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SATELLITE REMOTE SENSING STUDY OF THE TRANS-BOUNDARY MOVEMENT OF POLLUTANTS

Environmental Research Laboratory
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U.S. Environmental Protection Agency
Duluth, Minnesota 55804

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SATELLITE REMOTE SENSING STUDY OF THE TRANS-BOUNDARY MOVEMENT OF POLLUTANTS

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FOREWORD

Our nation's freshwaters are vital for all animals and plants, yet our diverse uses of water -- for recreation, food, energy, transportation, and industry -- physically and chemically alter lakes, rivers and streams. Such alterations threaten terrestrial organisms, as well as those living in water. The Environmental Research Laboratory in Duluth, Minnesota develops methods, conducts laboratory and field studies, and extrapolates research findings

- -- to determine how physical and chemical pollution affects aquatic life
- -- to assess the effects of ecosystem on pollutants
- -- to predict effects of pollutants on large lakes through use of models
- -- to measure bioaccumulation of pollutants in aquatic organisms that are consumed by other animals, including man.

This report demonstrates the usefulness of satellite based remote sensing in delineating the large-scale water quality in large lakes. The capability to assess a whole lake, in conjunction with normal chemical and physical analyses, has significance in monitoring the Great Lakes.

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ABSTRACT

A limited analysis of ERTS (LANDSAT) data of the western basin of Lake Erie and the southern portion of Lake Huron was performed. The objective of the program was to depict the large-scale movement of water masses, as manifested in terms of suspended solids, and to demonstrate the use of ERTS data in large lakes monitoring. ERTS (LANDSAT) data, as recorded on computer compatible tapes, were processed to display surface circulation features, surface suspended solids distribution, surface chlorophyll distribution, and secchi disc transparency. The results demonstrate the potential of satellite remote sensing for monitoring of large water bodies.

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SECTION 1

CONCLUSIONS

The synoptic view provided by ERTS (LANDSAT) provides signigicant information concerning suspended solids distribution and general surface circulation in the western basin of Lake Erie and Southern Lake Huron. High concentrations of suspended solids are typical along the Canadian shore of Southern Lake Huron and throughout the western basin of Lake Erie. In the latter case, high suspended solids concentrations are largely due to loading from the Maumee River, the Detroit River and resuspension of bottom sediments.

The four broad ERTS (LANDSAT) bands, which span the spectral range 0.5 - 1.1 μm, offer a water quality measurements potential which is essentially restricted to suspended solids, turbidity, transparency, and the detection of phytoplankton blooms. Attempts to correlate LANDSAT data with other substances in aqueous solution or suspension would be difficult to justify in scientific terms. A large variance in suspended sediment concentration constitutes an interference in the processing of data to display chlorophyll levels. Generally these ambiguities cannot be resolved solely on the basis of LANDSAT data analysis and reference to ground truth measurements for calibration purposes are necessary.

The data acquired from space and ship data are complimentary and neither can substitute for the other. The large area coverage provided from space can serve to provide unity to data collected by conventional point sampling and facilitate the interpretation of data collected by conventional methods.

SECTION 2

RECOMMENDATIONS

A continuing program of analysis of LANDSAT data for the two study areas discussed in this report is recommended. Repeat data under a variety of wind and lake-state conditions would contribute significantly to the information data base, facilitate interpretation of point sampled data, and aid in trend analysis.

SECTION 3

INTRODUCTION

The objective of the program were to delineate the large-scale distribution of water masses of markedly different water quality in the Western Basin of Lake Erie and Southern Lake Huron through the analysis of ERTS (Earth Resources Technology Satellite) data. In January 1975, the satellite was renamed LANDSAT, with the result that both names are used interchangeably in reference to data collected prior to 1975.

The intent of the program was to examine and process ERTS (LANDSAT) data for purposes of providing some insights into the general movement of water masses and also to provide information regarding suspended solids, transparency and phytoplankton, to the extent possible. The program, as originally defined, was limited to the analysis of three scene dates. The following ERTS (LANDSAT) scenes were examined in the analysis:

1.	E-1679-15403	2 June 1974	W. Lake Erie
2.	E-2081-15355	13 April 1975	W. Lake Erie
3.	E-1985-15290	4 April 1975	W. Lake Erie
4.	E-1697-15393	20 June 1974	S. Lake Huron

SECTION 4

METHODS

The data used in the analysis were collected by the ERTS (LANDSAT) satellite from an altitude of approximately 915 km in the following spectral bands[1]:

Spectral Band	Wavelength (μm)
4	0.5 - 0.6
5	0.6 - 0.7
6	0.7 - 0.8
7	0.8 - 1.1

The area of each resolution element is approximately 0.45 hectares. The information in bands 4, 5, and 6 is recorded with a 7-bit resolution (127 data levels), and in band 7 with a 6-bit resolution (63 data levels). Since the system was not optimized for data collection over water, the total information content was contained within a small range of data levels.

The processing of ERTS (LANDSAT) data recorded on computer-compatible tapes included density-level slicing of individual spectral bands, statistical analysis of selected target areas, and a modified second-derivative analysis. The general processing procedure included: (1) reformatting of the data, (2) preparation of working grey maps, (3) production of line prints through selected target areas, and (4) production of the final product. The final computer produces were generated using the hard-copy color output subsystem of the MIDAS (Multivariate Interactive Digital Analysis System) developed at ERIM.

Ground-truth data were provided by the Large Lakes Research Station. Limited data were available for 2 June 1974 (W. Lake Erie) and 20 June 1974 (Lake Huron).

SECTION 5

RESULTS AND DISCUSSION

The program of analysis was centered around the available ground-truth data. Of the three parameters of concern in this investigation, suspended solids, transparency, and chlorophyll; ground-truth data were available for the last two parameters for use in the Lake Erie analysis.

TRANSPARENCY - LAKE ERIE

Based on the Beer-Lambert law, an exponential correlation between the output signal and Secchi disc transparency can be expected. The problem remains, however, of calibrating the calculated radiance data with the available ground-truth information. Because of atmospheric path radiance considerations, band 5 was selected over band 4 for the examination of the relationship between Secchi disc transparency and radiance data and the production of the final map.

Using Turner's atmospheric model[2], an atmospheric correction was calculated for the condition of: (1) solar zenith angle of 31°, (2) visibility of 23 km., and (3) a marine atmosphere. The resulting path radiance for band 5 (centered at $\lambda = 0.65$ μm) was 0.170 mw cm^{-2} sr^{-1}. Using the ERTS conversion factors published in the ERTS User's Handbook[1], the data level equivalent (as recorded on the computer compatible tape) was calculated to by 10.8. This value compares with an observed data level of 9.88 (average of 441 resolution elements) over an area of relatively clear water in the central basin of Lake Erie. The latter value was accepted as the path radiance data level equivalent for use in applying the atmospheric correction to the data set. The effect of background albedo on the observed signal was not considered in this analysis.

Using the available ground-truth data, the following equation was derived for use in the Western Basin of Lake Erie:

$$T = \frac{\log L_5 - 1.869}{-0.392} \qquad (1)$$

where,

L_5 = radiance x 10, band 5

T = Secchi disc transparency, meters

The term L_5 in the above experession was calculated as follows:

$$L_5 = (D_5 - D_{A(5)})\ (0.0157\ \text{mw cm}^{-2}\text{sr}^{-1}) \qquad (2)$$

where,

D_5 = data value recorded on ERTS CCT, band 5

$D_{A(5)}$ = path radiance, band 5, data value equivalent

A comparison of calculated versus measured transparency is presented in Table 1. It should be noted in Table 1 that the time of field measurements varied by as much as six hours from the time of satellite data collection. The small amount of data precludes any statistical analysis of calculated versus measured results.

The resulting transparency map is shown in Figure 1. The results are in general agreement with field measurements for 2 June 1974. In this regard it should be stressed that close agreement between measured and calculated values may be visible by correcting for the effect of phytoplankton on the observed signal. Because of the limited scope of this investigation, this factor was not examined.

CHLOROPHYLL - LAKE ERIE

From a scientific standpoint, no satisfactory method for the measurement of surface chlorophyll, using existing ERTS (LANDSAT) data is possible. The positioning of the spectral bands, the number of spectral bands, and various other instrumental characteristics preclude the development of satisfactory algorithms for processing ERTS 1, 2 (LANDSAT 1, 2) data for surface chlorophyll measurement, applicable to a wide range of conditions. Consequently, various investigators have relied on empirical methods to extrapolate field measurement over a given study area. The processing technique used range from slicing of a single band to the use of ratios. The use of the ratio band 6/ band 5 has been previously discussed and found to be suitable only in the case of high chlorophyll concentrations and relatively homogeneous waters[3].

The technique adopted in this investigation involves the use of bands 4, 5, 6 to examine the interrelationship of the signal in the three bands. In general terms, an increase in phytoplankton will tend to increase the signal in band 4, decrease the signal in band 5, and increase the signal in band 6. These interrelationships can be evaluated by calculating a quasi-second derivative of the spectrum at λ = 65 μm, as follows:

Table 1. SECCHI DISC TRANSPARENCY, WESTERN BASIN LAKE ERIE

2 June 1974 E-1679-15043 (1104 EDT)

Station	Time (EDT)	Transparency (meters) Meas.	Calc.	Radiance Band 5 ($mw \cdot cm^{-2}sr^{-1}$)100
56	1745	2.9	2.3	9.6
57	1613	2.0	2.7	6.5
58	757	2.2	2.5	8.0
59	939	1.8	2.2	10.4
60	1320	1.7	2.2	10.4
61	1440	2.2	2.2	10.4
70	1103	1.0	1.0	29.6
75	1220	1.8	2.2	10.4
Central Basin	---	4.0	4.0	2.06

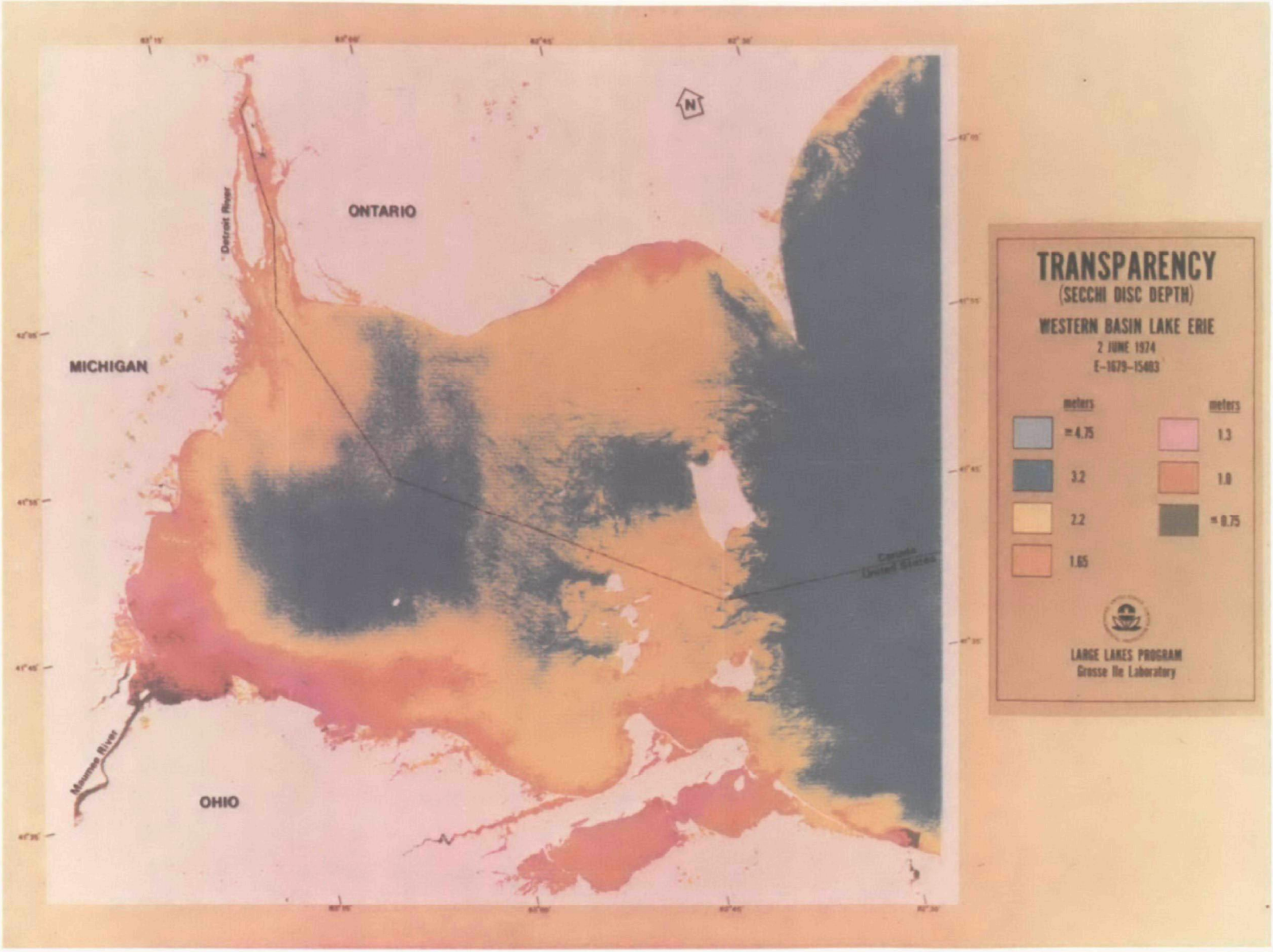

Figure 1. Transparency, Western Basin Lake Erie, 2 June 1974

$$\frac{d^2L}{d\lambda^2}(.65) = L_4 - 2L_5 + L_6 \qquad (3)$$

where L_4, L_5, L_6 equal the radiances in bands 4, 5, and 6 respectively. The relationship between the second derivative, using ERTS bands, and phytoplankton concentration (expressed as the extinction coefficient) is shown in Figure 2. The curves are based on calculated reflectance spectra using the Suits AQUACAN model[4]. Since chlorophyll concentrations are a function of cell size, species, physiological state, etc., phytoplankton concentrations are expressed as the extinction coefficient. This means that in practice the curves must be calibrated by field sampling at a given study location.

Although calculations indicate that the above approach is less sensitive to turbidity differences than working with individual bands the fact remains that a large variance in terms of suspended sediments will produce ambiguities which cannot be resolved on the basis of spectral analysis alone. In cases where turbidity may vary by a factor of 10 or less, turbidity (at low or moderate levels) will not seriously affect the results.

Surface chlorophyll for 2 June 1974 is shown in Figure 3. Once again, because of limited ground-truth data a statistical analysis of measured versus calculated results is not possible. Only enough data were available to allow calibration. Nevertheless, the results appear very reasonable and in line with expectations at key points in the scene. Field measurements indicate a surface chlorophyll concentration of 10 mg/m^3 on the east side of the Detroit River and concentrations of approximately 7 mg/m^3 to the west of the islands. Very high suspended solids in the areas indicated as "undefined", precluded any meaningful analysis in these areas.

SUSPENDED SOLIDS - LAKE ERIE

In spite of a lack of ground-truth data, an analysis was performed to show the suspended solids distribution in the western basin on 13 April 1975. Because of a lack of confirming data the concentrations are considered relative.

The approach involved the use of a previously developed empirical equation[3]. An atmospheric correction was calculated using the Turner model[2]. The calculated atmospheric parameters (band 5) for a solar zenith angle of 42° and a visibility of 23 km., were as follows:

$$L_A = 0.129 \text{ mw cm}^{-2}\text{sr}^{-1}$$

$$T = 0.75$$

$$E = 10.77 \text{ mw cm}^{-2}$$

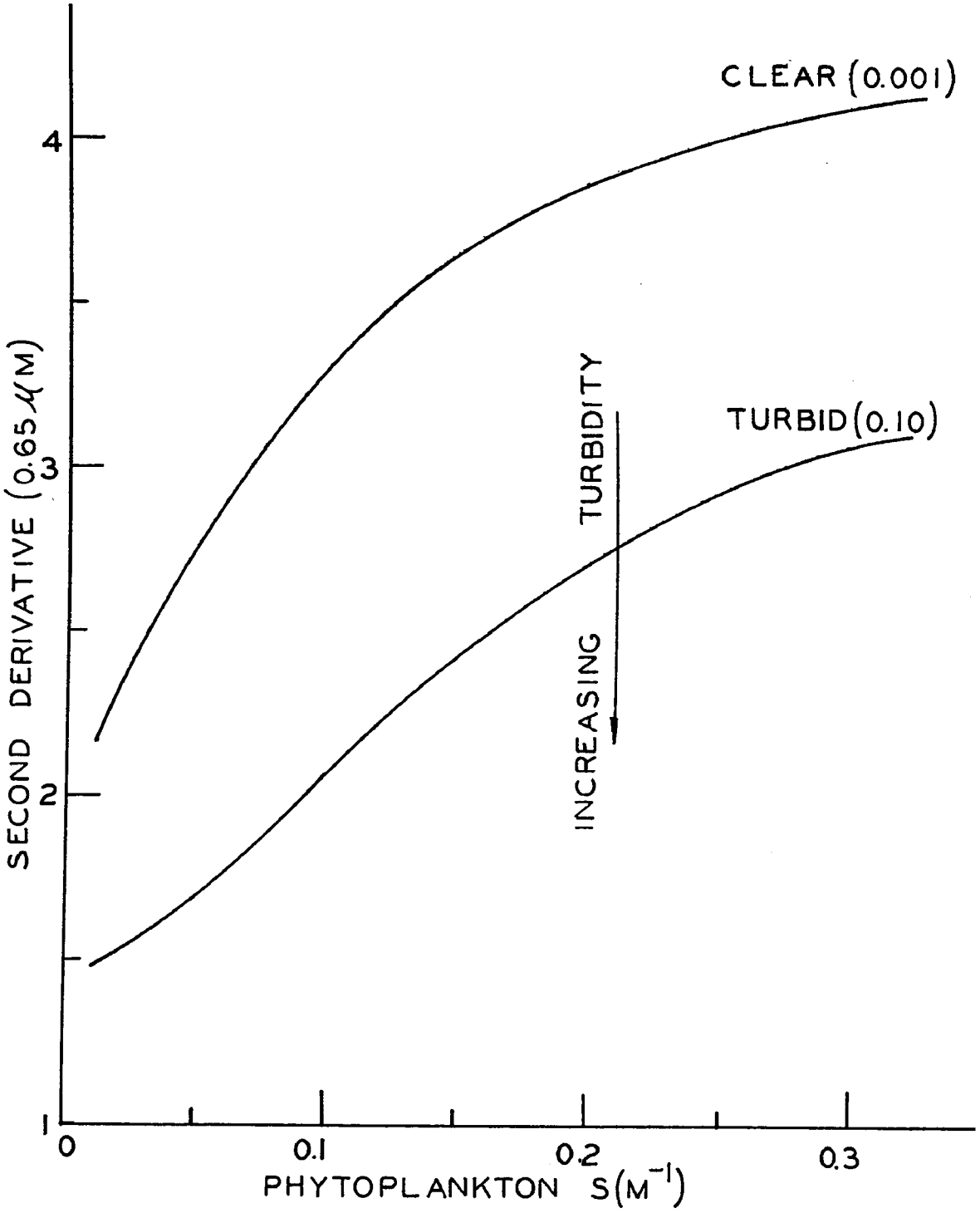

Figure 2. Second Derivative versus Phytoplankton Concentration

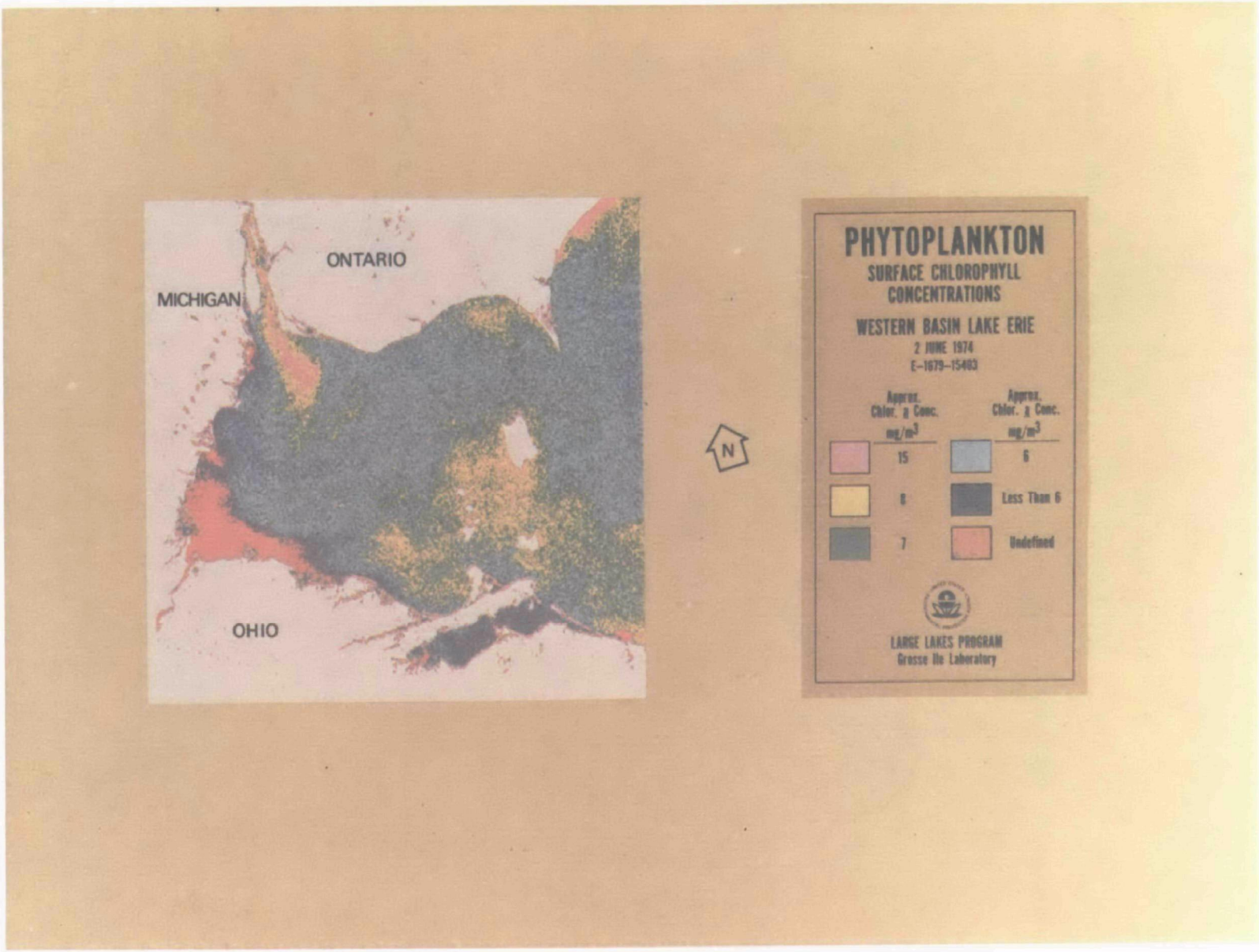

Figure 3. Surface Chlorophyll, Western Basin Lake Erie, 2 June 1974

where,

L_A = path radiance

T = transmittance

E = total downward irradiance at the water surface

The expression used in the analysis were:

$$C = 0.03991 \left[(L_5 - L_{A(5)}) \frac{\pi}{TE} \times 100\right]^{2.8216} \qquad (4)$$

where,

C = suspended solids (mg/ℓ)

L_5 = radiance at satellite altitude, band 5

$L_{A(5)}$ = path radiance, band 5

T = transmittance, band 5

E = total downward irradiance at water surface, band 5

The resulting map showing surface suspended solids distribution is presented in Figure 4.

SURFACE CIRCULATION - LAKE ERIE

A portion of frame E-1985-15290, 4 April 1975, was processed to show the dynamic surface circulation patterns in the vicinity of Pelee Island. The resulting map is presented in Figure 5. The general movement around Pelee Island in a southeasterly direction has been frequently observed in the examination of satellite data of the area.

LAKE HURON

The attempt to find a suitable ERTS (LANDSAT) data set of the southern portion of Lake Huron, at a time when ground-truth data were collected, proved unsuccessful. Limited ground-truth data were collected on 20 June 1974; however, unfavorable atmospheric conditions prevented a meaningful analysis of the satellite data. A working grey map of the area was produced and a statistical examination of all four bands were performed. The results indicated that the scene contained thin clouds and possibly ground fog; and that further analysis was unwarranted. The area was also partly obscurred by clouds on 2 June 1974. The above scenes are shown in Figures 6 and 7. The high turbidity pattern along the east side of the lake has been frequently observed in the examination of satellite data of this region.

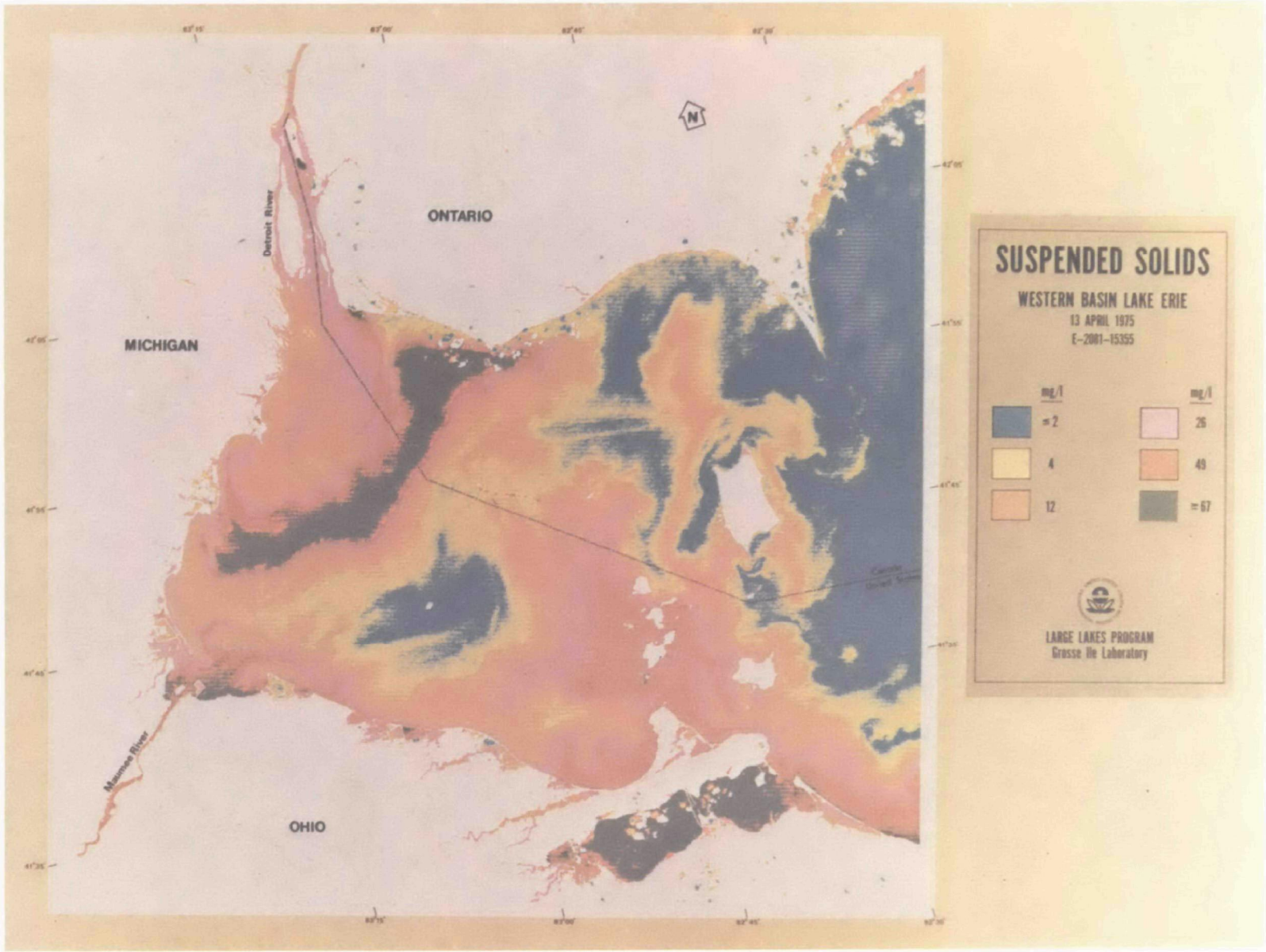

Figure 4. Suspended Solids, Western Basin Lake Erie, 13 April 1975

Figure 5. Surface Circulation Features, Lake Erie, Pelee Island Area, 4 April 1975

Figure 6. Southern Lake Huron, 20 June 1974, E-1697-15393

Figure 7. Southern Lake Huron, 2 June 1974, E-1679-15400

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16. ABSTRACT

A limited analysis of ERTS (LANDSAT) data of the western basin of Lake Erie and the southern portion of Lake Huron was performed. The objective of the program was to depict the large scale movement of water masses, as manifested in terms of suspended solids, and to demonstrate the use of ERTS data in large lakes monitoring. ERTS (LANDSAT) data, as recorded on computer compatible tapes, were processed to display surface circulation features, surface suspended solids distribution, surface chlorophyll distribution, and secchi disc transparency. The results demonstrate the potential of satellite remote sensing for monitoring of large water bodies.

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