CHAPTER 144

EFFECTS OF FLOODING ON A COASTAL PLAIN ESTUARY

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ABSTRACT

Rains from Tropical Storm Agnes resulted in unprecedented flooding of the Chesapeake Bay drainage basin in June of 1972. A monitoring program was established to follow the effects of the flood in the Chesapeake estuarine system and contiguous continental shelf waters.

Financial and logistic assistance was solicited and obtained from several federal and state agencies. The monitoring program, called "Operation Agnes" offered scientists a unique opportunity to watch the progress of the flood.

Results of investigations into the effects of the flood show that salinity structure exhibited a four stage reaction, tides in the lower reaches of the estuaries were essentially uneffected and currents returned to normal after a short period of continuous ebbing. Total recovery of the salinity distribution was affected within one hundred days of flood crest at the fall line.

I. INTRODUCTION

On 14 June 1972 a tropical depression developed over the Yucatan Peninsula. It intensified to hurricane strength in the Gulf of Mexico, traveled north, made landfall on the Florida panhandle at noon on 19 June, dissipated to tropical depression intensity as it passed northeast over Georgia and the Carolinas, traversed the southeastern corner of Virginia, moved out to sea near the mouth of

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Chesapeake Bay, intensified to a tropical storm as it moved northward parallel to the Delmarva Peninsula, made a second landfall near New York City on the afternoon of 22 June and curved cyclonically into north central Pennsylvania where it began dissipating as an extratropical depression on 23 June before turning eastward and moving out to sea once more (DeAngelis and Hodge, 1972). The storm, first of the 1972 Hurricane season, was named Agnes. Wind and wave damage from Agnes reached $40 million in Florida; however, greatest losses were due to flooding in the Chesapeake Bay drainage basin where damage was estimated to exceed $2 billion (NOAA, 1972).

During the period 21 to 23 June, the entire Chesapeake Bay watershed area was subjected to measured rainfall in excess of six inches, with approximately one-third of the region receiving more than twelve inches of water and isolated locations recording eighteen inches. This deluge, on a watershed which had been subjected to an exceptionally wet spring, resulted in immediate flooding. By 22 June, it was evident that the Chesapeake Bay region had fallen victim to Agnes. The enormity of the catastrophy could not be judged at that early date but the formulation of a plan to follow the passage of flood waters through tributary estuaries, the Bay, and out onto the continental shelf had begun. This paper describes the administrative effort required to mobilize federal, and state agencies and scientific institutions to monitor a natural disaster and the results of the monitoring program.

II. ADMINISTRATIVE AND LOGISTICAL ACTIVITIES

All local field activities of the Virginia Institute of Marine Science (VIMS) were cancelled on 23 June and efforts were redirected to monitor the effects of flood waters from Agnes on the James, York and Rappahannock Rivers, and lower Chesapeake Bay (south of the Potomac River). A sampling program was established which required measurement of various parameters in each major Virginia tributary to the Bay, the lower portion of Chesapeake Bay and contiguous continental shelf waters. The program included the following physical measurements:

1) Continuous measure of surface to bottom currents at no fewer than five stations at the mouth of Chesapeake Bay, four stations across the Bay near the mouth of the Potomac River, two stations near the mouth of the James River and two stations at the general head of the salt intrusion in the James, one station near the mouth of the York River and one station where the York is formed by the confluence of the Mattaponi and Pamunkey Rivers and one station near the mouth of the Rappahannock River.

2) Daily "same slack" sampling runs in the lower portion of the Bay and each of the three major Virginia tributaries were to provide surface to bottom measures of temperature, salinity, dissolved oxygen and suspended sediments at intervals of no more than five nautical miles in the rivers and ten nautical miles in the lower Bay.

3) No fewer than two cruises a month on the continental shelf to measure temperature and salinity at selected stations between Cape Charles, Virginia and Cape Hatteras, North Carolina.

4) Simultaneous weekly occupation of all current meter stations on any particular transect to obtain hourly measures of surface to bottom temperature, salinity, dissolved oxygen and suspended sediments for no fewer than 25 continuous hours.

Thus "Operation Agnes" was begun. It was evident that although the operation was an extremely ambitious undertaking for VIMS, there was much more that should be done, particularly in the upper portions of the Bay. Consequently, the directors of the Chesapeake Bay Institute (CBI) of The Johns Hopkins University in Baltimore, Maryland and the Chesapeake Biological Laboratory (CBL) of the University of Maryland's Natural Resources Institute were contacted, informed of our plans and urged to establish flood effect monitoring programs in the Maryland portion of the Bay.

The inventory of oceanographic equipment at VIMS was sufficient to undertake Operation Agnes but allowed for only minimal down time on most gear. The Institute's staff was adequate to execute the Operation, but would require many twelve-hour days in both field and laboratory. We lacked a sufficient fleet of crewed sampling vessels and had no immediately apparent source of funds to scientifically monitor the impending disaster.

Federal and Virginia State Agencies were called on to assist in our sampling platform needs. Responses were, in almost all cases, immediate and most negotiating was accomplished by telephone. Table I list agencies and institutions which furnished logistic and coordinating support to VIMS during Operation Agnes.

Securing funds to pay for the collection, processing and analysis of samples was a more difficult task. Funding agencies are justifiably reluctant to commit resources to spur of the moment research efforts with somewhat loosely defined goals. Nonetheless, after several weeks of negotiating, numerous federal agencies responded with grants and contracts to help pay for Operation Agnes.

They are listed in Table II and we are grateful for their response and cooperation.

Table I

Agencies Furnishing Logistic and Coordinating Support During Operation Agnes

A. Manned Vessels
<u>NOAA</u> - National Ocean Survey and National Marine Fisheries Service
<u>U.S. Navy</u> - Naval Oceanographic Office, Naval Ordinance Laboratory and Atlantic Fleet
<u>U.S. Army</u> - Corps of Engineers, Norfolk and, Transportation Corps, Ft. Eustis
<u>U.S. Coast Guard</u> - Coast Guard Training Center, Yorktown, Va., and 5th Coast Guard District
<u>Virginia Marine Resources Commission</u>
<u>Virginia Pilots Association</u>

B. Aircraft
<u>NASA</u> - Headquarters, Washington, D.C.; Langley Research Center and Wallops Station
<u>U.S. Air Force</u> - Langley Field

C. Other
<u>NASA</u> - Langley Research Center (Instrumentation)
<u>U.S. Coast Guard</u> - (Sampling from Light Stations)
<u>Virginia Department of Health</u> - (bacteriological assessment)
<u>Virginia Water Control Board</u> - (water quality, damage assessment)
<u>Virginia Division of Water Resources</u> - (streamflow)

D. Coordination
<u>NOAA Headquarters</u>
<u>U.S. Army Corps of Engineers, Chief's Office</u>
<u>NASA Headquarters</u>

Table II

Agencies Contributing Funding to Operation Agnes

National Oceanic and Atmospheric Administration
National Science Foundation
U. S. Army Corps of Engineers (Philadelphia, Baltimore and Norfolk Districts)
Environmental Protection Agency
Food and Drug Administration
Office of Emergency Preparedness

Intensive sampling during Operation Agnes persisted from 23 June to 31 August 1972 with monthly sampling extending to November 1972. The sampling program produced over 20 thousand hours of current meter records and over 25 thousand samples to be analyzed for salinity, dissolved oxygen and suspended sediment. Results of these analyses produced a comprehensive picture of the physical environmental effects of the most severe flood in the Chesapeake Bay region in recorded history.

III. SCIENTIFIC RESULTS OF OPERATION AGNES

In this paper, Chesapeake Bay is defined as the body of water between 37° and 38° North Latitude which is formed by the confluence of estuarine portions of the Susquehanna and smaller rivers from the north, the estuaries of the Potomac, Rappahannock, York, James and smaller rivers from the west and several small rivers from the east as shown in Figure 1. This definition will, no doubt, be disputed by some but best fits the discussions which follow.

A. River Flow

The deluge from Tropical Storm Agnes, on a saturated watershed, resulted in immediate flooding of the major tributaries to Chesapeake Bay. Most rivers crested at levels higher than previously noted in some two hundred years of record. Table III lists average flows for the month of June as well as average daily flows and instantaneous peak discharges for major tributaries to Chesapeake Bay for the period 20 to 27 June, 1972. These flows were measured (or estimated) at the furthest downstream gauging station in each river (usually just upstream of the region of tidal influence).

From 21 to 30 June, 1972, the Susquehanna River, usually responsible for 61% of the fresh water contributed to Chesapeake Bay in June, had flows averaging 15.5 times greater than normal. This river accounted for 64% of the fresh inflow to the Bay for the ten-day period and resulted in a 30 nautical mile translation of fresh water downstream (based on the movement of the 5 ppt isohaline) (Schubel, Carter and Cronin, 1974). Had Chesapeake Bay been a reservoir, the water level in the Bay and all its tidal tributaries would have been increased by approximately two feet from the ten-day Agnes-induced flooding of all major tributaries.

The relative effect of Agnes flooding on each major tributary becomes apparent when flows are normalized to average June flows. Figure 2 shows daily normalized flows for the major tributaries to the Bay during the period 20 June - 5 July 1972. Normalized peak instantaneous flows are also shown. From this figure, it is apparent

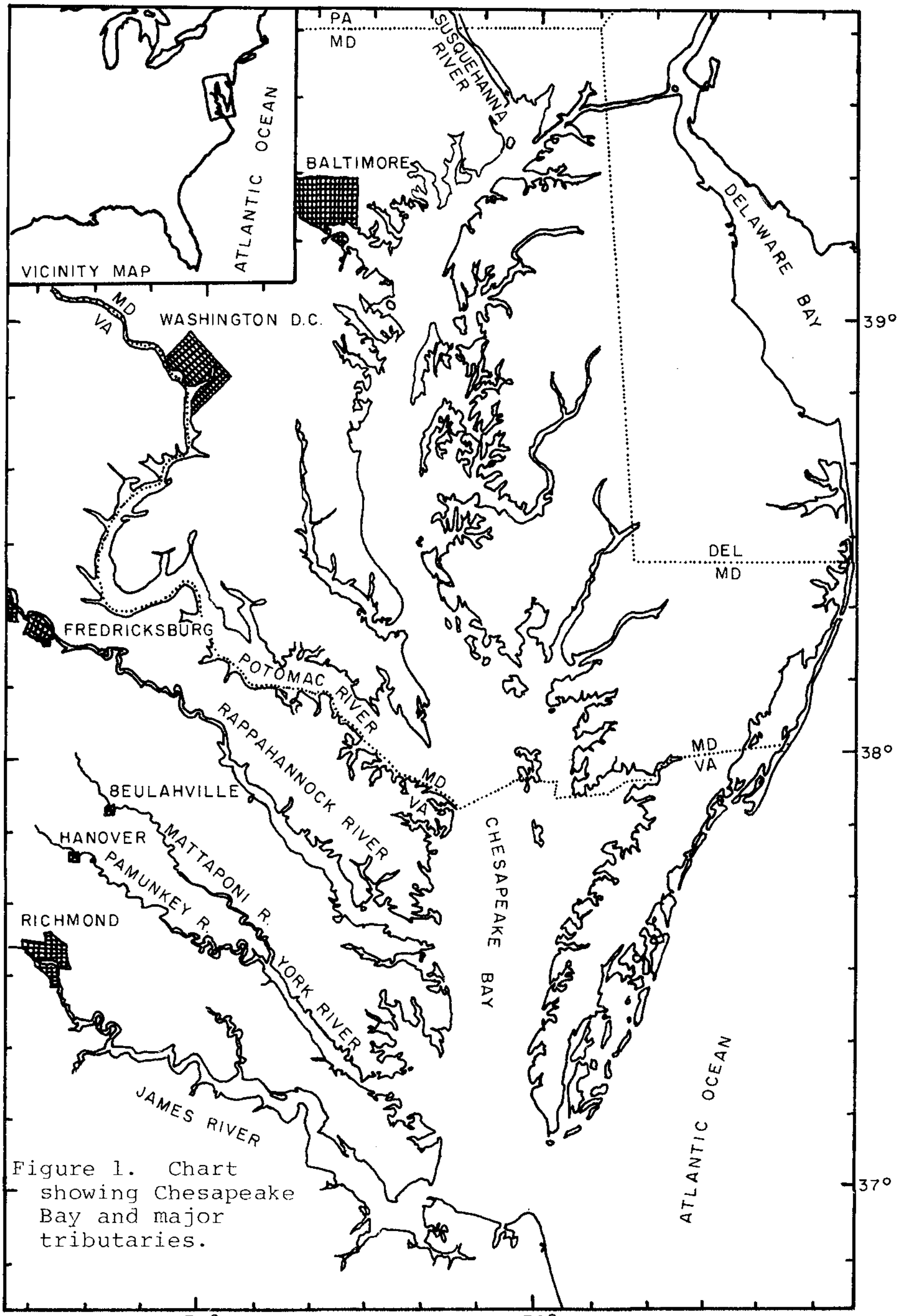


Figure 1. Chart showing Chesapeake Bay and major tributaries.

Table III

Gauged Flows for Major Tributaries to Chesapeake Bay
During Flooding from Tropical Storm Agnes
(Numbers in parenthesis indicate instantaneous peak flows)

River (Gauging Station)	Normal Avg. June Flows (cfs)[1]	Average daily flows (cfs)[1] for June, 1972: 20	21	22	23	24	25	26	27
Susquehanna (Conowingo, Md.)	35,000	48,600	50,400	445,000	1,040,000	1,120,000 (1,130,000)	1,010,000	696,000	418,000
Potomac (Washington, D.C.)	8,020	7,160	12,000	172,000	268,000	334,000 (359,000)	200,000	79,800	35,600
Rappahannock (Fredericksburg, Va.)	1,240	1,090	6,380	84,200 (107,000)	44,500	18,200	7,410	5,100	4,600
York (Beulahville, Va.) (Hanover, Va.)	859	1,793	3,091	10,460	30,730 (35,630)[2]	34,300	32,500 (33,200)[2]	28,700	21,480
James (Richmond, Va.)	4,650	9,220	14,300	136,000	296,000 (313,000)	210,000	88,700	28,700	19,900

Note: 1 - cfs = cubic feet per second.

2 - The York River has two major tributaries where furthest downstream gauging stations are located: On the Mattaponi River, the gauging station at Beulahville, Va. recorded a peak instantaneous flow of 16,900 cfs on 25 June; on the Pamunkey River the gauging station near Hanover, Va. recorded a peak instantaneous flow of 29,900 cfs on 23 June. These instantaneous peak flows, combined with average daily flows in the associated York tributary gave combined peak flows into the York system as shown.

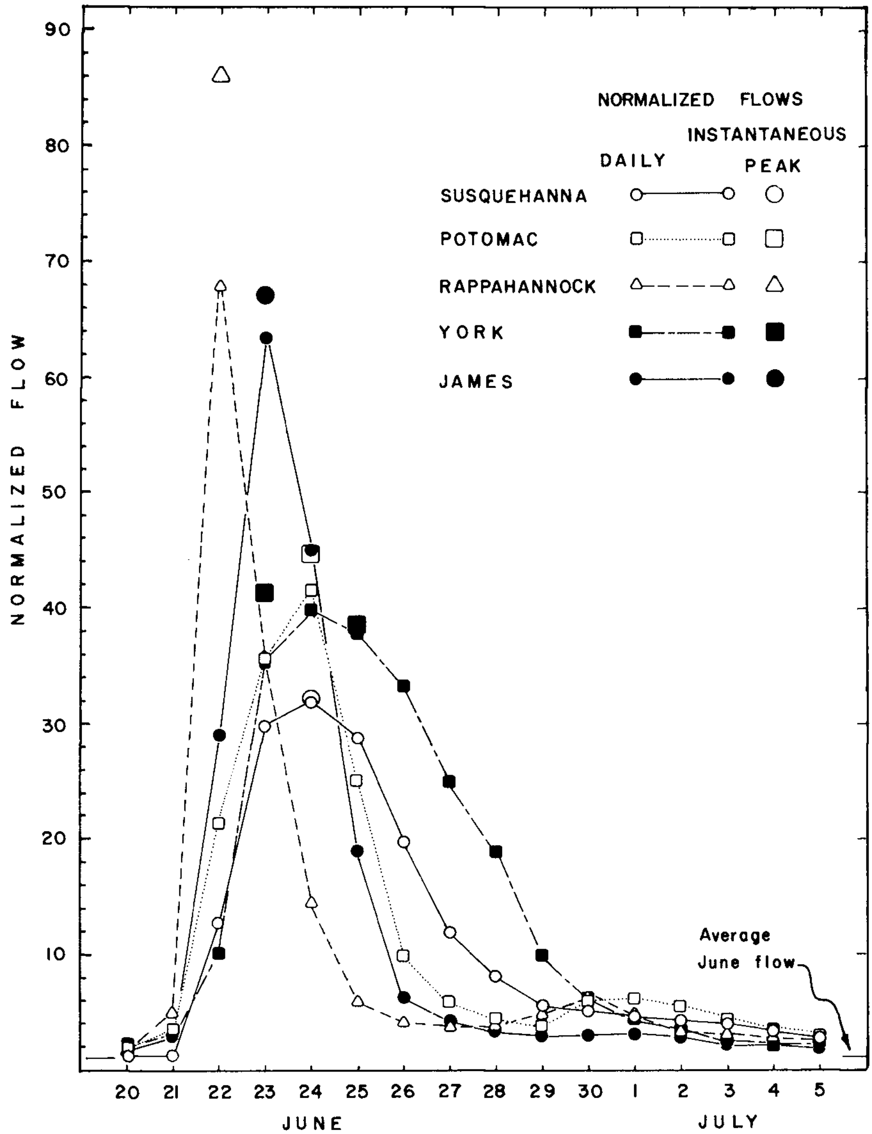


Figure 2. Normalized flows for major tributaries to Chesapeake Bay during flooding from Tropical Storm Agnes (1972).

that two forms of flooding occurred: (1) an abrupt flow increase in excess of 60 times normal, followed by an equally abrupt decrease in flow back to approximately six times normal as is illustrated by the James and Rappahannock Rivers, and (2) a somewhat slower increase in flow to 30 or 40 times normal followed by a decrease in flow which took twice as long as the increase as is illustrated by the Susquehanna and York Rivers. The normalized record for the Potomac River falls somewhere between these two. Table IV illustrates that for normalized flows, flooding in the York River was most severe. When actual volumes of water are considered, however, flooding in the York was least severe because of the low flows usually experienced in June (see Table III). Of all major tributaries to the Bay, the York was least affected by Agnes induced flooding.

Table IV

Normalized Flows for Major Tributaries to Chesapeake Bay for Various Periods of Flooding Due to Tropical Storm Agnes (flows are normalized to the long term average June flow).

River	Normalized Flows (1972)		
	7 Days 21 to 27 June	10 Days 21 to 30 June	15 Days 21 June to 5 July
Susquehanna	19.5	15.5	11.6
Potomac	19.7	15.4	9.2
Rappahannock	19.6	15.2	11.3
York	25.3	21.2	15.2
James	24.4	18.0	12.8
Total	22.2	17.3	12.4

B. Effects of Flood Waters on the Salinity Distribution in Chesapeake Bay, It's Major Tributaries and Contiguous Continental Shelf

Prior to the Agnes flood, Chesapeake Bay was in an unusual hydrographic condition. Whereas water temperature was similar to that expected in late spring or early summer, the salinity distribution was most akin to that expected in mid-spring owing to greater than average flows during the preceding winter and spring. Hence, salinity was depressed more than in June of a year of more normal rainfall.

Chesapeake Bay and each of its major tributaries showed similar reactions to Agnes flooding. Generally, four stages were observed by Kuo and Ruzecki (1974) and are shown in Figure 3.

1) Initially, flood waters forced surface salinities downstream several miles while bottom salinities remained somewhat constant, producing highly stratified estuaries. Distance and duration of the displacement were dependent on the dimensions of each particular basin and the magnitude of flooding within that basin.

2) The second stage of reaction to the flood was similar to the first but operated on bottom rather than surface waters shifting them downstream. This resulted in vertically homogeneous estuaries of very low salinity.

3) The third stage was essentially a reaction to the first two and is presumed to be the result of gravitational circulation. During this stage, there was a net transport of salt up the estuaries. This transport started in the lower layers, eventually acted on surface water and, particularly in the lower layers, moved salt water upstream substantially beyond the pre-Agnes position.

4) The final stage was vertical mixing between surface and bottom waters which resulted in salinity structure similar to that expected during a "normal" summer. This final stage of the reaction to Agnes-induced flooding was generally underway, for the Chesapeake Bay system, by the end of September, approximately 100 days after the flood waters crested at the fall line.

The generalized sequence of events described above was evident to some extent in the Bay and all major tributary estuaries but was most pronounced in the Bay and the James and York Rivers. The remaining major tributaries showed the first two (downstream directed) stages but were subjected to Bay-tributary interactions during the third (upstream directed) stage. At the time the Potomac and Rappahannock rivers went through the third stage, the up-Bay encroachment of high salinity water had not reached their mouths. The result was an upstream movement of slightly salty water into these rivers from the northernmost portion of the Bay. This situation did not occur in the James and York rivers because of their proximity to the ocean.

The Bay was subjected to a cascade of flooding from the Susquehanna and Potomac. The early effect is shown in Figure 4 which illustrates surface salinities for the period 29 June to 3 July. Flood waters from the

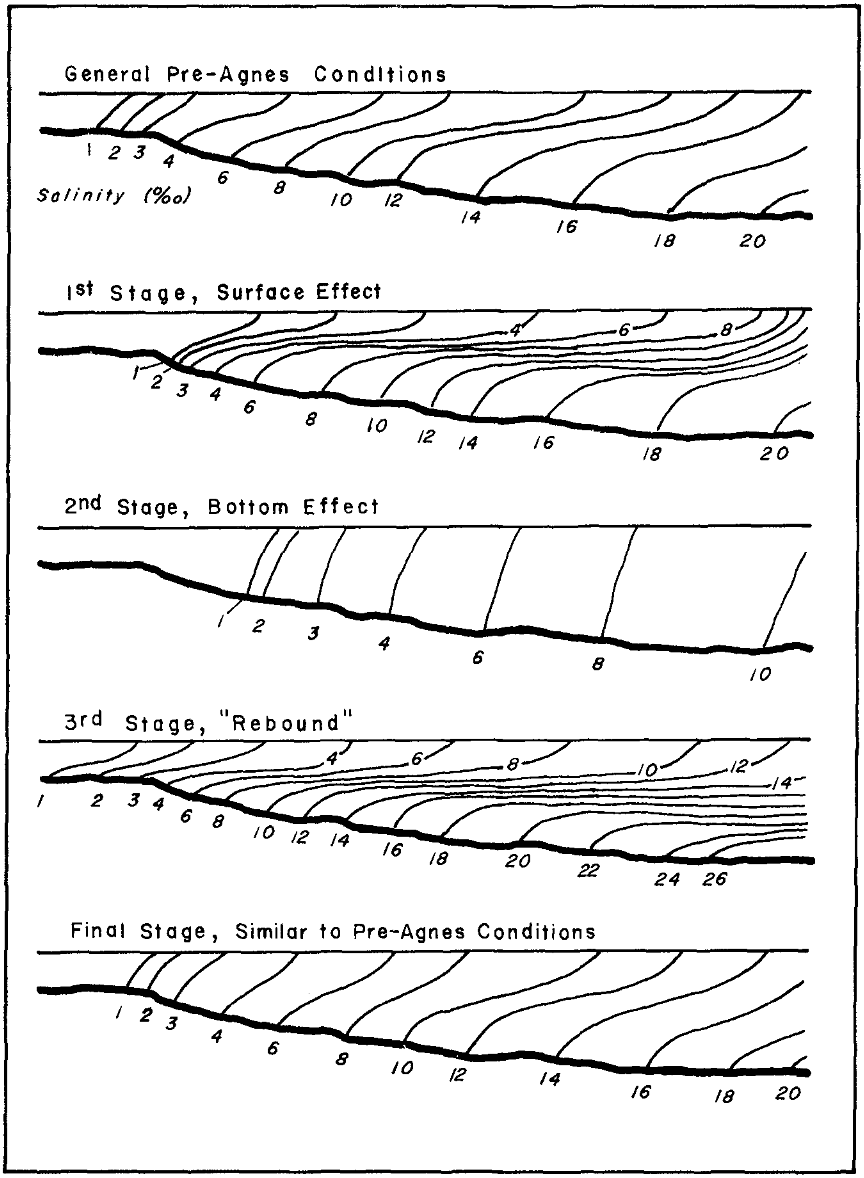


Figure 3. Schematic representation of sequential isohaline configuration in major estuaries of the Chesapeake Bay System resulting from flooding due to Tropical Storm Agnes.

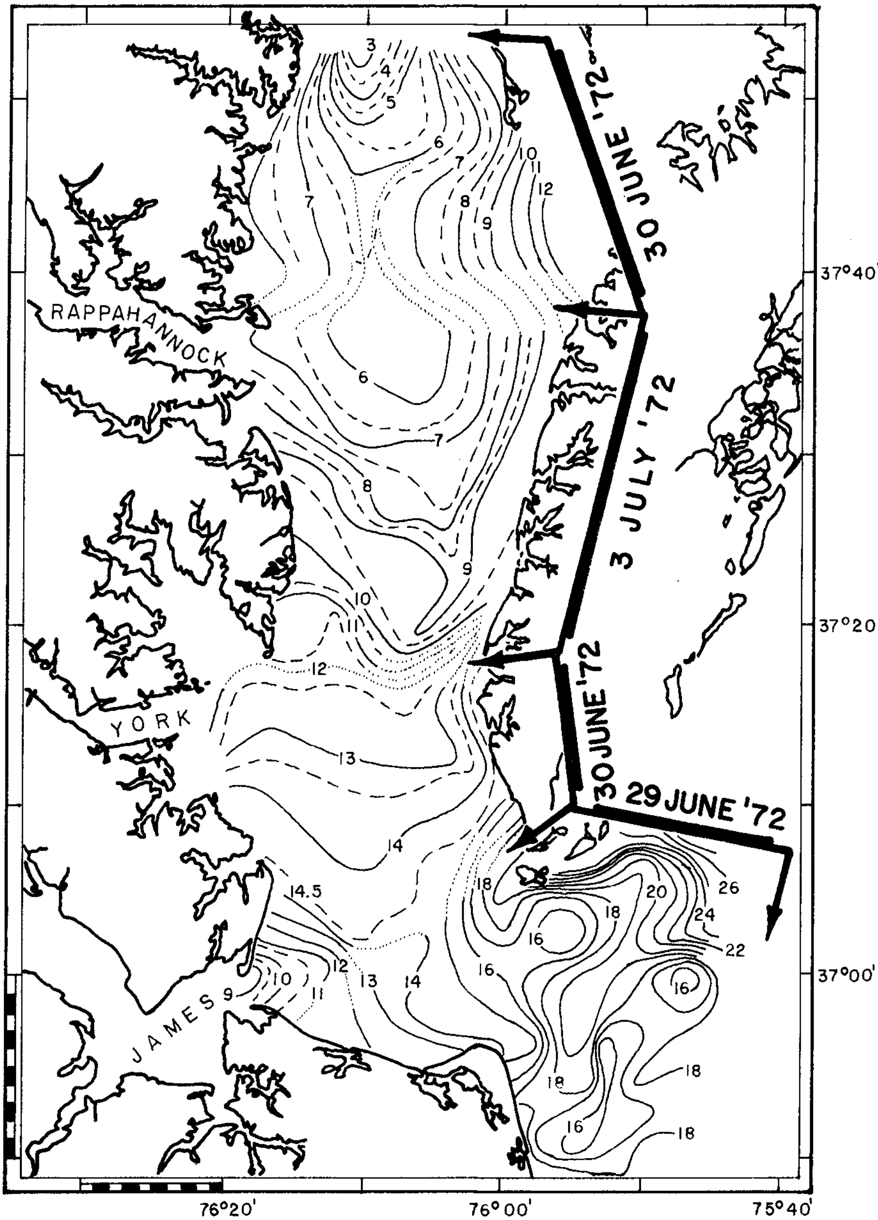


Figure 4. Surface salinities of Chesapeake Bay taken 29 June to 3 July 1972 approximately one week after flood waters from Tropical Storm Agnes crested at the fall line.

Susquehanna and Potomac coursed down the center of the Bay bypassing pockets of higher salinity water in smaller tributaries on either side. Sampling on 30 June and 3 July occurred at approximately the same tidal stage and results show a 12.5 nautical mile downstream excursion of the 6 part per thousand isohaline. The combined effects of wind and tide resulted in the pulsing of small patches of 16 ppt surface water from the Bay mouth. Approximately seven days later, large patches of freshened water from the Potomac and Rappahannock had progressed some distance downstream from their mouths. At the same time, high salinity water had begun moving up the Bay along its eastern side. By 15 September, surface salinities in the lower portion of the Bay (south of the mouth of the York River) appeared to be recovering towards more normal conditions as shown in Figure 5. For comparison, more "normal" surface salinities are shown in Figure 6 which covers the period 16-17 July 1973. Figures 4, 5, and 6 are each the result of surface water samples taken by helicopter on a square grid with station spacing of approximately 2 nautical miles.

Analyses of over 120 sampling runs conducted on the James, York, and Rappahannock Rivers indicate that these tributaries to the Bay were subjected to internal seiches which were generated by the flood shock. These internal oscillations with periods from four to fifteen days helped to vertically mix the estuaries (Hyer and Ruzecki, 1974).

Location of measurements of tide and currents and surface to bottom water sampling points are shown in Figure 7. Tide and current measurements discussed below were made at locations which have closed symbols in Figure 7.

Current and tide data from the James River analyzed by Jacobson and Fang (1974) indicate the following:

1) Rise in water level was slight in the tidal rivers when compared with that experienced above the fall line. Water level elevations of approximately 6 feet occurred in the upper portions of the tidal rivers, but no change was discernable at the mouths. Passage of the storm's low pressure center caused an increase in water level of a few inches. These features are illustrated in Figure 8a and b which resulted from tidal records at Hopewell and Norfolk (Seawells Point).

2) The normal tidal current pattern was disrupted, there being a continuously ebbing current for several days as far downstream as the zone of transition from fresh to salt water. Downstream of that zone, surface waters

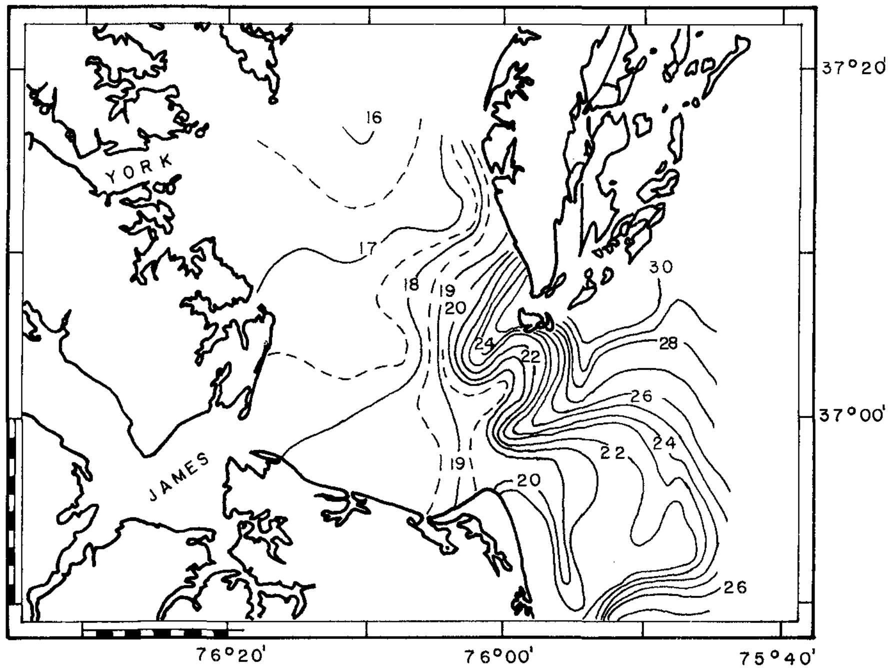


Figure 5. Surface salinities of Lower Chesapeake Bay and adjacent continental shelf taken on 13 September 1972, approximately 3 months after flood crest from Tropical Storm Agnes passed the fall line.

ebbed continuously for three days after the flood crest passed Richmond, but lower layers showed normal ebb and flood current oscillations.

Movement of Agnes flood waters onto the continental shelf was traced with one cruise by the Chesapeake Bay Institute and five cruises by the Virginia Institute of Marine Science and is described by Kuo, Ruzecki and Fang (1974). Flood waters leaving the mouth of the Bay moved southward along the coast. Freshened water remained in the upper 10 meters of the water column and was broken into large patches by tidal motion at the Bay mouth. Mixing of the patches of fresh water with ocean water was most prominent on their eastern boundaries, there being little vertical or north-south mixing.

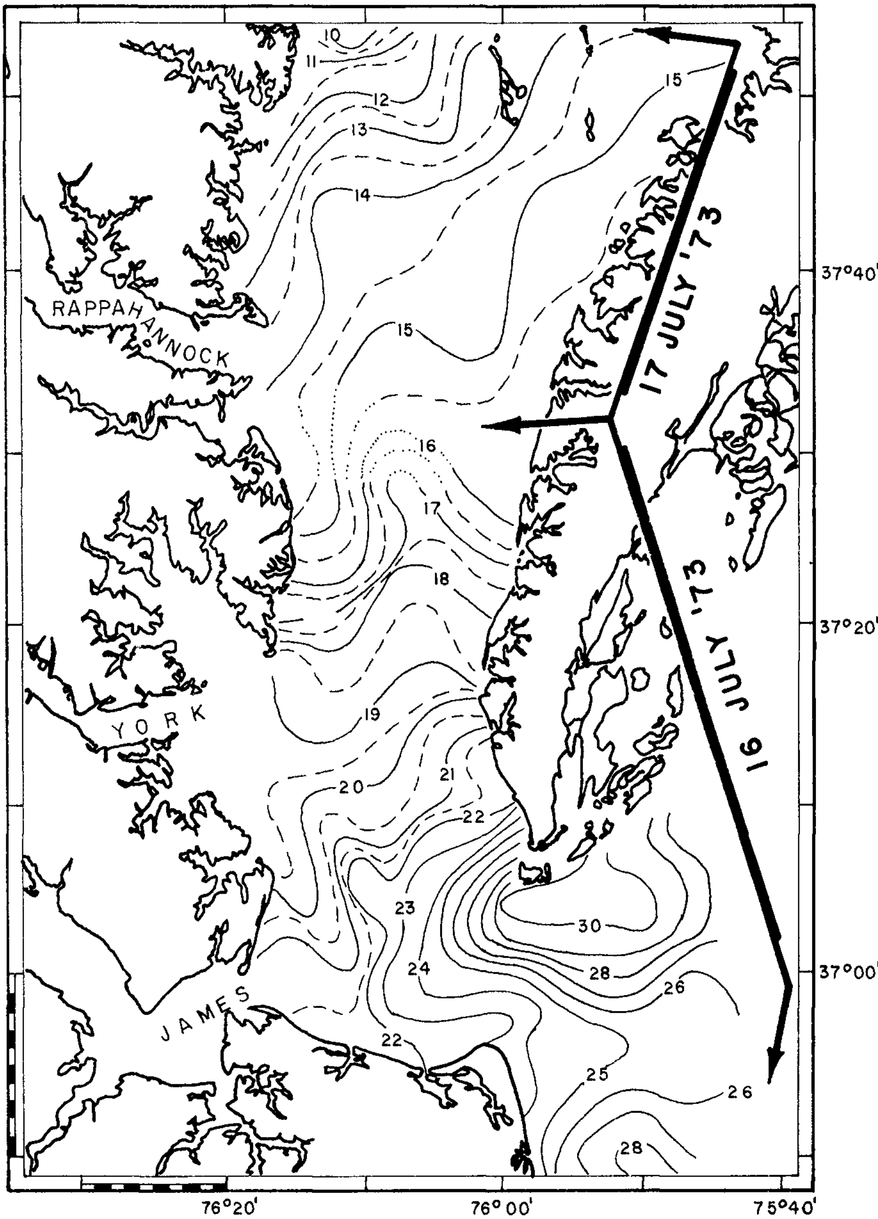


Figure 6. Surface salinities of Chesapeake Bay during July 1973.

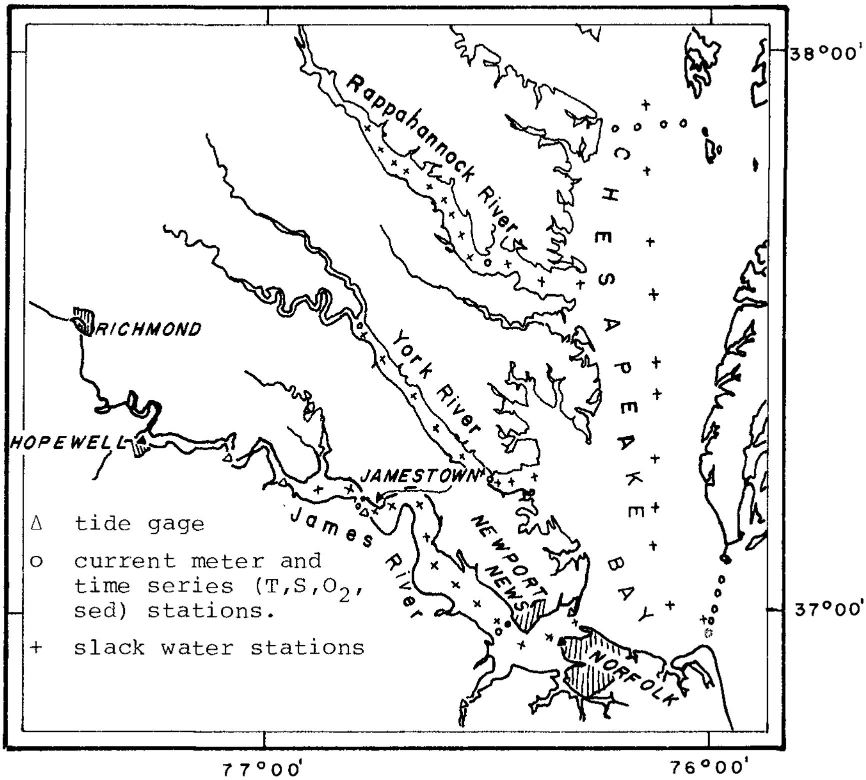
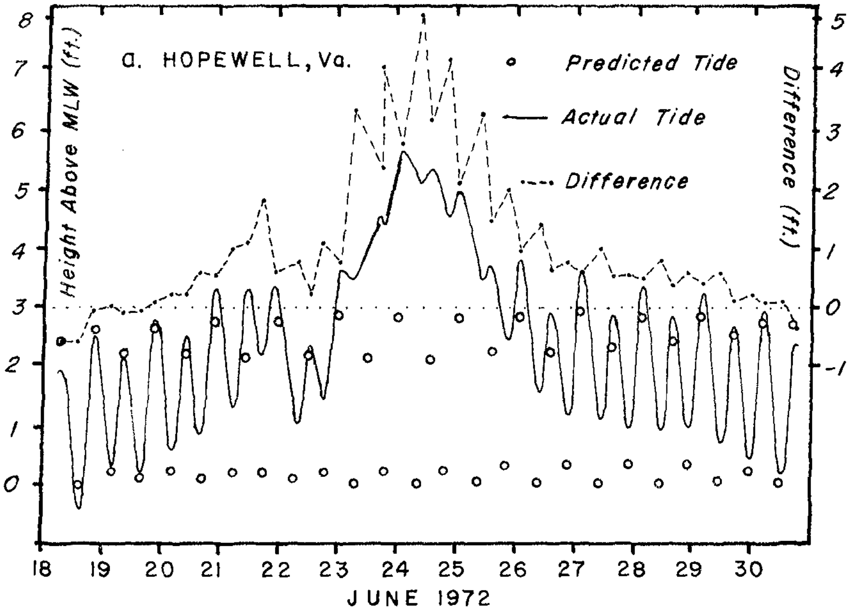


Figure 7. Locations of slack water and current meter stations and James River tide gages occupied during Operation Agnes June-Sept. 1972.

C. Effects of Agnes Flooding on Smaller Tributaries to Chesapeake Bay

In general, small tributaries to the Bay became reverse estuaries after the passage of the Agnes flood. Their normal source of salt water, the Bay, became substantially fresher than these small rivers. Fresh water moved upstream from the mouth in the surface layers and saltier water moved from the upstream reaches toward the mouth in the lower layers. These conditions persisted for varying lengths of time depending on the recovery of adjacent portions of the Bay. Seiche conditions similar to those observed in the large tributaries were evident as surface phenomena and were attributed to wind set-up rather than freshwater flooding.



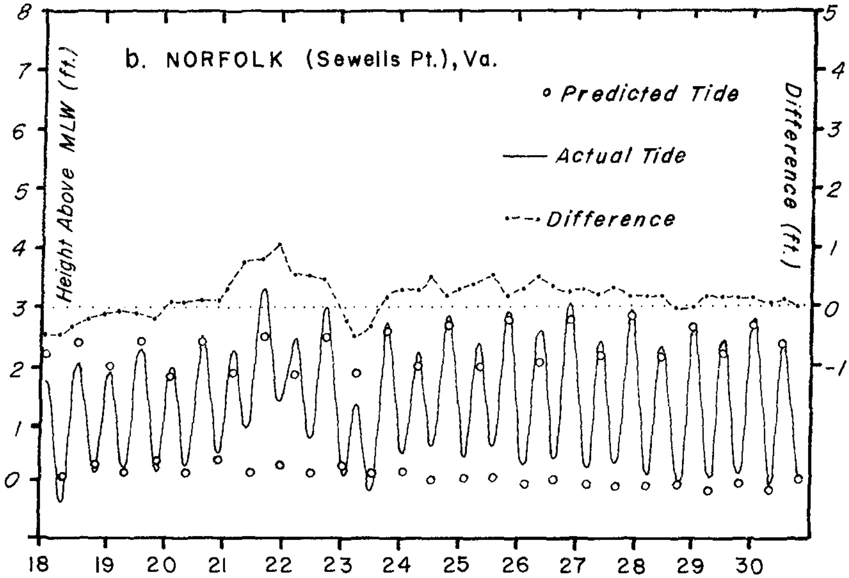


Figure 8. Predicted, and measured tides and their difference for a) Hopewell, (near the fall line) and b) Norfolk (near the mouth) in the James River during the period of flooding from Tropical Storm Agnes (Jacobson & Fang, 1974).

D. Recovery of the System

Flooding from Tropical Storm Agnes was catastrophic in the Chesapeake Bay drainage system. However, the effect on tides, currents and the distribution of sea salt within the estuarine portion of the system was short lived. Tidal fluctuations in the lower reaches of the James River estuary were only slightly effected by the flood waters. All tide gages in that river were recording normal fluctuations within a week of passage of the flood crest at the fall line. Predicted values of ebb and flood currents were matched within ten days. Salinities returned to normal within 100 days.

This rapid recovery progressed upstream, was initiated in the lower layers of all monitored portions of the system and was primarily the result of the "reaction" to the first two stages of the flood effect. If the Chesapeake Bay estuarine system had been subjected to the same volume of flood water over a substantially longer period of time, recovery of salinities would have taken much longer because the upstream surge of highly saline bottom water would have been much less intense.

E. Summary

It has not been possible to describe all of Operation Agnes, especially as it relates to the operations conducted in the upper portion of the Chesapeake Bay and its tributaries. Left for another communication must be descriptions of the efforts of the Chesapeake Bay Institute, the Chesapeake Biological Laboratory, the National Marine Fisheries Service, Laboratory at Oxford and the Environmental Protection Agency Laboratory at Annapolis. All participated and added much.

We have presented some details of the massive field and laboratory operations which evolved quickly to examine the various effects of Tropical Storm Agnes on this complex tidal system and adjacent coastal waters.

This multidisciplinary operation was designed to examine 1) physical, chemical and geological effects and attendant biological and social effects, and 2) the cycle of recovery.

It has been shown that the Chesapeake, itself, and its principal Virginia tributaries, behaved similarly. Smaller tributaries showed different responses.

In summary, the Bay and the Potomac, Rappahannock, York and James Rivers showed four stages:

a) Severe vertical stratification produced a large downstream displacement of surface isohalines.

b) Displacement of bottom isohalines downstream, eliminating the vertical stratification.

c) Net upstream transport of salt water in the lower layers to positions further upstream than before the flood.

d) Recovery, to normal isohaline patterns after vertical mixing. This last stage was reached within about 100 days after the floods.

There was some variation to this pattern depending upon proximity to the ocean.

Smaller tributaries became reverse estuaries with salt water moving out at the bottom while fresh water moved upstream on the top.

Water height observations showed that water levels in the tidal system did not rise a great deal on the average as compared with the situation at and along the fall line area. However, levels were much higher below the fall line and diminished downstream until no change was detected at tide gages located in the lower estuaries.

Tidal current patterns were disrupted. A continuous ebb occurred in the area above the salt water zone. Below the salt water transition zone surface water ebbed continuously for three days while the lower layers showed normal ebb and flood current oscillations.

The results are interesting since they represent a picture of a great tidal system under conditions of extreme fresh water stress and the phenomena related thereto. It is noteworthy that Agnes produced certain biological effects which have had severe economic and social repercussions. For example, much of the Chesapeake was closed to "body contact" sports and to direct harvesting of shellfish as a result of the high bacterial counts which occurred or of the threat of bacterial contamination.

Additionally, severely depressed salinities killed economically important oysters and soft clams over a wide area. This produced immediate damage to the associated fishery activities. Too, evidence is strong that Agnes prevented the setting and survival of oyster larvae and "spat" (immediate post-setting stages). Thus, the effects on the oyster industries of the Bay were immediate as well as of long duration.

Populations and the fishery have not as yet recovered--two years later.

As a result of the physical work and associated fishery observations, it was possible to justify economic assistance to public and private sectors of the oyster industry. To our knowledge, this is the first time that this has occurred in a situation of this nature. Thus, the physical research has not only yielded new insights into natural phenomena but has also produced immediate economic and sociological benefits.

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