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Mapping Potential Effluent Pathways in the Long Point Region of Lake Erie from LANDSAT Imagery[1]

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ABSTRACT

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As one component of an analysis of liquid effluent dispersion in the Long Point area of Lake Erie, the regional surface currents are mapped from LANDSAT satellite imagery for a sample of eight cases. These current patterns are interpreted from the configuration of sediment tendrils observed on enhanced and classified images. The current trajectories are viewed as potential effluent pathways. Evidence of a "coastal jet" which has been simulated in numerical models and which has been proposed to be an effective flushing agent, is found along the south shore of Long Point for all weather patterns studied. In Long Point Bay, a counterclockwise flow is observed along the coast in all cases. This appears to be part of a gyre within the Bay. It is possible that effluents released into the Bay would become part of a closed circulation. The implications for the sensitive marshes in the region must be considered.

ADDITIONAL INDEX WORDS: *Effluent pathways, current trajectories, coastal jet, gyre, Lake Erie, LANDSAT*

INTRODUCTION

In the late 1970's and early 1980's, several large industrial facilities began operation at Nanticoke on the north shore of Long Point Bay in Lake Erie (Figure 1). Prior to the 1970's, this was an essentially rural countryside. It has recently become a rapidly expanding industrial and urban community with new initiatives attracted by the inexpensive water transportation, available space and nearby markets. Environmental planning for the impacts of the complexes began in 1967 under the direction of the Nanticoke Environmental Committee.

In 1979, the senior author was commissioned to investigate the local dispersion characteristics of industrial liquid effluent from one complex using *in situ* data collection and large scale aerial photography. The objective was to map the regional geometry of the discharge plume for a variety of weather patterns as a supplement to engineering design predictions (LEDREW and FRANKLIN, 1983).

The study concluded that the visible plume was typically smaller than anticipated and there would be minimal ecological impact with the present discharge rates. Nevertheless, we thought it prudent to evaluate the dispersion characteristics from the smaller scale regional perspective as part of the resource management process. The pertinent question is: What are the ultimate long distance destinations of effluents? As the industrial park and supporting urban structure expands, we may expect a growing number of sources with increasing discharge rates. The cumulative effect must be assessed.

This question arises from the suggestion that the currents within Long Point Bay may form a closed gyre (CHANASYK, 1970). There would be transport along the shore and possible accumulation of sediments within the eye. If effluents follow the same transport system, these regional currents should be studied in detail as an extension of the interpretation of large scale dispersion from individual sources.

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The resultant maps of current patterns may be viewed in terms of potential pollution pathways. Of particular interest are the marshes of Turkey Point and Long Point on the other side of the Bay. Both areas have been the subject of extensive ecological and resource management studies and their sensitivity to stress has been noted (BAYLY, 1979; KNIGHT, 1983).

In this paper we examine LANDSAT imagery of the Long point region to identify the synoptic geometry of the surface currents for several dates. This is a first step towards addressing the question posed above. We must determine whether there is a gyre or alternative current configuration and what its spatial characteristics are. With this information, we may make an informed judgement as to whether there is a problem and design a subsequent study to provide *in situ* data regarding transport rates and dilution ratios.

Previous work at Lake Erie (HAMBLIN, 1971) and Windermere (GEORGE, 1981) has shown that the wind field is the major control on the surface current dynamics. Consequently, we wish to study the configuration of the currents in response to different regimes of the atmospheric wind stress. The sample of LANDSAT imagery represents a variety of weather patterns. This sample will not only give insight into the range of potential dispersion pathways but the synoptic maps of the current configurations also will be of interest to numerical modellers of surface currents and those studying the long standing problem of the processes of shoreline erosion and accretion in the Great Lakes (*e.g.* BOYD, 1979).

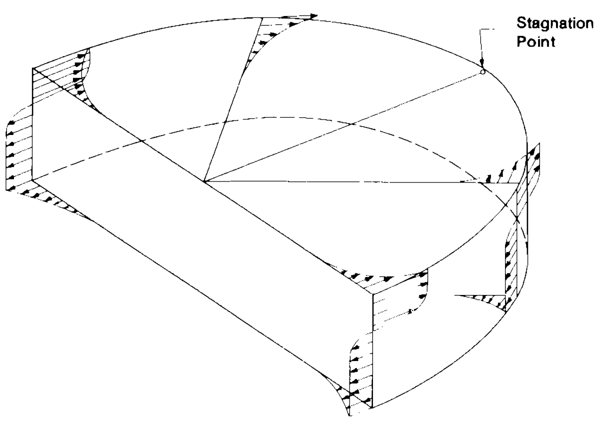

Figure 1. Long Point region and bathymetric map. Depth contours are in meters.

INTERPRETATION OF SEDIMENT PATTERNS ON LANDSAT IMAGERY

The synoptic and repetitive coverage of offshore regions since the launch of the first LANDSAT satellite in 1972 has attracted several studies of sediment patterns by coastal engineers and oceanographers. In pure water, Band 4 (reflected green radiance) has the capability of penetration up to 20 m (GORDON, 1975). The radiation can be reflected from subsurface topography or sediment settling at depth, if not obscured by intervening layers of particulate. Band 5 (reflected red radiance) has maximum penetration of 2 m and therefore reflected signals respond to near surface sediments. Penetration decreases further in the reflected near infrared (Band 6) and far infrared (Band 7) portions of the spectrum. In sediment laden water, the depth penetration is reduced considerably in all bands.

It is not clear which LANDSAT band provides the best demarcation of sediment density. In a study by ABIODUN and ADENIJI (1978), Band 5 pixel reflectances alone, adjusted for solar zenith angle and atmospheric attenuation, were correlated with secchi depths with coefficients in excess of 0.92 for four dates. Furthermore, an image classification based upon all four bands yielded maps that clearly depicted seasonal oscillations in the turbidity front within Lake Kainji in Nigeria. However, VERGER (1980) used a portable radiometer simulating the Landsat reflectance bands to measure upwelling radiance for different sediment densities and found a clear distinction between Bands 4 and 6 with respect to turbidity, but there was not a consistent contrast between Bands 4 and 5 nor between Bands 5 and 6.

Unfortunately we do not have historical records of sediment density that correspond to the LANDSAT images selected from the archives for this study. One image follows by one day a field session in the region (June 13, 1980) for which we have aerial photography of the near shore plumes which lends confidence to the qualitative mapping of pattern but does not allow quantitative measure of density.

Consequently, we follow ROUSE and COLEMAN (1976) and others (TELEKI *et al.*, 1973; ROBINSON and SRISAENGTHONG, 1981), and map sediment tendrils as proxy indicators of the current directions on the presumption of mass transport down the density gradient. It is recognized that a single image frame is a static representation and does not reveal the dynamic nature of a surface. We cannot infer velocities directly from the imagery. We can only deduce the direction of the surface mass movement at one point in time. Absolute sediment density is not necessary if we examine only relative densities for each image individually.

LANDSAT is deemed preferable in comparison to NOAA satellite sensors for this study because of the high spatial resolution that is necessary to map the fine structure of the sediment tendrils. For one of the cases discussed in this paper, the result of a LANDSAT analysis was compared with the result of a Coastal Zone Colour Scanner (CZCS) analysis. While the optimal radiometric characteristics of the latter enabled clear demarcation of sediment density at coarse resolution. we could not be confident of the details of the current pattern because of the larger pixel size of 825 m. In future studies, sequential CZCS images will be examined to understand the daily evolution of the macro features of the currents using one LANDSAT image to confirm the details.

METHOD OF ANALYSIS

Sediment patterns for eight dates were mapped. The cases were selected after examination of fiche records of LANDSAT imagery to identify images with sufficient gradation of tone within Long point Bay to map sediment tendrils.

These dates also represent a variety of weather patterns. For all cases the surface weather maps for 18Z on that day and also for the previous four days were examined to determine the development of the regional air flow. The mean surface wind speed and direction for the day were taken from the Delhi (Figure 1) climatological record which is the Atmospheric Environment Service station closest to the Long Point region.

For two cases, only hardcopy imagery was available and the contours of sediment density were mapped visually into subjective categories of dense, medium and light using Band 4. The major dispersion features are evident although there is little control on consistency of the boundaries across an image or between images. Digital data were available for the other six dates and digital image processing techniques were applied. Because of the limited dynamic range of LANDSAT within the suspended sediment and clear water values (KLEMAS, 1979), there is considerable noise in the signal of the light sediment concentration regions. A five by five spatial filter was applied to Bands 4 and 5 to smooth this effect. Then one image was geometrically corrected to UTM map co-ordinates. Other images were registered to this master for accurate mapping.

Various image enhancements of the sediment patterns were explored to clarify the spatial patterns. The most useful for the purpose of delineation of the fine structure of the sediment tendrils was a histogram stretch of Band 4 (green reflected radiance). In this procedure the original limited dynamic range of reflectance values is redistributed over the entire tonal range by assigning equal memberships to each possible class of reflectance values. A similar enhancement of Band 5 (red) provided little additional information for a visual appraisal. It did not resolve the important density patterns in the near shore environment which were evident in Band 4. Band 7, which has negligible reflectance from water, was used to identify the shoreline which was not clearly visible in the other bands where the near shore sediment merged with beaches.

To quantitatively map the sediment contours, two approaches were evaluated. An unsupervised classification was performed. This is a clustering of the four bands to determine the natural radiometric units that may be equivalent to "natural terrain" units (ROBINOVE, 1981). This did not provide as much information on the tendril patterns as did a density slice of Band Four, which was determined to be superior to Band 5 in this respect. The density slice breaks the reflectance signal into discrete classes that may be colour coded in a map. The density slice was implemented by applying a parallelepiped classification to Bands 4 and 7 so that information in Band 7 could be used to mask the land surface. Only digital numbers (D.N.) in the 0 to 15 range (out of a maximum range of 0 to 255) of Band 7 were included in the classification. D.N. intervals were assigned to Band 4 with a high radiance resolution of 5 per class in low sediment concentrations and decreasing resolution in higher concentrations within the steep near shore gradients.

The eight cases are illustrated in Figures 2 through 9. The sediment contours were mapped from the density sliced digital image (and visual analysis for the two hardcopy cases) and the arrows depicting our interpretation of current direction are based upon evaluation of these contours and the histogram enhancement of Band 4. Black and white renditions of the original colour enhancements and classifications are provided for each case.

DISCUSSION OF THE CURRENT REGIMES

In this discussion, we follow the convention that atmospheric currents are identified according to the direction from which they are coming and lake currents are identified according to the direction towards which they are going. Four cases are discussed and all are summarized in Table 1.

1) DECEMBER 2, 1973 (Figure 2): The regional winds on this day were controlled by a high pressure system over Ohio and as a result the direction was variable but with a net east component. The 24 hour mean wind speed at Delhi was 5.8 km/hr. On the previous day the wind direction was responding to the passage of a warm front associated with a low over James Bay and was predominantly northerly. It was westerly on the two days prior to that.

Along the Nanticoke shore, the sediment tendrils indicate a southwest dispersion which is in accordance with winds from the north to east quadrant of the previous day and the day of the image. A southwest littoral current was observed with northeast winds on another date in the Nanticoke region (LEDREW and FRANKLIN, 1983) in which rhodamine dye plumes were photographed from a helicopter.

This southwest current is in contrast to a zone of east transport along the south shore of Long Point. The conflict is evident in a large counterclockwise gyre within Long Point Bay. A smaller gyre is found immediately to the east of the spit of Long Point (demarcated by heavy sediment density) and a larger one is at the right of the image in the east basin of the lake. For the latter gyre a ring of light sediment outlines an intrusion of clear water which came along the south shore from the southwest.

2) JULY 6, 1974 (Figure 3): A high pressure system was centered over the region. The air flow at Delhi was southwest with an average surface velocity of 4.8 km/hr. On the previous day the mean

Table 1. *Summary of current characteristics.*

Date	Delhi Wind Direction (24 hr average)	Delhi Wind Velocity (km/hr, 24 hr average)	Current pattern south of Long Point	Current pattern in the Nanticoke Region
December 2, 1973	E Dec. 1: N Nov. 30: SW Nov. 29: NW	5.8	east coastal jet, gyre to east	southwest dispersion
March 20, 1974	N March 17-19: NW	3.1	east coastal jet, gyre to northeast	west of Nanticoke: west current east of Nantocoke: east current
July 6, 1974	SW July 5: NW July 3, 4: SW	4.8	east coastal jet, gyre to east	west of Nanticoke: west current east of Nanticoke: east current
March 29, 1975	NW March 27, 28: NE March 26: N	7.2	weak coastal jet, no gyre	
July 22, 1976	NE July 21: NE July 19, 20: SW	7.1	east coastal jet weak, gyre to east, offshore dispersion SW of the spit	west littoral drift
July 7, 1979	S July 6: NW July 5: N July 4: N	4.6	east coastal jet, no gyre, offshore dispersion SW of the spit	west of Nanticoke: west current east of Nanticoke: east current
June 13, 1980	SW June 12: S June 10, 11: NW	7.7	east coastal jet, no gyre	offshore dispersion
August 19, 1981	SE August 18: S August 17: NW August 16: N	5.0	weak coastal jet, gyre to SW of the spit	west component to offshore dispersion

(Note: wind directions for August, 1981 are interpreted from surface pressure charts. Station data are unavailable.)

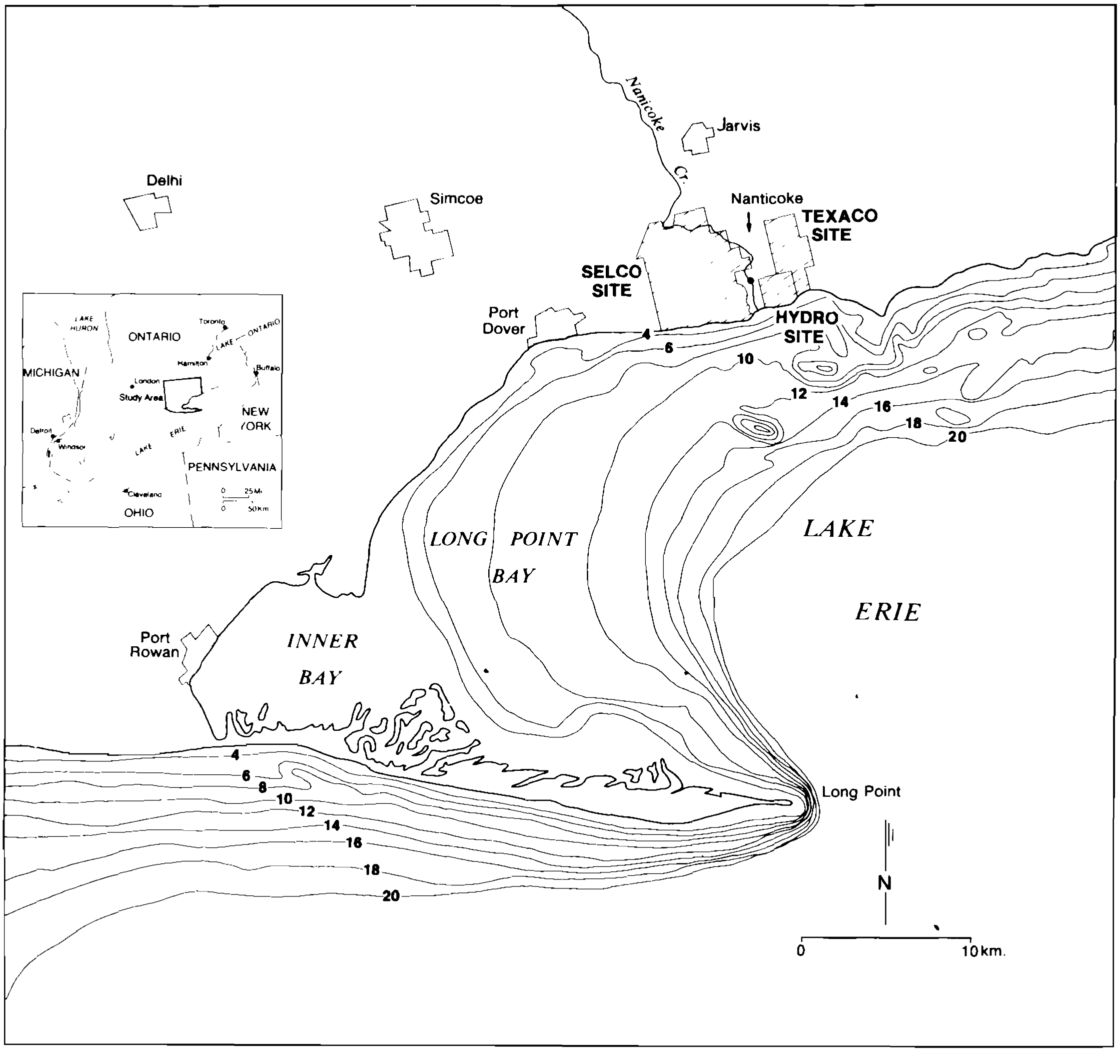

Figure 2. December 2, 1973: Interpretative map of the surface current direction (top) based upon interpretation of a histogram stretch enhancement of LANDSAT Bands 4, 5 and 7 (middle) and a parallelepiped classification of Bands 4 and 7 (bottom). The numbers represent relative sediment densities from high (1) to low (7).

wind was from the northwest but was from the southwest from July 1 through 4.

East of Nanticoke, there was an east component to the littoral drift while to the west it was westward. The sediment concentrations were higher in the Nanticoke region than to the west and south of Long Point Bay, which is indicative of higher erosion rates in this region.

To the south of Long Point, the littoral transport was very pronounced. The east drift continued along the shore until the coast curves north. At this point, the current became detatched from the shore, meandered southward and evolved into a pronounced gyre. It appears that the current had an inherent instability that became evident in a vortex after it left the confines of the shallows. These large horizontal eddies are typical of intense vertical turbulence (BENGTSSON, 1978).

3) JULY 7, 1979 (Figure 4): A high pressure system was centred over Pennsylvania and Delhi winds

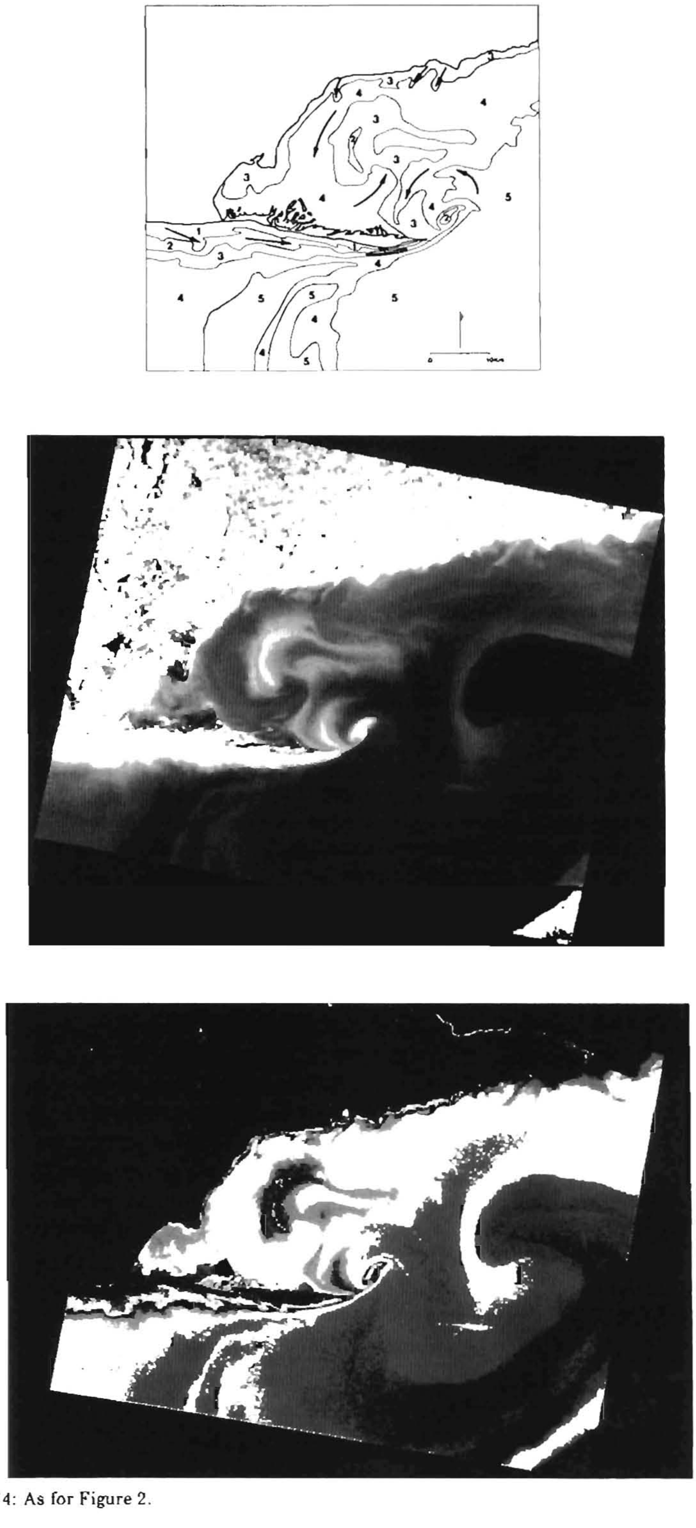

Figure 3. July 6, 1974: As for Figure 2.

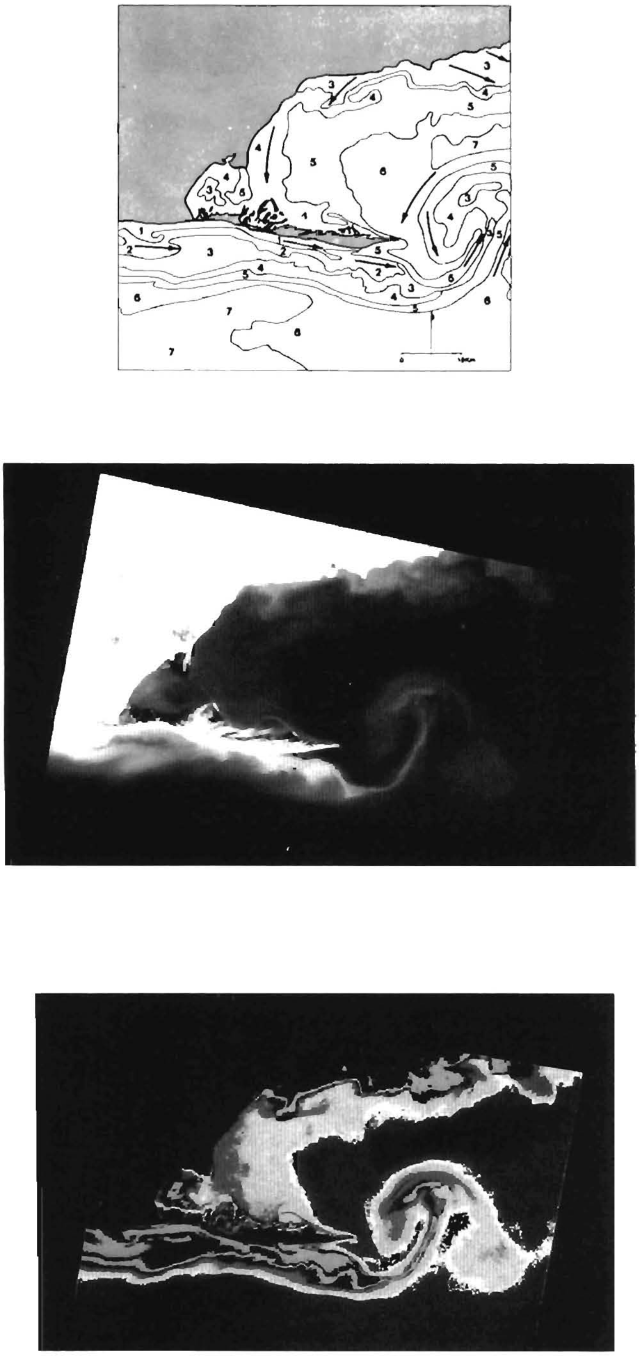

Figure 4. July 7, 1979: As for Figure 2.

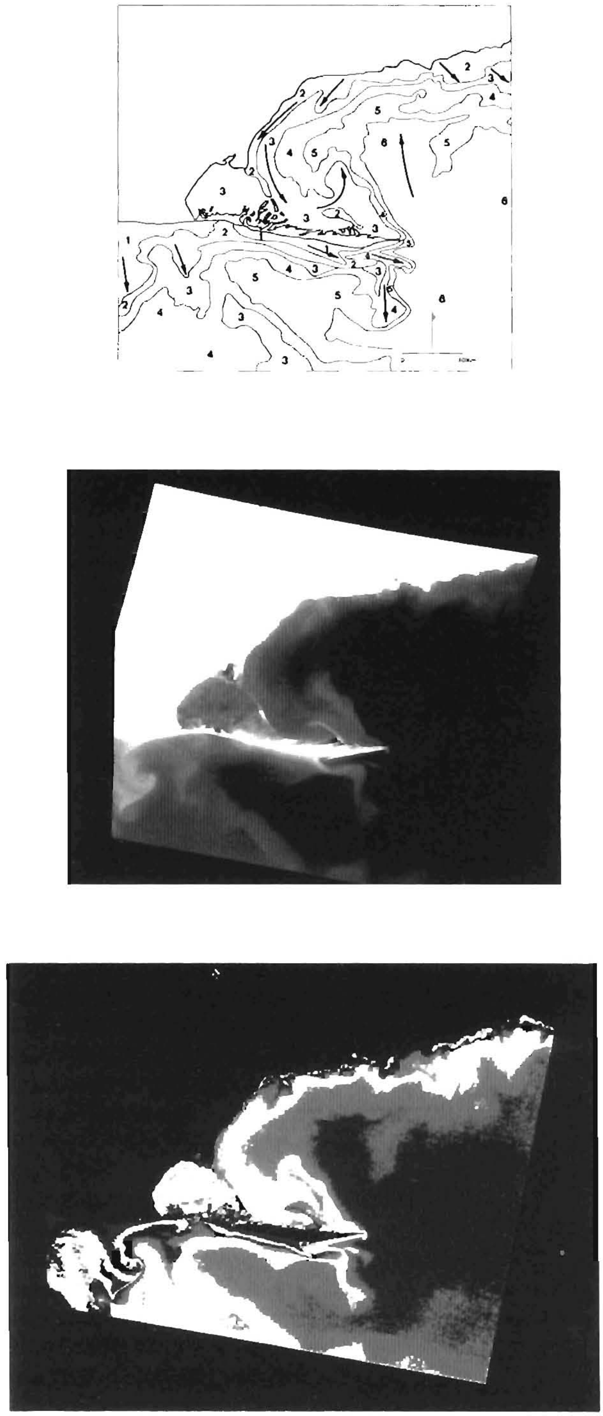

Figure 5. June 13, 1979: As for Figure 2.

Figure 6. July 22, 1976: As for Figure 2.

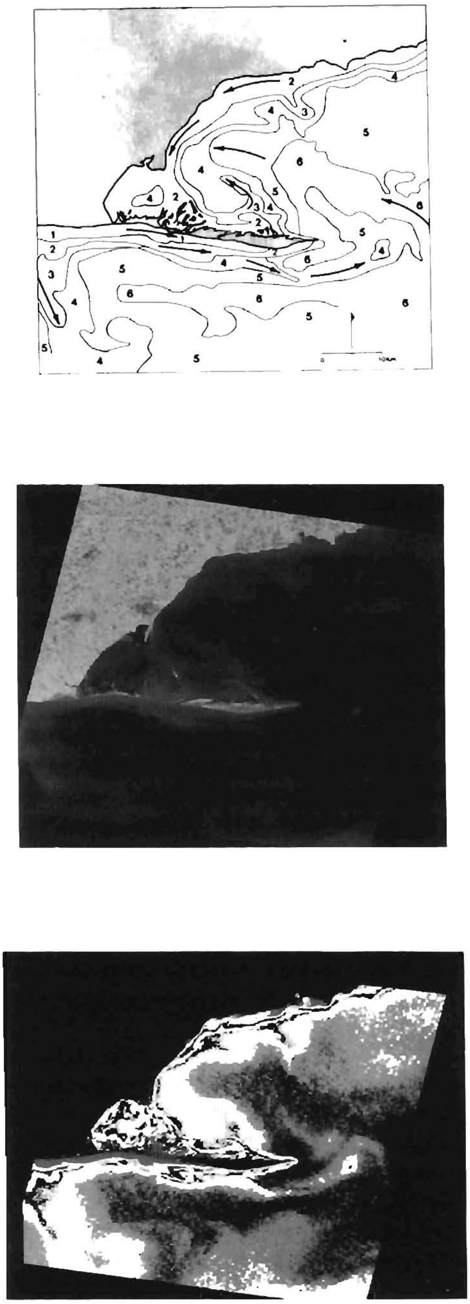

Figure 7. August 19, 1981: As for Figure 2.

were from the south with a daily average speed of 4.6 km/hr. It is significant for this example that the wind direction of the previous five days was from the north and northwest over land which would be translated to a more easterly component over water as a result of the change of frictional stress.

West of Nanticoke, the current pattern was very similar to that for July 22, 1976, which had

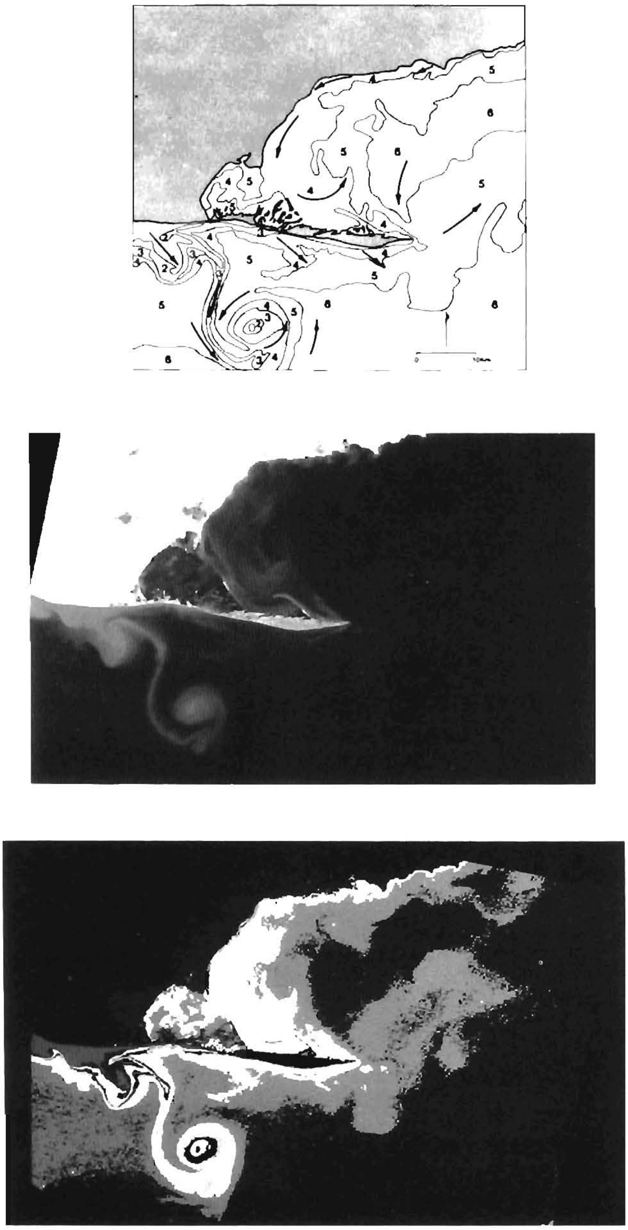

Figure 8. March 20, 1974: Interpretative map based upon visual analysis of hardcopy imagery.

northeast winds. For the July 7 case, the littoral sediment dispersion was constrained towards the shore in a counterclockwise rotation. This containment within the Bay north of Long Point may have been a consequence of the northeast winds of the previous few days.

East of Nanticoke, there is some evidence for an east drift in the littoral current.

Southwest of Long Point, where the spit joins the mainland, there was a pronounced offshore disper-

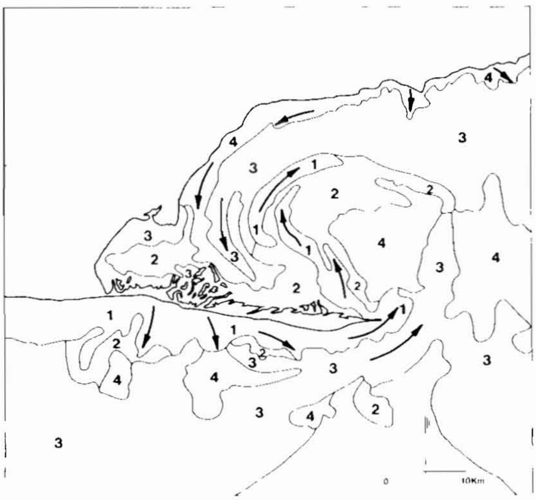

Figure 9. March 29, 1975: As for Figure 8.

Figure 10. Kelvin wave or "coastal jet" in a circular basin, with half basin cut away. Wind vector is from bottom left to upper right. After CSANADY (1972).

sion that extended to the centre of Lake Erie. This again is consistent with a northerly component of the wind stress which was found on the previous few days. Immediately south of the spit, however, the east littoral drift is evident and was attached to the shore until the coast curves northward. At this point, the current broke to the south and was dispersed with no clear gyre formation. Evidently, the offshore component resulting from the prior northerly wind stress weakened the turbulence of the littoral drift.

4) JUNE 13, 1980 (Figure 5): A low was over central Quebec. The regional surface winds were from the southwest at 7.7 km/hr, although it is significant for this case that they were from the northwest from June 8 to 11. They were from the south on June 12.

The east littoral drift is again evident along the south shore of Long Point. As was typical in other examples, it broke away from the coast where the shoreline curves northward and then the current began to meander. A clear gyre had not formed although the incipient stages are evident in the image. There was a considerable amount of offshore sediment which is of unknown source since the image does not extend towards the west end of the lake.

In the Nanticoke region the dispersion is interpreted to be offshore and to be contributing to a weakly defined counterclockwise gyre within Long Point Bay. This is consistent with aerial photography of the effluent plume of Centre Creek, near Nanticoke, taken on the previous day with south winds (LEDREW and FRANKLIN, 1983).

Of interest is the sediment plume from Nanticoke Creek. The plume can be traced up to 3 km out into the Bay. This is not seen on other images taken later in the summer season and is indicative of considerable momentum in the freshet.

The weak littoral drift south of Long Point and offshore dispersion in the Nanticoke region is consistent with the northwest wind stress for the previous few days.

SUMMARY AND CONCLUSIONS

The east littoral drift along the Long Point spit is a major and consistent feature for all weather patterns sampled. Where the coast line of the spit curves northward, the drift becomes detatched from the shore and meanders southward. In all but three cases, a gyre subsequently develops which is an indication of instability in the flow. In the three exceptions, the regional air flow had a northerly component on that day, or for a few days prior to the image date. In two of these three images, there was offshore dispersion to the southwest of the spit which undoubtably weakened the drift intensity.

The existence of the instability vortex is indicative of considerable momentum in the surface flow.

Although we cannot infer velocities from the imagery directly, this feature is consistent with a "coastal jet" type current along the south shore of Long Point where there is a great deal of sediment in transport and, presumably, notable erosion.

A "coastal jet" is a feature of large stratified lakes that has been simulated in model studies (CSANADY, 1972a) and verified in statistical analysis of *in situ* current measurements (BLANTON, 1974). It is described as a Kelvin wave which is a boundary layer phenomenon restricted to within 8 km of shore and observed at both ends of a lake diameter perpendicular to the wind vector. The two jets flow in the same direction and mass continuity is preserved by a return flow at depth (Figure 10). On remotely sensed imagery the spatial details of the current and the variations that evolve with different patterns of the wind field are evident. This information is important if the flushing action of the jet is invoked for pollution dispersion (CSANADY, 1972a,b). The ultimate downcurrent destination of pollutants must be identified. If industrial development were to occur along the south shore of Long Point, for example, it is conceivable that effluents would be carried into the Long Point Bay with some wind regimes as the jet evolves into the recurving vortex. It is also notable that a flushing jet does not occur within the Bay in the area of present development.

Along the north shore of Long Point Bay, there is a predominance of westward drift to the west of Nanticoke. This is a component of a counterclockwise gyre within Long point Bay which returns northward near the east tip of the spit.

To the east of Nanticoke, there is evidence for an east drift in three cases, which, combined with the west drift to the west, results in a region of divergence around Nanticoke. The regional wind had a south component for these dates and that may have been the prevailing force in the absence of the effect of the Long Point Bay gyre in this sector.

It cannot be determined with accuracy from these image data whether the effluent plumes from the Nanticoke industrial complex fall into the east or west drift for these split regimes. This is clearly of interest since the westward drift appears to be a component of a closed vortex with possible transport to the Turkey and Long Point marshes, while the eastward drift would be a pathway of effective dispersion into the east basin of Lake Erie. Measurements of currents by Ontario Hydro in this region indicate that east currents have a frequency of 43% while west currents have a 17% frequency (KOHLI and FAROOQUI, 1980). It appears that a location farther to the west would not be in such a positive position with respect to the natural dispersion forces.

Examination of the local plume dispersion characteristics alone is not sufficient for study of the impact of potential pollution. The cumulative effect of several developments and the associated urban infrastructure in the region must be considered. It is necessary to supplement the analysis of individual sites with study of the regional pathways from small scale satellite imagery as part of a multistage planning process. If indeed there is the potential for long distance impact or long term accumulation of effluents, an effective sampling network can be designed on the basis of the information in the satellite derived maps. *In situ* data collected for this network may be used to define the present status and the future implications of the problem more precisely.

ACKNOWLEDGEMENTS

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□ RESUMEN □

Ha sido obtenido el mapa do corrientes de superficie regionales a partir del conjunto de imágenes suministradas por el satélite LANDSAT para un conjunto de ocho casos, como un componente del análisis de la dispersión de efluentes liquidos en el área de Long Point en el Lago Erie. Estos modelos de corriente son interpretados a partir de la configuración de los dibujos de sedimentos observados en las imágenes clasificadas y mejoradas. Las trayectorias de la corriente son contempladas como trayectos potenciales del efluente. Se ha encontrado la evidencia de una corriente costera la cual ha sida simulada en modelos numéricos y propuesta como una agente efectivo de lavado, a lo largo de la costa Sur de Long Point para todos los modelos climáticos estudiados. En la Bahia de Long Point se ha observado un flujo antihorario a lo largo de la costa en todos los casos, la cual parece ser parte de un giro dentro de la Bahia. Es posible que los efluentes liberados dentro de la Bahia puedan formar parte de una circulación cerrada. Las implicaciones para las marismas sensibles de la región tienen que ser consideradas.--*Miguel A. Losada, Universidad de Santander, Santander, Spain*

□ ZUSAMMENFASSUNG □

Ortliche Oberflächenströmungen in der Nähe des Long-Point-Gebiets des Lake Erie wurden durch LANDSAT-Satellitbilder kartographisch vermesst. Acht Vermessungsbeispiele dieses Gebiets wurden gemacht, um ein Teil einer Studium der Abflussversteuung im besagten Gebiet zu vorbereiten. Diese Strömungsmuster wurden durch die Bildung der Sedimentranken auf den klassifizierten, erhöhten Satellitbilder ausgelegt. Die Strombahnen werden als mögliche Abflusswege betrachten. In der Nähe der südlichen Küste Long Points und für jedes studierte Wettervorbild wurden Spuren eines "küstlichen Strahl" gefunden, der mit Zahlmodellen simuliert wurden; es wurde vorschlagen, dass dieser Strahl ein wirkungsvolles Ausspülenmittel wäre. In der Long-Point-Bucht wurde einer linksläufige Strom auf jeden Fall beobachtet; er scheint eine Wirbeln innerhalb der Bucht zu zeigen. Es gibt dann die Möglichkeit, dass Abfluss in der Bucht ein Teil eines Schlusskeislauf werden könnte; die Einwirkung dieser Möglichkeit in bezug auf empfindliche Sumpfen des Gebiets sorgfältig angedacht müssen werden.--*Stephen A. Murdock, CERF, Charlottesville, Virginia, USA*