DELAWARE ESTUARY SITUATION REPORTS

This series of reports is devoted to discussion of current issues relevant to conservation, use, and development of Delaware Estuary resources, and of concern to managers, decision makers, and the general public.

Remote Sensing

Can Satellite Technology Contribute to a Better Understanding of Estuarine Processes?

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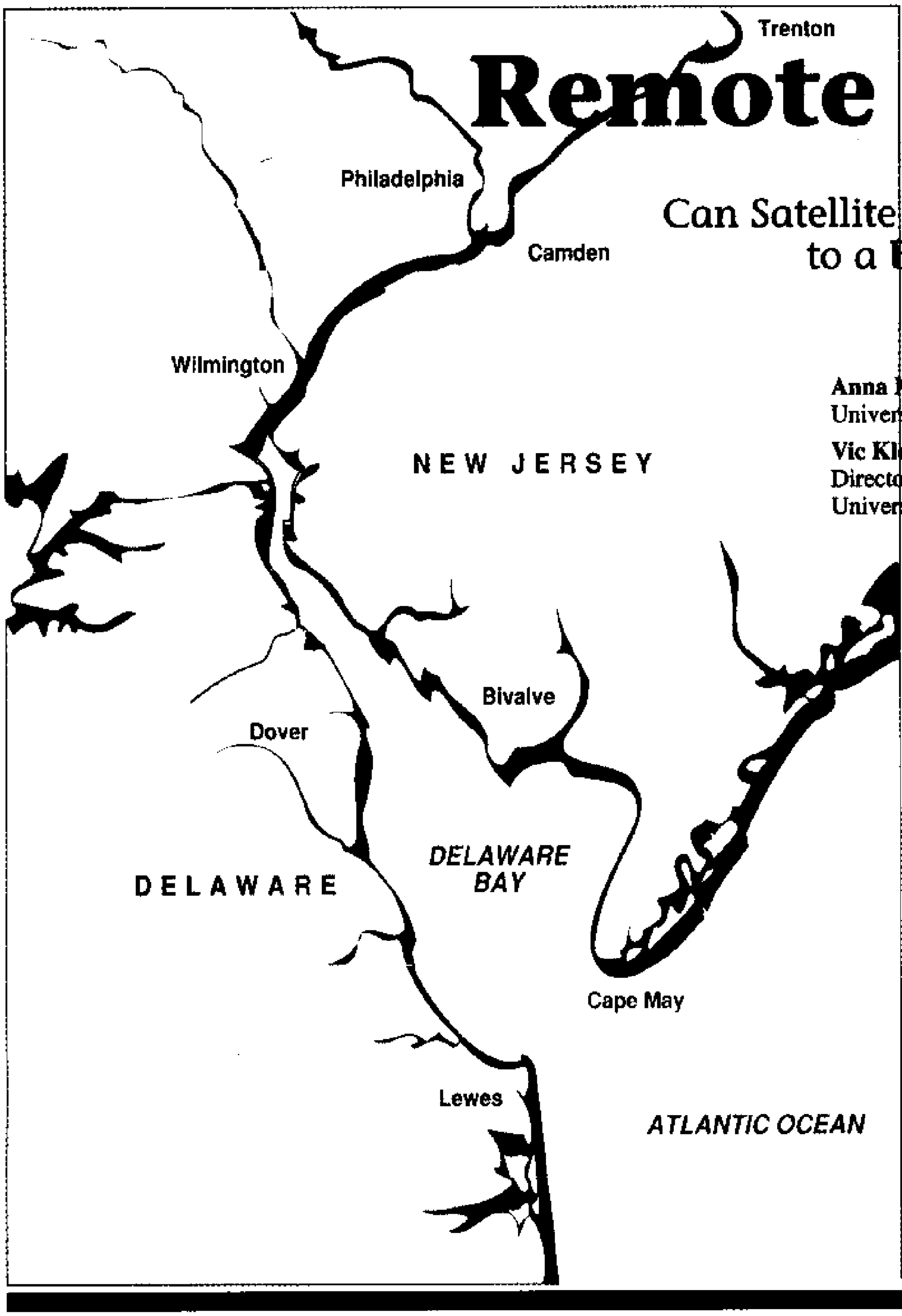


The Delaware Estuary, a multi-purpose bistate resource.

An estuary is a body of water that is part river and part sea. The Delaware Estuary is composed of the tidal portion of the Delaware River and its tributaries, and the Delaware Bay. This unique resource attracts diverse life, from microscopic plants that thrive on its abundant nutrients to shad that migrate from the ocean to the estuary's tributaries to spawn.

The Delaware Estuary also attracts people, who rely on its fisheries for food and livelihood, its cooling waters for industry, its shipping channel for trade. However, as more and more of us are drawn to the estuary, demanding space, fresh water, fish, and clean beaches, while at the same time generating sewage and litter, great stress on the ecosystem occurs. This is in addition to already existing pollution from farming (pesticides, fertilizers, soil runoff), industry (chemicals), and municipal sewage discharge.

The problem is that the Delaware Estuary is valuable for human use *and* it is valuable as a fragile, natural resource worthy of preservation. What is the answer to the dilemma of using the estuary while protecting its ecology? The answer is resource management. Today's resource manager must have scientific data on which to base decisions. And one of the most promising techniques for gathering large amounts of data in the Delaware Estuary is remote sensing.

University of Delaware
Sea Grant College Program

Background

In the U.S. today, responsibilities for safeguarding the environment and managing our natural resources are divided among agencies at various levels of government, from the national level, such as the Environmental Protection Agency, to the regional, state, and local levels, such as the Delaware River Basin Commission (DRBC), the Delaware Department of Natural Resources and Environmental Control (DNREC), and the New Castle County Planning Commission, respectively. The task of keeping resource managers at all of these levels informed falls to scientists.

Because estuaries are such complex and quickly changing natural systems, scientists must collect large amounts of data in and around them to find out how "healthy" they are. From data collection on the land around the estuary, scientists determine soil runoff, sewage and industrial inputs, and amounts of other pollutants. In the estuary itself, data collection is usually performed by scientists and their students during research cruises. This work entails measuring the water's concentrations of plant pigment (chlorophyll), suspended sediments, and pollutants such as phosphates and nitrogen compounds, or toxic substances such as copper, lead, mercury, PCBs, and other metals and chemicals. Typical water-quality parameters such as dissolved oxy- and carbon dioxide levels, as well as temperature and salinity are also measured.

Although research cruises provide a wealth of information, their costs add up very quickly, often preventing scientists from collecting data repeatedly throughout the year to understand the changes taking place in the estuary. Remote sensing may eventually solve the scientists' dilemma. This innovative research technique combines the use of estuarine data collected by sensors on satellites and aircraft with ship-collected data in a cost-effective way. In the future, remote sensing may become a priceless tool for scientists and resource managers who have had to rely solely on ship surveys to monitor the health of estuaries.

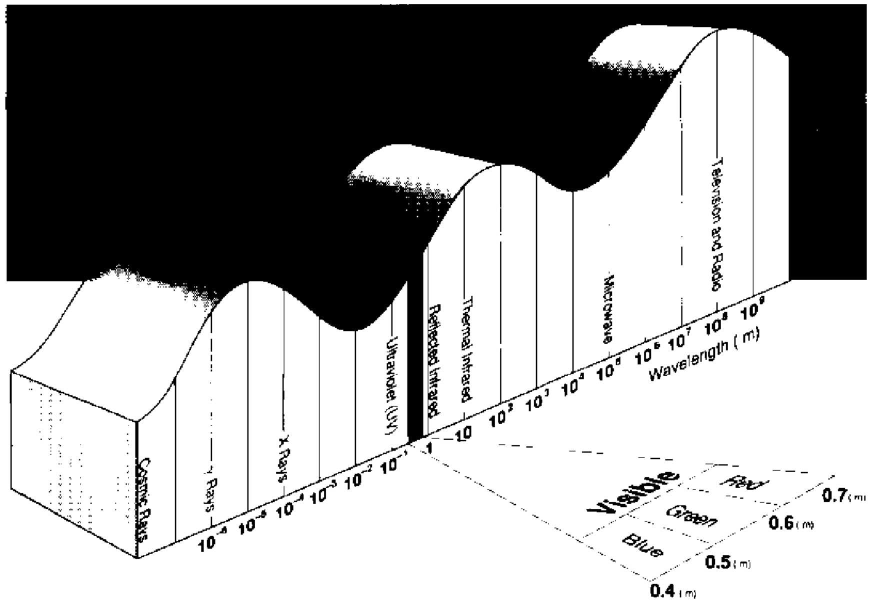


Figure 1. The Electromagnetic Spectrum. The term "electromagnetic radiation" describes a wide range of phenomena, from cosmic rays to radio waves. The radiation is all of the same form, but it is of different wavelengths and/or frequencies. For example, look at the different kinds of light—ultraviolet, visible, and infrared light. Ultraviolet light has the shortest wavelength, followed by visible light, and finally reflected infrared and thermal infrared light. Each kind of light is the same form of radiation, but the wavelength is different for each.

What Is Remote Sensing?

Remote sensing is a research technique based on electromagnetic radiation and its interaction with a target. Electromagnetic radiation is the scientific term used to describe light, heat, microwaves, and radio waves. All of these phenomena are the same form of radiation, but each has a different wavelength and/or frequency. For example, ultraviolet (UV) light is radiation of very short wavelength, in the order of one millionth of a meter, while microwaves and radio waves have much longer wavelengths, in the order of centimeters and even meters (see Figure 1).

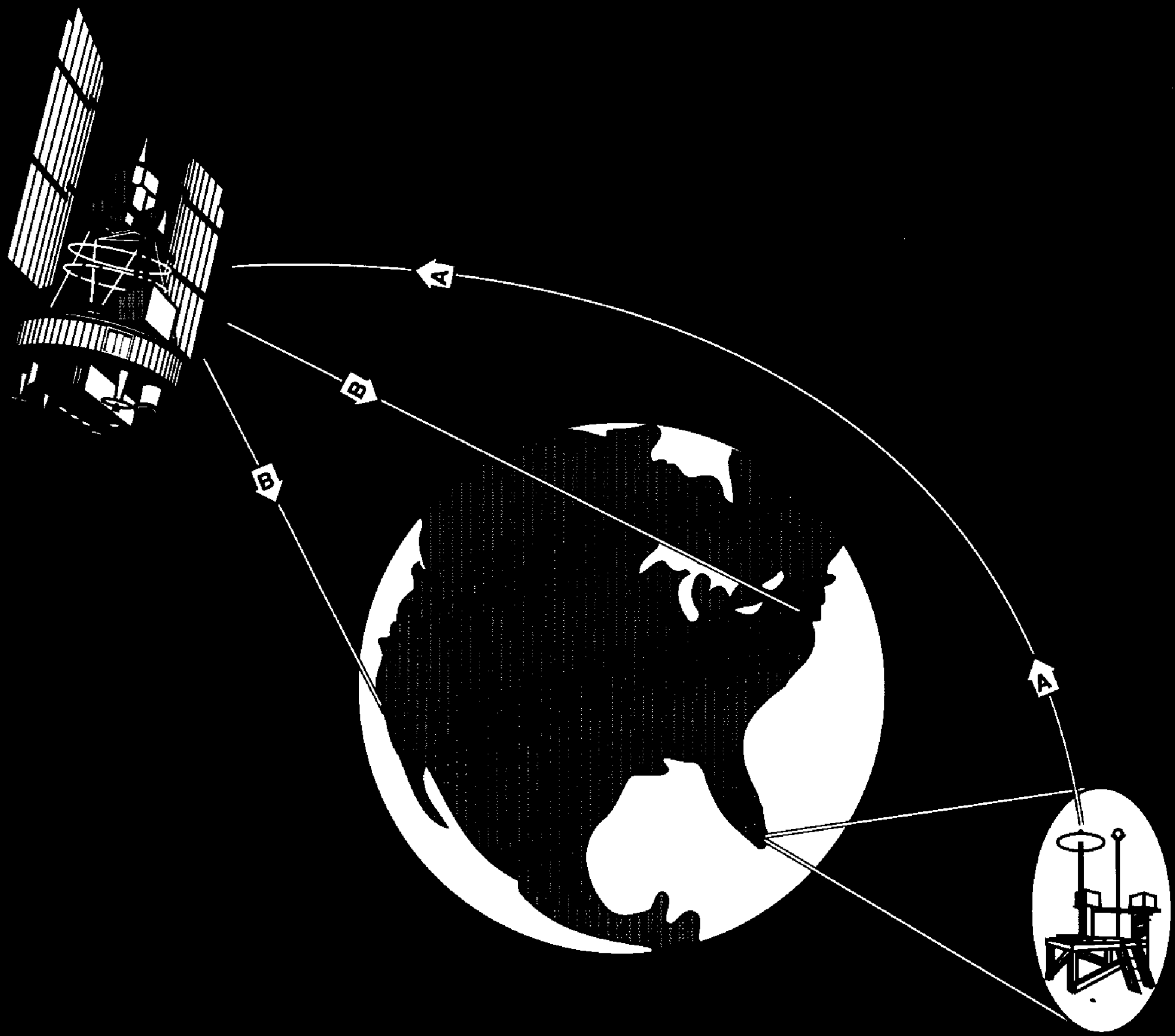
Remote sensing instruments range from our eyes to simple hand-held cameras to video recorders, radar systems, and x-ray machines. All of these sensors detect reflected or emitted radiation (light, microwaves, x-rays) from an observed area and use the intensity and distribution of this radiation to create an image of that area. For example, a camera detects light reflected from a subject or scene. When the shutter opens, the light falling on the film reacts with the film's chemical emulsion in direct proportion to the light's intensity. Thus, the film now contains a "latent image" and, once it is developed and printed, we get a true representation of what we photographed. The trick is that the film's emulsion, as well as our eyes and the camera itself, are all sensitive to the intensity of the reflected light so that the distribution of light (bright areas in full sun, darker areas in shade) is reproduced exactly in the subject's image.

Remote sensors aboard satellites work essentially the same way as a camera except that, instead of film, electronic light detectors are employed to "view" the scene with a side-to-side scanning motion and to record the light's intensity in each of about 2 million subsections of an image called pixels. These pixels are akin to the phosphorescent dots on the back of your television screen. This image data is then stored on digital tape aboard the satellite and periodically sent by telemetry to receiving stations in various parts of the world (see Figure 2).

How Are Remote Sensors Used?

Scientists use a variety of satellite and aircraft-borne sensors to study the land and ocean. The most widely used satellite sensors are the LANDSAT Multispectral Scanner (MSS) and the LANDSAT Thematic Mapper (TM); the NIMBUS-7 Coastal Zone Color Scanner (CZCS); the National Oceanic and Atmospheric Administration's weather satellites which carry the Advanced Very High Resolution Radiometer (AVHRR); the French earth observation satellite SPOT (Satellite Pour l'Observation de la Terre); and the GOES Visible Infrared Spin-Scan Radiometer. All of these satellites collect information in the visible portion of the light spectrum, while the NOAA and GOES satellites can also detect emissions in the "invisible," thermal infrared portion of the spectrum. These infrared measurements are directly related to the surface temperature of the observed area.

The National Aeronautics and Space Administration (NASA) operates several



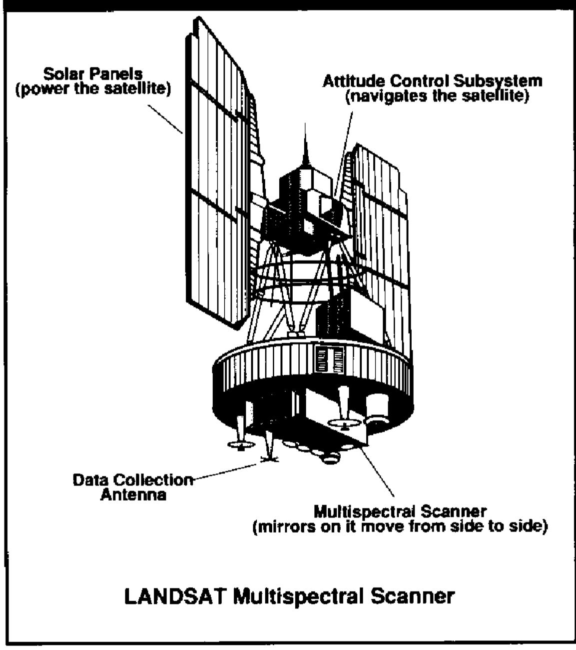


Figure 2. A Satellite and How It Works. *There are hundreds of satellites orbiting the Earth, continually gathering data. The LANDSAT Multispectral Scanner shown here collects geological and oceanographic data of all the Earth except areas at high latitudes, such as portions of the Arctic and Antarctic. As a subject is scanned, the satellite records the light intensity in tiny subsections of an image called pixels. This data is then stored on digital tape aboard the satellite and is periodically sent to Earth via telemetry to receiving stations such as in the Everglades, Florida. Data can also be transmitted from collection platforms in the Everglades (A) via LANDSAT to NASA tracking stations at Goldstone, California, and Greenbelt, Maryland (B). The LANDSAT-MSS takes 18 days to make a complete track of the Earth. Because its track is synchronous with the sun, imagery is always recorded at the same time of day.*

important aircraft-borne sensors for both land and ocean studies. The Ocean Data Acquisition System (ODAS), which is flown at low altitudes on small aircraft, is best suited for ocean color and surface temperature detection, while the Airborne Ocean Color Imager (AOCI) and the Multi-channel Ocean Color Sensor (MOCS), which are both flown on high-altitude aircraft, are highly sensitive in the visible light range. The MOCS has been used in small-scale studies of coastal and estuarine productivity.

Satellite and aircraft-borne sensors produce digital tapes of the data they collect, which are then archived by several agencies throughout the world. In the U.S., the National Oceanic and Atmospheric Administration archives meteorological data while private companies archive and market LANDSAT and SPOT imagery. Scientists must contact NASA to obtain data from aircraft-borne sensors. Often this data can be acquired at little cost through cooperative agreements.

To use remote sensing data, the scientist loads a digital tape into a computer with an image-processing system, which displays the brightness of each pixel, or tiny picture component, onto a graphics monitor. The result looks much like a photograph—in color or black-and-white according to the satellite and image-processing system used (see image, page 5).

Once this image data is stored in the computer's memory, the scientist can perform a number of operations on the data to extract the information he or she needs. Typically, a few corrections have to be made first, such as removing geometric distortion due to the position of the satellite relative to the area of interest (this is called remapping or geometric registration). Often atmospheric effects, which produce a brightness value, also have to be removed to get actual land or water brightness values.

After these corrections are made, the researcher can enhance the data in a number of ways to bring out the contrast (or variability) in the image, which is then related to physical processes or parameters. During this stage, color is often used to enhance certain features and to downplay others. Also at this stage, the scientist extracts quantitative information (concentrations, biomass estimates) from the image via mathematical relationships called algorithms, which relate brightness values in different bands with specific parameters. When the scientist's work is done, the resulting image is displayed with a color "scale" for different levels of concentration.

University of Delaware Sea Grant Remote Sensing Research

What can scientists learn from remote sensing research? In the Delaware Estuary, the answer ranges from the productivity of the wetlands that border it to the waterway's susceptibility to pollution.

Wetlands are important buffer zones between land and estuary. They absorb land runoff and diminish its effect by filtering out high percentages of sediment, excess nutrients, and some toxins, therefore raising the quality of the water that enters the estuary.

Through past research, researchers at the University of Delaware Sea Grant College Program perfected a remote sensing technique to measure the productivity, or health, of wetlands. Formerly, scientists could measure a marsh's productivity only by destroying part of it through a labor-intensive, time-consuming process: they harvested a large portion of vegetation on a parcel of land and then took the vegetation back to the lab to analyze its carbon content. However, Sea Grant scientists can now quickly assess the health of a marsh, and in a non-destructive way. By holding a sensor called a radiometer over the tops of marsh plants, they can measure the light reflected off of the leaves and then use this measurement to

From Airborne Photography to Satellite Data

Remote sensing actually began as airborne photography, first performed by daredevil photographers such as James Wallace Black who took the first aerial picture in the United States, a view of downtown Boston, in 1860. Photography from airplanes was first used for military reconnaissance during World War I, and when the potential of that application was realized, it spawned a whole new industry of remote sensing instrumentation and data analysis. During World War II, a great deal of research went into developing airborne photo equipment and interpretation techniques, and many of the instruments and terminology of remote sensing date back to those years, as evidenced by the terms "target scene," "target range," and "radar" (radio detecting and ranging).

Today, remote sensing techniques are employed in space exploration, in military intelligence gathering, in medicine (CAT scanner, NMR imager), in land use and forestry management, and in oceanographic and meteorological studies. Some remote sensing instruments can be operated from aircraft flying at various altitudes to observe different-sized areas of land or sea. And a good number of them are placed aboard satellites and sent into orbits whereby they can observe specific areas of the Earth almost continuously, like the geosynchronous satellites, or different areas of the Earth at specific time intervals, like the polar orbiting weather satellites. The next time you watch the weather on TV, notice the satellite weather maps—they are just one of the products of remote sensing.

Satellite Image of Delaware Bay, July 19, 1984. *This image, taken by the LANDSAT Thematic Mapper, shows reflectance from land and water for the color red only. This red band is good for detecting suspended sediments in the water, which appear whitish, and chlorophyll, which looks black because it absorbs red light. You can see a lot of sediment on the sides of the bay where the water is shallow and wind and tidal currents keep particles in suspension. In the upper bay, the very bright waters denote the turbidity maximum—the area of most extreme suspended sediment concentration. These waters are the muddiest in the estuary. Also visible are plumes of brighter water coming out of the mouth of the Delaware Bay and from some of the major inlets up and down the coast. The light region at the right edge of the image is not a sediment signal, but "sun glint"—the sun's reflection on the waves. If you look closely at this region, you can also see wave fronts and ship wakes. This is a high-quality satellite image because it shows little atmospheric interference (haze, clouds) and it is interpretable in this raw form, without atmospheric correction. It was purchased from EOSAT for University of Delaware Sea Grant research.*

estimate a marsh's productivity. The technique requires ten times less time and costs five times less than the traditional harvesting method (see photo, page 6).

Currently, the University of Delaware Sea Grant College Program is sponsoring research that aims to determine the Delaware Estuary's susceptibility to pollution or other environmental degradation. Just as a physician can determine a patient's susceptibility to certain diseases from that patient's lifestyle and medical history, Sea Grant researchers are using remote sensing to monitor the estuary's basic features to determine how prone it is to environmental maladies.

These scientists have built up an impressive data bank that is being used to develop and verify a series of spectral signatures, or "tags," that scientists can assign to distinct water masses within the estuary, such as areas of high turbidity (or muddiness) or of varying degrees of algae concentration.

The reflected and/or emitted energy that remote sensing instruments detect can be related to water properties, surface roughness, and dissolved or suspended substances in the water column. But to extract even more information from remote sensing data, scientists must come up with mathematical relationships between the water parameters of interest and the detected signal—these relationships are called "algorithms." The algorithms then must be tested and improved for specific applications. Through the development of algorithms that are verified by "ground-truth" ship data, and by repeatedly analyzing satellite images, scientists may be able to determine trends in estuarine properties such as suspended sediments, chlorophyll, salinity, water temperature, and others.

For example, it's now possible to estimate the concentrations of suspended sediments and of chlorophyll-bearing phytoplankton in the water by comparing the brightness signals in two different bands of a satellite sensor (i.e., the red and near-infrared bands on TM, MSS, or AVHRR). The algorithm developed by Stumpf and Tyler (1988) depends on the specific interaction of sunlight with the suspended sediments and the phytoplankton. Basically, particles in the water tend to scatter (reflect) the light back toward the water's surface in all wavelengths (all bands) more or less equally; chlorophyll-a and the other optically important plant pigments instead absorb light of certain wavelengths to produce energy for the plant (photosynthesis). So in some bands, high concentrations of chlorophyll-a will tend to reduce the reflectance (brightness of image) while sediments will tend to increase the reflectance. By comparing two or more bands, scientists can discriminate between the effects and assign an estimated value of concentration to each pixel's brightness.

Once "units" of water in an estuary are identified according to their biochemical information through remote sensing, and algorithms have been developed, the technique eventually may be applied to the study of an estuary's dynamics, or the forces that make it work, such as river flow and tidal currents. Theoretically, scientists should be able to track distinct water masses through a sequence of satellite images and therefore gather information on the surface circulation in both the estuary and the adjacent coastal zone. These tracking exercises could be performed for different time scales ranging from a few days to months, years, and decades, and thus provide an invaluable method of monitoring the estuary's health.

Satellite and aircraft imagery could also provide quick and accurate mapping of areas affected by oil spills, sewage, or industrial dumping. Sudden large inputs of pollutants are easily distinguishable in remote sensing imagery both from surface effects (e.g., oil spills create large slicks of very smooth water surface, and sewage is often associated with large amounts of floating debris) and reflected light. Small oil spills in the lower bay were identified and tracked by one of this report's authors in the late 1970s by

Using Remote Sensing to Assess Salt-Marsh Health. *Greatly resembling a flour sifter with a lens, the hand-held radiometer is a remote sensor that measures the light reflected off the leaves of marsh plants. It works in two bands: one visible (red) band, which is absorbed by vegetation, and one near-infrared band, which is reflected by vegetation. The difference between these two readings is divided by their sum to arrive at an estimate of the marsh's health. This device makes assessing salt-marsh health much easier and less costly than the traditional method.*

using a combination of remote sensing imagery (MSS) and hydrographic data (Klemas, 1980). In another application, drift and dispersal of several acid-waste plumes off the coast of New Jersey were monitored using MSS imagery and current-tracking drogues with a high degree of success (Klemas and Philpot, 1981). It's also possible to monitor the continuing effects of such spills on the estuary from comparisons of "before and after" imagery to assess the time required to return to normal conditions.

Once the tags and models for estuarine processes have been defined and verified for normal conditions, researchers will be able to detect changes in these processes through the change in the water mass's optical signature and determine their impact on the estuary's health. The next step then will be to use available ecological knowledge and predict the effect of different scenarios on finfish and shellfish populations and on estuarine water quality for a wide variety of human uses.

Advantages and Disadvantages of Remote Sensing

As with any technique, remote sensing has its advantages and disadvantages. The basic advantages of using satellite or aircraft remote sensing data for observing land, estuaries, coastal regions, and oceans are that each image represents essentially instantaneous observations of a large area, and it's possible to perform repeated observations of the same area at regular intervals. Another important plus is the cost of obtaining data. The cost varies with the particular product desired (photograph, digital image on magnetic tape, videotape, etc.) and the satellite used, but in most studies of large areas, remote sensing turns out to be more economical than traditional data surveys, which require a ship, the ship's crew, a number of sophisticated instruments, and scientists and their students to deploy the instruments and collect the data.

However, remote sensing does have several disadvantages. The basic disadvantage is that the data obtained by this technique is only "skin deep" for many applications. For example, due to the nature of remote sensing of light rays, the signal that satellite sensors receive is either reflected by the surface of the water or it emanates from a generally narrow volume of water just under the surface. Thus, assumptions must be made about the relationship between the remote sensing signal and the actual conditions in the water column, although in the majority of cases, such assumptions are later proven correct by the use of shipboard measurements.

Another frustrating problem is cloud interference. Visible and invisible (or infrared) light cannot penetrate clouds. In fact, their signals are often distorted by atmospheric haze and water vapor even under minimal cloud-cover. Recently, scientists have made major progress in correcting data distorted by haze and minimal cloud-cover and further progress will undoubtedly be made; however, the problem of solid cloud-cover seems to be insurmountable. Thus, at least for the time being, remote sensing monitoring of estuaries in the visible and infrared parts of the spectrum is confined to clear-weather days.

Remote sensing problems encountered in estuaries come down to concentrations of particles—either sediments, algae, or detritus (decaying plant and other organic material). These particles are much higher within estuaries than they are in the open ocean. Therefore, when instruments that were specifically developed for ocean observation are used to study estuaries, the remote sensors often become saturated (the resulting image looks too bright to be of any use), making it impossible to detect local changes in concentration. Additionally, because the variety of different particles and dissolved substances is higher in estuaries than in the open ocean, a finer spectral resolution in the visible range is needed for differentiating between all the optically important water constituents.

However, scientists are working to overcome these disadvantages by developing compensations for the technique's inadequacies and by developing more sophisticated sensors that can detect small changes in light reflected from nutrient- and often sediment-rich estuaries.

According to a recent NASA Advisory Council report, more satellites with specialized sensors capable of detecting a greater range of the electromagnetic spectrum are being planned now by the United States, in cooperation with other industrialized nations, and are targeted to be put into orbit in the next decade and beyond. Designed by engineers and scientists from many universities and government institutions, these future sensors are expected to reflect the great advances made in remote sensing in the last two decades. Many of these changes have resulted from a developing interest in remote sensing data applications among oceanographers, as well as from a greater popular awareness of the potential of this technique in land, ocean, and coastal resource management.

Management Applications

The ultimate goal of remote sensing research is to provide resource managers with a useful tool to monitor ecosystems such as estuaries and thus make better informed decisions about their use and conservation. For example, in estuaries, relationships between remote sensing's optical signal and the amount and type of photosynthetic algae in the water are of great importance in estimating the primary productivity of an area, which, in turn, refers to the potential of that area to support schools of finfish, beds of shellfish, and other aquatic life.

Fishermen need accurate forecasts of the location of good fishing waters. And fisheries managers need to monitor the water quality over shellfish beds to decide whether it's safe to allow clammers and other fishermen to collect clams, mussels, and oysters from those beds. These same shellfish beds are sensitive to highly turbid water conditions since shellfish cease feeding when the amount of suspended sediment is too great for them to filter out food particles efficiently. Remote sensing could aid both groups as well as contribute to the safeguarding of shellfish consumers in the process.

Reliable information on the amount of sediment in suspension gathered on a timely basis through remote sensing, together with forecasts of tendencies for sediment movement, would be a welcome tool for engineers, port authority managers, and ship pilots who are all affected by sedimentation and shoaling. In winter, reliable information about ice cover and ice floe movement in bays and estuaries would be invaluable in maintaining open shipping lanes and in protecting ships traveling to and from busy ports.

Ancillary information that is routinely gathered by remote sensors and used by land resource managers (forestry, urban planning, agriculture) would also be meaningful for estuarine monitoring and management. Land development, forest coverage in the uplands, and areal extent and health of wetlands rimming the estuary are all important parameters contributing to the state of the estuary. For example, forest coverage in the uplands affects the amount of runoff and the chemical composition of the fresh water that reaches the estuary. As forests are replaced by agricultural land or commercial and residential developments, the amount of runoff and the concentrations of undesirable chemicals, such as in pesticides, fertilizers, and treated sewage effluent, increase. This, in turn, leads to an imbalance in the ecology of the estuary, for while increased runoff and pollutants may fuel primary production or the growth of algae in the surface layer of the estuary, when this excessive plant life cannot be consumed fast enough by estuarine organisms, it sinks to the bottom and begins decomposing, consequently depleting oxygen in the bottom waters.

Measuring Light Intensity Near the Surface of the Delaware Estuary. *Chuck Bostater, a researcher at the University of Delaware's College of Marine Studies, prepares to deploy the Licor 1800 UW Radiometer. This instrument scans the light intensity at certain depths in the Delaware Estuary. Although light is severely limited within only a few feet of the estuary's surface, these remote sensing measurements are valuable in defining turbidity, or suspended sediment concentration, for specific wavelengths and depths.*

Conclusions

For scientists, remote sensing is a valuable tool for the study of an estuary—from its dynamics to the wetlands that border it. The technique's availability and the possibility of integrating all (or part) of its data into an easily accessible data system further improves remote sensing's potential as a tool for resource managers as well.

A geographic information system (GIS) is a structured framework for organizing and displaying large quantities of remote sensing and other data in map form. In this system, quantitative values can be color coded for display in map form, or they can be retrieved in table form. Several data sets also may be displayed at once according to the parameters of interest.

The GIS system currently is in use at many locations throughout the United States. Recently, for example, the Maryland Department of Natural Resources contracted Salisbury State University to develop such a system for use in managing the state's wetlands (see Lade, 1989). The system reportedly is easy to use and is applicable not only to wetlands management concerns but to a broad range of resource management tasks. The system allows resource managers to explore the data base of map and digital products, photography, vectorized plots, text, and tabular data quickly and productively.

With a GIS system at their fingertips, and a reliable set of interpreted remote sensing images, resource managers in Delaware, New Jersey, and Pennsylvania could track key water properties in the Delaware Estuary as these components change with time and thus more accurately predict the effects of future changes, resulting in improved decision making. Such a comprehensive retrieval system based on remote sensing would undoubtedly assist managers here and throughout the United States in reaching informed and timely decisions for the sake of those resources on which we all depend—our estuaries.

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