Signatures contained in suspended particulate matter with application to coastal-ocean environmental studies.

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ABSTRACT
Suspended particulate matter (SPM) samples from the New York Bight Apex collected during a sewage-dump experiment were analyzed for chemical as well as physical parameters such as particle-size distributions. The latter provided a signature of the SPM’s sewage component that allowed differentiation from other components. These results were applied to a series of eight Water Column Characterization (WCC) cruises in this area. Co-analysis of WCC and sewage dump particle-size distributions by factor analysis and Distribution Component Analysis revealed patterns that allowed differentiation of sewage-derived components for all WCC samples. From this, a long-termed budget of SPM components, including sewage-derived materials, was constructed.

Given this, we conclude that useful tools are available for developing signatures of anthropogenic components of SPM plumes which are independent of study sites or subject materials. These signatures can be applied to understand the sources, pathways and sinks of such materials in the coastal ocean as well as constructing long-termed budgets thereof. Ultimately such estimates can be critical to waste management strategies and decisions in an ever more anthropogenically-impacted coastal ocean.
1 Introduction

The coastal zone not only supplies man with recreational resources but is also an area of high biological productivity and as such is important to critical fisheries resources. Therefore, our impact on this area will ultimately affect man’s interest. This is brought into focus by realizing that approximately 50% of the world’s population today is believed to live within 60 km of a coastline. With a growing global population and therefore a growing number of people living adjacent to the world’s coasts, anthropogenic impacts of pollution and environmental alteration of the coastal zone have accelerated over the last decades.

Natural aqueous systems such as lakes, rivers and oceans can be described, in part, by their dissolved and particulate components. Particulate sources in coastal oceanic environments include natural materials from seaward riverine and estuarine flows as well as anthropogenic sources such as ocean dumping and outfalls. As such, plumes of SPM can be natural (lithogenic and biogenic), anthropogenic, and any mixture of these. Because SPM can range from environmentally neutral (i.e. lithogenic and biogenic) to hazardous (heavy metals, bacteria, viruses...), detecting, tracking, sampling and sourcing SPM plumes can be beneficial for the environment and human health.

It will therefore be the objective of our work to briefly describe acoustic methods for in situ detection of plumes resulting from sewage discharge and then focus on longer-termed detection of sewage effluent through both chemical and physical signatures. To accomplish the latter we will describe methods to analyze sewage waste dump materials, characterize the components and apply these results to long-termed monitoring of SPM in a study area. In turn, the final goal of the monitoring was to describe tools for a long-term, regionally-integrated characterization of SPM and component budgets thereof.

Data for this paper results from a combination of two studies. The first was a long-termed monitoring of the New York Bight Apex to understand the full spectrum of particle types and their seasonal variation in this study area (Nelsen, 1979). This effort implemented a temporal/spatial sampling pattern for eight monthly cruises over a 25-station sampling grid at consistent depth intervals (Fig. 1a). The second was a shorter-termed study focused on sewage dumping in this same area. (Johnson et al, 1977). Although this paper will focus on past sewage sludge dumping in the New York Bight Apex on the East Coast of the United States, the methods and approaches of this paper have a universal applicability.

2 Methods

2.1 Acoustics - Detection

Active in situ acoustic technologies have been show to provide real-time detection of water-borne particulate matter including sewage effluent plumes arising from both surface dumped (downward trajectory) and outfall related (upward trajectory) sources. These technologies are valuable for provision of
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the initial and short term, e.g. a few hours, spatial distribution of effluent material within the water column (Proni et al., 1976; Proni and Williams, 1997). However, for longer-termed observations, other tools must be used such as particle characterization.

2.2 Suspended Particulate Matter – Signatures

Suspended particulate matter, for this study, was sampled and total TSM was determined by standard at-sea CTD/rosette water bottle sampling of the water column and gravimetric analysis for TSM. Additional aliquots of water were taken for particle-size analysis and scanning electron microscope imaging, as previously described by Nelsen (1979, 1981) as well as limited particle chemistry by normalized energy dispersive analysis (Nelsen, 1978). In brief, particle-size analysis was done by Coulter Counter and expressed in standard \( \Phi \) intervals \([ \Phi = -\log_2 d, \text{where } d = \text{particle diameter in mm} ]\). The size domain of analysis, in most cases, extended from \( 4.0\Phi \) (62.5 \( \mu \text{m} \)) to \( 9.0\Phi \) (1.95 \( \mu \text{m} \)) and represents boundaries imposed by equipment rather than natural size limits. Open-ended distributions imply probable continuation of the natural particle size domain beyond analysis limits.

In an attempt to establish signatures of sewage-derived materials, particle-size distributions were subjected to Q-mode factor analysis as first describe by Nelsen (1981). This is a statistical technique for analyzing large volumes of data, which can be expressed in the form of a set of numbers associated with each sample (e.g. – frequency % in each class-interval of a particle size distribution). The objectives are to extract simple and meaningful relationships and patterns from these data sets by a small number of factors, also know as end-members (EM). In complex natural systems, any number of end-members can exist to explain sample variation but normally distributions are mixtures of more that one end-member such that typically \( EM > 1 \) but \( < 5 \). In a multi-EM system, results of Q-mode factor analysis can be expressed in relative percentages of respective end-members. For example, if \( EM = 3 \) for a given factor-analysis run, then the particle-size distribution of any sample in the analysis suite will be expressed as a relative proportion of each end member such that for sample “n”: \( EM_1 = "x" \) %; \( EM_2 = "y" \) % and \( EM_3 = "z" \) % where \( x+y+z \) % = 100 %. By plotting and contouring these relative end-member percentages for all samples in their field position, patterns may emerge that will help interpret the natural system being studied. Details of this method can be found in Nelsen (1981) and examples will follow in this paper.

Additionally, particle-size distributions were subjected to distribution-component analysis as first described by Curray (1960) and subsequently successfully applied to sediment-dispersal studies by van Andel (1964, 1973), Oser (1972) and Ashley (1978) to cite a few. In brief, Curray (1960) showed that multimodal sediment distributions are really composites of several intermingled normally distributed components. Oser (1972) demonstrated that although it is possible, in some cases, to slightly change the widths and heights of the component curves, the number of component modes and their means remain fixed for any given size-distribution. Although the existence and
maintenance of log-normalcy of components remains a moot point, log-normalcy for components will be assumed here in the absence of compelling arguments against it. Components were resolved from the particle-size distributions with Jandel Scientific’s “Peak-Fit” software with the intent of understanding the relationship, if any, between factor and component analysis and optimizing the information available from both techniques.

3 Results and Discussion

3.1 Acoustics – Detection

A field experiment to monitor and characterize a sewage sludge dump was carried out using acoustic remote sensing and water sampling. In this experiment both “line” and “spot” dumps of sewage sludge occurred (Johnson et al., 1977). In Fig. 1b are shown the acoustic data obtained during a series of passes over a line dump (from about 500 to 2300 meters on the bottom range scale) and a single pass over a spot dump (centered at ~2800 meters on the range scale). Two acoustic frequencies (20 kHz, Fig 1b upper; and 200 kHz, Fig 1b lower) were utilized to detect and map the subsurface distributions of dumped sewage sludge. Note that the sludge dump extends from the ocean’s surface to the seabed (depth ~23 meters). Signals such as these are displayed in real-time and allow guidance for both short-termed mapping of sewage dispersal as well as real-time guidance of water-column sampling. However, when particle concentrations fall below acoustic detection levels, alternate tools must be employed for longer-termed detection of sewage-sludge particle dispersal patterns.

3.2 Suspended Particulate Matter – Signatures

Water-borne SPM can be describe in a broad range of ways varying from a simple expression of the amount in a unit volume of water (TSM as mg/l), it’s mean particle size, the detailed nature of the particle-size distribution, as well as the physical and chemical nature of its constituent particles. The following discussion will consider all of these in that order.

3.2.1 Basic Measurements

A simple gravimetric measurement of TSM (mg/l) gives us an initial indication of how much material is present, essentially the water’s turbidity, but little information as to any other physical or chemical property. The limit of this level of information is clearly demonstrated in Fig. 2a-b where two samples from the study area have identical TSM values (0.4 mg/l) but quite different particle-size distributions (means = 6.16 vs. 7.68 Φ or 14.0 Vs 4.9 μm respectively). This implies, but does not prove, that we are probably dealing with, at least in part, two fundamentally different particle suites. From this it is clear that the use of particle-size distributions can provide additional information about particles through the use of simple statistical measures of their distributions. However, common statistical measures of central tendency such as mean and standard deviations were devised as descriptors of distributions,
which are or approach statistical normalcy. When distributions such as particle-size distributions become bi- or polymodal, such descriptors lose their rigor and become inappropriate or misleading. This is clearly demonstrated in Fig. 2c-d.

These samples, again from the study area, exhibit identical means (5.95 Φ) but have dramatically different distributions with the implication of different particulate constituency. As before, it is clear that more fundamental and useful information is available from these data.

3.2.2 Distribution Component Analysis

The unimodal and trimodal samples shown in Figs. 2c-d were analyzed using Distribution Component Analysis (DCA) and the results are shown in Figs. 2e-f respectively. From these figures the following observations can be made: 1) each overall particle-size distribution can be expressed as a suite of normally distributed overlapping components of varying size and position, the composite of which rigorously account (i.e. \( r^2 = 0.989 \) and 0.973 respectively) for the original overall distribution; 2) although little commonality seemingly existed between the unresolved distributions (Figs. 2c-d), DCA indicates some commonality. This is suggested by varying sized peaks centered at or near 4, 5, 6 and 7 Φ in both distributions. Commonalties such as these form the basis for SPM signatures and thus merit a more rigorous and detailed investigation for sewage-derived SPM materials and long-termed monitored SPM in the study area.

During a coordinated intensive study of sewage dumping in the New York Bight Apex (Proni et al., 1976; Johnson et al., 1977) water samples were taken to characterize the post-dumped physical and chemical nature of sewage sludge. Four samples of sludge dump materials (SD-3, -5, -7, -9) were collected for size-distribution and SEM/EDA analysis. Results of size analysis indicated essentially four identical distributions (i.e. 7.13 ± 0.02 Φ) of which two are illustrated in Fig. 3a along with a SEM image of the material (Fig. 4a). The unimodal distributions of SD-5 and SD-7 were then analyzed by DCA and the results are shown in Figs. 3b-c respectively. For each, three component peaks rigorously (\( r^2 = 0.986, 0.996 \)) accounted for the variation in the overall distributions and were characterized by a major peak centered near 6.9Φ and two smaller satellite peaks centered near 6.0 and 8.0Φ. Minor variations in the exact position of each component peak (i.e. – peak 1: 5.93Φ VS 6.04Φ; peak 2: 6.85Φ VS 6.93Φ; and peak 3: 7.89Φ VS 8.09Φ) are minor in terms of absolute size differences (i.e. peak 1: 16.4 Vs 15.2 μm; peak 2: 8.7 Vs 8.2 μm; and peak 3: 4.2 Vs 3.7μm respectively). As such, these components form a triplet of distinct peaks that we propose as a potential signature of sewage-derived SPM dumped in the study area. The validity of this signature will be demonstrated below when a comparison is made with SPM size-distributions collected during the long-termed monitoring study near and around the sewage dump site in the New York Bight Apex.
3.2.3 Factor Analysis

A time-series of Water-Column Characterization (WCC) cruises, to set station locations and sampling depths in the New York Bight Apex, was previously described by Nelsen (1979) for TSM, size-distributions and particle compositions. Subsequently, these data were used for the first application of Q-mode factor analysis on SPM samples (Nelsen, 1981). Results indicated that throughout an eight-cruise series, two to three factor-analysis end-members could account for >90% of all sample variation for each cruise. Moreover, these end-members formed a consistent pattern of constituent particles that seasonally shifted in relative importance such that not only could biological components be sorted out from non-biological components but also seasonal biological blooms could be identified. As such, these results indicated that the products of factor-analysis could be used as a SPM “signature analysis” tool. With this in mind, subsequent re-analysis of these data was focused on re-evaluating the WCC time series for sewage-derived components of this data set.

Re-evaluation of the 625 sample WCC data set, with the inclusion of sewage-derived samples (SD-3, -5, -7, -9), indicated that the known sewage-derived samples formed a strong affinity to one end-member for each of the eight cruises. This “sewage-like” end-member varied in importance from cruise to cruise but was always present, as summarized in Table 1.

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Table 1: Factor-Analysis Variance Scores with Sewage Component Communalities.

The numeric values in this table describe the total sample variance that is explained by each successive end-member while the grayed-toned values represent the end-members to which the known sewage sludge samples had the greatest affinity. A measure of this affinity, the communality (on a scale of 0-1) measures the “goodness-of-fit” of samples SD-3, -5, -7, and -9 to that end-member. Given these high communality scores (i.e. goodness of fit), all 625 samples from the WCC series could be meaningfully expressed as a relative percentage of sewage-like material based on the proportion of a sample that could be explained by the “sewage-like” end-member for that WCC cruise.

As demonstrated above with TSM and sample means, misleading conclusions can be derived from simple reliance on numbers, especially ones as abstract as factor analysis end-members derived from SPM size-distributions.
As such, independent validation of these results is essential. To this end, samples from the WCC data series were selected for comparative analysis with DCA as well as potential chemical signatures (SEM/EDA) and visual qualitative evaluation in SEM images.

3.2.4 Factor Analysis vs. Distribution Component Analysis

To test the validity of factor analysis resulting from inclusion of samples SD-3, -5, -7, -9, numerous WCC samples were selected which had sewage-like affinities ranging from 0-90%. First, three samples with high estimated sewage-like affinities were analyzed by DCA and the results are shown in Figs. 5a-c. In each case, the complex overall size-distribution envelope was resolvable into numerous subcomponents, the composite assemblage of which strongly accounted for (i.e. $r^2 \geq 0.996$) the total original frequency distribution. Of particular interest are the three bold-lined peaks centered at or near 6, 7, and 8$\Phi$ which closely correspond to the component positions noted for the sewage samples (Fig. 3b-c). For direct comparison of analytical positions of this triplet of peaks, Fig. 5d summarizes the $\Phi$-based peak positions for the known sewage samples, the three WCC samples of Fig. 5 and an additional sample (WCC 8 2-1) not illustrated but analyzed by DCA. It is clear from Fig. 5d that the centroid of each of the three component peaks forms a consistent, non-overlapping pattern with positions at $5.99 \pm 0.17 \Phi$, $6.98 \pm 0.10 \Phi$, and $7.90 \pm 0.10 \Phi$. Moreover, this, as well as inspection of Figs. 5a-c confirm, as earlier noted in work by Oser (1972), that peak width and heights may change in a given distribution but peak positions remain essentially fixed.

We therefore believe that these observations provide compelling evidence that DCA of the particle-size distributions provides a useful and powerful signature-analysis tool for discriminating the sewage-like components of WCC samples. As noted above, re-analysis of WCC size-distribution data with the inclusion of known sewage samples (SD-3, -5, -7, -9) allowed all WCC samples to be re-expressed with an estimated sewage-like component percentage. For the samples in Figs. 5a-c, such estimates ranged from 75%, 83% to 90% respectively. Similar estimates can be obtained from DCA by evaluating the area under the curves of the three critical component peaks. For the samples in this figure such estimates are 72%, 64% and 74% respectively. For the first sample (Fig. 5a) a very good agreement is reached while the second two differ by only 19% and 16% respectively. Although the DCA method is consistently lower than the factor analysis method, it is difficult to establish which tool provides the most accurate estimate. However, we believe that each method tells essentially the same story and as such both can be used for signature analysis of sewage-like material.

It would be reasonable to ask if these comparison are only good under conditions of high estimated percentages of sewage-like material. To evaluate this, the three end-member distributions from cruise WCC 7 were selected for two reasons. First, that two of the three end-members had no sewage-like component as estimated by factor analysis and secondly SEM/EDA of all WCC 7 samples for chemical tracers of sewage sludge was done as a final independent
check of the factor analysis and DCA results. A discussion of the latter will follow in the next section. Figure 6 shows the size- (6a, c, e) and component- (6b, d, f) distribution results for the WCC 7 end-members. For end-member 2 (Fig. 6d) the comparison is very good with factor analysis and DCA estimates of 75% vs 72% respectively. For end-members 1 and 3 (Fig. 6b & f respectively) factor analysis and DCA differ (EM-1: 0% vs 7% and EM-3: 0% vs 14%). Two points need be noted here concerning these minor differences. First, that in each case (i.e. EM-1 and EM-3), the DCA estimate resulted from the presence of only one small peak in the approximate position of one of the triplet signature peaks. Moreover, each occurred in the tail of these distributions where class intervals comprised only 1-2% each, of the total distribution and thus were potentially susceptible to analytical error and noise. As such, in the absence of the otherwise ubiquitous three signature peaks and their small size, the DCA estimates for EM-1 and EM-3 (Fig. 6b, f) probably represent unjustified inclusion, and therefore these samples constitute good agreement between factor analysis and DCA.

In support of this conclusion, SEM images of samples seen in Figs. 6b & d are shown in Figs. 4c & b respectively. Direct comparison of the materials that constitute the sewage-like SPM of Fig. 6d with the known sewage materials (SD-7) in Fig. 4 (i.e. Figs. 4b Vs 4a) indicate a strong visual similarity. In contrast, a similar comparison between the SPM materials of Fig 6b, with an estimated sewage-like component of ~0 %, to the known sewage materials (Figs. 4c Vs 4a) shows no apparent similarities.

3.2.5 Chemical Signatures

Both factor analysis and DCA relied on estimates of sewage-like components from comparison, although be it strong, to four known sewage sludge samples and all results to present have relied on only one parameter, particle-size distributions. It is reasonable to believe that particles other than sewage sludge can have size-distributions that mimic these shown (SD-3, -5, -7, -9 and WCC series) above. As such, an independent test of the validity of the above conclusions was sought and subsequently established with chemical signatures common to both the known sewage sludge and the inferred sewage-like components in WCC samples.

To test the chemical signature concept, all SD and WCC 7 samples were analyzed by SEM/EDA and results were normalize as noted in Methods. In brief, all four SD samples contained strong Ti and Fe signals. Similar analysis of all WCC 7 samples (n = 64) indicated essentially all contained Fe but only 12 contained Ti. The factor-analysis based estimated percentages of sewage-like materials of these 12 samples ranged from 10-56% and are seen co-plotted with the SD samples in Fig. 7. A linear fit to these data yielded an \( r^2 = 0.79 \). Moreover, the WCC 7 end-members 1 and 3 with factor-analysis estimated sewage-like percentages of zero had no detectable Ti and thus would have plotted at the origin of Fig. 7. We believe therefore, that these data provide compelling validation of the factor analysis and DCA results and establishes
three viable signature methods (factor analysis scores, DCA triplet component peaks, Ti/Fe ratios) for sewage sludge materials in the New York Bight Apex.

### 3.2.6 Suspended Particulate Matter – Sediment Budgets

The strong mutual agreement shown above for estimating the sewage component of SPM from factor analysis, DCA, and chemical signatures allows faith in the validity of these methods. From this, we now have tools to estimate long-termed SPM budgets and an estimated sewage component thereof. Three examples will now be given for both temporal, temporal and spatial, and spatial distributions of the estimated sewage sludge material in the study area.

Using factor-analysis estimated percentages of WCC series data, temporal sediment budgets were constructed as was previously done by Nelsen (1981) but now with sewage-like components separately identified. Based on known TSM values for each sample in the WCC series, in conjunction with estimated Apex station/depth volumes (see Nelsen, 1981 for details), a series-long sediment budget was constructed as seen in Fig. 8a. Expressed in metric tons of SPM per cruise, the relative rank and total estimated tonnage of sewage-like component (black intervals with adjacent numeric tonnage) is seen to vary for each cruise with the largest relative percentages seen for late-fall cruises WCC 12 and 13.

Viewed alternatively, data can be presented in a temporal series (i.e. April (WCC 6) to December (WCC 13)) but re-partitioned into spatial depth segments at 1, 10 and 20 meters as seen in Fig. 8b for *only the sewage component* of Fig. 8a. In this manner, we can determine the long-termed importance of not only seasonal loading of the New York Bight Apex as a whole, but also the relative importance and concentration depths of the sewage material over time and the seasonal variability thereof.

Finally, when time-series data such as the WCC series is collected over a consistent position/depth grid (Fig. 1a) detailed dispersion maps can be constructed for all cruises, depths and cross-sections therein. One such example is given in Fig. 9 for WCC 12, a cruise with abundant sewage-like materials (Fig. 8). Figure 9a shows a map view of the sampling grid and factor analysis results for 1-meter depth expressed as a concentration of only estimated sewage material (milligrams of sewage material per liter of water). From this the broad dispersal pattern of material can be seen across the Bight Apex relative to the sewage sludge dump site (SSDS) and the Hudson Shelf Valley (HSV). Notable too is the strong signal coming from the NW corner of the study area related to the outflow of the New York Harbor/ Hudson-Raitan estuary system. Figure 9b represents the A-A’ cross-sectional view marked in Fig. 9a. Worth noting here are not only the elevated concentrations at 10 m, as quantified in Fig. 8b, but also the downward dispersal into the HSV. Documented current movements and transport (Lavelle et al., 1975, Nelsen et al., 1978) in the HSV in conjunction with data such as Fig. 9 suggest these materials are delivered to and transported in the HSV. This suggestion is confirmed by work on sewage derived human steroids (coprostanol) found in sediments of the New York Bight Apex and Hudson Shelf Valley (Hatcher, 1977).
4 SUMMARY AND CONCLUSIONS

With growing global populations and increases in anthropogenic inputs such as sewage-derived materials into our coast oceans, concomitant increases in ecological stresses on this economically important zone continue to mount. As such, a knowledge of long-termed fates of our waste disposal materials may help us understand its relationship to dispersal patterns and perhaps interactions with the in situ biological food web upon which man, to one degree or another, depends.

To this end we have shown methods which we believe are useful for tracking of sewage sludge materials dumped in the New York Bight Apex. Although our example location and materials were site and type specific, we believe the underlying principles can be applied to any anthropogenic, and natural materials, placed into the coastal oceans where plume location and particle-signature identifications are useful for short- to long-termed tracking of subject materials.

Specifically, we have shown:

- Acoustic technologies are available and applicable to real-time tracking and sampling-guidance of dumped materials.
- Analysis of SPM obtained from water samples can aid in understanding longer-termed dispersal patterns of subject materials.
- Parameters such as TSM (mg/l) and simple particle-size means are of limited utility in complex natural environments.
- Information contained in particle-size distributions can be extracted with tools such as Distribution Component Analysis (DCA) and/or factor analysis and effectively constitute “signature analysis” of target components.
- Factor analysis and DCA not only give reasonable mutually consistent estimates of specific components in a particle-size distribution, in this case sewage sludge, but are consistent with independent chemical estimates of the same.
- The robustness of these techniques allow even retrospective analysis of data sets in order to estimate long-termed dispersal patterns and/or budgets of target components.
- Such estimates can be critical to waste management strategies and decisions in an ever more anthropogenically-impacted coastal ocean.
References


Figure 1. A) Map of study area for WCC cruises and location of Sewage Sludge (SS) dump site. B) Acoustic backscatter images at 20 kHz (upper panel) and 200 kHz (lower panel) of sewage-dumps in the study area.
Figure 2. Particle-size distributions illustrating A-B) identical concentrations (TSM) but different means; C-D) identical means but significantly different distributions; E-F) Distribution Component Analysis (DCA) of distributions shown in C-D.
Figure 3. Particle-size distribution characteristics of exemplary sewage-dump samples for A) simple size distributions for samples SD-5 and SD-7; B) DCA of SD-5; C) DCA of SD-7
Figure 4. Scanning electron microscope images, all at 200x, of A) SD-7; B) WCC 7 S17-20 (see Fig. 6c,d); C) WCC 7 S25-20 (see Fig. 6a, b)
Figure 5. A-C) DCA peaks for the particle-size distributions of three WCC samples estimated by factor analysis to contain high proportions of sewage-like materials including the triplet of signature peaks (bold lines) for the sewage component of SPM from the study area; D) comparative plot of the three phi-sized modal positions for the sewage-component signature peaks from the known sewage samples (SD-5, -7) and four WCC samples.
Figure 6. A,C,E) Size distributions and B,D,F) DCA peaks of the end-member samples from WCC 7.
Figure 7. Comparison of the Ti/Fe ratios of the samples (circles) from WCC 7 identified by factor analysis to contain sewage-like materials and the four known sewage samples (SD-3,-5,-7,-9 – squares).
Figure 8. Suspended particulate matter budgets for A) WCC 6-13 cruises the emphasis on the estimated sewage contributions (black interval with numerical tonnage values); B) Tonnage estimates of only the sewage component of data shown above in “A” for the WCC 6-13 cruises at depths of 1, 10 and 20 meters.
Figure 9. Factor-analysis based concentration (mg/l) estimates of only the sewage component for WCC 12 A) in map view for the entire study site at the surface (1 meter) showing the position (curved arrow) of the Hudson Shelf Valley (HSV) and the position of the sewage sludge dump site (SSDS) at the time of the cruise; B) cross-sectional view for line A-A' in map view above. Bottom shown in bold nature.