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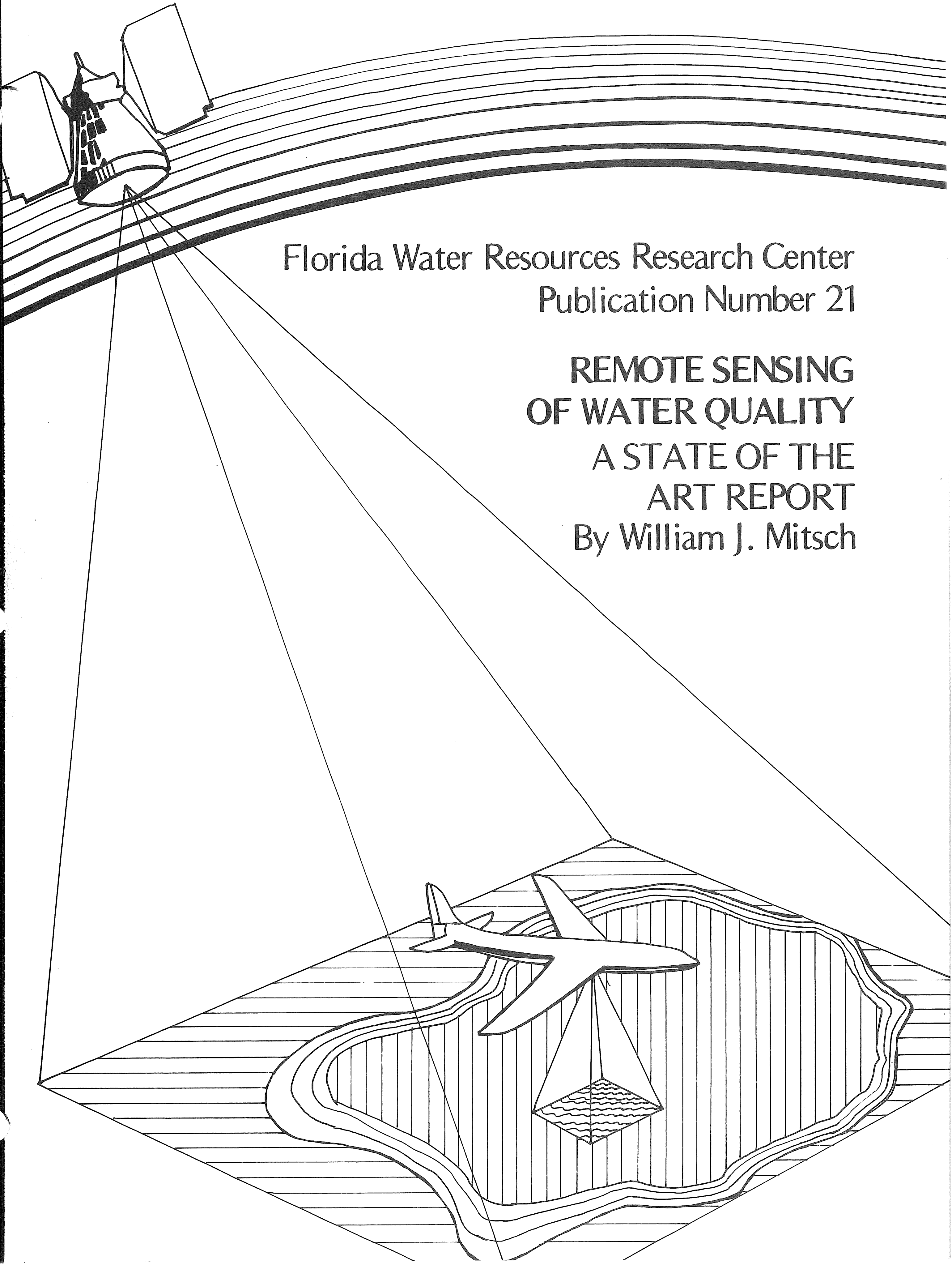
A STATE OF THE ART REPORT

By William J. Mitsch



REMOTE SENSING OF WATER QUALITY: A STATE OF THE ART REPORT

By

William J. Mitsch

Graduate Assistant, Department of Environmental Engineering Sciences

University of Florida

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Abstract

Remote Sensing of Water Quality: A State of the Art Report

Remote sensing, or the carrying out of aerial or space surveys of the earth's surface, is finding several applications in the fields of water quality and water resource management. It offers a means of obtaining large amounts of data, but its value is in the expansion of data in the spatial, temporal and spectral modes. The most valuable techniques presently are photography, infrared scanning and multispectral scanning. Aircraft applications include the measuring of the distribution of various waste discharges into water bodies and the study of aquatic plant growth and benthic communities. The ERTS (Earth Resources Technology Satellite) program of the U.S. Department of the Interior is investigating satellite applications of monitoring the earth's resources. The water resource applications are less obvious than those of the aircraft and concern environmental indicators on a much larger scale. However, the satellite offers the enhancement of data in the temporal mode with periodic remote sensing of most of the earth's surface.

Key Words: remote sensing, photogrammetry, infrared scanning, multispectral scanning, water quality, earth resources satellite

I. Introduction to Remote Sensing

Modern applications of remote sensing lead to a broad definition as follows: "the joint effects of employing modern sensors, data processing equipment, information theory and processing methodology, communications theory and devices, space and airborne vehicles and large-systems theory and practice for the purposes of carrying out aerial or space surveys of the earth's surface." (National Academy of Sciences, 1970). This definition is somewhat lacking in that a ground platform can be used, for example, in air pollution applications. The key difference between a remote sensor and a point sensor is that the latter must be in or contain the matter measured while the remote sensor "senses" the matter from a distance.

The decision of whether or not to use a remote sensing technique depends on the economics involved, the spatial (distance) and temporal (time) distribution desired, the resolution required and of course whether the parameters in question can be measured remotely. Often the additional data generated by remote sensing over *in situ* measurements may prove to be of very little incremental value. In some cases, remote sensing will prove to be more economical than presently employed monitoring systems; its value, however, is usually in its ability to expand the data in the spatial, temporal and spectral modes. (Deutsch, 1971).

The basic components of a remote sensing system include:

(1) **an energy source** - If a remote sensing system carries its own source of electromagnetic energy, such as the case with radar, it is called an active system. If it measures natural radiation, such as reflected sunlight, the system is defined as passive and the sun is the energy source. Active systems have the advantage of not being meteorologically dependent, but they are not always convenient to use.

(2) a **propagating medium** - This, for all practical purposes, will be the atmosphere, although propagation of energy through water is also an important consideration. The ability of the atmosphere to transmit and block electromagnetic energy is an important factor in remote sensing accuracy.

(3) **an energy detector or sensor** - A myriad of instruments, films and detectors have been and are being developed to measure electromagnetic energy at various wavelengths, and under various conditions. Sensing devices include, but are not limited to, cameras, thermal infrared scanners, multispectral scanners, radar and receivers, microwave systems, laser systems and radio.

(4) a **platform** - This is the location of the sensor and is usually listed as three possibilities: aircraft at various heights above the earth, spacecraft and satellites in earth orbits and ground platforms on the earth's surface.

(5) **data handling** - Once the data are collected in the form of photographs, imagery or electrical signals, analysis and data reduction can take many forms, ranging from the somewhat subjective method of photo interpretation to computerized reduction. "Ground truth" or the taking of discrete *in situ* readings for calibration is often a significant input to the data handling.

A basic flow diagram of an ideal remote system is given in Fig. 1.

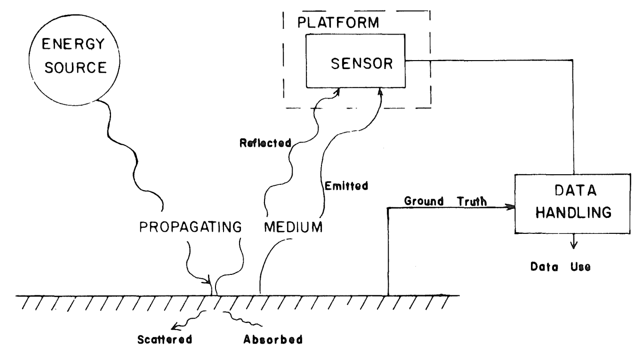


FIGURE 1. REMOTE SENSING SYSTEM

To consider the technology of remote sensing, a general understanding of the electromagnetic spectrum is necessary. Visible light, as we know it, was shown by Maxwell to be a component of the electromagnetic spectrum (Fig. 2) that also contains gamma rays, X-rays, ultraviolet rays, infrared rays, microwaves, radar and radio waves. In general when electromagnetic energy strikes the boundary of any matter, the energy is conserved according to basic physical principles and can be:

1. absorbed - giving up its energy largely into heating the matter.
2. emitted - or more commonly re-emitted by the matter as a function of temperature and structure, at the same or different wavelength
3. scattered - deflected to one side and lost ultimately to absorption of further scatter, or
4. reflected - returned unchanged to the medium (Colwell [1963]).

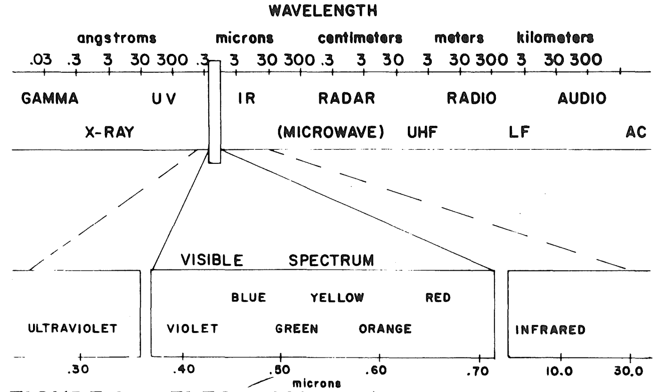


FIGURE 2. ELECTROMAGNETIC SPECTRUM (from COLWELL, 1963)

At temperatures above absolute zero, all objects continually emit electromagnetic energy as a result of their atomic and molecular motion. The amount of energy depends on the type of material and its temperature, while the wavelength of maximum energy is inversely related to the temperature. The earth, for example, with a temperature of 300°K has a maximum wavelength of about 10μ in the infrared region while the sun at 6,000°K has a peak wavelength at about 5μ in the visible region. Objects also have identifiable characteristics or "signatures" when reflecting energy. These two forms of energy, emitted and reflected, are the types that will be discussed in this report.

Photography is the most basic and widely used remote sensing technique today. It operates around the visible portion of the electromagnetic spectrum and measures reflected energy, usually from the sun. Both black and white and color pictures can be made from the reflected light, and the sensitivity of film has been extended into the near infrared and ultraviolet regions of the spectrum. The science of photogrammetry, that of obtaining reliable measurements from aerial photographs, has been in existence for about 100 years and is still the mainstay of remote sensing as it is known today.

The infrared scanner, also known as a thermal mapper or thermal scanner, measures the emitted energy of objects from the aircraft platform by sensing consecutive high resolution lines across the flight path. Individual lines are scanned by a rotating mirror which reflects a field of view, usually 120°, through an optical system and onto a cooled detector. The detector output is a small, linear, electrical signal which is amplified and used to modulate a variable intensity light source, such as a glow tube or a cathode-ray tube. The light produced, which is then proportional to the original measured infrared radiation, is scanned across film, usually 70 mm wide, in a process which duplicates the original scanning motion. Advancing the film duplicates the forward moving motion of the aircraft. (Taylor and Stingelin, 1969). The schematic of the infrared scanner is shown in Fig. 3.

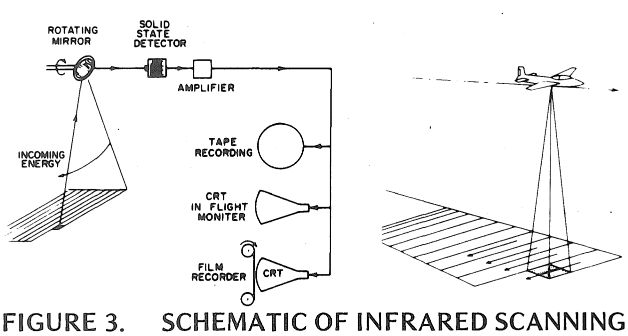


FIGURE 3. SCHEMATIC OF INFRARED SCANNING UNIT AND SCANNING TECHNIQUE (SCHERZ AND STEVENS, 1970)

A relatively new and very promising advance in the field of remote sensing is the multispectral scanner (MSS). It employs the principle of scanning from aircraft similar to that of the IR scanner. However, instead of a single detector the energy is spread out into its wavelengths (very similar to the spreading of white light by a prism), and a number of filtered detectors are arranged to observe different wavelengths bands. These are referred to as channels. The number of channels is variable with Bendix Corporation now developing a 24-channel multispectral scanner system (Zaitzeff *et al.*, 1970), although a much smaller number is usually optimum. A general schematic for a MSS is shown in Fig. 4. The advantages of the MSS system can be summarized as:

1. a broadening of the spectral range from that of photographic film. The system can be designed to measure emitted infrared energy on one of its channels.
2. The narrow wavelength increments or channels each has a special spectral area of different exploration interests.
3. The system is directly amenable to large-scale digital computer analysis.
4. The system has built-in calibration for repeatability of data collection.

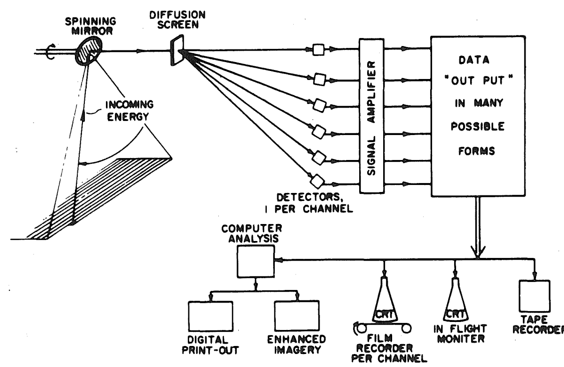


FIGURE 4. SCHEMATIC OF MULTISPECTRAL SCANNER (SCHERZ AND STEVENS, 1970)

This report presents the water quality and water resource applications that have been documented in the literature, emphasizing photography, infrared scanning and multispectral scanning from aircraft. A review of the earth resources satellite program is also included.

II. The Aircraft Platform in Water Pollution and Water Resources Monitoring

1. **Detection of Water Pollution Outfalls** - One of the first times that remote sensing is mentioned as a weapon against water pollution is in an April, 1962 **Chemical Engineering** article. Here the author (Cross, 1962) suggests the use of infrared imagery and color photography as a policing tactic to detect sources of water pollution. Cases of night surveys in Detroit, Kansas City, Chicago and New York by the Federal Water Pollution Control Administration are discussed. Infrared scanners were used to determine temperature differences in water bodies. These thermal anomalies usually indicate a pollution outfall that is discharging at a temperature different from the receiving water temperature. This first application was simply one of outfall detection.

The finding of pollution outfalls is still mentioned occasionally in remote sensing literature as a contribution to the environmental movement. Strandberg (1966) encourages his fellow aviators in the field of aerial reconnaissance to act as "water pollution detectives" by reporting potentially dangerous water pollution conditions through photography. Piech and Walker (1972) discuss the simple and economical use of conventional color and color infrared photography in outfall inventories from the air. Twenty-six major outfalls were determined from aerial photographs along a 10 mile stretch of the Cuyahoga River in Ohio. A subsequent field survey found only one additional discharge.

This approach, however, is becoming less applicable with environmental enforcement agencies simply because records are becoming available on almost every water outfall in the United States. The recent revitalization of the 1899 Rivers and Harbors Act by the Corp of Engineers required a reporting of every non-municipal waste discharge into any body of water and very few "secret" outfalls now exist.

2. **Thermal Discharges** - The use of infrared scanning devices to measure thermal discharges, especially from electric power plants, was one of the first concerted efforts to measure the transport of waste effluents. Dispersion and mixing patterns are strikingly displayed on infrared imagery.

Fig. 5 shows the imagery and completed isothermal map of the discharge area near Florida Power and Light's Turkey Point Power Plant from a Bendix Corporation (1969) infrared scan. The density of the imagery is translated into water temperature with the aid of ground truth measurements and empirical relationships between emitted energy and temperature. Daedalus Enterprises (1970) of Ann Arbor, Michigan offers a new approach to thermal mapping with density slicing. In this process, the signal is broken into a number of discrete thermal levels obtained from a single flight, recorded on magnetic tape and later converted into imagery sliced at various temperatures. The final imagery can also be assigned different colors for each temperature level in a process called color enhancement.

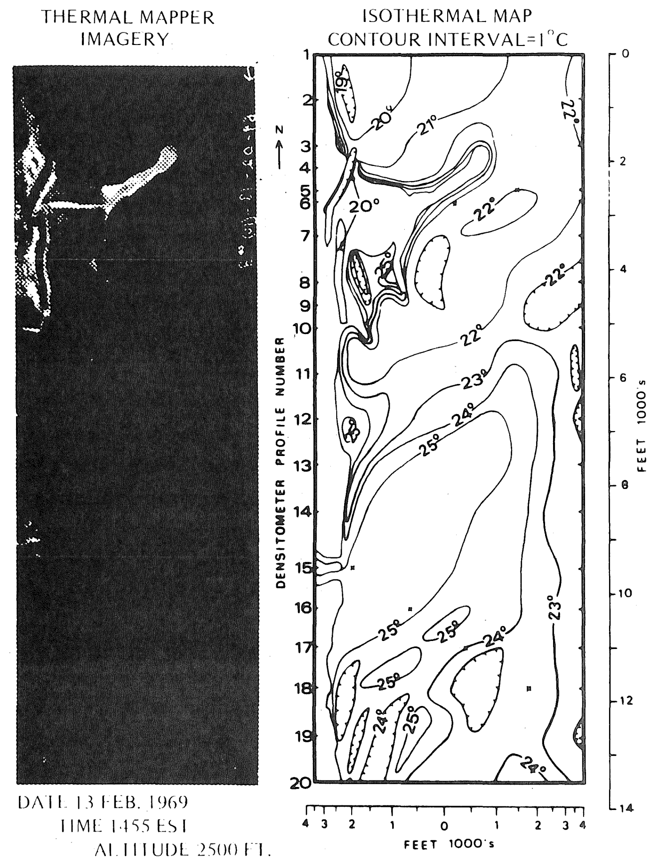


FIGURE 5. INFRARED SCANNER IMAGERY AND ISOTHERMAL MAP-TURKEY POINT POWER PLANT SOUTH OF MIAMI, FLA. (BENDIX CORPORATION, 1969)

Whipple (1973) reports on the use of infrared scanning as an integral part of New York State's surveillance of its waterways. Among other findings it is recommended that night flights give better imagery quality due to 1) no active heating of the upper water layers by solar radiation and 2) an improved signal to noise ratio because the detector need not be filtered against reflected solar radiation.

Determining the spatial distribution of thermal plumes with infrared imagery is not without failings. A depth profile is not possible as only the first few microns of water molecules are measured. On a windy day, the apparent plume may be spread over a much greater area than would normally be measured from a boat. A second shortcoming is that the final isothermal map is only as good as the ground truth measurements used to calculate the temperatures. It has been the author's experience that remote sensing usually gives a larger plume measurement than simultaneous boat measurements. Radiance values which are actually "measures of interrelated energy exchanges at the air-water interface rather than extensions of point-contact temperatures" (Whipple, 1973) may cause this phenomenon. This is an important factor for plumes in open bodies of water which are subject to effluent standards of a certain allowable temperature above ambient within a certain distance or area.

3. **Municipal Wastes** - Little has been done in investigating municipal waste discharges with remote sensing. Strandberg (1966) suggests that inferences can be drawn with color photography about the downstream reaches of a river from a sewage plant or untreated sewage discharge. Using saprobic zone notation to describe the area downstream of an organic outfall, he shows photos of an oily-grey appearance of the water indicating "a very obvious polysaprobic (low oxygen) zone develops below an outfall." This is based on the physical increase in turbidity as the oxygen supply is depleted to anaerobic conditions. An analytical relationship between oxygen and downstream distance has been determined with great success in the Streeter-Phelps equation and correlation of aerial photography with this relationship may be viewed as an academic possiblity. It would be foolish, however, to assume that photographic interpretation of oxygen depletion could be the rule rather than the exception. Many other outfalls and sediment loads are usually present and a strict cause and effect relationship between the waste and the turbidity would be difficult to establish.

Scherz (1969) and Kiefer and Scherz (1971) emphasize that photography cannot directly show dissolved oxygen, BOD, phosphates or nitrates in lakes or streams. The photographs primarily show suspended solids, turbidity and associated algae blooms.

4. **Various Industrial Wastes** - Scherz *et al.* (1969) determined reflection characteristic curves or signatures for various types of wastes (Fig. 6). These could then be applied to filtered color photography in the most promising wavelengths. Likewise, each lake and river has its own reflective characteristics, so one must consider curves for the water body as well as the waste.

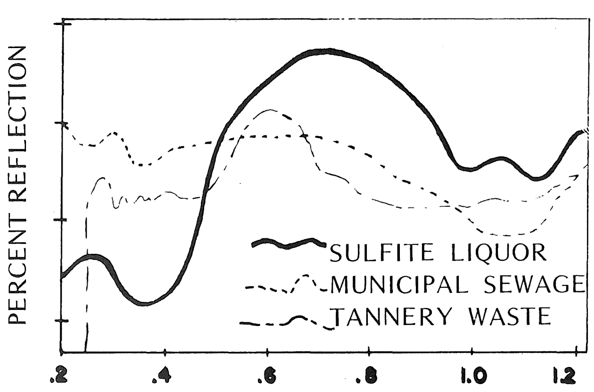
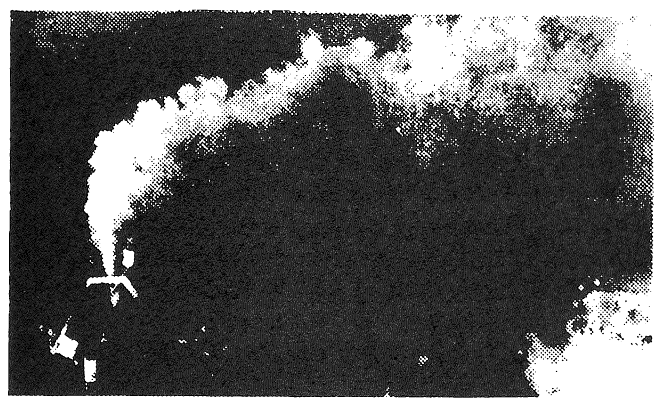


FIGURE 6. REFLECTION CHARACTERISTICS OF VARIOUS WASTES (SCHERZ, GRAFF AND BOYLE, 1969)

Piech, Silvestro *et al.* (1969, 1970) illustrated the diffusion of a fibrous effluent into the Niagara River near Buffalo, New York by aerial photographic techniques. The discharge consisted of buoyant particles about 10^{-4} inch in diameter and about 100 ppm in concentration. The camera system used a filter to limit its wavelengths to the 6,300 Å - 6,700 Å range. Calibration of the photograph included: (1) painted panels of known reflectance in the areas photographed to provide a sunlight standard at the moment of exposure and to aid in evaluating the effects of the atmosphere between the plane and the water, (2) a step wedge printed on an unexposed portion of the film to standardize variables in film processing, and (3) ground truth taken in the discharge plume.

A relationship was found between the back radiance or reflection and the concentration of the pollutant. This enabled an iso-concentration plot as shown in Fig. 7 to be determined through densiometric analysis of the photograph. The results were compared with a turbulent diffusion model for a buoyant discharge and the data and model agreed well. This experiment pointed out the basic feasibility of diffusion determination by remote sensing although the conditions were somewhat ideal. The pollutant was relatively radiant, it was in high concentrations and a great deal of knowledge of the reflective characteristics was determined previous to the test.



DISCHARGE OF FIBROUS POLLUTANT ON A CALM DAY

HOW POLLUTANT WAS DISPERSED ON THAT DAY

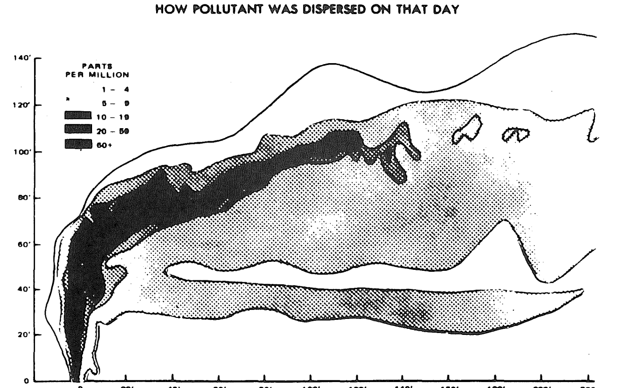


FIGURE 7. FIBROUS EFFLUENT PHOTOGRAPH AND ISO–CONCENTRATION PLOT-NIAGARA RIVER NEAR BUFFALO, NEW YORK (PIECH, 1969)

5. **Ocean Outfalls** - James and Burgess (1970) employed aerial color photography as a method for analyzing dispersion of wastes from an ocean outfall. It was contended that ocean outfalls are generally located on the shallow coastal shelf and collection of data from boats is made difficult because of heavy seas. Aerial data were collected in 1968 using a rhodamine dye tracer. The photographic information was converted to digital data with a photo densitometer and the waste (dye in this case) concentration was determined by a regression analysis. Boat sampling was conducted at the same time as the aerial survey and good correlation of about .9 was noted.

Although the authors admit that many of their assumptions in developing the relationship between the photographic images and the waste concentration are open to criticism, a refinement of this technique coupled with their computerized handling of the data offers a good method for determining the dispersion of wastes from ocean outfalls.

6. **Oil Slicks** - Oil spills in harbors and on the open seas have become a major pollution problem and as such require periodic flights over areas of known oil leakage to determine the extent of the slick. Welch (1970) suggests that the best photographic sensing of oil is done in the ultraviolet portion of the spectrum (.30 - .45μ) when low cost remote sensing is desired from aircraft. Many investigators have found recently that thermal infrared imagery shows the area of the spill clearly and accurately. Wobber (1971) feels that thermal infrared imagery and multiband photography can, with further research and development, permit volumetric estimates of spills, a question of great legal significance. Estes and Golomb (1970) discuss the significance of the little data that were gathered at the 1969 Santa Barbara Oil Spill in that "the systematic application of remote sensing technology was conspicuous by its absence." Infrared scanning is likewise suggested as the best remote sensing method for such spills. Chandler (1970), in a series of oil slick observations along the Southern California coast, determined the best definition of oil slicks was within the 8-14μ thermal infrared region. The oil-covered water produced colder anomalies, apparently due to the large difference between thermal conductivities of water in oil.

Kennedy and Wermund (1971) used both thermal infrared scanning (8-14μ) and microwave radiometric data (22 mm) in studying an oil spill in the Gulf of Mexico in March, 1970. The data were used to determine the thickness of various zones in the imagery and thus determine the volume of oil in the slick. Comparison of scans taken at two different times added another parameter to the analysis; that of the spill flow rate. In addition, the imagery compared favorably with a previously developed turbulent diffusion model for ocean oil slicks.

7. **Algae and Aquatic Plant Monitoring** - Another important consideration in water quality is the study of algea and aquatic plant proliferation in bodies of water. The possibility of using aerial photographic techniques and selective spectral bands to study this phenomenon has been investigated by several authors.

Plant growth on lakes can easily be outlined with simple infrared photography, as the infrared energy from the sun is reflected by the plants. Scherz (1971) states that if the growth is but a few inches below the surface of the water, the infrared energy will be absorbed by the water. Studies at the University of Wisconsin (Kiefer and Scherz, 1971) indicate that color infrared and color photographs taken simultaneously are useful tools in mapping and identifying types of aquatic plants. A color infrared photograph yielded four vegetative types by their colors in a survey of Lake Wingra near Madison, Wisconsin: (1) algae - light grey, (2) submerged weeds - dark blue, (3) weeds on water surface - dark pink, and (4) lily pads - bright pink.

Keene and Pearcy (1973) discuss high altitude photography of chlorophyll and phytoplankton concentrations off the coast of Oregon. The ratio of blue (.41 - .47μ) to green (.54 - .58μ) reflectances measured by a densitometer on Ektachrome transparencies was used to outline the productive areas that were probably a result of coastal upwelling and the influence of the Columbia River.

Some investigators have proposed that it may be possible to separate phytoplankton into major groups (e.g. blue-greens to greens). Gramms and Boyle (1971) of the University of Wisconsin evaluated the reflectances and transmittance characteristics of two green algae, *Selenastrum* and *Chlorella*, and two blue-green algae, *Microcystis* and *Anabaena*, in the spectral region of 3750 to 8000 Å. Their findings stated that it is possible to differentiate between blue-green and green algae by using the ratio of the reflectances at 6250 and 6500 Å. In attempting to find algae concentrations based on spectral reflectances, it was found that calibration was necessary to account for background turbidity and loss of chlorophyll due to phosphorous removal.

8. **Depth Penetration and Benthic Ecology** - One aspect that has gained the increased attention of marine biologists and oceanographers is the use of aerial photography to gain a synoptic understanding of the distribution of bottom biota in coastal areas.

Applying remote sensing to penetrating water depths is, however, different from such land applications as forestry and agriculture where energy comes back from the first leaf or piece of vegetation that it encounters. With water bodies, the ultraviolet is reflected directly from the surface, the middle wavelengths of blue and green penetrate into the water and show depth features, while the near infrared energy is absorbed by the first few inches of the water body (Fig. 8) (Scherz, 1971). The best wavelengths to see bottom characteristics are therefore in the blue-green visible wavelengths and can be achieved with normal color film, color infrared and multispectral scanning within this energy band. Depth penetrations of up to 40 feet have been reported, according to Scherz, but with some loss in detail.

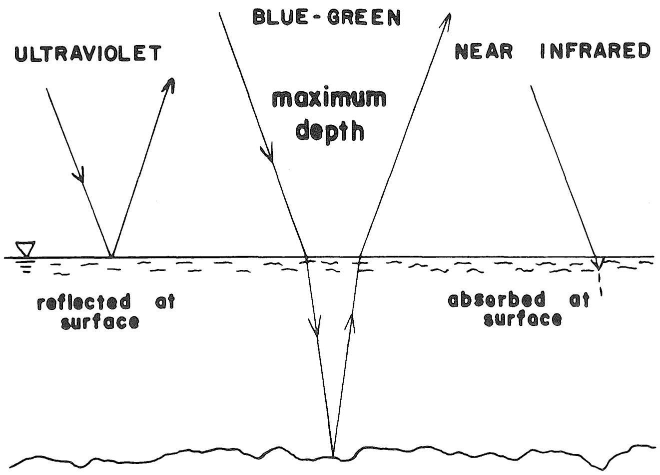


FIGURE 8. INTERACTION OF PHOTOGRAPHIC BAND ENERGY WITH WATER (SCHERZ, 1971)

Kelly and Conrod (1969) argue that although the depth penetration is limited to shallow coastal areas, it is these areas that are of most immediate importance to man. They note three types of information that can be detected with aerial photography: (1) it is possible to map the distribution of bottom biota and to determine subtle changes in the distribution, (2) it is possible to identify anomalies that indicate unusual features, and (3) the dynamic relationships and ecological interactions, both natural and man-made, can be detected by analyzing distributional patterns and geographic variations. In an investigation of a coastal site in the Bahamas, a photomosaic of bottom vegetation was constructed and several bottom features were also distinguished.

9. **Estuary Studies** - The ecologically and environmentally important estuaries of the United States have been regarded as possible applications of remote sensing. The studies of estuaries actually involve all previously mentioned applications of remote sensing, including tracing man-made pollutants, examining aquatic systems and delineating shallow areas.

In one of the first remote sensing studies of estuaries, the Patuxent River in Maryland was flown in 1968 by Anderson (1969) to determine what types of films, scanners and filter combinations would be best to describe the different parameters of an estuary. Color infrared proved to give good definition of marsh plant communities and detected sources and distribution of sediment. Infrared scanning was used to delineate marsh plant species, observe water temperature patterns and determine sources of groundwater flow into the river. In 1969, Anderson (1971) extended his studies to the Chesapeake Bay in an attempt to determine the spectral reflectance of selected marsh plant species for multispectral data being obtained.

Tuyahov and Holz (1973) used infrared scanning and color and infrared color photography in the study of a barrier island system off the south Gulf coast of Texas. Thermal imagery provided information on water detection and offshore currents. Color infrared showed moisture, vegetation delineation and plant communities and vigor. Conventional color proved best in water penetration and analysis. Earth Satellite Corporation (1972) reports on an extensive aerial survey being undertaken of New Jersey's coastal wetlands. Both black and white infrared and color infrared photographs yielded good inventories of vegetation and hydrologic conditions. *Spartina patens* and *Spartina alterniflora* salt marsh grass species could be distinguished. The program is suggested to illustrate a case of actual implementation of remote sensing to a specific inventory request from the state of New Jersey.

In some instances, the tidal cycle of estuaries can be determined with infrared scanning, using the temperature difference between sea water and the fresh water as well as the difference in emissivity between the two waters. The U.S.G.S. utilized infrared scanning in the lower reaches of the Merrimack estuary in Massachusetts to investigate the tidal currents. Imagery was obtained at each of the four stages of tidal flow and, along with ground data on salinity, temperature and flow, a synoptic description of the estuary was obtained. The results proved to give valuable data on the trapping of polluted water in shellfish culture areas (Taylor and Stingelin, 1969).

10. **Water Resource Studies in Florida** - There have been several significant studies that do not fall under any of the previous headings, but which nevertheless show aerial remote sensing applications in water resource studies. This report will briefly review several programs conducted in the State of Florida.

a. The Everglades - The Florida Everglades have been studied extensively by remote sensing because (1) the almost imperceptible differences in relief make it a difficult area to map, and (2) the Everglades are notoriously inaccessible (Schneider, 1966). In September 1967 multispectral scanning data collection and processing techniques were used (Higer *et al.*, 1969) in the Everglades to map tree islands, emergent aquatic grassland vegetation, surface water at two different depths and exposed limestone. The mapping area was only eight miles by 2000 feet but the reason for the study was to determine the feasibility of remote sensing in classifying and mapping Everglades parameters such as different types of vegetation, substrate and water as indicators of surface water supply conditions. This was cited as being especially significant to the Everglades for two reasons: (1) to better assess the effects of seasonal and annual fluctuations in surface water level on the ecosystem, and (2) to predict the consequences of water management practices.

b. West Central Florida Lakes - Remote sensing was used by NASA in 1968 of several lakes in the central Gulf coast area of Florida (Stewart, 1969). The overall purpose of the study was to determine the feasibility of using remote sensing for problems in lake hydrology such as the interrelation of the lakes of different characteristics in the area. It was concluded that the data obtained by both infrared imagery and color and infrared photography were useful for (1) water storage inventories, (2) determination of type, source and rate of water body eutrophication, (3) delineation of vegetative zones relating to soil moisture and declining lake levels, and (4) providing an insight into substrate drainage such as sink drains and artesian springs. Most of these applications would require periodic remote sensing, however, and ground truth use was not discussed. Also, no data processing techniques were used and the conclusions were based strictly on conventional photo interpretation and obvious anomalies.

c. Groundwater to Sea Discharges - Groundwater discharges from the Florida aquifer were believed to occur as submarine springs along the Gulf coast of central Florida. In 1968, the U.S.G.S. (Hunn and Cherry, 1969) flew the area with infrared scanners to determine the location of contrasting temperatures of sea and aquifer water. It was cited that the locations of these offshore spring discharges were important to predict areas where dredging of channels into rock might result in increased submerged discharge of valuable fresh water into the sea.

d. Sinkhole Prediction - In 1967, the U.S.G.S. (Coker *et al.*,1969), in conjunction with the University of Michigan collected data near Bartow, Florida in the west central part of the state to study land collapse phenomena using remote sensing techniques. The area is prone to active land collapse (sinkholes) and the experiment was conducted to test the hypothesis that areas of potential sinks could be detected at the land surface from the integrated effects of water loss at depth on vegetation physiology and terrain temperature. Multispectral, reflective, infrared data were collected to detect moisture-stressed vegetation while infrared imagery was used to chart surface temperatures. Results were correlated with known sinkholes and an area where subsidence did not begin until the following year was delineated. One important aspect of this testing was that the data collected from two different remote sensors were combined to prove a hydrogeological hypothesis. The physical significance of looking for pending sinkholes with remote sensing, however, probably has limited application.

e. Biscayne Bay Study - Intensive investigations of bottom features in Biscayne Bay have been reported by Kelly (1969). An ecological model is being developed by Higer *et al.* (1971) to use multispectral data in determining the effects of the cooling water discharge from the Turkey Point Power Plant. The model will predict effects of the cooling water on the benthic community for different operating conditions and dispersion patterns.

f. The Florida Keys - The Florida Keys have also been investigated for coastal parameters and bottom ecology (Kelly, 1969) and aerial photography has proven useful for detection of unknown or unrecognized submarine biological features. One possible application in this area is monitoring the effects of the extensive dredge and fill operations in the Keys. Satellite repetitive data may be useful here and hyperaltitude data were being collected to estimate what large-scale features would be resolvable for the then upcoming satellite program.

The remote sensing programs in Florida may be somewhat atypical of the rest of the nation because of the immediacy of NASA facilities and because of the complicated hydrological, biological and geological features of the state. However, the above studies do give an indication of the state of the art and applications that may be more common in the future. They also show the importance of expansion of data into the temporal (time) mode with repetitive measurements, a dimension that will be available with the satellite program discussed in the following section.

III. Satellite Monitoring of Water Resources

A new approach to remote sensing, that of monitoring the earth's resources from satellites and outer space, is now reaching a significant period in its short history. The first satellite to be used exclusively for monitoring the earth's environment was launched in July, 1972. Early indications from NASA say that the satellite is sending good pictures back to Earth (**Environmental Science and Technology**, September, 1972) (Maugh, 1973). Spatial and temporal modes will be drastically changed from those of conventional aircraft discussed previously.

Largely out of Secretary of the Interior Stewart Udall's efforts in the 1960's, there arose a cooperative program between NASA and the Department of Interior for investigating satellite surveys of earth. Extensive studies involving NASA, the Departments of Interior, Agriculture and Commerce, several other government agencies, and a number of colleges and universities, were sponsored. Out of these studies arose EROS (Earth Resource Observation Systems), a multidisciplinary branch of the Interior Department. The EROS program objective is defined loosely "to utilize aircraft and spacecraft remote sensing technology as complementary parts of integrated data collection, processing and dissemination systems to support resources research and management functions of the Department of Interior." (Fary, 1971). One of the major areas of activity of the EROS program is the Earth Resources Technology Satellite (ERTS) program.

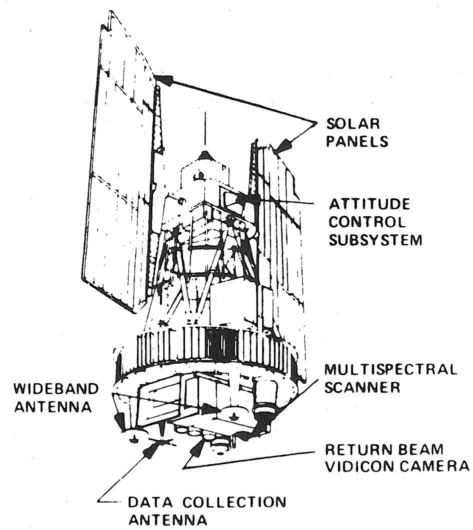
Under the ERTS program, NASA is developing experimental satellites ERTS-1 and ERTS-2 to provide data of a type requested by the Department of Interior. The first satellite, ERTS-1, was launched on July 23, 1972 with ERTS-2 now planned for an early 1976 launch. A postponement from its original launch time of November 1973 due to a NASA budget tightening has scientists concerned that a data gap will exist between the two satellites (Maugh, 1973). A parallel program to ERTS is EREP (Earth Resources Experimental Package) to be carried out by the manned Skylab program now getting underway. The coverage by this program however will not be as complete as ERTS.

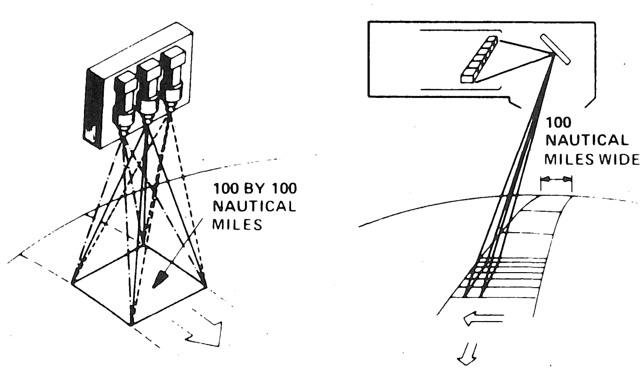
Design of ERTS is based on the highly successful Nimbus weather satellite of 1964. The ERTS observatory is operating in a polar orbit, 500 miles above the earth's surface, in sun-synchronism. Each satellite is designed to operate at least one year and, weather permitting, will image any given area every 18 days.

The ERTS observatory (Fig. 9) collects data in three modes:

1. **The Multispectral Scanner System (MSS)** - This scanner system collects imagery in a strip 100 miles wide in four spectral bands from .5 to 1.1μ (with a fifth band in the thermal infrared range planned for ERTS-2). The data are processed into 100 mile square frames to correspond with the RBV system described below (Colvocoresses, 1970). Each band gives the potential for additional information with one band best for land-water discrimination and vegetation monitoring, a second for topographic and cultural features, a third for depth and turbidity of standing water and a fourth best for tonal contrasts on various land use practices (Campbell, 1973).

2. **The Return Beam Vidicon System (RBV)** - Three cameras, functioning in three of the four MSS spectral bands, view the same 100 mile square ground scene, producing images about every 25 seconds with a 10 percent overlap. The images are then transmitted back to earth as video signals. The RBV system on ERTS-1 however was shut down soon after launch because of a failure in the power supply circuitry and currently data are being generated only from the MSS (Maugh, 1973).





Return Beam Vidicon Subsystem **Multispectral Scanner Subsystem**

FIGURE 9. ERTS SATELLITE (GENERAL ELECTRIC, 1971)

3. **The Data Collection System (DCS)** - The DCS will serve to relay data gathered by devices such as stream gages, water quality samplers and geothermal sensors from their surface bases through the satellite and to the ground collection stations. One experiment with this system will be

a data-relay link for a maximum of 20 hydrologic stations in the Delaware River Basin. The experiment has the potential for reducing the time lag between data collection and dissemination to less than 12 hours. At present a lag between the time the data are recorded to the time they are received by various agencies varies from two weeks to two months (Paulson, 1971).

Resolution obtained from ERTS-1 has been good. Maugh (1973) reports that some investigators can identify features as small as 90 meters in diameter and linear features only 15 meters wide. Colvocoresses (1972) determined an expected RBV resolution of 125 to 180 meters and an expected MSS resolution of about 225 meters at high contrast and 305 meters at low contrast.

An extensive system for data handling of ERTS output has been set up. Transmitted data are processed into photographs at NASA's Goddard Space Flight Center in Greenbelt, Maryland and sent to cooperating federal agencies and principal investigators. In anticipation of large requests from others, the EROS program recently opened a data center near Sioux Falls, South Dakota. As of April, 1973 ERTS had imaged more than 33,000 scenes in 4 spectral bands and more than 1.5 million photographs have been prepared. It has photographed the entire United States 10 times and mapped more than 75 percent of the earth's land mass (Maugh, 1973).

With all of these impressive statistics, it still remains to be seen what applications will prove most useful. Over 300 principal investigators are listed as having experiments associated with ERTS (ERTS Data Users Handbook, 1972). The EROS program has used previously flown outer space photos to illustrate possible studies from the satellites. The more significant anticipated water applications are summarized below.

Hydrologic and Water Resource Applications - A National Academy of Sciences panel in 1967 and 1968 identified hydrologic objectives amenable to satellite surveys. They were: (1) basic studies of the hydrologic systems, (2) snow and ice mapping, (3) surveys of coastal hydrologic features, and (4) real-time communication of ground-based hydrologic data (Bock, 1969). Additional applications may include: (5) improving our understanding of the groundwater regime through observations of overlying vegetation, (6) lake classification, and (7) determining the dynamics of water bodies through repetitive synopic observations of "markers" such as waterborne silt (Fischer, 1972).

Maugh (1973, 1973a), in evaluating preliminary results from ERTS-1, shows in one case an image of Utah's Great Salt Lake and how man's action has altered the algal composition of the lake. He also states that hydrologists are using ERTS imagery to locate new sources of groundwater while oceanographers are using ERTS to assess fishery resources and improve navigation conditions. Two recent symposia (NASA, 1972, 1973) reported on preliminary results of ERTS data use in coastal and oceanographic analyses, permafrost studies, streamflow investigations, and other water resource applications.

Water Quality Applications - Orbital imagery from the ERTS program will probably have a minimal application in local water quality problems, but can be of significance in a total systems approach. This idea, as presented by Wobber (1970), is best implemented by an integrated aerial/orbital data collection program. He goes on to state that water quality variations such as anomalous plumes will constitute major regional pollution outfalls from a number of small undetectable sources. Only rarely can the relationship between pollution sources and specific cultural features be determined. "Knowledge of the distribution of undesirable waterborne effluents provide data to minimize their harmful areal effects, or can result in preplanned site selection of problem industries. In some instances, orbital photographs reveal major seaward-sweeping current systems which could reduce the value of adjacent areas for recreational development, but serve as effective vehicles for disposal of municipal wastes." Wobber sees additional benefits of satellite imagery in determining the relationships between water quality and cultural development, in increasing the efficiency of ground sampling programs and in the study of seasonal changes of effluent patterns.

Lind of the University of Vermont has examined initial ERTS data of Lake Champlain and has observed effluent from a paper mill crossing state boundaries from New York to Vermont. This image may prove to be significant in a pending court suit by Vermont against New York to halt the discharge, not so much from a crucial evidence standpoint as from a precedent standpoint (Maugh, 1973a).

Some Specific Water Programs - A listing of the initial objective experiments for the ERTS/Skylab programs includes the following water resource studies (EROS Photo Nos. 1678-1679):

- Pollution of Lake Pontchartrain in Louisiana
- Protection of the sea coast and tidal marshes of New Jersey
- The role of the playa lakes in the resupply of groundwater in the high plains of Texas
- The movement of sediment plumes in the San Francisco and Chesapeake Bays
- The ecological effects of the meandering of the Gulf Stream
- Marine and coastal environments in Puerto Rico and the Virgin Islands
- The formation of icebergs in the Antartic
- Large-scale weather effects on the lee or southeast shores of the Great Lakes
- Storm and tidal erosion of the barrier island chain off the Gulf coast of Texas
- Extent of snow cover for river and flood forecasting in the Sierra Nevada Mountains.

IV. Concluding Remarks

Remote sensing offers a means of collecting large amounts of data in the study of water quality and water resources. The technology is now at a significant stage where particular techniques that have been developed are being matched with environmental applications. Many are natural applications such as the use of thermal scanners on thermal discharges; several, however, seem to be forced applications of a technology that is trying to make its presence felt in the seemingly lucrative field of environmental instrumentation. Research in many remote sensing aspects is proceeding at a significant rate to make literature over five years old of minimal value. It is essentially up to professionals from many disciplines such as ecology and environmental engineering to direct this macroscopic technique to their needs in the water resources field.

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