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REMOTE SENSING OF TURBIDITY PLUMES IN LAKE ONTARIO¹

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ABSTRACT

Preliminary analyses of ERTS-1 imagery demonstrates the utility of the satellite to monitor turbidity plumes generated by the Welland Canal, and the Genesee and Oswego rivers. Although visible in high altitude photographs, the Niagara River plume is not readily identifiable from satellite imagery.

INTRODU

The utility of high-altitude photography in hydrologic research has been under study in the Lake Ontario basin since July 1970. These studies, conducted by the Canada Centre for Inland Waters, McMaster University, Hamilton, Ontario, Guelph University, Guelph, Ontario, and the U.S. Geological Survey are concentrated over the western part of the basin and the southern shoreline of the lake. The research efforts focus on soil moisture and ground-water detection, water quality, and the sources, movement and fate of sediment entering the lake.

A new dimension was added to the research with the orbiting of the ERTS-1 satellite in July 1972. By way of illustration, promising results were obtained from high altitude (60,000 ft) photography with regard to monitoring the shape and area extent of turbidity* plumes entering the lake's south shore (Pluhowski, 1973). However, it was not known how effective ERTS imagery would be in detecting turbidity features greater than 100 ft in width. The purpose of this paper is to provide preliminary conclusions regarding identification of turbidity plumes in Lake Ontario from ERTS-1 imagery, and to define plume dynamics under a variety of wind stresses.

*Turbidity--the degree of opaqueness of water due principally to the amount of suspended matter.

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NIAGARA RIVER AND WELAND CANAL PLUMES

The Niagara River is, by far, the largest single source of suspended sediment entering Lake Ontario. Additionally, over 200 mgd (million gallons per day) of industrial discharge from chemical, primary metals, and paper plants in New York State enter the Niagara River (Linnos, 1972). Much of this effluent emanates in the Buffalo metropolitan area located at the eastern end of Lake Erie near the source of the Niagara River. This heavy sediment and industrial effluent loading, when combined with the very large average flow of the river (about 200,000 cfs) produces a widespread, well-defined turbidity plume in Lake Ontario in high-altitude photography.

For example, figure 1 is a high-altitude (60,000 ft) photograph of the Niagara River plume obtained on July 6,

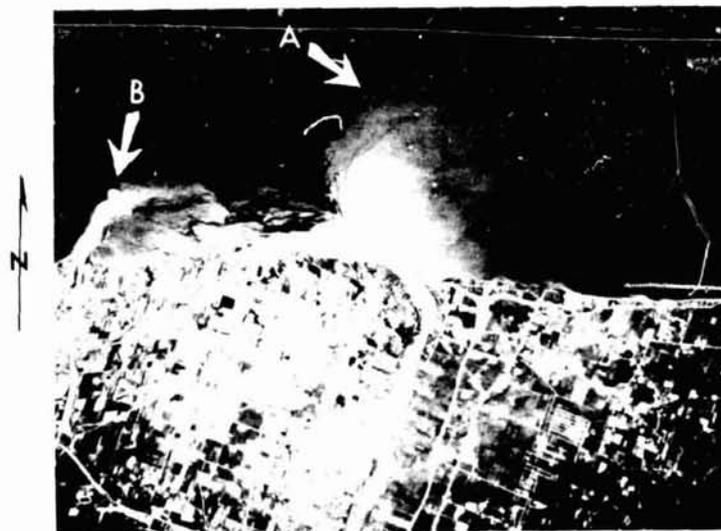


Fig. 1 -High-altitude photograph obtained July 6, 1970, showing the Niagara River plume (A), and the Welland Canal plume (B). Photography from NASA.

1972. The plume was oriented in a northwest direction at its mouth. It gradually veered to a north and finally to a east-northeast direction in response to a brisk 10-15 knot west-southwest wind. At its extreme point the plume was visible 6 miles offshore. A region of turbulent mixing is visible in the photograph along the western edge of the Niagara River plume, and in a zone within the jet itself, about 1/4 mile northwest of the river's mouth. Highly

turbid water, depicted by very bright tones, was being discharged at the entrance to the Welland Canal. The canal is affected by oil discharge and waste from cargo vessels and pleasure craft. Accordingly, the outflow from the canal, average flow, 7,000 cfs (DeCooke, 1968) appears bright in the high-altitude photography. Once beyond the canal's entrance, the Welland Canal discharge is swept to the east by prevailing west winds.

When viewed from the ERTS-1 satellite, the Welland Canal plume and a plume emanating from Port Dalhousie harbor several miles to the west are readily apparent (fig. 2).



Fig. 2. - ERTS-1 imagery obtained Aug. 21, 1972 showing the Niagara River (A), Welland Canal plume (B), Port Dalhousie harbor plume (D), and the inferred boundary of the Niagara River plume (C). Imagery from NASA.

This imagery, obtained August 21, 1972, shows both plumes drifting to the east-northeast under the influence of 10- to 15-knot west-southwest winds. The Niagara River plume is not visible. Despite its large sediment load, turbidity values of the Niagara River are low--generally about 1 JTU (Jackson Turbidity Unit). By way of contrast, turbidity readings during the shipping season are high in the Welland Canal, often near 50 JTU. Accordingly, the Welland Canal plume appears much brighter in the imagery than does the Niagara River plume.

Owing to a unique combination of meteorologic and hydrologic events, the west and north boundaries of the Niagara River plume were definable in the imagery. Turbid waters from the Welland Canal and Port Dalhousie harbor plume were driven east toward the mouth of the Niagara River. The bouyant surface-spreading of the warmer and less turbid river water over the colder lake water forms a sharp tonal discontinuity along the west and north boundaries of the Niagara River plume. Thus, despite the absence of a definitive tonal signature, the areal extent and shape of the Niagara River plume can be inferred from this imagery.

The position and shape of the Niagara River plume is difficult to define in ERTS imagery whenever the surrounding lake waters are relatively clear. By way of illustration prevailing northeast winds on November 1, 1972, swept both the Welland Canal and Port Dalhousie harbor plumes away from the mouth of the Niagara River (Fig. 3). Turbidity



Fig. 3.- ERTS-1 imagery obtained Nov. 1, 1972, showing the Niagara River (A), the Welland Canal plume (B), and the Port Dalhousie harbor plume (C). Imagery from NASA.

levels at the time of this imagery were as follows:

<u>Location</u>	<u>Turbidity</u> (JTU)
Niagara River (at mouth)	1 to 1.5
Port Dalhousie harbor	6 to 8
Welland Canal	25

Despite the presence of a cirrostratus cloud overcast, the relative tonal intensity of each watercourse in the imagery appears to corroborate the turbidity levels shown in the above table. Because the turbid waters were moving away from, rather than toward the mouth of the Niagara River, it is difficult if not impossible to identify the Niagara River plume in this particular image.

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 sizeable sediment yield of the basin, the river receives effluents from many sources, particularly from the Rochester, New York metropolitan area. The resulting high turbidity levels at the mouth of the Genesee River impart a distinctly light color to the river when viewed on aerial photographs. Accordingly, the Genesee River plume is easily identifiable on most aerial photographs owing to the normally large tonal contrast between the plume and the surrounding, relatively clear, waters of Lake Ontario.

A well-defined counter-clockwise circulation pattern within the Genesee River plume was visible in the high-altitude photography on October 19, 1970 (fig. 4). The

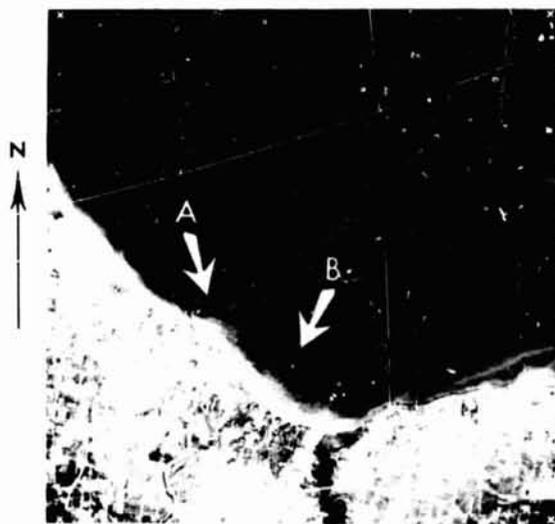
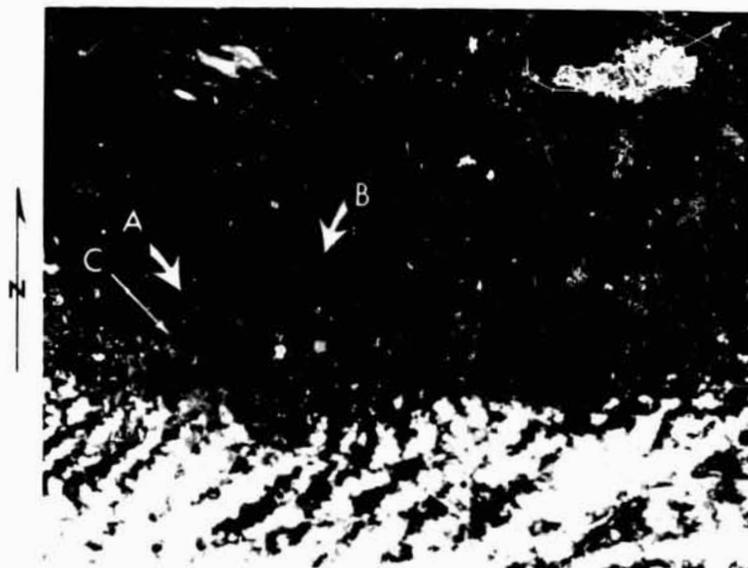


Fig. 4.- High-altitude photograph obtained Oct. 19, 1970, showing the Genesee River plume (A) and a submerged sewer outfall (B). Photography from NASA.

plume, covering about 2 sq. mi. of the lake's surface, was swept westward by prevailing 6-to 8-knot east-northeast winds. A counter-clockwise gyre, formed to the lee of the harbor breakwater, extends about one mile downwind from the mouth of the river (fig. 4). Turbidity levels ranged from 9 JTU in the Genesee River to 1 to 2 JTU in the clearer (darker) inshore waters along the base of the west breakwater. To the west of the plume, a strong northwest-trending longshore current is identifiable in the photograph. A less intense littoral current is visible east of the breakwater mixing, at that point, with flow from the Genesee River.

Effluent discharge from a submerged sewer outfall situated nearly 2 miles offshore is visible in the photograph. On October 19, 1970, pollutants from the outfall were swept westward, eventually merging with the Genesee River plume about 1 mile northeast of the river's mouth.

Two large turbidity plumes emanating from the mouth of the Genesee River were detected in the ERTS imagery obtained September 6, 1972 (fig. 5). Suspended sediment



-Fig. 5.- ERTS-1 imagery obtained Sept. 6, 1972, showing the Genesee River plume (A), a longshore plume (B), and the Genesee River mouth (C). Imagery from NASA.

carried by the river initially moves to the east due to prevailing west-southwest winds. The plume abruptly divides a short distance downwind, part moving northward into Lake Ontario and the remainder continued moving east along the coast line. At a point about 2 1/2 miles offshore, the northward moving plume once again abruptly changes direction, this time to the west. This anomalous pattern of motion suggests the existence of a large counter-clockwise clear-water gyre between the mouth of the Genesee River and the inside boundaries of the offshore plume.

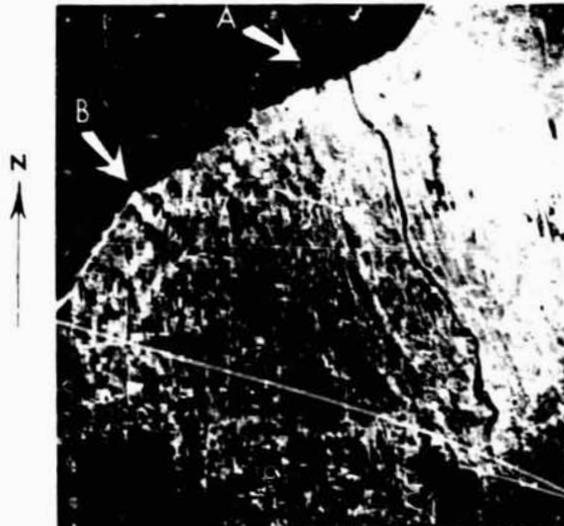
The eastward moving longshore plume is reinforced by turbidity from the previously mentioned sewer outfall, by outflow from Irondequoit Bay and shoreline erosion caused by waves approaching the shore at a large angle of incidence. The reinforced turbidity plume is clearly visible for a distance of 16 miles downwind from the Genesee River.

OSWEGO RIVER PLUME

A substantial portion of the sediment yield in the Oswego River basin is retained by numerous natural lakes and man-made impoundments found throughout the watershed. About 6 percent of the basin's 5,100 sq. mi. area represents lake surfaces (Liu and others, 1972). Extensive reaches of the Oswego River form part of the New York State Barge Canal system. Owing to these numerous man-made sediment sinks, turbidity levels at the mouth of the Oswego River are lower than might be expected. Accordingly, the Oswego River plume appears less intense in high altitude areal photography than either the Genesee River or the Niagara River plumes.

High turbidity, possibly caused by beach erosion, is evident in the high-altitude photograph obtained on October 19, 1970, adjacent to, and to the southwest of Burt Point (fig. 6). The shoreline below Burt Point is oriented on a northeast-southwest axis paralleling the prevailing northeast winds. A strong longshore current generated by the juxtaposition of shoreline and prevailing winds resulted in a beach erosion, and the resuspension of fine-grained bottom materials.

The predominantly onshore winds on October 19, 1970, confined the Oswego River plume to the harbor and to the lee of the harbor enclosure. The area of the plume, including the harbor, was only 1.2 sq. mi. The plume was only slightly more turbid than the surrounding lake water



-Fig. 6.- High-altitude photograph obtained Oct. 19, 1970, showing the Oswego River plume (A) and Burt Point, N.Y. (B). Photography from NASA.

so that it appears just a few tones lighter than the relatively clear lake waters.

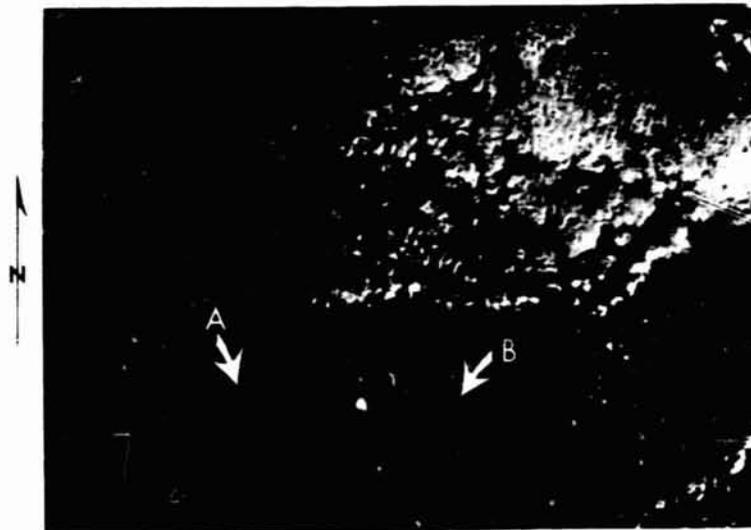
The Oswego River plume trails off to the northeast under predominantly west-northwest winds as portrayed in the ERTS imagery for August 19, 1972 (fig. 7).



-Fig. 7.- ERTS-1 imagery obtained Aug. 19, 1972, showing the Oswego River plume (A). Photography from NASA.

Turbidity levels in the clear lake waters normally average about 1 JTU whereas base flow turbidity levels of about 3 to 5 JTU are common in the Oswego River. Thus, despite the small differences in turbidity between river and lake, the Oswego River plume is identifiable from satellite imagery.

An intense zone of beach erosion over the western part of Lake Ontario was revealed by imagery obtained December 7, 1972 (fig. 8).



- Fig. 8.- ERTS-1 imagery obtained Dec. 7, 1972, showing longshore plumes. Imagery from NASA.

Strong northwest winds on December 6 and 7 generated rough waters in Lake Ontario. The resulting wave action and higher-than-normal lake levels along the lake's south shore resulted in extensive beach erosion. This is indicated by the thin but relatively sharp tonal discontinuities in the littoral zone bordering the south shore. Another interesting feature in this imagery are the cloud formations developing over the lake and its leeward shores as the cold northwest winds gain moisture in their traverse over the lake.

CONCLUSIONS

Large turbidity plumes generated by the Welland Canal, at Port Dalhousie harbor, and the Genesee and the Oswego rivers are plainly identifiable

in ERTS-1 imagery and in high altitude photography. Although visible in high altitude photographs, the Niagara River plume could not be visually identified from the satellite imagery. Zones of intense beach erosion are visible in both aircraft photography and satellite imagery.

High altitude aircraft photography provided valuable "baseline" data which was very helpful in evaluating and interpreting ERTS-1 imagery. The high altitude photographs were small enough in scale to capture most turbidity features on a single frame and they were good enough in quality to show the fine detail in the most delicate turbidity features. With this type of background information, it is possible to assess the quality and correctly interpret the hydrologic processes causing the turbidity phenomena illustrated by satellite imagery.

Best results for detecting plumes were obtained using MSS band 5 -- little or no information could be gleaned from MSS band 7. MSS band 4 yielded generally good results, but at times appeared to be affected by haze and atmospheric moisture. MSS band 6 produced only slightly better results than band 7.

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