General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

04

III

E7.6-1 0.3 7 0.

CR- 147963

DYNAMICS OF TURBIDITY PLUMES IN LAKE ONTARIO

U.S. GEOLOGICAL SURVEY

Open-File Report 75-249

Prepared in cooperation with the
National Aeronautics and Space Administration

```
(E76-10370)  DYNAMICS OF TURBIDITY PLUMES IN          N76-25616
LAKE ONTARIO  FINAL REPORT, 1 JUL. 1972 - 31
DEC. 1974 (GEOLOGICAL SURVEY, RESTON, VA.)
71 P HC $4.50                         CSCL 08H          UNCLAS
                                            G3/43   00370
```
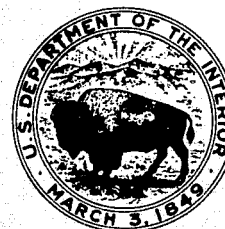
1342D

DYNAMICS OF TURBIDITY PLUMES IN LAKE ONTARIO

Edward J. Pluhowski
U.S. Geological Survey
National Center, MS-432
12201 Sunrise Valley Drive
Reston, Virginia 22092

1 May 1975

Type III Final Report for Period 1 July 1972 –
31 December 1974

Prepared for:

Goddard Space Flight Center
Greenbelt, Maryland 20771

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DYNAMICS OF TURBIDITY PLUMES IN LAKE ONTARIO (342-4D).		5. Report Date 1 January 1975
		6. Performing Organization Code
7. Author(s) Edward J. Pluhowski (IN 058)		8. Performing Organization Report No.
9. Performing Organization Name and Address U.S. Geological Survey National Center, MS-432 12201 Sunrise Valley Drive Reston, Virginia 22092		10. Work Unit No.
		11. Contract or Grant No. S-70243-AG
12. Sponsoring Agency Name and Address A. W. Fihelly Goddard Space Flight Center Greenbelt, Maryland 20771		13. Type of Report and Period Covered Type III Progress Rept. 1 July '72 – 31 Dec. '74
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

SEE FOLLOWING SHEET

17. Key Words Suggested by Author Turbidity plumes Longshore currents Lake dynamics Shoreline erosion	18. Distribution Statement

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Not Applicable	21. No. of Pages	22. Price

Figure 2A. Technical Report Standard Title Page. This page provides the data elements required by DoD Form DD-1473, HEW Form OE-6000 (ERIC), and similar forms.

U.S. DEPARTMENT OF THE INTERIOR, GEOLOGICAL SURVEY, WATER RESOURCES DIVISION

ABSTRACT-INDEX SHEET

1. Title (all caps) DYNAMICS OF TURBIDITY PLUMES IN LAKE ONTARIO

2. Authors   EDWARD J. PLUHOWSKI

3. Date to NR 5-9-75

4. No. pages   59

5. No. illustrations 34

6. No. tables   2

7. No. references 13

8. Type of publication   Open-File Report

9. Descriptors Turbidity, Currents, Limnology, Beach Erosion, Littoral drift, Sediment.

10. Identifiers   Turbidity plumes, Longshore currents, Littoral currents.

11. Abstract

Large-turbidity features along the 275 km south shore of Lake Ontario were analyzed using LANDSAT-1 images. The Niagara River plume, ranging from 30 to 500 sq km in area is, by far, the largest turbidity feature in the lake. Based on image tonal comparisons, turbidity in the Welland Canal is usually higher than that in any other watercourse discharging into the lake during the shipping season. Less turbid water enters the lake from the Port Dalhousie diversion channel and the Genesee River. Relatively clear water resulting from the deposition of suspended matter in numerous upstream lakes is discharged by the Niagara and Oswego rivers.

Plume analysis corroborates the presence of a prevailing eastward flowing longshore current along the entire south shore. This current is most persistent at the Oswego River outlet but is quite variable in the Rochester embayment. The position of the spring thermal bar was approximately located in images obtained during April 1973.

Plumes resulting from beach erosion were detected in the images. Extensive areas of the south shore are subject to erosion but the most severely affected beaches are situated between Fifty Mile Pt., Ontario and Thirty Mile Pt., N.Y. along the Rochester embayment and between Sodus Bay and Nine Mile Pt.

PREFACE

Objectives

To determine the movement of nearshore currents using turbidity plumes as tracers.

To identify areas subject to beach erosion.

To define the principal sources of suspended matter entering Lake Ontario along the south shore.

To analyze the characteristics and dynamics of large turbidity plumes.

Scope of Work

Field activities and image analyses focused on the 275-kilometre long south shore of Lake Ontario. LANDSAT-1 images were screened for large-scale turbidity features. The Stanford Research Institute ESIAC console was used to enhance, enlarge, and to obtain areal measurements of turbidity plumes portrayed in satellite images. Ground-truth measurements of temperature, turbidity, and several meteorologic parameters were obtained at selected sites along the south shore of the lake, at times coinciding with satellite overpasses. Large well-defined turbidity plumes were frequently observed at the mouths of the following watercourses:

> Niagara River
> Welland Canal
> Oswego River
> Genesee River

Accordingly, much of the field work and interpretive analysis in this study focused on the detection of nearshore lake currents adjacent to the outlets

of these large watercourses using the plumes as tracers.

Conclusions

Band 5 (0.6-0.7 micrometres) was generally most useful for plume analyses. Under high atmospheric transmissivity, band 4 (0.5-0.6 micrometres) yielded excellent results. To obtain the false-color photographs used in this report, band 4 or band 5 was used in conjunction with band 6 (0.7 to 0.8 micrometres) in the ESIAC console.

Analysis of plume dynamics is a useful tool for determining near-shore current direction in Lake Ontario. Although generally confirming the existence of an west-to-east littoral current along the south shore, notable exceptions to the prevailing direction were detected, especially in the Rochester embayment and in the vicinity of the Niagara River plume. Complex circulation patterns on both sides of the thermal bar were detected in images obtained during April 1973.

Based on plume characteristics during the shipping season, the Welland Canal yields the highest concentrations of suspended matter to Lake Ontario along its south shore. Moderate to high turbidity is introduced into the lake by the Port Dalhousie diversion channel and the Genesee River, whereas, both the Niagara and Oswego rivers yield relatively low suspended-sediment concentrations.

Although the entire south shore is subject to beach erosion, three high-risk erosion zones were identified in the images, (1) Fifty Mile Pt., Ontario to Thirty Mile Pt., N.Y. (2) the Rochester embayment, and (3) Sodus Bay to Nine Mile Pt.

Additional Data Needs

The ability of a large water body to assimilate waste largely
hinges on its mixing capacity. Wind-driven currents along the
periphery of Lake Ontario represent one of the principal mechanisms
for disposing river-borne suspended matter into the lake mass. Clearly,
water-movement studies are extremely helpful in defining the erosion,
deposition, and diffusion processes operating within the lake.

Better definition of circulation patterns in Lake Ontario would
be especially helpful during the predominantly overcast cold season.
The impact on nearshore circulation patterns of short-term changes in
wind stress is not well known. Accordingly, additional satellite data
would help resolve these points.

Time-lapse studies of plume dynamics using the ESIAC system would
aid in showing the impact of varying wind stresses on nearshore circulation
patterns. A sequence of frames portraying the various study plumes under
a progression of gradually changing wind directions would clearly show
persistence as well as the relative intensity of longshore currents. The
seasonal expansion and contraction of the Welland Canal and the Genesee
River plumes could be illustrated in dynamic fashion by a film sequence.
Additionally, time-lapse sequences would be helpful in showing the impact
on plume development of varying rates of discharge, ship traffic, and
unusual events, such as the gradual lakeward retreat of the thermal bar
in spring.

A thermal infrared detector with a resolution comparable to that of the LANDSAT MSS imager would help in identifying thermal plumes generated by the Ginna and Nine Mile Point nuclear powerplants. Studies of the dynamics of these plumes will fill some gaps in what is known of circulation patterns along the south shore of Lake Ontario. A satellite-borne thermal scanner would be of great assistance in defining the position of the thermal bar, which seems to have a profound effect on lake circulation patterns in spring and, to a lesser extent, in the fall.

NOTE

ILLUSTRATIONS ORIGINALLY IN COLOR ARE IDENTIFIED IN THEIR
CAPTION BY AN EDC-010 _____ NUMBER. COPIES OF THE ORIGINAL COLOR
ARE AVAILABLE FOR PURCHASE FROM THE EROS DATA CENTER, SIOUX FALLS,
SOUTH DAKOTA 57198, USING THE EDC NUMBER. PRICES ARE AVAILABLE ON
REQUEST.

CONTENTS

ILLUSTRATIONS

Page

ILLUSTRATIONS (cont'd)

ABSTRACT

Large-turbidity features along the 275-kilometre long south shore of Lake Ontario were analyzed using LANDSAT-1 images. The ESIAC system developed by the Stanford Research Institute, was used to obtain enlargements and false-color renditions of turbidity plumes. After projection on a video screen, individual turbidity features were analyzed, mapped, and photographed.

The Niagara River plume, as much as 500 square kilometres in area, is by far, the largest turbidity feature in the lake. Based on image tonal comparisons, turbidity in the Welland Canal is usually higher than that in any other watercourse discharging into the lake throughout the shipping season. Somewhat less turbid water enters the lake from the Port Dalhousie diversion channel and the Genesee River. Relatively clear water resulting from the deposition of suspended matter in numerous upstream lakes is discharged by the Niagara and Oswego rivers.

Plume analysis corroborates the presence of a prevailing eastward flowing longshore current along the entire south shore. This current is most persistent at the Oswego River outlet but is quite variable in the Rochester embayment, where rapid shifts in water movement were occasionally detected in LANDSAT images. The position of the spring thermal bar, a zone of maximum density water corresponding to the $4^{\circ}C$ isotherm, was approximately located in images obtained during April 1973. Although eastward moving currents were detected on the inshore side of the thermal bar, westward moving counter currents seem to be dominant along its offshore side.

Plumes generated by beach erosion were readily detected in the images. Such areas are identified by light to very light, long, narrow plumes paralleling the coastline. Extensive areas of the south shore are subject to erosion, but the most severely affected beaches are situated between Fifty Mile Pt., Ontario and Thirty Mile Pt., N.Y., along the Rochester embayment, and between Sodus Bay and Nine Mile Pt.

Color illustrations of figure accession numbers EDC-010077 to EDC-010106 are available for purchase from the EROS Data Center, Sioux Falls, South Dakota 57198.

INTRODUCTION

The bulk of the sediment and nutrient load entering Lake Ontario is borne by northward flowing watercourses entering the lake along the south shore. About 90 percent of the water leaving Lake Ontario by way of the St. Lawrence River is attributed to the combined input to the lake from the Welland Canal, and the Niagara, Genesee, and Oswego Rivers (fig. 1). The Niagara River, average discharge 202,000 ft^3/s (5,720 m^3/s), is, by far, the largest of these watercourses, accounting for about 85 percent of the total inflow to the lake.

The source, movement, and dispersion of suspended matter entering Lake Ontario is synoptically portrayed in ERTS (LANDSAT) imagery. Turbidity plumes are commonly visible in LANDSAT images at or near the mouths of large watercourses discharging into the lake. Moreover, resuspension of sediment and benthic matter along the shore due to wave action can be detected in images. Such features appear as narrow longshore plumes and are usually indicative of severe erosion.

The purpose of this study is to identify the principal sources of suspended matter entering the lake from the south shore and to detect the direction of littoral currents by analyzing the dynamics of large-scale turbidity plumes.

Study Area

Field activities and image analysis focused on south shore turbidity features from Nine Mile Point, N.Y. on the east to Fifty Mile Point, Ontario, on the west (fig. 1). In addition to the previously cited major
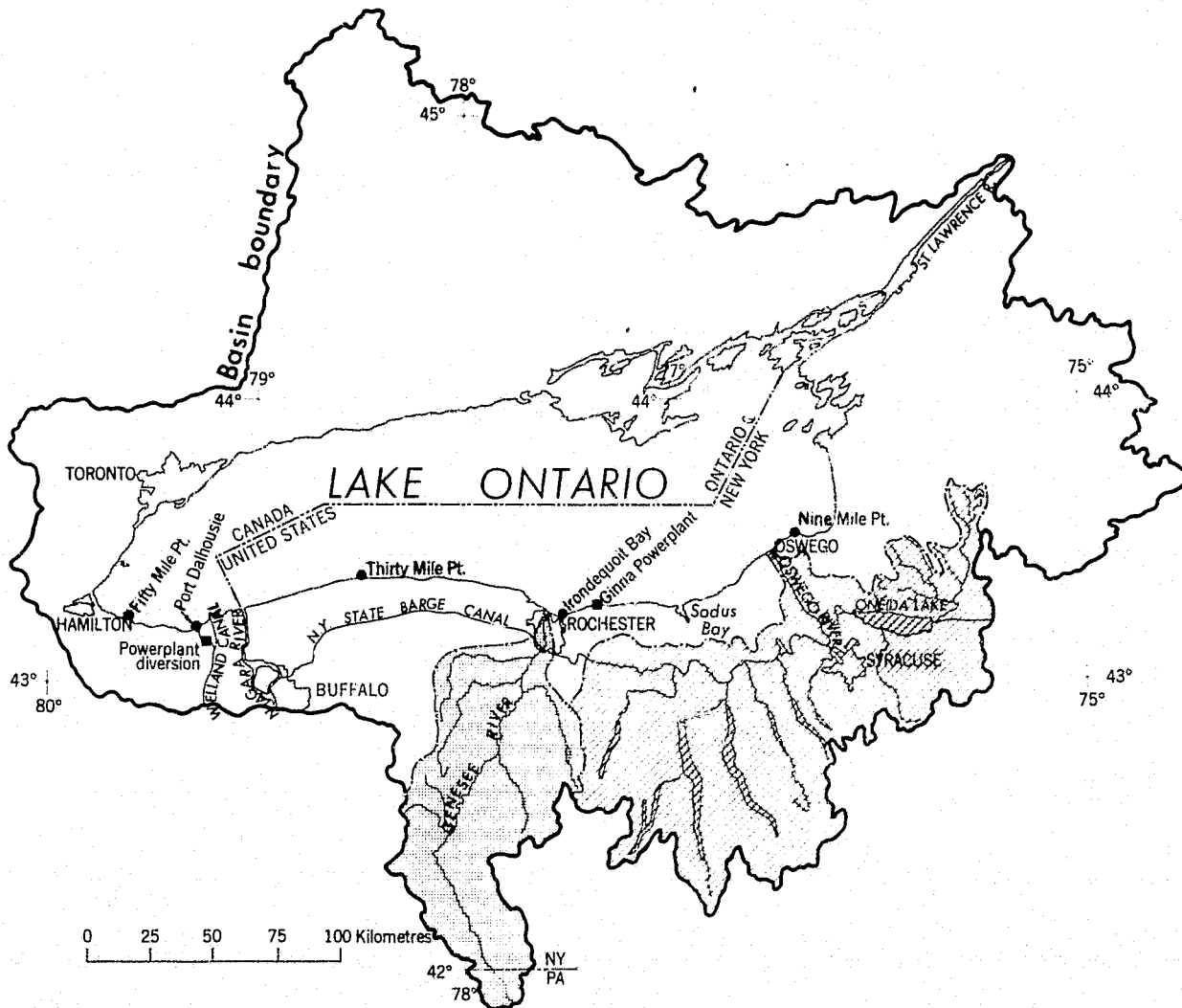
3

Figure 1. -- Lake Ontario basin showing the Genesee River
(dot pattern) and Oswego River (line pattern) subbasins.

watercourses entering Lake Ontario along the 275-km littoral study zone, powerplant diversions from the Welland Canal are discharged into Lake Ontario at Port Dalhousie, Ontario. These diversions are normally highly turbid and of sufficient volume to be visible in LANDSAT images.

Owing to the close proximity of Port Dalhousie to the mouth of the Niagara River (about 17 km), the plumes generated at these sites frequently mingle with that from the Welland Canal located 4½ km east of Port Dalhousie and 12½ km west of the Niagara River. Accordingly, in this report these plumes will be considered as a study unit. The Genesee River and Oswego River plumes are distinct features and will be considered separately.

Image Processing

The LANDSAT images were processed on the Stanford Research Institute (SRI) ESIAC (Electronic Satellite Image Analyzer Console) system. Enhanced false-color slides and photographs were made from the system's main video picture display. The ESIAC area-measuring capability was used to map plume size and shape. False-color renditions of particular points of interest were obtained from the ESIAC system using band 4 or 5 in conjunction with band 6.

Project Description and History

The writer has been engaged in this NASA LANDSAT-1 investigation (No. 342-D) under Contract S-70243-AG with the National Aeronautics and Space Administration since July 1972. Field work, which began in August 1972, was designed to provide ground truth at times coincident with

satellite coverage. This coverage is normally provided on three successive days over 18-day cycles. For example, if the eastern part of Lake Ontario was imaged during a particular day, coverage of the central part of the lake was usually obtained the following day and that for the western part of the lake on the third day. The entire sequence is repeated 18 days later, beginning, once again, over the eastern part of the basin.

Field observations of percent sky cover, wind direction, and water color and appearance were made at numerous sites along the south shore of the lake during selected satellite overpasses. Turbidity, as well as air and water temperature measurements were made at all sites. Suspended-sediment concentrations were determined for the principal watercourses entering the lake from the south. Using a portable anemometer, wind velocity and direction were recorded at frequent intervals during periods when supporting field data were acquired.

A sufficient quantity of LANDSAT images were obtained from NASA by March 1973 to make possible optimum use of the ESIAC console. The console's utility in image analysis was demonstrated to the writer on March 20-22, 1973, when high-quality color slides and prints illustrating enhanced video portrayals of large turbidity features in Lake Ontario were initially pro-duced. On subsequent trips to SRI (October 16-18, 1973, and May 7-9, 1974), sketches of selected plumes were made using the ESIAC system. Discussions were held with SRI scientists concerning possible application of time-lapse photography to portray plume dynamics as well as correlation of scene-radiance intensity, as measured by the ESIAC console with turbidity.

Hydrologic Setting

In addition to the Niagara River (average discharge, 5,720 m^3/s), substantial flows enter Lake Ontario along its south shore from the Welland Canal and the Genesee and Oswego rivers (fig. 2). The Welland Canal is the largest of these watercourses averaging 198 m^3/s (cubic metres per second) (DeCooke, 1968) followed closely in magnitude of flow by the Oswego River, 184 m^3/s. The Genesee River, mean annual discharge 76.5 m^3/s is, by far, the smallest of the four major watercourses along the south shore. Part of the Welland Canal flow is diverted to supply the DeCew Falls powerplant on the Niagara Escarpment about 5 km west of the canal. The diverted water empties into Lake Ontario at Port Dalhousie, Ontario, the original Welland Canal terminus. In addition to the Welland Canal powerplant diversions, about 19.8 m^3/s is diverted from the Niagara River to the New York State Barge Canal (Day, 1972). The bulk of this water eventually reaches Lake Ontario, principally by way of the Genesee River. Although the combined discharge of the Welland Canal (including water diverted for powerplant operations) and the Genesee and Oswego rivers averages nearly 460 m^3/s, this large flow is only eight percent of the Niagara River discharge.

Physical and hydrologic data for the Oswego and Genesee river basins are shown in table 1. Slightly higher precipitation and runoff occur in the Oswego River basin, but the relative differences between runoff and precipitation for the two basins are about equal. By way of contrast, significantly greater land and channel slopes characterize the Genesee

7
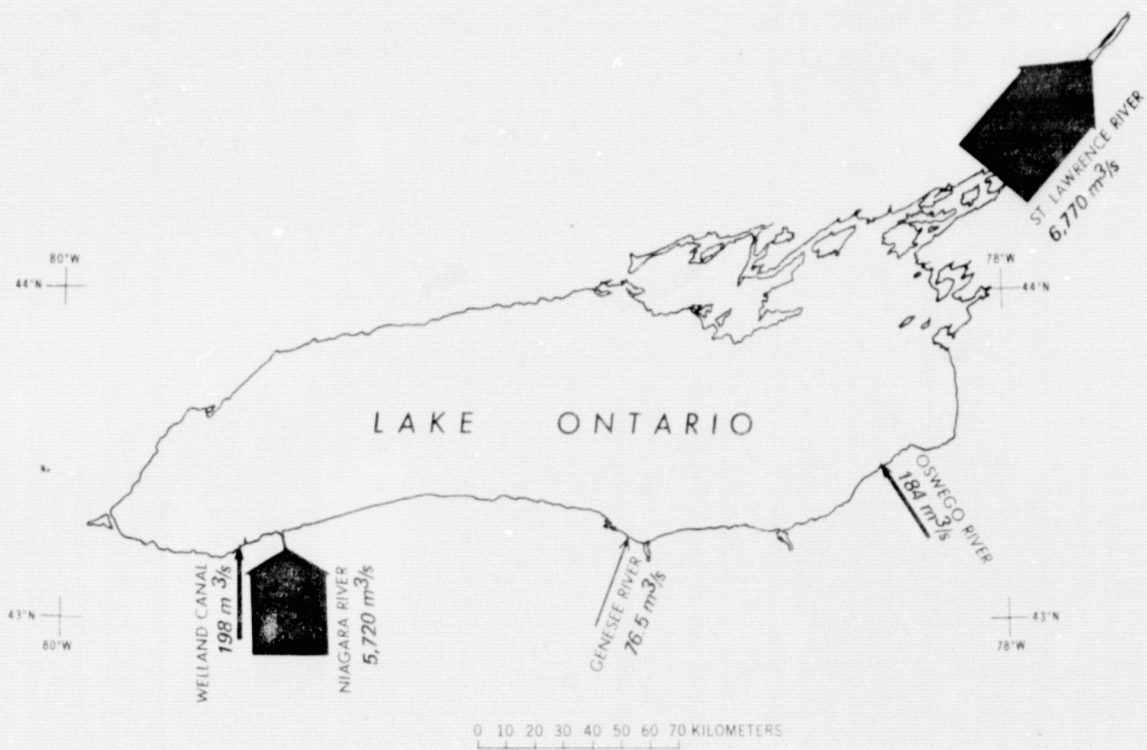
Figure 2. -- Relative magnitude of discharge entering Lake
Ontario along the south shore and outflow to the
St. Lawrence River.

8

River basin, including higher local relief. This factor, when combined with limited storage capacity, ʊᵴ demonstrated by a low percent free water surface, predisposes the Genesee River basin to higher erosion potential than the Oswego River basin.

Table 1. -- Physical and hydrologic characteristics of the

Genesee River and Oswego River basins (Pentland, 1968).

Basin characteristics	Genesee River at Rochester	Oswego River at Oswego
Drainage area	6,390 km^2	13,300 km^2
Mean annual runoff	377 mm	416 mm
Mean annual precipitation	802 mm	856 mm
Mean altitude	406 m	238 m
Mean land slope (m/m)	0.0723	0.0494
Mean channel slope (m/m)	0.00168	0.00079
Percent free water surface	1.00	6.75

GENESEE RIVER PLUME

Erodible soils and extensive agriculture within its basin combine to insure delivery of a large supply of sediment to the Genesee River. In addition to the large sediment yield of the basin, the river receives waste discharge from many sources, particularly from the Rochester, N.Y. metropolitan area. The resulting high levels of turbidity at the mouth of the Genesee River impart a distinctly light color to the river when viewed on high-altitude aerial photographs (Pluhowski, 1973). Some loss in the fine tonal detail of the Genesee River plume, as provided by high-altitude photographs was anticipated in satellite imagery, however, the loss of detail in images is not great. Accordingly, much useful hydrologic data based on plume analyses at the mouth of the Genesee River can be extracted from space data.

By way of illustration, a fortuitous combination of overlapping images of the Genesee River plume on successive days (August 19 and 20, 1972) and high-altitude photography on August 20, 1972, illustrates the importance of rapid wind direction changes on plume dynamics. Once beyond the channel-stabilizing bulkheads which extend 0.7 km into the lake, the Genesee River plume drifted southeast under the influence of a gentle northwest breeze (5 knots) on August 19, 1972 (fig. 3). The plume was trapped in a triangular area bounded by the shoreline, the east bulkhead, and clear lake water to the northeast.

Figure 3. -- Part of LANDSAT-1 image 1027-15233, obtained Aug. 19, 1972 showing the Genesee River plume (A) and the Genesee River outlet (B) (photograph from Stanford Research Institute). Wind speed in knots: full feather represents 10 knots and half feather, 5 knots. EDC-010077.
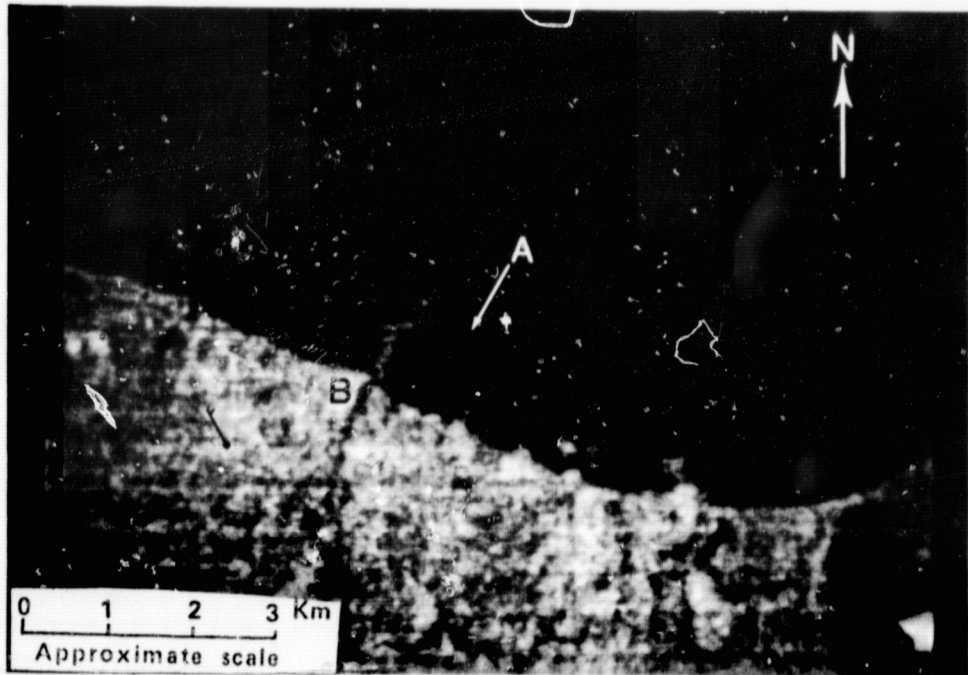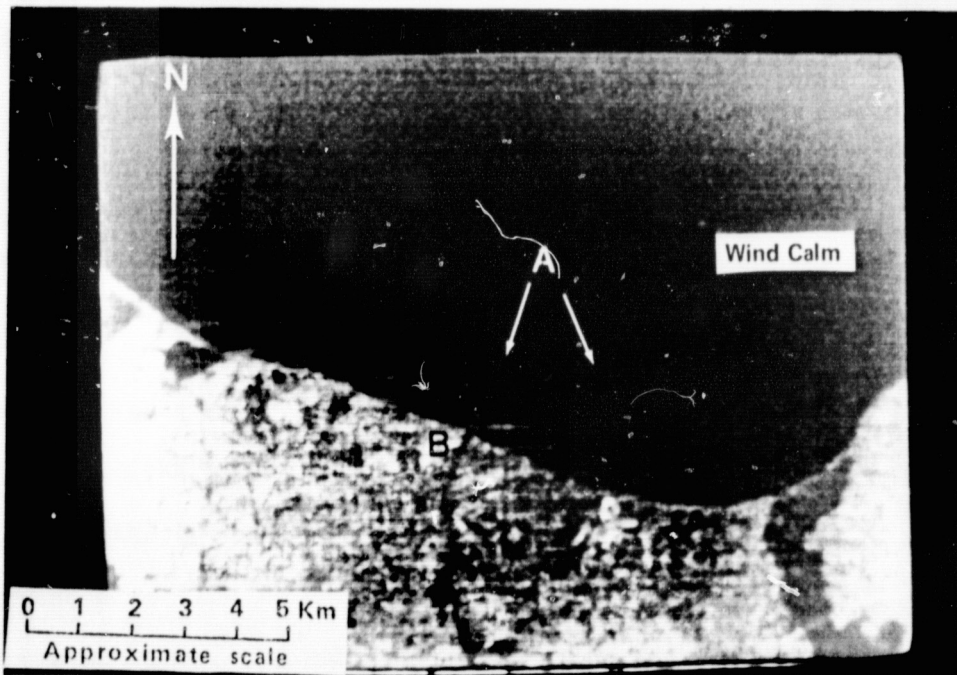
Figure 4. -- Part of LANDSAT-1 image 1028-15290, obtained Aug. 20, 1972 showing the Genesee River plume (A) and the Genesee River outlet (B) (photograph from Stanford Research Institute). EDC-010078.

A satellite image obtained the following morning shows the plume still trending toward the southeast (fig. 4). It was, however, no longer bounded by the shore or the harbor bulkhead and appears as a distinct plume extending about 3 km east-southeast of the harbor entrance. Winds at the time of the satellite overpass were calm, but a gentle southwest (offshore) breeze was reported during the early morning of August 20th. This breeze doubtless caused the plume to rotate counterclockwise away from the shore to the position shown in figure 4.

By early afternoon on August 20th, a gentle northeast lake breeze was established over the area. Figure 5, prepared from 18,500-m aerial photography, illustrates the impact of the onshore winds on the plume (A). Conforming with the imposed wind stress, the plume rotated south-westward toward the shore and the west bulkhead. A compact counterclock-wise gyre was formed, completely altered in shape and direction from the plume in existence only four hours earlier. The movement of longshore water west of the Genesee River is indicated by a powerplant effluent plume (fig. 5). Under the northeast wind during the early afternoon of August 20th, the powerplant plume trended northwestward along the coast toward Buck Pond.

The Genesee River discharges near the base of a catenary-shaped irregularity in the lake shoreline, about 35 km long by 10 km wide (fig. 1), known as the Rochester embayment. Based on the preceding analysis, current direction in the embayment seems to depend on the ambient wind field. Thus, the embayment is largely sheltered from a prevailing west-to-east coastal jet just off the south shore of the lake (Scott and Landsberg, 1969).

LAKE

ONTARIO

Cranberry
Pond

Long Pond

Buck Pond

Powerplant

A

N

Genesee River

Rochester

Irondequoit
Bay

Water-surface radiance

Bright Medium Dull

Dull   Dark

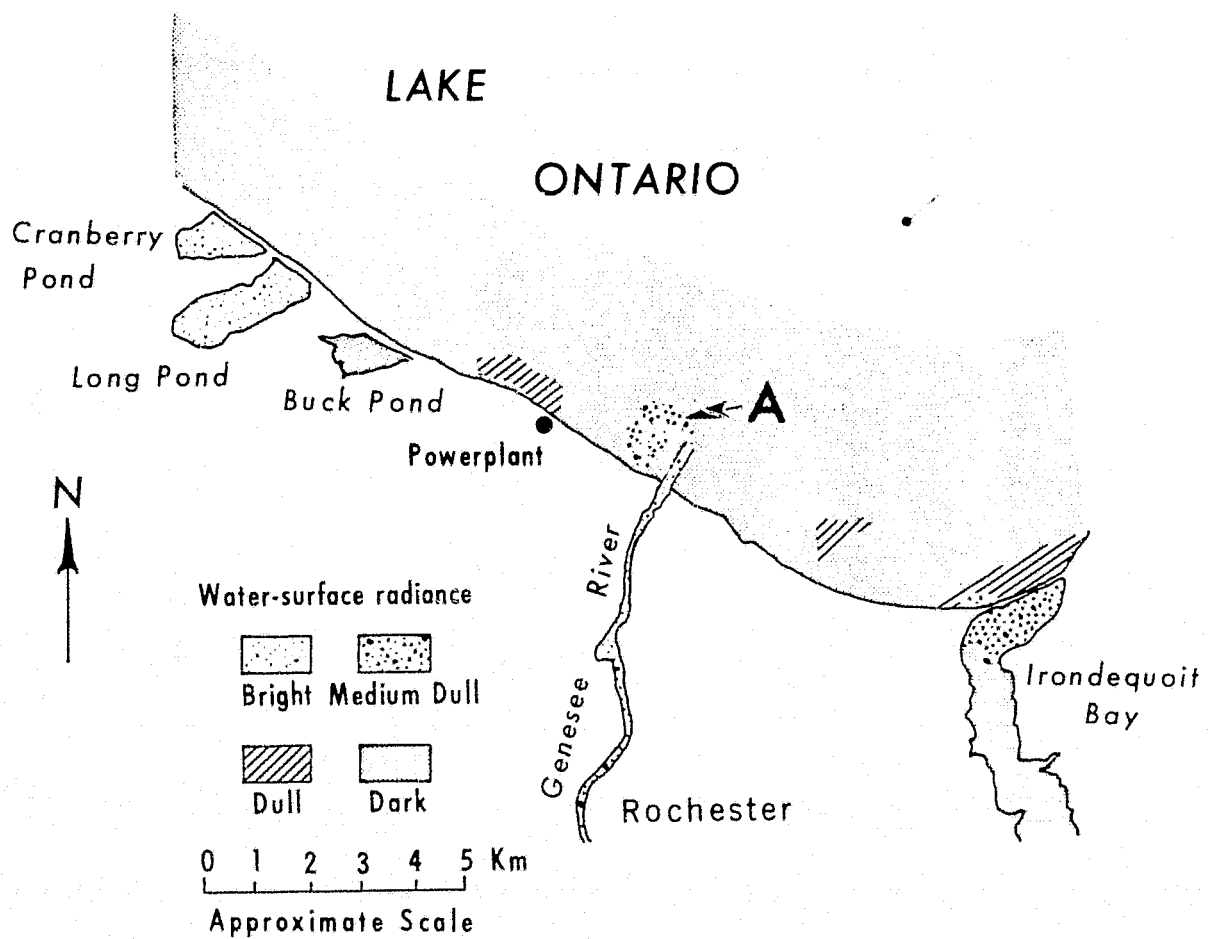0 1 2 3 4 5 Km
Approximate Scale

Figure 5. -- Genesee River plume as interpreted from aerial
   photographs obtained Aug. 20 .972, at 1300 hours EST
   (photographs from NASA).

14

The size a particular plume will attain is partly a function of discharge. For example, on May 16, 1973, the Genesee River was discharging 99 m^3/s into Lake Ontario. An extensive plume (fig. 6) was generated in the Rochester embayment, which extended 4 km offshore and was identifiable nearly 12 km downwind. Under the influence of a 15-knot southwest wind, the plume moved eastward toward Irondequoit Bay and then northeastward along the coast. Turbidity at the mouth of the Genesee River ranged from 30 to 35 JTU (Jackson Turbidity Units), and the plume covered 26 km^2 (square kilometres) of lake surface.

On July 9, 1973, discharge in the river averaged 37.4 m^3/s or 38 percent of the flow on May 16. The resulting plume (fig. 7) was greatly reduced in size, covering only about 1 km^2 of lake surface. Turbidity at the mouth of the river ranged from 5 to 9 JTU. The plume extended 1.5 to 2 km downwind about 1 km offshore.

Except for a narrow outlet channel, Irondequoit Bay is isolated from Lake Ontario by a sand spit. In spring the bay appears clear because its waters are too cold to permit active plant growth. By way of illustration, on May 16 the bay appears darker (less turbid) than the lake in figure 6. In fact, turbidity in the bay was only 3 JTU compared with 8 to 10 JTU in the lake to the north. By July 9, algae blooms were common in the bay, so that it appears lighter (more turbid) than the lake (fig. 7). Turbidity in the bay reached 8 JTU, whereas nearshore lake turbidity was only 2 JTU.

Figure 6. -- Part of LANDSAT-1 image 1297-15243, obtained May 16, 1973, showing the Genesee River outlet (A), Irondequoit Bay (B), and the Genesee River plume (C) (photograph from Stanford Research Institute). EDC-010079.
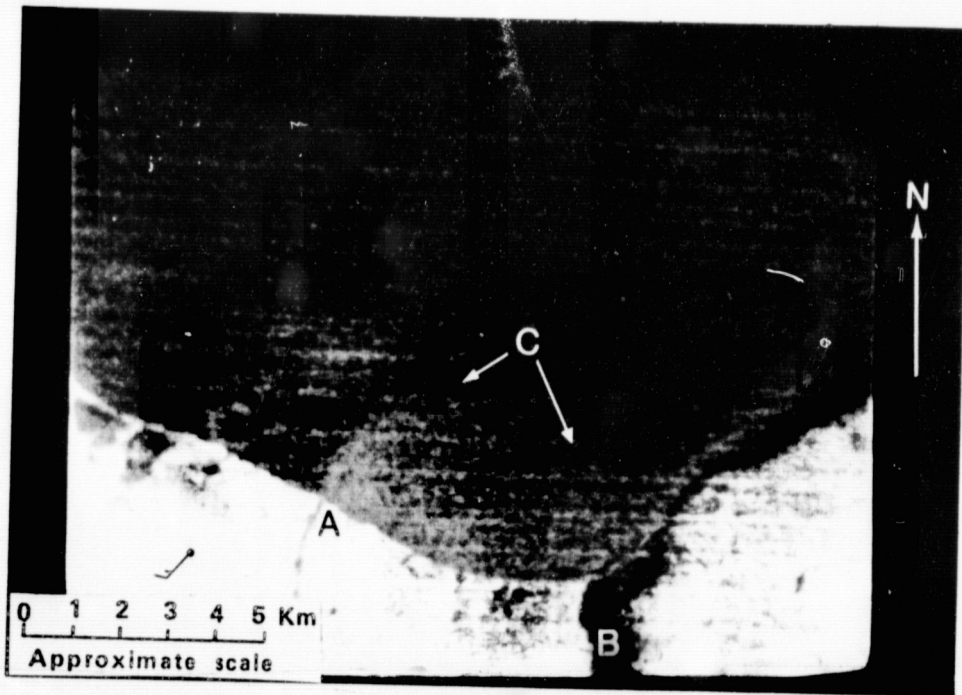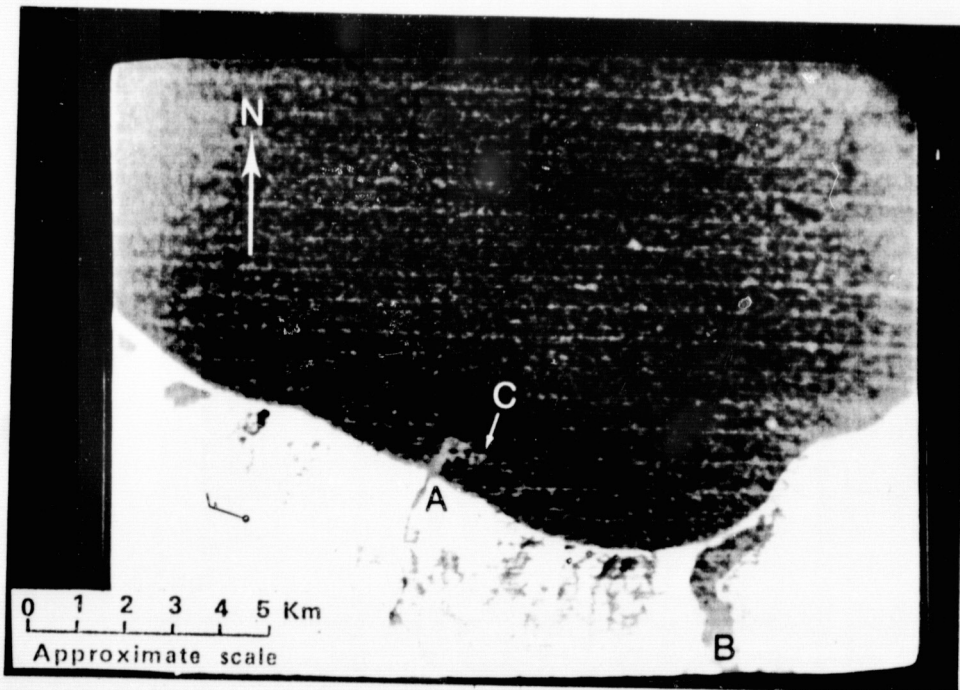
Figure 7. -- Part of LANDSAT-1 image 1351-15235, obtained July 9, 1973, showing the Genesee River outlet (A), Irondequoit Bay (B), and the Genesee River plume (C) (photograph from Stanford Research Institute). EDC-010080.

Under the influence of a west wind, which persisted for several days before September 6, 1972, image 1045-15234 obtained on that date shows active beach erosion occurring along the coast east of Irondequoit Bay (fig. 8). This littoral erosion plume was only about 1.5 km wide. It extended northeast about 23 km, initially hugging the coast but then trailed out into the lake as the shoreline bends eastward. The strong longshore currents required to create this turbidity feature were predicted for west wind regimes in model studies of the Rochester embayment (Bonham-Carter and Thomas, 1973). What was not predicted, however, was the apparent existence of an offshore countercurrent, as suggested by the abrupt change in direction, to the northwest, of the Genesee River plume at a point 4.5 km offshore. Initially, the plume moved to the east in response to the west wind. However, a short distance east of the Rochester harbor inlet, part of the plume turned northeast into the lake, where it became entrained in the offshore countercurrent.

Of special interest in image 1423-15224 obtained September 19, 1973, is a small light colored area 2.2 km offshore (fig. 9). This turbid zone is the surface expression of a submerged municipal sewer outfall, which was discharging 3.5 m^3/s of effluent from the city of Rochester (U.S. Dept. of Interior, 1968).

A general northwest nearshore circulation pattern was predicted in model studies of the Rochester embayment under prevailing southerly winds (Bonham-Carter and Thomas, 1973). This prediction is corroborated in figure 9, which shows northwest-trending plumes from the Genesee River mouth and from a nearby powerplant while a 10-knot south-southwest wind prevailed. The offshore sewer-outfall plume was oriented due west,
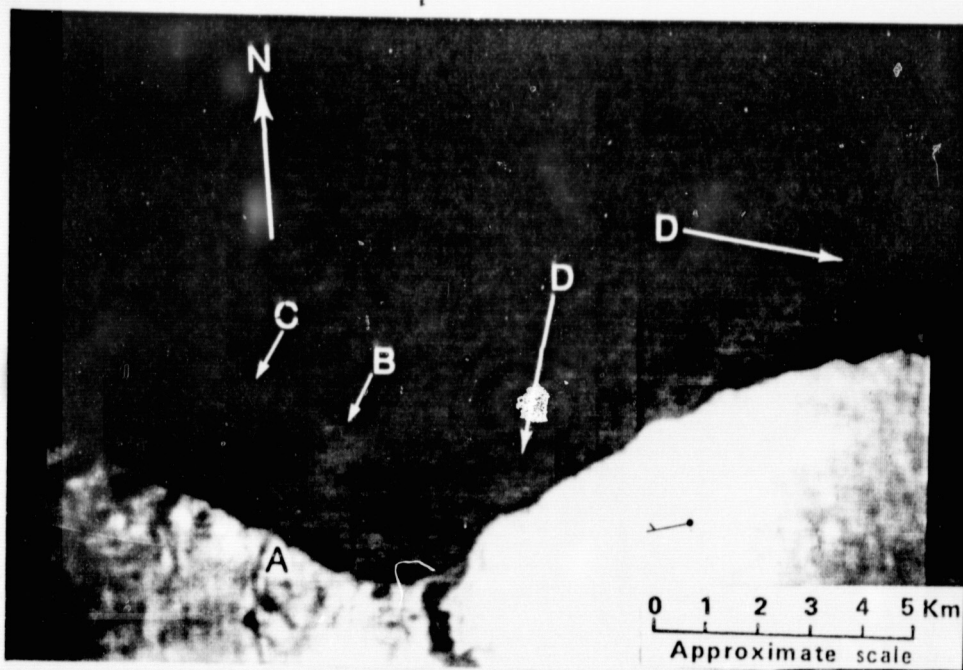
Figure 8. -- Part of LANDSAT-1 image 1045-15234, obtained
Sept. 6, 1972, showing the Genesee River outlet (A),
the main Genesee River plume (B), northwest extension
of the plume (C), and a beach erosion plume (D).
Concentric bands (left center) are due to film-lens
imperfections (photograph from Stanford Research
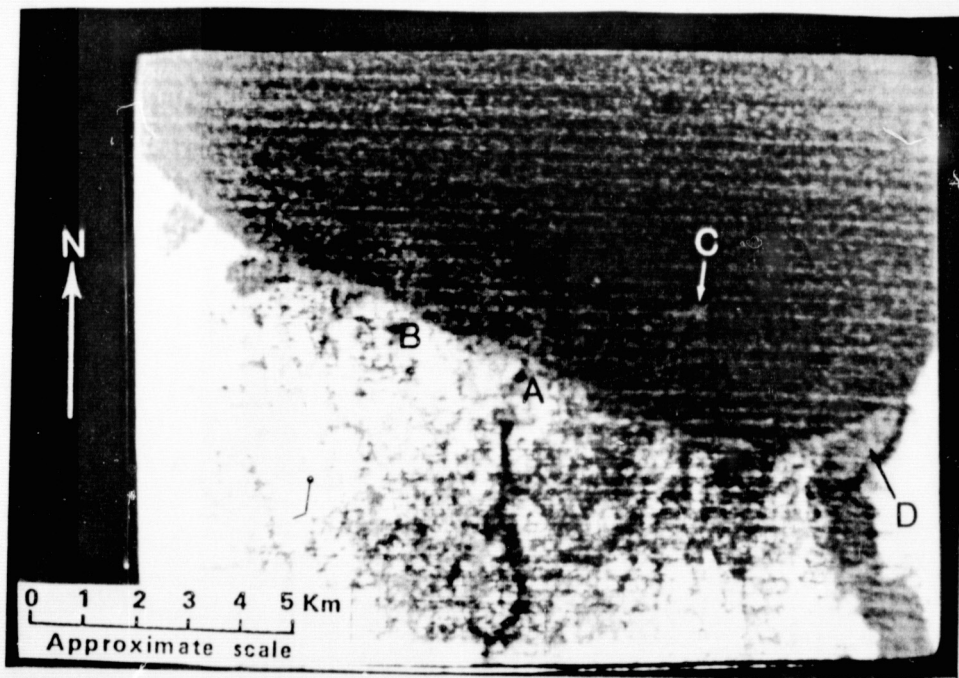Institute). EDC-010081.

Figure 9. -- Part of LANDSAT-1 image 1423-15224, obtained
Sept. 19, 1973, showing the Genesee River outlet (A),
powerplant (B), an offshore plume (C), and Irondequoit
Bay (D) (photograph from Stanford Research Institute).
EDC-010082.

18

indicating that the entire Rochester embayment was under the influence of a broad clockwise-moving littoral current.

Algal blooms were observed at the north end of Irondequoit Bay on September 19. Bay turbidity was 8 JTU -- higher than that measured in the Genesee River (6.5 JTU) or at the powerplant (4.0 JTU). As shown in figure 9, the bay appears lighter (more turbid) than Lake Ontario, where turbidity ranged from 1 to 1.5 JTU in the relatively clear parts of the lake. Moreover, the most turbid part of the bay was at its north end, where a sand spit trapped the lakeward-moving algal masses (fig. 9).

The possibility of plume detection along the south shore of Lake Ontario is lower in winter than in other seasons. Frozen ground, snow cover, shoreline icing, and minimal construction and farm activity, without doubt diminishes the probability of sediment movement during the cold season. Thunderstorms are very rare over the study area in winter so that much of the erosive energy of the intense rainfall often associated with such events is curtailed. Moreover, a high percentage of precipitation is in the form of snow or sleet which, when compared with rainfall, move less sediment to streams. Icefoot formations (fig. 10) are especially effective in dissipating wave energy along the coastline. Exposed beaches and headlands are insulated from heavy wave action by ice formations that frequently extend several metres into the lake, terminating beyond the natural shore. Accordingly, runoff-generated plumes, as well as those due to longshore drift, are usually not visible from mid-December to mid-March along the south shore of Lake Ontario.

A winter view of the Rochester embayment is depicted in figure 11. Despite a discharge of 68 m^3/s, minimal tonal contrast between stream water and lake water precluded formation of a discernible plume at the mouth of the Genesee River. Seasonally low suspended-sediment concentrations and sharply curtailed harbor activities lowered turbidity in the river to near that in the embayment. Under 15-knot south-southwest winds, brash ice formations are seen drifting offshore far beyond the coast.

Figure 10. -- View of Lake Ontario shore at Webster Beach
County Park near Rochester, N.Y., Feb. 15, 1973, showing
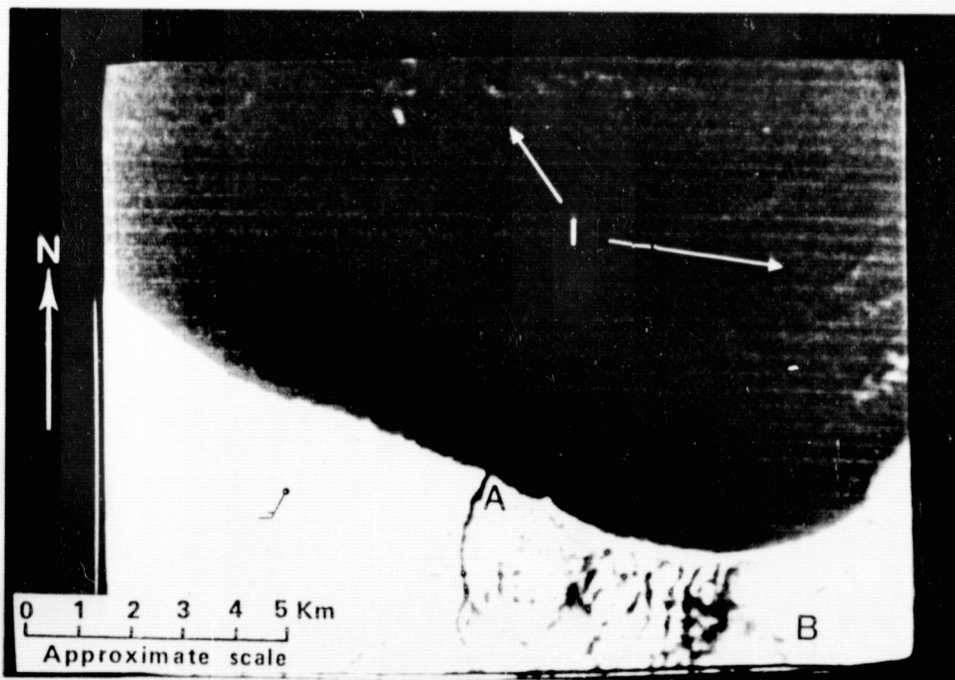icefoot formations (A). EDC-010083.

Figure 11. -- Part of LANDSAT-1 image 1567-15194, obtained
Feb. 10, 1974, showing the Genesee River outlet (A),
frozen surface of Irondequoit Bay (B), and ice floes
(I) (photograph from Stanford Research Institute).
EDC-010084.

Beach Erosion

Numerous examples of active beach erosion were detected in LANDSAT images. Wind-driven waves and currents along the south shore of Lake Ontario are highly effective erosional agents. The erodible headlands and plains facing the lake are highly vulnerable to wave action (fig. 12). Dislodged matter is readily suspended by longshore currents and deposited offshore, frequently in navigation channels and across harbor entrances. Where combined with high lake levels, considerable property damage may be sustained along beaches unprotected by bulkheads (fig. 13).

In LANDSAT images beach-erosion plumes were frequently visible between Fifty Mile Point, Ontario and Thirty Mile Point, N.Y., along the Rochester embayment, and from Sodus Bay to Nine Mile Point, N.Y. Intense plumes were detected during periods of west or northwest winds. Winds from these directions act to reinforce and intensify the normal west-to-east moving longshore currents. Easterly and northerly winds occasionally caused high inshore turbidity east of the Niagara River to Thirty Mile Point. South (offshore) winds, as might be anticipated, cause the least destruction of landforms along the south shore. With the exception of south winds, breezes as gentle as 5 knots may produce beach erosion plumes that are identifiable in satellite images.

West-northwest winds produced extensive beach erosion along a 35-km length of shoreline from Port Dalhousie to near Hamilton, Ontario on December 7, 1972 (fig. 14). Despite cold temperatures on December 7th, icefoot formations were only beginning to develop, so that the usual

Figure 12. -- Seawall constructed to
minimize shoreline erosion just east
of Port Dalhousie, Ontario. EDC-010085.

Figure 13. -- Lakeshore property damage
at Irondequoit, N.Y. (Nov. 13, 1973).
EDC-010086.

23

protection provided by shoreline ice was unavailable at that time.
Although gentle winds prevailed during the satellite's overpass, much
stronger winds earlier in the day generated rough water on the lake.
As indicated by the shape of the plumes, suspended beach material
generally moved eastward along the coast. The plumes are identifiable
as much as 4½ km offshore, averaging about 2 km in width. The existence
of a northwest-trending longshore current is suggested by the shape of
the plume nearest to Hamilton, Ontario.

Figure 14. -- Part of LANDSAT-1 image 1137-15355, obtained
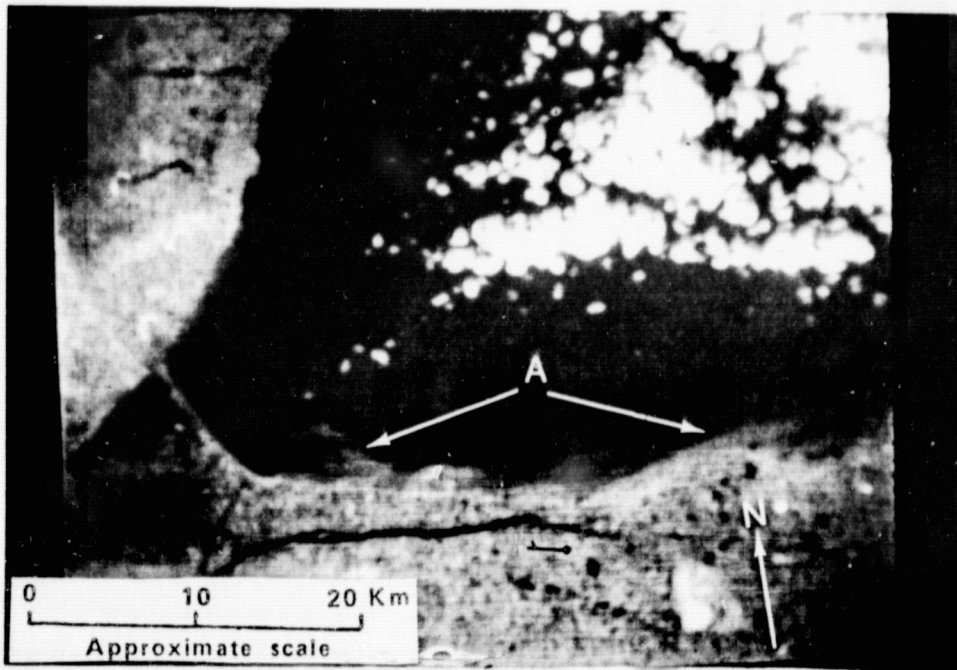Dec. 7, 1972, showing beach erosion plumes (A) along
the Ontario shoreline (photograph from Stanford
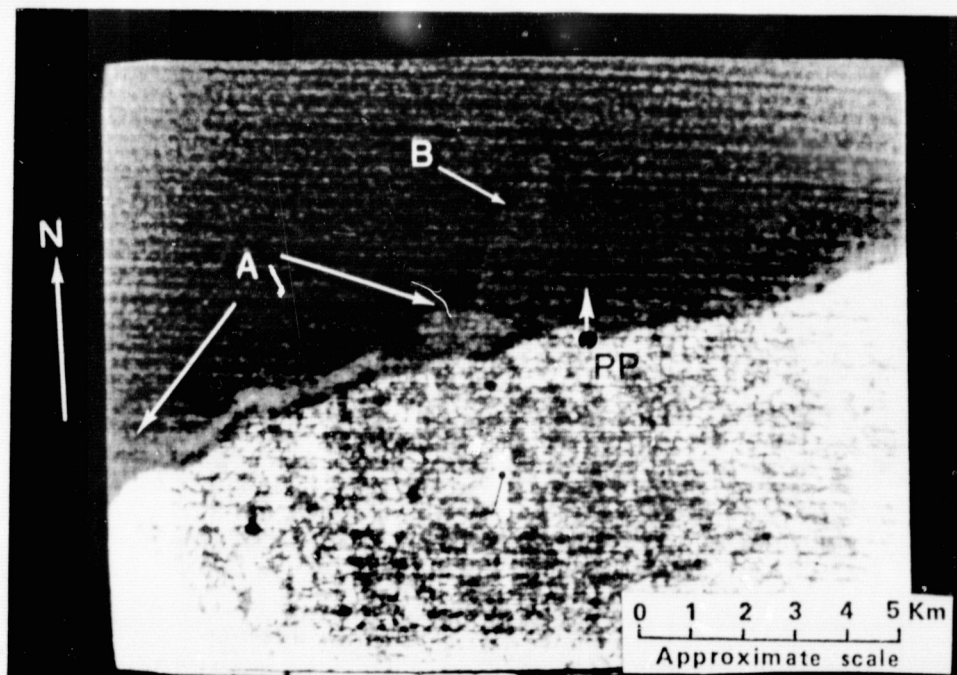Research Institute). EDC-010087.

Figure 15. -- Part of LANDSAT-1 image 1423-15224, obtained
Sept. 19, 1973, showing beach erosion plumes (A), and a
plume (B) created by discharge from the Ginna powerplant
(PP) (photograph from Stanford Research Institute).
EDC-010088.

Ginna Powerplant

The Ginna nuclear powerplant is located on the south shore of Lake Ontario 32 km east-northeast of Rochester, N.Y. (fig. 1), at the east end of the Rochester embayment. Cooling water is withdrawn from the lake from submerged intakes 945 m offshore at a depth of about 10 m. After circulating through the plant's turbine-condenser and service-water systems, the heated water (about $10^{o}C$ above ambient lake temperature) is discharged at the rate of 25.3 m^3/s as a surface jet oriented orthogonal to the shoreline. Because LANDSAT-1 is not equipped with a thermal infra-red sensor and due to close correspondence of powerplant discharge to lake turbidity levels, the powerplant plume was not detected in any LANDSAT images.

Active beach erosion was in progress to the west of the plant on September 19, 1973 (fig. 15), owing to wave action generated by 10-knot south-southwest winds. Suspended matter, carried by wave-induced long-shore currents, moved along the coast toward the east-northeast. The transport of littoral drift was blocked by the lakeward-oriented thermal jet from the powerplant. Drift can be seen concentrating at a point about 2 km west of the plant (fig. 15). Part of this very turbid water was then swept 3.5 km offshore, causing a pile-up of murky water against the west flank of the powerplant's thermal plume. Thus, the position of the western boundary of the thermal plume was defined in figure 15, even though the plume itself could not be identified in the image.

OSWEGO RIVER PLUME

The Oswego River basin is a complex hydrologic system. Although the Oswego River itself is only 39 km long, within the watershed there are approximately 11,300 km of streams and 170 km of barge canal (Jackson and others, 1964), and nearly 7 percent of the 13,300 km^2 drainage area represents lake surfaces (table 1). The seven Finger Lakes are all within the basin. These lakes effectively trap sediment delivered to them by streams draining the erodible Appalachian Uplands physiographic province in the southern part of the watershed. Oneida Lake, the largest lake wholly within New York State, is also part of the Oswego River basin. This lake, surface area 128 km^2, likewise performs as a very effective sediment trap by intercepting and detaining much of the suspended material borne by streams draining the eastern part of the basin. Owing to these and other natural and man-made sediment sinks, turbidity of the mouth of the Oswego River is lower than one might anticipate.

That relatively low turbidity levels characterize the Oswego River may be inferred from figure 16. This photograph, composed from images obtained May 16, 1973, shows a diffuse band of smoke drifting northeast over the lake. The smoke originated from a steam-electric powerplant about 2 km southwest of the Oswego River mouth. Despite a discharge of 280 m^3/s, no plume is visible at the river mouth. Accordingly, it is inferred that turbidity in the river was close to that in the lake. This was corroborated by ground truth obtained on May 16th, which showed turbidity in Oswego Harbor to be within 1 to 2 JTU's of that in Lake Ontario. By way of contrast, on the same image a widespread well-defined

plume was detected at the mouth of the Genesee River (fig. 6), despite the fact that its flow was about half that of the Oswego River. Although both rivers drain largely similar terrain, only 1 percent of the Genesee River basin represents free water surfaces (table 1), contrasted with almost 7 percent in the Oswego River basin. Clearly, lake and reservoir sediment trapping would appear to be a major factor governing plume generation at the mouths of both rivers.

Storm runoff entering the Oswego River may introduce sufficient suspended sediment to permit plume detection on satellite images. For example, figure 17 produced from images obtained June 2, 1973, shows a large plume emanating from Oswego Harbor. This turbidity feature overspread 13 km^2 of lake surface and was visible up to 4.5 km offshore. The arrowhead shape of the harbor is clearly visible. A strong movement of water is directed northwest from the harbor entrance. Despite an onshore northerly flow of air, the plume veers from northwest to north to northeast, suggesting the presence of a northeast-moving longshore current.

Although the June 2nd scene (fig. 17) was made on the very next orbit cycle after May 16 (fig. 16) under virtually identical rates of river discharge, the views of the harbor area differ considerably. Dry weather conditions prevailed for several days prior to May 16, so that storm runoff to the river was negligible at that time. Accordingly, the bulk of the river discharge consisted of baseflow or ground-water runoff. The turbidity of ground-water runoff (spring discharge and underflow) is generally very low; thus despite moderately high baseflow discharge, river flow was fairly clear on May 16. Before June 2nd, however, sporadic showers occurred throughout the Oswego River basin. As a direct result, a sufficient

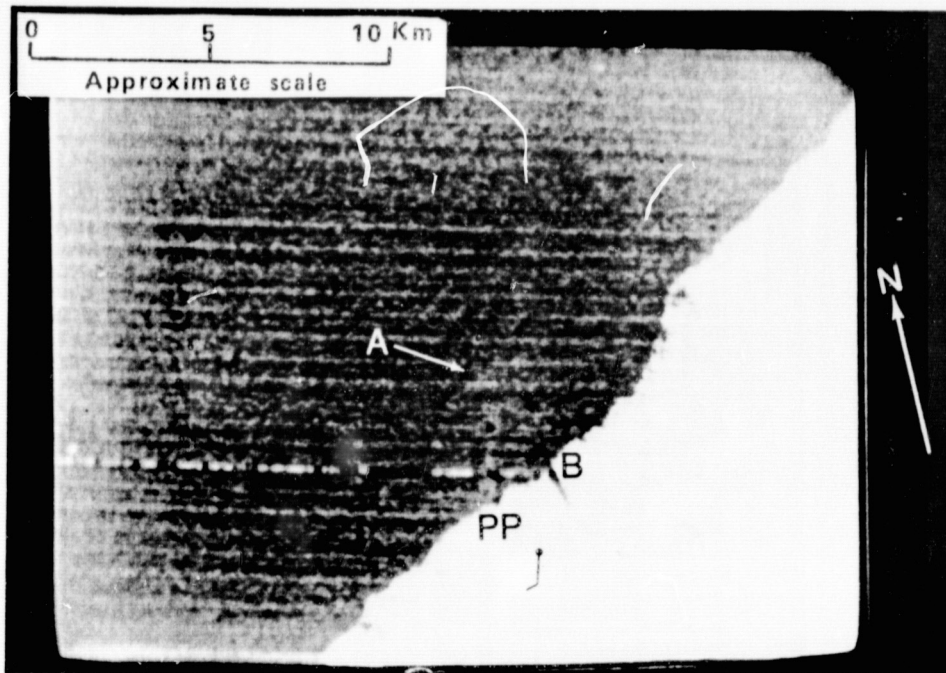Figure 16. -- Part of LANDSAT-1 image 1297-15243, obtained
May 16, 1973, showing smoke (A) from a powerplant (PP)
located near the Oswego River (B) (photograph from
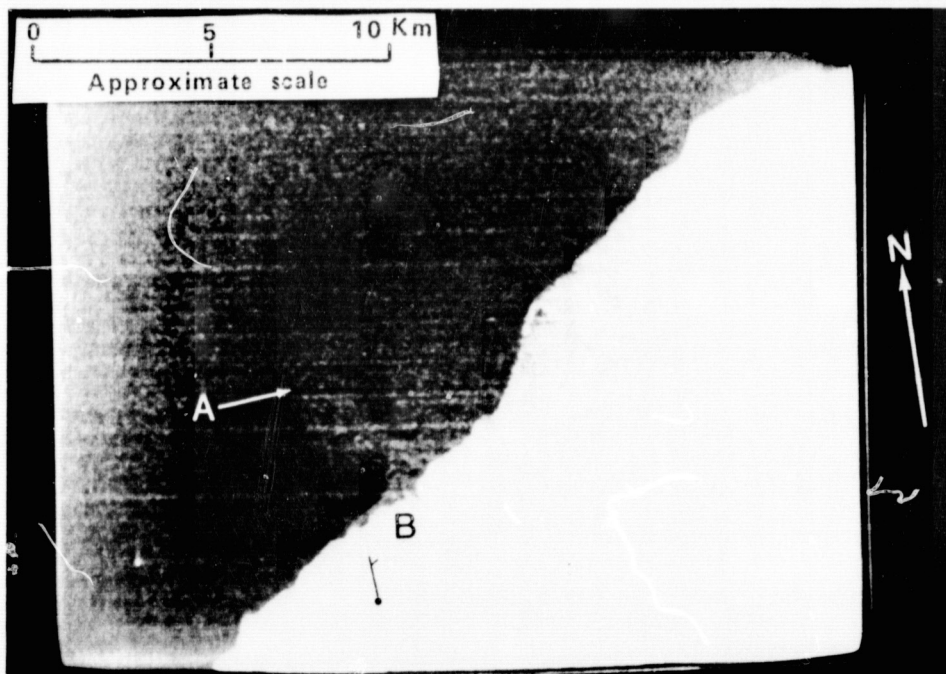Stanford Research Institute). EDC-010089.

Figure 17. -- Part of LANDSAT-1 image 1314-15183, obtained
June 2, 1973, showing the Oswego River plume (A) and the
river mouth (B) (photograph from Stanford Research
Institute). EDC-010090.

quantity of highly turbid storm runoff was generated which, upon mixing

with the in-channel waters, produced sufficient turbidity in the river

to ensure plume detection.

Dark "clear-water" plumes are occasionally visible at the mouth of

the Oswego River during the summer and early fall. Stepped-up algal and

plankton production during the warm season results in increased nearshore

turbidity levels in Lake Ontario. Under baseflow conditions, the turbidity

of the river may fall significantly below that of the receiving lake waters,

permitting detection of a dark or reverse-type plume as portrayed in

figure 18. This photograph, obtained August 13, 1973, shows a dark plume

at the mouth of the river, which extended 7 km downwind along the shoreline.

A strong northeast-flowing littoral current generated by westerly winds

confined the plume to nearshore waters within 1.5 km of the shore.

As previously noted, in winter, plumes seldom form along the south

shore of the lake. However, brash ice (broken and free floating ice,

fig. 19) is a useful indicator of current movement. By way of illus-

tration, on February 10, 1974, under a southerly wind field, brash ice

floes were detected moving northeast, initially toward and then around the

Oswego Harbor enclosure (fig. 20). The snow and ice covered breakwaters

forming the harbor enclosure are clearly visible in this photograph. Except

for a 3- to 4-km reach, the Oswego River appears to be completely ice

covered (fig. 20, B). As anticipated, there was no evidence of a plume

at the mouth of the river.

Based on LANDSAT-1 imagery and high-altitude photography, there is

strong evidence of a persistent northeast-trending longshore current in

the southeast part of Lake Ontario throughout the year. The current seems

strongest under westerly wind fields, but is evident even with a flow of air

directly from the northeast (Pluhowski, 1973).
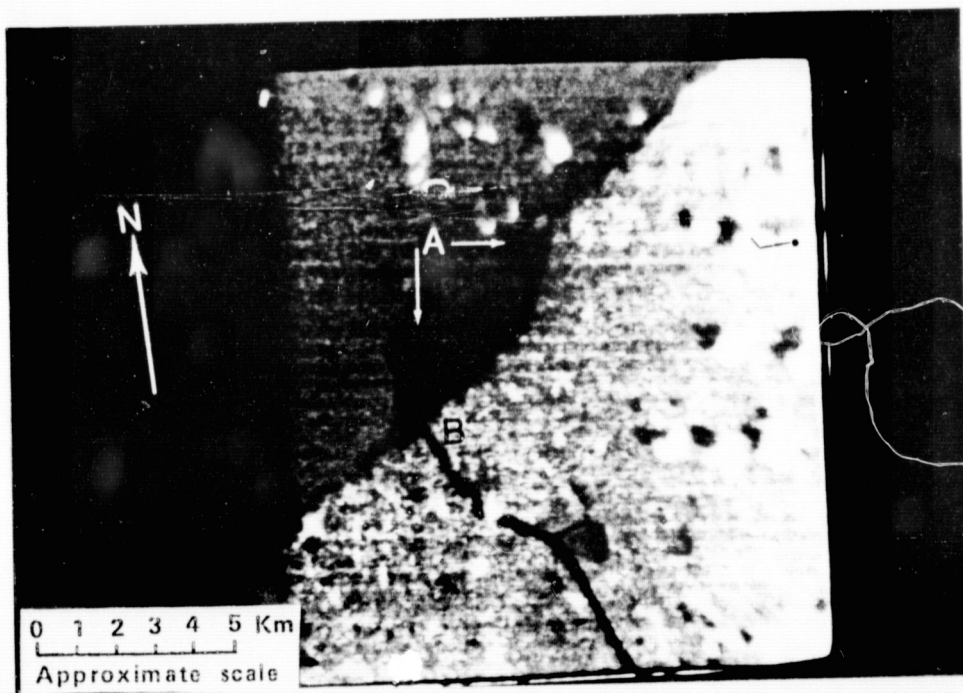
Figure 18. -- Part of LANDSAT-1 image 1386-15174, obtained
Aug. 13, 1973, showing a clear water (dark) plume (A) at
the mouth of the Oswego River (B) (photograph from
Stanford Research Institute). EDC-010091.

Figure 19. -- View of the Lake Ontario shoreline looking
east toward Oswego, N.Y. on Feb. 15, 1973, showing
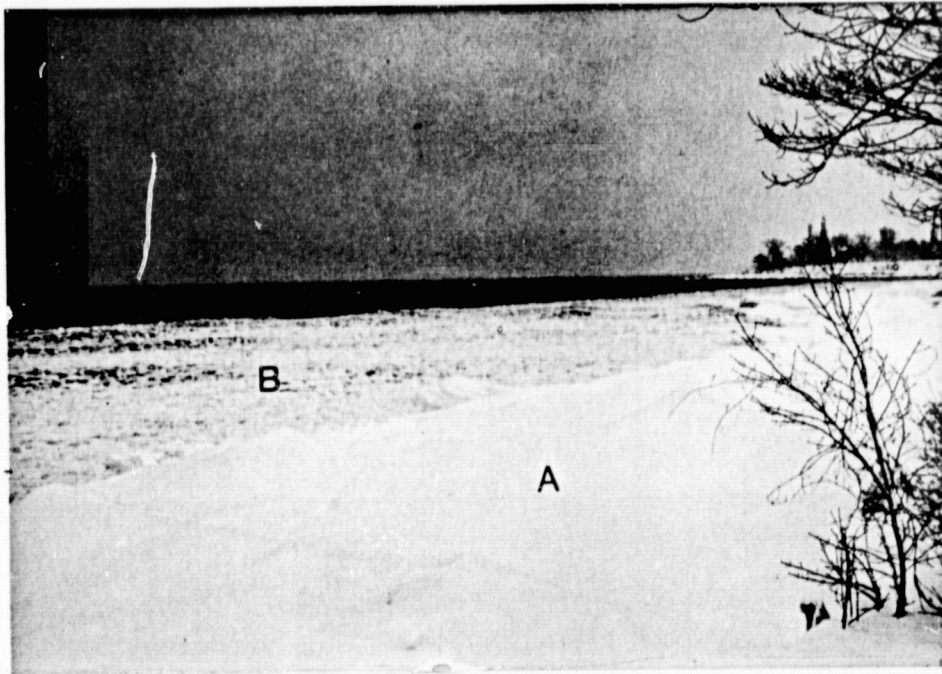icefoot formation (A) and floating brash ice (B).
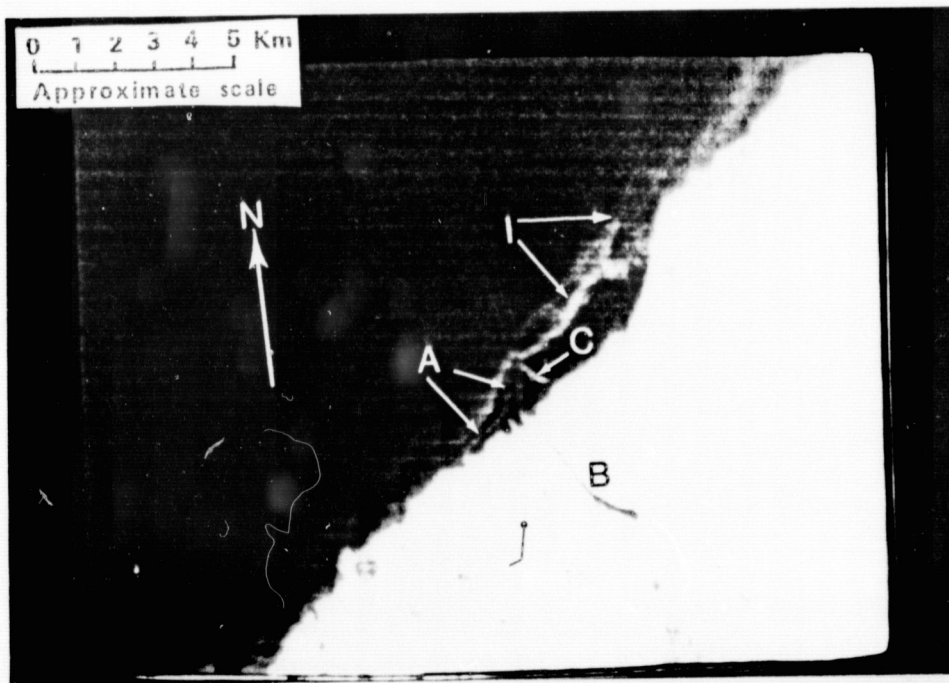EDC-010092.

Figure 20. -- Part of LANDSAT-1 image 1567-15194, obtained
Feb. 10, 1974, showing west (A) and east (C) Oswego
harbor breakwaters, an open-water river reach (B), and
floating brash ice (I) (photograph from Stanford Research
Institute). EDC-010093.

NIAGARA RIVER AND WELLAND CANAL PLUMES

The Niagara River receives more than 8.8 m^3/s of industrial dis-
charge from chemical, primary metals, and paper plants in New York
State (Limnos, 1972). Much of the industrial discharge emanates from
the Buffalo, N.Y. metropolitan area at the east end of Lake Erie near
the source of the Niagara River. Waters of the Welland Canal and the
Port Dalhousie diversion channel are affected by oil and waste from
cargo vessels, tankers, and pleasure craft. A considerable amount of
fine-textured material is kept in suspension or is frequently resuspended
in the canal by turbulence from ship propellers and heavy boat traffic
throughout the shipping season. Accordingly, turbidity is often high in
waters entering Lake Ontario from the Welland Canal from April 1 to about
December 15 (fig. 21). A listing of extreme and average suspended-sediment
concentrations made during this study are shown in table 2.

The low suspended-sediment concentrations in the Niagara River are
due, in large part, to the settling of suspended matter in Lake Erie.
Additionally, a large relatively uniform flow dilutes the industrial
effluent entering the river. Thus, Niagara River water is usually rela-
tively clear and is often characterized by low turbidity levels. That
dilution by the river is not entirely effective in improving water quality
is demonstrated by the county health department's closing of Fort Niagara
immediately east of the Niagara River mouth (fig. 22).

Because the nearshore receiving waters of Lake Ontario are also
occasionally clear, there may be little or no tonal variation between the
Niagara River and the lake. At such times the Niagara River plume may be
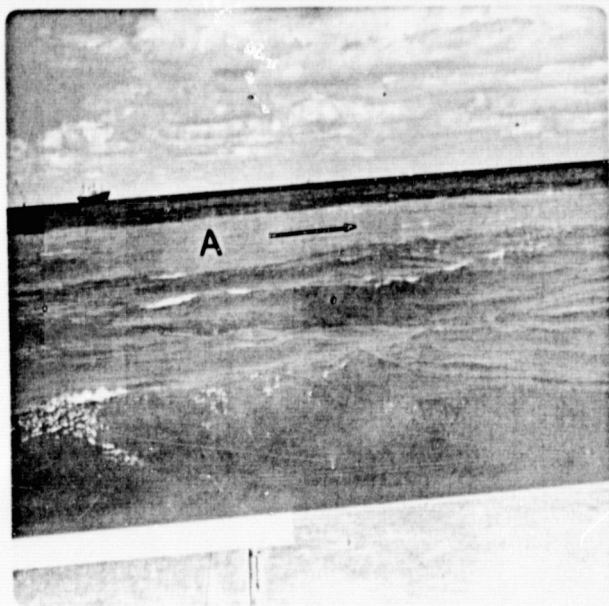
Figure 21. -- Turbid canal water (A) moving
east into Lake Ontario past the east
bulkhead of the Welland Ship Canal
(July 10, 1973). EDC-010094.

Figure 22. -- Fort Niagara Beach closed to
swimming by the County Health Dept.
(July 10, 1973). EDC-010095.

Table 2. -- Suspended-sediment concentrations, in milligrams per litre, in selected north flowing watercourses discharging into Lake Ontario (September 1972 - April 1974).

Station	No. of samples	Maximum conc.	Minimum conc.	Average conc.
Genesee R. at Rochester	7	123	14	48
Diversion at Port Dalhousie	6	96	37	49
Niagara R. at mouth	7	22	2	12
Oswego R. at Oswego	6	30	5	15

undetected in LANDSAT imagery. For example, on August 20, 1972, no plume could be seen at the mouth of the Niagara River (fig. 23). A large diffuse triangular-shaped plume is visible beyond the Welland Canal entrance, and a small plume can be seen drifting east from Port Dalhousie harbor. A gentle onshore lake breeze resulted in some beach erosion along the New York shore. The eastward-trending Port Dalhousie diversion plume is still responding to a land (offshore) breeze that prevailed the previous night, whereas the Welland Canal plume has begun to drift westward due to a recently established lake-breeze circulation.

By the next day (August 21), a brisk 10-knot southwest wind, overspread the entire region, resulting in the creation of a well-defined northeast longshore current. Both the diversion and Welland Canal plumes were detected moving east along the Ontario shoreline (fig. 24). The Niagara River jet, oriented northwest at the mouth of the river, forms an effective hydraulic barrier to the movement of littoral drift. Propelled by the powerful jet, Niagara River water gradually fans out over the lake, losing momentum in the process. Upon reaching the boundary of the Niagara River's zone of influence, littoral drift was forced to move around the hydraulic barrier. Unlike the previous day, part of the Niagara River plume was visible on August 21 due to a strong eastward-moving longshore current that carried turbid Welland Canal water beyond the Niagara River mouth.

A somewhat analogous cold-season situation is depicted in figures 25 and 26. A strong northwest flow of dry arctic air from Canada moved over the lake on February 11, 1974 (fig. 25). As the air gained moisture from

Figure 23. -- Part of LANDSAT-1 image 1028-15293, obtained
Aug. 20, 1972, showing the Port Dalhousie harbor plume
(A), Welland Canal plume (B), Niagara River (C), and a
beach erosion plume (D) (photograph from Stanford
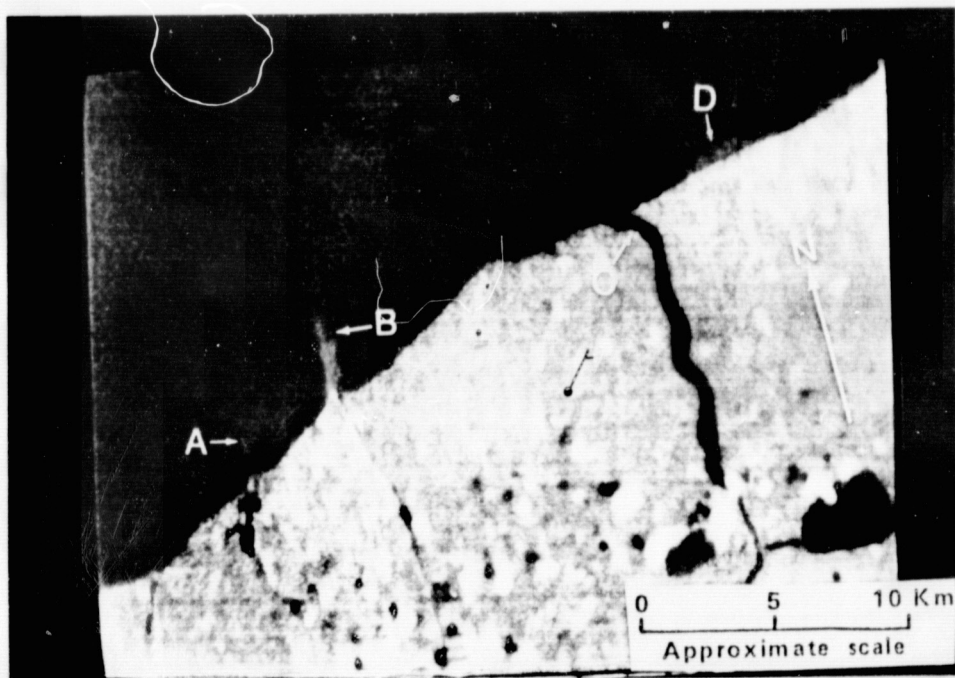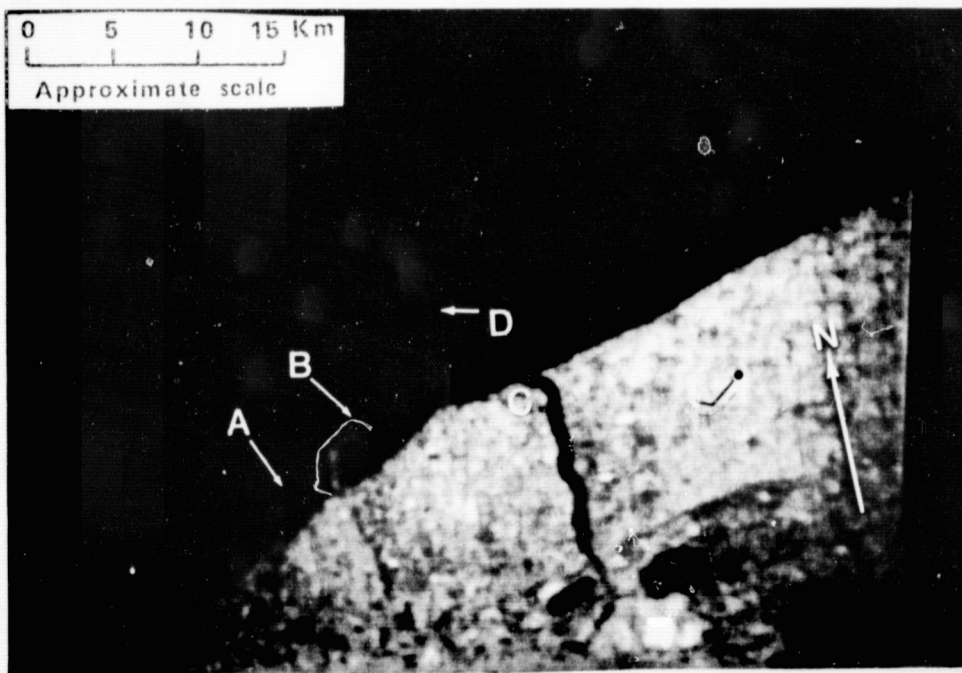Research Institute). EDC-010096.

Figure 24. -- Part of LANDSAT-1 image 1029-15345, obtained
Aug. 21, 1972, showing the Port Dalhousie harbor plume
(A), Welland Canal plume (B), Niagara River (C) and
boundary of the Niagara River plume (D) (photograph
from Stanford Research Institute). EDC-010097.

the relatively warm lake, cirrocumulus cloud streets began forming at mid lake. The cloud streets are seen oriented from northwest to southeast parallel to the prevailing wind field. That a strong eastward moving longshore current was generated by the 20-knot northwest winds is virtually a certainty. However, since neither the Welland Canal or the Niagara River plumes are visible in figure 25, visual corroboration of current movement is not possible. Suspension of Welland Canal operations during the winter effectively eliminated the canal as a source of turbidity, thereby temporarily neutralizing an important current tracer.

A shift to a prevailing southwest wind the next day (February 12th) dislodged much of the brash (floating) ice forced against the beaches on February 11 by predominantly onshore winds. Brash ice floes were carried east along the Ontario coast until stopped by the Niagara River jet about 2 km west of the river. Part of the ice can be seen moving around the Niagara River clear-water plume (fig. 28). That the large volume of water debouching into the lake from the Niagara River pushed eastward-moving longshore currents about 5 km offshore at the river's mouth is strongly suggested by the brash-ice configuration portrayed in figure 26.

During the winter, surface temperatures in Lake Ontario are below $4^{o}C$, the temperature corresponding to maximum water density. In spring, heating near the shoreline raises nearshore water temperatures above $4^{o}C$, while offshore waters are still below $4^{o}C$. As the $4^{o}C$ isotherm moves offshore with the approach of summer, maximum density water associated with it acts as a barrier to both the warmer (less dense) inshore water and the colder (also less dense) mid-lake water. This contracting boundary zone of very dense water is called the "thermal bar" and was first detected by Tikhomirov (1964).

Figure 25. -- Part of LANDSAT-1 image 1568-15252, obtained
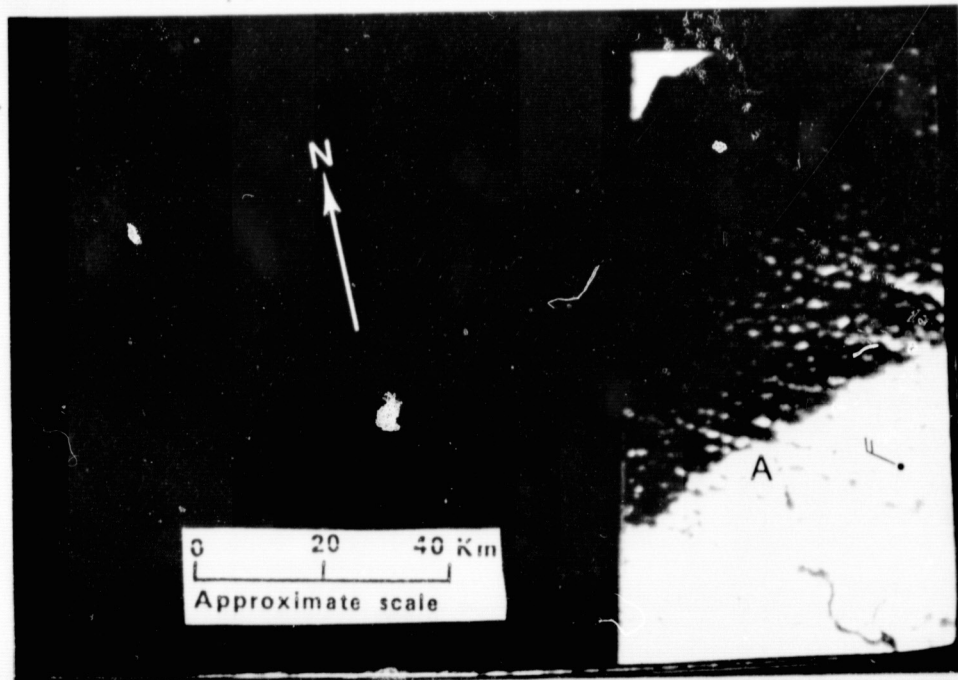Feb. 11, 1974, showing the Niagara River outlet (A)
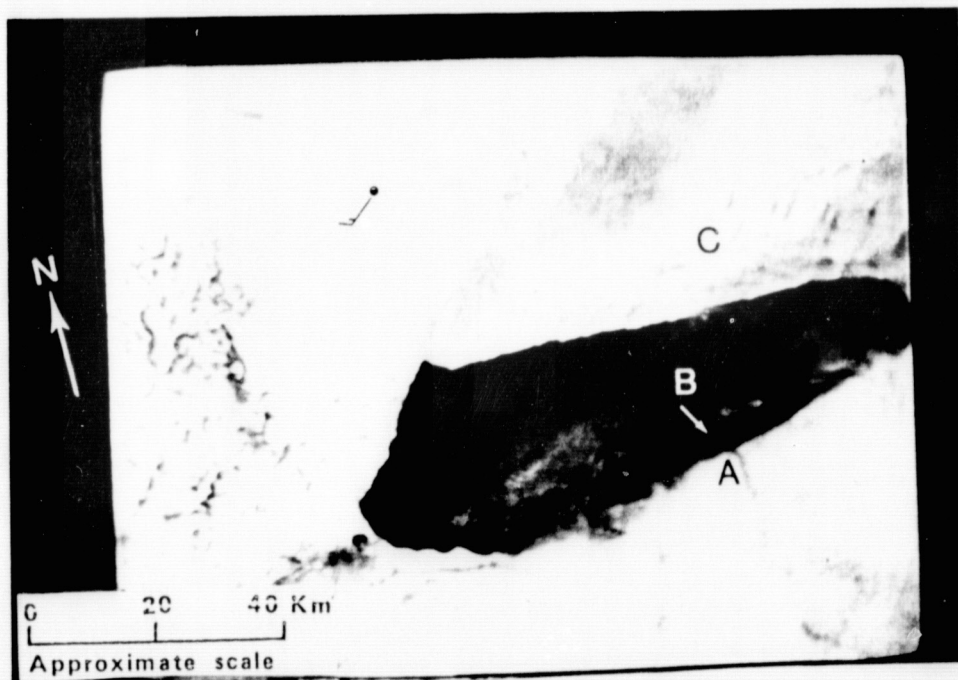(photograph from Stanford Research Institute).
EDC-010098.

Figure 26. -- Part of LANDSAT-1 image 1569-15310, obtained
Feb. 12, 1974, showing the Niagara River outlet (A),
brash ice moving around the Niagara River plume (B),
and a continuous cloud formation (C) (photograph from
Stanford Research Institute). EDC-010099.

As heating progresses, the thermal bar, similar to a contracting cylinder, moves toward the middle of the lake. In Lake Ontario, a dimictic lake, thermal bars form twice yearly, once in the fall and again in the spring. Rodgers (1966) describes the spring thermal bar in Lake Ontario as a moving convergence zone separating uniform cold mid-lake waters from warmer stratified waters on the shore side of the bar. The thermal bar extends from the surface of the lake to the bottom and is characterized by a strong horizontal temperature, turbidity, and color gradient at the lake surface. Owing to slack thermal gradients in the lake, the fall thermal bar is less distinct than its spring counterpart.

The position of the thermal bar may be inferred from image No. 1263-15361 obtained April 12, 1973 (fig. 27). Niagara River waters were at or very near 4°C, so that the plume boundary, shown as a bright semi-circular band of turbid water, defines the position of the thermal bar near the mouth of the river. The plume was 56 km^2 in area and, at its extreme point, extended 6.5 km offshore. A bright thin highly turbid band paralleling the New York coastline east of the Niagara River plume defines the position of the thermal bar at about 2 km offshore. The temperature of nearshore waters flanking the 12 km of coastline influenced by the Niagara River plume ranged from 4° to 6°C, whereas water temperatures were below 4°C on the offshore side of the thermal bar.

An intense plume is visible at the Welland Canal (fig. 27), which drifted east under a prevailing northwest wind field. Turbidity in the canal was as high as 400 JTU, one of the highest values measured during this study. Five to 7 km offshore, the plume bent abruptly to the south-west, strongly suggesting the presence of an offshore countercurrent
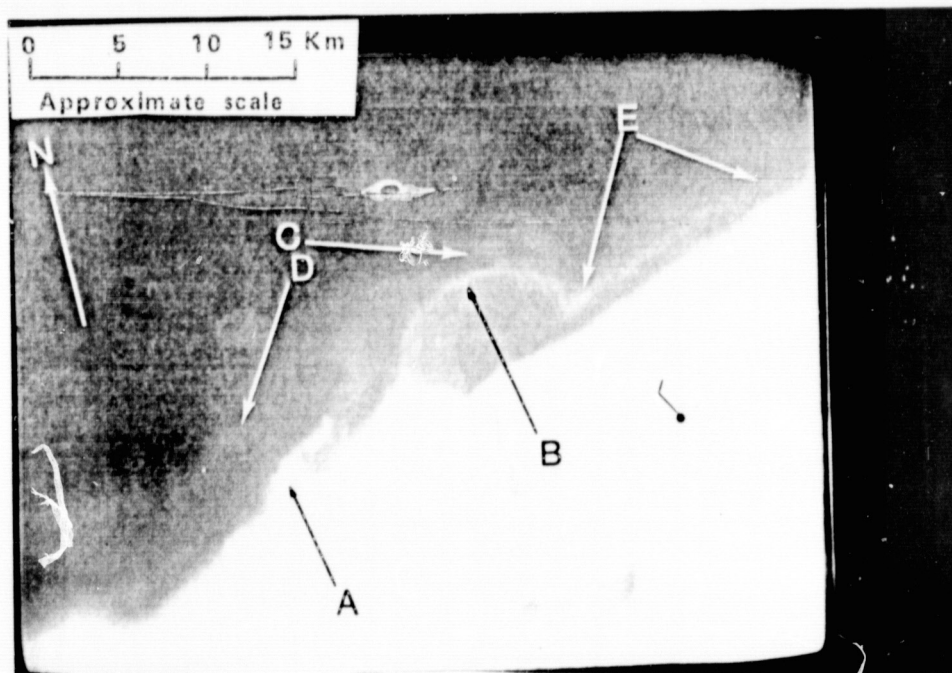
Figure 27. -- Part of LANDSAT-1 image 1263-15361, obtained April 12, 1973, showing the Welland Canal plume (A), boundary of the Niagara River plume (B), turbulent mixing (C), an offshore plume (D), and a drift convergence zone (E). The approximate position of the thermal bar is marked by (B) and (E) (photograph from Stanford Research Institute). EDC-010100.

(fig. 27, D). That a countercurrent did exist lakeward of the thermal bar may be inferred from the numerous small eddies visible along the periphery of the Niagara River plume. Once beyond the influence of the plume, turbid water released by the eddies drifted in a general west-southwest direction.

A strong eastward-moving longshore current was generated on April 29, 1973, by a gusting 20-knot west wind, and the shearing action of this current on the Welland Canal and Niagara River plumes is readily apparent in figure 28. The Niagara River clear-water plume was confined within 3.5 km of the shore; however it extended 17 km downwind along the New York State shoreline, covering 34 km^2 of lake surface. A combination of high lake levels and a northwest wave train resulted in extensive beach erosion along the Canadian coast and for about a 30-km length of New York shoreline east of the Niagara River. Some protection from beach erosion was provided by the Niagara River jet along the New York shoreline immediately east of the river. Much of the energy of the ambient wave train was absorbed by the lakeward-flowing waters of the Niagara River plume. Unfortunately, the river's protection extended only about 7 km east of the Niagara River mouth, as portrayed by a gradual widening band of highly intense littoral drift along the shoreline (fig. 28, D). As the coastline orientation shifts somewhat away from the impinging wave train about 39 km east of the Niagara River, beach erosion becomes less intense. The impact of waves on the beaches is less severe in this area (fig. 28, E) because the wave train is approaching the coastline at an increasing angle of incidence to the shore.

Figure 28. -- Part of LANDSAT-1 image 1280-15302, obtained
April 29, 1973, showing Port Dalhousie (A), Welland Canal
(B), Niagara River (C), beach erosion plumes (D and E),
turbidity waves (F), offshore plumes (G and H).

Confinement of turbid runoff on the inshore side of the thermal bar (Hubbard and Spain, 1973) may permit locating its position from satellite imagery. For example, in figure 28 turbidity is confined principally to within 5 km of the New York shoreline lying beyond (east of) the Niagara River plume. Thus, the thermal bar is assumed to be 5 km offshore on April 29 or 3 km lakeward of its position on April 20. The large turbidity waves from 5 to 10 km beyond the New York coast are indicative of a westward-trending countercurrent along the offshore side of the thermal bar. Too, the probability of an offshore countercurrent may be inferred from the movement of turbid water north of the Niagara River plume to a position about 20 km west-northwest of the plume (fig. 28, G). The probability of water movement toward mid lake is suggested by a broad, slightly turbid zone beyond the Welland Canal-Niagara River plumes (fig. 28, H). There, an apparent northward flowing offshore current is moving toward mid lake orthogonally to the west-to-east airflow.

With the gradual retreat of the thermal bar toward mid lake in spring, the bar's tendency to contain runoff to nearshore waters is slowly relaxed. By July, surface temperatures are above 4°C throughout the lake so that the thermal bar is eliminated, and the lake becomes completely stratified. Accordingly, under favorable wind conditions during summer and early fall, warm low-density waters of the Niagara River jet may be carried far out into the lake.

By way of illustration, on September 3, 1973, an extensive clear-water plume was detected at the mouth of the Niagara River (fig. 29).
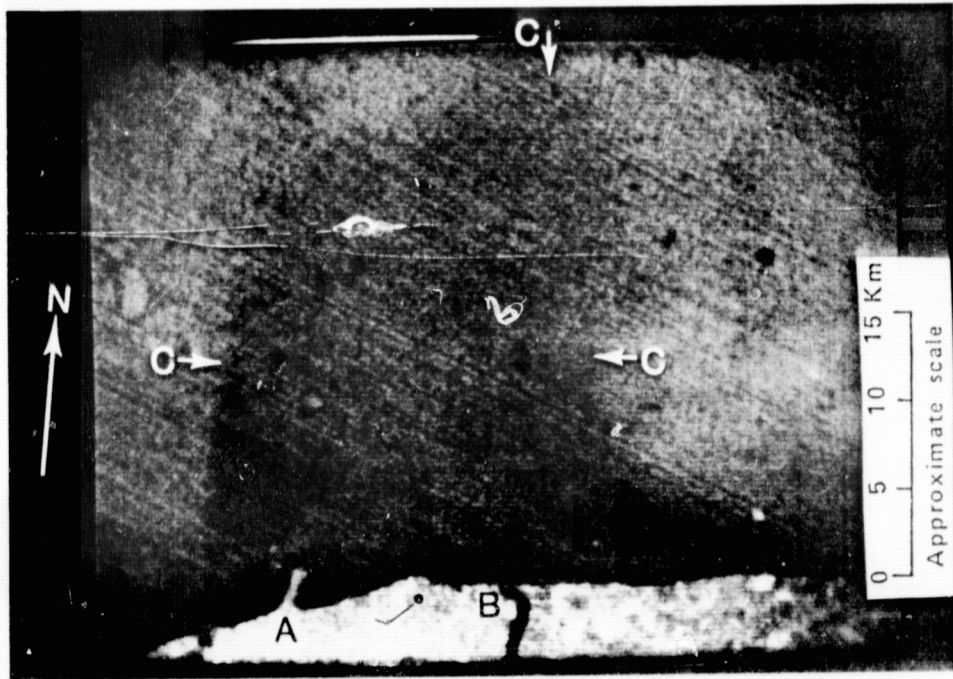
Figure 29. -- Part of LANDSAT-1 image 1407-15343, obtained
Sept. 3, 1973, showing the Welland Canal (A), Niagara
River (B), and the Niagara River plume (C) (photograph
from Stanford Research Institute). EDC-010101.

This large turbidity feature was more than 500 km^2 in area, extending 30 km offshore, with an average width of 15 to 20 km. Background turbidity levels in Lake Ontario were high due to seasonally increased biologic activity. The relatively low (2 JTU) turbidity water in the Niagara River appears dark in the image. A gentle southwest breeze reinforced the northwest (lakeward) directed Niagara River jet causing the surface-spreading river water to move far offshore. This particular plume was the largest turbidity feature found, to date, in LANDSAT imagery of Lake Ontario. The plume extended more than half way across the lake, and could have been detected in its entirety only by satellite imagery.

Clear-water (dark) plumes are frequently visible at the mouth of the Niagara River and, to a lesser extent, at the Oswego River outlet. Characteristically low turbidity in both rivers relative to that found in nearshore lake waters accounts for the phenomenon. However, with certain wind stresses, turbidity may be added to the Niagara River, resulting in the formation of a "conventional" light (turbid) plume at the river outlet. For example, with a 15-knot north wind on July 11, 1973, active beach erosion was occurring along the New York shoreline as portrayed in figure 30 by a bright narrow band along the coast east of the Niagara River. The littoral drift zone was only about 1 km wide, and suspended matter was being swept westward toward the mouth of the Niagara River. Upon reaching the river, the suspended matter merged with the Niagara River jet and was swept offshore. As a direct result, the entrained drift created a clearly defined light-toned plume at the mouth of the river (fig. 30). Initially, the plume moved west-northwest into the lake. At

46
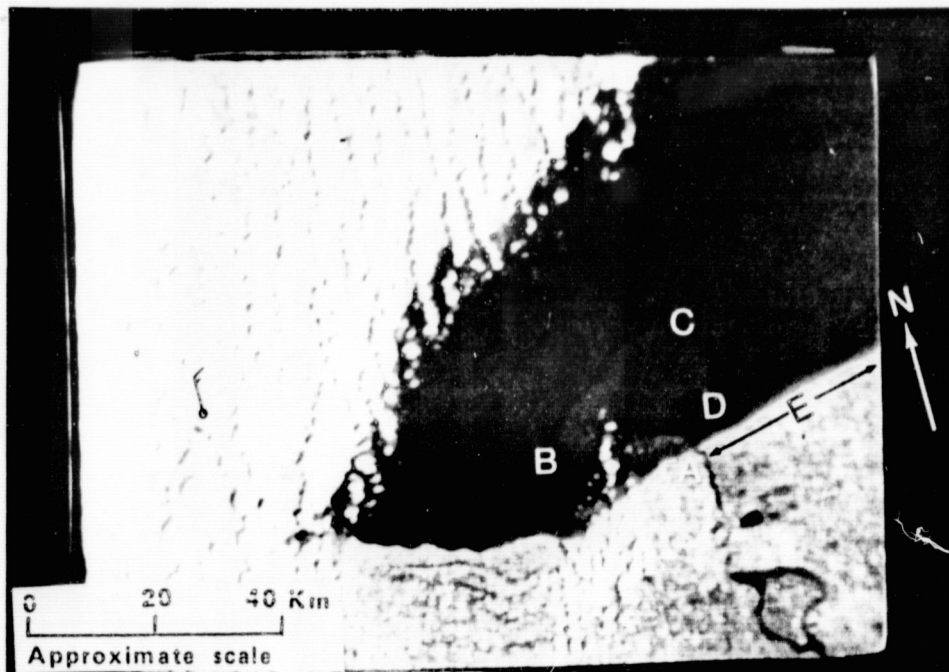
Figure 30. -- Part of LANDSAT-1 image 1353-15352, obtained
July 11, 1973, showing the Niagara River (A), successive
positions of its plume (B, C, D) and beach erosion (E)
(photograph from Stanford Research Institute). EDC-010102.

Figure 31. -- View toward the northwest
across the mouth of the Niagara River
on July 11, 1973, showing direction of
flow of the Niagara River jet (large
arrow) and turbid littoral drift in
foreground. EDC-010103.

47

a point about 10 km offshore, it abruptly hooked to the north, then curved northeast in direct opposition to the southwest-moving longshore current. About 22 km offshore due north of the Niagara River outlet, the plume once again abruptly changed direction by moving south, eventually losing its identity near the mouth of the river. This extensive turbidity feature formed a large clockwise gyre whose principal axis was 34 km long.

A ground-level view across the Niagara River mouth obtained concurrently with image No. 1353-15352, is shown in figure 31. The Canadian shoreline is to the left, and Lake Ontario extends to the horizon in the center and right hand parts of the photograph. A sharp difference in water color is readily apparent. The gray westward-moving water in the foreground is very turbid (200 JTU), whereas the blue clear Niagara River jet averaged less than 2 JTU. As shown in figure 30, the turbid nearshore waters were entrained in the jet and swept offshore. The irregular meandering color boundary in figure 31 defines the turbulent east flank of the Niagara River jet as it moves northwest into the lake.

A somewhat similar cold-season situation, illustrating formation of a relatively "high turbidity" plume at the mouth of the Niagara River, is depicted in figure 32, obtained January 25, 1974. Owing to a prolonged thaw, which began in mid-January, there was scant ice cover in Lake Erie near the Niagara River source. Moreover, a persistent southwest wind piled up a considerable amount of turbid water along the east end of Lake Erie, forcing some of the water into the Niagara River. By way of contrast, the nearshore waters of Lake Ontario were relatively
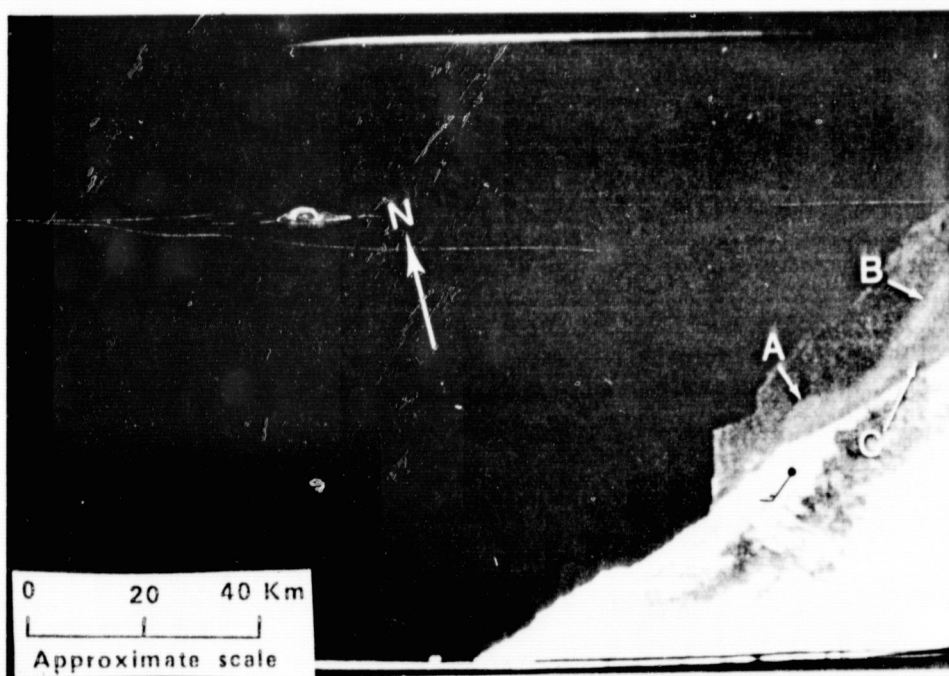
Figure 32. -- Part of LANDSAT-1 image 1551-15313, obtained Jan. 25, 1974, showing the Niagara River plume (A), its extension along the New York shore (C), and a cirrus cloud street (B) (photograph from Stanford Research Institute). EDC-010104.

clear at that time. Thus, higher turbidity in the Niagara River ensured plume development at its mouth (fig. 32). The resulting plume was swept eastward along the New York shoreline by the southwest wind field being confined to within 6 km of the coast.

The prevailing wind direction over Lake Ontario is from the southwest (Baum and others, 1973). This factor along with a net mass movement of water from west-to-east results in a predominantly eastward-moving coastal current along the south shore of the lake. There are, however, frequent occasions when easterly winds are encountered, some-times for several days at a time. Easterly winds are most prevalent during cyclonic storms, lake breezes, and anticyclones passing north of the lake. Unfortunately, such winds are often associated with cloudiness, so that the opportunity to study their effect on plume dynamics is limited. Nevertheless, on several occasions, useable images were acquired during times of easterly surface winds, despite a high percentage of cloud cover.

On November 1, 1972, a well-defined plume was detected at the Lake Ontario terminus of the Welland Canal (fig. 33). This plume was oriented in a west-southwest direction generally downwind from the prevailing gentle northeast wind field. The apparent high lake turbidity at the Niagara River outlet is attributed to a thin veil of cirrus clouds, which covered the sky. Turbidity in the canal was 25 JTU; it ranged from 1 to 3 JTU in clear waters of the lake and about 1 JTU in the Niagara River.

Although not visible in figure 33, a less intense plume was detected at Port Dalhousie harbor about 5 km west of the canal. This plume extended nearly 11.5 km into the lake. Initially, the plume trended west-southwest; however, it curved to the northwest (away from the shore) about 5 km west of Port Dalhousie. As demonstrated in figure 33, under a northeast wind field nearshore currents west of the Niagara River are likely to move away from the river in direct opposition to their usual eastward direction.

From high altitude (18,300 m) photography obtained October 19, 1970, under a due east wind field, the Welland Canal plume also moved to the west (Pluhowski, 1973). However, the outermost part of the plume sheared toward the east, suggesting the presence of an eastward-flowing offshore countercurrent about 3 km offshore.

Under the southeast wind field on December 2, 1973, the Niagara River, Welland Canal, and Port Dalhousie harbor plumes were all clearly visible (fig. 34). Both the Welland Canal and Port Dalhousie diversion plumes, after moving a short distance west, abruptly turned toward the east, 2 to 3 km offshore, thereby identifying the presence of an eastward moving offshore current. The Niagara River plume appears quite turbid in figure 34 due to (1) mixing of westward moving littoral drift from the New York shoreline with river discharge and (2) the movement of highly turbid water into the river from the east end of Lake Erie. The 3-km wide light band along the New York shore (fig. 34, D) outlines

Figure 33. -- Part of LANDSAT-1 image 1101-15354, obtained
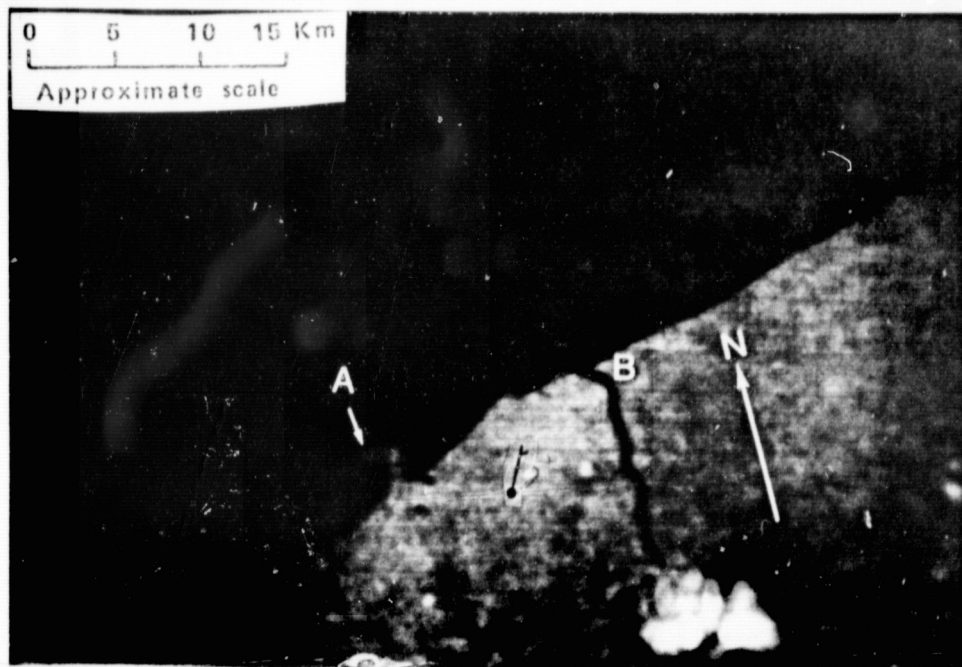Nov. 1, 1972, showing the Welland Canal plume (A), and
the Niagara River (B) (photograph from Stanford Research
Institute). EDC-010105.
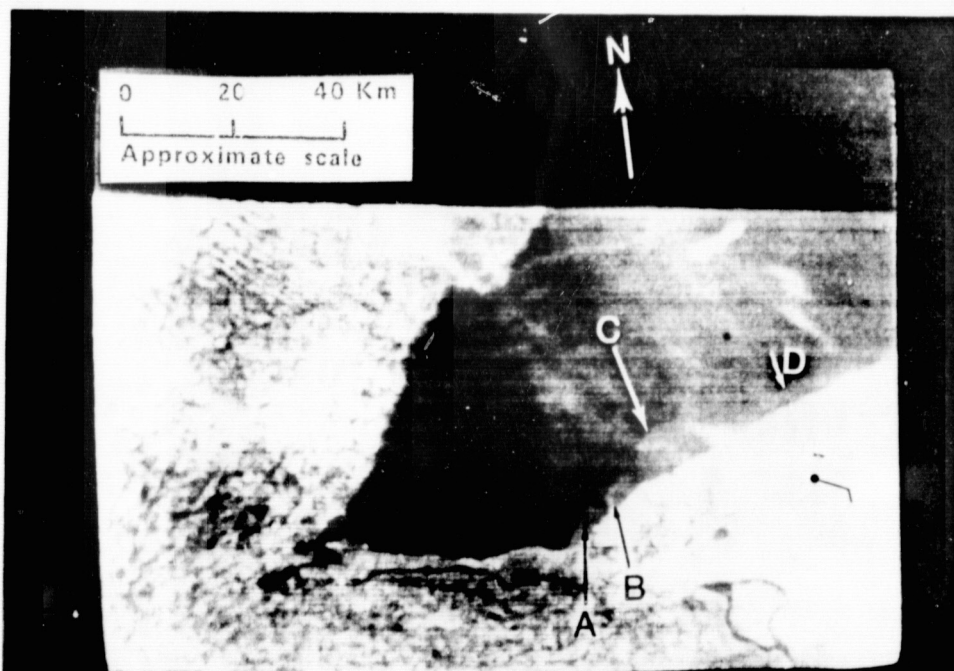
Figure 34. -- Part of LANDSAT-1 image 1497-15330, obtained
Dec. 2, 1973, showing Port Dalhousie (A), the Welland
Canal (B), Niagara River plume (C), and a beach erosion
plume (D) (photograph from Stanford Research Institute).
EDC-010106.

the position of the westward-flowing littoral drift zone. As in all late fall and early spring images received to date, the Niagara River plume was confined to within 10 km of the shore, probably due to the nearshore position of the thermal bar.

SUMMARY

Of the four multispectral channels provided by the LANDSAT-1 MSS system, band 5 (visible red) generally proved to be the most useful for plume analyses. Under clear skies and high atmospheric transmissivity, band 4 (visible green) frequently yielded high quality images. After preliminary screening, pertinent 70-mm frames were analyzed on the ESIAC console. False-color renditions of selected LANDSAT-1 scenes were obtained on a video display by superimposing band 5 or band 4, on band 6 in the ESIAC system.

The most important factors governing the size, shape, and intensity of turbidity plumes in large quiescent water bodies, such as Lake Ontario, are wind speed and direction, volume of incoming runoff, and the difference between the turbidity of the discharging river and that of the receiving water body. In Lake Ontario, thermal features, such as the spring thermal bar, tend to confine plumes to nearshore waters.

Highly turbid plumes appear very light toned in LANDSAT images. Such plumes were frequently detected at the mouth of the Genesee River, Port Dalhousie harbor, and, during the shipping season, at the Welland Canal terminus. Effective sediment trapping in the Great Lakes above the Niagara River and by numerous impoundments in the Oswego River basin occasionally produces "clear water" or dark plumes at the outlets of both rivers. Turbidity in the Niagara River is sometimes equivalent to levels measured in Lake Ontario. At such times, the Niagara River plume will not likely be visible in LANDSAT imagery.

Owing to its very large discharge, the plume created by the Niagara River is, by far, the largest turbidity feature in Lake Ontario. The plume is confined to inshore waters by the thermal bar during early spring and late fall. However, on one occasion during summer stratification, the Niagara River plume extended 30 km offshore under a southerly (offshore) wind field. As demonstrated in satellite images, the Welland Canal is the most turbid water source discharging into Lake Ontario. The highly turbid outflow from the canal is confined to the shipping season -- in winter very little turbidity enters the lake from this source.

Beach erosion was frequently identified in LANDSAT imagery at wind speeds in excess of 5 knots from all directions except the south. Although the entire south shore of the lake is subject to beach erosion, excessive rates were discerned along the following coastal segments (1) Fifty Mile Pt., Ontario to Thirty Mile Pt., N.Y., (2) the Rochester embayment, and (3) from Sodus Bay to Nine Mile Pt. Owing to the buffering action of shoreline ice formations, beach erosion plumes were seldom visible in LANDSAT images during the winter.

A persistent west-to-east littoral current was detected throughout the year at the mouth of the Oswego River. Nearshore currents are much more variable in the Rochester embayment, where direction changes occur rapidly in response to shifting wind fields. Westerly winds reinforce the dominant eastward nearshore currents, frequently resulting in excessive beach erosion from Irondequoit Bay to the Ginna powerplant. East and northeast winds frequetly generate west-moving currents in the embayment, while south winds result in a northwest flow of water.

The Niagara River plume, after initially moving northwest, normally turned north, then veered northeast into the lake before losing its identity. The thermal structure of the lake exerts a powerful constraint on the size and shape of the plume. In April 1973, the plume was contained within 4 km of the shore due to a westerly wind field and the nearshore position of the thermal bar. A powerful littoral current carried the plume eastward along the New York shore at that time. By way of contrast, warm Niagara River waters, floating in a thermally stratified lake were carried north beyond mid lake by gentle offshore winds on September 3, 1973.

West of the Niagara River, littoral currents tend to respond rapidly to changing wind direction. Short-term changes in direction of both the Welland Canal and Port Dalhousie diversion plumes, in response to imposed wind stresses were frequently visible in LANDSAT images. Nevertheless, here, as elsewhere along the lake's south shore, the prevailing direction of nearshore currents is toward the east. Westerly winds tend to intensify and accelerate the prevailing easterly littoral currents. East winds frequently reverse direction of littoral currents causing them to move to the west. However, under east and southeast wind fields, a reversal in current direction back to the east (against the wind) occurred on several occasions about 2 km lakeward of the Welland Canal terminus.

By yielding synoptic data on nearshore current movement in the lake, LANDSAT imagery provides researchers with a powerful tool that is useful in developing and verifying models protraying lake dynamics. Furthermore, in addition to detecting high turbidity sources entering the lake, satellite images are helpful in defining seasonal turbidity patterns emanating from any particular site. For example, the high sediment concentration at the mouth of the Genesee River are clearly visible during spring freshets when unprotected soils are especially vulnerable to erosion. Much less erosion normally occurs during the growing season as indicated by the small diffuse plumes frequently visible at the river terminus in summer. Monitoring of sediment transport along the lake's borders is readily attainable from satellite images. This information is useful in shoreline evolution studies and in the design of harbor and coastal control structures.

REFERENCES CITED

Baum, J. V., Tierney, J. M., and Sticksel, P. R., 1973, Climatological
and environmental factors that influence survival on the Great
Lakes: Dept. of Transportation, U.S. Coast Guard, Interim Rept.
No. CG-D-11-74, 127 p.

Bonham-Carter, G., and Thomas, J. H., 1973, Numerical calculation of
steady wind-driven currents in Lake Ontario and the Rochester
embayment: in Proc. 16th Conf. on Great Lakes Res., p. 656.

Day, J. C., 197 , International management of the Great Lakes - St.
Lawrence basin: Water Resources Bulletin, Am. Water Resources
Assn., v. 8, no. 6, p. 1130.

DeCooke, B. G., 1968, The Great Lakes Water levels problem: Limnos,
v. 1, no. 1, p. 22-26.

Hubbard, D. W., and Spain, J. D., 1973, The structure of the early
spring thermal bar in Lake Superior: in Proc. 16th Conf. on
Great Lakes Res., p. 735-742.

Jackson, D. F., Nemerow, N. L., and Myrton, C. R., 1964, Ecological
investigations of the Oswego River drainage basin: in Proc.
7th Conf. on Great Lakes Res., p. 88-98.

Limnos, 1972, The situation lake by lake: Limnos, v. 5, no. 1,
p. 19-23.

Pentland, R. L., 1968, Runoff characteristics in the Great Lakes basin:
in Proc. 11th Conf. Great Lakes Research 1968, table 2(a), p. 332.

Pluhowski, E. J., 1973, Remote sensing of turbidity plumes in Lake
Ontario: in Jour. of Research, U.S. Geol. Survey, v. 1, no. 5,
p. 609-614.

Rodgers, G. K., 1966, The thermal bar in Lake Ontario, spring 1965

    and winter 1965-66: _in_ Proc. 9th Conf. on Great Lakes Res.,

    p. 369-374.

Scott, J. T., and Landsberg, D. R., 1969, July currents near the

    south shore of Lake Ontario: _in_ Proc. 12th Conf. on Great

    Lakes Res., p. 705-722.

Tikhomirov, A. I., 1964, The thermal bar in Lake Ladoga: Soviet

    Hydrology, Selected Papers 1963, p. 182-191.

U.S. Dept. of the Interior and New York State Dept. of Health, 1968,

    Water pollution problems and improvement needs, Lake Ontario and

    St. Lawrence River basins: Federal Water Pollution Control Admin.

    and Div. of Pure Waters, N.Y. State Dept. of Health, p. 46.

APPENDIX A

Published or in-press articles that were the result of this project:

Pluhowski, E. J., 1973, Remote sensing of turbidity plumes in Lake

    Ontario, in National Aeronautics and Space Admin. Symposium

    on significant results obtained from the Earth Resources

    Technology Satellite-1, p. 837-846.

_____, 1974, Detection, movement and dispersion of turbidity plumes

    in Lake Ontario, in Earth Environment and Resources Conf. Digest

    of Technical Papers, v. 1, p. 170-171.

_____, 1975, Dynamics of suspended sediment plumes, in U.S. Geol. Survey

    Prof. Paper _____ (in press).

_____, 1975, Dynamics of turbidity plumes in Lake Ontario: U.S. Geol.

    Survey Open-file rept. 75-249.