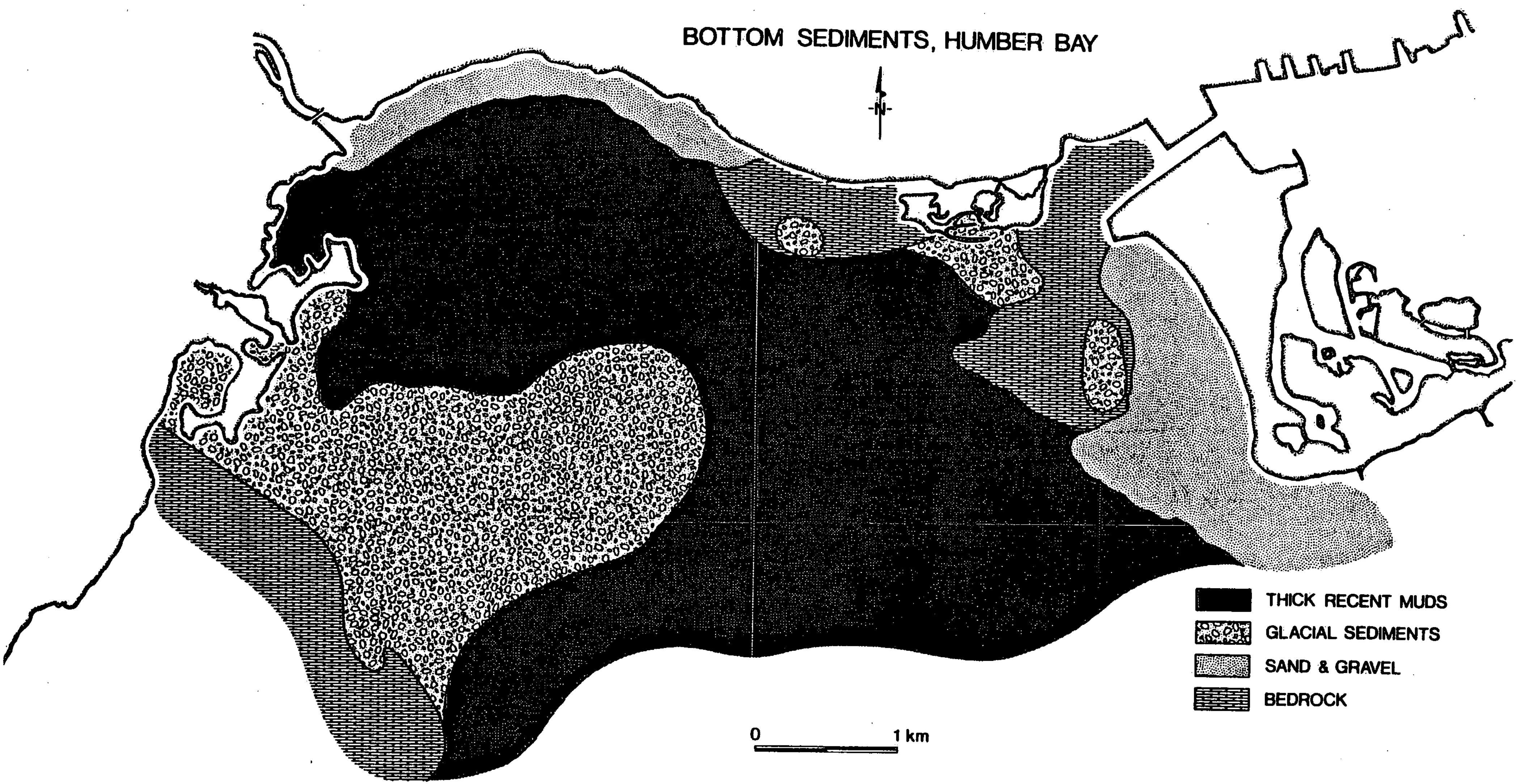
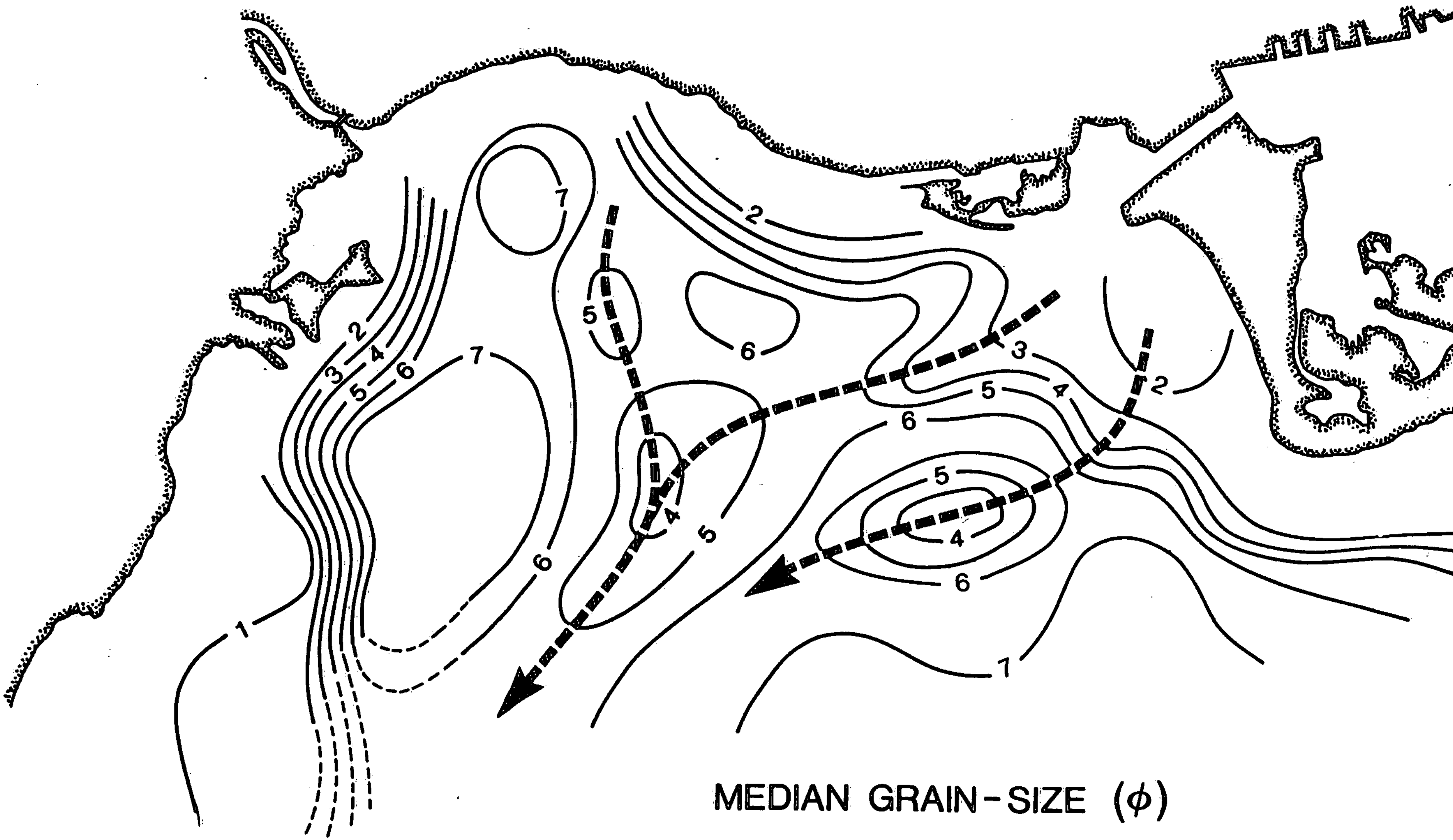
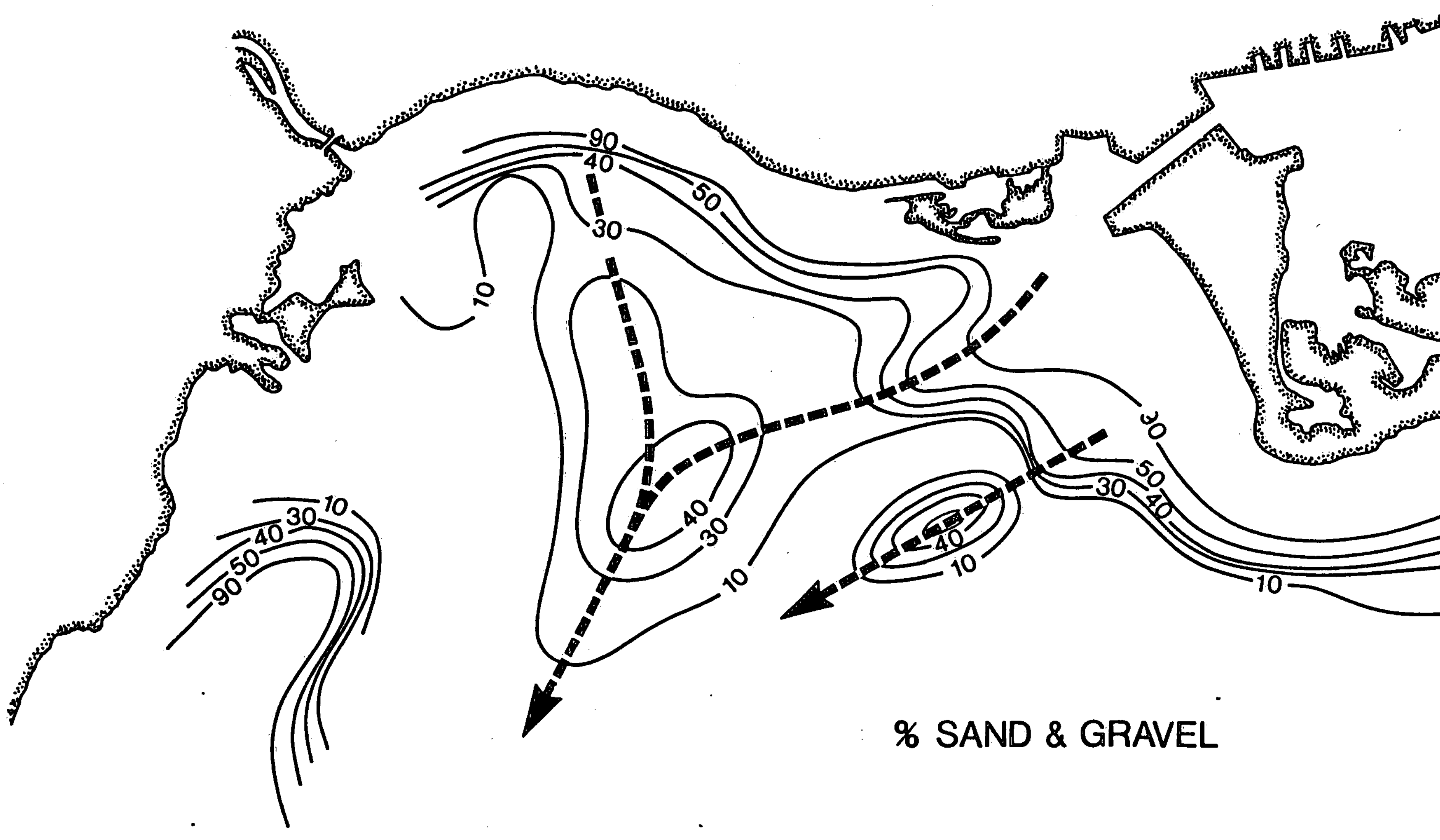

BOTTOM SEDIMENTS, HUMBER BAY
N
THICK RECENT MUDS
GLACIAL SEDIMENTS
SAND & GRAVEL
BEDROCK
0
1 km

FIGURE 3

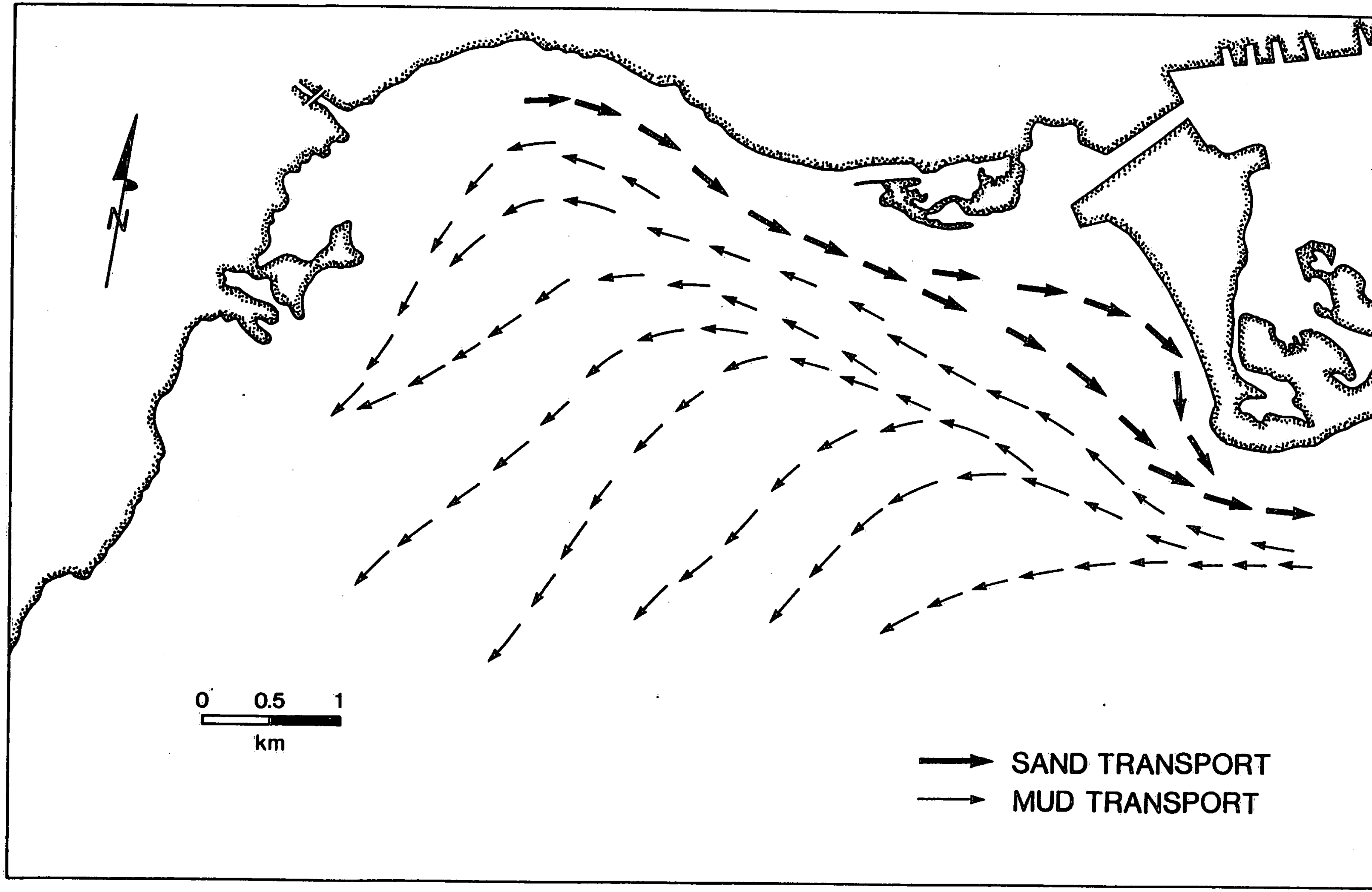


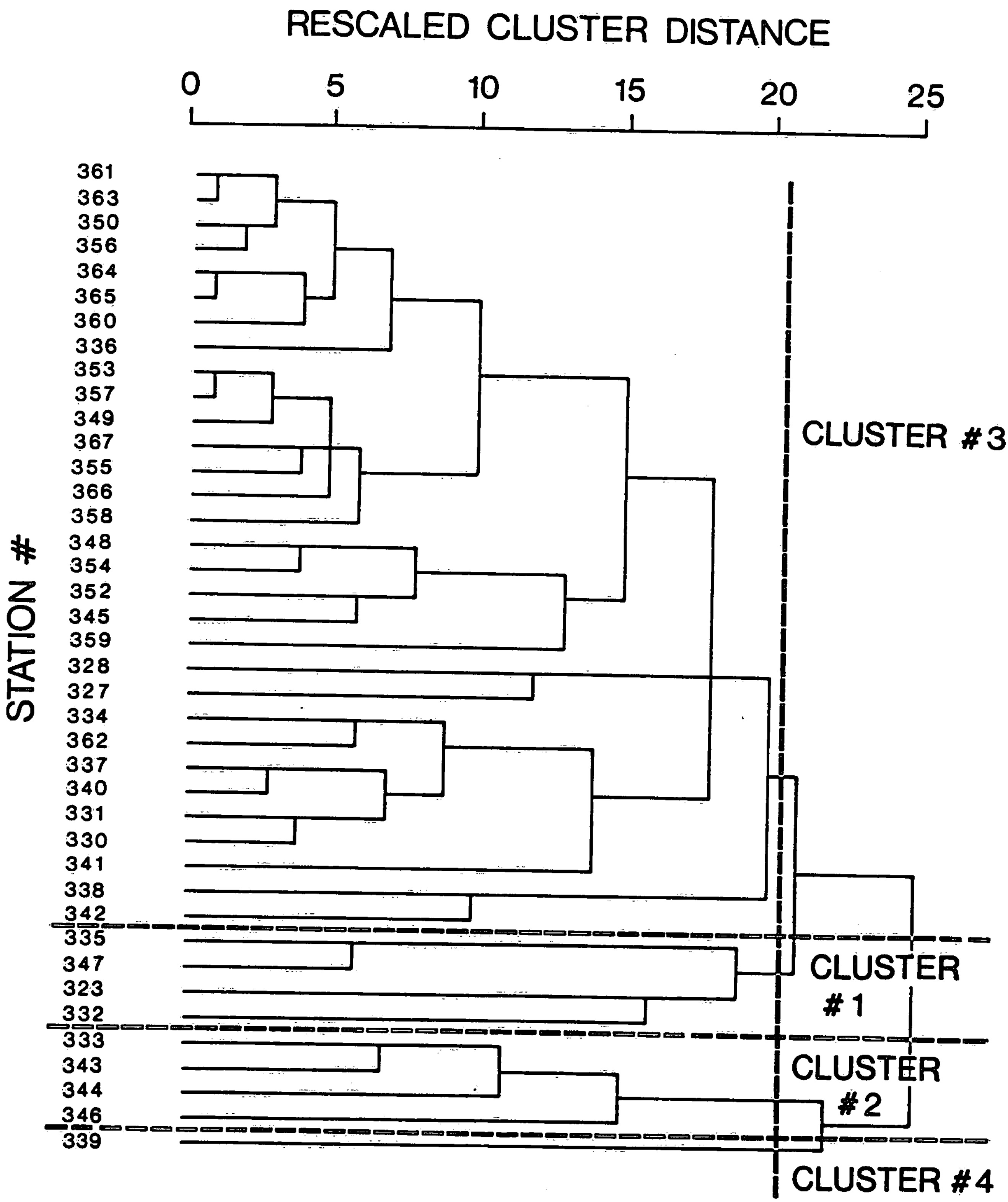
MEDIAN GRAIN-SIZE ($\phi$)

FIGURE 4



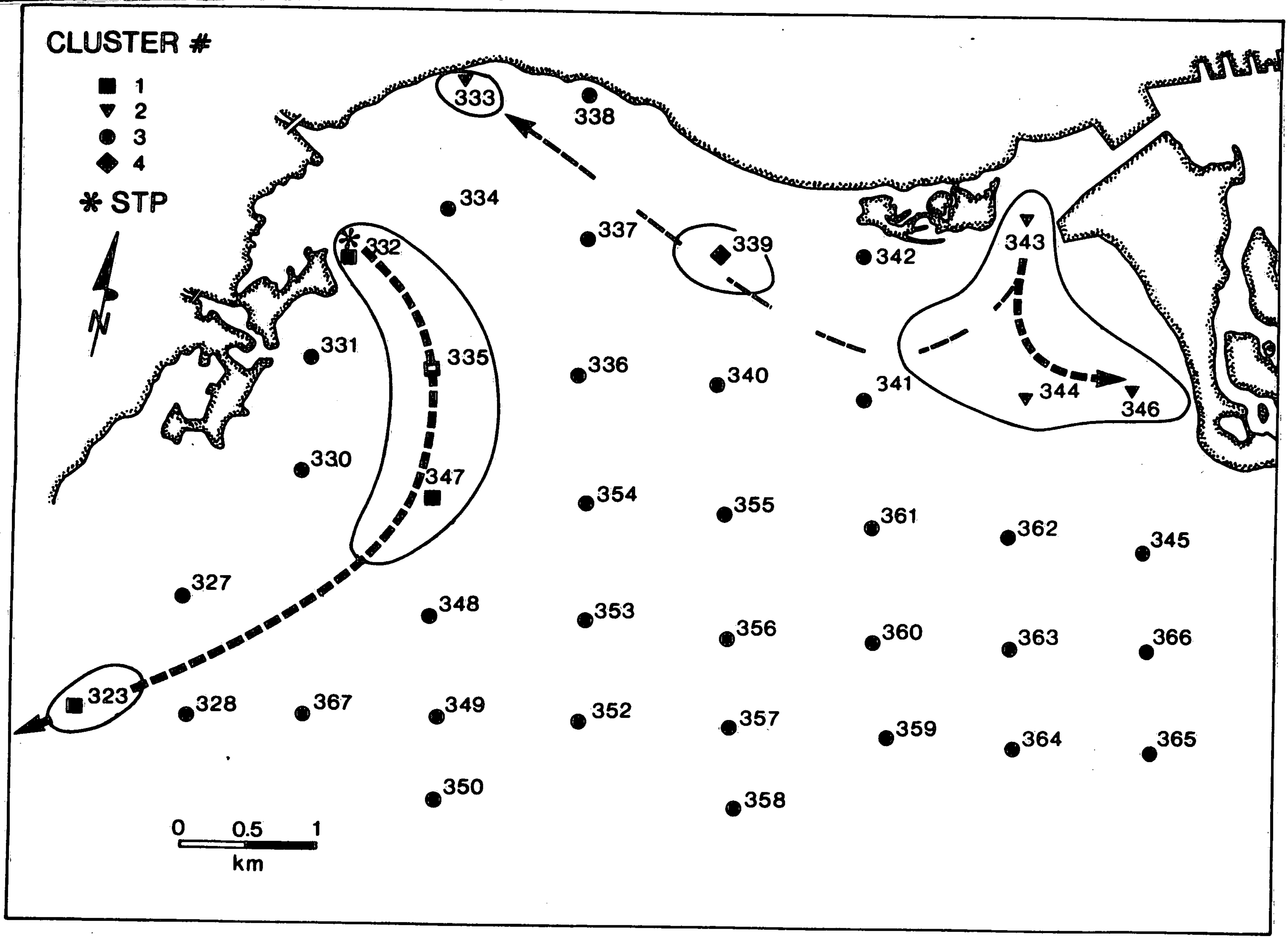

% SAND & GRAVEL


N
0
0.5
1
km
SAND TRANSPORT
MUD TRANSPORT



RESCALED CLUSTER DISTANCE
0
5
10
15
20
25
STATION #
361
363
350
356
364
365
360
336
353
357
349
367
355
366
358
348
354
352
345
359
328
327
334
362
337
340
331
330
341
338
342
335
347
323
332
333
343
344
346
339
CLUSTER #3
CLUSTER #1
CLUSTER #2
CLUSTER #4


FIGURE 7


CLUSTER #
1
2
3
4
* STP
N
333
338
334
337
339
342
343
332
331
335
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340
341
344
346
330
347
354
355
361
362
345
327
348
353
356
360
363
366
323
328
367
349
352
357
359
364
365
350
358
0
0.5
1
km

FIGURE 8

CESIUM TRACER (ppm)

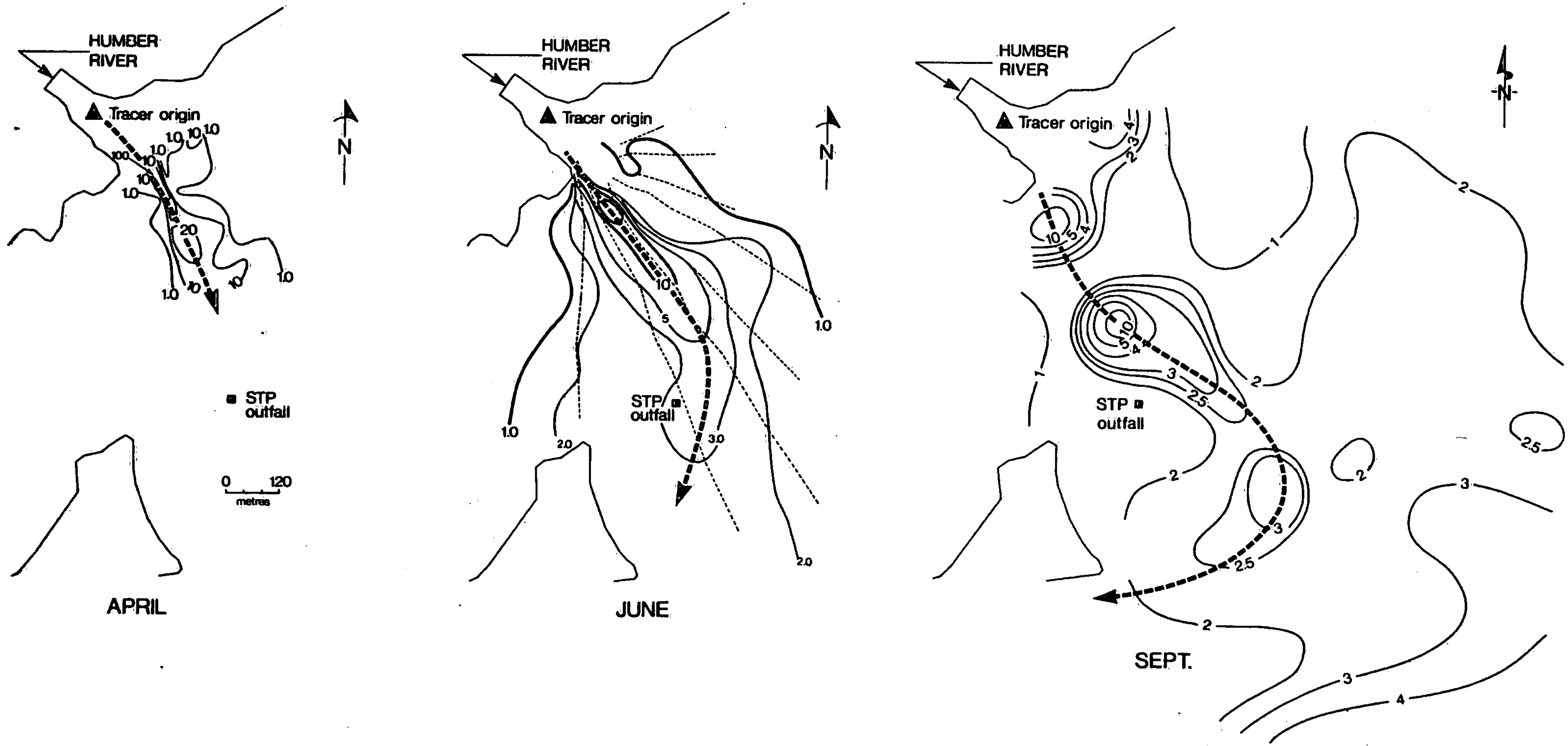


FIGURE 9

COBALT (ppm)

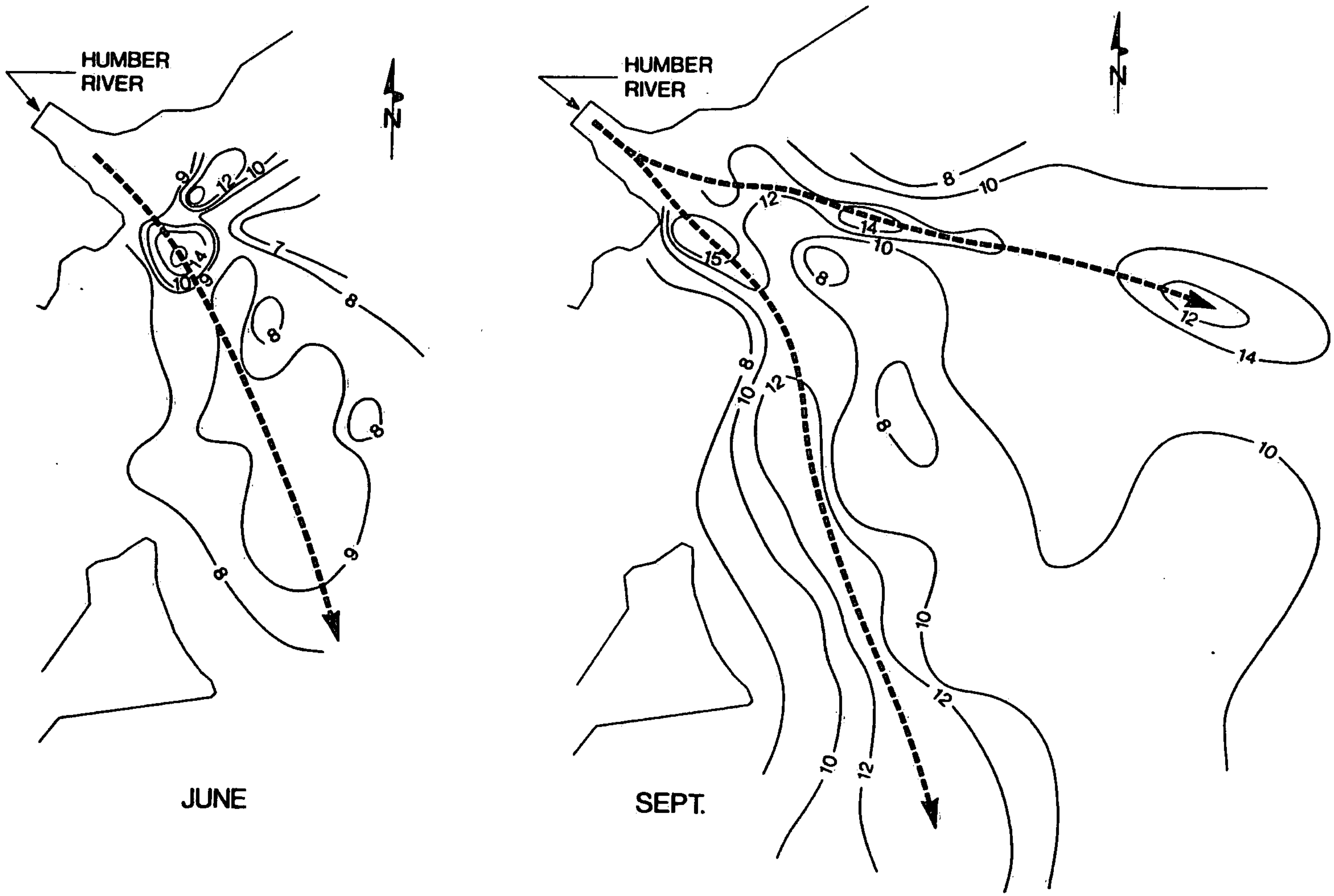


FIGURE 10

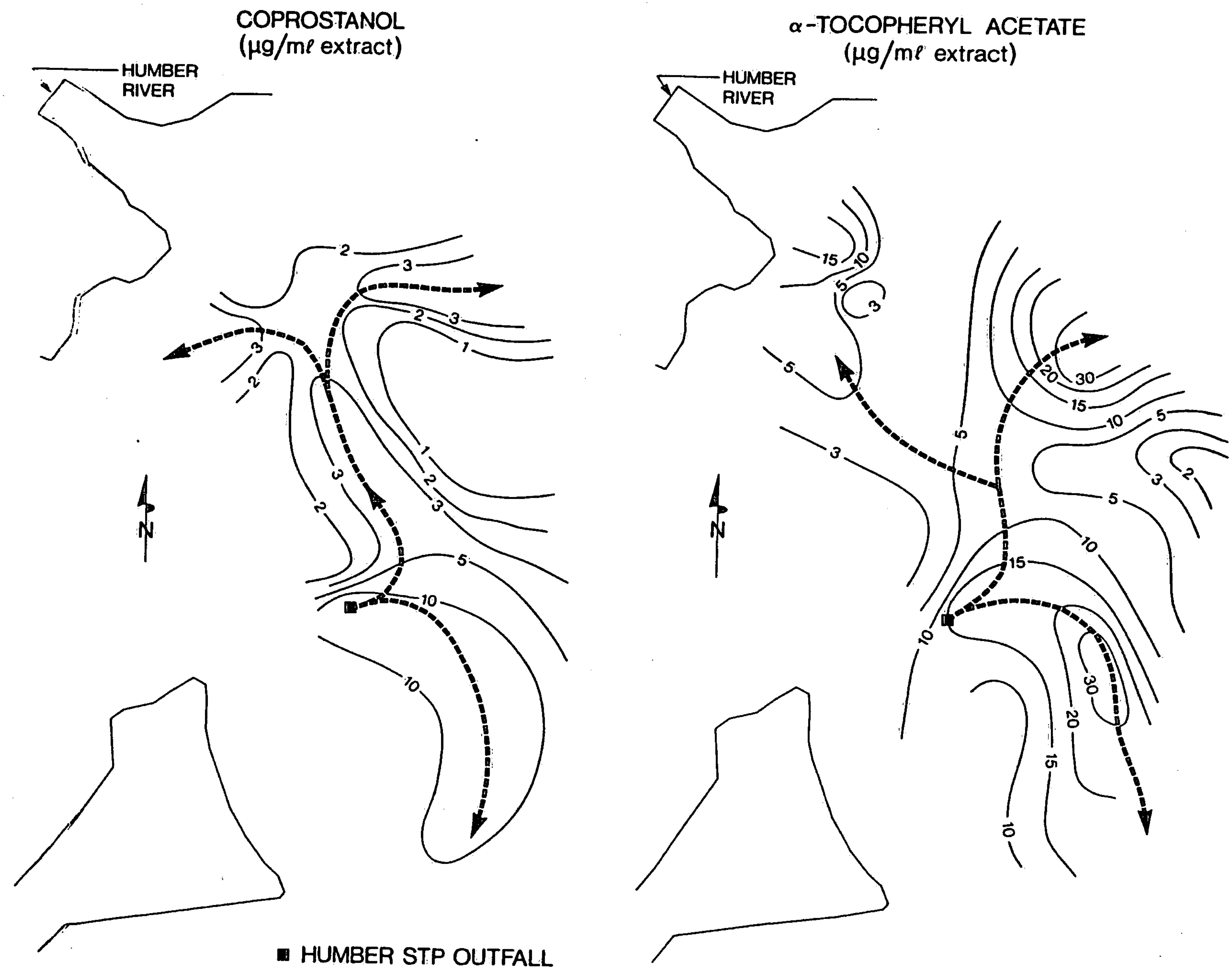
COPROSTANOL
(µg/mℓ extract)
HUMBER RIVER
N
α-TOCOPHERYL ACETATE
(µg/mℓ extract)
HUMBER RIVER
N
■ HUMBER STP OUTFALL

FIGURE 11

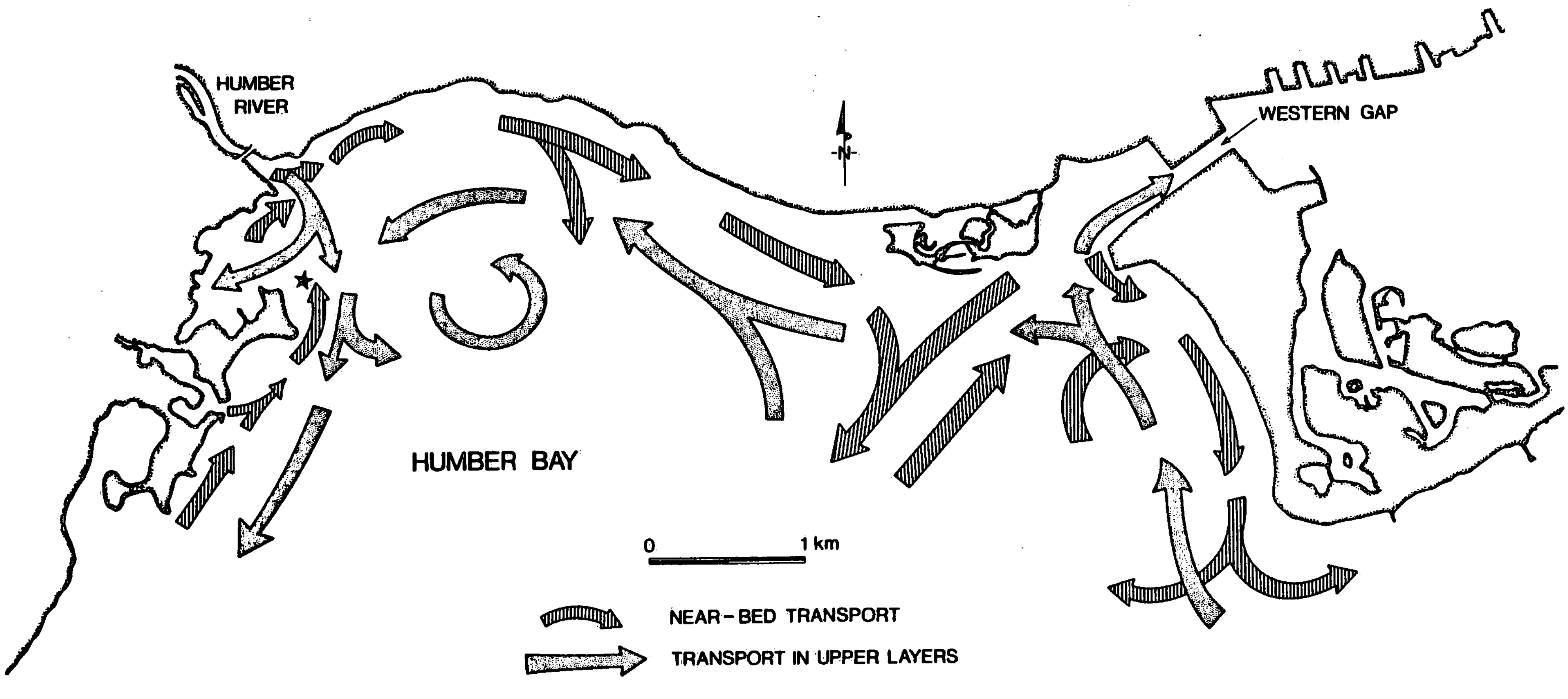
HUMBER RIVER
WESTERN GAP
N
HUMBER BAY
0
1 km
NEAR-BED TRANSPORT
TRANSPORT IN UPPER LAYERS

FIGURE 12

NATIONAL WATER RESEARCH INSTITUTE
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Environment Canada | Environnement Canada

Canada

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