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Transport of Sewage-Contaminated Sediment in Northeastern Hamilton Harbour

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ABSTRACT. *Dispersal patterns associated with sewage discharges from an STP outfall in northeastern Hamilton Harbour were obtained in 1992 and 1996 using coprostanol as a tracer. Both surveys revealed a distinctive shore-parallel pattern, characterized by a south-eastward trend and a second transport direction toward the northwest and southwest. As physical support for the tracer patterns, vertical profiles of currents near the outfall were monitored during four time periods from 1991 to 2000. Current data indicated the flow at the outfall was complicated; there was flow in all directions at all depths. However, the cumulative surface flow followed the prevailing wind (toward the east and northeast), while the bottom flow was approximately in opposition to the surface flow (to the west-northwest). Combining this circulation structure with the seasonal variation in buoyancy of the effluent discharge, the bi-directional transport pattern interpreted from the tracer distribution could be explained using a model in which the STP effluent plume was advected by local current at a position in the water column where the plume was stable. During January through August when the effluent was denser than ambient harbour water, it tended to be advected by flows lower in the water column moving the plume toward the north to west and into the central basin. During the rest of the year, it was lighter and more influenced by surface currents, which advected the plume onshore (toward the east and northeast) where it was deflected by shoreline geometry in a shore-parallel direction toward the southeast.*

INDEX WORDS: *Sediment, tracer, coprostanol, Hamilton Harbour, sewage, contaminants.*

INTRODUCTION

Hamilton Harbour (Fig. 1) has been identified by the International Joint Commission (IJC 1978) as an Area of Concern (AOC), i.e., one of the 42 Great Lake sites whose aquatic environment has become so degraded that remedial action must be undertaken. The harbor was also one of 41 sites where contaminated sediments were cited as critical in the assessment and remediation process. The harbor receives a large variety of contaminants from surrounding industrial and municipal sources. Among the municipal sources, four sewage treatment plants (STPs) in the watershed discharged more than 400,000 m^3/day of treated sewage effluent directly or indirectly to Hamilton Harbour (Remedial Action Plan (RAP) 1992). In addition to being the main sources of nutrients such as ammonia (> 80%) and phosphorus (~ 55%), STP outfalls are major sources of persistent organic pollutants (POPs) and heavy metal contamination (RAP 1992). Furthermore, these effluents are now considered to be the major vectors for the entry of estrogen-mimicking chemicals into the aquatic ecosystem (Purdom *et al.* 1994). When hazardous components of an outfall are combined with proximity to nearby clean-water amenities such as major bird rookeries (cormorants, gulls, terns), municipal water intakes, and recreational areas, their potential impacts assume importance for safe water management.

An understanding of the potential influences of STP outfalls on aquatic systems requires the development of methodologies for the study of their dispersal dynamics and mixing characteristics. These characteristics can be studied using both physical and chemical profiling techniques. Chemical tracers

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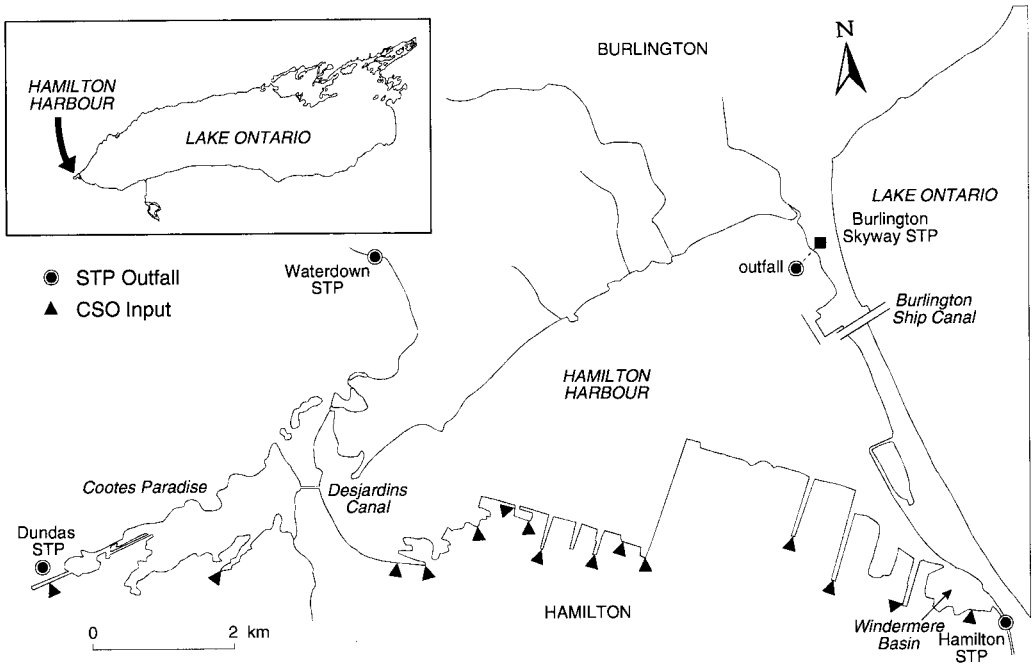

FIG. 1. Map of Hamilton Harbour showing the location of the Burlington Skyway STP outfall, outfalls of other STPs, and combined sewer overflows (CSO).

of pollution must be primarily sediment-bound and stable such that gradients in concentration are due to dilution and not to decay, consumption, or chemical reaction. These compounds must also be related to a unique source, in this case, treated sewage discharged through the outfall. Coprostanol (5β-cholestan-3β-ol) was selected as a sediment tracer for this study. It is produced by gastric breakdown of cholesterol, and is the major fecal sterol of humans, comprising 40 to 60% of the total neutral sterols excreted. Virtually the only source of this chemical is feces of humans and other mammals (Venkatesan and Santiago 1989, Leeming *et al.* 1997). Coprostanol has been widely used as a marker of sewage contamination (Eganhouse 1997, Kirchmer 1971, Hatcher *et al.* 1977, Brown and Wade 1984, LeBlanc *et al.* 1992, Grimalt *et al.* 1990, Holm and Windsor 1990, Coakley and Poulton 1991, Coakley *et al.* 1992). A preliminary study of sediment transport in Hamilton Harbour using coprostanol as a tracer was carried out by Bachtiar *et al.* (1996); results of this study are included in the present report.

Chemical tracer studies can be enhanced by physical measurements including current velocity profiles that cast light onto the dispersal dynamics and mixing characteristics of water masses. We have previously used several current meter types for monitoring the water flow in the vicinity of the STP outfall. Our earlier fieldwork made use of single point meters. However, in 1999 and 2000, acoustic Doppler current profilers (ADCP) were used in addition to a single point meter. The ADCP is a powerful tool in assessing the currents. These instruments emit an acoustic signal that is reflected off small particles moving with the water. The ADCP monitors the reflected signal, which has a shift in frequency depending on the direction of travel (the Doppler shift). By timing or gating the reflected signal and measuring the Doppler shift, it is possible to determine the average current velocities at specific ranges from the instrument. Thus a velocity profile can be acquired from a single instrument.

A combined physical and chemical profiling methodology was applied to an STP discharging directly into northeastern Hamilton Harbour, the Burlington Skyway STP (Fig. 1). This STP was constructed in 1964 with an annual discharge volume of over 10,000 m^3/day, compared to 1996 discharges of over 90,000 m^3/day of treated sewage effluent (B. Seminario, Plant Manager, Burlington Skyway STP, pers. comm.). The effluent discharges

through a diffuser pipe located in approximately 7 m of water and 1.5 m above the bottom. This study demonstrates the applicability of combined measurements of sediment levels of coprostanol and measurements of current velocities using an ADCP for defining net dispersal patterns and contaminant transport pathways from a known STP point source. These techniques serve as a complementary tool to hydrodynamic modeling. The study also has water management implications by providing a measure of the capacity of northeastern Hamilton Harbour to dilute sewage effluent volumes to water quality levels acceptable for the clean-water uses. Moreover, despite its restricted geographic focus, the work has potential application in other restricted water bodies and AOCs in the Great Lakes where long-term patterns of contaminant dispersal from point sources are required for remediation planning.

METHODS

Sample Collection

Two sets of 30 sediment samples each were analyzed for coprostanol and other sterols. Samples were collected on a radial grid (Fig. 2) centered on the outfall of the Burlington Skyway STP in northeastern Hamilton Harbour. One set of samples was collected in 1992 using a Shipek grab sampler, while the other set was collected in 1996 using a Mini Box Corer. As much as possible, samples were collected at the same site, but in 1996 some original sites were occupied by artificial islands constructed the previous year (Fig. 2). A suite of six samples was collected in the vicinity of the islands in September 2000 to verify high values detected in 1996. Sediments making up the top 1 cm layer were carefully collected and refrigerated aboard the survey vessel until storage in a cold room. Care was taken to avoid loss of the soft surface layers. All samples were freeze-dried, homogenized, and passed through a 62 μm sieve prior to analysis.

Sterol Analyses

The analytical method for the 1992 samples was based on gas chromatography with electron capture detection as described in Bachtiar *et al.* (1996). This method was modified to include quantitation by gas chromatography-mass spectrometry for the

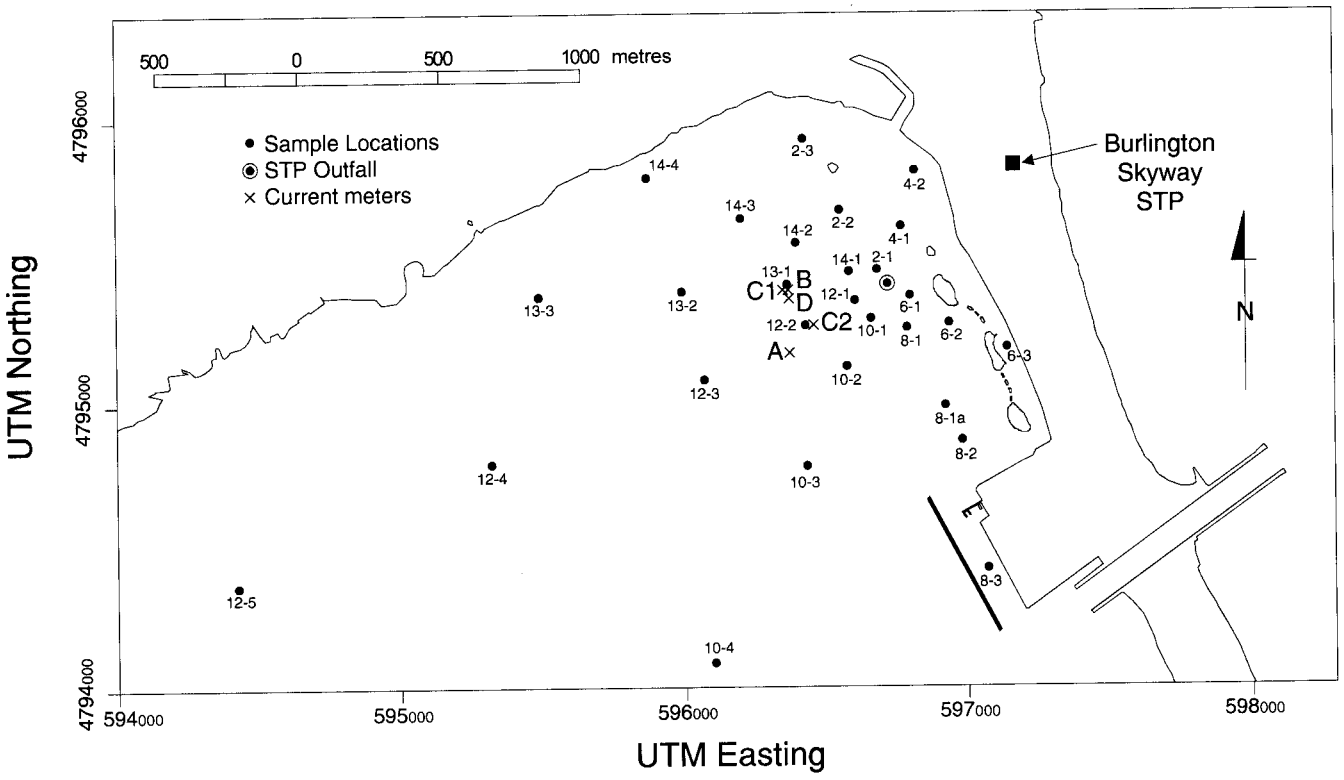

FIG. 2. Location of sediment samples (see Table 2) and current meter moorings (see Table 1). Note presence of artificial islands to the east of outfall constructed shortly before the 1996 survey.

1996 samples. Standard sterol compounds were obtained from Sigma (Mississauge, ON): epicoprostanol (95%); cholesterol (99+%); stigmasterol (95%); dihydrocholesterol (95%); stigmastanol (97.2%); coprostanol (98%). The derivatizing agent N-methyl-N-trimethylsilyl-trifluoroacetimide (MSTFA) was obtained from Pierce (Rockford, IL). All solvents were of analytical grade. Water was prepared using a Milli-Q purification system.

Freeze-dried sediment samples were extracted in dichloromethane using a Dionex ASE Model 200 accelerated solvent extractor. Samples (0.5 g–1 g) were mixed with Ottawa sand to fill the entire volume of the extraction cell. Solvent extracts were then subjected to an open-column cleanup procedure employing 1.0 g of neutral alumina (Brockman activity 1, 80–200 mesh); sterols were eluted with 12 mL of dichloromethane. Extracts were gently evaporated to dryness under nitrogen and derivatized with 100 µl MSTFA for 20 minutes at 130°C. After cooling, extracts were reconstituted in 1 mL of iso-octane for GC-MS analysis.

Analyses were performed using a Hewlett-Packard 5890 gas chromatograph with a 30 m 0.25 mm i.d. 0.25 µm stationary phase DB-5 column and a Model 5971A mass selective detector operated in selected ion monitoring (SIM) mode. The injection volume was 1 µL on-column with a carrier gas velocity of 40 cm/sec. The transfer line temperature was maintained at 300°C. The following ions were monitored: m/z 388, 355, 231, 386, 316, 215, 370, 233, and 264. The following temperature program was used: initial temperature 100°C; 100°C to 170°C at 20°C/min; 170°C to 300°C at 3°C.

Surrogate standards for the sterol analytes were not available; sediment samples were spiked with a laboratory standard containing four polycyclic aromatic hydrocarbons (PAH) including naphthalene-d_8, fluorene-d_{10}, pyrene-d_{10}, and benzo[a]-pyrene-d_{12}. Spike recoveries were typically greater than 75%. Method blanks were routinely carried through the sample preparation and analysis procedures. Between-run reproducibilities were typically within 10%. Method detection limits were estimated at approximately 60 ng/g (3:1 S/N) for individual sterols in a 1 g dry weight sample in full scan mode and 6 ng/g in SIM mode.

Water Circulation and Nearshore Currents

Records of local currents collected near the outfall (Fig. 2) were assembled for four periods from 1991 to 2000 (Table 1). Included were two periods where the vertical structure of the flow was measured in addition to the horizontal distribution. The current data were examined in an effort to understand the long-term circulation patterns in this portion of the harbor. In Table 1, Stations A and B were part of earlier studies of the overall harbor circulation. Stations C1 and C2 represent one deployment in 1999; a *Sontek* Hydra meter and a *RD Instruments* Acoustic Doppler Current Profiler (ADCP) were placed out as a pair. Station D was deployed in 2000. The Hydra meter is an acoustic Doppler current meter that measures velocity in a very small volume at a fixed location about 18 cm distant from the meter head. It was deployed on the bottom such that the measuring volume was 0.6 m above the bottom, at a depth of 8.0 m. The ADCP broadcasts a more powerful beam into the water (it was also bottom mounted and "upward looking"). The ADCP was set up so that the average horizontal current was determined in one-meter sections, or bins, of the water column. Because of the characteristics of the ADCP and its deployment configuration, the lowest bin was centered at a depth of 6.25 m, and the highest bin at a depth of 1.25 m. The data from the Hydra were considered to represent the bottom current, and the data from the top bin of the ADCP were considered to represent the surface current.

TABLE 1. Current meter deployments in northeastern Hamilton Harbour. Locations are shown in Figure 2.

Station/Year/ Julian Days	Meter Type	Measurement Depth, m	Water Depth, m
A: 1991/184-295		5	8
B: 1993/162-314		7.2	8.2
C1: 1999/181-258	Hydra	8.0	8.6
C2: 1999/181-258	ADCP	1.25 ≤ Depth ≤ 6.25 (1.0 m bins)	8.0
D: 2000/150-276	ADCP	1.25≤ Depth ≤ 6.25 (1.0 m bins)	8.0

RESULTS AND DISCUSSION

Validation of Coprostanol as a Sewage Tracer in Hamilton Harbour

The chemical stability of coprostanol under oxidizing conditions in the water column or on the sediment surface in the Great Lakes was questioned by Dutka *et al.* (1974). However, studies by Hatcher

and McGillivary (1979) in the New York Bight demonstrated that coprostanol concentrations in cores were unchanged over 25 years. Elevated coprostanol concentrations were also found in sediment cores dated at more than 40 years taken near the Burlington Skyway STP outfall (Coakley *et al.* 1996). Nishimura and Koyama (1977) observed no decomposition of cholesterol and cholestanol under anaerobic conditions during 450-day lake sediment incubation experiments, while only minor decomposition of cholesterol occurred under aerobic conditions. Based on these studies, coprostanol appears to be sufficiently stable to be adequate for tracer applications in surficial sediments in Hamilton Harbour.

Despite its wide use, some researchers urge caution in the use of coprostanol as a tracer, especially in certain tropical areas where concentrations in sediments are very low, for example, below 5 ng/g (Sherblom *et al.* 1997), because of the possibility of contamination by feces of marine mammals and by the breakdown of algal sterols (Grimalt *et al.* 1990). Studies by Venkatesan and Santiago (1989) in marine waters offshore of the southern California coast, and by Leeming *et al.* (1997) in both fresh waters and marine areas of Australia indicate that confirmation of a human origin is obtained by the ratio of some of the sterol epimers (e.g., coprostanol to epicoprostanol) in the sediments. Grimalt *et al.* (1990) used the ratio of coprostanol to cholestanol to distinguish coprostanol derived from diagenesis of algal sterols from that of human origin. In order to assess the possibility of coprostanol being added by the bird rookeries in the study area, samples of bird guano from the island northeast of the STP outfall were analyzed for sterols. In addition to very low values of coprostanol (27 ng/g), the results (Coakley, J.P., unpublished data) show epimer ratios far outside the range for human origin. Therefore, the coprostanol measured within the study area sediments is thought to have a primary source (the STP), and is not significantly influenced by proximity to local bird colonies.

Relative Density of STP Effluent

Effluent density (based on temperature and conductivity) as a function of month of the year was available from a study for a proposed new outfall placement of the Burlington STP. Using the water temperature and conductivity data for the upper 5 m of Hamilton Harbour (Charlton *et al.* 1998), the density of the receiving water was also estimated

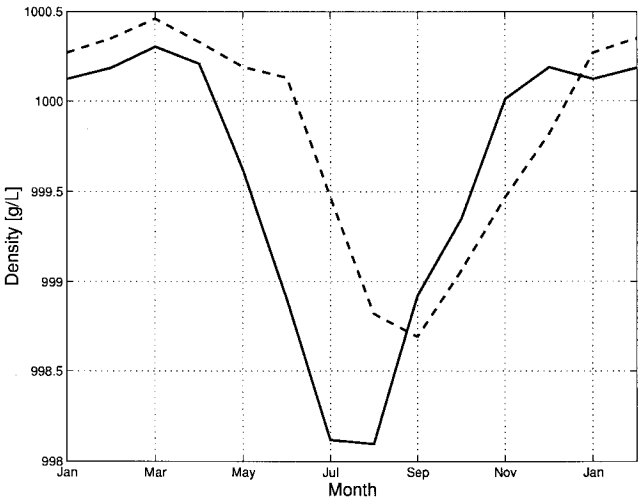

FIG. 3. Annual trends in outfall effluent density (dashed line) relative to ambient Hamilton Harbour water density (solid line).

(Fig. 3). From September to December the effluent was significantly less dense than the receiving waters, while during the rest of the year it was more dense (due to the elevated conductivity). These data indicated that during September to December the effluent would have had a tendency to rise to the surface, while at other times it would have sunk to the bottom. This process will be discussed later in concert with the vertical current profile data in constructing a transport scenario compatible with the tracer patterns.

Tracer Results and Transport Interpretation

The results of the analyses of sediment coprostanol concentration for the two sampling surveys are presented in Table 2. Values ranged from highs of 930 µg/g (1992) and 1,600 µg/g (1996), to ambient background levels of less than 3 µg/g. The maximum values corresponded to sites within 100 m of the outfall and were consistently lower than that of raw human feces (5,600 µg/g, Leeming *et al.* 1997). Coprostanol levels for both sample sets were found to be generally similar. Sample locations exhibiting high coprostanol levels were the same in both the 1992 and 1996 surveys. The average value of all samples in 1992 was 43 µg/g, compared to 102 µg/g for 1996 that was primarily the result of a value of 1,600 µg/g at one station. This site had a value of 37 µg/g in 1992, before the surrounding area was modified in 1995 and 1996 by construction of artificial islands to the east and

TABLE 2. Sterol determinations in sediments from northeastern Hamilton Harbour.

Sample Identification 1992	1996	UTM Coordinates (NAD27) North	East	1992 Coprostanol µg/g	1996 Coprostanol µg/g	1996 Epicoprostanol µg/g	C/E ratio
HH 2-1	2-1	4795492	596640	7.2	3.3	2.1	1.6
HH 2-2	2-2	4795679	596554	1.6	18	6.3	2.8
HH 2-3	2-3	4795952	596433	0.2	0.4	ND	
HH 4-1	4-1	4795614	596773	2.9	1.7	0.7	2.4
HH 4-2		4795774	596813	0.1			
HH 6-1	6-1	4795386	596774	37	**1,600**	1,600	1.0
HH 6-2	6-2	4795292	596936	0.1	2.6	0.4	6.5
HH 6-3		4795287	597000	< 0.1			
HH 8-1	8-1	4795242	596782	**150**	190	110	1.6
HH 8-1A	8-1A	4794963	596916	14	57	53	1.1
HH 8-2	8-2	4794856	596972	0.5	51	38	1.4
HH 8-3	8-3	4794417	597052	9.3	5.3	2.5	2.1
8-4				6.3	2.2	2.9	
HH 10-1	10-1	4795295	596670	13	85	58	1.5
HH 10-2	10-2	4795117	596588	0.3	0.1	ND	
HH 10-3	10-3	4794756	596422	1.6	7.1	2.0	3.5
HH 10-4	10-4	4794055	596093	2.8	6.8	2.7	2.5
HH 10-5	10-5	4793106	595699	4.8	18	4.0	4.5
HH 12-1	12-1	4795355	596603	47	63	72	0.9
HH 12-2	12-2	4795257	596432	3.1	3.7	1.0	3.7
HH 12-3	12-3	4795070	596075	0.9	10	3.0	3.4
HH 12-4	12-4	4794762	595326	3.2	16.3	4.6	3.5
HH 12-5	12-5	4794326	594426	2.7	13	2.5	5.3
HH 13-1	13-1	4795409	596365	3.0	6.4	3.1	2.1
HH 13-2	13-2	4795381	595999	15	12	5.9	2.1
HH 13-3	13-3	4795366	595491	4.4	3.5	0.7	5.0
HH 14-1	14-1	4795458	596577	30	41	15	2.7
HH 14-2	14-2	4795559	596397	1.5	2.7	0.4	6.8
HH 14-3	14-3	4795644	596210	1.9	8.8	5.1	1.7
HH 14-4	14-4	4795753	595943	0.2	ND	0	
HH STP	STP	4795403	596717	930	740	600	1.7
			Avg. Copr.	**43**	102		
					49 *		

*(Avg. without outlier)

southeast of the outfall (Fig. 2). Analysis carried out on additional samples from around this site in September 2000 showed background levels. This result suggested that the high 1996 value represented a transient or very localized hot-spot, whose significance cannot be extrapolated to the surrounding areas. If this anomalous value is removed, the 1996 average is reduced to 49 µg/g, which is only slightly higher than the 1992 average. There were also significant increases in concentrations at sites farthest from the outfall between the 2 study years. This could have been a reflection of greater impact of the effluent associated with the steady increase in the STP discharges between 1992 (79,000 m^3/day) and 1996 (91,000 m^3/day). In addition, ratios of coprostanol to epicoprostanol were, with the exception of one value of 0.9, always greater than 1. This confirmed the earlier assessment that, despite the large gull and cormorant populations on nearby islands, the coprostanol was primarily of human origin and predominately associated with the effluent of the Burlington Skyway STP.

The tracer concentrations were plotted onto the radial grid and contoured by hand at intervals selected to enhance the definition of the concentration plumes. The singular hot-spot was not included in the 1996 plot. The tracer distribution patterns for both the 1992 and the 1996 sampling surveys are presented in Figure 4. The contoured tracer concentration pattern is characterized in both surveys by

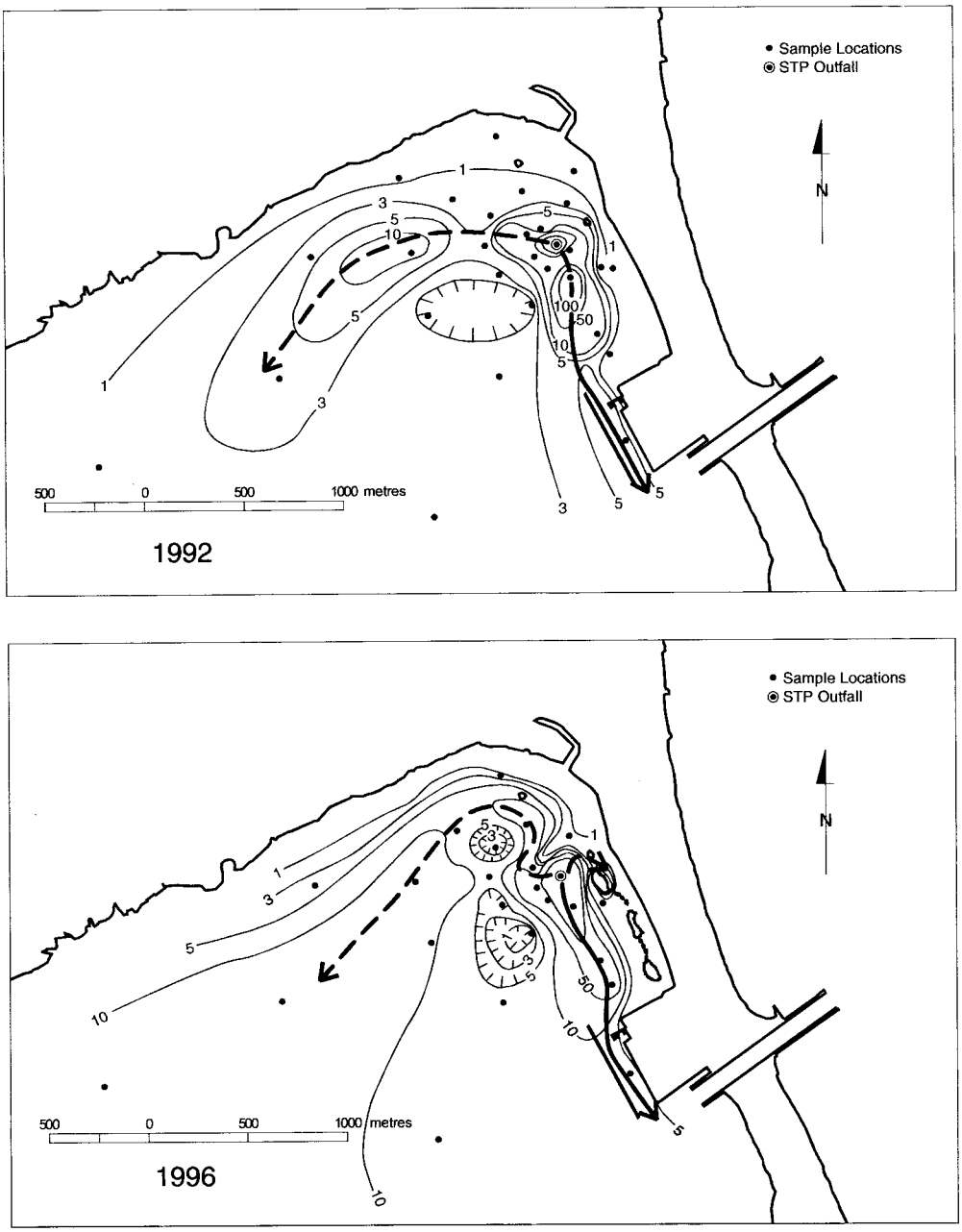

FIG. 4. Spatial concentration patterns for the sediment tracer, coprostanol, in the northeastern sector of Hamilton Harbour. Top panel shows concentration patterns for the survey done in 1992; bottom shows similar data for 1996. Heavy solid lines represent the interpreted southeast dispersal trend; the dashed lines represent the southwest trend.

two main lobes, a southward trend (containing the higher concentration values) and a second trend curving from north to west to southwest. Although the radial grid samples were deficient in covering large areas to the west and southwest, a region of very low values immediately to the west of the outfall was confirmed in both surveys. The persistence of this low-concentration region relatively close to the outfall is surprising, and is an indication of minimal transport (and deposition) in that direction. The possibility of scour by waves was discounted because the bottom sediment was similar to that at

other sites (mud) and the depths were as deep or deeper. The area was probably one consistently outside the transport plume for STP effluent. The superimposed arrows included in Figure 4 show the principal sediment transport directions interpreted from the tracer results.

Current Regime

Wu *et al*. 1996 documented that several driving processes could be identified from current data but that wind was dominant. They found that drogues at 2 m followed the wind, and at 5 m, some drogues followed the wind and some moved against the wind. The use of the ADCP in the present study allowed a detailed examination of the vertical structure in the vicinity of the STP outfall.

The characteristics of the flow were examined using progressive vector diagrams which give "pseudo" displacements (Emery and Thomson 2001) and current roses calculated from the velocity time series. The currents in 1999 and 2000 showed considerable vertical structure, particularly in terms of direction. In Figure 5, progressive vector diagrams are shown for depths of 1.25, 3.25, 6.25, and 8.0 m for the July to September 1999 deployment. The net surface displacement, as indicated by the trajectory at 1.25 m depth, was to the east-northeast. At increasing depth the net displacement directions were rotated counterclockwise down to the bottom, where the direction was to the west-northwest. All the trajectories were very irregular, indicating that the flow was constantly changing direction. There was displacement in all directions, and hence dispersion in all directions, but greatest in the dominant directions mentioned. These progressive vectors did not provide as useful an estimate of water particle movement as Lagrangian tracers. Nevertheless, when used in conjunction with a map of the local shoreline, they proved to be useful indicators. The easterly surface displacements were intercepted by the shoreline, likely deflecting the flow parallel to the shore to the southeast. Similarly the north and northwesterly bottom displacements will eventually by deflected westerly and southwesterly along the north shoreline. The displacement at 3.25 m depth may well be bifurcated, some flowing southwest along the north shore and some southerly along the east shore. The displacement at 6.25 m depth would eventually be forced to the southwest.

The current roses for depths of 1.25, 3.25, 6.25, and 8.0 m for 1999 and 2000 are shown in Figure 6.

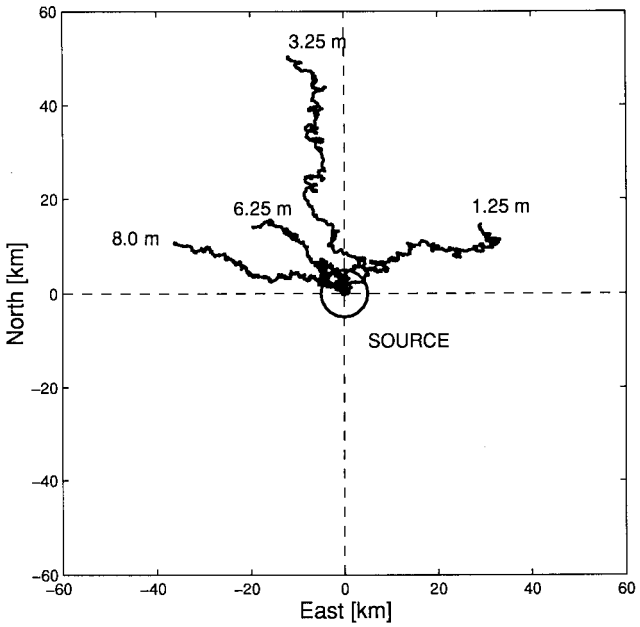

FIG. 5. Progressive vector diagrams calculated from the velocity time series at four depths for the July to September 1999 deployment.

The Hydra meter was not deployed in 2000, so there were no data collected at 8.0 m. These plots confirm that the current at the site was highly dispersed at all depths. The flows near the surface (1.25 m depth) were very similar in direction, distribution, and magnitude for both years. The largest number of occurrences was toward the east and significant flow occurred in all other directions with the least toward the south. The flows near the middle of the water column (3.25 m) were also similar in the 2 years, with the largest number of occurrences to the northwest and the least to the south. The flows near the bottom (6.25 m depth) were rather different in the 2 years, being generally higher in magnitude in 2000 compared to 1999, and more directed toward the west, in contrast to the northerly flows in 1999. Closest to the bottom (8.0 m depth) in 1999, most of the occurrences were to the west and southwest, and the least toward the southeast.

The direction patterns of the roses for the 2 years suggested that the flow structures were similar. The most important direction at the surface was to the east, and at the bottom to the west, and northerly at intermediate depths. The shapes of the current roses indicated a current regime similar to that described based on the progressive vector diagram. However, the roses did not illustrate the persistence in direc-

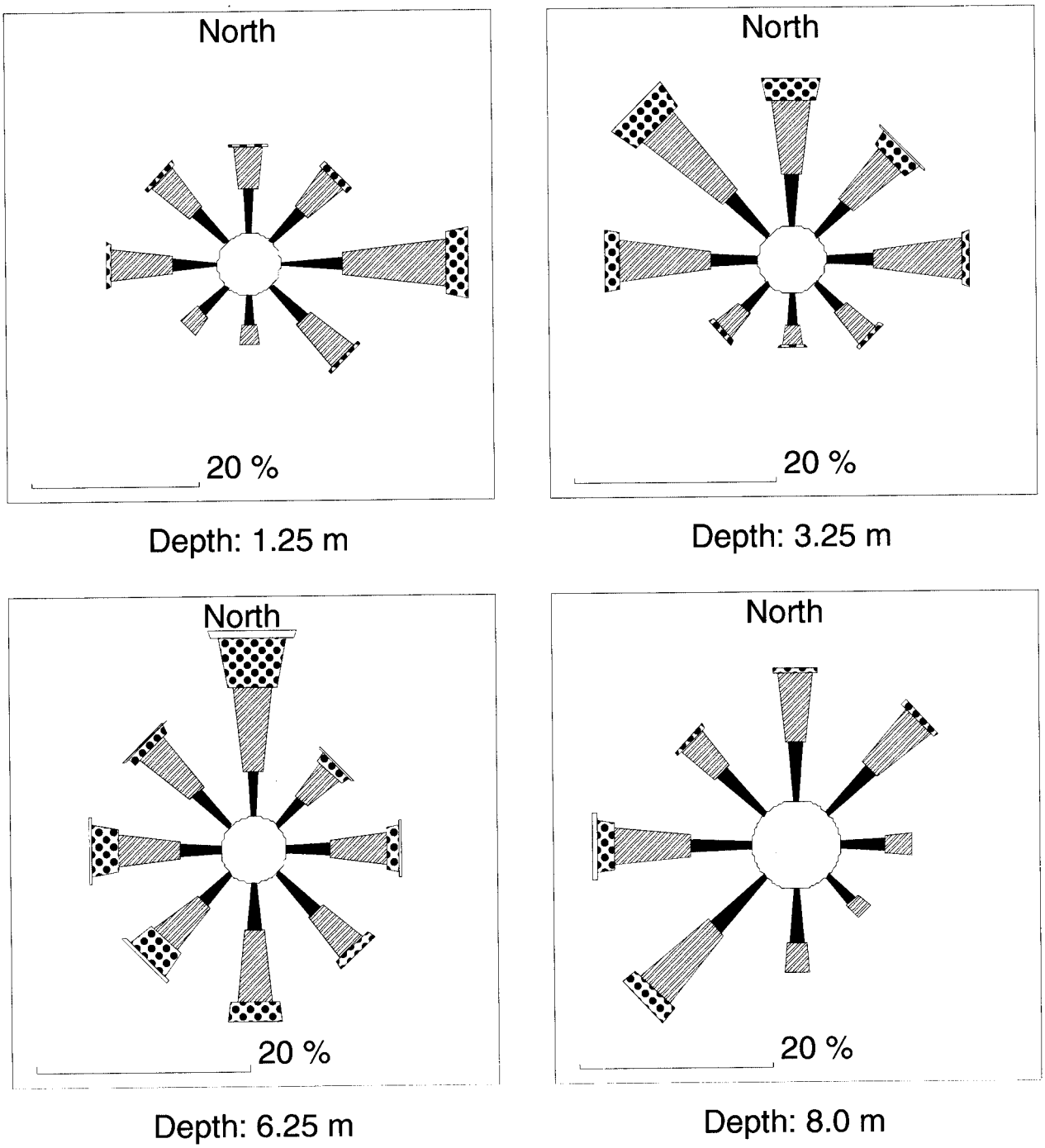

FIG. 6a. Current roses at the four depths for the July to September 1999 deployment. The circles represent calms (less than 0.005 m/s); the other velocity ranges are shown in the lower right panel of Figure 6b.

tion as well as did the progressive vector diagrams. The currents measured in 1991 and 1993 at intermediate depths were compared with the ADCP data at the same depths. The earlier data and the ADCP data were consistent in terms of variability and dominant flow direction, adding confidence to the interpretation of the 1999 and 2000 data being representative of long term patterns.

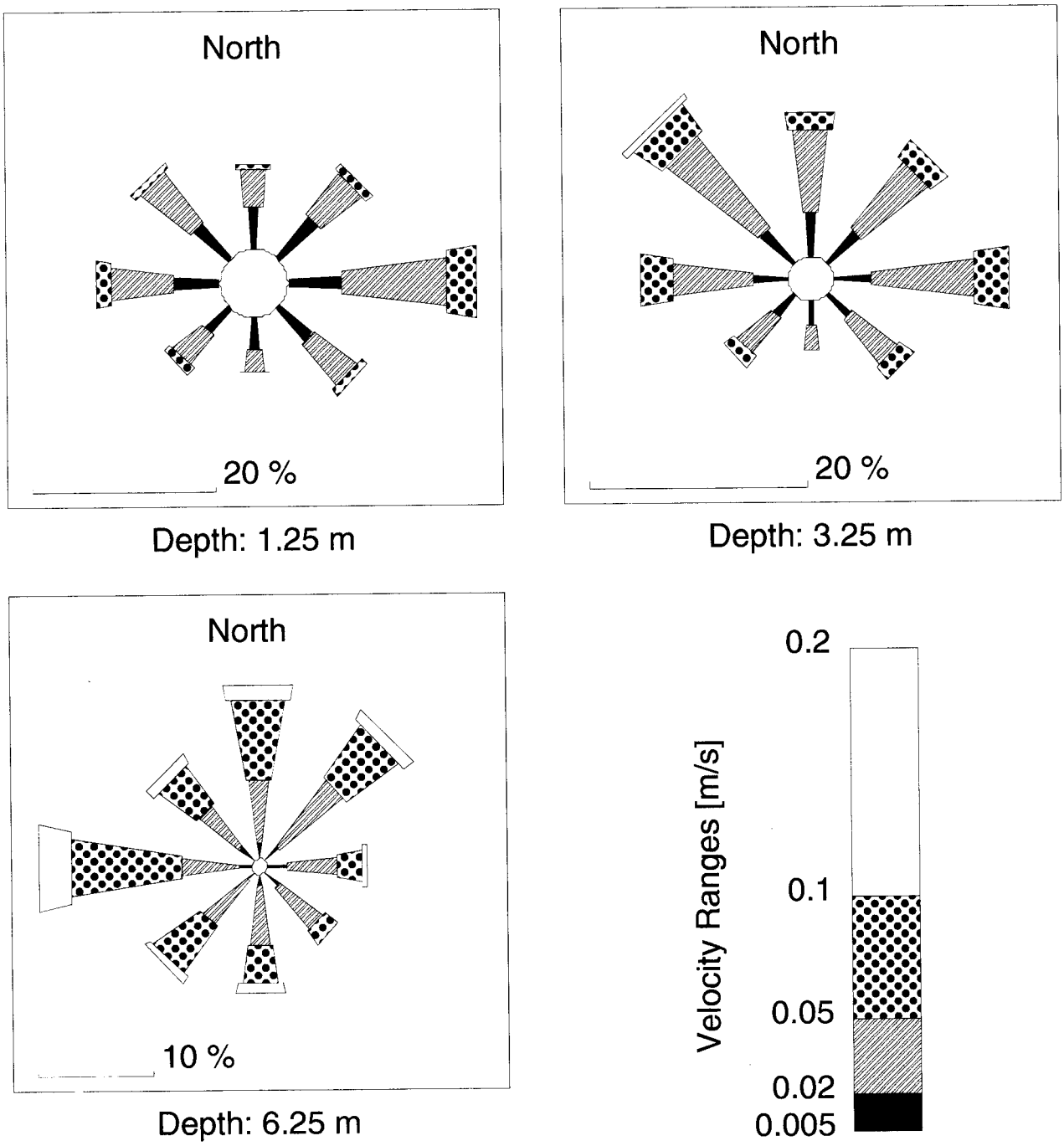

FIG. 6b. Current roses at the three depths for the May to October 2000 deployment. The circles represent calms (less than 0.005 m/s); the other velocity ranges are shown in the lower right panel.

Analysis of the current records, especially those collected in 1999 and 2000 containing information on vertical structure, showed that there was some flow in all directions at all depths. However, progressive vector plots of the various depths showed that the cumulative surface flow was influenced by the prevailing wind (toward the east and northeast). However, such onshore flows would soon be deflected by the nearshore bottom and shoreline topography along the shore. Because of the south-

easterly orientation of the downwind shoreline, it was expected that the flow would diverge and move parallel to the shore either northwesterly or southeasterly, depending on the initial direction. Judging from visual observation of the area after a period of onshore winds and heavy rainfall, it was expected that the southeasterly direction would predominate. It is commonly observed that high-turbidity plumes from streams entering the northeastern corner of the harbor tend to follow the eastern shoreline southward before reaching the Burlington Ship Canal.

The progressive vector plot for the bottom currents showed an overall pattern that was approximately in opposition to the surface flow (i.e., to the west-northwest). This was the expected pattern of return from onshore-wind-driven flow. At intermediate depths, the flows were generally northward with an increasingly westerly component with depth. It would appear that the least movement would be expected toward the south.

Plume Density

In reconciling the current patterns with the concrete evidence of the long-term tracer patterns, it appeared that there was a correspondence with the bi-directional dispersal pattern inferred. However, the strong systematic differences in the vertical structure of the currents at the outfall suggested that the location of the outfall plume in the water column would play an important role in its dispersal direction. Figure 3 shows that the relative density of the effluent plume varied considerably with time during the year. During the period January to August (roughly 8 months), the effluent was denser than the receiving waters and would have a tendency to sink and follow the generally northward and westward direction of the bottom and intermediate flows. Such a model would explain the tracer plume trend toward the north, then west, then southwest as shown in Figure 4. On the other hand, during the September to December period (4 months), the STP effluent was less dense than the receiving waters and would thus be expected to rise to the surface layer with the additional upward push of the outlet diffuser ports. As indicated by the surface progressive vector plots, the effluent plume would have been strongly advected onshore (eastward), then deflected generally southeastward along the shore before deposition. It can be expected that this eastward advection had been muted somewhat by the advection westward in the lowest part of the water column, but that the net effect is eastward.

Temporal Trends in Effluent Transport Patterns

Mixing of the STP effluent with the harbor water is influenced by factors such as the characteristics of the diffuser's discharge jets, the nature of the local hydrodynamic climate, and the relative density of the effluent with respect to the receiving waters. Comparison of the tracer patterns for the two surveys separated by 4 years showed little overall change. Although the data do not allow a rigorous statistical analysis of trends over this time, there appears to be an increase in the areas far removed from the outfall to the southwest where above-background values (~ 3 µg/g) extended past the limits of the grid. Discounting the anomalous value in the 1996 survey, the average coprostanol concentration increased very little over the 4-year interval, i.e., 49 µg/g in 1996, versus 43 µg/g in 1992 (Student's $t = -0.14$). The 1996 mean is slightly higher, but sample populations for both years are statistically identical. This suggested that, despite an increase in STP discharges from less than 80,000 m^3/day in 1992 to more than 90,000 m^3/day in 1996, the area of maximum impact remained virtually unchanged, except for those areas mentioned above. The impact of this volumetric increase could have been offset by an overall decline in the suspended solids content of the treated effluent from around 10 mg/L in the early 1980s to less than 6 mg/L in 1996 due to plant improvements. Furthermore, the number of major STP bypass events responsible for much of the high-coprostanol discharges fell from 119 in 1992 to 63 in 1996. The high coprostanol value near the islands, though statistically discounted, raised the possibility of occasional entrapment of contaminated sediment in the area behind the artificial islands where a warm-water fish habitat is planned. The rapid concentration reduction in the coprostanol levels near the outfall, and the maintenance thereafter of well-defined plumes, suggested that much of the effluent dilution took place in the vicinity of the outfall. The net effect of the diffuser jets was to mix the effluent with surrounding bay water and to propel it toward the surface. As a result, the effluent thereafter tended to follow the surface flows for at least one-third of the year, i.e., the roughly 4-month period when the plume was buoyant as well as other times when the density difference was slight and could have been overcome by diffuser momentum. The trajectory plots of the surface flows (Fig. 5) showed that most of these flows were toward the east and

northeast, and were later deflected southeastward toward the Burlington Ship Canal. The fate of the plume in the canal area was difficult to predict. Barica *et al.* (1988) found that although flows in both directions took place in the canal, the net outflow from the harbor to Lake Ontario was 646,000 m^3/day, or 0.5% of the total harbor volume. However, due to the complexity of the exchange flows within the canal, it was difficult to predict the effluent volume entering the lake versus that diverted back toward the central basin of the harbor. The tracer plume that curved north through south-west showed the most rapid dilution, although above-background values in areas far removed from the outfall could have been influenced by other effluent inputs, such as CSOs, the other 3 STPs (Fig. 1), or by dumping from ships in the harbor. The final sink of these contaminated sediments was apparently the central basin of the harbor.

Comparison with Hydrodynamic Models

Tracer results were compared with circulation model simulations for the northeastern area of Hamilton Harbour reported by Tsanis and Wu (1995). Using a 2-D (depth-averaged) nested-grid model, they ran simulations for several sections of the harbor. In the northeastern area, they ran the model for winds of 10 m/s from the north and west with varying topography including the presence of islands, no islands, and different bottom roughness. All the simulations indicated transport toward the south for both wind directions. There was no simulation that reflected the tracer's transport toward the north. This discrepancy revealed a potential shortcoming in the hydrodynamic model used, most likely the result of using a 2-D (depth averaged) approach and thus ignoring the important vertical changes in flow characteristics revealed in the current data described here. The above circulation model also was not set up to take into account seasonal changes in buoyancy of inputs.

SUMMARY AND CONCLUSIONS

The distribution patterns identified by the coprostanol tracer around the Burlington Skyway STP outfall reflected net transport and dispersal trends of STP-related contaminants in the northeastern sector of Hamilton Harbour. They could also be a potential proxy for the transport of other particle-reactive pollutants, such as POPs and trace metals. Although the current measurements near the outfall covered only the summer months (July to September) and omitted fall and winter periods, they nevertheless indicated a complex vertical structure in the water column. Surface currents were predominantly in the downwind (toward the east and northeast) direction, while bottom flow was approximately in opposition to the surface flow (toward the west-northwest). In addition to the current regime, the relative density of the effluent, which was seen to vary seasonally, played a significant role in the vertical location within the water column with which it tended to be advected. Thus, during the spring and summer months when the effluent was denser than the ambient harbor water, it tended to be advected by flows lower in the water column, thus moving the plume toward the north-to-west sector. Such a flow could explain the tracer plume along the north shore. During the rest of the year, the effluent was lighter and more buoyant and would have been more influenced by the surface current, which would have advected the plume more strongly onshore, where it would have been deflected alongshore toward the south. This model explained the bi-directional nature of the tracer pattern in the sediment. It also argues strongly for the incorporation of a 3-D perspective in hydrodynamic models used even in shallow-water nearshore areas.

From a Hamilton Harbour management and remediation perspective, the spatial impact of the STP outfall showed only a slight increase over the period studied, primarily due to plant improvements. Furthermore, the tracer patterns indicated the effluent was reduced fairly rapidly to near background levels (< 3 μg/g) within 2 kilometres of the outfall, although between the 1992 and 1996 surveys, the mixing zone appeared to have increased slightly toward the southwest. The large area of non-deposition of coprostanol offshore from the outfall increased in size toward the north. The results also suggested the potential for entrapment and accumulation of STP-source contaminants and nutrients behind the small artificial islands constructed in 1995 to the east and southeast of the outfall. Nevertheless, the dominant trend was for the STP effluent and its contaminant/nutrient burden to be transported as a plume southeastward to the area of the Burlington Ship Canal, where it was advected inward or outward according to undefined, but complex, processes. The other trend toward the north and west eventually was reduced to background levels near the central basin of the harbor. A particularly noteworthy result of the study is the conclusion that the STP plume did not move di-

rectly offshore where minimum values were consistently found, but inshore and alongshore. This raises questions regarding the potential impact of the plume distribution on other Hamilton Harbour issues such as aquatic recreation activities, nearshore macrophyte growth, and uncontaminated habitats for fish and birdlife in these nearshore zones.

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