Dr. Janice M. Whipple*
U.S. Geological Survey
Albany, New York 12201

Surveillance of Water Quality

Because aerial thermal-infrared imagery can present data with little reliance on text, it is important in communicating to those who do not have detailed scientific training in hydrology.

Abstract: *Aerial thermal-infrared sensing was added to the New York State water-quality surveillance program in 1970 through cooperation with the U.S. Geological Survey. Because thermal radiance can be used as a natural tracer of water circulation, it is useful in verifying the validity of point-sample locations and hydrodynamic models. Measurements are needed for archival thermal records. Airborne equipment consisted of a fixed-field radiometer, line-scanner with thermal references, a.c. and d.c. amplifiers, tape recorder, display screen, and film printer. Correlative information included weather data and water-temperature records from the State automatic water-quality network and other sources. Data collection was monitored in flight so that proper areal and thermal data would be obtained. The quantitative data permitted observation of local water-heat budgets. Thermal-infrared imagery is useful to water managers if it is calibrated so that regional interpolations between existing point measurements can be made. In addition, the pictorial format can present data in an expedient manner to water planners, managers, and users.*

Introduction

The surface waters if New York State include some 70,000 miles of streams, over 3,500,000 acres of inland lakes, and extensive ocean shoreline. These abundant water resources present a challenge to those responsible for ensuring that water-quality degradation does not limit their usefulness. For this purpose, the New York State Department of Environmental Conservation, an agency cooperating with the U.S. Geological Survey, maintains a surveillance program to evaluate results of water-pollution-abatement activities. The four major components of the State program are manual and automatic sampling, aerial observation, and public reporting (Maylath, 1970, 1971).

Aerial surveillance complements the sampling program by providing a near-synchronous space continuum to the time-continuous data from separated locations and by providing a single-instrument correlation for different kinds of ground equipment. It also is less subject to damage by vandalism or by natural water events than is *in situ* equipment.

Uses for Thermal-IR Data

The potential usefulness of remotely sensed data in water management became apparent in a research study sponsored by the National Aeronautics and Space Administration, using data provided by the Rome Air Development Center, N.Y. (Whipple and Haynes, 1970). Thermal-infrared imagery and radiometry were found to be informative because water thermal radiance measurements are new information yet can be related to traditional *in situ* (bulk, of contact) temperature. This correlation through Planck's radiation laws can be made because water is a virtually homogeneous material and almost perfect blackbody radiator. Correlation for terrain temperatures is much more difficult because the variety of vegetation, rock and soil types, and other features have different emitting characteristics.

Detection of artificial or natural discharges can be done easily with infrared imagery because a thermal differential generally occurs between water masses of separate ori-

* Publication authorized by the Director, U.S. Geological Survey.

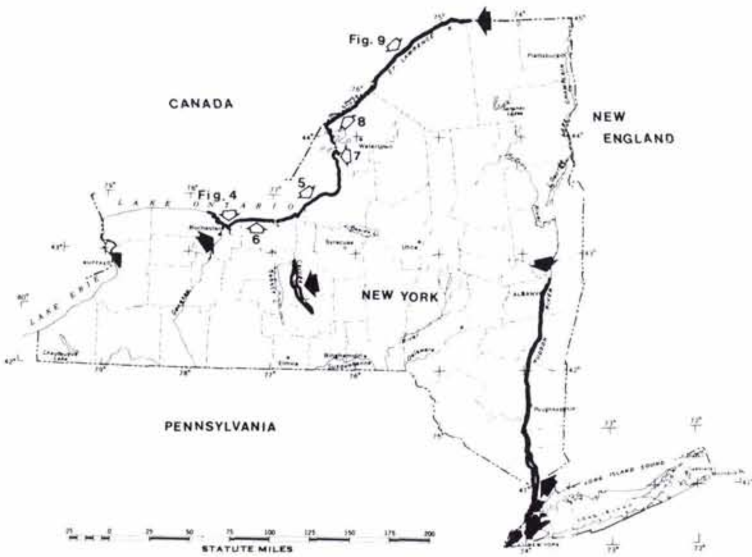


FIG. 1. Aerial Surveillance Program Sites (shaded).

gins. For simple location purposes, radiance measurements are not required. Radiance variations can also be used as an economical tracer to determine circulation and flow patterns. If radiance measurements are made, natural data can be provided for verification of scaled hydrodynamic models.

THE AIRBORNE PROGRAM

A cooperative program for aerial surveillance was begun in 1970 by the U.S. Geological Survey and the New York State Department of Environment Conservation, Division of Pure Waters (Whipple, 1971). The program was set up to provide thermal infrared radiometry of waterbodies where water-use priorities existed and to represent large and small lake, river, and estuarine environments. During 1970–71, flights were made over the following sites on the dates given. (See Figure 1.):

- Lake Ontario, south shore, about 100 miles: November 19 and December 10, 1970; April 15 and June 9, 1971.
- Cayuga Lake, about 40 miles: November 19, 1970, and April 15, 1971.
- St. Lawrence River, about 120 miles: December 10, 1970 and June 9, 1971.
- Hudson River Estuary, about 130 miles: November 27–28, 1970; April 23–24, 1971; and June 7–8, 1971.

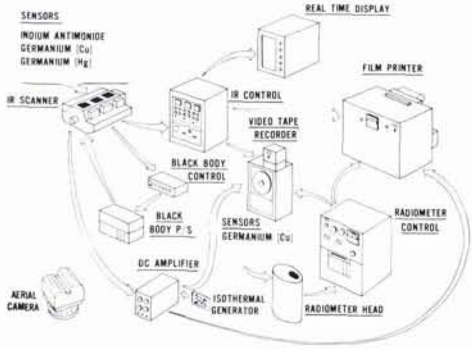
CORRELATIVE DATA: WEATHER AND WATER

Local weather records were obtained from the National Oceanic and Atmospheric Administration Environmental Data Service. Data included sky cover, ceiling, visibility, air temperature, relative humidity, precipitation, and wind speed and direction. These parameters are necessary to analyze water-surface radiation phenomena and wind-generated circulation patterns as well as radiance transmission through the atmosphere and its relation to *in situ* temperatures.

Manual *ground-truth* operations for water data must be kept to a minimum if coordination between field parties, aircraft, and weather must be done repeatedly. The automatic-monitor system therefore became the most reliable and economical source of water data, even if five minutes of additional flying time was required to incorporate the monitor site in the remotely sensed data. In addition, recording thermographs were placed at several locations, and manual observations were available at others. For one overflight, a portable infrared radiometer was used at the water surface. Laboratory studies of the relation of radiance to temperature have also been made (Somerscales, 1971).

AIRBORNE INFRARED EQUIPMENT

The infrared sensing equipment used during 1970–71 was loaned by the Air Force Avionics Laboratory. The military system was modified for environmental use by HRB-Singer, Inc., Rome, N.Y., contractors for the data-collection (Stingelin and



from Stingelin and Traxler, 1971

FIG. 2. Schematic diagram of infrared equipment.

Traxler, 1971). Background information on scanning systems is presented by Lowe (1968) and Parker (1968).

Figure 2 is a schematic diagram of the data flow through the equipment. Data collection was accomplished with the *Reconofax X* line-scanner and *AR-2* fixed-field radiometer. Data processing was carried out with *a.c.* and *d.c.* amplifiers with manual controls. Reference blackbody plates for calibration of the detector signal required their own power supply. Data storage for delayed playback was done through a magnetic video tape recorder. Data display equipment included a long-persistence display screen, or *B*-scope, as well as standard oscilloscopes for monitoring data as collected. The airborne film printer was used so that hard-copy film could be viewed within several hours after the data-collection mission and any tape recorder noise could be bypassed.

The doped-germanium detectors in the scanner and the radiometer were responsive to radiation wavelengths up to 20 and 14 micrometers, respectively, a range which includes the peak radiation from bodies at earth temperatures. Because a trade-off occurs between thermal resolution and spatial resolution for these single-element detectors, acceptable limits must be set for each. For example, is the 0.01°C.-resolution of thermal change between adjacent radiating areas 35-feet square more meaningful than recognition of a 1.0°C. change between areas one-half foot square? For water-quality surveillance purposes, at the present state of the art, the 2-milliradian field of view of the scanner detector provided an acceptable resolution of 2 feet at an altitude of 1,000 feet.

The thermal sensitivity that actually can be recorded depends on the setting of the amplifier gain; for quantitative data, another trade-off occurs between recording for total thermal range and maximum thermal sensitivity (corresponding to a minimum noise-equivalent-temperature difference). The equipment was operated so that radiometer readings to about 0.1°C could be made, and the scanner could record fine thermal detail of only the water surfaces.

The total angular swath-width of the scene viewed by the scanner was about 90°, or 1,000 feet on either side of the aircraft nadir line from a 1,000-foot flying height. The image was not corrected for geometric scanner distortion; therefore, the transverse scale decreases from center to edge. (Square objects near the edge are imaged as rectangles, and straight lines crossing the scene diagonally are imaged as S-curves).

Additional explanation of data parameters appears later on in the section, "Selected Imagery Examples." Production of *quantitative* thermal-infrared radiance data increases equipment complexity and operational decisions, and care must be taken to ensure that the data are faithful to the natural scene.

AIRCRAFT OPERATIONS

Because the aircraft was based in central New York State, commuting time to each of the data-collection sites was short, and flying could begin soon after notification that suitable weather conditions prevailed.

Most missions were flown at night because better quality data could be collected then. Emitted thermal radiation correlates best with bulk-water temperatures because no active heating of the upper water layers occurs from solar radiation. Signal-to-noise ratio is also improved because the detector need not be filtered against reflected solar radiation.

Familiarity of the crew with some target areas eased the problem of night operations with limited navigation devices; and, as missions were repeated, the difficulties were considerably reduced. Reduced air turbulence and metropolitan air traffic were advantages for night flying. Two late-day missions were flown, but the data were inferior to that acquired at night in both thermal detail and flight-path location.

The project hydrologist accompanied most missions. This practice is strongly recommended for initial surveillance missions and for investigations using only a single overflight. The hydrologist can monitor data quality and can direct changes in flight path and altitude for proper areal and thermal

FIG. 3. Data-collection monitoring.

coverage. These factors, which greatly influence data quality, can never be corrected in delayed playback of magnetic tape. (See Figure 3.)

Because of the trade-off between large-area coverage and scene detail, several aircraft altitudes were used over many sites. This technique also gives information on atmospheric attenuation by comparison of radiance values obtained from different heights. (Flying heights ranged from 1,000 to 3,000 feet above ground level.) A figure-eight flight path configuration was used over detail areas to help correct image geometry and to superimpose scanner and radiometer readings for crosschecking.

SELECTED IMAGERY EXAMPLES

In addition to measuring radiances of water areas for archival thermal records, the program provided a new insight to many hydrologic features which have not yet been fully investigated. The illustrations that follow are all thermal-infrared imagery and radiometry flown on the night of June 9, 1971, at the Lake Ontario and St. Lawrence River sites. The illustrations are reduced in scale from $8\frac{1}{2} \times 11$-inch contact prints of film printed in flight.

The weather on June 9, 1971, was excellent for data collection, with light northwest winds, clear skies, and low humidity. The first major precipitation during June was half an inch on June 8, 1971, at Syracuse, although there had been minor fog, haze, and thunderstorms.

Figure 4 shows the Lake Ontario shoreline and Genesee River near Rochester, N.Y. The data format will be explained in conjunction with the hydrologic features.

The bottom of three data strips is the

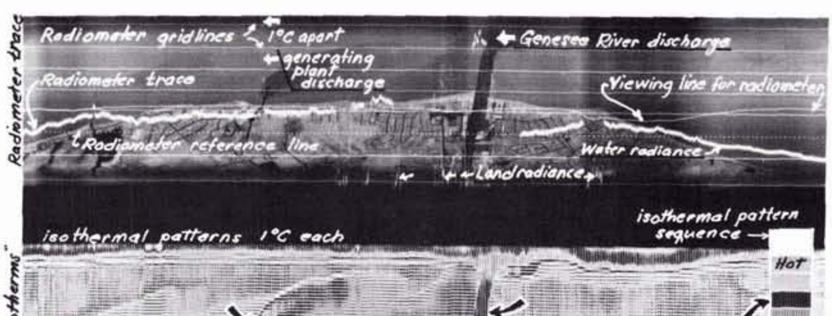


FIG. 4. Infrared imagery of Genesee River near Rochester, Lake Ontario.

scanner-generated *d.c.* imagery in which gray shades are proportional to radiance within a range defined by the blackbodies, whose gray shades are shown along the top and bottom edges of the picture strip. The intermittent vertical lines along the edges are binary coding of the blackbody radiant temperature settings. Large radiances corresponding to high temperatures are shown by the light-gray shades; low temperatures are dark. Scanner transverse geometry is indicated at the right; *h* is the flying height.

On June 9, 1971, nearshore water (top of image) of Lake Ontario is generally warmer than the land (bottom of image), except for streets. The warmest water areas are, left to right, shallow Round Pond, Long Pond outlet carrying the cooling-water discharge of a generating plant, and next, the Genesee River flowing between breakwaters extending some 2,000 feet offshore. All the discharges into the open lake have a thermally pulsating or surging appearance, as shown by gray shades, and have distinct thermal boundaries. Boat wakes are also evident at the outer edge of the river plume. The middle data strip shows the scanner-generated isothermal pattern where voltage changes trigger pattern printout circuitry at preset levels referenced to the blackbodies. The levels are shown in the coding along the bottom edge of the strip. The pattern sequence is shown at the right and is set to change at invervals of 1°C. Note that areas with the same radiance have the same pattern and also that the patterns bring out thermal changes on land, where the gray shade is too dark for legibility. (The actual radiance values where gray shades cannot be recognized may not be linearly related to voltage, however.)

This real-time printout points out that at this particular time the surface of the Genesee River is warmer than all but a small part of the generating-plant plume. This thermal relationship depends on many factors, particularly the location of the cooling-water intake in the lake and normal stream warming through the spring season.

The top data strip shows the radiometer trace superimposed on *ac.* imagery presented in negative (hot areas are black) format. The horizontal grid lines for the radiometer are set at intervals of 1°C; the dashed line corresponds to the setting of the radiometer reference blackbody. (This setting is available but not presented here.) The readings follow the wavy white line shown on this and the isotherm strip. (The line is wavy because aircraft roll is corrected in the scanner but not in the radiometer.)

The surface thermal radiance of the generating-plant discharge at the shoreline is more than 5°C greater than that of the radiometer reference, or about 6°C greater than that of the open lake water to the east (right). The radiance of the Genesee River is about 4.5°C greater than that of the reference and is less than that at the near-shore part of the plant plume.

Figure 5 shows the Lake Ontario shoreline at Oswego, the harbor formed by breakwaters containing the mouth of the Oswego River (center of image) and the cooling-water discharge from a generating plant (left). Here again the thermal radiance of the river is greater than that of the lake (over 5°C) and appears to be at least 1°C greater than the water from the generating plant area.

Figure 6 shows the Smoky Point area on Lake Ontario between Rochester and Oswego. Evidence of thermal pulsation or surging in the generating plant cooling-water discharge plume is again present. This phenomenon has also been observed at natural river discharges into the open lake during most, but not all, overflights.

Figure 7 shows the Stony Point area on the east shore of Lake Ontario. Warmer water extending from the shoreline may represent ground-water discharge, overland runoff, or shallow near-shore water warmed during the day. The last interpretation is least likely, however, because the largest warm area occurs off the north-facing shore and because the heated water appears to radiate outward in fans from the shoreline. A field investigation is necessary to define local hydrology.

Figure 8 shows part of the St. Lawrence River near the Thousand Island area. Radiance in the bay areas is some 2° to 3°C greater than that of the major body of the river. The main stem is carrying water which has cooled during the winter in Lake Ontario, whereas tributaries and bay areas have been considerably warmed by spring solar radiation. The complex flow pattern created by the islands is indicated by the warm bay-water plumes projecting upstream toward the southwest (winds were light westerly).

Figure 9 shows the Oswegatchie River entering the St. Lawrence River at Ogdensburg, N.Y., about 50 miles downstream from the area shown in Figure 8 and out of the island area. Compared with Figure 8, relatively high velocity is indicated in the main

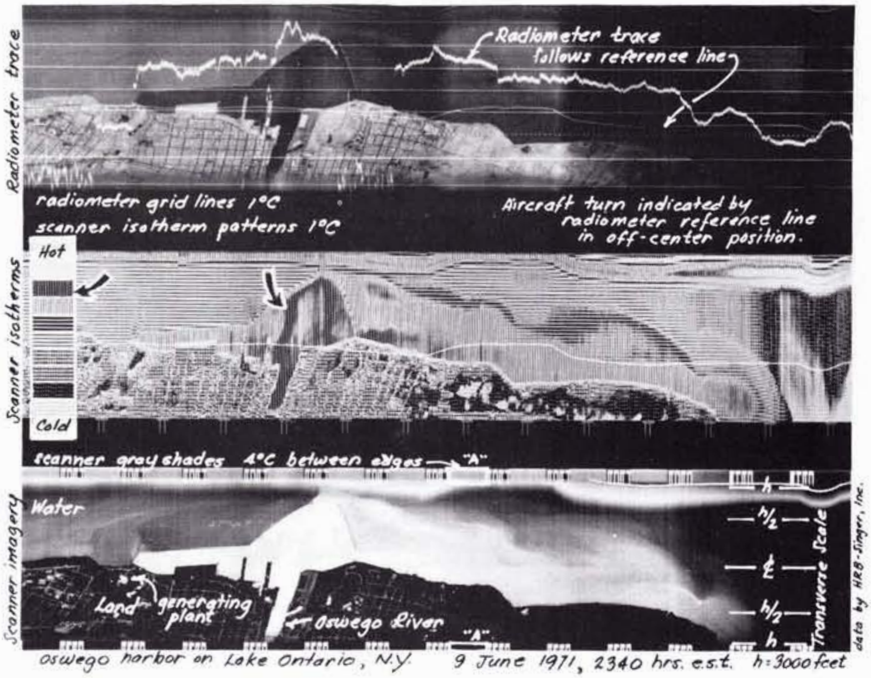


FIG. 5. Infrared imagery of Oswego River and harbor, Lake Ontario.

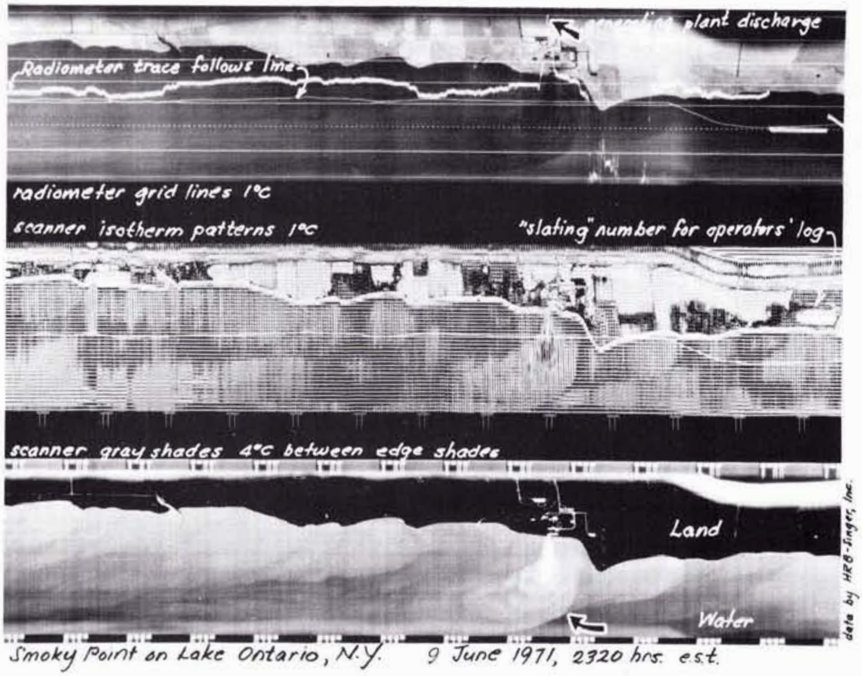


FIG. 6. Infrared imagery of Smoky Point, Lake Ontario.

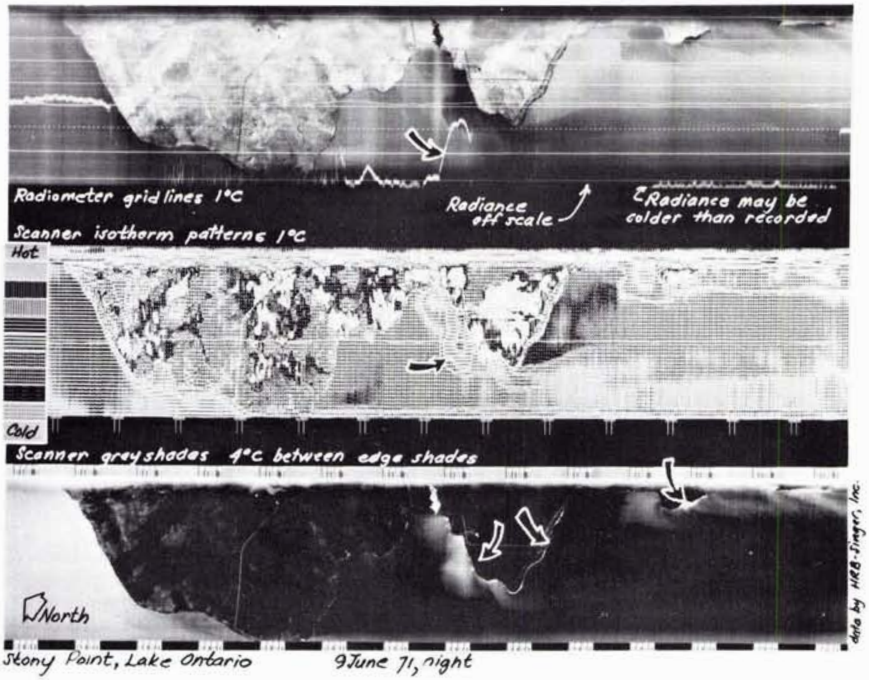


FIG. 7. Infrared imagery of Stony Point, Lake Ontario.

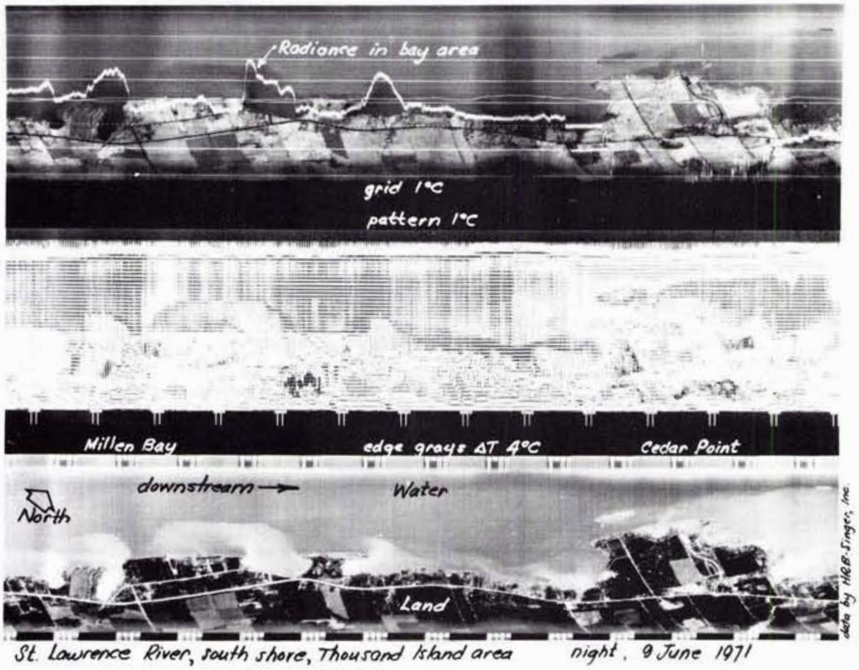


FIG. 8. Infrared imagery of St. Lawrence River near Thousand Islands.

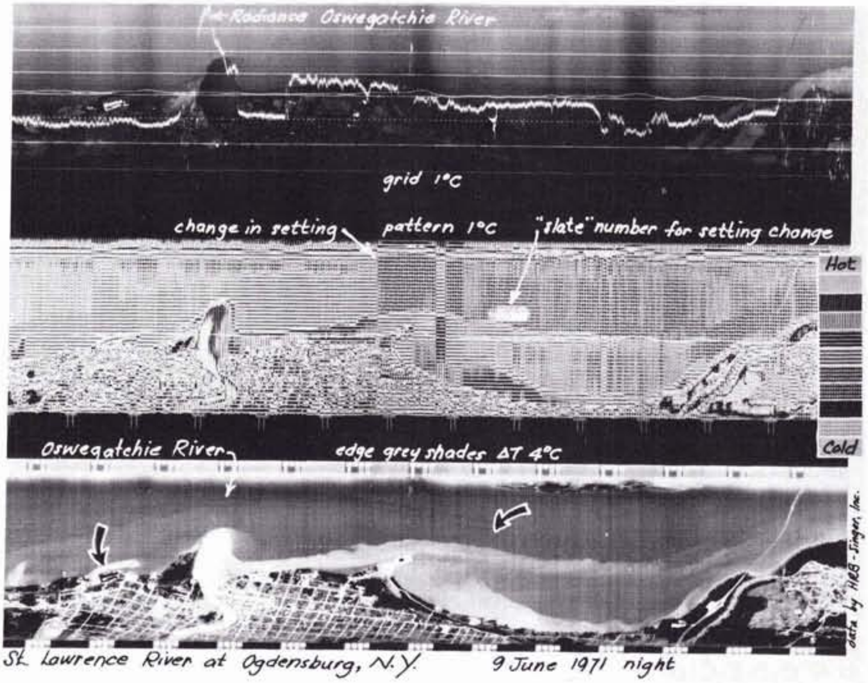


FIG. 9. Infrared imagery of St. Lawrence River at Ogdensburg.

channel by the cool area of thermal flowlines and by the intense downstream pluming of the warm Oswegatchie River discharge. The extension of the plume into the river is precisely controlled by a land projection on the upstream side. The temperature of the Oswegatchie is more than 5°C greater than that of the St. Lawrence. Similar relationships of flow and radiance between tributaries and main stem were noted downstream.

CONCLUSIONS

Thermal-infrared imagery is immediately useful in evaluating the hydrologic relationship of manual and automatic sampling points to the water body, for existing and future sites. Radiance measurements added to water-circulation data provide archival thermal records for locating future generating plants that require and discharge condenser cooling water. The data relate to the thermal criteria of water-quality standards by showing ambient water temperatures before plant operation and comparing criteria requirements with actual generating-plant discharges.

At present, thermal-infrared data are generally interpreted as surface *temperatures*. Because this is not strictly true, resistance to using the data has developed. Contact thermometers have been used for so long that point temperature has become the standard heat parameter to measure. Now, however, the technological state of the art permits measurement of emitted radiation. The thermal-infrared data can become hydrologically most informative if radiance values are interpreted as measures of interrelated energy exchanges at the air-water interface, rather than as extensions of point-contact temperatures. This surface has an important role in hydrodynamics—heating, cooling and freezing, evaporation, aeration, and wind-stress occur here—and these phenomena have been difficult to measure by traditional methods.

Aerial data collection should continue as surveillance programming because a catalog of thermal data is necessary as a reference for the *thermal pollution* arguments already taking place. If correlating weather and water-temperature data are obtained simultaneously with the aerial data, more complete interpretation of radiance may be done in the future, whereas the particular hydrologic conditions at one point in time can never be restored.

The program has shown that thermal-infrared imagery can add considerable new information to a water-quality surveillance program. Water managers are accustomed to working with point measurements, and only imagery that is calibrated can complete areal surface distribution of the existing point samples.

Perhaps the most important attribute of calibrated imagery is that it conveys information efficiently. Because a pictorial or graphical format can present data with little reliance on text, it is important in communicating to those who do not have detailed scientific training in hydrology. Water facts, in the long run, have little value if they are not in the hands of planners, managers, legislators, and users who need them.

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——— and Haynes, R. B., 1971, "Management applications for thermal-infrared imagery of lake processes," Third annual earth resources program review, National Aeronautics and Space Administration, Houston, Texas, Dec. 1–3, 1970: Houston, Tex., Natl. Aeronautics and Space Adm., p. 52.

Meetings Schedule

Annual Conventions

March 11–16, 1973,* Washington Hilton, Washington, D. C.

March 1974,* Chase-Park Plaza, St. Louis, Mo.

March 7–12, 1975,* Washington Hilton, Washington, D. C.

Fall Technical Meetings

Oct. 1–5, 1973,* Disneyworld, Orlando, Florida; Jon S. Beazley, Florida Dept. of Transportation, H. Burns Bldg., Tallahassee, Florida 32304.

Sept. 8–13, 1974,† Washington Hilton, Washington, D. C.

1975,* (open), Phoenix, Arizona.

Sept. 28–Oct. 1, 1976,* Olympic Hotel, Seattle, Wash.: C. E. Buckner, 803 Seattle Municipal Bldg., Seattle, Wash. 98104.

Oct. 18–21, 1977, Little Rock, Arkansas.

Seminars and Symposiums

July 1973, Univ. of Maine, Orono, Maine. Fourth Biennial Workshop—Color Aerial Photography in the Plant Sciences.

October 1973, Sioux Falls, S. Dak. Management & Utilization of Remote Sensing Data. Convention Center and USGS EROS Data Center. Cosponsored by AIAA, IEEE and AGI. Dr. Harold T. Rib, 10129 Glenmere Road, Fairfax, Va. 22030.

International Meetings

July 1973, Mexico City, Mexico. Joint Technical Meeting with the Mexican Society of Photogrammetry.

Sept. 9–16, 1974, Washington Hilton, Washington, D. C., *14th Congress of the International Federation of Surveyors* (FIG); Jeter P. Battley, Jr., P.O. Box 14262, Washington, D. C. 20044.

* Jointly with the American Congress of Surveying and Mapping.

† To be held as part of the International Congress of FIG.