Remote Sensing, a Tool for Managing the Marine Environment: Eight Case Studies

Gregory Behie and Peter Cornillon

Ocean Engineering · NOAA / Sea Grant
University of Rhode Island Marine Technical Report 77

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On the cover is a Coastal Zone Color Scanner (CZCS) image obtained from the NIMBUS 7 spacecraft. Three different wave-length bands in the blue to green portion of the spectrum have been used to enhance the image, a different primary color assigned to each. The choice of colors was quite arbitrary, since their function was merely to clarify various oceanographic features. Notice Georges Bank cutting across the bottom of the Gulf of Maine, Cape Cod to the left (west), and Nova Scotia to the northeast. Notice also the detailed patterns that cover much of the Gulf of Maine.

Contents

Acknowledgments

This publication was made possible by the interested and helpful participation of a number of people to whom the authors are deeply indebted. In particular, we would like to express our appreciation to Elisabeth Keiffer for her many helpful suggestions and editorial contributions; to Vicki Desjardins and Larry Pearce, of the URI Publications Office, for the final editing and the design and layout; and to Donna Gardiner for typing the many drafts of each section and Joan Fink for typing the final draft.

Finally, we would like to express our very special thanks to Sara Callaghan for her encouragement, organization, and attention to detail which has made this a piece of work of which we are proud.

Computer enhancement of an image from the Synthetic Aperture Radar (SAR) aboard the now inactive SEASAT-1 satellite, showing Nantucket Island and a portion of Nantucket Shoals to the southeast. (Northerly direction is toward the upper left-hand corner.) This image has been processed to a resolution of approximately 25 meters. The differing intensities seen in the water result from different degrees of surface roughness. The brighter bands to the east and southeast of Nantucket very possibly result from the increased steepness of surface waves, shoaling as they move over the shallow sand ridges in that region. *Photo prepared by NASA Jet Propulsion Laboratory.*

Preface

Weather forecasting and land resource management have made dramatic strides in recent years due to satellite-derived data. The global view of weather patterns that satellite imagery has made possible since 1960, coupled with meteorological data from weather stations, has revolutionized the way man perceives atmospheric phenomena.

Earth resource satellites in orbit since 1972 are providing a rich view of the earth's surface. Land-use mapping of large and often impenetrable regions has become routine. Continued research and an increase in satellites devoted to this task promise an even greater yield of invaluable information.

While remote sensing is now a standard tool for monitoring weather and terrestrial areas, the use of satellite data for better understanding and management of the oceans is relatively new.

The ocean offers a far greater challenge to satellite technology than resource management or weather forecasting ever did. Because ocean-surface features change quickly, cloud cover can obscure the ocean surface during one pass of a satellite and cause data for that time period to be lost. On land, in contrast, little will have changed by the next day or even a week or two later.

A second difficulty met in remote sensing of the ocean is the very low relative contrast of light reflected from it. The range of visible light (red, green, blue, etc.) reflected from land is about ten times greater than that reflected from the ocean. The range of thermal contrast in the ocean is also very small. Temperature variations are hardly ever greater than 10°C between the Gulf Stream and surrounding waters, while radiation emitted by clouds in the earth's atmosphere can vary many tens of degrees Centigrade from the center of a cloud to its edge, or from cloud to cloud.

Because of these and other difficulties, little attention was paid to remote sensing of the ocean until 1978. That year, a landmark, the first satellites to carry instrumentation for this purpose were launched. Results of research based on satellite-derived ocean-sensing data are just now beginning to appear, and they offer promise of greater understanding of the ocean.

In this publication, the applications of remote sensing described are not confined to satellite-derived imagery. The common link between all eight applications, which involved several remote-sensing techniques, is the usefulness of remote sensing in making needed management decisions. Similar projects in the future will definitely use satellites in some instances, while in others aircraft may remain the best tool.

The purpose in presenting these case studies is to suggest the variety of ways in which remote sensing can be useful in studying the coastal and marine environment. We hope the diversity of applications described, of data sources and platforms used (satellite/aircraft), as well as the high-quality photographs that resulted, may identify for the reader potential applications in his or her own area of interest.

Mapping Submerged Aquatic Vegetation in Chesapeake Bay

It is becoming increasingly important to measure the submerged aquatic vegetation (SAV) in the wetlands of Chesapeake Bay, since SAV contributes to the Chesapeake Bay ecosystem in a number of important ways. It is the principal food of waterfowl and some herbivorous fish species. It provides nursery areas and shelter for many species of fish and crabs. It is the habitat of species of copepods and mollusks, which are an important food of waterfowl and fish, and is a primary producer of the vegetative biomass that contributes nearly all the aboveground crop to the detrital food chain. Finally, in addition to these ecosystem-related contributions, SAV reduces shoreline erosion through its wave-damping action.

The first comprehensive survey of SAV in Chesapeake Bay was begun in 1958 by the U.S. Fish and Wildlife Service's Migratory Bird Habitat Research Laboratory (MBHRL). The relative abundance of major SAV species was monitored by boat at a number of randomly selected sampling stations. However, because these stations covered a very small fraction of the area, the accuracy of the resulting percent-cover estimates was poor. Between 1967 and 1969, V. D. Stotts developed a new system for determining variations in distribution and abundance of SAV from his boat sample stations, but because of the limited number of stations, this system, like the earlier MBHRL system, failed to accurately quantify the SAV population. G. H. Fenwick directed the most exhaustive shoreline transect survey of SAV in the eastern Chesapeake Bay area in 1976. A total of 2,192 stations was sampled, yielding a significantly higher-percent estimate of vegetated areas than another Stotts survey of the same area done earlier in the year. The variability in these results indicates that sample size, as well as the time of the survey, may be important factors affecting the results. Although the Fenwick survey produced much useful information, the expense, length of time required to amass the data, and the errors in the percent-vegetated estimates proved that the methodology has only marginal utility.

These weaknesses, along with the need for more accurate and frequent surveys to determine annual trends in the SAV distribution, led to funding from the Environmental Protection Agency through the American University of a proposal by Earth Satellite Corporation (Earthsat) and Aerial Ecological Analysts (AeroEco) to try a totally different approach. In 1978, Earthsat and AeroEco undertook a distribution inventory (extent and type of SAV) for the Maryland waters of Chesapeake Bay in a single growing season. Their approach was unique—remote-sensing aerial photography coupled with a seaplane sampling program.

Aerial photos were taken by the AeroEco photo aircraft of Maryland waters covered by 77 U.S. Geological Survey quad maps. The aircraft used was a Cessna 180H STOL, equipped with a Wild aerial metric mapping camera. The nominal scale of aerial photography was chosen to match the 1:24,000 scale of the

U.S.G.S. quads (Figure 1), requiring a flying height of 12,000 feet. Scale-adjustment equipment was not required, and any minor scale differences were compensated for by "floating" the photo beneath the quad to obtain a "best fit."

The film chosen for the survey, after research and careful analysis by AeroEco, was a black-and-white negative aerial film with a speed in the medium to high range. The peak sensitivity of the film was in the red, allowing maximum penetration of the water column with minimum effect from atmospheric haze. Furthermore, photographs were taken with a yellow filter to screen out blue light.

The limiting factor in the photographic process was found to be the coincidence of proper photographic conditions. Specifications include ± 1½ hours from low tide, no cloud cover, minimum turbidity, low wind velocity, and a 20° to 45° sun angle to minimize sun glitter. When these conditions were not met, the day was lost and no photographs were taken. On other days, the length of time during which photographs could be taken was greatly limited.

A key factor of the program was the close coupling between the remote-sensing segment of the mission and the ground truthing. A Piper Supercub seaplane was used to gather ground-truth data. The field team, which consisted of a coastal ecologist/pilot and a biologist/pilot, visited areas in which aerial photos indicated there was a need to clarify species association. Sample points of information were gathered rapidly and inexpensively due to the mobility and versatility of the seaplane, with four extrapolative techniques incorporating direct contact and species identification, surface observations at low taxi speeds, random bottom samples, and low-altitude reconnaissance, an example of which is seen in Figure 2. The field team was also the photo interpretation team. This led to the greatest efficiency possible in the quantification of SAV distribution and species.

The 3,825-square-mile inventory was completed in seven months at a cost of less than $40 per square mile (about 6¢/acre). Remote sensing proved to be not only cheaper than previous survey methods but also

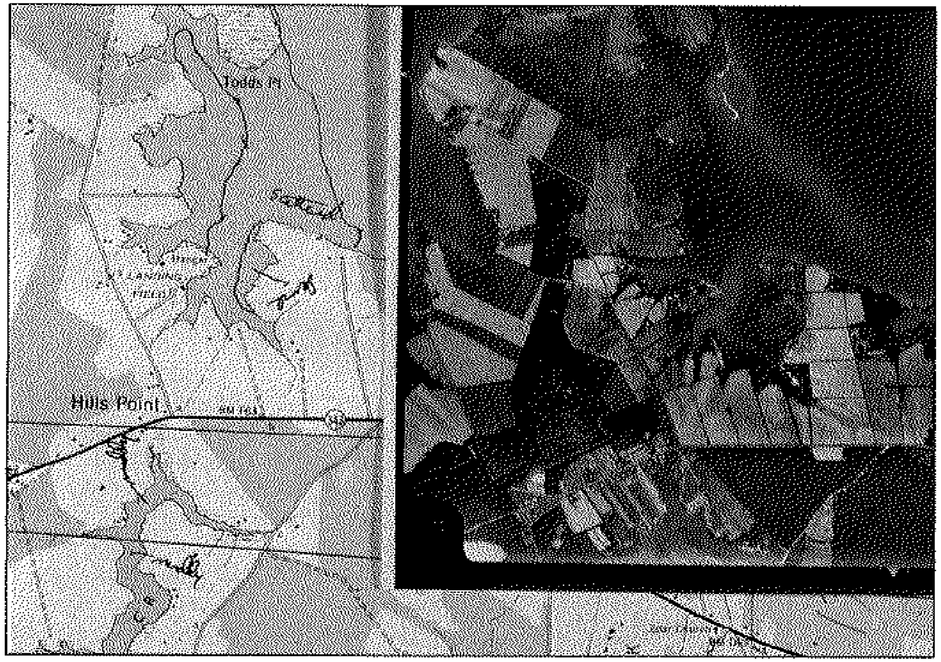

Figure 1. This figure presents the comparison of one U.S.G.S. quad map with the corresponding aerial photo. In the 1978 inventory, 77 of these quad maps were used. The dark areas of the aerial photo in the coves north of Hills Point and in the eastern edge of the cove east of the landing field are those areas where SAV distribution is the densest. The coastal zone south of Todds Point is a mixture of dense and sparsely populated SAV. The vegetated areas were visited by a team of scientists who determined the species distribution. *Photo courtesy of Robert T. Macomber.*

Figure 2. Example of a coastal zone area which required closer investigation upon examination of the initial overflight survey flown at 12,000 feet. Scientists visited the area to obtain an accurate species determination, which then facilitated other species identifications in other aerial photos. It is obvious that one can determine the actual amount of SAV coverage in the shallow coastal waters more accurately from above than from a boat. *Photo courtesy of Robert T. Macomber.*

Figure 3. An example of how the U.S.G.S. quad map mylar overlay is used to display SAV species information and distribution. The map legend of species identification represents the scientific names for the SAV present. Pc, Pr, and Rm (common names: sago pondweed, redhead grass, and widgeon grass, respectively) are SAV types which are preferred as food by many of the waterfowl in the area, while Ms (eurasian water milfoil) is rejected. Knowing where the food areas are can affect decisions made about maintaining the environment in these locations. Areas with many species associations are explained as having different percent cover throughout the site of each type of SAV. *Photo courtesy of Robert T. Macomber.*

more accurate in estimating distribution, percent cover, and species association. In addition, the 1978 inventory provided guidance in selecting areas of the bay whose importance warranted more detailed management-level maps.

The inventory also confirmed that maximum distribution of all SAV species does not occur at the same time. There are two distinct periods within the growing season when maximum distribution of certain species occurs. For accurate inventorying, it is important to observe SAV during periods of maximum distribution. Consequently, it was necessary to make overflights twice, in May and September. The seaplane ground truth was vital to the identification of those peak periods.

The output of the 1978 distribution inventory included mylar quad map overlays with SAV distribution delineations and species information and locations (Figure 3). A number of uses for these data sheets are now being recognized. The EPA and the Fish and Wildlife Service have found the base map series useful for such things as waterfowl count versus SAV bed location correlation. Once annual updating and more extensive mapping is conducted, the versatility of these maps will be greatly increased.

The efficiency and accuracy of the aerial methods provided impetus for a similar inventory of SAV in the coastal waters of New Jersey, as part of that state's coastal zone management program, and these methods are likely to extend to other parts of the United States and abroad.

Additional information is available from:

Robert T. Macomber, President
AeroEco
2303 Archdale Road
Reston, Virginia 22091

More detailed articles dealing with the study are:

The Chesapeake Bay Foundation. 1979. The Chesapeake Bay SAV Management Atlas. Management Level Maps of Distribution, Per Cent Cover, and Species Association of Submerged Aquatic Plants in Selected Watersheds of Chesapeake Bay, Maryland. Unpublished. For copies, contact Robert T. Macomber.

Macomber, R. T. 1979. Aerial Photography and Seaplane Reconnaissance to Produce the First Total Distribution Inventory of Submerged Aquatic Vegetation, Chesapeake Bay, Maryland. Proceedings of the First U.S. North Atlantic Regional Workshop, in *Remote Sensing in the Coastal and Marine Environment*, James B. Zeitzeff et al., eds., University of Rhode Island and Woods Hole Oceanographic Institution, pp. 242-248.

References

Fenwick, G. H. 1977. Survey of Submerged Vascular Vegetation of Eastern Bay and Adjacent Tributaries of the Chesapeake Bay, Maryland, June through September, 1976. Unpublished.

Stotts, V. D. 1970. Survey of Estuarine Submerged Vegetation. Maryland Fish and Wildlife Administration, Maryland Pittman-Robertson, W-45-2. 7 pages.

Remote Sensing of an Inland Wetland

Passage of Connecticut's Inland Wetlands and Water Courses Act in 1972 has required delineation and ongoing regulation of these vital natural areas. Wetlands are important as integral parts of the hydrologic cycle, as significant habitats for a diverse collection of plants and animals, and for aesthetic reasons. The first step in equitable regulation of wetlands is to gain accurate information on their location.

In 1975, Drs. William Kennard and Michael Lefor, scientists at the University of Connecticut, embarked on a research effort aimed at testing the practicability of various wetland definitions. This work has developed into a many-phased program of detection and delineation of natural resource features via remote-sensing techniques. Aerial photographs reveal the ground conditions at the time of the photographs. Each species of plant or other ground feature reflects light differently. Wave lengths of light not visible to the human eye are also absorbed or reflected. The totality of the wave lengths reflected and absorbed is called the "spectral signature" of the object. Contrasts between objects with different signatures are enhanced on color infrared film. Figure 1, a color photograph, is an oblique view of a pond and associated wetlands near a highway. Figure 2 shows nearly the same area in a color infrared, which detects the amount of infrared radiation emitted by the earth below.

The film type which holds the most promise for wetlands detection and delineation is false-color infrared (FCIR). The emulsion of FCIR film is sensitive to both normal colors of light and light at lower (infrared) frequencies invisible to the naked eye. Water and wet soils absorb heavily in the infrared portion of the spectrum. Therefore, wet areas appear darker than their surroundings on FCIR photos, since little infrared is being emitted.

Imagery and digitized information from satellites can be used effectively for synoptic studies of wetlands. Results of such studies can be correlated with aerial photographs taken at various altitudes.

In the research undertaken by the University of Connecticut, the town of Mansfield, Connecticut, which is approximately 50 square miles in area, was selected for detailed study, since its freshwater wetlands are representative of such areas throughout Connecticut and southern New England. Maps of inland wetlands in Mansfield were prepared through interpretation of aerial photographs taken in midspring, when deciduous trees are leafless, and again in early autumn, when such species are in full leaf. The appearance on color infrared film of vegetation photographed at various times of the year can be strikingly different. Figures 1 and 2 are examples of imagery obtained late in the season.

During the same period as the aerial survey, an intensive field study was completed of the physical and biological characteristics of the wetland/upland interface on selected sites in Mansfield. This study has indicated the plant species and soil

Figure 1. View of a pond and associated wetlands near a highway in Mansfield, Connecticut, from an altitude of about 700 feet. It is not clear exactly where the wet areas lie, although the presence of water is rather obvious. *Photo courtesy of William Kennard.*

parameters that combine to demarcate where wetland ends and upland begins. These results for forested wetlands (the most difficult to delineate on aerial photographs) were correlated with the appearance of those features on the imagery.

It is not enough, however, merely to draw a line around a dark area on a FCIR photo and say "Here is a wetland." Although "year-round wet" wetlands are clearly visible on FCIR photos, the "gray areas" of seasonally wet soils may not show up clearly to the human eye. Work is underway on a sophisticated computer-based image-processing system which will discriminate many more variations in tone and texture in the photographic image than is possible for the human eye. Computer programs now being developed at the University of Connecticut have given classifications of image features for ten land-use classes which are more than 95 percent correct. A wetland map appears as a computer print-out giving the boundaries and wetland type, as well as the character of surrounding uplands.

The results of these studies have shown that inland wetlands are a

Figure 2. Nearly the same view as in Figure 1, except a false color infrared film has been used. Note that areas which are wet or moisture-saturated appear dark. These are areas which are absorbing infrared radiation, while trees are reflecting it. Note also that different species of tree can be identified by varying color signatures. *Photo courtesy of William Kennard.*

natural resource which can be analyzed quite readily by remote-sensing techniques. The maps made with these procedures have provided more detailed and accurate information about Connecticut's freshwater wetlands than had previously been available. These investigations have resulted in contributions to the science of remote sensing of natural features. This work is expected to lead to comprehensive land-use mapping via specialized imagery and computer-image analysis techniques. Such research is essential if the natural resources of Connecticut, and of the entire United States, are to be preserved and managed to the benefit of future generations.

Additional information is available from:

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College of Agriculture and Natural Resources
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University of Connecticut
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Remote Sensing of Coastal Pond Discharge

In order to meet projected power requirements of the next two decades in New England, the New England Power Company seriously considered constructing a pair of nuclear power plants in Charlestown, Rhode Island. In addition to the numerous engineering design considerations required for such an undertaking, a careful analysis of the potential environmental impacts was required. One of the more significant environmental concerns was the effect of the power plants' cooling system on adjacent and nearby ponds. This concern had to do both with an increase in the temperature of the ponds resulting from the power plants' warm-water discharge and with the entrainment into the power plant intakes of biological organisms (e.g., fish larvae) leaving the ponds.

In an attempt to determine the significance of these potential problems, the Yankee Atomic Electric Company, of Westborough, Massachusetts, employed Aero-Marine Survey, Inc., of Groton, Connecticut, to fly a series of thermal infrared surveys along the southern Rhode Island shoreline. Coincident with these overflights, Yankee Atomic and the Raytheon Company were to make in-situ measurements of the vertical temperature profile, wind time series, and current time series. These data were then to be integrated with the thermal infrared imagery to obtain a coherent, synoptic picture of the near-surface, near-shore circulation.

Aero-Marine Survey elected to fly a Cessna Skymaster II equipped with a Barnes thermal mapper along a single flight line at an altitude of 3,500 feet. The resolution of the thermal mapper from this altitude is approximately 2.5 meters (8.5 feet). The course selected ran from west to east approximately parallel to the southern Rhode Island coast, from Watch Hill to Point Judith.

Flights were scheduled for late afternoon on August 22, 1978, but, due to camera difficulties, only two flights were completed that day. The mission was repeated on August 23, 1978, with four good flights covering the tidal interval from maximum ebb to slack before flood, a period of about four hours.

The flights were scheduled to allow maximum heating of the ponds before they discharged into the ocean. This provided the most significant thermal contrast possible between the warm discharge plumes and the cooler offshore water. It must be noted that thermal imaging detects only the radiation emitted from the surface of the water, and, depending on the direction of the heat transfer, the surface water may be slightly warmer or cooler than the bulk of the underlying water. With these considerations in mind, the flights were planned for late afternoon and evening, when the sun angle was low or nonexistent. Accordingly, it was assumed that surface temperatures were indicative of the upper water layer as recorded by the in-situ temperature monitoring stations. Monitoring equipment was installed at the mouth of the Charlestown breachway and just offshore to measure ocean parameters. Ocean current and wind speed along with surface temperature data were recorded at all phases of the ebb tide. It was felt that the in-situ temperature stations could be used to calibrate the aerial images.

The imagery obtained from this aerial survey showed that plume movement from the coastal ponds is controlled mainly by tidal movement along the coastline. Flood tide flows toward the west and ebb tide flows toward the east. The synoptic currents observed with the radiometer for both August 22 and 23 were very similar, with a strong water movement parallel to the coastline and a small amount of offshore movement.

Figures 1 through 8 show the thermal images for the southern coast of Rhode Island, from Winnapaug Pond to Point Judith Pond. Figures 1 through 4 represent Flights A and B, which were flown on August 22, while Figures 5 through 8 represent Flights C, D, E, and F, which were flown on August 23. Flights C, D, E, and F are a complete ebb-tide sequence, beginning about two hours into ebb and continuing until the beginning of flood tide. Flights A and B cover only a portion of the ebb tide due to the camera difficulties mentioned earlier, and correspond approximately to the same tidal phase seen during Flights E and F.

For all the ponds observed, the difference in the discharge temperature is directly related to the flushing rate of the pond. The larger the flushing rate, the less the buildup of heat in the pond. For example, Ninigret Pond, seen in Figures 3 and 7, is large, is not very deep, and has a complex delta formation, all of which produce limited flushing, and hence a fairly substantial temperature differential with the ocean.

For Flight B in Figures 1 through 4 and Flight F in Figures 5 through 8, the tidal height in the ocean exceeded the tidal level in the ponds, and the coastal water started to flow back into the breachways. This can be seen in the aerial images by the darker (indicating colder) water in the breachway and by the detachment of the thermal plumes from the mouths of the breachways. In both flights, the thermal plumes are seen to be attached to the beach areas as the plumes drift to the west.

The results of this study show that the technique of aerial thermal survey can be used effectively to present a synoptic view of water movement into and out of coastal ponds. The technique is necessarily limited to times when a temperature difference exists between the ponds and adjacent ocean water. The photographs show that temperature gradients of less than 0.5°C are readily distinguished.

Accurate ground-truth stations are necessary to calibrate the survey and must be precisely clocked so that synoptic events can be established sequentially and any phase lag or lead determined.

If the discharge of several ponds is being monitored simultaneously, it is important to monitor continuously the temperature of at least one of the breachways to determine both the discharge temperature and the time history of the discharge. The thermal images can then be used to relate the unmonitored discharge plumes to the monitored discharge plume.

In future studies, spot measurements of the near-surface temperature made by boat within the thermal plume are recommended. These measurements would better define the actual surface temperature seen by the aerial thermal scanner and also the temperature gradient in the upper part of the water column. The scanner would be able to locate an offshore vessel taking measurements by a "hot spot," which could be generated by a contained flame on board.

Additional information is available from:

Michael Krabach
Yankee Atomic Electric Company
Environmental Sciences Group
25 Research Drive
Westborough, Massachusetts 01581

A more detailed report on the study is:

Krabach, Michael. 1978. Aerial Thermal Survey of the Southern Rhode Island Coastal Waters. The report is available from the Yankee Atomic Electric Company.

Figure 1. Thermal images of southern Rhode Island coast from Winnapaug Pond to Quonochontaug Pond. During Flight A, Block Island Sound was at about mean water level, near the end of the ebb-tide sequence. Water currents were almost slack, with the pond's thermal discharge nearly completed. This tidal phase corresponds to the one in Flight E (Figure 5), and the two images can be used for comparison. Flight B shows the very end of ebb tide, when the tidal height in the ocean exceeded the tidal level of the pond. Flight B was flown slightly before Flight F (Figure 5) in the tidal sequence.

Figure 2. Thermal images of southern Rhode Island coast from Quonochontaug Pond to Ninigret Pond. Flights A and B correspond in time to Flights A and B of Figure 1, except that the location is slightly farther to the east. Again, slack water dominates Flight A, with Flight B beginning to show effects of early flood. Colder water begins penetrating the breachway during Flight B, with the thermal plume drifting to the west. The tidal effect on the Rhode Island coastline is to transport water eastward during ebb tide and westward during flood tide. Transport, however, remains parallel with the shoreline.

Figure 1, Flight A

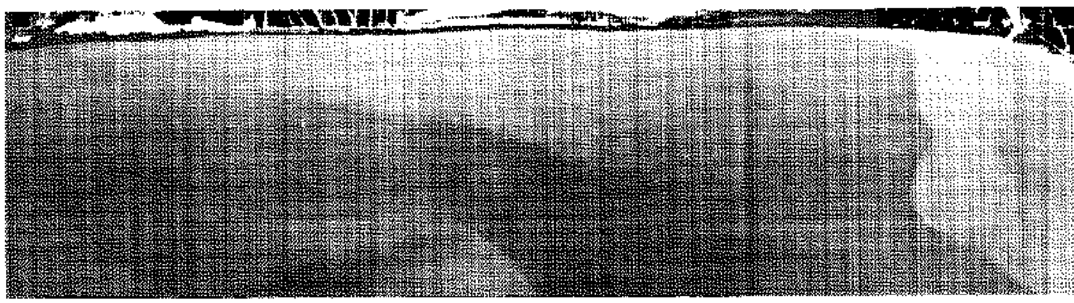


Figure 1, Flight B

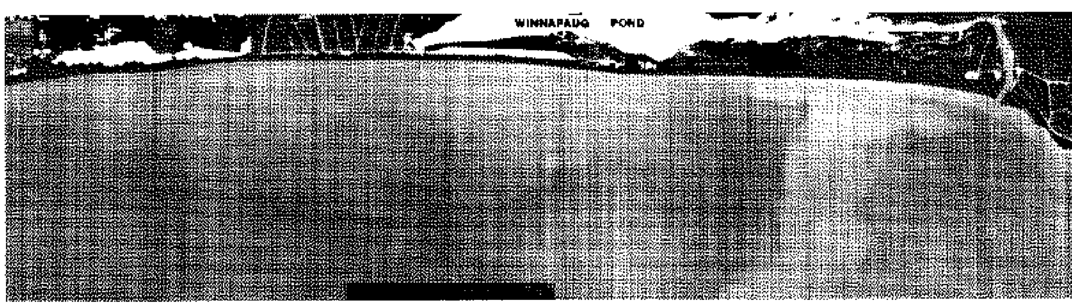


Figure 2, Flight A

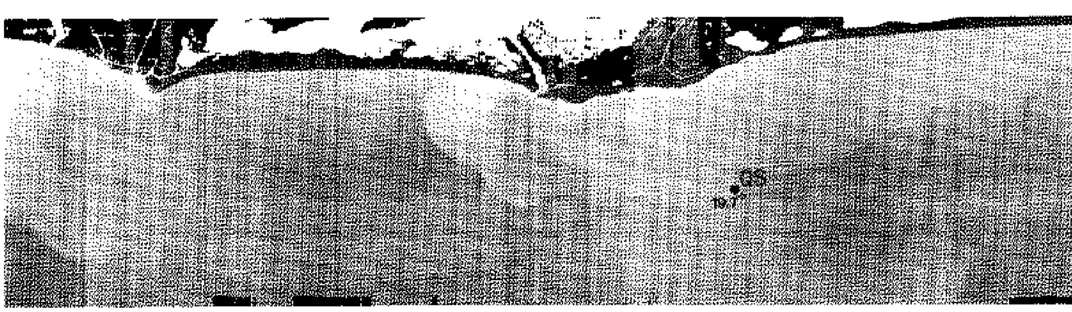


Figure 2, Flight B

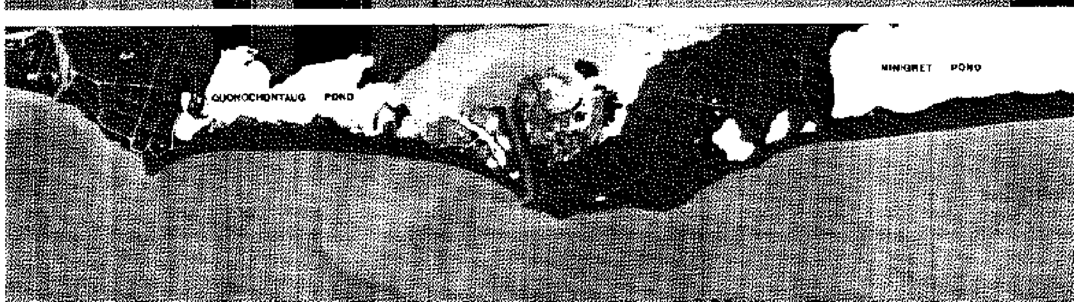


Figure 3. Thermal images of the southern Rhode Island coast from Ninigret Pond to Trustom Pond. Again, Flights A and B correspond to Flights A and B of Figures 1 and 2. During Flight A, Ninigret Pond was still discharging heated water, but the current meter at Point A was indicating slack water. Wind was out of the northwest at just over 5 mph. By Flight B, Ninigret Pond had stopped discharging, and offshore water enters the breachway as the beginning of flood tide sets in. The current meter at Point A indicates this situation in sensing a current direction to the west at 0.51 feet per second.

Figure 4. Thermal images of the southern Rhode Island coast from Trustom Pond to Point Judith Pond. Flights A and B correspond in time to Flights A and B of Figures 1, 2, and 3. Very little westward drift can be seen from the thermal plume of Point Judith Pond. This is due to the stone jetties which make up the Harbor of Refuge and prevent any real movement of a discharged thermal plume. The image taken during Flight B, however, does show the onset of the flood tide, with the cooler offshore water being transported up the mouth of the pond.

Figure 3, Flight A

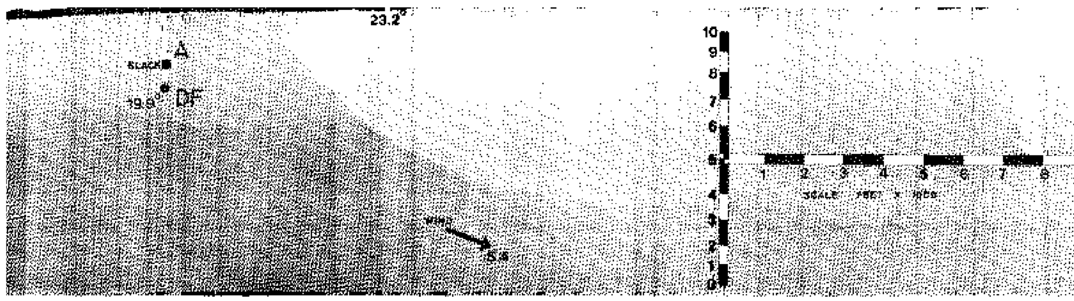


Figure 3, Flight B

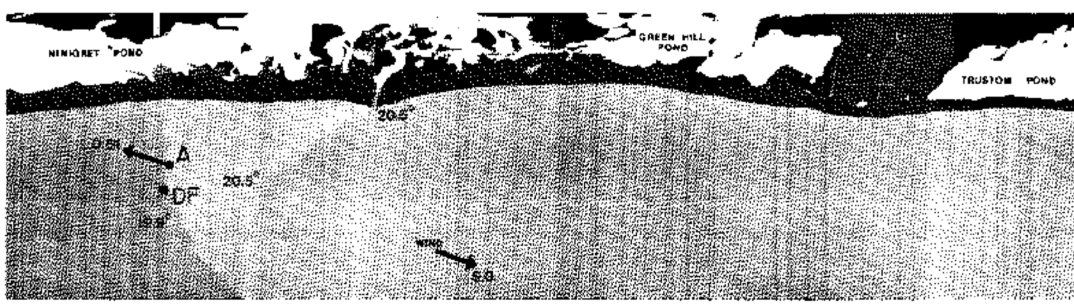


Figure 4, Flight A

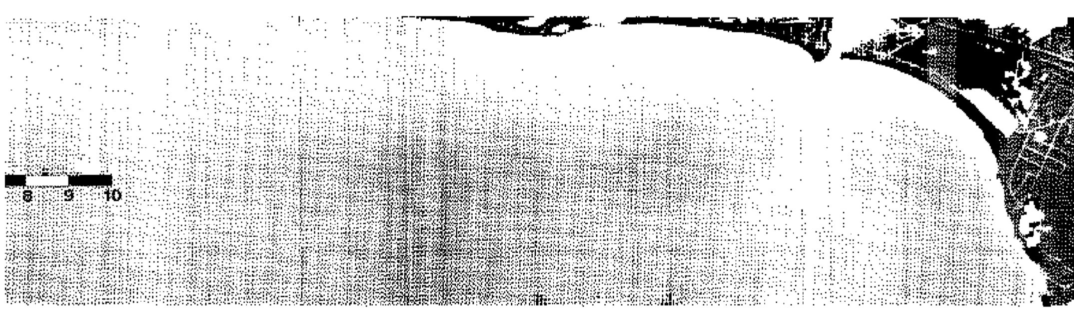


Figure 4, Flight B

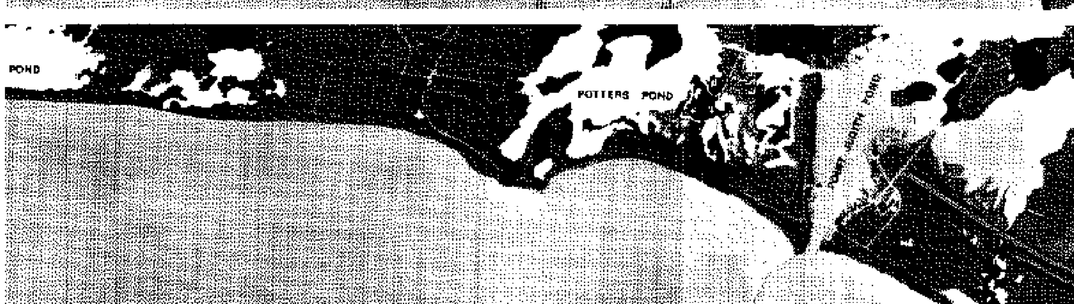


Figure 5. Flights C, D, E, and F show thermal images from Winnapaug Pond to Quonochontaug Pond of the Rhode Island coastline, the same location as in Figure 1 but one day later. This sequence of photos covers early ebb tide through the onset of flood tide. Flights A and B of Figures 1 through 4 correspond closely in time to Flights E and F of Figures 5 through 8. Flight C, which occurred at low tide, shows the pond's thermal plume discharging at its maximum velocity. The plume is displaced to the east, the direction in which the ebb tide flows. By Flights D and E, the tidal level was increasing and the coastal water velocity was decreasing. The thermal plume moves slightly farther offshore, but because the breachway discharge angle is more toward the west, the plume did not have the momentum to move much farther offshore. Flight F, at the end of ebb tide, shows water transport beginning to the west and offshore water entering the breachway, indicating that flood tide is beginning.

Figure 5, Flight C

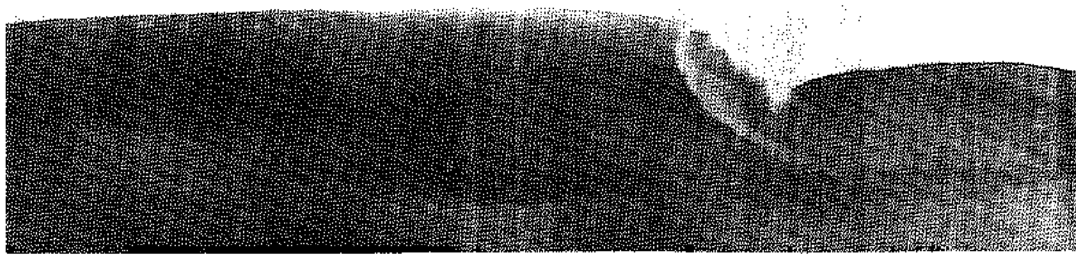


Figure 5, Flight D

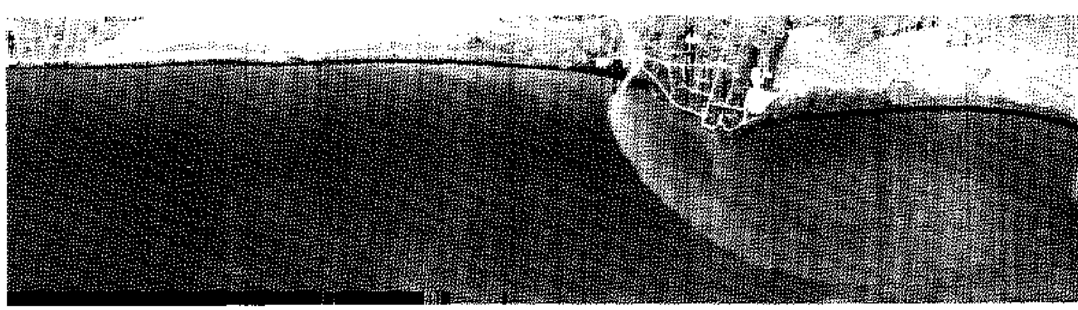


Figure 5, Flight E

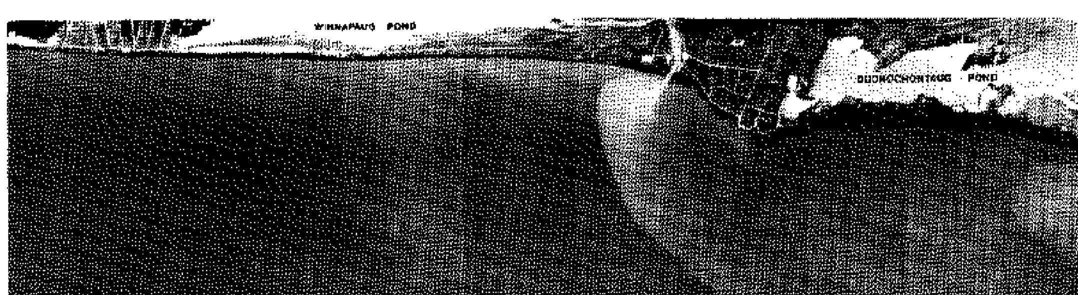


Figure 5, Flight F

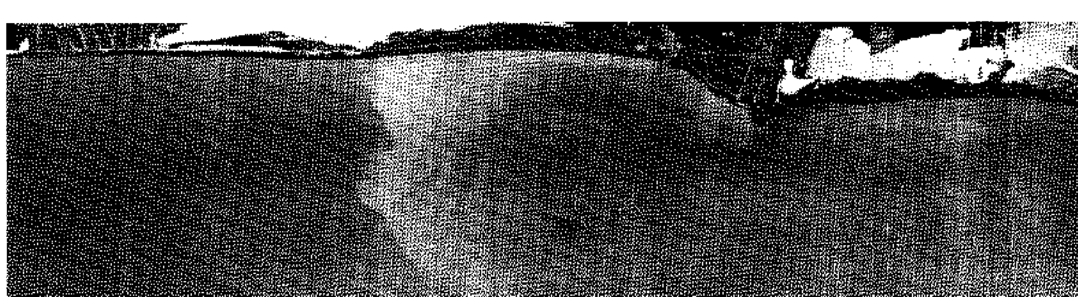


Figure 6. Flights C, D, E, and F show the coast from the Winnapaug breachway to Ninigret Pond, the same time sequence as in Figure 5 but with the location slightly farther east, the location in Figure 2 but one day later. This sequence shows the thermal plumes from both Winnapaug and Quonochontaug Ponds to be spreading slightly westward as the time sequence progresses. This reflects the slacking ebb tide. The discharge from Winnapaug Pond is seen to be slightly warmer than that from Quonochontaug, due mainly to the shallowness of Winnapaug Pond and a lesser flushing ability. Flight C shows current activity at low tide.

Figure 6, Flight C

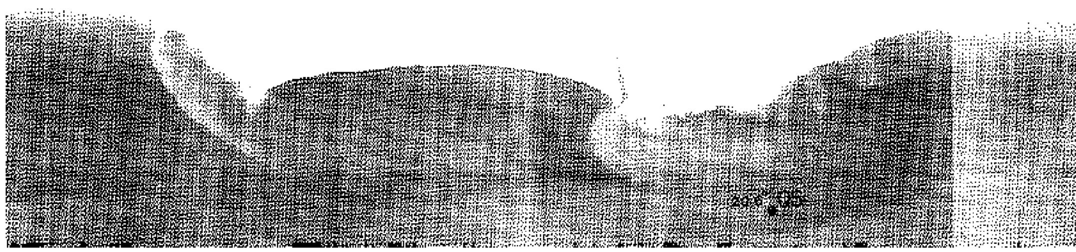


Figure 6, Flight D

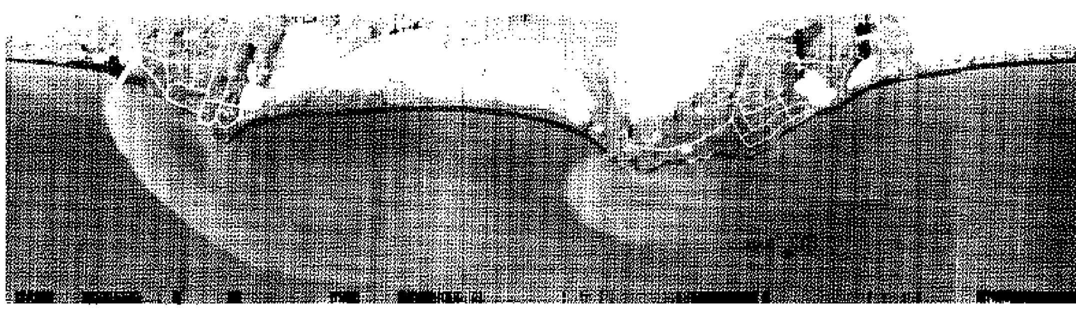


Figure 6, Flight E

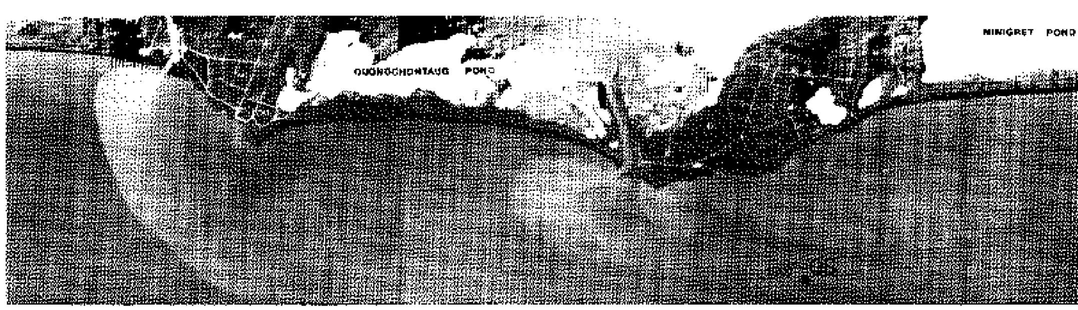


Figure 6, Flight F

Figure 7. Flights C, D, E, and F show the coast from Ninigret Pond to Trustom Pond, and describe the ebb-tide sequence from low tide to the onset of flood tide. Flight C shows the greatest eastward water transport, as seen by the current vectors obtained at monitoring Point A. Discharge from Ninigret Pond through the Charlestown breachway continues during Flight E and is similar to what is seen in Figure 3, Flight A. The thermal discharge observed in Flight E, below, appears to extend farther offshore than the comparable tidal sequence image of Flight A, Figure 3. This can be explained by the increased wind speed from one day to the next. The wind speed was greater on the 23rd than on the 22nd (9.0 mph vs. 5.4 mph), and the northwesterly direction of the wind has driven the discharge plume farther offshore. Comparable situations can be seen between the similar tidal sequence of Flights E and F below and Flights A and B of Figure 3. Temperatures and tidal current velocities and directions compare very closely on consecutive days.

Figure 7, Flight C

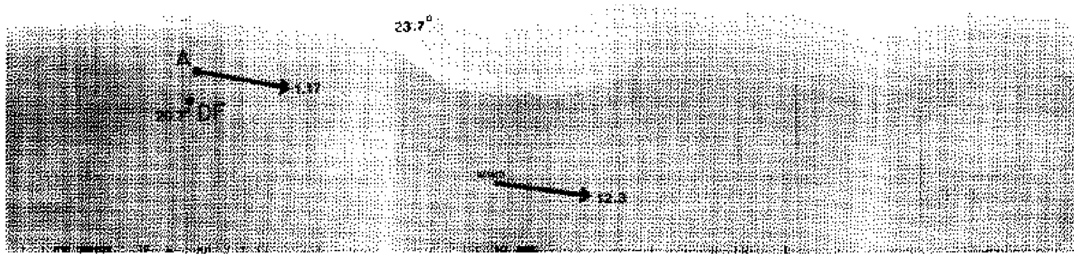


Figure 7, Flight D

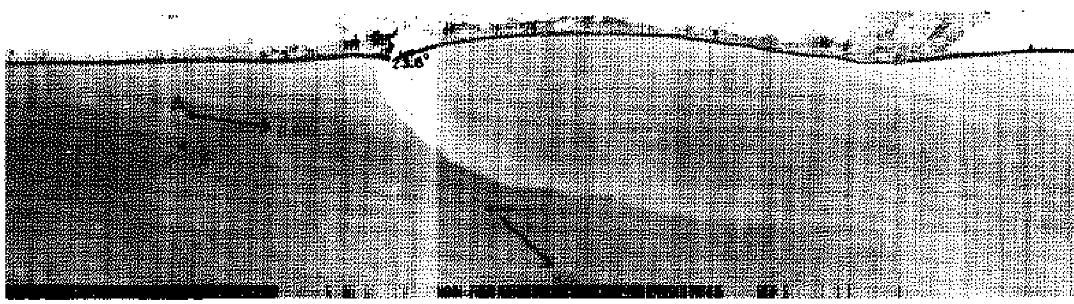


Figure 7, Flight E

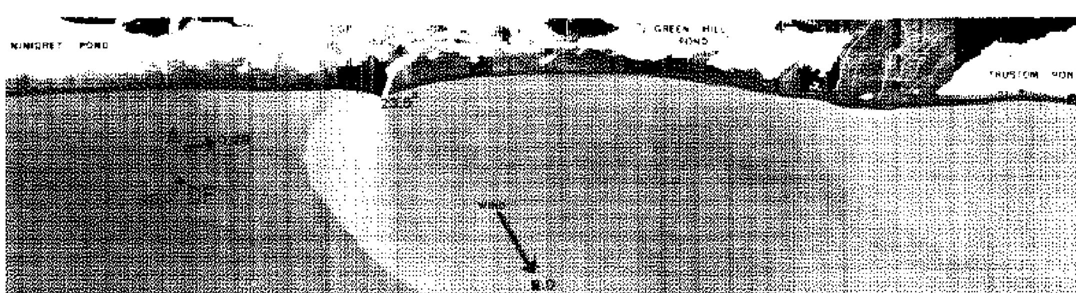


Figure 7, Flight F

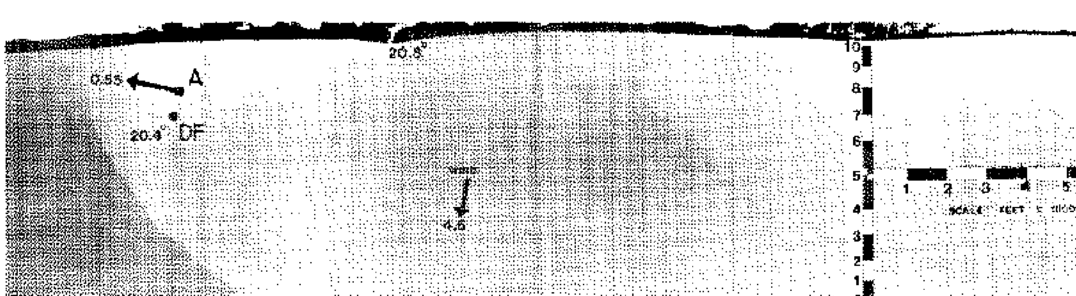


Figure 8. Flights C, D, E, and F show thermal images for the shoreline from Trustom Pond to Point Judith Pond. The location is the same as that shown in Figure 4, except one day later. From the sequence below, there appears to be little movement of the thermal plume discharge. This is due to the Harbor of Refuge, which shelters any discharge and prevents influence from coastal water currents.

Figure 8, Flight C

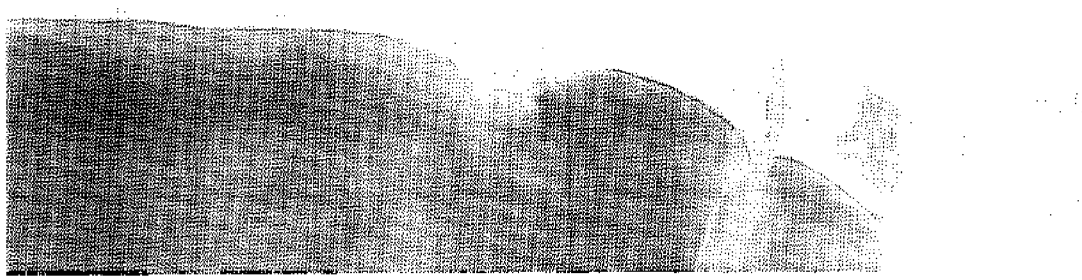


Figure 8, Flight D

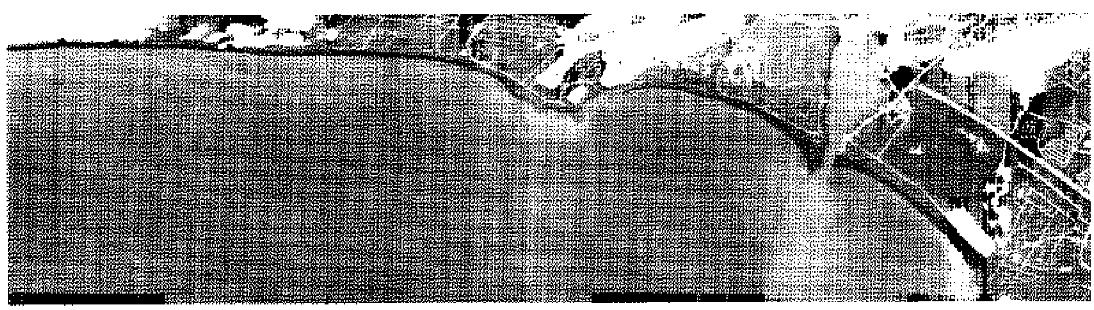


Figure 8, Flight E

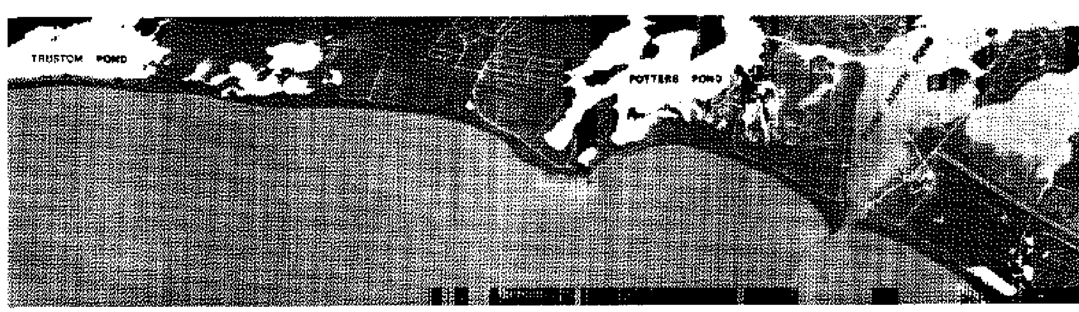
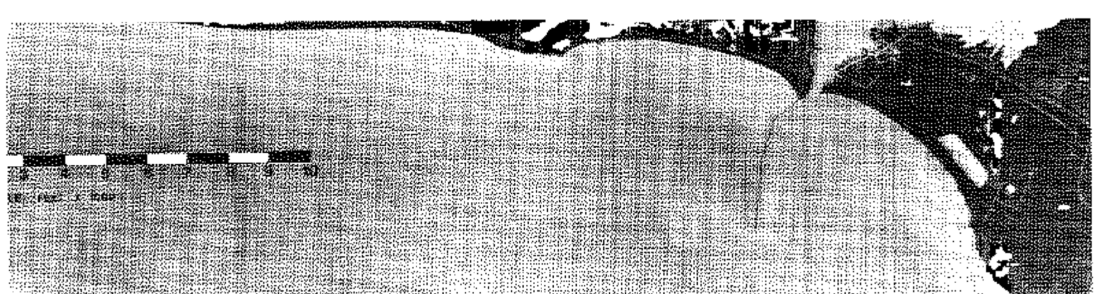


Figure 8, Flight F



Dye-Buoy Remote Sensing of Coastal Circulation for Outfall Siting

The Hampton Roads Sanitation District Commission (HRSDC) of Newport News, Virginia, is responsible for locating, designing, constructing, and operating sewage treatment facilities in the Hampton Roads region. HRSDC is upgrading and tripling the capacity of its sewage treatment plant on the James River, at the end of Newport News Point. HRSDC also plans a new sewage treatment plant on the opposite shore at Pig Point, to serve the city of Portsmouth and Nansemond County.

The help of the Virginia Institute of Marine Science (VIMS) was solicited to determine, with their combined aerial photography/dye-release technique, the best site among several proposed for the new outfall of the Newport News sewage treatment plant upgrading. VIMS was also asked to address any dangers that the proposed outfall site might have on the Virginia oyster industry, with the use of the same technique. The new sewage treatment plant at Newport News Point would be adjacent to the route of the proposed I-664 bridge/tunnel. There was concern that the bridge/tunnel would alter the flow of water in the channel, and dispersion patterns determined beforehand would no longer apply. The fear was that any change in dispersion rates could allow sewage waste to reach the Nansemond channel and the oyster beds that lie nearby. These beds produce virtually all the seed oysters of Chesapeake Bay.

The VIMS methodology allows the identification of small-scale surface and subsurface circulation patterns, which are important factors in outfall siting. Fronts and convergence zones of ocean circulation are generally neglected when small-area circulation dynamics are studied. This is a major drawback in studies within the Chesapeake Bay system, where tidal fronts are a regular and prominent feature. An attack on the dynamics of fronts and convergence zones can be made with remote sensing by the proper choice and placement of tracers. Small dye-emitting buoys have several advantages. They are resolvable in aerial imagery at a scale of up to 1:60,000 and have negligible wind drag. The buoys are readily deployed near fronts as observed from the air. The dye streams from the anchored buoys reveal the short-term history of current directions near these frontal boundaries. The abrupt disappearance of dye streams pinpoints submergence zones, and shows the link between submergence zones and water color boundaries.

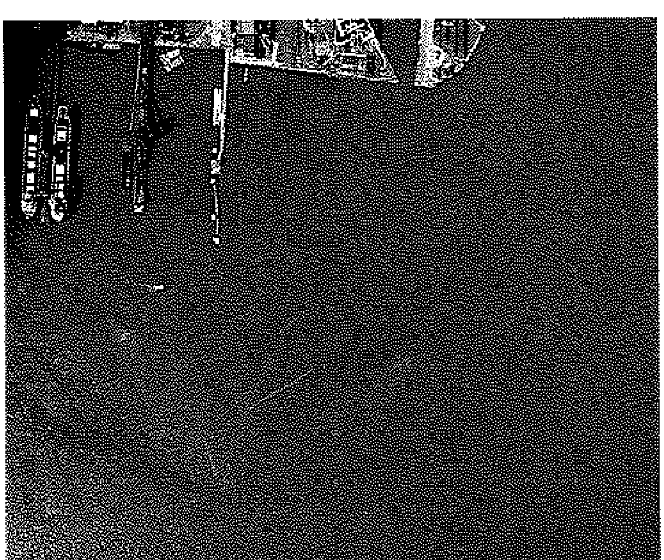
VIMS uses three types of dye buoys in circulation analyses. One is a surface-current follower, biodegradable and free-floating. Another has an anchor and a spherical plastic float 15 cm in diameter. The third type is a window-shade Chesapeake Bay drogue, which allows remote sensing of currents at depth. The shade is one square meter of muslin supported by a wooden frame and suspended at the desired depth. For the purpose of this study, VIMS employed the anchored dye-release buoy and free-floating dye buoys to identify more effectively tidal-

Figure 1. Aerial photos of Newport News Point showing the position of a flood-tide convergence zone, a boundary which develops when the inflowing tide meets an established water mass. The first evidence of conversion was when the dye markers converged rapidly into a color boundary, shown in Figure 1a. Concern exists over the development of a convergence zone because of the collective ability it has on floating pollutants. This may make cleanups of floating pollutants easier but also creates a secondary source of pollution by being spread out during the next ebb tide. Early in flood tide the current is strongly inshore to the left (Figures 1a and 1b). Five hours into flood tide, water on both sides of the boundary are seen moving toward the boundary. At this point, all waters passing into the convergence zone are submerging, with the convergence boundary itself remaining relatively stationary during the whole convergence sequence. This situation will keep outfall pollutants seaward of the convergence boundary, as can be seen by P in Figure 2, the outfall location proposed by VIMS. Pollutants cannot make any inshore progress at such a location and are dispersed on ebb. *Photos courtesy of John C. Munday, Jr.*

1a. 3:35 hours into flood tide.

1b. 4:25 hours into flood tide.

1c. 4:50 hours into flood tide.



1d. 5:05 hours into flood tide.

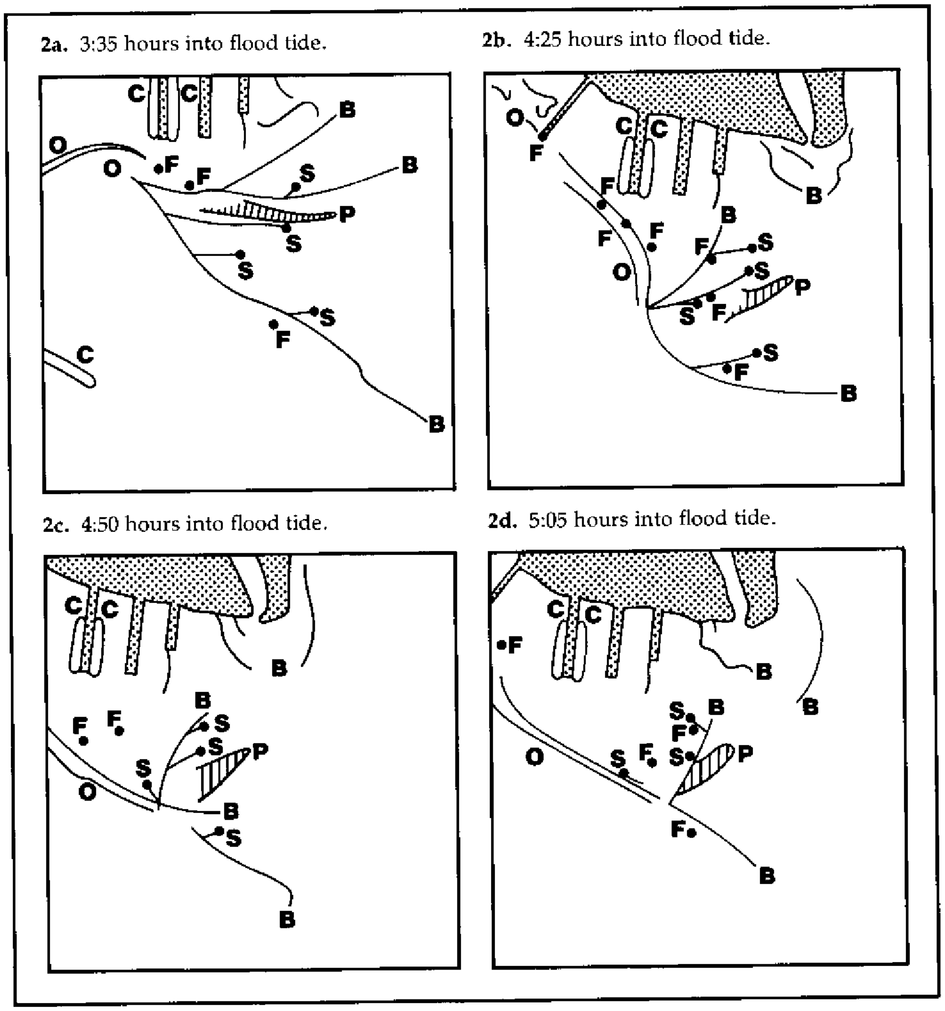


Figure 2. A diagrammatic representation of the time sequences in Figure 1, identifying the position of boundaries, dye buoys, and outfall plumes. (B) water color boundary; (C) seagoing vessels; (F) dye patch from free-floating dye buoy; (O) oil slick; (P) sewage outfall plume (hatch marks); (S) dye stream (line) flowing from anchor buoy (dot), indicating current direction. *Diagrams courtesy of John C. Munday, Jr., with permission from* Photogrammetric Engineering and Remote Sensing.

excited convergence zones. Figures 1a through 1d show the development of a flood-tide convergence zone at Newport News Point. Figures 2a through 2d are diagrammatic explanations of what is seen in Figure 1.

The typical field operation requires a boat, an aircraft equipped with a nadir-viewing camera, and radio communication between the boat and aircraft. Radio permits specific placement of dye buoys so as to elucidate flow in the neighborhood of foam lines and water color boundaries. The airborne cameraman employs a pocket recorder for record keeping.

Any images of dye marks observed in the aerial photographs are transferred to enlarged-scale base maps. Coordinates obtained from these maps are identified and have computer-corrected current vectors manually plotted on copies of the base maps. A consideration of errors allowed at each step of the data-handling procedure yields a possible total error of < 10 m for a buoy position. This error generally results in an error of under 2 cm/sec in the computed average current speeds for a 20-minute period.

For the Newport News Point sewage plant study, VIMS determined that surface-circulation patterns obtained via remote sensing (in contrast to subsurface data obtained by other methods) were sufficient and realistic because sewage effluent is observed to rise to the surface near existing outfall sites due to its low density relative to the receiving waters (see Figure 2).

Two studies were performed at Newport News Point, one for each half of the semidiurnal tidal cycle. In addition to the use of VIMS photography, color and color infrared NASA imagery (scale 1:49,000) was studied for indications of stream flow around Newport News Point.

Results showed that the most shoreward site had the highest dispersion rate during early ebb, but in late ebb the dispersion was highest at the farthest offshore site. Because the outer site had the greater dispersion in late ebb, VIMS recommended the outer site for the outfall.

The surface flow on flood tide was not dispersive; rather, it was strongly convergent, with a convergence zone associated with a visible color boundary in the imagery, as seen in Figure 1.

At the turn of the tide, the observed color boundary disappeared, and the floaters spread out again during ebb tide across much of Hampton Roads. In effect, the stagnant area formed during flood tide acted as a source of floating material on the following ebb.

Such an area, called a secondary source, can be misinterpreted as a primary source, an important consideration in detecting and identifying sources of pollution. It is interesting that the ebb-phase imagery showed a number of oil slicks downstream of Newport News Point. These had apparently originated from near Newport News Point but were not traceable back to a "point" source. The interpretation is that these slicks came from the gathering of material which took place throughout the preceding flood phase.

The HRSDC has decided to build a new sewage treatment plant at Pig Point to serve the city of Portsmouth and Nansemond County. For this sewage outfall site, an estimate of the tidal excursion was obtained by presuming the intertidal volume of the Nansemond River to flow as a slug of water from Hampton Roads. From the size of the slug, a preliminary assessment was made of the potential of the wastes from the proposed outfall site to reach the Nansemond River and the sensitive oyster beds. This study was aided by NASA color infrared and thermal infrared imagery, which identified the most appropriate locations for dye-buoy locations.

Results at Pig Point showed that effluent from the site *would* reach the oyster beds, and that shifting the site a relatively short distance northward would keep effluent away from the oyster beds. During early flood, waters flow past the site in a southerly arc toward the Nansemond County shoreline but never reach the significant oyster beds. However, during middle and late flood, the flow divides just south of the munitions pier, the southern flow heading directly toward the Nansemond River and the oyster beds. VIMS therefore recommended that the site be located north of 36° 56′ N, to keep the effluent in the northern branch of the flood flow during middle and late flood.

The success of the dye-buoy remote-sensing technique in elucidating circulation was confirmed by HRSDC in accepting the VIMS siting recommendations. The consequence for future work is that the technique is fully integrated as one of the standard tools used at VIMS for answering siting questions. It is easily implemented, provides the needed circulation data, and is inexpensive. A particular advantage is that it enhances fronts and convergence zones by revealing nearby current directions as well as submergence at boundaries.

Additional information is available from:

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Gloucester Point, Virginia 23062

A more detailed report dealing with these studies is:

Munday, John C., Jr., Christopher S. Welch, and Hayden H. Gordon. 1979. Outfall Siting with Dye-Buoy Remote Sensing of Coastal Circulation. *Photogrammetric Engineering and Remote Sensing*, Journal of the American Society of Photogrammetry, Vol. XLIV, No. 1 (January 1978), pp. 87-96.

Remote Sensing Applied to Marinas and Boating

In 1977, the Raytheon Company and the University of Rhode Island undertook a comprehensive aerial survey of marinas along the Rhode Island coastline. This survey was part of a qualitative assessment of the effects of marinas and boating on water quality in Rhode Island. Almost half the state's residents are involved in some way with boating. Other recreational uses of the shoreline are also extensive, and the state's shellfish resources are an important component of its economy. Water quality is a critical factor in maintaining a reasonable balance between various uses of Narragansett Bay.

Under Section 208 of the Federal Water Pollution Control Act Amendments of 1972, the Rhode Island Statewide Planning Program was assigned the task of estimating current degrees of pollution in particular areas, including marinas, and identifying those with potential pollution problems. A major concern is compliance with new regulations governing boat toilets, which will require that a certain number of marinas install pump-out stations for vessels with holding tanks (Marine Sanitation Devices Type III, MSDs). Determining the location and the number of pump-out facilities needed to maintain water quality was only one objective of this study. It was also important to determine how dredging and marina expansion affect water quality in boating areas.

The series of aerial photographs taken of the marinas in the state was particularly helpful to scientists preparing the report. From these photos, boat numbers, sizes, power sources, and probable number of MSDs were discernible, along with marina facilities in general. The photos made it possible to identify marinas suitable for pump-out facilities, and they also showed which marinas have been dredged and allowed estimations to be made on a marina's potential for expansion.

For this aerial survey, all saltwater marinas in the state (defined as any shoreside docking facility serving ten or more recreational boats) were photographed at a scale of one inch to 250 feet on nine-by-nine aerochromatic color transparencies. The photos were taken on two October weekdays, after the end of the boating season but before the boats were hauled for winter storage.

The transparencies were analyzed under magnification using light tables by a panel of seven experts* as to existing capacity, structure, visual environmental impacts, and potential for expansion. Each boat photographed in the marinas was classified as to size, class (sail or power), estimated number of sleeping accommodations, and toilets. Not only did the photos achieve the purpose initially planned for them; they have also provided a dated archive for later use by other planners.

In the state's 178 saltwater marinas, 11,079 boats were found in 20 geographic areas, in contrast with

**These included a yacht surveyor, a sailboat marina owner, a powerboat marina owner, a geographer, a marine biologist, an engineer, and a marine recreation specialist.*

Figure 1. Newport Harbor is an area where limited potential exists for either land or sea expansion without major construction. Photo shows multipurpose marinas in one of the most active recreational boating harbors on the Atlantic Coast. *Photo courtesy of Rhode Island Statewide Planning.*

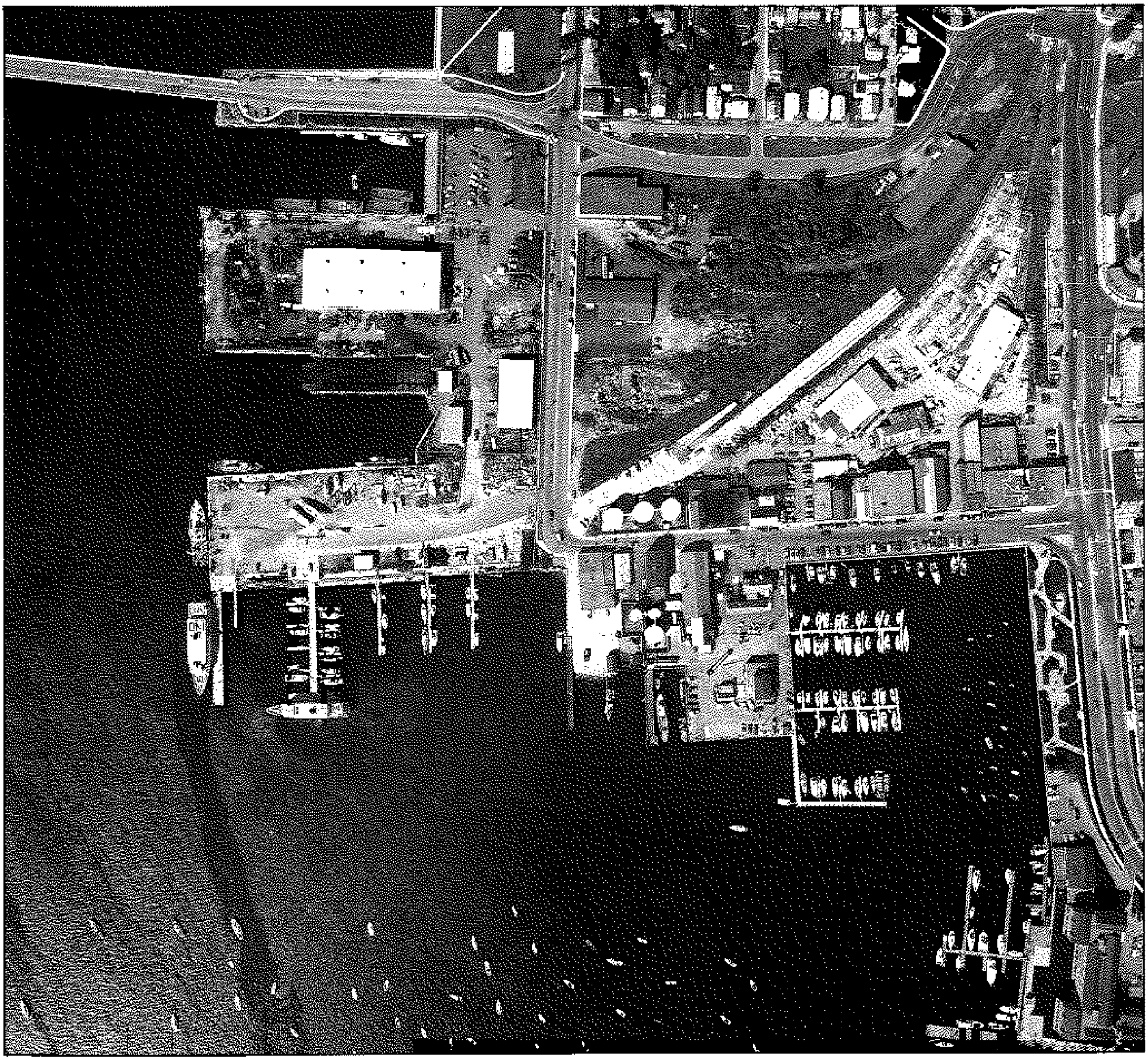
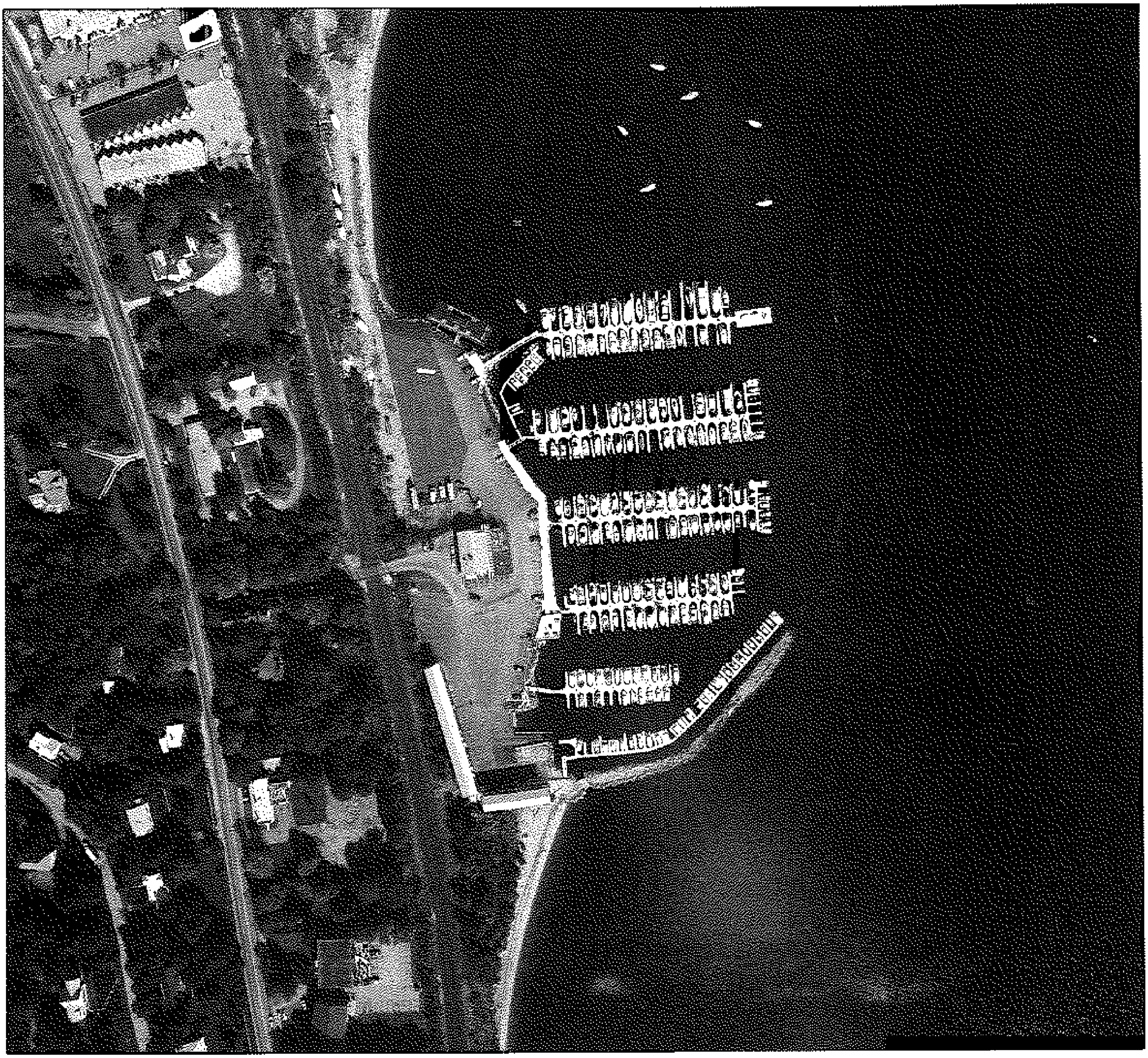


Figure 2. Cowesett Marina is one of the state's larger marinas with 252 boats (of which 200 are powerboats), 7 floating docks, dry-stack boat-storage rack system, launching ramp, waterfront restaurant, and riprap bulkhead. It is a suitable site for the MSD Type III pump-out. Estimated expansion potential is moderate on the land but high in the water; dredging has occurred. Wave protection in this very exposed location is provided by a combination breakwater of rock groin rubble mound, wood bulkhead barrier, and two half-sunken barges, with the latter requiring improvement. *Photo courtesy of Rhode Island Statewide Planning.*



previously reported data. In one area, for example, 771 dock spaces had been estimated from a telephone survey of marina owners, while the photos showed over 1,000 recreational vessels present. Interpretation of the photos included estimating the volume of sewage from pleasure boats present in each of the 20 areas.

The photographs show that 35 percent of the boats counted are less than 17 feet long, 64 percent are 19 to 45 feet long, and 1 percent are over 45 feet long. Thus, most of the boats kept in Rhode Island marinas have four or more bunks and one or more MSDs. The statewide ratio of powerboats to sailboats is slightly more than two to one. Newport Harbor (see Figure 1) is an example of a multi-operation marina area with boats of all sizes and uses.

It was concluded from the marina study that potential environmental impacts can arise from three types of activities: 1) marina construction, 2) marina maintenance, and 3) recreational boating and marina use.

Environmental effects of construction are perhaps greatest when a new marina is being built in a formerly undeveloped area, a fact for coastal managers to consider. Careful analysis of aerial photos of marina areas could suggest alternatives to new construction, such as expansion of existing facilities or construction in already developed waterfronts. Interpretation of aerial photos indicated that 33 percent of the marinas in Rhode Island have adequate potential for land expansion, while 67 percent have potential for water expansion. The position and composition of bulkheads, breakwaters, and docks must be considered to maximize a marina's efficiency and to allow the greatest number of people to have access to boating with minimum negative impacts. The use of remote sensing can show what has been built, indicate maintenance construction (dredging, bulkhead repairs, etc.), and identify potential for modifications to the

Figure 3. Kenport Marina has little potential for land or water expansion without major dredging and filling activity. With all 84 boats under 25 feet, it is an example of a marina that may not need a pump-out station, since the photo shows no large boats present with on-board toilets. *Photo courtesy of Rhode Island Statewide Planning.*

facility, as seen at Cowesett Marina (see Figure 2). Remote sensing of marinas can also help predict runoff from potential and existing marina parking lots.

The color aerial photographs of Rhode Island marinas showed 81 percent had been dredged. An example is Kenport Marina (Figure 3). It is important to know where dredging has occurred because maintenance dredging will usually be required periodically. The greatest environmental problems occur during the dredging process. Besides the obvious problem of where the dredge material is to be disposed, there are the temporary impacts of increased turbidity which limits light penetration into the water column, decreases the dissolved oxygen content, and disrupts the habitat of bottom-dwelling organisms. The positive impacts of dredging are the in-water storage of deeper-draft boats, improved water circulation, and increased estuarine productivity when marshes are nearby. In some cases, the photos give clues to possible marina expansion with little or no extra dredging. Photos of Greenwich Cove, which is extensively used by sailboats, showed that the capacity of all the marinas could be doubled without any dredging, simply by moving the channel toward the center of the cove.

In addition to the impacts associated with marina construction and maintenance, there are the minor adverse environmental impacts that can be caused by the boats themselves, primarily in the immediate marina area. Antifouling paints (which release copper and other toxic components), motor-exhaust, litter, and, most important for shellfishing, the release of organic sewage from boats all may degrade the water quality of marina areas. On the presumption that some larger boats are more likely to have holding tank toilets (MSD Type III) and the finding that some marinas have more large boats than others, one of the most significant findings from the aerial survey was the determination that less than ten properly located pump-out facilities in Rhode Island could effectively handle the organic waste generated. Figure 3 is an example of a marina not needing a pump-out station, since no large boats are present.

Concentrations of copper in harbor waters have been documented by other studies in bottom sediments at levels toxic to some bottom-dwelling organisms. Hydrocarbons from exhaust, besides being unsightly, have temporary adverse effects on surface organisms. Aerial photos can accurately depict recreational boat concentrations and, when coupled with sediment and water samples, can reveal areas where a problem has developed.

Upgrading water quality in marina areas is essential for continued use of this valuable natural resource. Ultimately, the goal of coastal management is to maintain high-quality facilities and service for recreational boaters while keeping water quality standards at or above federal guidelines. Improved water quality in Rhode Island harbors could enhance the public's enjoyment of boating and expand the use of Rhode Island marinas. It is hoped that remote sensing will be used to the fullest extent toward fulfillment of these goals so that Rhode Island will continue to be a desirable setting for boaters of the Northeast.

Additional information is available from:

Neil W. Ross
Marine Advisory Service
University of Rhode Island
Narragansett, Rhode Island 02882

More detailed reports dealing with this study are:

Johns, Warren, Neil W. Ross, Gail Chmura, Philip Tabas, and Josef Schwalbe. 1978. Marinas Task, Preliminary Evaluation (Title II, Section 208, Federal Water Pollution Control Act Amendments of 1972, for the R.I. Statewide Planning Program). Raytheon Company, Portsmouth, R.I. Chapter IV.

Chmura, Gail, and Neil W. Ross. 1978. The Environmental Impacts of Marinas and Their Boats, a Literature Review with Management Considerations. Marine Memorandum 45, University of Rhode Island, Kingston, R.I. 32 pages.

Reference

Collins, Clarkson, and Stephen Sedgwick. 1979. Recreational Boating in Rhode Island's Coastal Waters: A Look Forward. Marine Technical Report 75, University of Rhode Island, Kingston, R.I. 76 pages.

Satellite Monitoring of Ocean Behavior as It Applies to Commercial Fishing

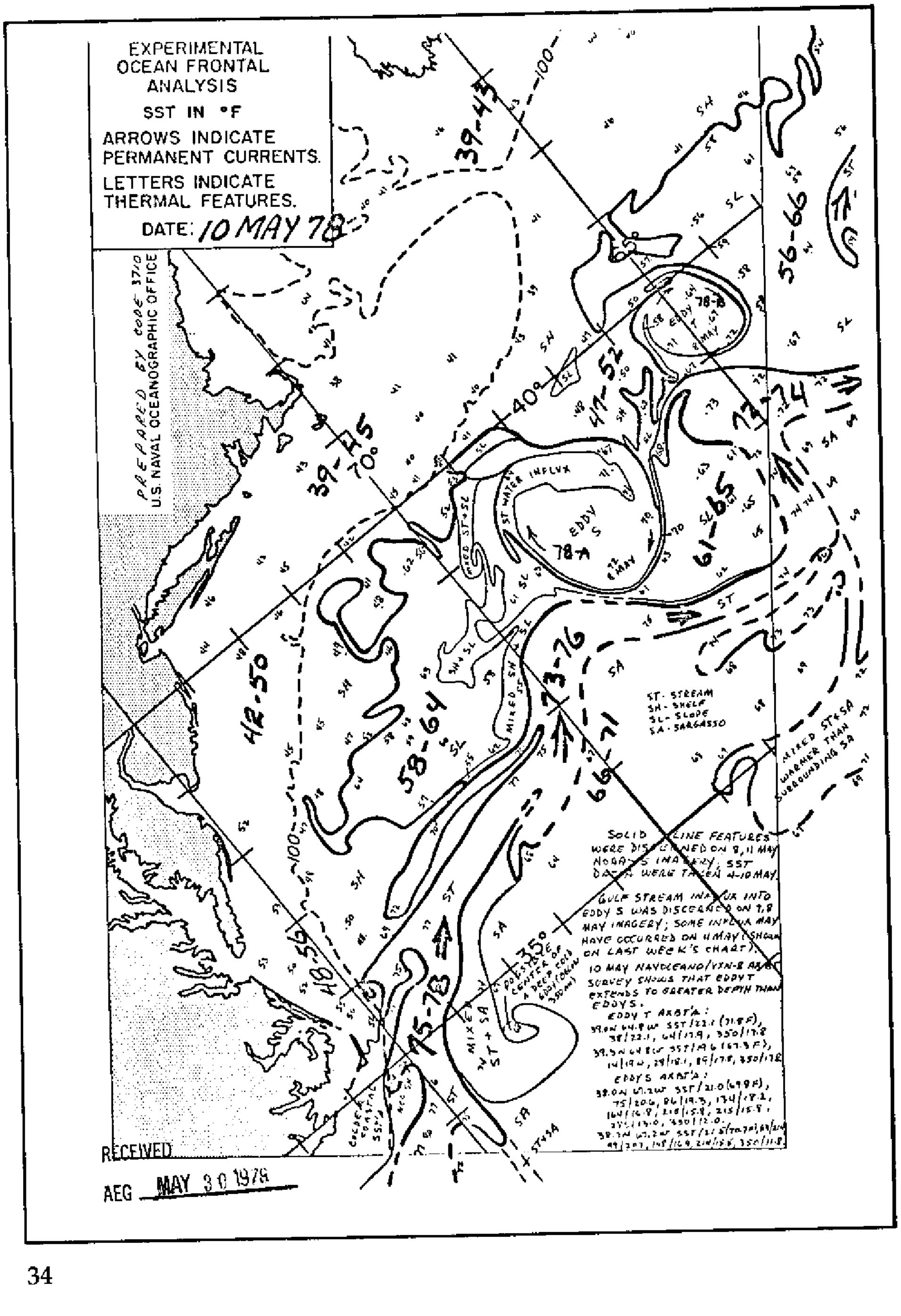
Currents associated with the large-scale oceanographic features known as warm-core eddies, or Gulf Stream rings, appear to have been one of the primary causes for the unusual gear loss suffered by lobster and crab fishermen in 1977. Apparently, the strong currents from passing eddies, which were about twice as numerous as they had been in the three previous years, submerged surface floats, causing them to deflate. Although few floats were recovered, it was verified that the traps themselves had not moved from where they had been set. The implied correlation between eddies and lost fishing gear has given added impetus to work by the National Marine Fisheries Service's Atlantic Environment Group (AEG) to monitor the effects of large Gulf Stream eddies and meanders on environmental conditions in the fishing grounds off New England and the Middle Atlantic states.

In recent years scientists have learned that vast rings of water separate from the Gulf Stream as it flows northward parallel to the Atlantic Coast. Warm-core eddies form in the slope-water region off the continental shelf when meanders separate from the northern side of the Gulf Stream. The warm-core eddies seen off New England and the Middle Atlantic coast form primarily in the slope-water region southeast of Georges Bank, where meandering of the Gulf Stream is extensive. Eddy diameters range between 70 and 270 km. Although meanders and eddies occur on both sides of the Stream, it is only those on the north and west that sometimes move into the fishing grounds of the continental shelf and slope. These eddies have a warm core because they enclose Sargasso Sea water that has crossed the Gulf Stream within the originating meander. The clockwise rotational flow of these warm-core eddies can reach speeds of 1.8 knots.

Unlike Gulf Stream meanders, which move slowly eastward, warm-core eddies typically move west and southwest in the slope-water region at varying rates of up to about 0.2 knots. This westward drift is not uniform, however; the eddy may halt or move in irregular directions for periods of days or even months. Some eddies recontact the Gulf Stream soon after their formation and are reabsorbed. Those which continue to move to the west and southwest may persist for over six months, eventually being trapped and reabsorbed by the Gulf Stream off Cape Hatteras, where it runs close to the continental slope.

Warm-water eddies are of interest because they apparently cause the strongest subsurface currents and nonseasonal (aperiodic) variations in water-mass properties found in the slope-water region adjacent to the outer continental shelf. Although both meanders and eddies are of common occurrence in this region (about six warm-core eddies per year during 1974 and 1975), they characteristically remain in deep water, with apparently little direct effect on environmental conditions in the waters of the continental shelf and slope. However, the infrequent meander or eddy which moves close

Figure 1. Example of an Experimental Ocean Frontal Analysis chart prepared by the Naval Oceanographic Office which were previously used by the AEG for locating and tracking warm-water eddies. These charts are interpretations of NOAA-5 Very High Resolution Radiometer (VHRR) thermal imagery. This chart is an interpretation of the satellite image seen in Figure 3. Numbers indicated are sea-surface temperatures as reported by commercial and research vessels.



along the continental slope can have considerable effect on these waters. It is also thought that large eddies which remain in deep water can have significant effects on the shelf waters by offshore entrainment of these waters. The influence of this kind of variability on the fishery resources is largely conjectural, but possible environmental effects can be identified, in addition to the obvious effect of subsurface currents.

Deep-sea fishermen are particularly interested in the position of eddy fronts, because of the warm-water species of fish which congregate there. Apparently, large game fish such as sharks and swordfish find food more plentiful along the rotating perimeter of a warm eddy. The colder surrounding waters have a bountiful food supply which the larger fish prey upon. These colder waters are less habitable for the game fish, however, so they remain in warmer water along the eddy front within reach of food.

There are two principal components of the AEG monitoring program: one is to use interpretations of infrared-radiometer imagery from NOAA satellites to observe the locations, movements, sizes, and other characteristics of meanders and eddies as they appear at the sea surface; the second is to observe these features directly from vessels.

Until recently, the primary source of satellite data on eddy positions was the weekly Experimental Ocean Frontal Analysis (EOFA) charts of the U.S. Naval Oceanographic Office (NAVOCEANO), a sample of which can be seen in Figure 1. Recently, however, these charts have ceased being available to the general public. For this reason, the primary source of satellite data for the AEG work is currently the Oceanographic Analysis charts (Figure 2) issued by the National Weather Service (NWS) and the National Earth Satellite Service (NESS). Figure 3 is an example of the type of imagery interpreted in the preparation of the Oceanographic Analysis charts. Warm water appears dark,* making the identification of Gulf Stream eddies quite easy. As in the past, GOES satellite infrared imagery (see Figure 4) is used in conjunction with the NWS-NESS charts and satellite imagery to help establish eddy formation and destruction. The GOES data do not have the resolution of the NOAA satellite imagery, but the fact that they are taken much more often (every half hour) makes their use as a base map desirable. Often, computer enhancements of the GOES imagery are necessary because the contrast between water masses of different temperatures is sometimes not discernible with the unaided eye. The computer is able to distinguish many more divisions between black and white than the human eye can. Once adequate imagery has been identified, only eddies observed west of 60°W longitude are considered for analysis.

Twelve warm-core eddies occurred during 1977. Knowing their formation and destruction dates plus their lifetimes is extremely useful. A track-line map similar to the one in Figure 5, which tracks the position of Eddy 78-A, is constructed for each eddy during a year, with plotted points being the estimated eddy centers for all dates when information is available. In order to verify the satellite-determined eddy location, research vessels regularly make temperature-profiling cruises in the region. Fishermen also help by

Note that in the aircraft-derived thermal infrared imagery in the case study entitled "Remote Sensing of Coastal Pond Discharge," cold water appears darker than warm water.

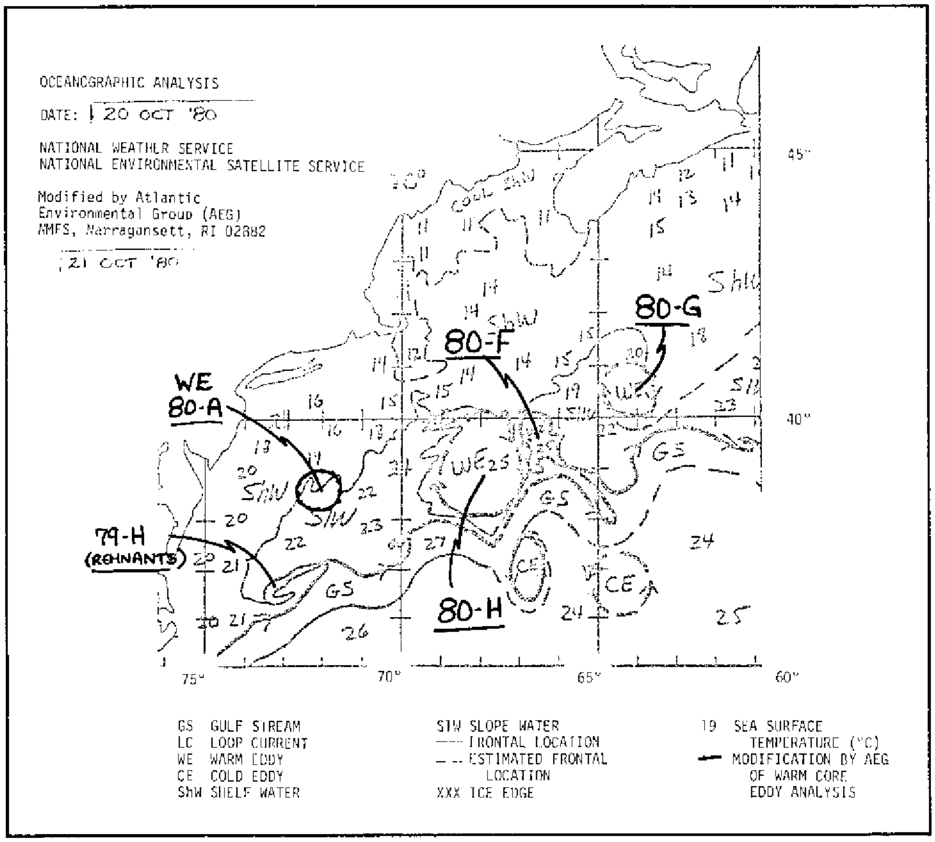
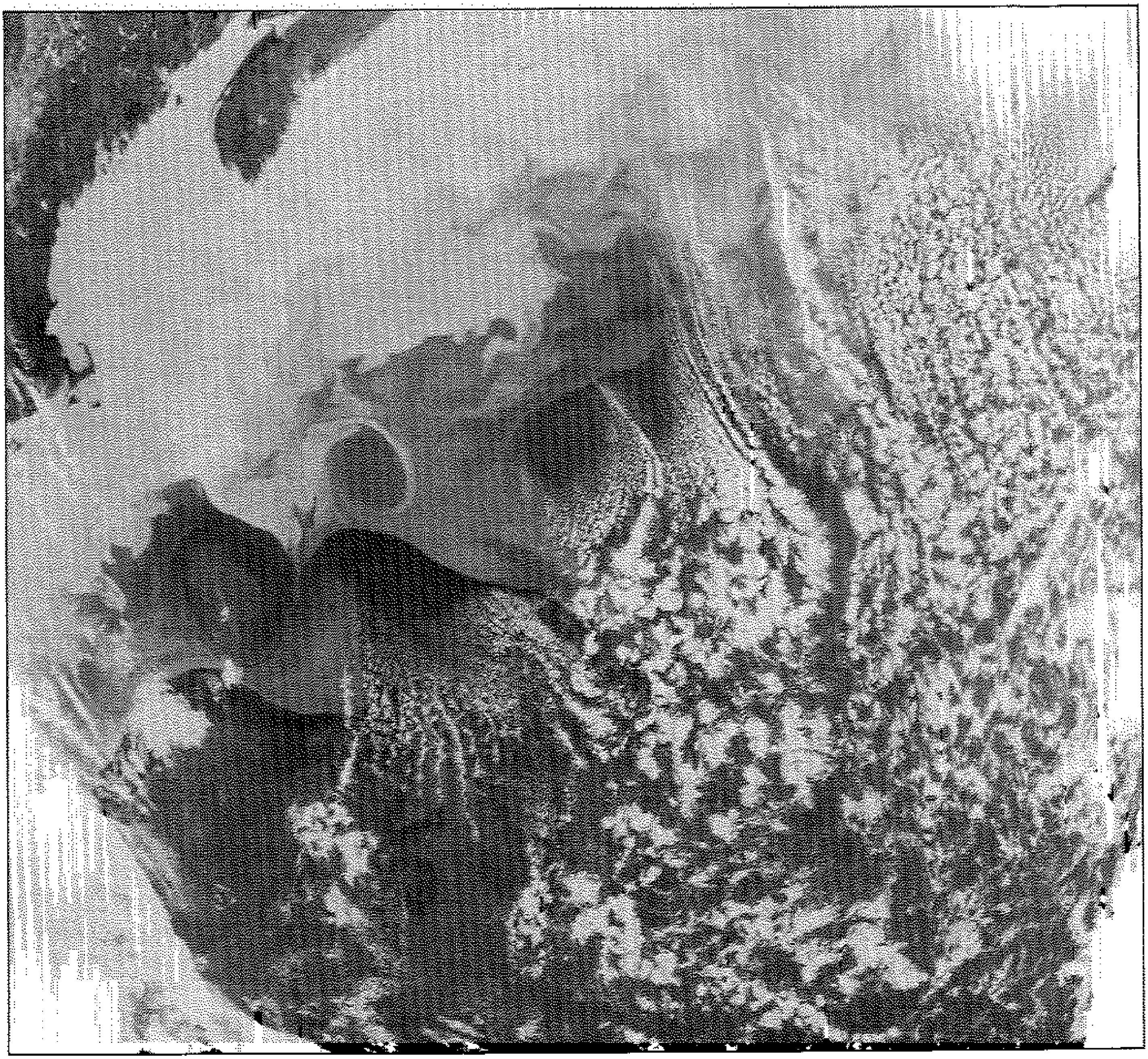


Figure 2. Example of the Oceanographic Analysis charts currently used by scientists of AEG to study the Gulf Stream and associated warm-water eddies. The chart is an interpretation of the Advanced Very High Resolution Radiometer (AVHRR) thermal sensor aboard the NOAA-6 satellite. Modifications of the chart are made by AEG of warm-core eddies when surface thermal resolution is poor or when cloud cover obscures the satellite's view. Eddies are labeled with the year of their formation as well as a sequentially assigned letter.

Figure 3. Satellite image from NOAA-5 showing oceanographic features south of Georges Bank. Two warm eddies, labeled 78-A and 78-B, appear as dark circular features north of the Gulf Stream, which shows up as a dark ribbon in the lower part of the image. Eddy 78-B, moving in a southwesterly direction (opposite to the flow of the Gulf Stream), was reabsorbed by the Gulf Stream the following week. *Photo courtesy of the Atlantic Environment Group.*



notifying the National Marine Fisheries Service of any unusual conditions or catches which may identify an eddy front.

In the first quarter of 1978, the satellite infrared imagery revealed a spectacular displacement of the shelf-water front offshore, beginning in February just 10 km from the shelf edge and moving out to 130 km by the first week in April. This anomalous displacement coincided with the unusual absence of warm-core eddies in the slope-water region, suggesting a dynamic relationship between the eddies and the front, or a mutual dependence of the two features on a common set of forcing functions.

An interesting result of this unusual offshore excursion of the shelf water was the apparent offshore diversion of migrating schools of Atlantic mackerel. Off Virginia, the schools passed about 35 km farther offshore than usual, generally escaping the domestic fishing fleet, which was working nearer shore.

Satellite imagery has proved effective for monitoring warm-core eddies but does have inherent limitations. Satellites often give an inaccurate measure of both the size and the location of meanders and eddies when these features are overridden at the surface by surrounding waters, or chilled at the surface by cold winds. This is because satellite imagery reveals surface features only. A feature located near the Gulf Stream may appear as a meander in satellite imagery, while the main body of water beneath the surface circulates as an eddy.

Figure 4. Computer enhancement of a GOES satellite thermal image. Image shows the same oceanographic features seen in Figure 3, with a somewhat lesser resolution. These images are available on a daily basis, making them a valuable source of reference. *Photo courtesy of the Atlantic Environment Group.*

Eddies sometimes seem to disappear in the satellite imagery, for days and even weeks, and then often reappear many miles from where they were last seen. This is due to the fact that during the summer, surface temperatures in the slope water may approach that in the eddies, causing the latter to "disappear" in the imagery because of the poor thermal contrast. Finally, regions in which these analyses are performed are subject to long periods of cloudiness, during which eddies may be formed or destroyed.

Adequate measurement of the effects of meanders and eddies on the fishing grounds is feasible at present only with combined observations from ships and satellites. Shipboard observations are paramount for revealing such effects as upwelling adjacent to meanders or eddies, subsurface injection of warm Gulf Stream or eddy water onto the shelf, and subsurface entrainment of the shelf water off the shelf. Combined observations should be particularly advantageous for measuring the volume of surface entrainment of shelf water. The areal extent of entrainment can be estimated from satellite imagery and the depth of the entrainment layer from shipboard measurements.

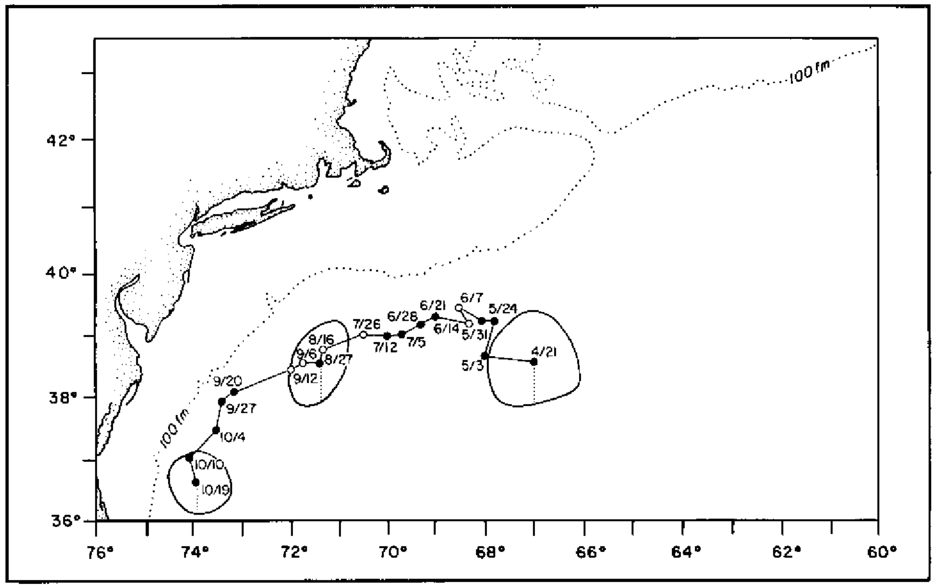


Figure 5. Track line for Eddy 78-A, which can be seen in Figure 3. Prepared by the AEG, these charts plot the progress of warm eddies from date of formation to date of destruction. When the positions of eddies are clearly seen, the eddy's center position is plotted as a closed circle (●). Center positions estimated entirely by interpolation are plotted as open circles (o). Eddies may be invisible due to poor thermal contrast or cloud cover. Surface boundaries of the eddy are shown for the date of formation and at representative stages within the life of the eddy. These boundaries are interpreted directly from the satellite imagery on days the position is clearly seen.

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There are also the following articles on the results of these studies which can be consulted:

Chamberlain, J. L. 1977. Monitoring Effects of Gulf Stream Meanders and Warm Core Eddies on the Continental Shelf and Slope. International Commission for the Northwest Atlantic Fisheries, Selected Paper No. 2, pp. 145-153.

Chamberlain, J. L., and D. Mizenko. 1977. Gulf Stream Anticyclonic Eddies (Warm Core Rings) off the Northeastern United States in 1977. *Annales Biologiques*, Vol. XXXIV, 1977 (1979), pp. 39-44.

Chamberlain, J. L., and D. Mizenko. 1977. Anticyclonic Gulf Stream Eddies off the Northeastern United States During 1976. In *Ocean Variability in the U.S. Fishery Conservation Zone, 1976*, NMFS Circular 427, National Marine Fisheries Service, Washington, D.C., pp. 259-280.

Chamberlain, J. L. 1976. Gulf Stream Meanders and Warm Core Eddies. Irregularly Occurring Influences on the Fishing Grounds. In *Proceedings of the NMFS/EDS Workshop on Climate and Fisheries*, April 26-29, 1976, National Oceanic and Atmospheric Association, Washington, D.C., pp. 173-179.

Chamberlain, J. L. 1977. Monitoring the Effects of Gulf Stream Meanders and Eddies on the New England Fishing Grounds. In *Oceans '77*, Conference Record Vol. 1, the Marine Technology Society and the Institute of Electrical and Electronics Engineering, pp. 14D1-14D7.

Aerial Mapping of the Southern Rhode Island Shoreline

For reasons poorly understood at present, there appears to have been in the early 1960s a significant shift in the path followed by late summer/early fall hurricanes as they move north along the northeastern coast of the United States. Instead of following the coast all the way to Cape Cod, hurricane centers now generally follow the coast up to approximately the outfall of the Hudson River, at which point, rather than turning east, they continue up the Hudson River Valley. The result of this fairly significant meteorological change has been that no major hurricanes have hit the Rhode Island coast in the last 20 years. This has led to a certain complacency regarding shoreline construction, and the damage to property from severe storm events has increased dramatically.

The loss of property, coupled with an apparent acceleration of coastal erosion in the same region in recent years, has led to serious concern about coastal development among Rhode Island authorities. In recent years, several beach houses have been swept out to sea in winter storms. However, without hard data on which to base building restrictions, Rhode Island's coastal managers have been considerably handicapped.

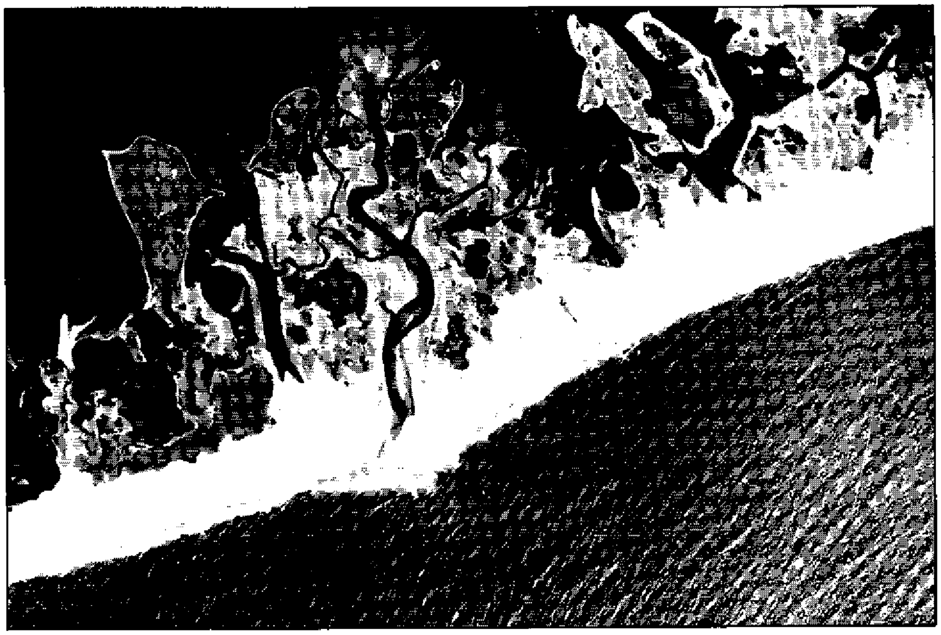
Dr. John J. Fisher, of the Department of Geology, University of Rhode Island, undertook to provide such data with regard to shoreline erosion. He was funded by the University of Rhode Island Sea Grant Program to perform a photogrammetric survey to determine the rate of erosion and of total overwash and tidal deposition for the southern Rhode Island coastline. The last two quantities are important in determining 1) the volume of eroded sediment that will be redeposited, and 2) the impact of excessive washover on the receiving marsh system.

Following the devastating hurricane of 1938, an aerial photographic survey was made of the Rhode Island shoreline by the federal government. Some 250 photographs are available from the National Archives in the Library of Congress. Figure 1 is a sample photograph from this survey, showing the Charlestown inlet. In 1977-78, the Department of Geology at the University of Rhode Island, with funds from Sea Grant, undertook a comparison of these photographs with 250 black-and-white aerial photographs taken at 10,000 feet by a commercial firm in 1975. Figure 2 is a product of the 1975 aerial survey and shows the area in Figure 1 as it appeared more than three decades later. Changes in the beach profile, measured at the high-water line, indicate the amount of sediment available to be transported landward. Determining the difference in a receded shoreline indicates to what extent sediment is moving offshore.

The Rhode Island coast is considered most suitable for this type of analysis, since it is not extensive and receives no input of sediment by rivers, either to the coast or to any lagoon. Once the aerial survey was completed, shoreline erosion, sediment overwash, and inlet tidal deposits were measured, using a stan-

Figure 1. Aerial view of the Charlestown, Rhode Island, inlet on May 16, 1939, before construction of the breachway. The washover plain can be seen as bright white. The tidal delta in the pond is not well developed. *Photo courtesy of John J. Fisher.*

Figure 2. View of the Charlestown breachway on April 14, 1975. Increased flushing of Ninigret Pond, due to construction of the breachway, has led to a well-developed inland tidal delta. The washover plain is evident as a lighter band of gray landward of the beach front. Homes have been built on this washover plain and are in a vulnerable position in the event of a severe storm. The beach front has also receded, apparent when compared to the May 1939 photo. *Photo courtesy of John J. Fisher.*

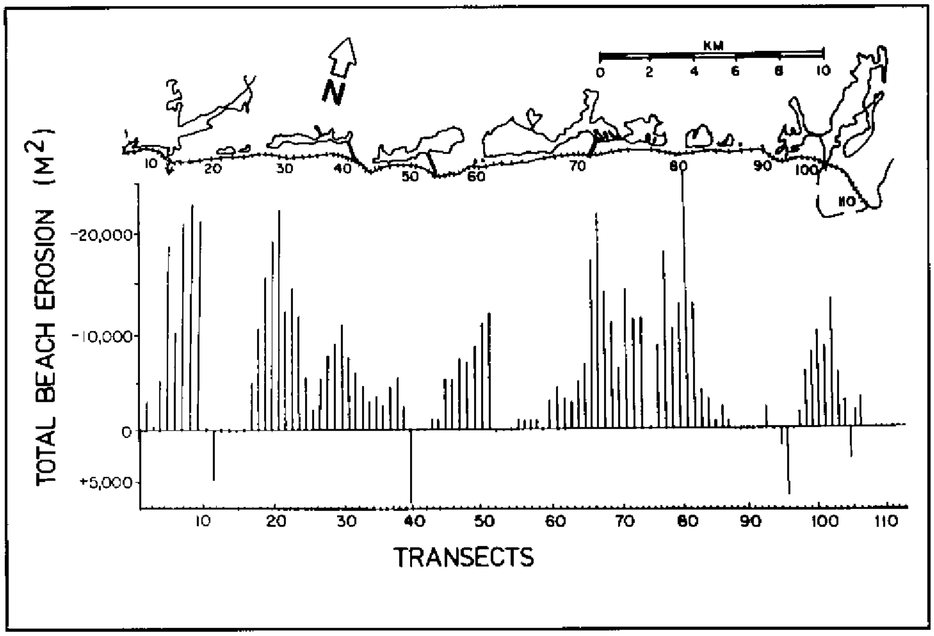


dard grid point-count technique on stable mylar overlays, which has recently been improved to include digital planimeters. The photos were optically rectified to compare with the 1938 photos, as to scale and ground controls, with a Bausch and Lomb Zoom Transfer Scope. The continuous enlargement system allows each aerial photograph to be enlarged optically to exactly the scale of ground-control survey points. Comparison of aerial and ground-control measurements indicated accuracies of 3 meters. The quantitative amounts of error, or variance resulting from the linear and aerial measurements of objects of known area, averaged 2.1 percent.

During the 36 years between the two aerial surveys, the total erosion rate was determined to be 0.2 meters/year along the entire Rhode Island barrier coast. Figure 3 shows the results of a station-by-station analysis, utilizing the comparative procedure described earlier. The total accumulation of washover sedimentation was estimated to be three-quarters of a million square meters for the same period, while the total tidal delta deposition in ponds and lagoons amounted to one million square meters. Tidal inlet deposition was probably affected by the stabilization of the inlets with jetties and revetments, locally called "breachways." Straightening and dredging of these inlets increased the tidal prism of the lagoons, resulting in higher-flow velocities, with consequently greater amounts of sediment being transported and deposited. The total analysis indicates that for the southern shore of Rhode Island tidal delta sedimentation is 1¹/₃ times more effective than washover in the landward transportation, deposition, and storage of sediment. The effects of overwash are nearly nonexistent, however, toward the eastern part of the coast, where the dunes are relatively high and the barrier beach is very wide.

The measured beach erosion over the 36-year period is directly related to the rate of overwash occurrences at different points along the coast. At 27 percent of the transects at which washover accretion was above average, beach erosion was also greater than average. In addition, at 66 percent of the transects at which washover accretion was present or above average, beach erosion was also present or greater than average. It was noted that the only beach accretion during the 36-year time period is associated with updrift deposition related to groins and jetties.

One general conclusion reached and verified by others is that long-term erosion is the general trend along the Rhode Island south shore. It is suggested that there is a tendency for the barrier beaches to be submerged by a rising sea level. Erosion is then necessary to restore the offshore profile to equilibrium. It is also realized that trying to prevent washover deposition from destroying marshlands would have detrimental effects. Man-made protective foredunes would prevent material from being deposited, allowing it to be lost offshore or carried alongshore, thus reducing the size of the barrier beaches.



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There are also the following technical articles on the subject which can be consulted:

Fisher, John J., and Elizabeth J. Simpson. 1979. Washover and Tidal Sedimentation Rates as Environmental Factors in Development of a Transgressive Barrier Shoreline. In *Barrier Islands from the Gulf of St. Lawrence to the Gulf of Mexico,* Academic Press, New York.

Fisher, John J., and D. R. Regan. 1977. Photogrammetric Study of Rhode Island Coastal Erosion. American Association of Petroleum Geologists, Annual Meeting, Washington, D.C.

Fisher, John J. 1977. Relationship of Shoreline Erosion to Eustatic Sea Level Rise, R.I. Coast. Northeastern Geological Society of America, Annual Meeting, Binghamton, N.Y., p. 317.

Figure 3. Station-by-station results of the calculated beach erosion and accretion, from comparison of 1939 and 1975 photos. Note that there is accretion only at those locations immediately adjacent to man-made breachways and inlets. *Diagram courtesy of John J. Fisher.*

Landsat Data for Coastal Zone Management

Coastal zone management took on new challenges in the 1970s with implementation of the Federal Coastal Zone Management Act of 1972. This act provides funds to states, encouraging them to set up federally approved coastal zone management programs. The state of New Jersey, one of whose single most valuable assets is its coastal zone, has received some of these federal funds by defining a coastal planning and management program. One essential ingredient to this program is a well-documented and up-to-date collection of coastal zone data and information. Initially, state planners there lacked such data and were forced to use a somewhat novel approach to their problem. Working with the NASA-Eastern Regional Remote Sensing Applications Center (ERRSAC), the New Jersey Department of Environmental Protection (NJDEP) has been exploring the potential of using Landsat satellite imagery in coastal planning and management.

The first goal of NJDEP was to test the resolution of the NASA-provided satellite data by producing a surface-cover map. Hands-on experience working with the NASA computer system was essential to NJDEP in understanding the analysis techniques and the potentials and limitations of the Landsat data. NJDEP's first step was to select candidate areas for surface-type classification. The southernmost peninsula of the state, Cape May County, was the first examined. In conjunction with the Landsat data, the best ground-truth information and the knowledge of local planners were used to aid the coastal zone land-cover classification. The coastal ecozone, however, presents special problems for candidate area classifications, due to the narrow and linear features associated with it. Beaches, dunes, and many types of vegetation tend to approach the limits of satellite data resolution. Careful analysis, however, allowed the statistics of certain candidate areas to show resolutions of about 1.1 acres. All the Landsat data analyses discussed so far are based on data which are two-dimensional patterns of surface reflectance. The satellite sensor monitors this reflectance and transmits the bits of information in a form known as pixels. These pixels when put together produce an image like those shown in Figure 1. Pixels from the Landsat satellite cover real surface dimensions of 79 × 56 meters or about 1.1 acres. (Plans are in the works to increase sixfold the resolution of the Landsat data, utilizing a new satellite sensor. This increased resolution would allow for easy identification of roads, streams, and woodlot boundaries, all necessary for improving the accuracy of land-cover classification.) Figure 1 shows an example of a computer-processed map generated with 38 classes of detail, quite adequate for regional coastal planning on land and at the water's edge. The classification was developed by NASA/ERRSAC working with NJDEP and the Cape May County Planning Board. The analysis of ground cover shown in Figure 1 represents only a part of New Jersey's evaluation of Landsat

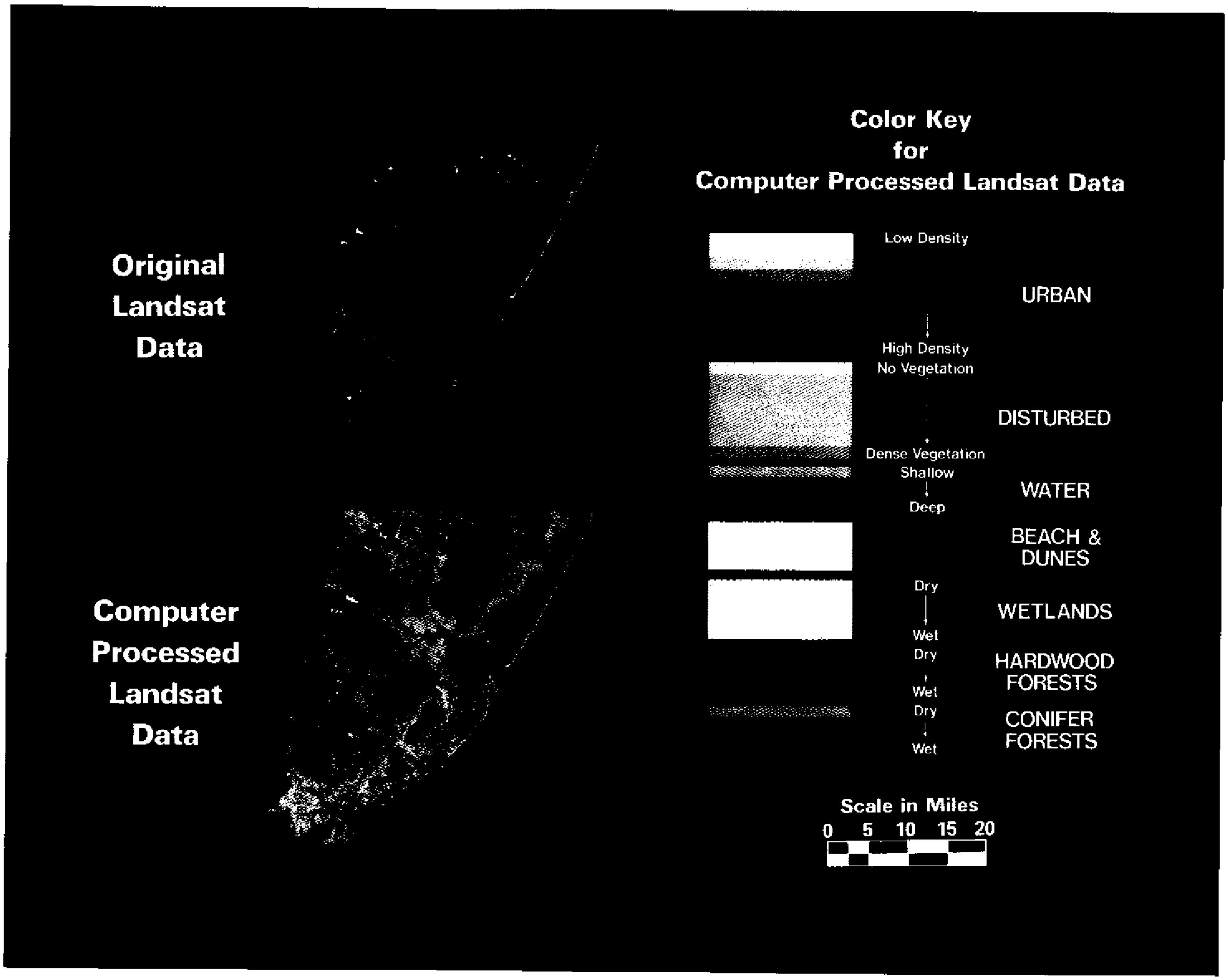

Figure 1. The New Jersey coastline around Atlantic City is shown in both an enhanced Landsat color composite and a computer-aided classification of the Landsat data. Acquired in June of 1978, the false-color scene shows the vast extent of vegetation from salt marsh (the brown tones) to the pineland vegetation characteristic of southern New Jersey (the bright red tones). Atlantic City and nearby developed areas are strikingly evident as blue-gray areas along the barrier islands.

In the computer-classified image, many of the features mentioned above are also apparent. The classification contains 38 different land-cover types. Several classes are of particular interest. Shades of red are urban areas, with the deepest red corresponding to the highest density. Shades of green in the inland areas are forested areas—the denser the forest, the darker the green. Finally, the blue-gray marsh areas show the degree to which water availability influences species distribution. In the marshes, the bluer the color, the more water is required by those marsh plant species to survive.

The mouths of the Egg Harbor and Mullica River watersheds are clearly seen on the Landsat images in the center of the scene, along with their associated extensive tidal wetlands. *Photo courtesy of Scott Cox.*

data, but this portion has undergone the most scrutiny. Along with the computer-processed image, Figure 1 shows the color key as well as a copy of the original false-color Landsat image.

The two-dimensional pattern associated with satellite imagery has left planners at NJDEP with the need to develop a series of overlays which will detail valuable parameters. These will include natural resources (water table depth, soil types, topography, etc.), environmental sensitivity, and socioeconomic variables (transport systems, property boundaries, etc.). When combined with Landsat data, the whole system becomes more valuable than the summation of the individual components. This is the value of a well-organized and planned program for coastal planning and management.

Following the completion of classification analysis of data from the month of June, data from the months of April and November were also processed. Once this was done, the images from all three months were overlaid to see if any variations were noticed throughout the growing season. In those locations where variations were noticed, classification maps or the detailed overlays were refined or corrected. Most of the image differences come from different plant growth patterns and their variations in reflectivity through the growing season.

The ultimate goal of the Management Act of 1972 is "to preserve, protect, develop and where possible to restore or enhance the resources of the nation's coastal zone for this and succeeding generations." It is hard to imagine any geographic planning or management program not benefiting from a good remote sensor-computer system. Once results of the first pilot projects are released, the technique should spread rapidly to similar programs in other states.

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