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ECOLOGICAL AND PHYSIOLOGICAL STUDIES OF THE EFFECT OF SULFATE PULP MILL WASTES ON OYSTERS IN THE YORK RIVER, VIRGINIA

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Ecological and Physiological Studies of the Effect of Sulphate Pulp Mill Wastes on Oysters in the York River,[1] Virginia

For more than a quarter of a century the oyster industry of the York River in Virginia has experienced a gradual decline resulting from poor quality of the oysters, particularly from the upper section. This decline in the yield of oyster bottoms has brought severe losses and hardship to many people dependent on this industry for a means of livelihood. Numerous requests were made from time to time for the former United States Bureau of Fisheries, now a part of the Fish and Wildlife Service of the Department of the Interior, to determine the cause of the poor quality of the oysters. The first request was made in December 1916, when many of the oyster planters of the York River drew up a resolution expressing their belief that the discharge of wastes by a paper mill established at West Point, Va., in 1913, was damaging their oysters. They urged that the Federal Government investigate the cause of the failure of their oysters to grow and fatten. In response to this request, the first survey of the York River oyster bottoms was made in September 1917 by L. H. Almy, fish pathologist of the Bureau of Fisheries. After determining the salinity, alkalinity, and the dissolved oxygen content of the water at three stations near West Point, he arrived at the conclusion that the pulp mill was not at that time polluting the river "with any material which can in any manner affect the growth of oysters." He admitted, however, that some subtle change had taken place in the York River, the extent and nature of which could not be determined.

In 1918, another investigation was made by E. P. Churchill and J. S. Gutsell of the Bureau of Fisheries, in cooperation with W. W. Skinner and J. W. Sale of the Bureau of Chemistry, Department of Agriculture. In the course of these studies three trips were made, in winter, spring, and late summer, to collect samples of water, mud, and oysters at different stations. So far as the solution of the problem is concerned, the investigation produced negative results for it failed to arrive at any definite conclusion. No heavy metals which may be toxic to oysters were found in the samples of water, and the presence of sulfites and sulfides, which may exert deleterious effects on oysters, was not demonstrated in the effluents, presumably because no field tests for these oxidizable substances were carried out and the samples were examined only in the laboratory. The investigators suspected, however, that extractive matter of the pulp-mill effluent may have contributed indirectly to the destruction of oysters. They also stated that "the appearance of the condition of oysters * * * suggests the possibility of a depleted food supply and that the oysters are actually starving" but "are not being directly injured by the effluents from the mill."

It was obvious from the results of the two surveys that the York River conditions presented a very difficult and complex problem which could not be solved by casual ecological observations or by analyses of the samples of oyster-meats, mud, and water collected incidentally from a few stations. The solution of the problem called for well-planned and long-continued field and laboratory studies on the biology and physiology of the York River oyster, and chemical investigations into the nature of the pulp-mill wastes. An investigation of this type involves systematic ecological observations, physiological experimentation, and chemical studies. A well-equipped shore laboratory, special field equipment, and suitable boats are needed for the conduct of such a research problem.

Funds for the York River investigations were made

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[1] Approved for publication October 11, 1946. Fishery Bulletin 43.

available in 1935 by a special allotment from the Public Works Administration. Continuation of the project was made possible by regular allotments by the Bureau of Fisheries and appropriations from the Commonwealth of Virginia through its Commission of Fisheries. In October 1935 a laboratory was established at Yorktown, Va., where a satisfactory supply of sea water was available for physiological studies on oysters. A boat suitable for the field observations was supplied by the Virginia Commission of Fisheries. Studies of the chemical nature of the pulp-mill effluents were carried on from July 1938 to July 1940 at laboratories made available by the College of William and Mary.

The general plan of the investigation was outlined by Dr. Paul S. Galtsoff, who is responsible also for developing the technique of bioassays employed in testing the effects of pollutants on the rate of pumping of water by oysters. The largest part of the laboratory and field work was carried out by Dr. Walter A. Chipman, Jr., in cooperation with Dr. Arthur D. Hasler, who participated in this project from October 1935 to June 1937. James B. Engle was engaged from June 1936 to July 1937 in field observations on methods of oyster cultivation employed by local oyster growers, and participated in other routine laboratory and field work. Dr. Howard N. Calderwood, who joined the staff in July 1938, conducted chemical studies of the pulp-mill effluents and was responsible for the fractionation of the pollutant and preparation of extracts used in the bioassays. Pathological studies of the York River oysters and analyses of experimental data on the effect of the pollutant on the physiology of the oyster were made by Dr. Paul S. Galtsoff with the assistance of Mrs. Dorothy H. Algire, formerly a junior zoologist of the Service. The authors are indebted to Dr. Chester I. Bliss for his advice regarding the evaluation of experimental data, and to Dr. L. B. Tuckerman of the National Bureau of Standards, for the computation of the possible accumulation of the pollutant in the York River tidal basin.

The work of establishing the laboratory and installing a sea-water system and other equipment was accomplished by Dr. Nelson A. Wells during the first few months of the investigation. In the course of the labboratory and field work, assistance was given also by Lloyd R. Garriss, Robert O. Smith, L. Winder Lane, and Alfred R. Armstrong. Valuable cooperation was rendered by the late Richard Armstrong, commissioner of the Virginia Commission of Fisheries, and his successor, the late G. Walter Mapp, and the staff of the commission. To H. A. Marmer and other members of the United States Coast and Geodetic Survey the authors are indebted for the use of some of the instruments needed for hydrographic observations, and analyses of the data of tidal-current observations in the York River. The oystermen of the vicinity have been extremely helpful in giving information regarding methods of oyster culture and in permitting the examination of their books and records. Officials of the Chesapeake Corp. have been very kind in supplying information and providing samples of pulp-mill wastes to the investigators. The authors also wish to thank J. J. Dirzulaitis, of the United States Geological Survey, for the loan of equipment, and Stewart Richardson and W. L. Howlett for their assistance in obtaining water and oyster samples.

PLAN OF INVESTIGATION

An investigation into the causes of the decline in the productivity of shellfish grounds should take into consideration various possibilities. Abnormal changes in the appearance, growth, and chemical composition of shellfish may be due to a functional disease, the presence of pathogenes, or infestation by parasites or commensals; they may be a result of adverse conditions caused by sewage pollution, the presence of poisons in the water, or some other environmental factor. On the other hand, an indirect effect brought about by man's activities should not be overlooked. Changes in ecological conditions of the river, and consequently in the productivity of its bottom, may be caused by deforestation of its drainage area, increased sedimentation, dredging of channels, and other improvements for navigation. To provide a basis for conculsions, observations made in waters suspected to be affected by pollution should be compared with those made simultaneously in another body of water which is known to be free of pollution. These control observations may be of great use in eliminating from consideration the factors present in both streams and in determining those which are primarily responsible for the decline of the fishery. Furthermore, the decline may be the result of depletion of natural resources due to lack of management and unsatisfactory methods of cultivation. All these possibilities have been taken into consideration by the investigators.

In the present investigation attempts were made to follow the natural course of events in the York River by observing seasonal changes in temperature, salinity, pH, oxygen content, currents, phosphates, and plankton. Parallel observations were carried out in the Piankatank River, which was selected for its proximity and similarity to the York River from the ecological point of view. By conducting these observations it was expected that a comparative study of the principal ecological factors operating in the two rivers might reveal the existence of some distinct differences, such as deficiency of food, lack of oxygen, etc., which would explain the poor condition of the York River oysters.

The biology of the oyster in the York River was studied in detail with special attention to the time and intensity of spawning and setting and to glycogen accumulation in oysters grown in various sections of the river. A number of field tests were conducted to determine the changes in glycogen content of York River oysters removed from the polluted area and in the seed oysters from James River planted in polluted and nonpolluted sections of the York River and in the Piankatank.

Since the official statistics of the oyster fishery cover large administrative areas and therefore are not available for the York River separately, special efforts were made to obtain authentic data from individual oyster planters and dealers who consented to submit their records and books for examination. By analyzing and separating these data it was possible to report on the condition of the oyster industry in the York River during the last 30 years.

Thorough examination of abnormal oysters was made for evidence of disease, parasitic infestation, or other pathological conditions that might be found from detailed microscopic study of the various organs and tissues. Because of the abnormal condition of the shells, detailed examination was made of the structure of the shell material.

Laboratory investigations consisted in determining the direct physiological effect of pulp-mill wastes on oysters and on the growth of a diatom *Nitzschia*, which is used by oysters as food and is frequently found on oyster grounds. Using the technique developed in previous work, records were obtained of the shell movement, efficiency of ciliated epithelium, and rate of filtration of water through the gills in clean water and in water containing known amounts of pulp-mill wastes.

Observations made during the first year of these studies showed that the pulp-mill effluent has a distinct physiological effect on oysters. In the following years attempts were made by Dr. Calderwood to explore the chemical nature of these complex materials with the view of isolating, if possible, the specific compound or compounds producing this physiological response, determining their chemical and physical properties, and rendering them harmless. This chemical investigation was closely coordinated with the experimental studies of the effect of various fractions of the pulp-mill effluent on the physiology of the oyster.

DESCRIPTION OF THE YORK RIVER

GEOGRAPHICAL AND GEOLOGICAL

The York River system, composed of the York River and its two chief tributaries, the Pamunkey and Mattaponi, together with their tributaries, is situated in central Virginia between the watersheds of the Piankatank and Rappahannock Rivers on the north, and the James Basin on the south. The drainage area of the York River system is shown on the map in figure 1. According to the United States Engineers (1930), the total drainage area is 2,663 square miles, of which about 90 percent, 2,386 square miles, are drained by the two rivers, the Pamunkey and the Mattaponi, whose confluence forms the York River at West Point. The two chief tributaries of the Pamunkey River are the North and South Anna Rivers, which have their origin in the foothills of the Blue Ridge and flow in a southeasterly direction through the Piedmont Plateau to the fall line and into the coastal plain, joining to form the Pamunkey a short distance from Ashland. The Mattaponi River is composed of the union of a number of small branches originating in Spotsylvania County. This river drains the eastern portion of the area and joins the Pamunkey at West Point.

Within the flat coastal plain the rivers are in broad valleys, the lower reaches of which meander through many miles of low country flanked by marsh lands from ¼ to 2 miles wide on either side. Almost one-half of the watershed lies within the Piedmont Plateau and is characterized by an irregular rolling topography with the streams confined to narrow valleys.

The York River (fig. 2) is a brackish estuary, an arm of the Chesapeake Bay, noteworthy for its very deep channel and the directness of its course. At

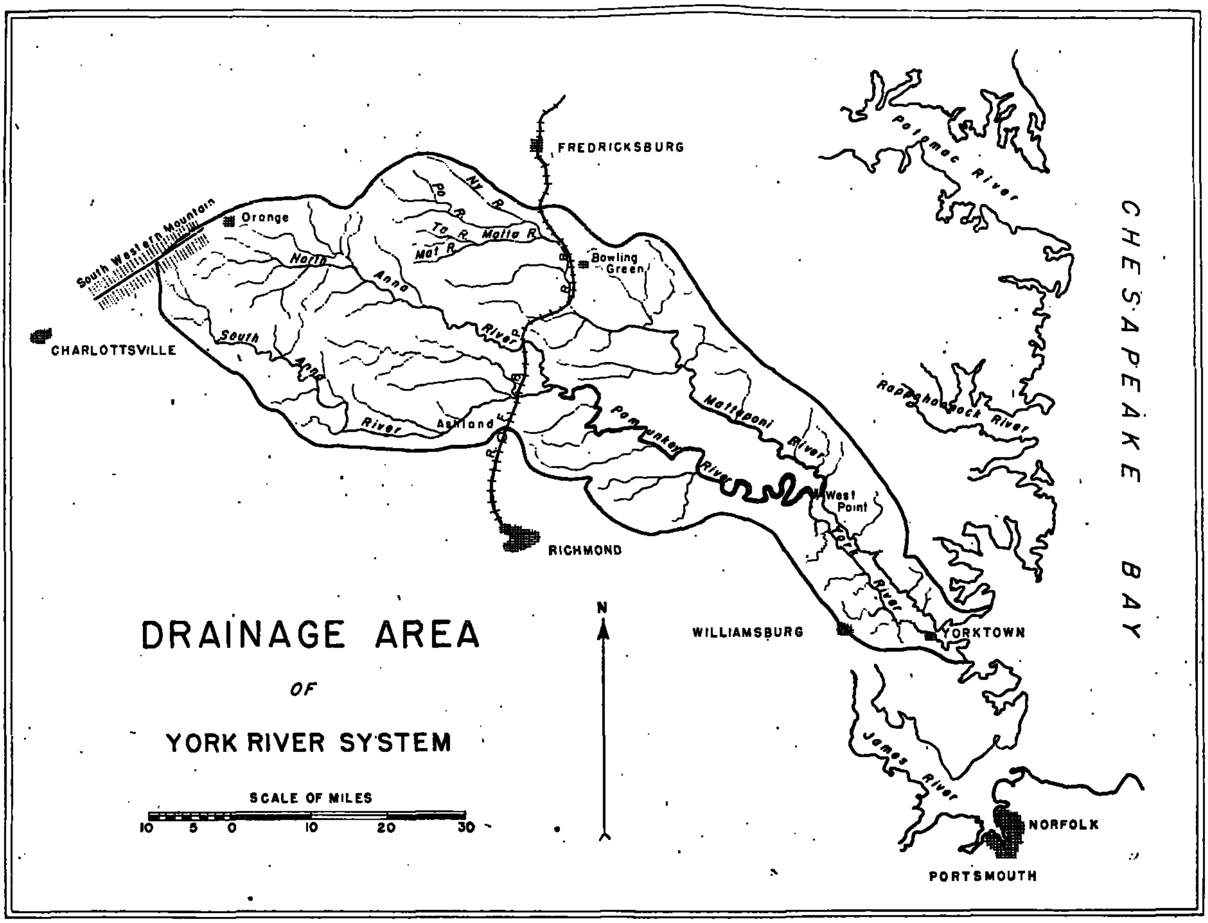

FIGURE 1.—Drainage area of the York River system. Reproduced from Document 54, Seventy-first Congress, United States House of Representatives, Pamunkey River, Va., York River system, figure 1: 1.

West Point the width of the river is 1¼ miles, and in its southeastward course of 26 miles to Yorktown the average width is 1.7 miles. Below Yorktown, the course is easterly for 7 miles and then southeasterly for another 7 miles, the river emptying into the Chesapeake Bay about 20 miles from the Atlantic Ocean and 15 miles north of Hampton Roads. As for depth, it has a navigable depth of 30 feet to within 9 miles of West Point and 35 feet to Yorktown. Improvements by the Federal Government, started in 1881, allow a navigable depth of 22 feet at low water at West Point, and depths of 6½ feet for 33 miles in the Mattaponi, and of 7 feet for 50 miles in the Pamunkey.

The creeks draining into the York River are small and inconsequential. Their presence, however, aids in the formation of the food supply for the oysters which are planted in beds in the shallow water bordering the river banks. The banks of the river are nearly parallel, and the few bays and inlets are of little importance. Purtan Bay, on the left shore, comprises about 275 acres and has a semistiff bottom used for the cultivation of oysters. Three small creeks enter Purtan Bay. Poropotank Bay, on the same side of the river about 3 miles above, is formed by the widening of the Poropotank River and is somewhat smaller. This bay is also used for the growing of oysters.

The oyster grounds of the York River are found on the flats on both sides of the river from the mouth to the head and, in a few instances, in deeper water where the bottom is of suitable nature. The largest part of the oyster-producing bottom is leased from the State by private interests. There are, however, about 800 acres of natural "rocks" owned by the State and open to the public for tonging. The names and locations of these "rocks" are: Green Point Rock, from Gloucester Point to Green Point; Pages Rock,

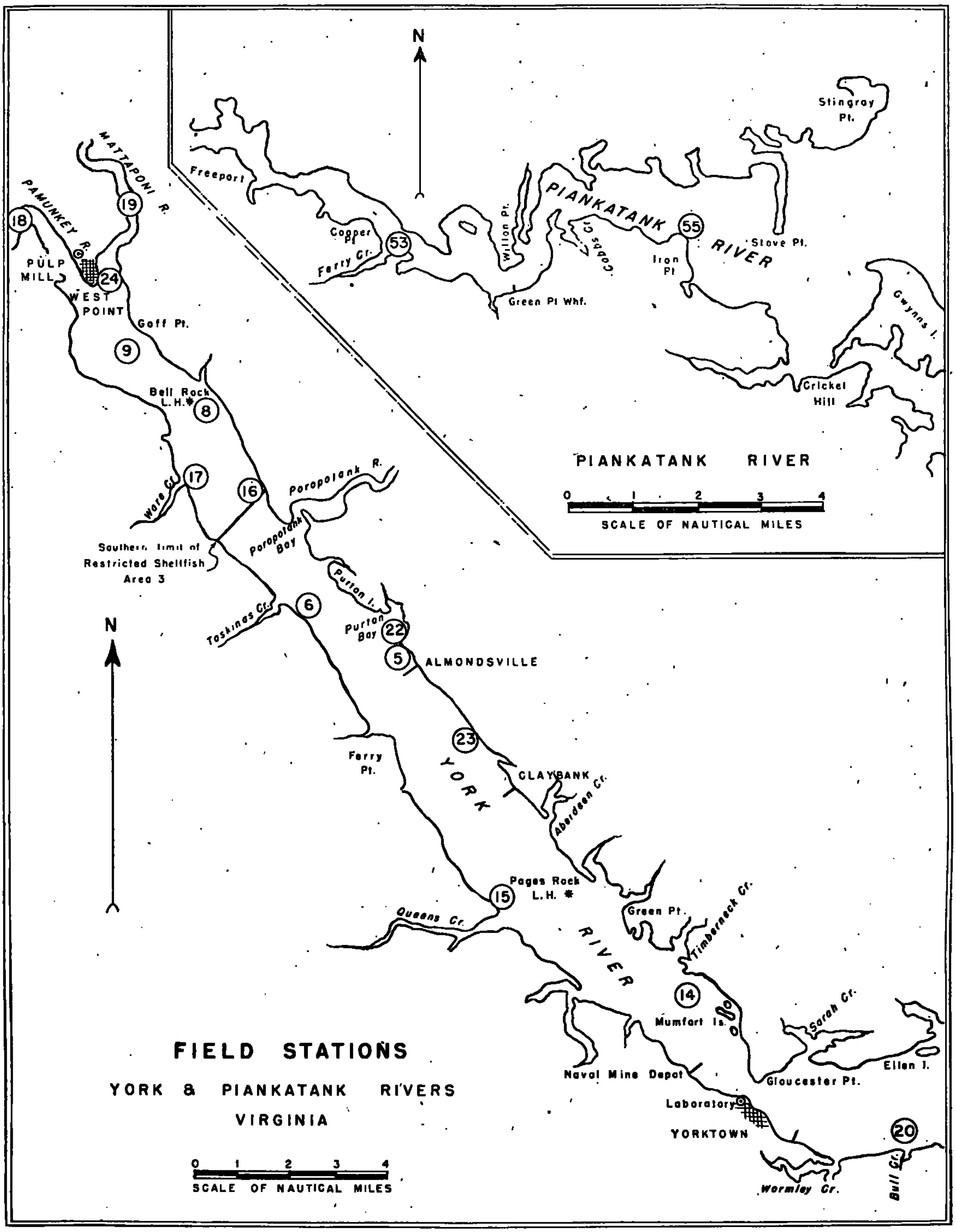

FIGURE 2.—The York and Piankatank Rivers. Sampling stations are indicated by numbers in circles.

from Green Point to Aberdeen Creek; Navy Mine Rock, off the Naval Mine Depot; Bell Rock, in the vicinity of Bell Rock Light; and Pig Rock, above Bell Rock.

The river bottom varies from soft mud to hard sand and shell gravel. Over the oyster beds it ranges from stiff mud to gravel. In the deep channels soft mud predominates.

Geologically the York River Basin is similar to the basins of adjacent streams. It is typical for the sections lying in the coastal plain and the Piedmont Plateau. Most of the following brief description is summarized from the report of the United States Engineers (1930).

The deposits of the coastal plain, the area including all of the tidewater section, are chiefly soft, unconsolidated beds of sand, clay, loam, and marl. There are a few instances of the consolidation of the sand to sandstone and of the clay to shale. The sand and clay are filled with the shells of marine animals, an indication that at one time the region was covered by the sea.

The lands of the coastal plain are of the Eocene deposit and are among the most fertile in the State, particularly those along the Pamunkey. This superiority is due to the extensive marl deposits underlying them, appearing close to the surface along the borders of the streams. The lands of the Mattaponi rest on marl and blue clay, while those of the Pamunkey rest on the more fertilizing marl known as greensand. The Mattaponi marl beds contain shells, corals, and traces of phosphates, but do not reveal the greensand common on the Pamunkey.

The Piedmont Plateau portion, extending from the fall line to the foothills of the Blue Ridge, is sharply defined along its eastern border by the fall line where the rocks of the plateau pass beneath the nearly horizontal sediments of the coastal plain. The rocks of this area are the oldest in the State, ranging from pre-Cambrian to Silurian, and are largely crystalline masses, granites, gneisses, and schists occurring locally.

The topography of the country combined with many other factors, such as the preparation of virginland for agriculture, deforestation, climatic conditions, construction of city improvements, the development of roads, has an effect on the run-off of water. The stream flow of a river is, therefore, dependent on the precipitation and on all conditions determining the run-off of waters in its drainage basin.

Owing to the proximity of the ocean, the York River Basin receives a substantial share of precipitation falling along the Atlantic coast. According to the United States Engineers (1930), the average precipitation for the entire area amounts to 41.25 inches, varying from 40 to 45 inches. The area above West Point receives 41 inches. The snowfall varies from 8 inches at the coast to about 18 inches at the western edge of the watershed, the mean being 14.3 inches for the entire area. Highest rainfall occurs in June, July, and August, the maximum for the year coming in August. March, April, and May receive the next highest amount. The minimum rainfall occurs in November. The greatest run-off occurs during the winter, and the least during the summer.

According to the records published in the Water Supply Papers, United States Geological Survey, there are only two localities in the York watershed where discharges are measured. One station is located at Ashland, Va., on the South Anna River, the drainage area being 393 square miles, or 14.8 percent of the total, and the other at Doswell, Va., on the North Anna River, the drainage area being 439 square miles, or 16.5 percent of the total. Both rivers are tributaries of the Pamunkey, and the discharges have been measured at these localities from 1929 to date. During the period 1926 to 1928, discharges were measured at Vontay and Hewlett, Va., on the South and the North Anna Rivers, respectively. The results of the measurements at these stations give the flow of the Pamunkey River above the fall line. No data are available for the Mattaponi River.

Of more importance to a consideration of the rate of flow and discharge of water for the lower portion of the watershed is the hydrograph prepared by the United States Engineers (1930) and reproduced in figure 3. This hydrograph, based on precipitation records for the York River and adjacent streams and on mean monthly run-off records for adjacent streams, shows the average monthly flow of the York River at West Point for the 20-year period starting in 1907 and ending in 1928. The mean run-off into the York River at West Point was 2,263 second-feet. The maximum was 11,431 second-feet and the minimum about 300 second-feet.

TIDES AND CURRENTS

One of the causes of the cylic changes in the environment of organisms living in estuaries is the

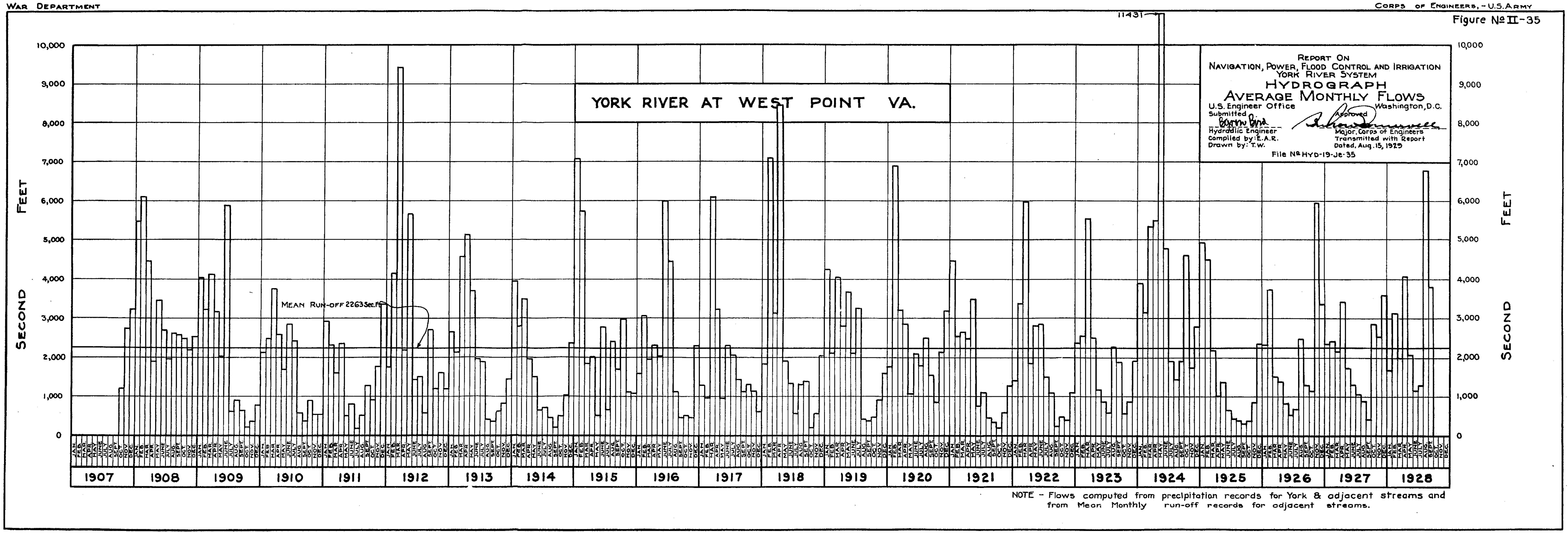

Figure 3.—Hydrograph of the York River at West Point. The average monthly flows were computed from precipitation records for the York River and adjacent streams and from mean monthly run-off records for adjacent streams. Reproduced from the Report of the United States Engineers [1929], War Department [1930].

rythmical motion of the tidal waters. In order to understand these changes it is necessary to consider what effects are brought about by this motion and how the sea and the fresh water moving down the river interact to vary the environmental conditions.

Tidal movement is of two types, vertical rise and fall and horizontal forward and backward movement, both forming parts of the same phenomenon resulting from the tidal forces of sun and moon. The horizontal movement of the tidal current generally has considerable velocity in entrances to bays and rivers. It continues in one direction for a period of about 6 hours and then reverses and flows in the opposite direction for the next period of about the same duration.

In rivers the tidal current is influenced by the nontidal movement of water. Generally speaking, the nontidal movement affects the rectilinear tidal current by making both the periods and velocities of flood and ebb unequal and by changing the time of slack water. It does not affect the times of flood and ebb strengths. The speed with which the particles of water move past any point depends upon the volume of water that must pass this point and the cross section of the channel at that point. From the product of time and the average velocity during the interval of time, the distance can be determined.

Observations of tides and currents in the York River and its tributaries have been made at various times from 1857 to 1928. The results of these surveys have been summarized by Haight, Finnegan, and Anderson (1930), who state (pp. 53–54):

> The observations show that the high water interval increases from 8.5 hours at York Spit Lighthouse to about 9 hours at Gloucester Point, and to about 10.8 hours at West Point. It is noted that the time of high water is earlier in the Mattaponi River than in the Pamunkey for equal distances from West Point. The duration of rise shows a slight decrease in value between York Spit Light and West Point. There is also a decrease in the duration of rise from West Point up the Mattaponi River. There is an apparent increase in the duration of rise in the Pamunkey River from 5.68 hours at West Point to 5.89 hours at Northbury Landing.
>
> The range in the York increases from about 2.2 feet at the entrance to about 2.5 feet at Gloucester Point and to about 2.8 feet at West Point. The range in the Mattaponi River increases from about 2.8 feet at West Point to about 3.9 feet at Walkerton. The range in the Pamunkey River increases from about 2.8 feet at West Point to about 3.3 feet at Northbury Landing. In the upper reaches of the latter two rivers the range decreases rapidly.

Observations of tide at West Point for 1 day in 1857 showed the high-water interval to be 10.23 hours. The duration of rise was found to be 5.81 hours. The low-water interval was 4.42 hours, and the mean range of tide 3.36 feet. For a period of 150 days in 1911–12 the high-water interval was found to be 10.79 hours, and the low-water interval 5.11 hours. The duration of rise was 5.68 hours. The mean range of tide was 2.82 feet. Observations for 3 days in 1918 showed the high-water interval to be 11.65 hours, the low-water interval 5.92 hours, the average duration of rise 5.73 hours, and the mean range of tide 3.65 feet.

From the data for 21 current stations, Haight et al. summarize results as follows (pp. 107-108):

> Two stations off Tue Point at the mouth of the river and a third about 3 miles above the mouth show current velocities at strength of slightly less than 1 knot. Observations in mid-channel between Gloucester Point and Yorktown show an average velocity of 1.4 knots at strength of flood and 1.8 knots at strength of ebb. Two stations nearby, one near each side of the channel, give strength velocities of about 1.2 knots for both flood and ebb in these locations. Velocities from three stations between Yorktown and West Point range from 1.1 to 1.4 knots for strength of flood and from 1.5 to 1.7 knots for strength of ebb.
>
> At the bridge over the Mattaponi River near West Point velocities of 1.3 knots for the flood and 1.4 knots for the ebb strengths were indicated by the observations. At a station below Mattaponi the flood and ebb strengths were 1.4 and 1.7 knots, respectively. At Walkerton the observed flood and ebb strengths were slightly less than 1 knot. At Aylett the current did not flood during 10 hours of observation, the maximum velocity being about 1 knot in an ebb direction.
>
> Flood and ebb strengths of 1.7 and 1.9 knots, respectively, were obtained from observations at the bridge over the Pamunkey River near West Point. Below White House one day of observations gave a flood velocity of 1.2 knots and an ebb velocity of 1 knot. Farther up the river about half way between White House and Bassett Ferry a similar series gave flood and ebb strengths of 0.5 knot and 1.3 knots respectively. At a station a short distance above Bassett Ferry during 7 hours of observation the current did not flood, the maximum ebb velocity being about 1 knot.
>
> Inspecting the time relations for the York River some roughness appears in the observational values, but from a general consideration of the results the following approximate relationships are derived. From the mouth of the river to Yorktown the strength of flood occurs about 1 hour before high water at Old Point Comfort. Above Yorktown the current becomes later, the strength of flood in the general vicinity of Ferry Point being simultaneous with high water at Old Point Comfort.
>
> Results of observations at the two bridges near West Point substantiated by observations near by, indicate that at the bridge over the Pamunkey River the current is 0.8 hour later than at the bridge over the Mattaponi River. Above West Point in the Mattaponi River the current becomes progressively later. At Walkerton, observations during one day show that strengths of flood occur almost 2½ hours after high water at Old Point Comfort or 3½ hours after the corresponding phase of the current at the mouth of the York River.
>
> Similarly the current becomes later in the Pamunkey River, observations at stations below White House and about half way

between White House and Bassett Ferry indicating strengths of flood apparently 2½ hours and 4 hours respectively after high water at Old Point Comfort.

In the York River the current and tide appear to advance up the river at about the same rate, each movement requiring about two hours to travel from the mouth of the river to West Point. Above West Point in the Mattaponi and Pamunkey Rivers the current becomes progressively earlier with respect to the tide.

SILTING

Deposition of silt in the tributaries of York River takes place principally at the time of floods. In the lower sections of these tributaries this process is expedited by the holding back of flood water by tidal action. Silting is also responsible for filling in the estuaries and gradual formation of mud flats and bars. The process is offset, however, by tidal or flood currents and by the sinking of the coast line.

Some studies of the silting of the upper York River estuary have been made by the United States Engineer Corps in the course of their work of maintaining the channel for navigation purposes. According to their reports, prior to 1880 there existed two bars obstructing navigation of the river for vessels of large draught. One of these was situated below West Point, and the other opposite Poropotank River. Both bars were formed over a period of many years and were composed principally of fine black sand, blue mud, and broken shells.

The still existing project for improvement of navigation in the York River, adopted by the River and Harbor Act of June 14, 1880, and modified in 1884 and 1887, provides for dredging through the bars a channel 22 feet deep at mean low water and 400 feet wide, and a basin of the same depth at the wharves at West Point on the Pamunkey River side. The project includes the construction of a dike on the right bank of the York River at West Point to assist in maintaining the channels.

The project was about 75 percent completed in 1899; the part not completed was the dredging of the channels to the full width of 400 feet, which was not considered necessary at that time. Subsequently, the amount of navigation on the York River has not justified the completion of the project. In 1899 a pile and timber dike, 10,412 feet in length, was built parallel to the right shore of the river, a short distance below West Point. The dike is now in poor condition although still of value in channel rectification. Dredging on the project has been confined to the bar below West Point, the turning basin at the West Point wharves in the Pamunkey River, and the bar at the mouth of Poropotank River.

Poropotank Bar has been dredged only once, from December 28, 1880, to March 31, 1881. An examination made in January 1890 of the channel at this bar disclosed a deposit of between 2 and 3 feet accumulated during the period of 9 years. This rate of silting was much less rapid than that observed at West Point. Examinations of the controlling depths at Poropotank Bar, made in July 1905, November 1927, March 1929, November 1934, and June 1936, showed that shoaling on the bar took place only during the first few years after dredging. From that time until the present the bar has not shoaled to any appreciable extent.

To meet the specifications of the project and to maintain the desired depth, extensive dredging has been carried out at the West Point Bar and at the turning basin. The rate of silting in this area was so great that in 1 year (1890) from 2 to 3 feet of sediment accumulated in the bar. Construction of the dike in 1893–94 aided in transferring the silting action farther down stream, and except for the dredging in 1901, all subsequent maintenance operations have been restricted to the removal of the material from the turning basin at West Point.

A controlling depth of at least 20 feet was reported after dredging in 1901. The controlling depths at the channel reported after this last dredging are:

Year:	*Feet*
1910	18–21
1927	19
1929	21.5
1934	21
1936	19.5

During the fall of 1938 an investigation of sedimentation in the York River estuary was made by the Section of Sedimentation Studies, Division of Research, Soil Conservation Service, of the United States Department of Agriculture. The preliminary report (Brown, Seavy, and Rittenhouse, 1939) deals chiefly with the comparative survey data and does not consider the character of sediment on the bottom or discuss the causative factors of sedimentation.

The method adopted in this study consisted in comparing the water depths in 1938 with water depths in 1857, 1911, and 1918, as shown on United States Coast and Geodetic Survey charts. This comparison was made within the 20 upper miles of the York River along the 13 ranges across the estuary, and the amount of fill, or scour, was computed.

From 1857 to 1911 the cumulative volume of sediment deposited was 5,591 acre-feet as compared with 15,293 acre-feet accumulated between 1911 and 1938. Thus, for the first period of 57 years there was an accumulation of 104 acre-feet per year. For the following 27 years the net accumulation was 566 acre-feet per year. The water volume for this segment of the river was computed to be 206,896 acre-feet in 1938. In 1911 it was 222,189 acre-feet, and in 1857 it was 227,780 acre-feet. The annual loss of water volume was at the rate of 0.05 percent per year from 1857 to 1911 and 0.25 percent per year from 1911 to 1938.

From 1857 to 1911 there were two main areas of heaviest silt accumulation, one at the head of the estuary between West Point and Fillbates Creek, and one in the upper middle estuary between Ware Creek and lower Purtan Bay. There was an area of scour at Bell Rock separating them. A larger area of scour was below Purtan Bay. During the period from 1911 to 1938 there were also two areas of fill and two of scour. The point of greater accumulation in this period, however, had moved downstream below lower Purtan Bay along Capahosic almost to Jones Creek. Also during this period scour occurred in the area below West Point where fill had occurred from 1857 to 1911. The annual rate of accumulation during the latter 27-year period was more than five times the rate during the preceding 57-year period.

Comparison made between the two periods of different durations raises a question of the significance of the difference in the rate of sedimentation computed by the investigators. They qualify, however, their conclusion by stating (p. 9), "the filling has not been a continuous process between these dates" (1857, 1911, 1938). "There appears, however, to be some orderly relation of scour and fill at the various ranges."

The selection of the above-mentioned dates was governed by the availability of three sets of hydrographic charts of the United States Coast and Geodetic Survey used for comparison. It is fortunate, however, that the second period (1911–38) almost coincides with the operations of the pulp mill, which was organized in 1913.

The authors' conclusion regarding the "downstream migration of the locus of most active sediment deposition" is of particular interest in the present investigation, for it throws some light on a probable distribution of a pulp-mill pollutant in the river. Discussion of this question is given on page 171.

POLLUTION

The York River receives domestic sewage and industrial waste, nearly all of which are emptied at the head of the river at West Point, Va.

Previous to 1935 the greater part of the sewage from the city of Williamsburg, Va., was discharged untreated into the headwaters of Queens Creek, which enters the York River from the right side about 8 miles above Yorktown. As a result of this, the creek was highly polluted and restrictions were made by the Virginia Department of Health on the sale of shellfish from the creek. In the early part of 1935, the city of Williamsburg installed two sewage pump stations and a plant for complete treatment of the sewage from the city. Since that time all sewage from the city is being discharged into College Creek, a tributary of the James River. On April 8, 1935, after shoreline surveys indicated that all unsanitary conditions had been corrected, and bacteriological samples showed safe water conditions, the restriction was lifted and Queens Creek was no longer classified as a restricted shellfish area.

At the confluence of the Pamunkey and Mattaponi Rivers the York River receives raw, untreated sewage from the city of West Point. Because of this pollution the Virginia Department of Health prohibits the sale of shellfish taken from the upper York River. This order, issued October 5, 1929, outlines the restricted area as "that portion of the York River lying above a line drawn in a northeasterly direction from the point of land at Mount Folly through Red Spar Buoy No. 10 to the shore near Roane; that portion of the Mattaponi and Pamunkey Rivers lying below a line drawn at right angles to the King William County shores two miles from their points of entrance into the York River." The lower limit of this area[2] is shown in figure 2.

The only important source of industrial pollution of the York River arises from the effluents of a pulp and paper mill located about 1½ miles upstream from the head of the York River on the outskirts of the city of West Point. This mill was established in 1913 as the Chesapeake Pulp & Paper Co. and was reorganized in 1918 as the Chesapeake Corp. In 1930 it absorbed the plant of the Albemarle-Chesapeake Co. which converted the pulp to paper and paperboard. At present the finished products of the mill are pulp and unbleached paperboard used in the

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[2] In 1942–45, the sewage pollution in the York River greatly increased owing to the establishment of military camps. Consequently, the restricted area has been extended and covers at present a large portion of the oyster bottoms in the lower part of the river.

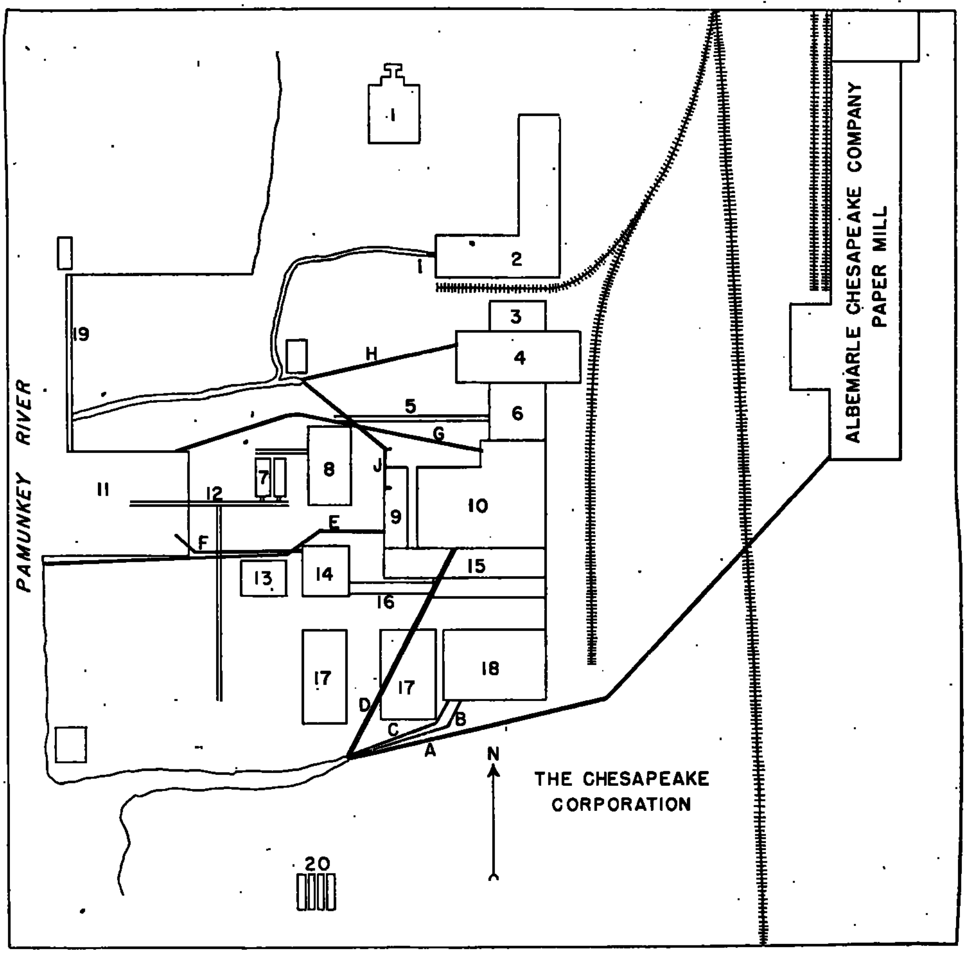

FIGURE 4.—General arrangement of buildings and sewer outlets of the Chesapeake Corporation pulp mill and the Albemarle Chesapeake Company paper mill in January 1936. The buildings are numbered from 1 to 19, and the sewer outlets are lettered from A to J, inclusive.

Buildings

1. General office.
2. Old board mill.
3. Screening building.
4. Diffuser building.
5. Chip conveyor.
6. Digester building.
7. Barking drums.
8. Chipper house.
9. Evaporator building.
10. Recovery room.
11. Lighter slip.
12. Log conveyor.
13. Bark boiler.
14. Slacker house.
15. Causticizing building.
16. Kiln.
17. Steel building.
18. Power house.
19. Wharf.

Sewers

A. 15-inch sewer from paper mill.
B. 14-inch sewer for drips, leaks, cooling water, etc., from power house.
C. 4-inch blow-down line from power house.
D. 39-inch sewer from recovery room.
E. 14-inch salt water return from vacuum jet.
F. 10-inch sewer from slacker house.
G. 2½-inch blow-down line from boiler.
H. 30-inch sewer from diffuser building.
I. Small drain from old board mill.
J. 15-inch sewer from evaporator building.

manufacture of containers. The combined plants have been increasing their facilities rapidly and the production has kept pace with the expansion.

Data on annual production, supplied by the Chesapeake Corp., are shown in table 1. There has been a steady increase for each year except 1930 and 1934. Starting in 1930, the increase in production has been much more rapid. The drop in 1934 was compensated by an increase in 1935 sufficient to bring the production figure back in line with the increases for other years.

The processing of pulp and paper requires large quantities of water, which this plant obtains from deep wells. Information furnished by the plant chemist gave the approximate quantity of water used by the Chesapeake Corp. in 1936 as 9,500 gallons per ton of pulp. In comparison with other mills this is a surprisingly small amount (Hagenauer 1937). In 1919 the plant pumps were said to have a capacity of 600 gallons per minute, or nearly a million gallons daily. At present the maximum amount of water delivered per minute by the pumps is 4,510 gallons, and daily delivery has reached 4,874,400 gallons.

Table 1.—*Annual production of pulp by the Chesapeake Corp., West Point, Va.*

Year	Tons	Year	Tons	Year	Tons	Year	Tons
1919	4,884	1924	19,714	1929	37,090	1934	71,641
1920	10,862	1925	23,193	1930	36,779	1935	86,844
1921	13,870	1926	25,883	1931	50,990	1936	95,075
1922	15,127	1927	29,910	1932	61,608	1937	101,004
1923	18,064	1928	34,808	1933	72,666		

Although the mill uses every effort to reduce to a minimum the water needed in both the washing of pulp and the making of paper, much of the process water finally reaches a condition where it is no longer reusable and is discharged into the sewers and released into the river.

An approximate lay-out of the buildings and sewers of the plant (fig. 4), obtained from an official of the mill, in January 1936, shows 10 sewers discharging into the Pamunkey River directly or through ditches which flow into this river. The sewer lines have been labeled alphabetically in order of their occurrence from south to north. At that time the estimated flow of the main sewers was as follows: sewer *A*, 200 gallons per minute; sewer *D*, 150 gallons per minute; and sewers *J* and *H*, 1,200 gallons per minute. Thus, the total amount of mill water discharged at that time into the river was 1,550 gallons per minute, or 2,232,000 gallons a day.

HISTORY OF THE YORK RIVER OYSTER INDUSTRY

The history of the oyster industry of the York River was compiled from a variety of sources. Records of oyster dealers handling York River oysters were examined and interviews were held with 30 oyster planters of the river and with State oyster inspectors and others associated with the industry.

In former years the upper York River produced oysters of excellent quality. This opinion is substantiated by the fact that in 1904 A. F. Smither, one of the oyster packers at West Point, was awarded a silver medal for the excellency of the oysters grown in the upper part of the York River and exhibited at the Louisiana Purchase Exposition in St. Louis, Mo.

Further evidence of the good quality of the oysters produced in the upper York River in earlier years and their subsequent decline is found in the books of the local oyster dealers. Their records showing amount of business, prices of shucked oysters, and other data reveal a marked decrease in the quantities of oysters handled and the fall in prices resulting from poor quality. It seems that the downward trend, which began in 1916–18, has continued until the present time (1939).

A typical example of the falling off in the industry can be found in the records of A. L. Van Name, who kept a detailed account of his operations. His grounds, covering 200 acres, are located about 9 miles below West Point. For the first 13 years, 1901–13, the total profit of this company was $38,577.85, averaging $2,967.33, annually. During the following 23 years, from 1914 to 1936, the total profit was only $11,181.30, or $486.14 a year. Because of the small returns, or in many cases actual loss, the planting of oysters was discontinued by this company in 1931.

Complete information as to the number of bushels of oysters marketed from the York River from year to year is impossible to obtain. A decline, however, can be seen from the records of oysters bought by M. D. Shields of Dandy, Va., who operated two 75-foot oyster boats each holding from 400 to 500 bushels. Figure 5 shows the number of bushels of upper York River oysters bought by him by years from 1920 to 1935. This decline resulted from the inability of this dealer to obtain good marketable oysters from this area.

The condition of the oyster industry in the upper York River can be readily understood when it is realized that one of the four oyster shucking houses at West Point was forced out of business in 1920, another in 1925, another went into bankruptcy in the spring of 1937, and the fourth ran its business at a loss until 1938. In all cases, the chief cause of failure was the refusal of the shippers and dealers to buy the oysters because of poor quality.

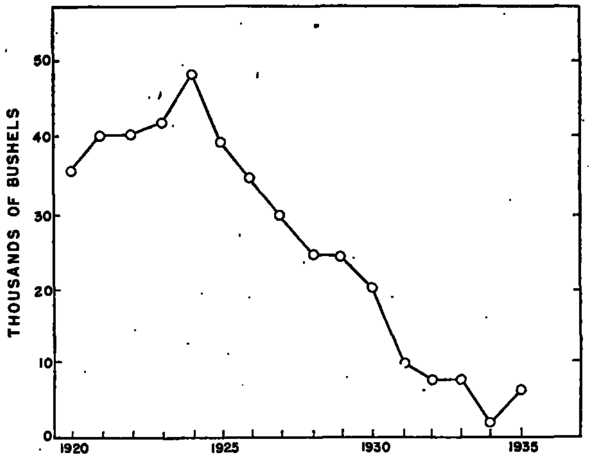

FIGURE 5.—The number of bushels of oysters bought in the upper York River by M. D. Shields from 1920 to 1935, inclusive.

Information from the York River oyster planters, obtained through interviews and correspondence, is summarized in table 2, in which the lessees are arranged in geographical order, starting from West Point. One can notice that the line of demarcation between the sections producing oysters of good quality and those producing oysters of inferior quality can be roughly drawn about 15 miles below West Point, near Claybank. The year when poor oysters were first noticed by the planters is given in column 7. In case no definite answer was received to this question, the statement of the planter is quoted in the footnote.

Because most of the planters kept meager records of oysters handled, and because of the diversified methods of transporting them to market, it is impossible to trace the fluctuations in the total production of the river over a period of two or three decades. Several of the dealers and State oyster inspectors, when asked to give an approximate estimate of the quantity of seed oysters planted and the vol-

TABLE 2.—*Summary of information obtained from the York River oystermen through interviews and questionnaires*

Miles below West Point	Side of river	Lessee	Acres	Character of bottom	Bushels planted per acre	Year bad oysters first noticed	Last planting
2	East	Richardson, G. W	40	Broken [1]	1,000	1917–18	1923
2	West	Towsend, R	4½	Hard	600–800	1916	1923
8	East	Roane, C	149	Soft	1,400	1916	1923
8	do	Allmond, J	17½	do	1,246	1916–17	1926
9	do	Van Name, A	200	do	600–800	1915–16	1931
10	do	Eastwood, E. C	22	Stiff	800	1925	1928
10	West	do	8	do	800	1925	1928
11	East	Scanlan, J. E	175	do	600	1920	1931
11	West	do	156	Soft	800	1930	1931
12	East	Twyford, F. P	38	Stiff		1920	1931
12	West	Twyford, J. H	40	Soft	1,210	1928	1931
13	East	Allmond, J. M	15	Broken	1,246	1929–30	1931
13	do	Allmond, W. W	15	Hard	1,452	1917	1931
13	West	Allmond, W	60	Soft	1,452	1917	1931
13	East	Eastwood, E. C	24	Stiff	800	1928	1928
13	West	Tuttle, E. T	18	Soft	1,452	(2)	1930
14	East	Twyford, J. H	26¼	Stiff	1,210	1928	1931
14	do	Groh, Louis	120	Broken	1,500	1926–27	1927
14	do	Marnix, C. C	15½	Stiff	522	1928	1927
14	West	do	21	do	1,452	1928	1927
14	East	Puller, R. F	18	do	1,452	1921–23	1927
14	West	do	48	do	1,452	1921–23	1929–30
14	East	Stubblefield, R	30		700	1920	1929–30
14	West	do	12		1,000	1920	
16	do	Newman, A. H	41	Stiff	826	[3] 1918	1929–30
16	do	Townsend, R	53	do	600–800	(4)	(5)
16 17	do	Powers, D. A	130	do	1,000	(6)	(5)
17	do	Maynard, E. W Hansford, J. D	85	Soft	1,000	1917–18	(5)
21	East	Wilburn, R. L	12	Stiff	1,000	(7)	(5)
21	do	Diggs, W. H				(8)	(5)
21	do	Carmine, R. S	31	Stiff	1,000	1935	(5)
23	do	Tillage, A. H	25	Hard	500–1,000	(8)	(5)
23	do	Tillage, J. C	3	Soft	500	(8)	(5)
26	do	Blake, T. J	120	Broken	500	(8)	(5)
28	do	Tillage, A. H	75	Hard	500–1,000	(8)	(5)
26	do	Tillage, J. C	17	do	500	(8)	(5)

[1] Of various degrees of consistency.
[2] "Not many years ago."
[3] Freeze.
[4] Not affected.
[5] Still planting.
[6] "When pulp mill started on large scale."
[7] "Weakened in last few years."
[8] No change.

ume of oysters marketed, agreed that, before 1928, the planting was in excess of 200,000 bushels annually and that the annual production of market oysters was about 400,000 bushels. This activity necessitated the employment of about 500 tongers and the use of about 30 locally owned boats to plant seed oysters and to carry the oysters to market. In more recent years only about 50,000 bushels of oysters have been marketed annually.

An early method of oyster culture in the York River consisted of transplanting oysters from the lower and middle sections of the river to beds extending to about 5 miles below West Point. In recent years the process has been reversed, not because of the closing of restricted oyster grounds of the upper York River by the Health Department, but because of the failure of oysters to grow and fatten in that section. Although the marketability of oysters from the upper and middle river is subject to great seasonal variations, it can be said that as a general rule oysters from the upper and middle sections of the river have to be moved to the lower York River, or out of the river entirely, in order to obtain a satisfactory marketable product.

Official records in the office of the Virginia Commission of Fisheries show that in June 1937 there were 5,971.41 acres of oyster bottom under lease in the York River. This figure has fluctuated from year to year as the parcels of bottom have been given up or leased again. As all of the leased parcels probably are not cultivated every year, the total acreage of leased bottoms does not necessarily represent the total number of acres under cultivation. The bottoms cultivated by the oystermen who consented to supply information regarding their business cover 1,864.75 acres, or about one-third of the acreage under lease. They represent a good proportion of the bottoms in the sections of the river seriously affected by pollution.

PHYSICAL AND CHEMICAL CONDITIONS OF THE WATERS OF THE YORK AND PIANKATANK RIVERS

No study of the biology of any waters would be complete without a consideration of the physical and chemical conditions under which the organisms are living. Physical and chemical factors of the environment may have either direct effect on living forms by controlling their growth and propagation or they may exert indirect, but nevertheless important, action by influencing the abundance, distribution, and sequence of changes in the populations of microscopic organisms upon which other forms subsist.

Reproduction and growth of the oyster or of any other organism which obtains its food by filtering water are often limited by the deficiency in the type of food needed by them. Thus, the productive capacity of an oyster bottom is determined by the availability of the microorganisms necessary to support the life of the oyster during its larval and adult stage. Observations of various investigators indicate that diatoms, dinoflagellates, and other groups constituting phytoplankton, comprise the principal items of an oyster's diet. It is possible that bacteria also have a part in the feeding of oysters, although convincing evidence on the subject is still lacking. The abundance of phytoplankton, estimated indirectly by Harvey's method of pigment units, can be accepted only as a more or less general indication of the abundance or scarcity of oyster food in water, for the nutritive value of various forms comprising the phytoplankton has not yet been ascertained.

Although most of the studies in this paper deal with conditions of the York River, a number of parallel observations were made in the Piankatank River. Situated a short distance north of the York River, the Piankatank is also one of the tributaries of the Chesapeake Bay. With respect to the character of the bottom, water conditions, tides, and other hydrographical features, it resembles the York River, but it is not contaminated by domestic or industrial pollution. The river is known to produce excellent oysters. For these reasons, observations made in it are considered as controls for those carried out in the York River.

A number of sampling stations for physical, chemical, and biological observations were established at rather regular distances from the mouth of the York River to localities above West Point in the Pamunkey and Mattaponi Rivers, and at two localities in the Piankatank River, one in the lower portion and one in the upper. Many of these stations were also used for experimental oyster planting and for regular examination of the oysters. Locations of the stations are shown in figure 2 and described in table 3. Other substations were established for special needs and are described in the text as discussed.

TABLE 3.—*Location and character of hydrographic stations in the York and Piankatank Rivers*

Station	Location	Depth of water in feet	Character of bottom
	YORK RIVER		
	Yorktown, Steamboat Dock	14	Hard, sand.
	Naval Mine Depot Dock	12	Do.
	West Point, Bruce Memorial Bridge.	----------	Soft, mud.
5	Off Allmondsville	3.9	Medium, stiff mud and shell.
6	Below Scimmino Creek	5.2	Do.
8	Bell Rock Lighthouse	13.6	Hard, shell, oyster rock.
9	Middle Ground below West Point.	12.4	Hard, sand with little mud.
14	Off Carmines Islands	8.3	Hard, mud and sand.
15	Above Queens Creek	3.4	Medium, mud and shell.
16	Off Roanes Point	4.2	Soft, stiff mud.
17	Off Ware Creek	3.9	Soft, mud, little shell.
18	Pamunkey River above West Point.	29.5	Soft, mud.
19	Mattaponi River above West Point.	15.0	Do.
20	Off Sandbox, above Bull Creek	10.5	Hard, sand.
22	Inside Purtan Bay	4.1	Medium, stiff mud and shell.
23	Above Claybank	4.6	Medium, mud and sand, shell.
	PIANKATANK RIVER		
53	Off Ferry Creek	7.3	Medium, stiff mud, shell.
55	Off Iron Point	4.2	Hard, sand and shell.

OBSERVATIONS ON CURRENTS

Although the tide tables issued by the Coast and Geodetic Survey and the paper by Haight, Finnegan, and Anderson (1930) give essential information regarding the tides and surface currents in the York River, it was considered necessary to obtain more detailed knowledge regarding the velocity of currents at different depths and at different stages of the tide. These data were particularly needed for evaluating the river discharge (the excess of the discharge during the entire ebb period over the entire flood period) and for computing the velocity of the resultant current of the river.

For the observation of tides a station was established on the Texas Oil Co.'s dock on the Mattaponi River at West Point. According to the specifications of the United States Coast and Geodetic Survey (1935), a tide house was constructed over a wooden float-well formed by joining four 2-inch by 14-inch planks into a box. After the establishment of bench marks, a standard automatic tide gage, loaned by the Coast and Geodetic Survey, was installed and put into operation. Observations were continued from August 25, 1936 to May 5, 1937.

Measurements of the currents of the York River were made during the fall, winter, and spring of 1936–37 as follows: August 10–11; September 16–17 and 23–26; October 28–30; November 18–20; December 17–19; January 18–20; February 8–10; March 8–10; April 13–14 and 29. The stations occupied were arranged in a line across the river at Purtan Island (fig. 2) so that a relatively complete cross section of the river was made. This section was chosen because of the straightness of the channel at that point. Depths of water on this line were determined by soundings made at regular intervals and the position determined by angles at each sounding. The contour of the bottom at this section is shown in figure 6. Station 1 was located in the deepest water of the channel and was occupied and observations were made continuously whenever any measurements of flow were determined at any station. This served as a reference station for stations 2, 3, 4, and 4A, where observations were made for shorter periods of time.

The procedure of observations was patterned after that described by Zeskind (1926). The boat was brought up on station and anchored from the bow by as short a cable as was practical. It was found inconvenient to anchor fore and aft, and for this reason position angles were determined by sextant each hour as the boat swung with the tide. The Price current meter suspended by the electric cable and weighted to insure a vertical position of the cable, was lowered to a level of two-tenths of the total depth. The revolutions were then counted for 1 minute with the use of a stop watch. Following this, the meter was lowered to five-tenths of the total depth and observations were made. After this the meter was again lowered and observations were made at eight-tenths of the total depth. A second set of observations was made at eight-tenths, five-tenths, and two-tenths of the total depth as the meter was raised.

Immediately after the meter readings were completed, observations were made of the current velocity by using the current pole floating vertically in the water. The graduated line was allowed to run out for 1 minute and the distance the pole traveled recorded. The direction of the pole from the boat was then determined either by a pelorus or by sextant angles. The wind velocity and direction as well as the ship's head by compass were also noted.

These observations were continued every half hour as long as the station was occupied. The time varied from 13 hours to 3 days, a 13-hour complete tidal cycle being the minimum period of observation. With interruptions, the current meter studies were conducted between August 1936 and April 1937.

The results of the measurements of current velocities at each station are shown in table 4. All of the

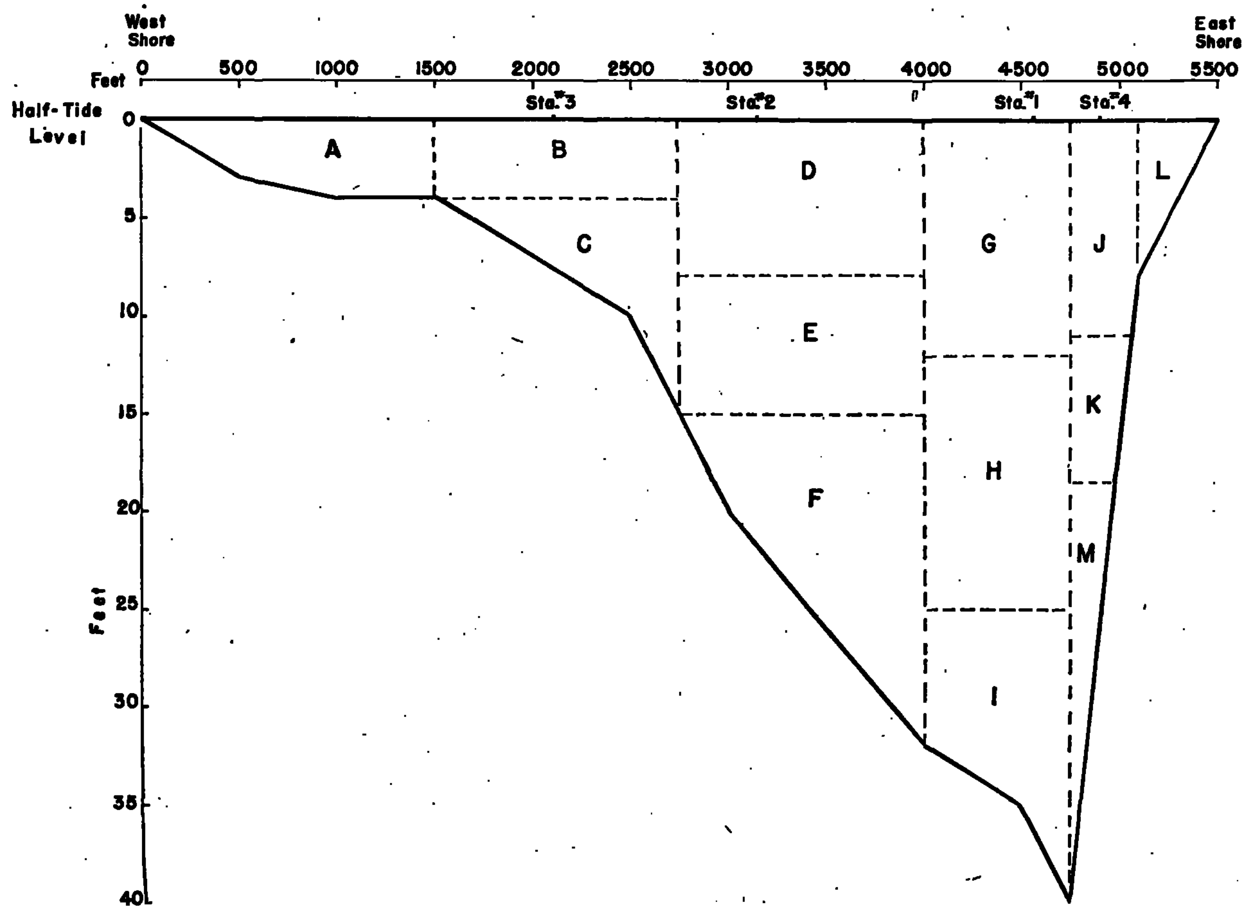

FIGURE 6.—Approximate cross-section of York River (Purtan Island) for determination of river flow based on current observations made in 1936–37. The depths and widths are approximate values derived from data obtained from the United States Coast and Geodetic Survey hydrographic sheet 3311 showing the results of a survey in this area in 1911. The approximate area of each section in square feet follows: A—4,500; B—5,000; C—5,125; D—10,000; E—8,750; F—11,625; G—9,000; H—9,750; I—7,375; J—3,750; K—2,130; L—1,600; M—2,688.

data were analyzed by the United States Coast and Geodetic Survey and summarized as follows:

Staff readings corresponding to the different local tide planes as determined by comparison with the standard station at the Naval Operating Base, Hampton Roads, showed 4.57 feet at mean high water, 3.07 feet at half-tide level, and 1.57 feet at mean low water. The mean range of tide was 3.0 feet. High waters occur, on the average, 1.86 hours later than at the Naval Operating Base, and low waters 2.32 hours later. The average duration of rise was 5.62 hours, and the average duration of fall 6.80 hours.

One of the purposes of current-meter observations at the section of the York River at Purtan Bay was to obtain estimates of the total flow at flood and ebb periods. These data can be computed if the cross-sectional area and the changes in the velocity of current at various depths across the river during various stages of tide are known. To aid in the computation, the entire cross section of the river was divided into several small sections (A to M, fig. 6), the limits of which are outlined wholly or in part by dashes. The area of each small section is indicated in the figure. The depths and widths shown in this diagram represent approximate values derived from data obtained from United States Coast and Geodetic Survey hydrographic sheets 3311 showing the results of a survey made in 1911. The upper limit represents the half-tide level of the river. On the basis of these data, the cross-sectional area of the river at this point was found to be equal to 81,293 square feet at half-tide level. In 1938 at our request, G. L. Evans, a surveyor of the Chesapeake Corp., determined the width of the river at Purtan Bay and made a series of careful soundings. Computed on the basis

TABLE 4.—*Current measurements in the York River in 1936 and 1937.*

[Referred to times of predicted tides at Hampton Roads, Va.]

Station No.	Date	Length of series	Method of observation	Average depth	Current intervals				Observed velocity		Correction factor	Corrected velocity		Duration		Resultant or nontidal current
					Slack before flood	Strength of flood	Slack before ebb	Strength of ebb	Flood	Ebb		Flood	Ebb	Flood	Ebb	
	1936	*Days*		*Feet*	*HW+*	*HW+*	*LW+*	*LW+*	*Knots*	*Knots*		*Knots*	*Knots*	*Hours*	*Hours*	*Knots*
1	Aug. 10 to 11	1.0	Meter	4 to 7	−3.30	−0.30	−3.95	−1.50	1.20	0.85	1.10	1.30	0.95	5.69	6.73	−0.06
	Sept. 16 to 17	1.0	do	7	−2.80	−0.30	−3.45	+0.05	1.10	1.30	0.96	1.05	1.25	5.69	6.73	+0.13
	Sept. 23 to 26	3.0	do	7	−2.90	−0.07	−3.66	+0.06	1.35	1.18	1.43	1.89	1.72	5.58	6.84	+0.03
	Oct. 28 to 30	2.0	do	7	−3.12	−0.40	−3.60	+0.02	1.85	1.85	0.75	1.39	1.39	5.86	6.56	+0.07
	Nov. 18 to 20	2.0	do	7	−3.12	+0.50	−2.78	+0.38	1.40	1.48	1.17	1.64	1.72	6.68	5.74	−0.04
	Dec. 17 to 19	2.0	do	7	−2.90	+0.02	−3.05	−0.30	1.48	1.50	1.03	1.52	1.54	6.19	6.23	+0.01
	1937															
	Jan. 18 to 20	2.0	do	7	−2.85	−0.17	−3.90	−0.25	1.70	1.65	1.01	1.72	1.67	5.29	7.13	+0.14
	Feb. 8 to 10	1.75	do	7	−2.70	+0.48	−3.40	+0.03	1.72	1.97	1.01	1.74	1.99	5.64	6.78	+0.19
	Mar. 8 to 10	2.0	do	7	−3.07	+0.35	−3.22	−0.22	1.60	1.78	1.10	1.77	1.95	6.19	6.23	+0.06
	Apr. 13 to 14	1.5	do	7	−3.27	−0.43	−3.67	+0.23	1.97	1.80	0.77	1.54	1.37	5.94	6.48	0.00
	Apr. 29	0.5	do	7	−2.70	+0.20	−3.90	−0.50	0.80	1.60	1.16	0.99	1.79	5.14	7.28	+0.39
	1936															
1	Aug. 10 to 11	1.0	do	14 to 16	−3.75	−0.10	−3.80	−0.95	1.20	0.95	1.10	1.31	1.06	6.29	6.13	−0.09
	Sept. 16 to 17	1.0	do	18	−3.00	−0.40	−3.30	−0.20	0.80	0.90	0.94	0.75	0.85	6.04	6.38	+0.05
	Sept. 23 to 26	3.0	do	18	−2.93	−0.10	−3.60	0.00	1.38	1.10	1.43	1.90	1.62	5.67	6.75	−0.02
	Oct. 28 to 30	2.0	do	18	−3.12	−0.30	−3.42	+0.28	1.88	1.68	0.75	1.44	1.24	6.04	6.38	−0.03
	Nov. 18 to 20	2.0	do	18	−3.30	+0.30	−2.75	+0.42	1.45	1.28	1.17	1.67	1.50	6.89	5.53	−0.15
	Dec. 17 to 19	2.0	do	18	−3.60	−0.15	−2.95	−0.12	1.68	1.35	1.03	1.73	1.40	6.99	5.43	−0.23
	1937															
	Jan. 18 to 20	2.0	do	18	−3.22	−0.43	−3.92	−0.55	1.80	1.35	1.01	1.82	1.37	5.64	6.78	−0.05
	Feb. 8 to 10	1.75	do	18	−3.03	−0.25	−3.68	−0.43	1.82	1.63	1.01	1.84	1.65	5.69	6.73	+0.03
	Mar. 8 to 10	2.0	do	18	−3.40	−0.58	−3.38	−0.20	1.65	1.60	1.10	1.81	1.76	6.36	6.06	−0.04
	Apr. 13 to 14	1.5	do	18	−3.30	−0.33	−3.73	−0.23	2.03	1.93	0.77	1.57	1.47	5.91	6.51	+0.03
	Apr. 29	0.5	do	18	−3.50	0.00	−4.00	−0.70	1.50	1.60	1.16	1.75	1.85	5.84	6.58	+0.09
	1936															
1	Aug. 10 to 11	1.0	do	16 to 26	−3.75	−0.55	−3.65	−0.85	0.85	0.75	1.10	0.93	0.83	6.44	5.98	−0.05
	Sept. 16 to 17	1.0	do	29	−3.10	−0.40	−3.53	−0.80	0.70	0.90	0.94	0.65	0.85	6.09	6.33	+0.07
	Sept. 23 to 26	3.0	do	30	−2.86	−0.30	−3.66	−0.44	1.37	0.94	1.43	1.87	1.44	5.54	6.88	−0.06
	Oct. 28 to 30	2.0	do	28	−3.20	−0.05	−3.45	+0.30	1.78	1.45	0.75	1.38	1.05	6.09	6.33	−0.09
	Nov. 18 to 20	2.0	do	30	−3.42	−0.07	−2.78	+0.35	1.20	1.00	1.17	1.39	1.19	6.98	5.44	−0.15
	Dec. 17 to 19	2.0	do	28	−3.63	−0.35	−3.08	−0.25	1.22	1.08	1.03	1.25	1.11	6.89	5.53	−0.12
	1937															
	Jan. 18 to 20	2.0	do	28	−3.82	−0.60	−3.92	−0.40	1.67	1.02	1.01	1.68	1.03	6.24	6.18	−0.21
	Feb. 8 to 10	1.75	do	30	−3.20	−0.30	−4.02	−0.10	1.32	1.27	1.01	1.33	1.28	5.52	6.90	+0.08
	Mar. 8 to 10	2.0	do	28	−3.68	−0.55	−3.72	−0.40	1.12	0.98	1.10	1.22	1.08	6.30	6.12	−0.05
	Apr. 13 to 14	1.5	do	29	−3.50	−0.40	−3.67	−0.60	1.50	1.33	0.77	1.17	1.00	6.17	6.25	−0.05
	Apr. 29	0.5	do	29	−4.15	−0.90	−3.90	−0.09	1.10	1.40	1.16	1.30	1.60	6.59	5.83	+0.05
	1936															
2	Sept. 24	0.5	do	5	−3.40	−1.00	−4.10	+0.20	1.20	1.20	1.56	1.87	1.87	5.64	6.78	+0.07
	Oct. 28	0.5	do	4	−2.80	−0.60	−3.70	−0.10	1.60	2.10	0.81	1.25	1.75	5.44	6.98	+0.31
	Nov. 18 to 19	0.5	do	5	−3.10	+0.20	−3.30	−0.10	1.00	1.80	1.16	1.22	2.02	6.14	6.28	+0.26
	Dec. 17	0.5	do	4	−3.50	−0.20	−4.30	−0.90	1.00	2.00	1.02	1.03	2.03	5.54	6.88	+0.42
	1937															
	Feb. 10	0.5	do	5	−2.80	+0.30	−3.40	−0.20	1.60	2.00	0.91	1.44	1.84	5.74	6.68	+0.21
	Mar. 9	0.5	do	5	−2.70	−0.10	--------	+0.30	1.40	2.30	1.14	1.66	2.56	--------	--------	--------
	Apr. 13	0.5	do	4	−3.20	−1.00	−3.50	−0.30	2.10	2.10	0.75	1.58	1.58	6.04	6.38	+0.04
	1936															
2	Sept. 24	0.5	do	12	−3.40	−0.60	−3.90	+0.10	1.20	0.90	1.56	1.79	1.49	5.84	6.58	−0.06
	Oct. 28	0.5	do	10	−2.70	−0.40	−3.65	+0.10	1.40	1.60	0.81	1.12	1.32	5.39	7.03	+0.19
	Nov. 18 to 19	0.5	do	12	−3.00	0.00	−3.00	0.00	1.15	1.40	1.16	1.35	1.60	6.34	6.08	+0.06
	Dec. 17	0.5	do	11	−3.50	−0.20	−3.90	−0.80	1.00	1.60	1.02	1.03	1.63	5.94	6.48	+0.23
	1937															
	Feb. 10	0.5	do	12	−3.20	+0.20	−3.50	−0.40	1.60	1.50	0.91	1.46	1.36	6.04	6.38	0.00
	Mar. 9	0.5	do	12	−3.30	−0.10	--------	−0.40	1.40	1.80	1.14	1.62	2.02	--------	--------	--------
	Apr. 13	0.5	do	10	−3.20	−1.00	−3.30	−0.40	1.90	1.90	0.75	1.42	1.42	6.24	6.18	0.00
	1936															
2	Sept. 24	0.5	do	20	−4.00	−0.50	−4.00	−0.10	1.00	0.60	1.56	1.45	1.05	6.34	6.08	−0.14
	Oct. 28	0.5	do	16	−2.70	−0.20	−3.65	0.00	1.10	1.30	0.81	0.87	1.07	5.39	7.03	+0.16
	Nov. 18 to 19	0.5	do	18	−3.20	+0.25	−2.80	0.00	0.85	1.00	1.16	1.00	1.15	6.74	5.68	0.00
	Dec. 17	0.5	do	18	−3.50	−0.30	−3.80	−0.10	0.60	1.10	1.02	0.62	1.12	6.04	6.38	+0.17
	1937															
	Feb. 10	0.5	do	20	−3.40	−0.30	−4.20	0.00	1.00	1.10	0.91	0.91	1.01	5.54	6.88	+0.10
	Mar. 9	0.5	do	19	−3.20	−0.60	--------	−0.20	1.10	1.20	1.14	1.26	1.36	--------	--------	--------
	Apr. 13	0.5	do	16	−3.70	0.00	−3.50	−0.20	1.30	1.40	0.75	0.96	1.06	6.54	5.88	−0.01

TABLE 4.—*Current measurements in the York River in 1936 and 1937*—Continued

Station No.	Date	Length of series	Method of observation	Average depth	Current intervals				Observed velocity		Correction factor	Corrected velocity		Duration		Resultant[1] or nontidal current
					Slack before flood	Strength of flood	Slack before ebb	Strength of ebb	Flood	Ebb		Flood	Ebb	Flood	Ebb	
	1936	*Days*		*Feet*	*HW+*	*HW+*	*LW+*	*LW+*	*Knots*	*Knots*		*Knots*	*Knots*	*Hours*	*Hours*	*Knots*
3	Aug. 10 to 11	1.0	Meter	0.8 to 1.3	−4.00	−0.40	−4.40	−1.80	0.90	0.75	1.10	0.98	0.83	5.94	6.48	−0.02
	Sept. 25	0.5	do	1.7	−3.50	−1.20	−4.80		0.70					5.04	7.38	
	Oct. 29	0.5	do	1.5 to 2.0	−3.00	−0.50	−4.10		1.00	1.00	0.72	0.72	0.72	6.14	6.28	+0.01
	Nov. 19	0.5	do	1.4	−3.80		−4.50	−1.70	0.70	0.90	1.19	0.85	1.05	5.64	6.78	+0.11
	Dec. 18	0.5	do	1.6	−4.10	−0.90	−4.60	−1.60	0.80	0.80	1.04	0.83	0.83	5.84	6.58	+0.03
	1937															
	Feb. 9	0.5	do	1.8	−3.60	−0.50	−3.80	−1.10	0.80	0.80	1.02	0.82	0.82	6.14	6.28	+0.01
	Mar. 10	0.5	do	1.6	−4.00		−4.00	−1.90		1.20				6.34	6.08	
	Apr. 14	0.5	do	2.6	−2.80	−0.30	−3.90	−1.60	1.30	1.40	0.79	1.02	1.12	5.24	7.18	+0.17
	1936															
3	Aug. 10 to 11	1.0	do	3.0 to 5.3	−4.05	−1.00	−4.40	−1.80	0.70	0.70	1.10	0.77	0.77	5.99	6.43	+0.02
	Sept. 25	0.5	do	6.8	−3.20	−0.80	−4.70		0.70					4.84	7.58	
	Oct. 29	0.5	do	5.2 to 7.3	−4.10	−0.80	−4.00		0.90	0.80	0.72	0.66	0.56	6.44	5.98	−0.05
	Nov. 19	0.5	do	5.6	−3.40	−0.90	−4.50	−1.20	0.80	0.90	1.19	0.96	1.06	5.24	7.18	+0.12
	Dec. 18	0.5	do	6.4	−4.40	−1.10	−3.90	−1.00	0.60	0.90	1.04	0.63	0.93	6.84	5.58	+0.05
	1937															
	Feb. 9	0.5	do	7.2	−3.60	−0.50	−3.90	−0.90	0.70	0.70	1.02	0.71	0.71	6.04	6.38	+0.01
	Mar. 10	0.5	do	6.4	−3.60		−3.50	−0.90		0.70				6.44	5.98	
	Apr. 14	0.5	do	10.4	−3.30	+0.10	−3.80	−1.30	1.10	1.00	0.79	0.88	0.78	5.84	6.58	+0.01
	1936															
4	Sept. 23	0.5	do	6	−3.80	+0.10	−4.20	−2.10	1.10	0.80	1.51	1.58	1.28	5.94	6.48	−0.07
	Oct. 29	0.5	do	5	−3.30	−0.60	−4.0	−0.80	1.40	0.70	0.72	1.11	0.41	5.64	6.78	−0.16
	1936															
4	Sept. 23	0.5	do	16	−3.90	−0.10	−4.20	−1.50	1.20	0.80	1.51	1.71	1.31	6.04	6.38	−0.11
	Oct. 29	0.5	do	12	−3.30	−0.80	−3.80	−0.70	1.20	1.00	0.72	0.89	0.69	5.84	6.58	−0.02
	1936															
4	Sept. 23	0.5	do	25	−3.55	−0.30	−4.00	−0.80	0.90	0.80	1.51	1.33	1.23	5.89	6.53	0.00
	Oct. 29	0.5	do	20	−3.30	−0.90	−3.80	−0.60	1.00	0.70	0.72	0.76	0.46	5.84	6.58	−0.06
	1937															
4A	Apr. 29	0.5	Pole	2	−2.80	−0.40	−4.90	−1.90	0.60	0.90	1.16	0.72	1.02	4.24	8.18	+0.25
	Apr. 29	0.5	Meter	2	−2.40	−0.50	−4.60	−1.80	0.70	1.00	1.16	0.84	1.14	4.14	8.28	+0.28
	Apr. 29	0.5	do	5	−2.80		−4.60	−1.80		0.90				4.48	7.94	
	Apr. 29	0.5	do	8	−2.60	−0.50	−4.60	−2.20	0.60	0.80	1.16	0.71	0.91	4.34	8.08	+0.20
	Mean values as derived from the entire series															
1	Aug. 10, 1936, to Apr. 29, 1937.	4.0	Pole	7	−3.10	−0.21	−3.77	−0.22	1.66	1.78	0.98	1.63	1.75	5.67	6.75	+0.13
		19.0	Meter	7	−2.98	−0.01	−3.45	−0.11	1.54	1.56	1.02	1.57	1.59	5.87	6.55	+0.10
		19.0	do	18	−3.24	−0.22	−3.45	−0.16	1.62	1.42	1.02	1.65	1.45	6.13	6.29	−0.05
		19.0	do	29	−3.44	−0.35	−3.54	−0.27	1.33	1.10	1.02	1.35	1.12	6.24	6.18	−0.08
2	Sept. 24, 1936, to Apr. 13, 1937.	1.5	Pole	2	−2.70	−0.20	−3.87	−0.13	1.60	1.73	1.01	1.62	1.75	5.17	7.25	+0.22
		3.5	Meter	5	−3.07	−0.28	−3.71	−0.16	1.36	1.93	0.99	1.34	1.91	5.70	6.72	+0.27
		3.5	do	11	−3.19	−0.26	−3.56	−0.26	1.35	1.53	0.99	1.34	1.52	5.97	6.45	+0.09
		3.5	do	18	−3.39	−0.18	−3.66	−0.09	0.98	1.10	0.99	0.97	1.09	6.07	6.35	+0.05
3	Aug. 10, 1936, to Apr. 14, 1937.	2.0	Pole	2	−3.40	−0.87	−4.25	−1.50	0.85	0.80	0.93	0.79	0.74	5.49	6.93	+0.05
		4.5	Meter	2	−3.74	−0.63	−4.28	−1.64	0.89	0.95	1.00	0.89	0.95	5.80	6.62	+0.06
		4.5	do	7	−3.74	−0.71	−4.10	−1.27	0.78	0.80	1.00	0.78	0.80	5.98	6.44	+0.03
4	Sept. 23 to Oct. 29, 1936.	1.0	Meter	6	−3.63	−0.25	−4.10	−1.45	1.25	0.75	0.98	1.23	0.73	5.87	6.55	−0.12
		1.0	do	14	−3.70	−0.45	−4.00	−1.10	1.20	0.90	0.98	1.18	0.88	6.04	6.38	−0.08
		1.0	do	22	−3.47	−0.60	−3.90	−0.70	0.95	0.75	0.98	0.93	0.73	5.91	6.51	−0.04

[1] A plus (+) sign denotes downstream and a minus (−) sign denotes upstream resultant or nontidal current.

of this recent survey, the cross-sectional area was found by the authors to be equal to 77,308 square feet at mean low water, and 92,718 square feet at mean high water. These figures give satisfactory agreement with the computations based on the 1911 survey.

From the current-meter observations at four stations across the river, the stream flow for flood and ebb tide was estimated by computing the average velocity of current, which is equal to the velocity at the strength of the tide multiplied by 0.637, and by the duration of flood or ebb tide. The resulting nontidal current, or the excess of ebb over flood tide, was then calculated for each section. In sections A and L the velocities and durations were estimated. By summing all the areas, the following final figures were obtained. Total flow of the river at Purtan Bay during flood period amounted to 2,235,416,000 cubic feet; during ebb period, 2,484,875,000 cubic feet; ebb excess, 249,459,000 cubic feet. By dividing the excess ebb flow by the area of the cross section multiplied by tidal cycle (12.42 hours, or 44,712 seconds) we obtained the value of the nontidal current, which was found to be equal to 0.0686 foot per second, or 0.04 knot, downstream.

As to the distance traveled by a particle during a tidal cycle, this can be computed for any station by making use of the fact that a current curve approximates a cosine curve, and on a cosine curve it is known that the ratio of the mean ordinate to the maximum ordinate is $2 \div \pi$, or 0.6366. Since the strength of the tidal current corresponds to the maximum ordinate, it follows that during any given flood or ebb period the average current will be the strength of the current multiplied by 0.6366. The horizontal distance traveled by a particle or floating object, therefore, would be given by multiplying the average velocity during any flood or ebb period by the corresponding duration of flow.

It should be noted that this formula can give only approximate results, for the use of the cosine relationship gives only an approximate value of the average current. Furthermore, even more serious is the assumption made in the formula that the floating object during the various stages of its journey will experience the same changes in velocity which occur at the point where it started.

In order to determine the direction that effluents leaving the pulp mill at West Point would take on an ebb tide and the distance that a particle would travel downstream, a study was made using floats released off the pulp mill at high-water slack on October 17, 1938.

Each float consisted of two citrate bottles fastened one above the other by cord so that the total height was 24 inches. Sand in the bottles was adjusted so that they would float with less than a half inch of the top of the upper bottle exposed to the air. Visibility of the floats was increased by the use of small flags made from bicycle spokes to which were fastened small pieces of white cloth. The floats were followed by boat, and observations of the position of the floats were made at half-hour intervals during a complete change of tide on October 17, 1938, starting at high-water slack at 6:30 a. m. off the pulp mill at West Point. Observations were continued to high-water slack late that afternoon. Neap tides occurred during this period, the moon being in the last quarter. The predicted times of tides and currents are given in table 5. The weather was clear with almost no wind all day so that the water was perfectly smooth. A dense fog settled down for a period of about an hour and a half in the late forenoon so that visibility was poor during that time. The course of the bottles during the ebb and flood tides is shown on the map presented in figure 7.

TABLE 5.—*The predicted times of tides and currents of the upper York River on Oct. 17, 1938* [1]

TIDE AT WEST POINT

Latitude 37°32′, Longitude 76°48′

Tide	*Time*	*Height, in feet*
High water	5:18 a.m.	2.9
Low water	11:35 a.m.	0.8
High water	5:49 p.m.	3.2

CURRENT AT WEST POINT

Tide	*Time*	*Velocity, in knots*
High-water slack	6:16 a.m.	----------
Greatest ebb	10:42 a.m.	2.1
Low-water slack	2:11 p.m.	----------
Greatest flood	4:58 p.m.	1.5

CURRENT ¾ MILE BELOW WEST POINT

Latitude 37°31′, Longitude 76°48′

Tide	*Time*	*Velocity, in knots*
High-water slack	5:21 a.m.	----------
Greatest ebb	9:47 a.m.	1.5
Low-water slack	1:16 p.m.	----------
Greatest flood	4:03 p.m.	1.1

[1] Data were obtained from the Tide Tables, Atlantic Ocean, and Current Tables, Atlantic Ocean, North America, published by the U. S. Coast and Geodetic Survey.

At high-water slack 10 floats were released off the unloading platform at the mill. Three were lost immediately, probably as a result of sinking caused by improper adjustment of the sand. Visibility in this area was poor at this time, because of the steaming of the water. The river near the mill was brown with mill effluent and felt hot. A surface thermometer showed that the water of this area had a temperature of 76° F., while that of the river elsewhere had a temperature of 64° F. The water was discolored brown with the effluent for a distance of about 1½ miles, as far down as West Point Bar. The remaining bottles separated; four went slightly offshore and upstream with the last of the flood tide that was still running in the channel, and three went downstream with the first of the ebb tide running along the shore, where they became entangled with barges tied along the shore and had to be taken out and started again in the channel. From the place

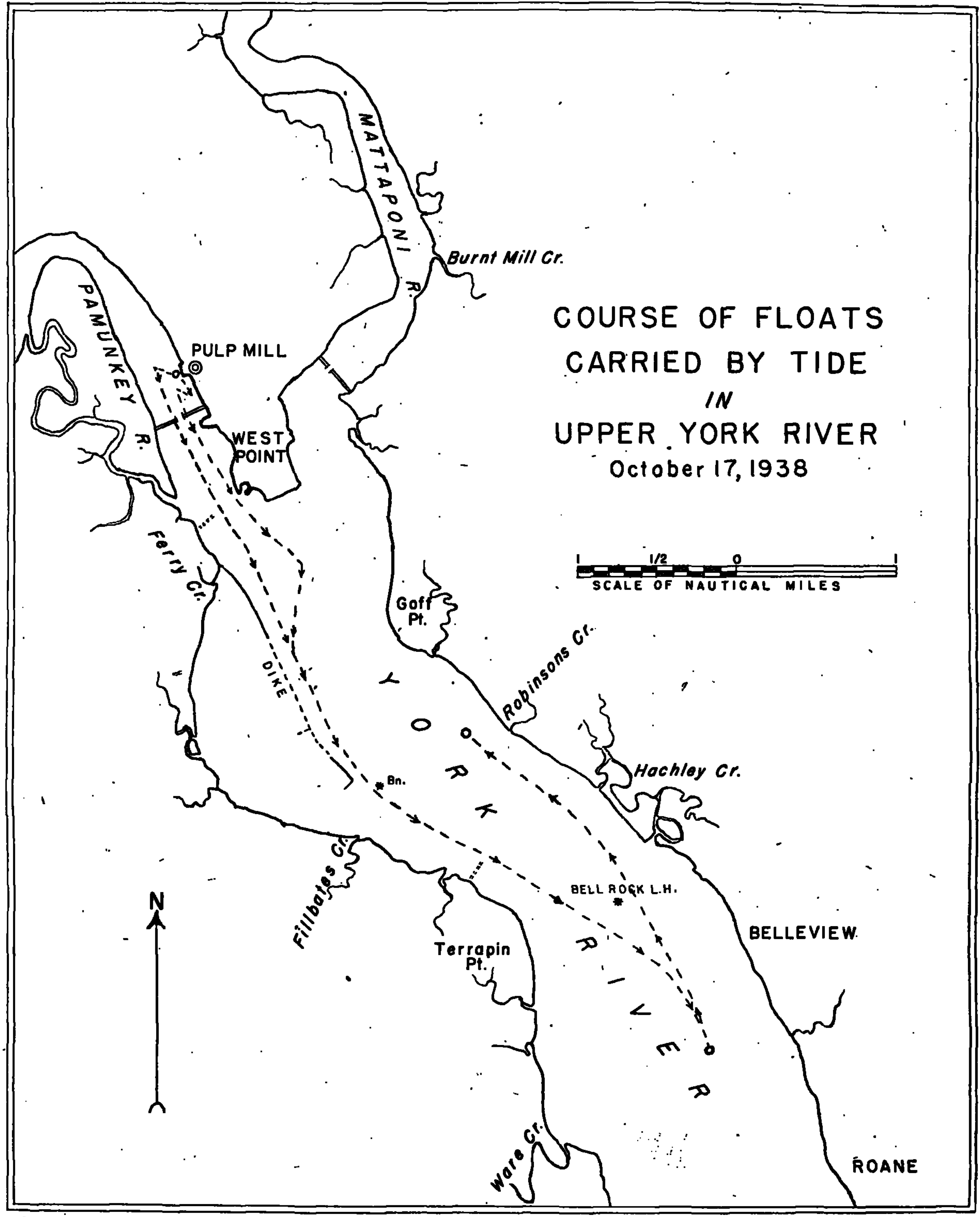

FIGURE 7.—Course of floats carried by the tide in the upper York River on October 17, 1938.

of release they floated along the shore past West Point and curved in across West Point Bar nearly to the channel of the Mattaponi River, then, turning back, joined the others coming down the right edge of the channel of the Pamunkey River. From this point all the bottles kept well together and passed down the river just inshore of the black buoys on the right edge of the channel to the bell buoy at Bell Rock. Here they went across the channel and continued down the left edge of the channel to a point about half way between Bell Rock Light and Roanes Point Beacon. The lowest point reached on this tide was about 5¼ miles from the place of release.

On the following flood tide the floats moved slowly up the river; they crossed the channel toward the left shore of the river, going in the water from 6 to 10 feet deep, and passed well inshore of Bell Rock Light. When the tide slacked off and further observations were discontinued, they had reached the point just above Robinson's Creek.

It is of interest to note that on October 19 one of the floats was recovered 5 miles above West Point in the Pamunkey River. This float must have become entangled with the barges at the start and then traveled upstream on a flood tide.

TEMPERATURE

Temperature observations of the bottom water of the York River at Naval Mine Depot just above Yorktown were made continuously by means of a gas-operated recording thermometer. The sensitive bulb was held just off the bottom, placed with its cable inside a capped galvanized pipe. Slots along the sides of the pipe in the vicinity of the bulb allowed a ready interchange of the water. The depth of water at the location of the instrument was 12 feet at mean low water. Observations were started on October 19, 1935. The water temperature for each hour from midnight of one day to midnight of the next was taken from the chart, and the minimum, maximum, and mean for the day noted.

Observations of surface-water temperatures of the Pamunkey River at Bruce Memorial Bridge at West Point were made by use of an ordinary mercury thermometer at high and low water each day starting May 1, 1936. With the deep-sea reversing thermometer, readings were made at high and low water off the steamboat dock at Yorktown three times a week at both surface and bottom. Water temperatures at the various hydrographical stations in the York and Piankatank Rivers were ascertained at various times. Observations of water temperatures were also made in studies of isohalines and tidal cycles at various places and times throughout the investigation.

The climatological conditions of the area of the York and Piankatank Rivers were unusual in many respects during the time of the investigations. Unusually cold weather with considerable snow characterized the first winter. December 1935 was next to the coldest December on record, while January and February 1936 were the fourth and eighth coldest on record. Unusual ice conditions prevailed with considerable portions of the York and Piankatank Rivers frozen. March 1936 was unusually warm, and air temperatures from May to October of that year averaged above normal with many record-breaking maxima observed during June and July. The winter of 1936–37 was mild, and air temperatures during January 1937 were unusually high, being the next highest on record.

Minimum and maximum air temperatures were taken from the records of the nearest meteorological station at Williamsburg, Va., as reported in the Climatological Data, United States Department of Agriculture, Virginia section. These were averaged for 5-day periods and are shown in figure 8. The maximum temperature during the period from October 1935 to July 1937 occurred on June 30, 1936, with an air temperature of 102° F. (38.9° C.), and the minimum occurred on February 1, 1936 with a temperature of 0° F. (—17.8° C.).

Considering the records obtained at the Naval Mine Depot station, shown in figure 8, the water temperature fluctuated but slightly from day to day. There was a general rise in the spring and summer and a drop in late summer and fall. Starting October 19, 1935, the records show a drop from temperatures of about 20° C. Unusually cold weather in December 1935 and again the last of January 1936 resulted in exceptionally low-water temperatures. The lowest temperature occurred on February 7 and 8, 1936, when readings of —1.5° C. were observed. At this time much of the river was covered with ice, even as far down as Yorktown. The water temperature rose rather rapidly and continued to rise until July and August. The maximum of the summer occurred on August 25 and 26, 1936, when a temperature of 29.5° C. was recorded. The drop in water temperature following the maximum was rather regular until January 1937, when there was a very marked rise which reflected the unusually

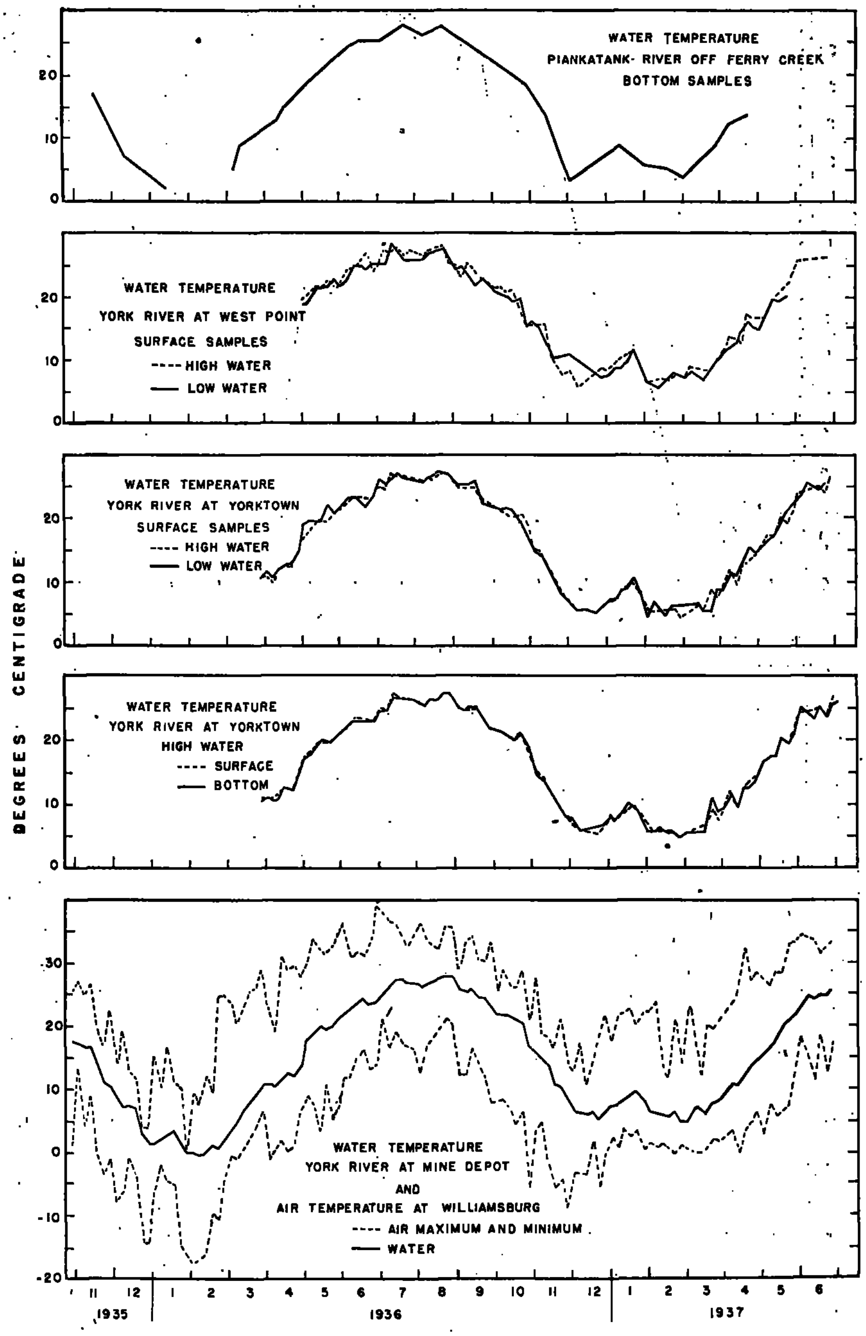

Figure 8.—Seasonal changes in air and water temperature in the York and Piankatank Rivers. The plotted points represent 5-day averages.

high air temperatures. The minimum for the winter of 1936–37 occurred on March 1, when 3.5° C. was recorded. A gradual increase in the water temperature followed during the spring.

It will be noted from the comparison of water and air temperatures in figure 8, that the water warmed more slowly than the air during the spring and cooled more slowly during the fall.

Similar seasonal changes in water temperature were observed at West Point, although the records were not so complete. The observed water temperatures at high water and low water grouped in 5-day

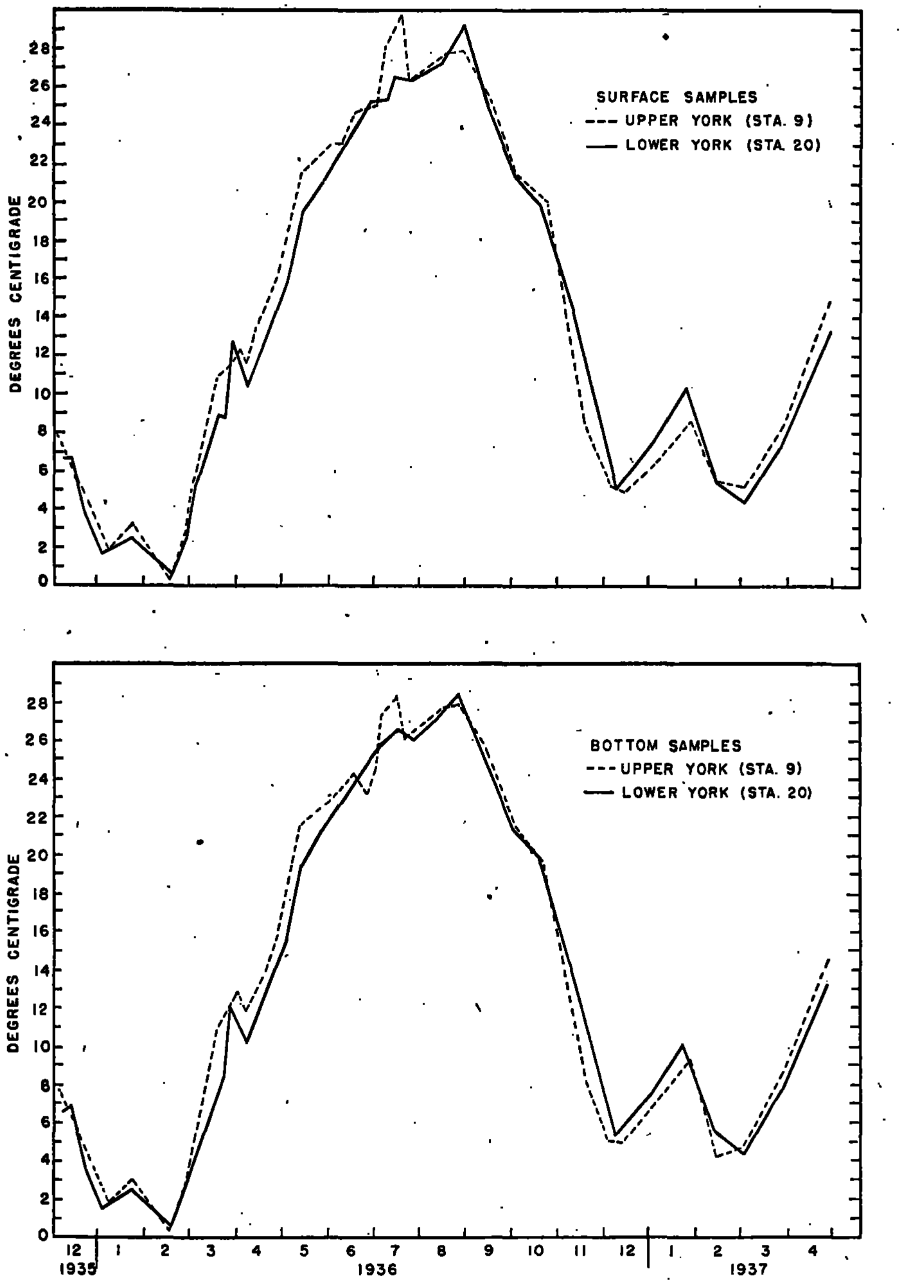

Figure 9.—Water temperatures in the lower (station 20) and upper (station 9) parts of York River.

periods, are shown in figure 8. Starting May 1, 1936, with temperatures of 18° C. at low water and 20° C. at high water, there was a gradual warming of the water during the spring and early summer. The maximum temperature of 29° C. was recorded July 14 and 18, 1936, and again on August 22, 1936. Following this, the water cooled during the fall. A marked rise occurred during the warm weather of January 1937. The minimum was 5° C. on February 11 and 12. The following spring the water warmed gradually and reached 29° C. on June 21, 1937.

The water temperature at Yorktown followed the same seasonal changes. Observations made three times a week at high water and low water at the surface and bottom are shown in the curves in figure 8. During the period from March 26, 1936, to July 1, 1937, the minimum water temperature was 4.1° C. on March 1, 1937, and the maximum 29.6° C. on August 25, 1936.

Similar seasonal changes were observed in the Piankatank River (fig. 8) and at other stations at which temperature of the water was measured (tables 6–20, pp. 177–186).

As for the horizontal distribution of water temperatures in the York River, it was observed that there was but slight variation throughout its length. The upper portion of the river had a slightly warmer temperature during the spring and summer than the lower, but during the winter this situation was reversed. The changes, however, were remarkably slight. The amount of fresh water entering the York River from above appears to have but slight influence in warming the water in the summer and cooling it in the winter. Figure 9 shows a comparison of the water temperatures at station 20 in the lower York and station 9 in the upper York Rivers. It will be noted that, although the differences in water temperature were very slight, the upper river warmed earlier in the spring and was warmer than the lower during the summer. There was little difference during the late summer and fall. In the winter the lower river was slightly warmer than the upper. This was due to the influence of the warmer sea water of Chesapeake Bay at that time of year.

Differences in the vertical distribution of water temperature were nearly absent except at the deeper stations. It will be seen that the curves showing water temperatures at high water at the surface and bottom (14 ft.) at Yorktown are almost identical (fig. 9). The surface water warmed more quickly than the bottom water during the spring.

Tidal effects on water temperature were unimportant. A comparison of water temperatures at Yorktown and West Point at high water and at low water throughout the season (fig. 8) shows almost no differences at those stages of tide. Observations made of changes throughout tidal cycles show that the effect of time of day on water temperature was more important than the stage of tide.

TURBIDITY

Data on the relative turbidity of the water at the various stations in the York and Piankatank Rivers were obtained throughout the time of observations. Measurement was made through the use of a Secchi disk, 6 inches in diameter, which was lowered and then raised, the depth at which it disappeared on lowering and reappeared on raising being determined by several trials and recorded to the closest tenth of a meter. The observations for two stations, station 9 of the upper York and station 20 of the lower York, are compared in figure 10. The results of measurements at all stations are given in tables 6 to 20 (pp. 177–186).

Precipitation conditions have an important bearing on the turbidity of the water. Precipitation records from the Climatological Data, United States Weather Bureau, for the period from October 1935 through June 1937 at stations on the York watershed are presented in the graph in figure 10.

During September 1935 there was considerable rainfall in the area of the York watershed, and many of the streams were at flood stage. January, March, and December 1936 were unusually wet months, January exceeding all former records. Dry weather characterized the period from May to August 1936, the amount for May being the next to the least on record. The year 1937 was the wettest year on record, and in January 1937 there occurred the greatest precipitation ever recorded for that month. April and August were the third wettest, while March was unusually dry. Noteworthy floods occurred throughout the streams of the area during April 1937.

There was an increased turbidity throughout the spring of the year 1936. This was followed by a decreasing turbidity through the summer and fall, the summer of this year being particularly dry as well as being the time of year of least run-off. Increased rainfall during January 1937 brought about an increased turbidity, which was continued throughout the following spring. Unusually high rainfall in April 1937 caused a marked increase in turbidity, the water appearing brownish red even below Yorktown.

The water of the upper part of the York River was consistently more turbid than that of the lower section where fluctuations in turbidity were more pronounced. Disk readings at station 9 of the upper river ranged from 0.2 meter to 1.0 meter, and averaged 0.47 meter. In the lower York at station 20 the range was from 0.7 meter to 2.0 meters, and the mean was 1.39 meters.

The Piankatank River was clear throughout the time of the investigations. The disk could be seen clearly on the bottom in the lower river at each sampling. The upper part of the river was more turbid than the lower but still much less turbid than the York River. The readings at station 53 in the upper Piankatank ranged from 0.5 meter to 2.2 meters, or bottom, the mean being 1.44 meters.

SALINITY

The salinity in a tidal river is in a state of unstable equilibrium which, for each given point, is determined by its distance from the mouth, the stage of the tide, and the river discharge. Under these conditions daily and seasonal fluctuations are to be expected. Furthermore, from the head of the river toward its mouth, there must be a definite salinity gradient, which also changes with the river stage. Observations made in the York and the Piankatank Rivers show these conditions.

Samples for salinity were taken by means of the Eckman bottle and transferred to citrate bottles with patent stoppers for transportation to the laboratory. In a few instances the salinity was computed from specific gravity determinations made by the use of standardized hydrometers, but in most cases the samples were titrated for chloride by the Knudsen method as described by Oxner (1920), and the salinity computed by the use of hydrographic tables (Knudsen 1901).

Observations of seasonal changes in salinity were made at the surface and the bottom for both high and low water three times a week from the steamboat dock at Yorktown, and for the surface at each tide at the Bruce Memorial Bridge at West Point. Salinity of the water was also determined at the various hydrographic stations of the York and Piankatank Rivers at regular intervals. Other observations included studies of the horizontal distribution of salinity at one tidal stage in the York and Piankatank Rivers, and studies of the changes in salinity of the water throughout tidal cycles at various localities. Seasonal changes in salinity at Yorktown and West Point are shown in figure 10. Observations at all the stations are reported in tables 6–20 (pp. 177–186).

At Yorktown during the period from March 1936 to July 1937 the salinity ranged from a minimum of 5.46 parts per thousand on May 5, 1937, to a maximum of 23.96 parts per thousand on October 15, 1936. When the observations were started in March 1936 the salinity was about 11 parts per thousand. There was a steady increase in salinity throughout the spring and summer. The salinity remained at a relatively high figure during the fall and early winter, dropping markedly in January 1937 as a result of considerable precipitation. During the following spring the salinity change was slight until the flood conditions of April 1937, when there was a sharp drop. This was followed by a rapid rise during May and June 1937.

Changes in salinity at West Point were much more abrupt. The range was from 0.08 part per thousand on January 22, 1937, and May 2, 1937, to 18.10 parts per thousand on October 27, 1936.

Observations made at station 53 off Ferry Creek in the Piankatank River from November 1935 to May 1937 show a minimum of 5.54 parts per thousand on May 6, 1936, and a maximum of 17.90 parts per thousand on November 10, 1936.

In general, it may be said that the seasonal changes in salinity followed the seasonal conditions of run-off, being high at the time of least run-off in the summer and fall and low during the time of greatest run-off in the spring, flood conditions being reflected by marked drops in salinity. The summer of 1936 being unusually dry, as well as being the season of least run-off, the salinity of the water was rather high. The relationship between salinity and precipitation can be seen by comparison of the curves in figure 10. The flood conditions of January and April 1937 are particularly marked in the resulting low salinity of the river at those times.

It is noteworthy that the range of salinity at Yorktown was 18.50 parts per thousand and at West Point was 18.02 parts per thousand.

Differences between surface and bottom salinities were very slight except at times of extreme floods (fig. 10). In general, the surface salinity was slightly less than the bottom salinity because of the flowing of the fresher water on top of the sea water.

The horizontal distribution of salinity of the York and Piankatank Rivers was studied at various times, samples being taken as nearly as possible at the same stage of tide throughout the river length. The results are presented in figures 11 and 12.

There was a gradual decrease in salinity from the mouth toward the head, depending on the amount of fresh water brought down the river from above and the inflow of salt water from Chesapeake Bay.

In the York River on March 17, 1936, at the last of ebb tide, the range of salinity was from 14.60 parts per thousand above Yorktown to 1.44 parts per thousand off Fillbates Creek. On December 15, 1936, the range at the last of flood tides was from 21.92 parts per thousand off Sandbox, below Yorktown, to 14.20 parts per thousand at a station in the Pamunkey River 1¾ miles above the bridge at West Point. On January 16, 1937, the range of

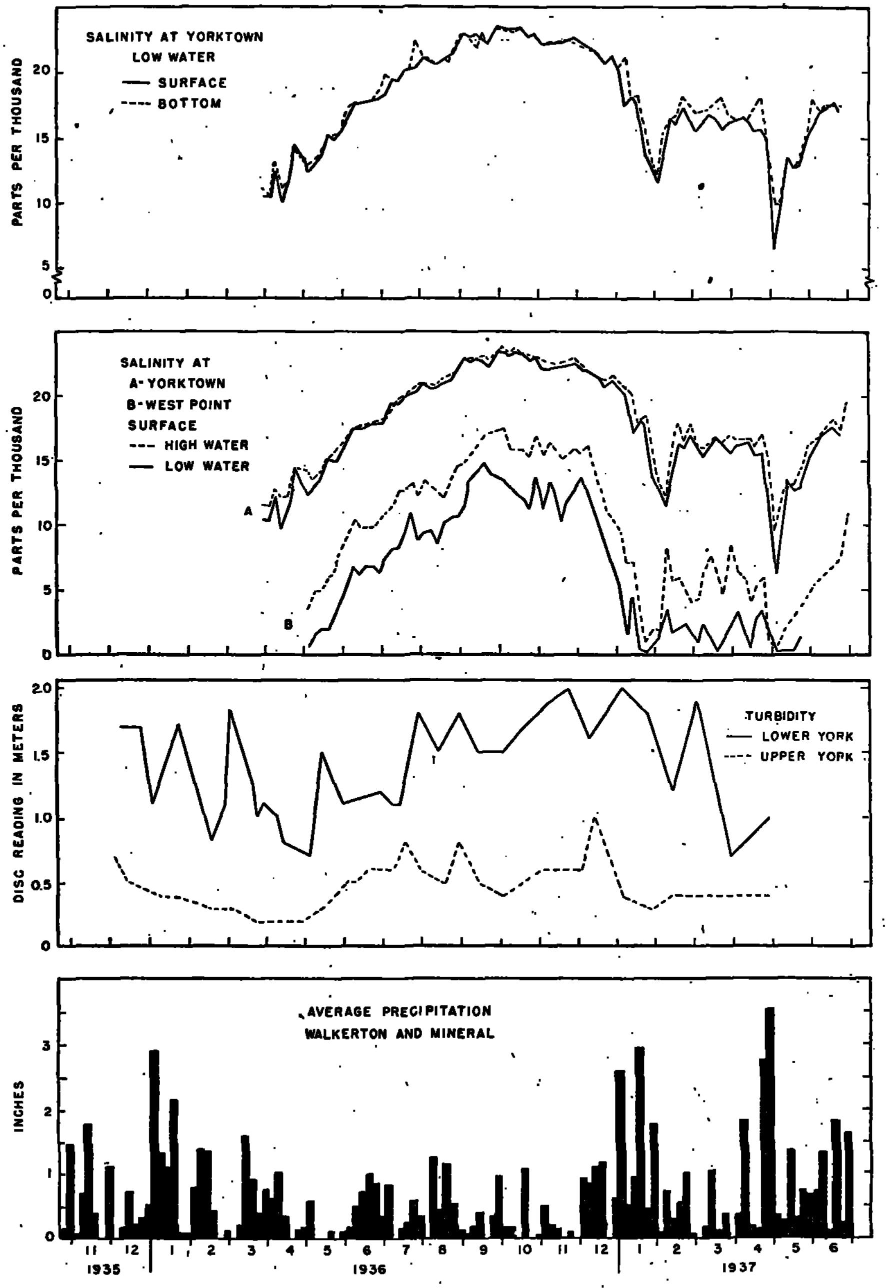

FIGURE 10.—Seasonal changes in precipitation in the York River drainage basin, the relative turbidity, and the salinity of the water of the upper and lower parts of the York River, from October 1935 to June 1937.

salinity at half-flood tide was from 19.45 parts per thousand off Carmines Islands to 2.65 parts per thousand at the above station in the Pamunkey River. On April 27, 1937, at the last of flood tide, the range was from 20.05 parts per thousand off Ellen Island to 14.83 parts per thousand at the above station in the Pamunkey River. On May 17, 1937, the range at the last of ebb tide was from 13.01 parts per thousand above Yorktown to 0.12 part per thousand at the above station in the Pamunkey River. At the last of flood tide on May 24, 1937, the range was from 15.25 parts per thousand above Yorktown to 1.89 parts per thousand at the above station in the Pamunkey River.

In the Piankatank River at the last of flood tide on May 5, 1936, the range in salinity was from 9.43

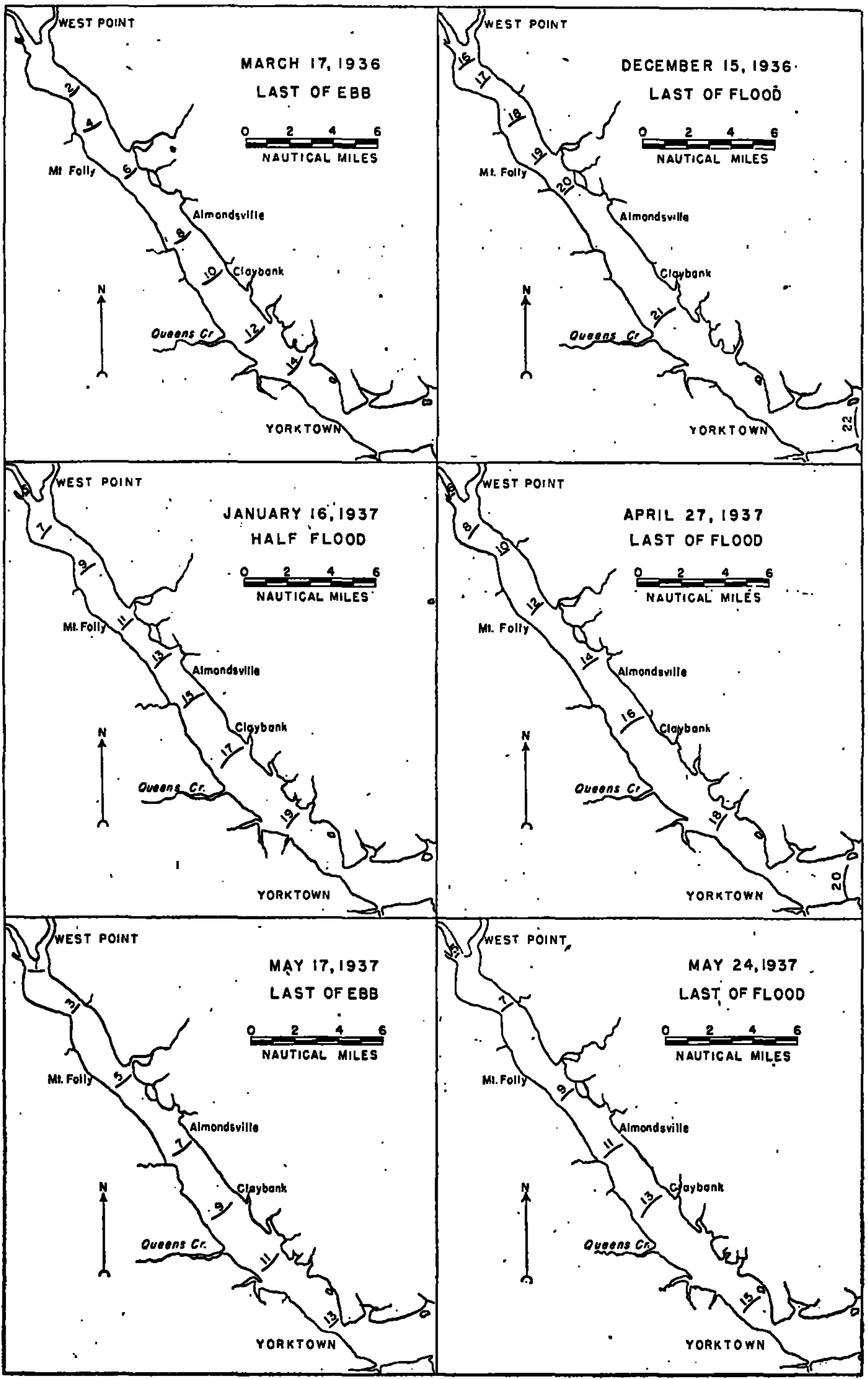

FIGURE 11.—The horizontal distribution of salinity of the water of the York River at various times. The numbers and heavy lines on the maps indicate isohalines in terms of salinity in parts per thousand.

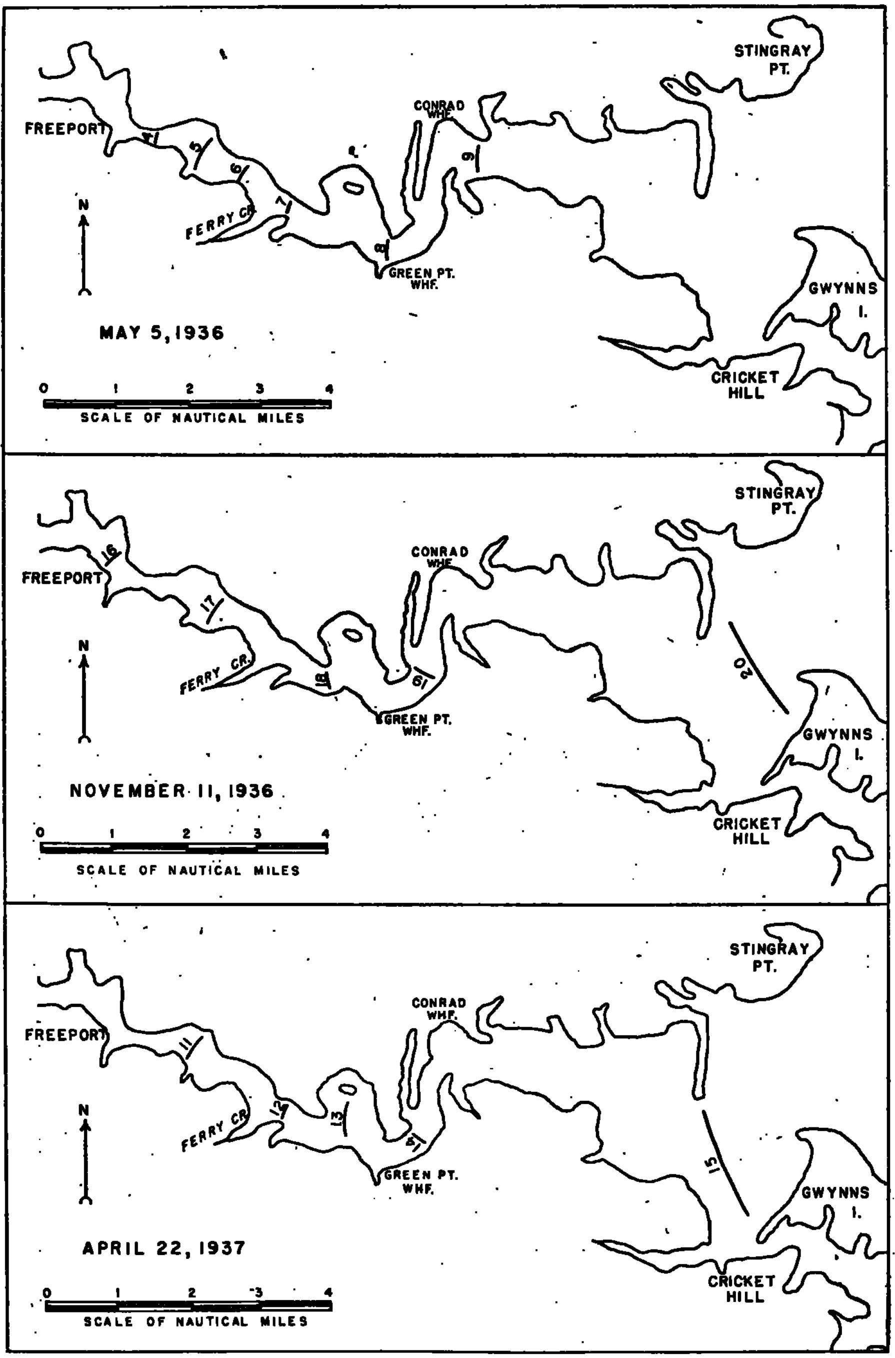

FIGURE 12.—The horizontal distribution of salinity of the water of the Piankatank River at various times. Observations were made during the last of flood tide on the dates indicated. The numbers and heavy lines on the maps indicate isohalines in terms of salinity in parts per thousand.

parts per thousand at the mouth to 3.60 parts per thousand at Freeport. On November 11, 1936, at the last of flood tide, the salinity ranged from 20.08 parts per thousand at the mouth to 15.99 parts per thousand at Freeport. On April 22, 1937, at the last of flood tide the range was from 15.18 parts per thousand at the mouth to 10.90 parts per thousand at a station off Bland Wharf, below Freeport.

The influence of tide on salinity was observed at various times at stations at Yorktown, Purtan Island, Bell Rock Lighthouse, and West Point. The results of these studies are shown in figures 13 to 20.

Figure 13 represents the tidal changes in salinity and temperature at Yorktown on February 24 and 25, 1936. It will be noted that at the bottom the highest salinity occurred 1¾ hours after high water and the lowest salinity occurred approximately one-half hour after low water. At the surface the highest salinity occurred 1¾ hours after high water and the lowest 1½ hours after low water. The salinity changes during this time were relatively small, varying from 12.99 parts per thousand to 16.24 parts per thousand at the surface, and from 14.78 to 19.11 parts per thousand at the bottom. The difference in salinity between high and low water was about 4 parts per thousand at the bottom and about 3 parts per thousand at the surface.

At a station just below West Point (fig. 14) on February 25 and 26, 1936, more marked differences between high and low water occurred. The salinity ranged from 0.59 part per thousand at low water to 6.53 parts per thousand at high water at the bottom, and from 0.11 to 6.31 parts per thousand at the surface. The surface salinity dropped more markedly after high water than did the bottom salinity, and the change of tide took place at the surface first at the start of ebb tide, and at the bottom first at the start of flood tide. The highest salinity at the sur-

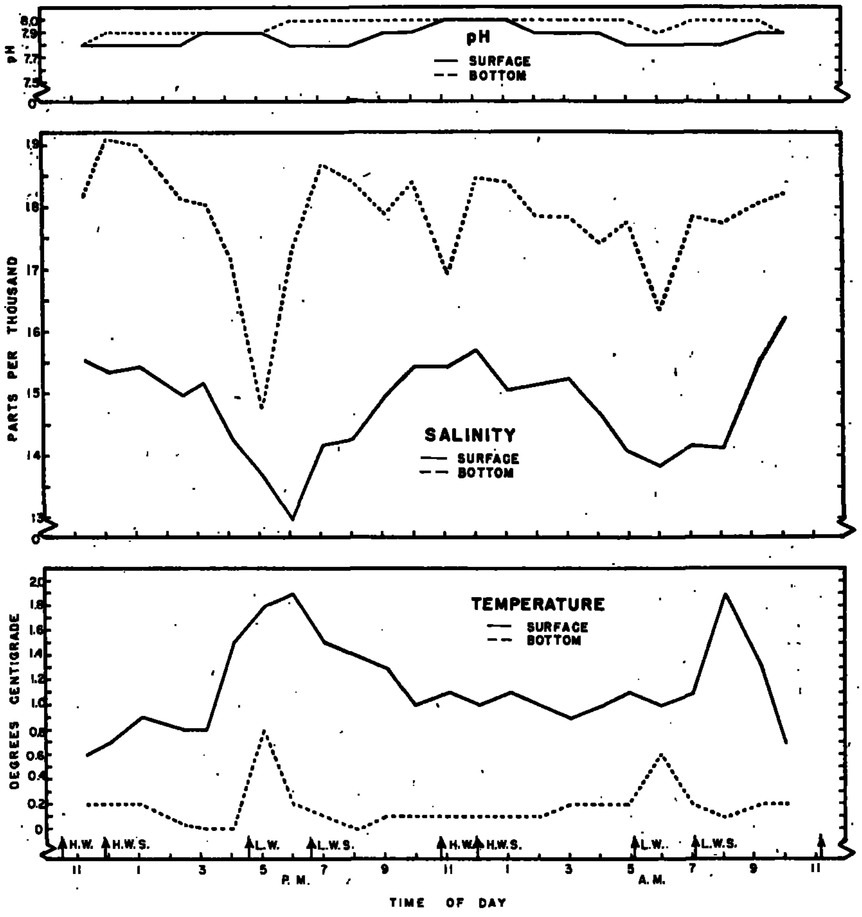

Figure 13.—Tidal changes in the temperature, salinity, and hydrogen-ion concentration of the water of the York River at Yorktown on February 24, and 25, 1936. Arrows indicate the stage of tide. L. W.=low water; L. W. S.=low water slack; H. W.=high water; H. W. S.=high water slack.

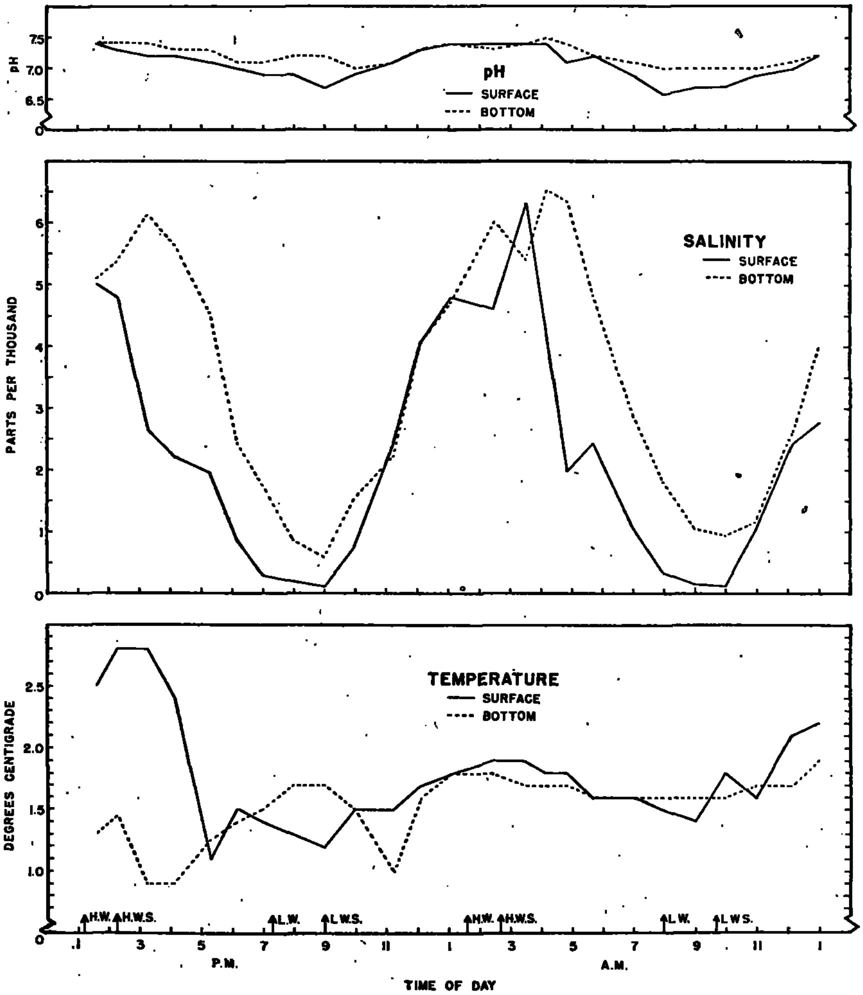

FIGURE 14.—Tidal changes in temperature, salinity, and hydrogen-ion concentration of the water of the York River just below West Point on February 25 and 26, 1936. Arrows indicate stage of tide. L. W.—low water; L. W. S.—low water slack; H. W.—high water; H. W. S.—high water slack.

face occurred approximately 2 hours after high water and at the bottom 2½ hours after high water. The lowest salinity occurred about 2 hours after low water.

Salinity changes during a tidal cycle at Yorktown on May 20, 1936, are shown in figure 15. Very slight differences were observed in salinity at high and low water, the range of salinity at the surface being only from 13.63 to 15.61 parts per thousand, and at the bottom from 14.36 to 16.04 parts per thousand. The highest salinity occurred one-half hour after high water and the lowest occurred 2 hours after low water.

Figure 16 shows the tidal changes in the Pamunkey River at West Point on May 21, 1936. The range of salinity was from 3.55 parts per thousand to 7.94 parts per thousand at the surface, and from 3.86 to 8.26 parts per thousand at the bottom. There was very little difference between surface and bottom samples. The highest salinity occurred about 2½ hours after high water and the lowest approximately 1½ hours after low water.

Salinity changes at Yorktown during a tidal cycle on September 24, 1936 (fig. 17) show a range from 18.75 parts per thousand to 20.26 parts per thousand for the surface water and from 19.47 parts per thousand to 20.95 parts per thousand for the bottom water. The highest salinity occurred about 2½ hours after high water at the surface and 2¾ hours after high water at the bottom. The lowest salinity was observed 2½ hours after low water.

During the tidal cycle studied at Yorktown on

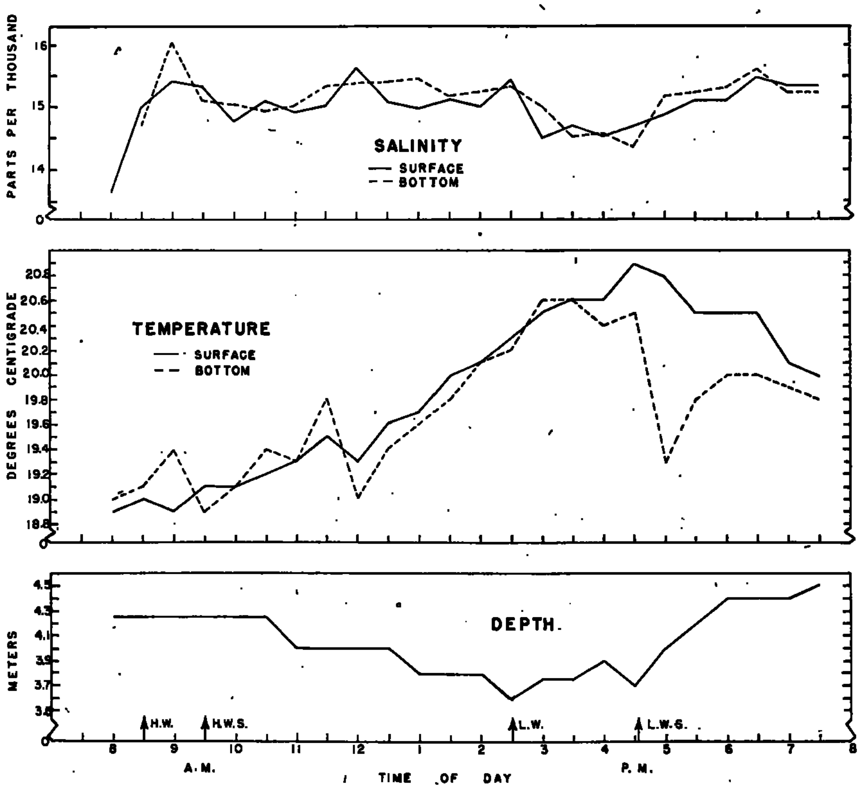

FIGURE 15.—Tidal changes in temperature and salinity of the water of the York River at Yorktown on May 20, 1936. Arrows indicate stage of tide. L. W.—low water; L. W. S.—low water slack; H. W.—high water; H. W. S.—high water slack.

October 29, 1936 (fig. 17), it was observed that the salinity range of the water at the surface was from 19.00 to 20.91 parts per thousand. At the bottom the range was from 19.63 to 21.24 parts per thousand. The highest salinity at the surface occurred 1¼ hours after high water and at the bottom 2¼ hours after high water. At the surface the lowest salinity was found 3¾ hours after low water and at the bottom 2¾ hours after low water.

Figure 18 shows the results of observations of salinity of the surface water during a tidal cycle off Purtan Island on February 10, and April 13, 1937. The salinity on February 10 ranged from 11.62 parts per thousand to 13.62 parts per thousand. The highest salinity was observed 1½ hours after high water, and the lowest salinity occurred approximately 2 hours after low water.

On April 13, 1937, the salinity of the bottom water during a tidal cycle off Purtan Island varied from 7.16 parts per thousand to 11.04 parts per thousand. On this day the highest salinity occurred one-half hour after high water and the lowest one-half hour after low water.

Figure 19 shows the data of tidal studies made at Yorktown on April 23, 1937. It is difficult to place the time of highest salinity in relation to time of high water in this series. The observations were started at high water in the morning and continued to high water in the evening. The salinity was decreasing at the time of the start of observations and was increasing when the measurements were ended. The lowest salinity occurred about 1½ hours after low water on the bottom and 2 hours after low water at the surface. The range of salinity at Yorktown during this tidal cycle was from 15.61 parts per thousand to 17.45 parts per thousand for the surface samples and from 15.68 to 18.51 parts per thousand for the bottom samples.

The results of tidal studies at Bell Rock Lighthouse on May 20, 1937, are presented in figure 20. The greatest salinity occurred one-half hour after high water and the lowest salinity occurred 1¾ hours after low water. The surface salinity varied from 3.91 to 7.41 parts per thousand and the bottom salinity from 4.13 to 7.99 parts per thousand.

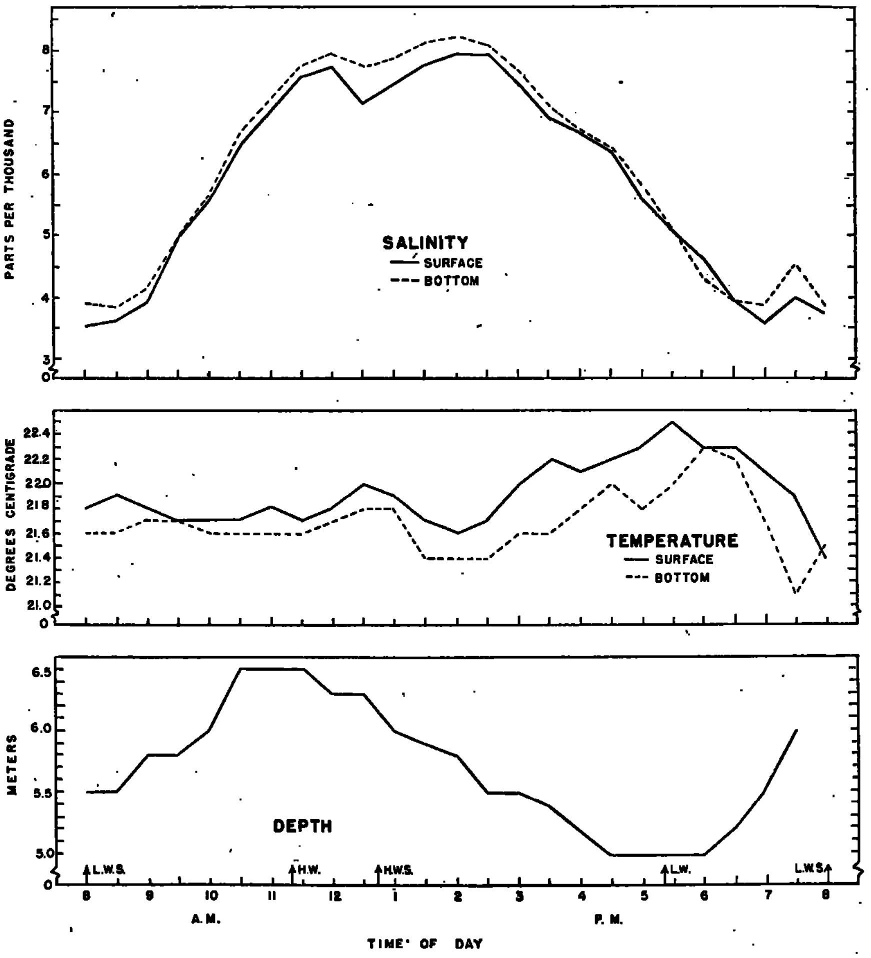

FIGURE 16.—Tidal changes in temperature and salinity of the water of the Pamunkey River at West Point on May 21, 1936. Arrows indicate stage of tide. L. W.—low water; L. W. S.—low water slack; H. W.—high water; H. W. S.—high water slack.

DISSOLVED OXYGEN

The dissolved oxygen content of the water of the York and Piankatank Rivers was determined for both surface and bottom samples at the different field stations at various times throughout the investigation.

The samples for the determination of oxygen were obtained with the Eckman water bottle. The water was then collected through a rubber tube extending to the bottom of a citrate bottle. Care was taken to have the tube full and to prevent aeration of the sample by bubbling. The dissolved oxygen content was determined by the Winkler (1888) method, as described by Kemmerer, Bovard, and Boreman (1923), and with the permanganate modification as given by the American Public Health Association (1933). The results were expressed in percentage of saturation, using the table of saturation of water with oxygen at various temperatures and salinities given by Whipple and Whipple (1911).

Despite the fact that the pulp-mill waste emptied into the York River at West Point has considerable oxygen demand, the dissolved oxygen content of the river was found to be not particularly low. At times during hot weather the oxygen of the water of the upper York does get rather low, but only rarely does it reach a figure critical to aquatic life. The Piankatank River was found to be relatively high in dissolved oxygen. The results of all observations at the various stations are presented in tables 21 and 22.

At times the water was found to be supersaturated with oxygen owing either to photosynthesis or to wave action. The latter has been responsible for most of the results showing a very high oxygen content.

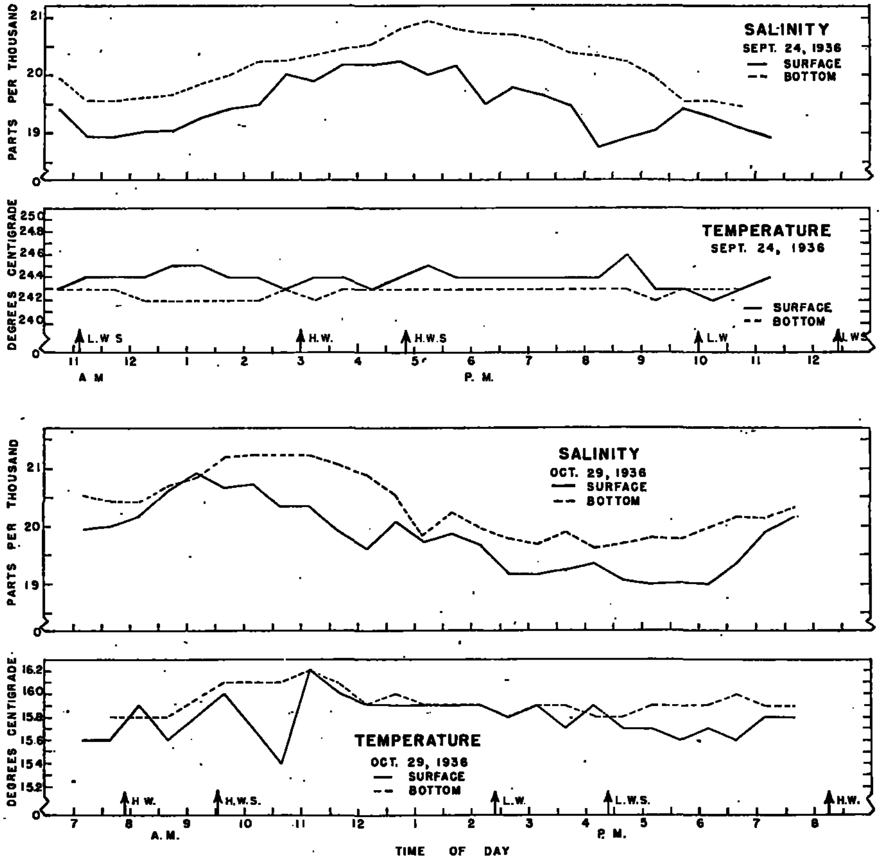

FIGURE 17.—Tidal changes in the temperature and salinity of the water of the York River at Yorktown on September 24 and October 29, 1936. Arrows indicate stage of tide. L. W.—low water; L. W. S.—low water slack; H. W.—high water; H. W. S.—high water slack.

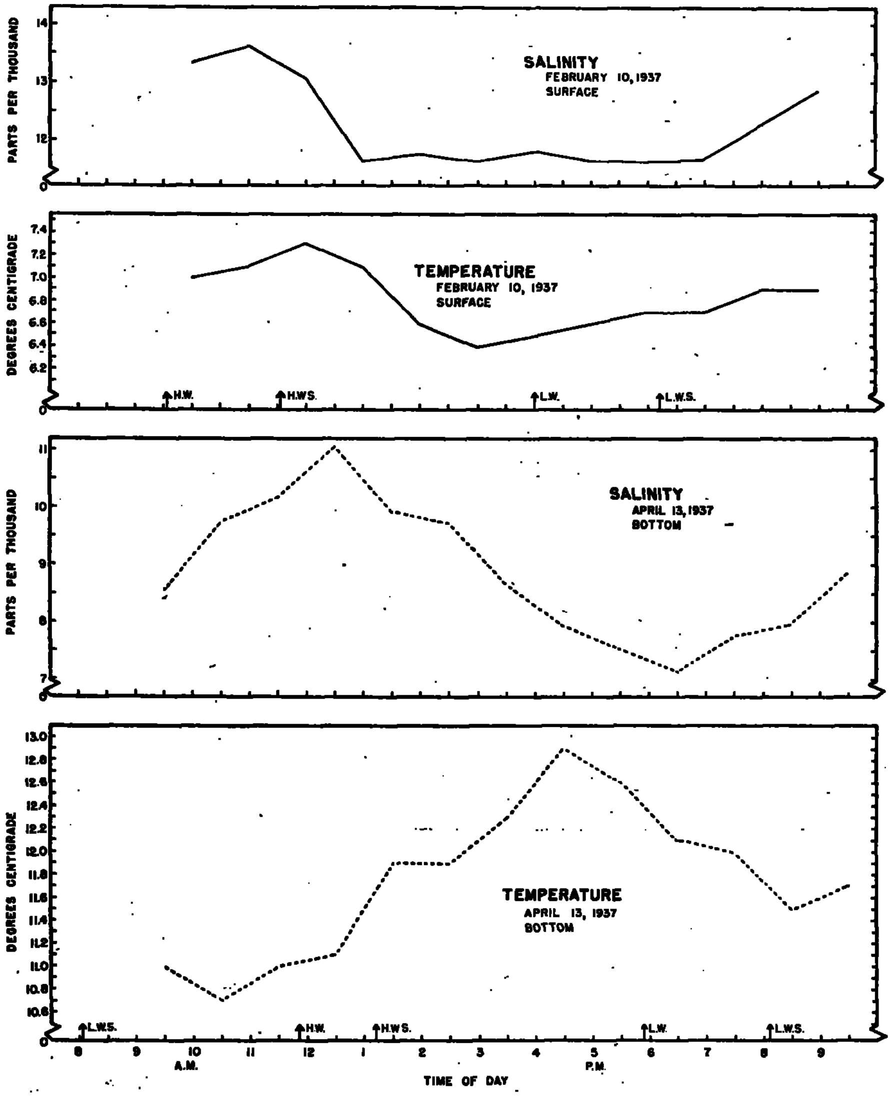

FIGURE 18.—Tidal changes in the temperature and salinity of the York River at Purtan Island on February 10 and April 13, 1937. Arrows indicate stage of tide. L. W.—low water; L W. S.—low water slack; H. W.—high water; H. W. S.—high water slack.

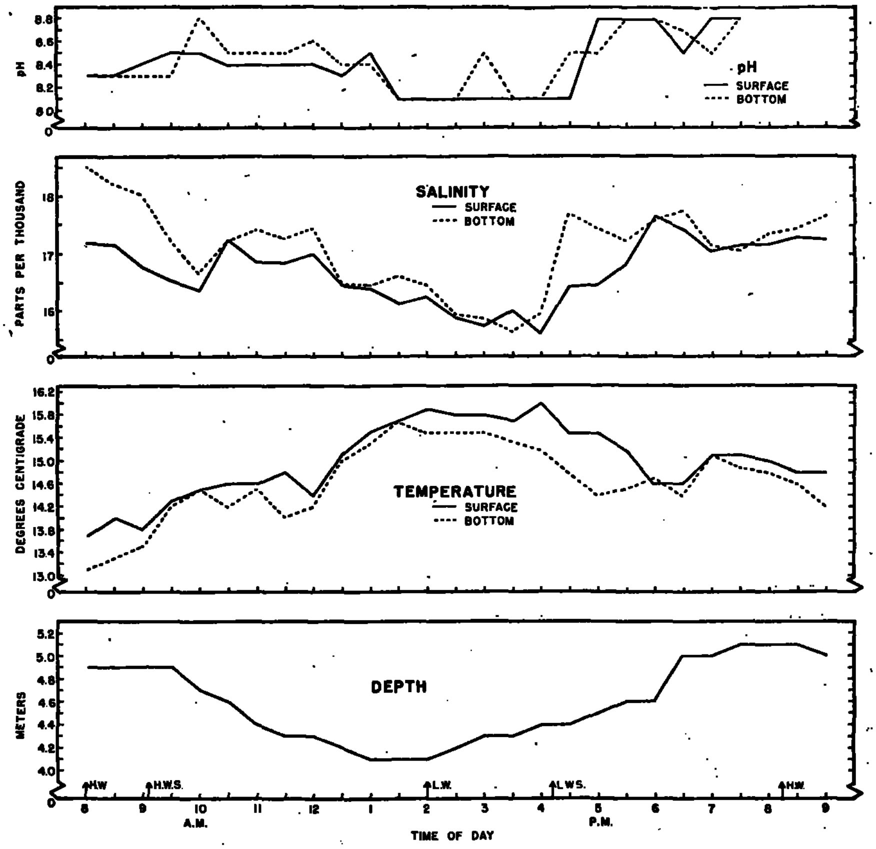

FIGURE 19.—Tidal changes in temperature, salinity, and hydrogen-ion concentration of the water of the York River at Yorktown on April 23, 1937. Arrows indicate stage of tide. L. W.—low water; L. W. S.—low water slack; H. W.—high water; H. W. S.—high water slack.

TABLE 21.—*Percentage of saturation of the water of the York River with dissolved oxygen*

Date	Stations																		
	20		14		15	23	5	22	6	16	17	8		9		18		19	
	Surface	Bottom	Surface	Bottom								Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
1935																			
Dec. 2			92.5	93.0	103.2														
Dec. 6	94.2	92.2					91.7			98.9	97.5								
Dec. 12	96.2	90.5	95.8	96.4	109.0		88.6												
Dec. 13										80.5				89.0	89.7	80.9	80.8	82.3	82.9
Dec. 23	110.8	96.8																	
1936																			
Jan. 3			96.8	97.4	97.6		94.1												
Jan. 4	95.1	94.1																	
Jan. 6																76.0	77.1	82.3	71.3
Jan. 7										95.3	87.7			88.8	90.3				
Feb. 19	94.5	93.9		93.4	90.8														
Feb. 20							95.0							87.9	86.0	87.1	87.1		
Feb. 21										88.3	87.4								
Feb. 27			96.6	85.6			93.5							85.2	72.3				
Mar. 16	101.2	104.7			104.7														
Mar. 18			103.5	109.0			101.1			100.6									
Mar. 19											73.8			80.2	86.2	55.1	52.7	86.1	85.7
Mar. 30	114.4	114.6			108.9		90.7			90.1									
Apr. 1											82.3			76.7	80.3	77.6	71.3	91.7	78.8
Apr. 14	99.7	96.5	92.3	100.0	94.9		89.1												
Apr. 16										92.6	100.8			94.3	106.8	87.1	99.2	94.0	103.5
Apr. 27				117.5	95.2		113.8												
Apr. 28										95.1		86.1	82.0	85.2	83.9	80.3	77.0	90.0	82.9
Apr. 29											108.3								
May 28	94.3				101.1														
June 1							107.0			101.7	109.4			114.9	108.7				

Table 21.—*Percentage of saturation of the water of the York River with dissolved oxygen*—Continued

Date	Stations																		
	20		14		15	23	5	22	6	16	17	8		9		18		19	
	Surface	Bottom	Surface	Bottom								Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
June 3																101.6	86.6	81.1	87.9
June 30	106.9	115.5		100.3	104.0		91.8												
July 2										76.0	84.5			97.1	87.1	78.3	72.3	83.8	76.8
July 27	110.2	101.1	109.2	107.6	108.3														
July 29						91.5	90.6	90.3	87.6										
July 31										66.9	77.9		78.2	83.4	57.2	89.4	78.4	86.7	64.4
Aug. 16											102.6		99.8	96.7	89.1	78.3	64.2	93.5	69.7
Aug. 26	105.3	101.0	86.8	87.4	82.0														
Aug. 28										85.0	89.8			59.0	62.3	95.6	83.3	76.8	77.0
Aug. 31						92.8	88.2	106.0											
Sept. 9				101.1	106.0	90.6													
Sept. 10							96.5	98.3	115.1	96.1	100.5								
Sept. 11													101.1	90.2	87.3	84.6	69.0	86.5	83.8
Sept. 14	84.8	88.4																	
Sept. 29			83.3	82.1	88.0	82.9	88.2												
Oct. 1								84.0					83.3						
Oct. 2	93.8	97.7							93.5	69.8	96.6			86.6	91.7				
Oct. 21	74.2	88.5	115.5	120.2	83.0	91.2	104.8	96.8	97.4	92.5	84.3								
Oct. 22												81.4	65.0	83.6	81.6	76.4	68.6	79.3	78.4
Nov. 4										83.3	88.2	85.5	82.9	81.4	76.8	75.1	74.9	84.4	83.4
Nov. 5				92.5	93.7	91.0	102.8	93.2	96.3										
Nov. 6	92.0	95.6																	
1937																			
Jan. 25	99.6	95.4																	
Jan. 26				87.9	90.8	89.1	87.3	85.5	86.4										
Jan. 27										83.6	84.7	84.7	81.1	74.8	70.6	57.7	54.7	62.8	68.8
Mar. 3										84.2	88.2	85.1	83.8	78.3	75.2	68.3	77.0	69.1	53.4
Mar. 4	101.8	94.8	91.7	92.4	98.1	96.3	96.0	94.8	93.1										
Mar. 30							99.4	100.0	91.3	98.5				96.9	95.3	95.0	89.4	91.5	89.6
Mar. 31	105.5	104.0	105.4	107.2	103.9	106.7													
Apr. 23			100.2	102.1	111.8	107.3	105.9	112.3	99.2										
Apr. 26	96.8	90.7																	
Apr. 27										90.9	107.9	87.3	81.7	84.5	77.9	71.1	75.0	75.5	70.6
May 17																65.8	65.3		
Average	99.1	97.7	97.7	98.6	98.8	93.9	96.0	96.1	95.5	88.5	92.2	85.0	83.9	86.4	83.6	79.1	75.2	83.2	78.3

Table 22.—*Percentage of saturation of the water of the Piankatank River with dissolved oxygen*

Date	Stations		
	55	53	
		Surface	Bottom
1935			
Dec. 10	101.4	97.4	100.7
1936			
Jan. 11	97.0	91.2	92.4
Mar. 3	108.6		99.4
Mar. 12	73.1	75.8	75.7
Apr. 3	102.9		97.8
Apr. 16	106.7		98.4
May 6	103.3	91.4	93.9
June 4	90.3	96.1	76.0
July 1	91.9		77.9
Aug. 3	87.7	79.8	82.6
Aug. 21	106.5	110.3	66.8
Sept. 3	96.0	100.4	101.6
Oct. 6	97.6	105.8	97.4
Oct. 26	96.4	92.6	94.0
Nov. 10	112.2	98.1	100.8
1937			
Feb. 2	99.2	86.7	78.0
Feb. 16	99.2	106.2	101.8
Apr. 6	113.6	105.3	105.0
Apr. 21	111.4	117.7	113.5
Average	99.7	97.0	92.3

Changes in the dissolved oxygen content of the water during a tidal cycle in the upper York River at Bell Rock Lighthouse on May 20, 1937, are shown in figure 20. It will be noted that fluctuations in the oxygen tension were following the time of day rather than the tidal cycle.

The horizontal distribution of dissolved oxygen in the water of the York River on the last of ebb tide on May 17, 1937, is shown in figure 21. It will be seen that there was less oxygen in the upper York than in the lower. The fact that the upper York was consistently lower in dissolved oxygen than the lower York can be seen from examination of figure 22, which shows the average percentage of saturation at the various stations.

Analysis of the data presented in table 21 shows a very definite decrease in the percentage of saturation from the mouth of the river (station 20) towards its head (stations 9 and 19). The annual mean values, which are more significant than single observations, show that in surface water samples, taken between these two points, the percentage of dissolved oxygen gradually decreases from 99.1 to 83.2. The figures for bottom samples, as one would expect, are lower, ranging at the same stations from 97.7 to 78.3 percent. For the Piankatank River the annual

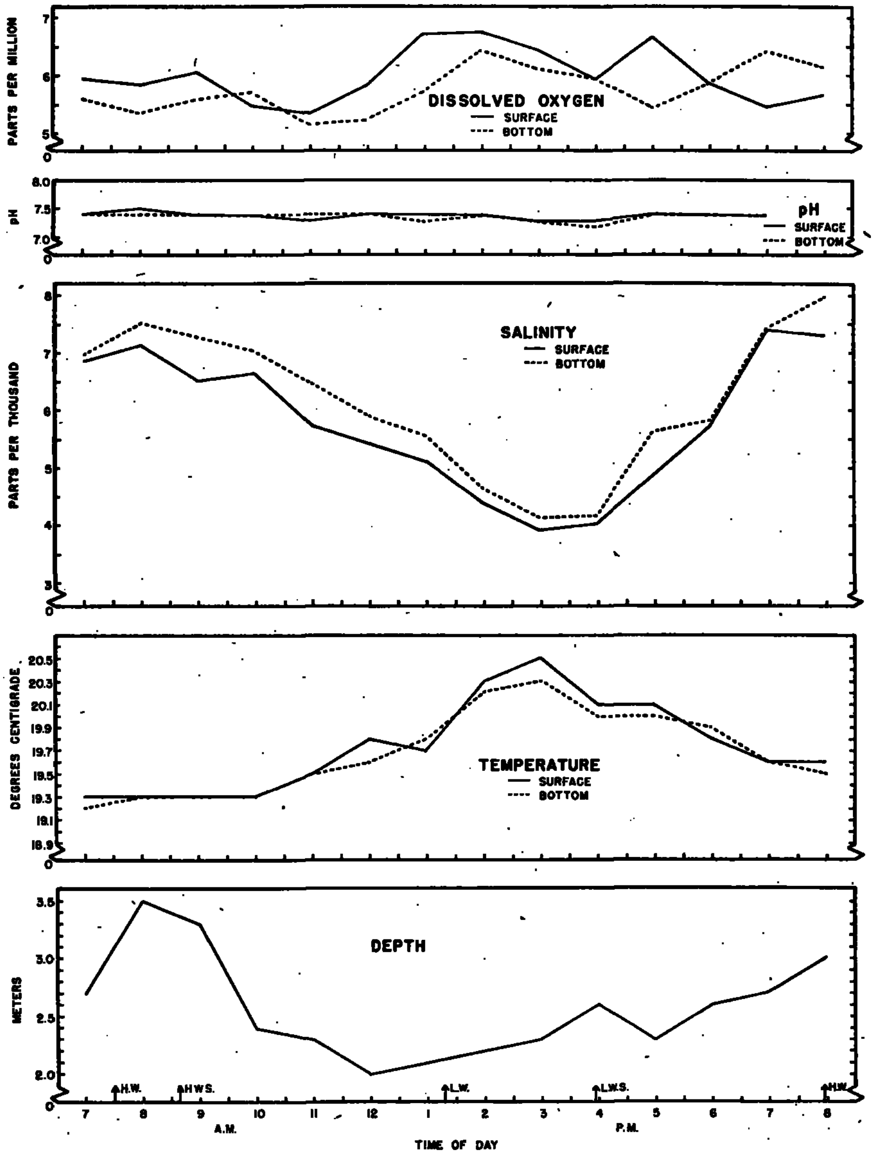

FIGURE 20.—Tidal changes in temperature, salinity, hydrogen-ion concentration, and dissolved oxygen of the water of the York River at Bell Rock Lighthouse on May 20, 1937. Arrows indicate stage of tide. L. W.—low water; L. W. S.—low water slack; H. W.—high water; H. W.S.—high water slack.

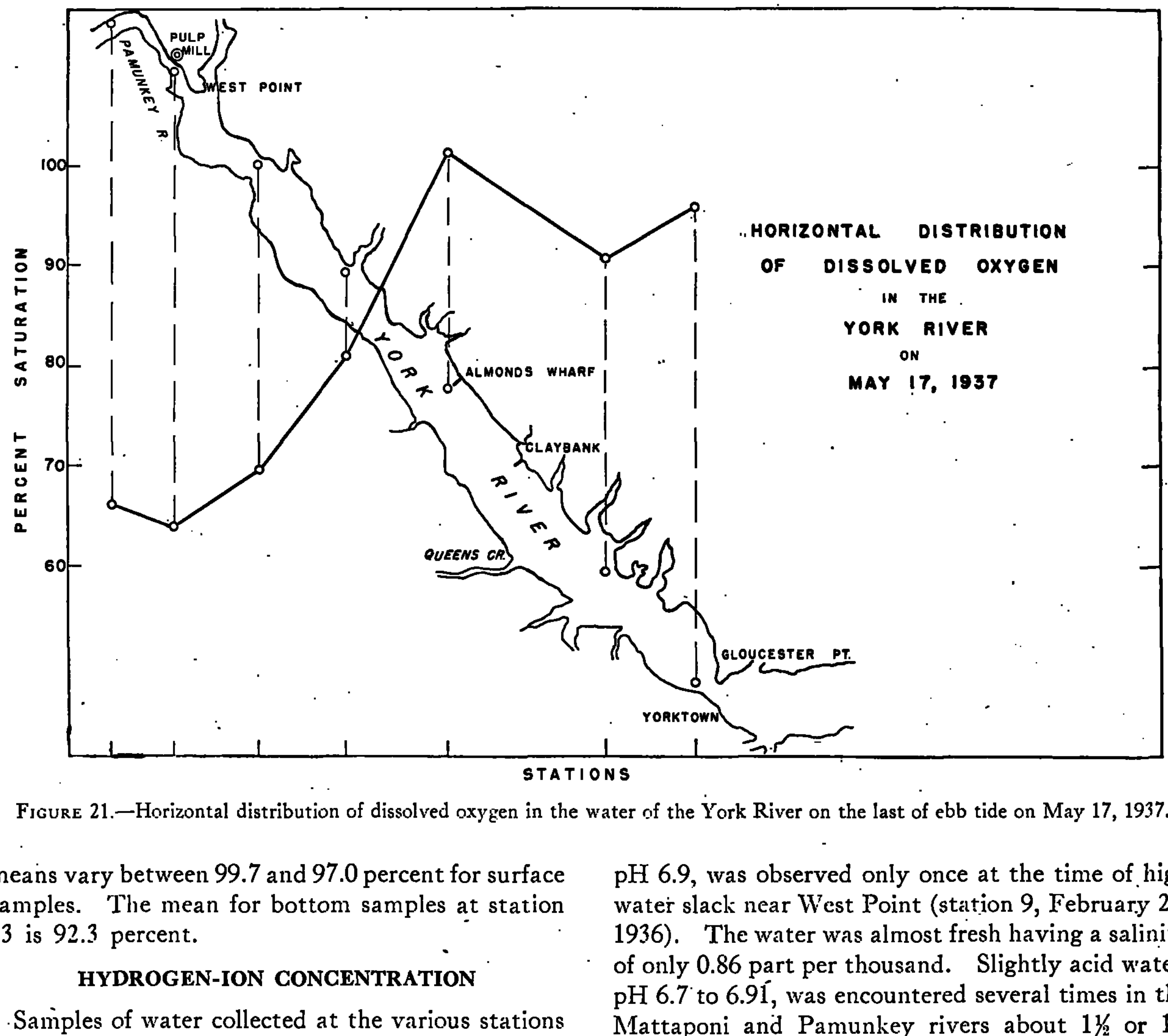

FIGURE 21.—Horizontal distribution of dissolved oxygen in the water of the York River on the last of ebb tide on May 17, 1937.

means vary between 99.7 and 97.0 percent for surface samples. The mean for bottom samples at station 53 is 92.3 percent.

HYDROGEN-ION CONCENTRATION

Samples of water collected at the various stations in the York and Piankatank Rivers were tested for their hydrogen-ion concentration, using Hellige comparator and standard indicators. In nearly all instances cresol red was used, but in a few cases brom-thymol blue was employed. The observed values were corrected for salt error according to the corrections given by Ramage and Miller (1925). The hydrogen-ion concentration of all water samples tested is given in terms of pH in tables 6–20 (pp. 177–186) and figures 13, 14, and 19.

The fluctuations in the pH of water were found to be rather extensive, varying from 6.9 to 8.4 in the York River and between 7.1 and 8.6 in the Piankatank. In both rivers there was a gradual decrease in the pH from the mouth to the head. This was due to the greater proportion of fresh water at the head of each stream. The lowest value, pH 6.9, was observed only once at the time of high water slack near West Point (station 9, February 20, 1936). The water was almost fresh having a salinity of only 0.86 part per thousand. Slightly acid water, pH 6.7 to 6.91, was encountered several times in the Mattaponi and Pamunkey rivers about 1½ or 1¾ miles above the bridge at West Point (tables 17 and 18).

As a general rule lower pH values occurred during times of freshets. Other seasonal and daily changes in the hydrogen-ion concentration were probably associated with the intensity of photosynthesis and other biochemical processes in the river.

PHOSPHORUS

Among the phytoplankton nutrients the phosphates feature importantly as the constituents of the sea water necessary for the growth of the algae. In this investigation biweekly samples of water were taken at various stations in the two rivers for phosphorus analysis. The cycle of phosphorus was followed from January 1936 to April 1937, using the

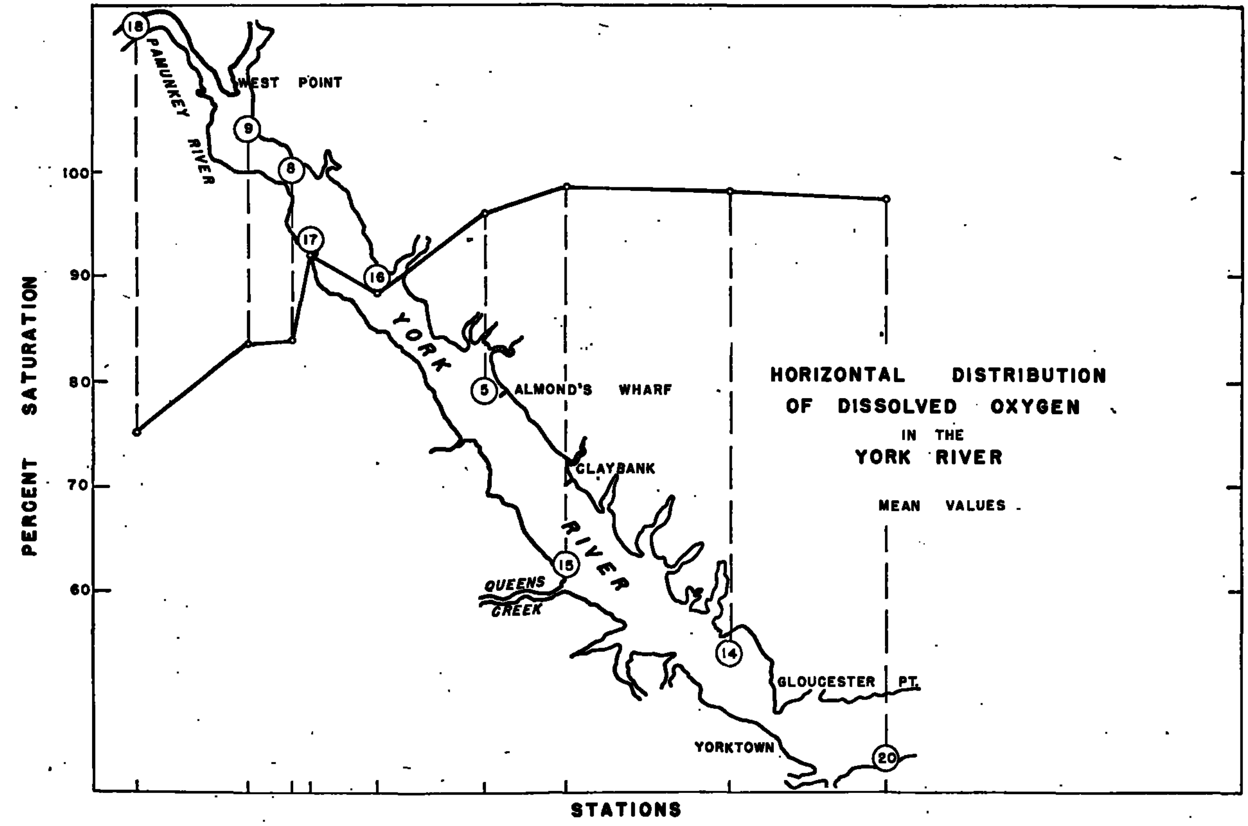

FIGURE 22.—Horizontal distribution of dissolved oxygen in the York River. Percentage of saturation based on mean values.

method of Atkins-Deniges as given by Seiwell (1935).

The results (given in tables 6 to 20)[3] show comparatively small quantities of phosphorus in the water of the two rivers. During the spring and summer months the quantities were negligible. In the fall and winter months the phosphorus content in the York River rarely reached 30 milligrams per cubic meter. Unexpectedly high content of 93 milligrams per cubic meter observed on January 27, 1937, at stations 8, 9, 16, 17, was of short duration, having disappeared within a fortnight.

Conditions similar to those found in the York River prevailed in the Pamunkey, Mattaponi, and Piankatank Rivers. Only on rare occasions did the phosphorus content reach 30 milligrams per cubic meter.

From these observations conclusions can be reached that fresh water entering these tributaries of the Chesapeake Bay contributes but very little to the supply of phosphates needed for the propagation of plankton.

ACCUMULATION OF PULP-MILL EFFLUENT IN THE YORK RIVER

THE RATE OF DISCHARGE OF PULP-MILL EFFLUENTS AT WEST POINT

Determination of the total quantity of pulp-mill effluents discharged daily into the river at West Point was desired for evaluating the degree of pollution of the river and for computing the concentration of the pollutant in the river water. Unfortunately, no systematic records of the rate of flow of effluents in the various sewer outlets were available.

Observations had shown that the rate of flow, the appearance, and the specific gravity of pulp-mill effluents were subject to rapid and sudden changes depending on the various stages of operation of the mill. Since information on rates of flow was not available, observations were made on a number of occasions over sufficient periods to record these variations and to obtain data which would serve in evaluating the degree of pollution of the river and for computing the concentration of the pollutant in the river water. These observations are presented here with the necessary details for such computations.

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[3] Tables 6 to 20 will be found on pp. 177–186

Experimental data described (pp. 134–157) show that only the waste arising from the pulping process contained the physiologically active material in sufficient amount to demonstrate its effect within the limitations of the experiments. The following observations refer therefore only to the discharge of these effluents.

At the start of the investigation in the late fall of 1935, the visible sewer outlets at the mill were as follows:

1. A small ditch dug at the south end of the plant, draining the sludge pond located east of the mill and emptying into the river. The bottom of this ditch had an accumulation of gray sludge, which, from time to time, was cleaned by workmen. There was a small flow of a light brownish liquid in the ditch.
2. A ditch of considerable size leading to the river from a small pool located at the rear of the power plant and shops and which received the outlet of a number of pipes of various sizes. This ditch was lined with piling and completely covered over with planks. This pool and ditch carried considerable effluent of a moderately dark-brown color with small amounts of rather firm froth and at times contained some oil (fig. 4, A, B, C, D).
3. A large pipe with considerable flow emptying from a height of a few feet into the river at the south end of the lighter slip. This material appeared to be light yellow in color (fig. 4, E).
4. A large open ditch in back of the digester house running from the old pump house to the river. At the head of this ditch emptied a large tile pipe and a smaller cast-iron pipe. There was also a small ditch from the old board mill entering here. This small ditch had a very small flow of clear water. The large tile pipe carried a large flow of dark brown effluent and the smaller pipe carried some steam and water, also, large amounts of steam at the time of blowing a digester (figs. 4, J, H, I).

A blueprint received from an official of the plant showed the approximate lay-out of 10 sewer lines. The size of the sewers and their purpose was also listed and are given in the caption of figure 4. At this time, the rate of flow of the main sewers was given as follows: sewer *A*—200 gallons per minute; sewer *D*—150 gallons per minute; and sewers *J* and *H*—1,200 gallons per minute. These estimates were based on frequent observations which consisted in timing the travel of small wooden chips tossed into the sewers.

It was learned that early in 1936 an additional pipe (not shown in fig. 4) was installed leading from the weak-liquor storage tank to the head of the ditch leading from sewers *J* and *H*. This line carried off the foam that accumulated at the top of the tank. From observations made by the authors during the summer and fall of 1936 it was noted that this pipe ran black at times with a very alkaline, syrupy mixture and at other times was water-clear. The times of running black, however, were numerous and continued for long periods.

On April 7, April 20, and May 4, 1937, observations were made with a Price current meter on the rate of flow of effluent in the ditch leading from sewers *J* and *H*. A short distance down the ditch from its head a location was selected at which the flow was confined to a regular channel between well-defined banks and where the bottom was rather regular. It was observed that the greatest flow occurred at one place a little to one side of center. The current meter was placed in the swiftest current and the revolutions counted. The meter was then placed in the slowest current and the revolutions again counted. Observations were made at intervals of 10 to 15 minutes. At each time of reading of the current meter, the width of the flow was measured and the depth measured at three different locations in a line across the flow. From this information it was possible to compute the volume of effluent passing this point.

The rate of flow as measured by this means in the ditch leading from sewers *J* and *H*, for short periods, gave results of 400 gallons per minute on April 7; 642 gallons per minute on April 20; and 1,849 gallons per minute on May 4, 1937. The average flow computed from all these short periods of observation would be 990 gallons per minute.

During the early summer of 1937, wooden weirs were installed by the pulp mill in the ditch below sewers *J* and *H*, and in the ditch from the paper mill at the south end of the plant. These weirs were of sharp-crested rectangular form with end constrictions, the opening in the weirs being 36 inches by 12 inches. The volume of discharge was computed from measurements of the height of flow over the weir.

Observations made by the authors of the rate of flow at the wooden weir in the ditch below sewers *J* and *H* gave measurements averaging 1,031 gallons per minute on August 9; and 689 gallons per minute on September 1, 1937. At the latter date, the weir broke and observations ended. Because of the leaks around the weir causing the banks to give way, the readings for September 1 obviously are incorrect.

On January 18, 1938, representatives of the Chesapeake Corp., while visiting the Yorktown laboratory for the discussion of the progress of the investigation, stated that, according to observations made at the wooden weir by mill employees, the rate of flow in the ditch below sewers *J* and *H* averaged at that time 1,500 gallons per minute, or 2,160,000 gallons per day.

Considerable difficulty was experienced by the mill with these weirs as a result of the soft banks and the leakage around the weirs. Large amounts of clay were added to the banks from time to time, but finally the weirs were discarded. The wooden weir in the ditch leading from the paper mill at the south end of the plant never proved satisfactory and insofar as is known, no readings were made that were of value.

On April 4, 1938, it was observed that well-constructed weirs of reinforced concrete were being built at the lower end of sewers *J* and *H*. Two weirs were installed in the ditch, the more southerly one receiving materials from the overflow pipe from the liquor-storage tanks and the blow-down line from the digesters, and the more northerly one receiving material from the large tile pipe *J* and *H*, mostly wash waters from the diffusers. Automatic samplers were installed consisting of a hollow arm rotated by an electric motor. This arm, with a cup on the end, picks up a sample and delivers it through the hollow tube to a small storage tank. A float connected to a recording arm makes a record of the height of the liquid in the weirs. Only the sampler of the north weir was in operation. The flow of the other weir was not measured and no samples were taken. A shower spray of fresh water kept down the foam on the top of the weirs.

On October 13, 1938, it was learned from the plant chemist that, beginning sometime the first part of the year, an excess of salt water from the condensers had been added to the flow in weirs *J* and *H*. This was added irregularly, some shifts adding it and others not. It was added sometimes for days at a time and at other times not added at all for a week. When salt water was added, the flow was nearly doubled. According to a plant official, the rates of flow obtained during six hour shifts averaged 500 gallons per minute when the salt water was not added and 833 gallons per minute when it was added.

Subsequent changes in the sewer lines have been made by the pulp-mill company with the view of conserving water. Certain effluents, such as part of the waste water from diffuser washings formerly emptied into sewers *J* and *H*, were now utilized for washing logs in the barking drums and hence entered the river from other outlets. It was also noticed that the pipe from the black-liquor-storage tanks did not carry so much heavy material into the weir as formerly.

While collecting samples on December 9, 1938, it was observed that the small ditch from the old board mill (fig. 4) carried a considerable flow of a dark-brown effluent with much fiber. Hitherto, this ditch had only a small flow of clear water. On tracing back it was found that this material was entering the ditch from a hole in the side about half way to the old board mill. The ditch above this point had a very small flow of clear water.

During the late fall of 1938 the ditch below sewers *J* and *H* leading to the river was filled in and a new ditch was dug, reinforced with pilings, and completely covered with planks. The new ditch emptied into the barge slip beyond the barking drums (fig. 4, No. 7).

No measurements of rate of flow were made by the authors using the new concrete weir. It was learned from one of the assistants to the plant chemist in January 1939 that the rate of flow in the weir receiving the effluent of sewers *J* and *H* averaged 2,500,000 gallons per 24 hours (1,736 gallons per minute) and that the flow originated in the screening building and in the evaporator house (fig. 4, Nos. 3 and 9).

TABLE 23.—*Rate of flow in ditch below sewers J and H and specific gravities of effluents as observed on Apr. 7, Apr. 20, and May 4, 1937*

Time of day	Cross section area in square inches	Rate of flow		Specific gravity of effluents at 17.5°C.
		Feet per second	Gallons per minute	
APRIL 7				
3:40 p. m.	193.5	0.51	308	1.0027
3:50 p. m.	193.5	.71	428	1.0021
4:00 p. m.	193.5	.61	368	1.0065
4:00 p. m.	193.5	.65	392	1.0025
4:20 p. m.	258.0	.66	398	1.0014
4:30 p. m.	258.0	.92	740	1.0041
4:40 p. m.	258.0	.62	499	---------
4:50 p. m.	301.0	.35	328	---------
5:00 p. m.	344.0	.27	136	---------
Mean	---------	---------	400	---------
APRIL 20				
2:40 p. m.	236.5	0.45	372	1.0049
2:58 p. m.	215.0	1.19	798	1.0013
3:10 p. m.	193.5	.70	422	1.0066
3:20 p. m.	236.5	.54	446	1.0023
3:30 p. m.	236.5	.75	620	1.0048
3:45 p. m.	215.0	.58	389	1.0032
3:55 p. m.	279.5	1.62	1,412	1.0032
4:35 p. m.	387	.58	675	1.0042
Mean	---------	---------	642	---------
MAY 4				
1:20 p. m.	427.2	1.53	2,252	1.0027
1:30 p. m.	472.3	1.77	2,618	1.0029
1:40 p. m.	404.9	1.16	1,463	1.0029
1:50 p. m.	495.0	1.49	2,300	1.0025
2:00 p. m.	495.0	.91	1,405	1.0044
2:10 p. m.	---------	---------	---------	1.0031
2:20 p. m.	676.0	.50	1,054	1.0055
Mean	---------	---------	1,849	---------

As many changes were made in the arrangement of the sewer outlets from time to time, and the wooden weirs constructed did not prove satisfactory and often washed out, the authors employed for their calculations only the observations which they made personally by using the current meter. The data of the rate of discharge through sewers *G* and *H* are summarized in table 23.

For the computation of the concentration of the effluent the mean of the three series observations reported in table 23 were used. The estimated rate of influx of this effluent of 963.6 gallons per minute appears to be conservative compared to others obtained at different times by the authors and by pulp-mill representatives. Converting it into feet per acre the value of 4.26 feet per acre per day is obtained. This value has been used in the subsequent computations.

CONCENTRATION OF THE PULP-MILL EFFLUENT IN THE TIDAL WATERS OF THE YORK RIVER

If the material discharged by the pulp mill is stable and is not immediately destroyed by river water, one would expect that a steady influx of it over a period of several years would result in building up a definite concentration in a tidal basin. Since the rate of destruction of the effluent in the river is not known and no chemical method is available at present for its quantitative determination, we must consider a theoretical case, assuming first that there is no destruction of the effluent and that the effluent is thoroughly mixed and is uniformly distributed in the cross-sectional area of the stream. Under these conditions the dilution of the effluent over the oyster grounds would depend on two variable factors, namely, the rate of its discharge by the pulp mill, and the river flow. The resulting concentration of the pollutant and the time required for reaching an equilibrium can be computed.

It has been shown above that 4.26 acre-feet per day may be considered a conservative rate at which a physiologically active pulp-mill effluent is discharged into the head of York River at West Point.

From the observation on currents at the cross-sectioned area of the River opposite Purtan Island, described in detail on pages 72–78, it has been determined that the influx of tidal water into the river basin is equal to 11,054.54 acre-feet per day.

An estimate of the volume of the river basin is available from the data of Brown, Seavy, and Rittenhouse, published in the Report on Investigation of Silting in the York River (1939). Table 1 of this report gives estimates of the water volume of the river of 222,189 acre-feet in 1911 and 206,896 acre-feet in 1938. For the purpose of the present work the middle value of the two figures, namely 214,542 acre-feet, has been used. In determining the volume of water in the York River, Brown, Seavy, and Rittenhouse (loc. cit.) obtained the cross-sectional areas of water below mean low water and measured the corresponding surface by planimeter using the United States Coast and Geodetic Survey Chart No. 495, published in 1931. From these data the volume of water was calculated for each segment by using Dobson's formula for reservoir capacities (Dobson 1936). The length of the York River was divided into 12 segments shown in figure 23 which represents a reproduction of the Sedimentation Survey chart. Unpublished data received from the Soil Conservation Service give the water capacities for each segment separately (table 24). If the two lower segments (11 and 12, figure 23), located in the part of the river in which the oysters are not affected by pollution, are excluded, the volume of that part of the river in which oysters show abnormal symptoms (segments 1–10 inclusive) can be estimated as equal to 131,411 acre-feet.

The proportion of the pulp-mill effluent in the river basin can be calculated by using the formula suggested by Prof. H. Hotelling, then of Stanford University, and employed in the studies conducted by the former United States Bureau of Fisheries on the effect of red liquor (waste from the sulfite pulp-mill process) on Olympia oysters, *Ostrea lurida* (Hopkins, Galtsoff, and MacMillin, 1931, 183–184).

TABLE 24.—*Water capacity of various segments of the York River, determined by the sedimentation survey of Oct. 25 to Nov. 25, 1938, made by the Soil Conservation Service, U. S. Department of Agriculture*

Bounding ranges	Water capacity	Surface area
	Acre-feet	*Acres*
6–7	7,898	1,079
7–8	9,746	1,288
8–9	9,133	995
9–10	9,553	1,216
10–11	11,717	1,578
11–12	18,816	2,157
12–13	12,634	1,216
13–14	15,516	1,576
14–15	15,131	1,635
15–17	21,267	2,145
17–18	21,614	2,030
18–19	53,871	4,748
Total	206,896	21,663

According to Hotelling's formula—

$$p=\frac{a}{a+b}\left[1-\left(1-\frac{a+b}{V}\right)^t\right]$$

where p—is the proportion of pulp mill effluent in basin
a—the rate of discharge of pulp mill effluent in acre-feet per day
b—the rate of influx of water into the basin in acre-feet per day
V—total volume of the river basin
t—time in days since the pollution started.

The problem of computing the concentration of pulp-mill effluent in the York River was presented this time to Dr. L. B. Tuckerman, Assistant Chief, Mechanics and Sound Division, National Bureau of Standards, who was kind enough to prepare a memorandum which is quoted in part.

Let a= rate of discharge of poisonous pulp liquor at the pulp mill in acre-feet per day
b= the rate of influx of water into the river basin in acre-feet per day. This includes the influx of water from the river above the mill and the daily influx of tidal water
V= total volume of the river basin
p= proportion of poisonous pulp liquor in bay
p_∞= limit which proportion of poisonous pulp liquor in bay approaches after a long time
t= time in days since the pollution started.

Assuming that these processes are continuous and that the mixing of the poisonous liquor with the water of the bay is practically instantaneous the daily efflux of poisonous liquor from the bay will be equal to $p\,(a+b)$ so that the total rate at which the poisonous liquor increases in the bay is:

$$\frac{d(pV)}{dt}=a-p(a+b)$$

which gives the linear differential equation for p as

$$\frac{dp}{dt}+\frac{a+b}{V}p=\frac{a}{V}$$

The solution of this differential equation under the terminal condition

$$p_{t=0}=0$$

readily is found to be:

$$p=p_\infty(1-e^{-kt})$$

where

$$p_\infty=\frac{a}{a+b},\ \text{and}\ k=\frac{a+b}{V}$$

The difference between this solution and the solution

$$p=\frac{a}{a+b}\left[1-\left(1-\frac{a+b}{V}\right)^t\right]=p_\infty[1-(1-k)^t]$$

given by Hotelling, lies in the fact that in this solution the influx of poisonous liquor and water and the efflux of the mixed fluid of concentration, p, are assumed to be continuous while Hotelling assumes that the influx and efflux occurs discontinuously once a day. These two solutions indicate the same value for the limiting value of p

$$p_\infty=\frac{a}{a+b}$$

but differ in the rate at which this limit is approached. However, for small enough values of $k=\frac{a+b}{V}$ these two rates are practically identical, since

$$e^{-k}=(1-k)+\tfrac{1}{2}k^2-\tfrac{1}{6}k^3+\ \ldots$$

and if k is small enough the terms

$$\tfrac{1}{2}k^2-\tfrac{1}{6}k^3+\ \ldots$$

make little difference.

The maximum difference between the concentration calculated from the two formulas will occur at a time given by

$$t=\frac{\log\,[\log\,(1-k)/\log\,e^{-k}]}{\log\,[e^{-k}/(1-k)]}$$

or approximately for k small in comparison with 1,

$$t=\frac{1}{k}(1-\tfrac{1}{4}k+\ \ldots)$$

If a=4.26 acre-feet per day, b=11053.54 acre-feet per day, and

$$V=214542\ \text{acre-feet}$$

$$k=\frac{a+b}{V}=0.05154$$

$$1-k=0.94846$$

$$\text{and}\ e^{-k}=0.94976$$

For these data the maximum difference between the concentrations calculated by the two formulas will then occur at about

$$t=\frac{1}{0.05154}(1-0.0129)=19.2\ \text{days.}$$

This was checked by computing $(1-k)^t$ and e^{-kt} and their difference for t=19.0, 19.2 and 19.4 days.

t *Days*	$(1-k)^t$	e^{-kt}	$(1-k)^t-e^{-kt}$
19.0	.63411130	.62442122	.00969008
19.2	.63796324	.62827291	.00969033
19.4	.64177463	.63208510	.00968953

The computations were carried to 8 decimal places since over this range the difference was constant to 6 decimal places. These results show clearly the existence of a maximum difference between the two formulas of less than 1 percent in the neighborhood of t=19.2 days.

In view of the broad assumptions made in formulating the problem this difference is wholly insignificant. Since Hotelling's formula uses somewhat simpler calculations, it is to be preferred if estimates are to be made upon assumptions such as those used here.

Either formula gives for the final concentration

$$p_\infty=\frac{a}{a+b}=\frac{4.26}{11057.8}=0.000385$$

Below are calculated by Hotelling's formula the values of

$$\frac{p}{p_\infty}=1-(1-k)^t$$

for a number of days up to 100:

t Days	$\frac{p}{p_\infty}=1-(1-k)^t$
1	0.052
2	.100
3	.147
4	.191
5	.232
6	.272
7	.310
8	.345
9	.379
10	.411
15	.548
20	.653
25	.734
30	.796
35	.843
40	.880
45	.908
50	.929
60	.958
70	.975
80	.985
90	.991
100	.995

The formula $\frac{p}{p_\infty}=1-e^{-kt}$ would give 0.990 for 90 days and 0.994 for 100 days which emphasizes again how little choice there is between the two formulas. As can be seen the final limit of $p_\infty=0.000385$ is practically (within 1 percent) reached in 90 days after the start of the pollution.

These assumptions are of course inadequate to give any picture of the decrease of pollution with increasing distance down the bay from the mill.

There seems to be no reasonable way to attack this problem so long as the concentration at any station is assumed to vary with the time. However, after a relatively short time, say 100 days, compared with the total time of pollution, several years, it may be assumed that at each station along the river a practically steady regime has been reached. Some idea of the law, but not the magnitude of that decrease, may then be gained from the following further assumptions.

Assume that p has reached its limiting value $p_\infty=\frac{a}{a+b}$ throughout the basin. Assume further that the flow of fluid down the basin is uniform across the stream bed. Then the time required for any given volume of polluted water to flow from the mill to any lower station will be proportional to the total volume, v, of water lying between that station and the mill, i. e., $t=cv$, where c is some constant.

If it is further assumed that there is some process acting which removes or destroys the poisonous constituents in any given portion of the poisoned water at a certain rate per day, the poisonous effect of the water at any station in the basin may be represented by πp_∞, where π is the fraction of the poisonous constituent which has not yet been removed or destroyed at that station. Since the regime is assumed to be steady

$$\frac{\partial\pi}{\partial t}=0$$

and

$$\frac{d\pi}{dt}=\frac{\partial\pi}{\partial t}+\frac{\partial\pi}{\partial v}\frac{dv}{dt}$$

reduces to

$$c\frac{\partial\pi}{\partial v}=\frac{d\pi}{dt}$$

Two different assumptions as to the rate of removal or destruction of the poisonous constituents suggest themselves.

1. The time rate of decrease of the concentration of the poisonous effect at any station

$$\frac{\partial\pi p_\infty}{\partial t}=-c'$$

is a negative constant (a constant rate, c', of supply of the removing or destroying agent).

2. The time rate of decrease of the concentration of poisonous character at any station

$$\frac{\partial\pi p_\infty}{\partial t}=c''\pi p_\infty$$

is proportional to its concentration (a monomolecular reaction).

The first assumption leads to the equation

$$\frac{\partial\pi}{\partial v}=-cc'$$

where c' is some other constant.

This gives $\pi=1-cc'v$ so that below a certain station given by

$$v=\frac{1}{cc'}$$

the water will be wholly innocuous.

The second assumption leads to the equation

$$\frac{\partial\pi}{\partial v}=-cc''\pi$$

which gives

$$\pi=e^{-cc''v}$$

where c'' is still another constant.

According to this the poisonous effect will diminish exponentially with volume of water between the station and the mill but will be present to some extent throughout the whole basin and out into the bay beyond.

Dr. Tuckerman's computations show two important facts: first, that at the rate of discharge of 4.26 acre-feet per day the final concentration is about 0.0004. This figure is very close to the threshold concentrations observed in laboratory tests (see pp. 134–157) which showed that pulp-mill effluent is physiologically effective in the concentration between 1:1000 and 1:2000. It is significant that the concentration computed on a theoretical basis is of the same degree

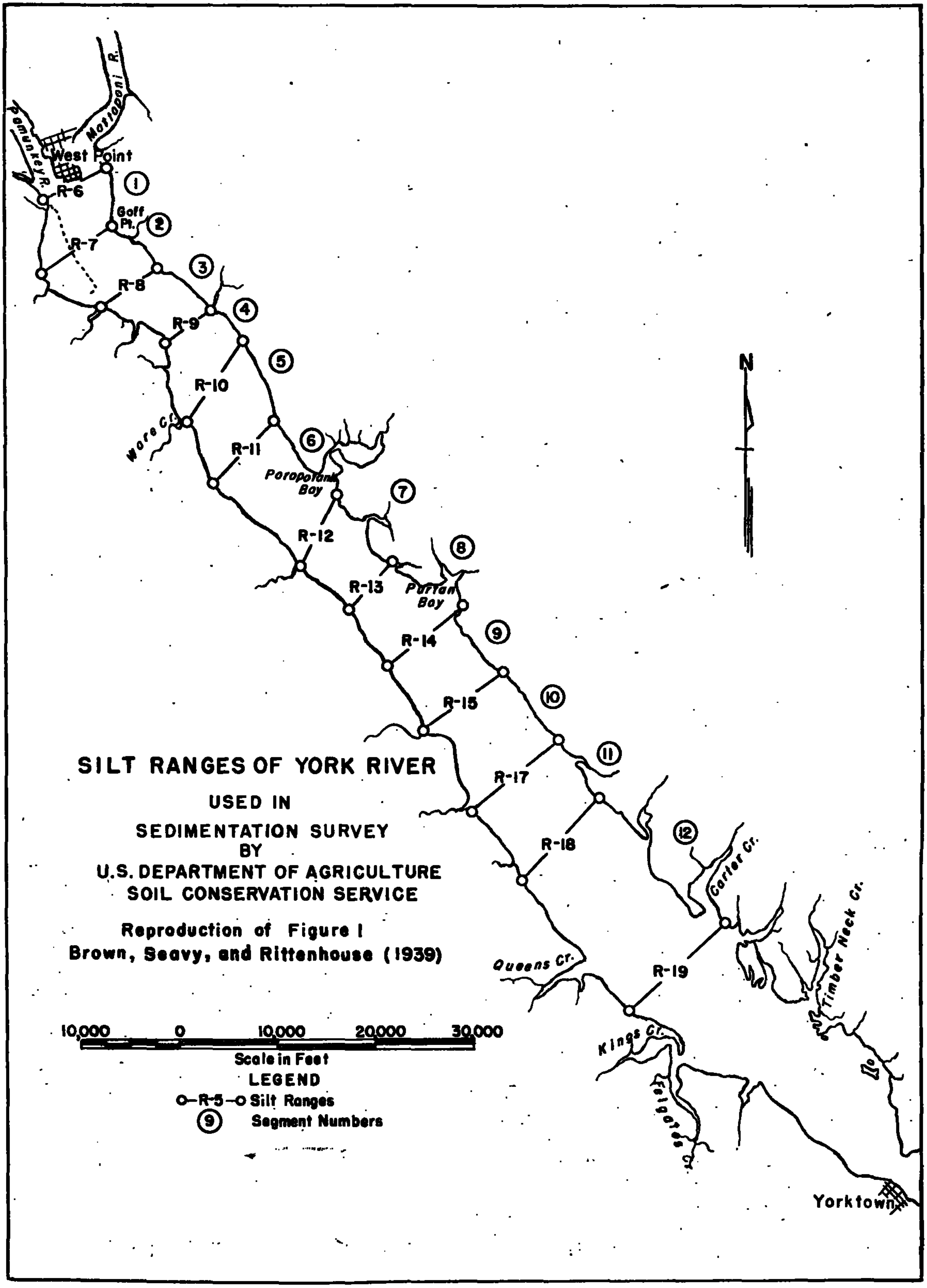

FIGURE 23.—Silt ranges of York River used in sedimentation survey by Soil Conservation Service, United States Department of Agriculture. Reproduction of figure 1 of the report by Brown, Seavy, and Rittenhouse (1939).

of magnitude as the physiologically effective concentration determined experimentally. It can be easily seen that with the slightly increased rate of discharge of about 1,500 gallons per minute or 6.63 acre-feet per day[4] which has been frequently recorded by the pulp-mill officials, the final concentration in the river equals 0.0006 or 1:1666.

The second important conclusion revealed by the computations is that, assuming there is no destruction of the effluent, the equilibrium is reached in about 90 days after the beginning of the pollution. If we consider only the upper two-thirds of the river basin, the volume of which is 131,411 instead of 214,542 acre-feet used in the computation, the final concentration, $p=\frac{a}{a+b}$ will be reached in a correspondingly shorter time.

Dr. Tuckerman's suggestion that the toxic effect will diminish exponentially with the volume of water between the source of pollution and a given point along the river is very valuable for further research. Condition of oysters in the York River clearly show that at present no toxic effect is noticeable in the lower part of the river.

PLANKTON CONTENT OF THE YORK AND PIANKATANK RIVERS

A study of seasonal changes in the plankton content of the waters of the York and the Piankatank Rivers was especially pertinent as there was the possibility that a scarcity of available oyster food might be responsible for the poor condition of the oysters in the upper York River.

By means of a Birge-Juday plankton trap biweekly samples were obtained of the surface water (0.5 meter) overlying oyster bottoms at stations 20, 14, 5, 16, 17, and 9 in the York River, and 55 and 53 in the Piankatank River. At stations 20, 14, 9, and 53, where the depth was greater than 2 meters, a sample of water just off the bottom was also taken.

Two liters of the water sample were passed through a Foerst-Juday centrifuge rotating at 20,000 revolutions per minute. The centrifugate was then transferred to a 15-millimeter tube, and centrifuged for 5 minutes in a clinical centrifuge. The water was decanted and 10 milliliters of 80-percent acetone added to the sediment in the bottom of the tube. After shaking, the tube was set aside for 15 minutes for extraction of the green coloring matter and was then again centrifuged for another 5 minutes. Comparison of the color was then made with the Harvey (1934) standards of nickel sulfate and potassium chromate, and the results expressed in pigment units per liter of original sample. Each unit was equivalent to approximately 10,000 organisms (diatoms and dinoflagellates).

In addition, 500 milliliters of the sample were likewise centrifuged and the sediment preserved in vials with formalin for identification and counting.

The reliability of Harvey's method has been checked by the authors by comparing the values of the pigment units with the total number of diatoms and dinoflagellates found in the same sample. The results, plotted in figure 24, show that in general the two curves follow the same trend and with the exception of the first observation (February 1936) are in agreement. As we may expect, the pigment unit curve is less jagged than the curve of the total number of forms. The pigment unit technique is, therefore, very useful in following the seasonal fluctuation in the abundance of phytoplankton. It cannot be used, however, in case it is necessary to determine the amount of living matter produced in the form of plankton.

Results of the observations of the amount of plankton present at the various stations are given in table 23. The averages for the entire period have been plotted on the maps in figure 25.

Mean plankton content in the York River computed from all the observations was equivalent to 48.7 pigment units as compared with 31.9 units in the Piankatank. The means computed separately for the lower and upper parts of the York River (table 25) are 47.4 and 50.0, respectively. Obviously, the difference between the plankton production in the lower and upper parts of the river is insignificant. A comparison with the Piankatank River, which is known to produce good oysters, shows that there is no deficiency in the phytoplankton productivity in the York River. Evidence from plankton studies points rather to an opposite direction suggesting that the potential supply of plankton is more abundant in the York River than in the Piankatank, where the annual mean of pigment units per liter was 31.9

A study of the seasonal distribution of plankton at different stations (table 25) shows that throughout the major part of the year the upper part of the York River was slightly richer in plankton than the

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[4] One acre-foot equals 325,851 gallons.

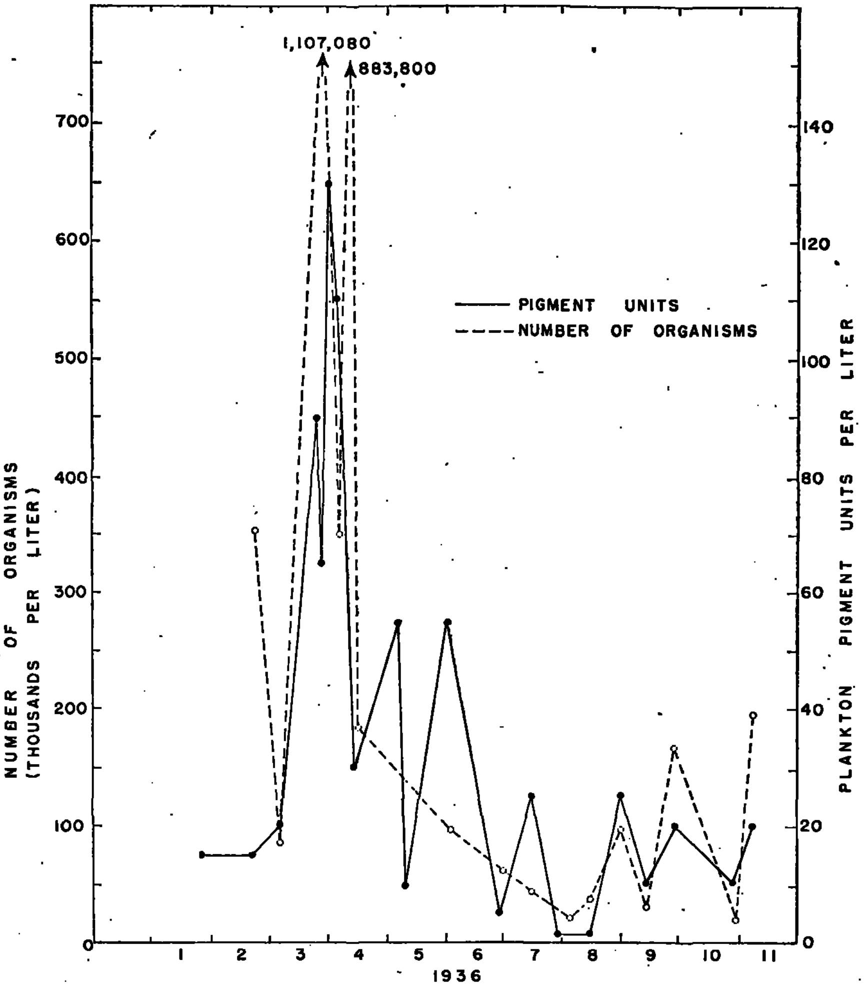

FIGURE 24.—Comparison of the results of counting, using the plant-pigment method for quantitative determination of the plankton in the York River, 1936.

lower part. Station 17 in the upper part of the river was especially rich in plankton. In April 1937 the plankton content reached here the highest mark of 240 units, equivalent to over 2 million organisms per liter. Such a density of phytoplankton has not been encountered at other stations.

A comparison of the cyclic changes in the plankton crop based on pigment unit determinations at stations in the York and Piankatank Rivers is presented in figure 26. It was found that in both rivers the maximum occurred at the usual vernal period, March to April. Slight increases noted in July, August, November, and December were insignificant in comparison with the spring maxima. Throughout the summer the amount of plankton remained relatively low. The increased spring production of plankton in the York River occurred between temperatures of 8° to 16° C. in 1936, and the amount of plankton decreased rapidly after the temperature rose above 16° C. During the spring of 1937 the maximum was likewise reached at a temperature of 8° C. In the Piankatank River the same situation was recorded, the maximum vernal crop having occurred at 8° C. in 1936 and at 13° C. in 1937.

The results of counting the predominant forms in phytoplankton samples collected from December 1935 to November 1936 at stations 20 and 17 in York River are shown in tables 26 and 27. The genus *Nitzschia* exceeded any group of diatoms in the river but was not the most abundant organism throughout the year, for the summer months brought the genus *Rhizosolenia* to the maximum at station 20, while *Thalassiothrix* was most abundant during the summer at station 17. With the exception of

TABLE 25.—*Plankton pigment units per liter of water in the York and Piankatank Rivers.*

[Stations 20, 14, 15 are located in the lower part of the river; stations 5, 16, 17, and 9, in its upper part]

Date	York River									Piankatank River		
	Stations in lower part				Stations in upper part							
	20	14	15	Mean	5	16	17	9	Mean	55	53	Mean
1936												
Jan. 21–23	11	17	11	13.0	15	18	15	10	14.5	--------	--------	--------
Feb. 19–20	90	30	55	58.3	15	50	42	30	34.3	--------	--------	--------
Mar. 4–6	36	30	25	30.3	20	24	140	22	51.5	16	22	19.0
Mar. 23–25	110	20	52	60.7	65	85	200	65	103.8	--------	--------	--------
Mar. 30–Apr. 1	30	--------	130	80.0	130	130	165	65	122.5	38	55	46.5
Apr. 8–9	70	100	200	123.3	110	50	50	45	63.3	--------	--------	--------
Apr. 14–16	24	100	190	104.7	30	65	55	24	43.5	70	110	90.0
Apr. 27–May 1	200	20	75	98.3	50	65	120	30	66.2	10	10	10.0
May 12–14	10	10	10	10.0	10	75	100	52	59.2	--------	--------	--------
June 1–3	10	10	28	16.0	55	55	75	10	48.7	10	10	10.0
June 16–19	--------	32	--------	32.0	--------	5	65	42	37.3	10	12	11.0
June 30–July 2	5	5	5	5.0	5	27	42	10	21.0	5	10	7.5
July 15–18	20	5	--------	12.5	25	60	45	28	39.5	0	18	9.0
July 27–31	0	5	--------	2.5	35	45	70	50	50.0	10	16	13.0
August 14–17	15	5	28	16.0	0	0	55	37	23.0	5	5	5.0
Agust 26–31	10	10	16	12.0	25	18	28	15	21.5	10	14	12.0
Sept. 9–14	12	12	80	34.7	10	10	10	17	11.7	--------	--------	--------
Sept. 29–Oct. 1	15	35	20	23.3	5	22	25	20	18.0	10	15	12.5
Oct. 20–22	15	15	15	15.0	10	25	35	24	23.5	32	20	26.0
Nov. 4–6	0	50	80	43.3	20	--------	--------	25	22.5	10	15	12.5
Nov. 20–24	18	12	45	25.0	15	35	25	35	27.5	18	25	21.5
Dec. 3–9	10	25	50	28.3	25	32	25	22	26.0	--------	--------	--------
Dec. 14–23	17	10	20	15.7	20	30	45	40	33.8	--------	--------	--------
1937												
Jan. 4–8	10	15	160	61.7	40	60	45	45	47.5	20	25	22.5
Jan. 25–27	22	17	65	34.7	25	30	30	15	25.0	15	60	37.5
Feb. 11–16	16	20	37	24.3	45	45	37	37	41.0	37	50	43.5
Mar. 3–4	20	30	37	29.0	7	60	60	20	44.2	40	45	42.5
Mar. 22–23	100	90	140	110.0	120	--------	--------	--------	(120.0)	100	100	100.0
Mar. 30–Apr. 6	200	210	170	193.3	180	200	240	220	210.0	50	210	130.0
Apr. 23–27	100	10	100	70.0	90	--------	90	90	90.0	20	20	20.0
Mean	41.2	32.7	68.3	47.4	42.5	48.9	69.1	39.5	50.0	24.4	39.4	31.9

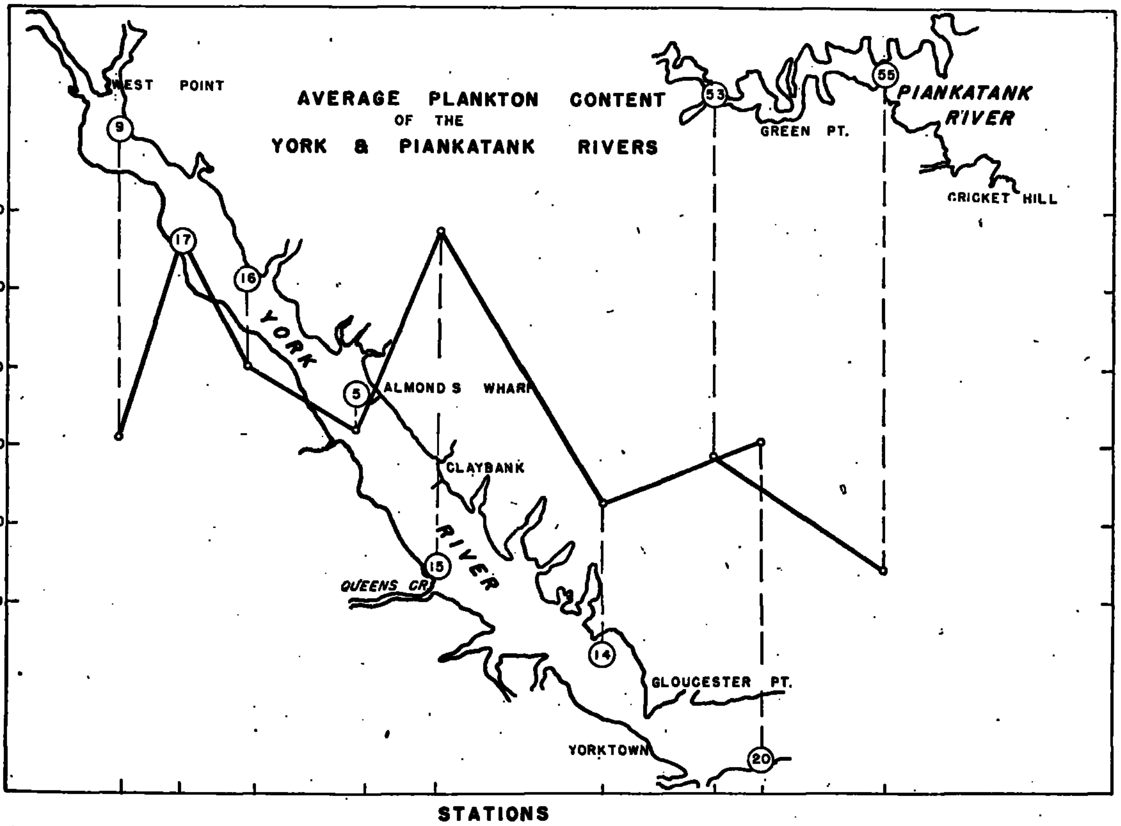

FIGURE 25.—Average plankton content of the York and Piankatank Rivers in 1936 and 1937.

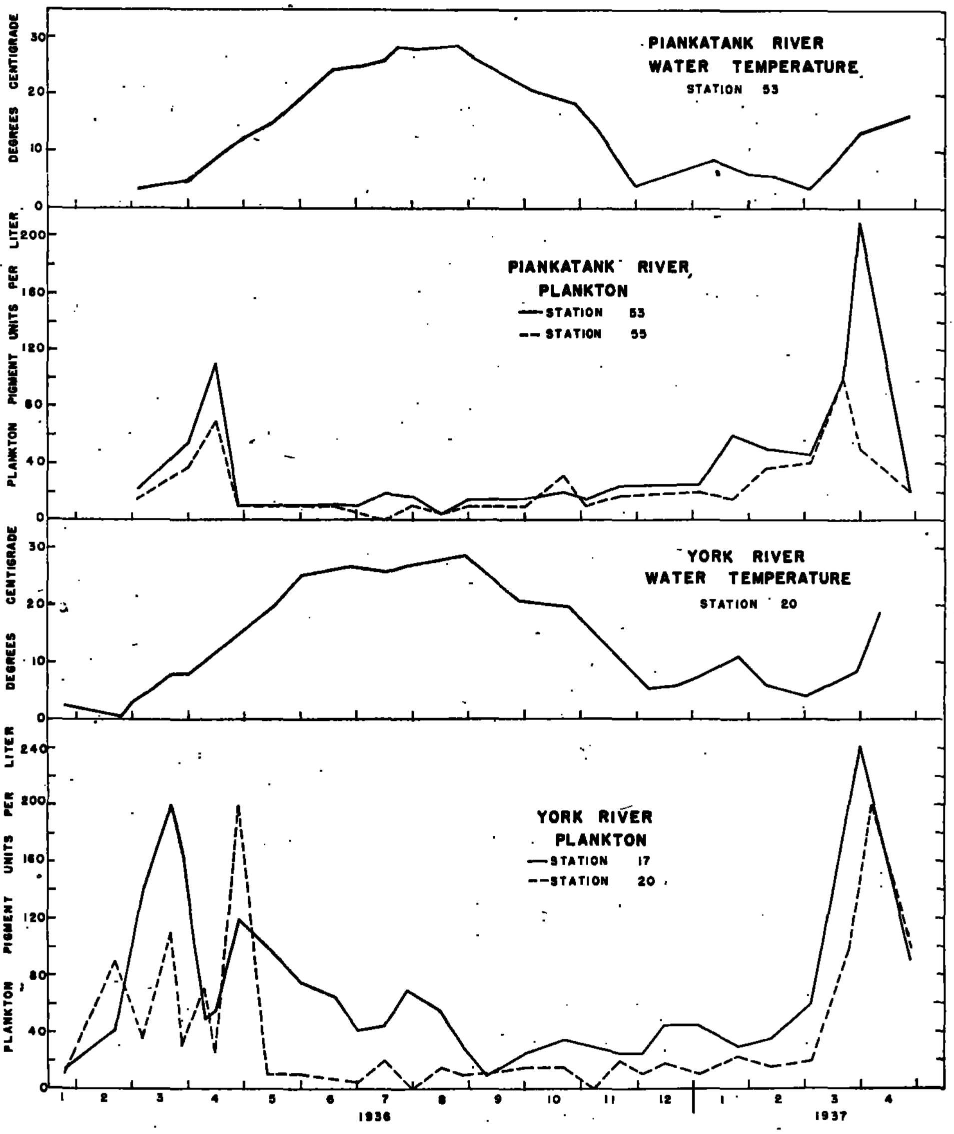

FIGURE 26.—Seasonal changes in plankton content in York and Piankatank Rivers in 1936 and 1937. Pigment-unit method.

Thalassiothrix and *Rhizosolenia* the diatoms listed in the tables are frequently found in the stomachs of the oysters and apparently constitute their normal diet.

The low counts of dinoflagellates may be due in part to the fact that these organisms disintegrate very rapidly in preserved samples (Martin 1923). The plant-pigment method, since it is based on the fresh sample, undoubtedly includes these organisms and in this respect is probably more reliable than the counting of individual forms.

The differences in the number of organisms per liter as determined by plankton counts in the samples from these two stations do not appear to be significant.

Because the nutritive value of various plankton organisms has not yet been determined and we do not know which of them are being utilized by the oyster, the quantitative plankton data gave us no direct reply to the question whether there was an adequate supply of oyster food in York River. It is, however, reasonable to infer that since general productivity of river plankton was not impaired by pollution or other adverse factors, the supply of food needed by the oysters was adequate. Slightly increased plankton production in the upper part of

TABLE 26.—*Number of plankton organisms per liter at station 17 in the York River*

GENERA OF DIATOMS

Date	Nitzschia	Skeletonema	Coscinodiscus	Rhizosolenia	Pleurosigma	Navicula	Thalassiothrix
1935							
Dec. 6	3, 900	1, 980	984				
1936							
Jan. 7			9, 840				
Mar. 6	344, 000			9, 840	9, 840		
Mar. 19	590, 000	9, 840	39, 000			19, 800	
Mar. 25	660, 000		49, 000			39, 000	19, 700
Apr. 1	560, 000		29, 500				39, 300
Apr. 9	354, 000		29, 500				
Apr. 16	640, 000		118, 000			59, 000	138, 000
June 1			39, 000		98, 000	39, 000	98, 000
June 19	78, 000					19, 680	
July 2	98, 000		19, 000				39, 000
July 17	59, 000		39, 000		19, 000	59, 000	98, 000
July. 1			19, 000				78, 000
Aug. 17	78, 000		39, 000			39, 000	39, 000
Aug. 29	660, 000				196, 000		39, 000
Sept. 10	176, 000		54, 000		196, 000		54, 000
Oct. 1			71, 000		35, 000		
Oct. 22	19, 680	19, 680			19, 680		53, 000
Total	4, 320, 580	31, 500	555, 824	9, 840	573, 520	274, 480	695, 000

TABLE 27.—*Number of plankton organisms per liter at station 20 in the York River*

GENERA OF DIATOMS

Date	Nitzschia	Skeletonema	Coscinodiscus	Rhizosolenia	Pleurosigma	Navicula	Thalassiothrix	Asterionella	Fragilaria	Dinoflagellates
1935										
Dec. 6	7, 900	37, 000	1, 960	984			8, 500			
Dec. 23	63, 000	5, 900	2, 900	984	1, 970			5, 900		
1936										
Feb. 28	440, 000		29, 000						19, 700	
Mar. 4	443, 000	78, 500		29, 000				29, 000		
Mar. 30	1, 180, 000						118, 000	264, 000		
Apr. 8	265, 000			19, 800						
Apr. 14	648, 000		39, 000	59, 000						
May 27	118, 000		19, 000							
June 30										75, 000
July 27				12, 000	5, 800					9, 800
Aug. 14			11, 800	138, 000	1, 900					5, 900
Aug. 26	3, 960			116, 000		39, 000				3, 960
Sept. 14	3, 960			5, 800		1, 968				5, 900
Oct. 1	35, 400	1, 968	1, 968							
Oct. 21	13, 800			78, 400						11, 800
Nov. 5	40, 600		1, 968	31, 400			3, 960			5, 900
Nov. 24	1, 968		1, 968	1, 968						
Total	3, 264, 588	123, 368	109, 564	495, 304	11, 638	40, 968	130, 460	298, 900	19, 700	118, 260

the river was very likely due to the fertilizing effect of pollutants which contain considerable amounts of carbohydrates and other organic compounds. Laboratory experiments with *Nitzschia* culture described below show that reproduction of this diatom is stimulated by low concentrations of pulp-mill effluent and therefore confirm this conclusion.

EFFECT OF PULP MILL EFFLUENTS ON GROWTH OF NITZSCHIA CULTURE

The effect of pulp-mill effluents on the propagation of diatoms was studied in the laboratory with the use of a marine species, *Nitzschia closterium*, commonly found in estuaries and known to be used by the oyster as food. A vigorous culture of a single species has been maintained in the laboratory for several years without showing any signs of degeneration. The culture was kept in round 150-milliliter pyrex flasks with Miquel solution containing a small amount of sterile soil extract. The flasks were placed in a glass cabinet provided with a temperature control capable of keeping the temperature between 15° and 17° C. Each side of the cabinet was uniformly and continuously illuminated by nine 25-watt Mazda lamps mounted on two adjustable stands and provided with reflectors. Details of the arrangement have been fully described by Galtsoff (1937: 34–35) and need not be repeated here. The densities of *Nitzschia* population in different flasks were determined by means of a Weston photoelectric cell and a sensitive microammeter. In order to convert the readings of the instrument into the number of cells per milliliter, a calibration table and a curve were prepared by counting the number of *Nitzschia* in various dilutions of stock culture and plotting the results against the readings of the instrument. Intermediate values were obtained through interpolation. Using this technique, which has been already described in previous publications (Galtsoff *et al* 1935), a series of experiments were carried out with the effluent arising from the pulping process (sewers *J* and *H*) added to Miquel solutions in concentrations of 1:1000, 1:10,000. and 1:100,000. In each experiment an equal number of flasks, varying from 2 to 6 were used for the control and for the test. Every day the content of each flask was stirred to avoid settling of the *Nitzschia* on the bottom and the position of the test flask and its control was interchanged to equalize the possible differences in the intensity of illumination. The initial density of *Nitzschia* culture varied between 5,000 and 7,000 cells per milliliter but was always identical in the test flask and its control.

In a first series of experiments, the sample of pulp-mill effluent was sterilized for 15 minutes at 15 pounds pressure. In a second series of tests, raw effluent, stored in the refrigerator, was used.

The growth of *Nitzschia* culture in Miquel solution continues at a definite rate until a maximum population density is reached. After that the slope of the curve gradually flattens and the density of the culture remains more or less constant for many days, or begins to decline probably due to exhaustion of food material and accumulation of metabolites. In testing the effect of pulp-mill effluent, the cultures were usually maintained as long as it was practical, and readings were made at regular intervals. Some of the tests lasted as long as 77 days. During these prolonged tests, the population of *Nitzschia*, after reaching its maximum of about 1,900,000 cells per milliliter, remained constant for at least 2 weeks. It has been noticed that, in several instances, the longevity of cultures kept in the media containing raw pulp-mill effluent was shorter than in the controls or in the flasks with sterile effluent. The degeneration of the cultures was always associated with a sudden increase in bacterial growth, flocculation of *Nitzschia* cells, and their rapid settling on the bottom. In several cases the cultures to which raw effluent was added became badly contaminated with large and fast-moving *Spirillae* and all *Nitzschia* perished. Because of this difficulty, it was impractical to continue the tests with raw effluent for more than 28 days.

Analyses of experimental records clearly show that the addition of effluents in concentrations not exceeding 1:1,000 has no adverse effect on the growth of *Nitzschia* culture. As shown by figure 27, experiment A, the growth in the control culture and in the medium containing sterile effluent is almost identical. The difference is, however, apparent when raw effluent is added in the same concentration (fig. 27, experiment B). Stimulating effect of the effluent also is shown by a more rapid propagation of *Nitzschia*, the difference between the test flasks and their controls becoming more pronounced as the population densities increase.

Table 28 gives a summary of all the tests with sterile (series A) and raw effluent (series B) added in concentrations of 1:1,000, 1:10,000, and 1:100,000. With the exception of one test, B7 (concentration 1:10,000), the final densities of *Nitzschia* cultures grown in flasks with raw effluent were greater than in the controls. This difference was not observed when sterile effluent was used.

Raw effluent added in concentrations of 1:100 inhibits the growth of *Nitzschia*, as can be clearly seen from table 29, which summarizes these tests.

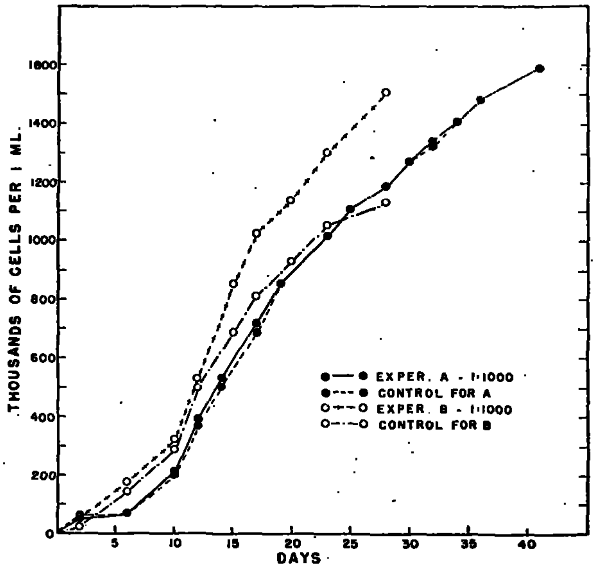

FIGURE 27.—Growth of *Nitzschia* culture in Miquel solution containing sterile and raw pulp-mill effluent in the concentration of 1:1,000. Experiment A (solid circles), sterile effluent; experiment B (open circles), raw effluent. Temperature 15°–17° C.

Concentrations less than 1:100,000 have little or no stimulation as compared with the controls.

The laboratory experiments demonstrate that low concentrations of pulp-mill waste stimulate the growth of *Nitzschia* culture. They are in accord with the field observations, which disclosed greater abundance of phytoplankton in the upper York River, polluted with pulp-mill effluents, than in its lower part where pollution is not noticeable.

TABLE 28.—*Densities of Nitzschia cultures at the end of tests in Miquel solution (control) and in various concentrations of pulp-mill effluent*

[Tests A1 to A13 made with sterile effluent; tests B1 to B12, with raw effluent. In all tests, figures given in the table represent the densities of populations before they began to decline]

Experiment No.	Concentration of effluent	Days of growth	Thousands of *Nitzschia* in 1 milliliter	
			Sterile effluent	Control
A1	1:1,000	40	1,370	1,750
A2	1:1,000	40	1,275	1,610
A3	1:1,000	60	1,600	1,775
A4	1:1,000	60	1,600	1,775
A5	1:1,000	77	1,300	1,900
A6	1:10,000	60	1,755	1,740
A7	1:10,000	60	1,755	1,740
A8	1:10,000	77	953	1,800
A9	1:10,000	77	1,900	1,900
A10	1:100,000	77	1,750	1,755
A11	1:100,000	77	1,710	1,800
A12	1:100,000	77	1,900	1,330
A13	1:100,000	77	1,610	1,183

Experiment No.	Concentration of effluent	Days of growth	Thousands of *Nitzschia* in 1 milliliter	
			Raw effluent	Control
B1	1:1,000	25	1,750	1,175
B2	1:1,000	25	1,150	825
B3	1:1,000	25	1,235	1,090
B4	1:1,000	14	1,100	675
B5	1:1,000	14	1,075	680
B6	1:1,000	14	1,035	805
B7	1:10,000	22	1,075	1,225
B8	1:10,000	22	955	900
B9	1:10,000	25	1,115	955
B10	1:100,000	21	1,300	1,025
B11	1:100,000	21	1,230	1,025
B12	1:100,000	16	1,025	775

TABLE 29.—*Inhibition of Nitzschia growth in strong concentration of raw pulp-mill effluent*

[The concentration used was 1:100 and the period of growth was 20 days]

Experiment	Thousands of *Nitzschia* in 1 milliliter	
	Effluent	Control
1	425	891
2	442	1,028
3	435	998
4	416	1,013
5	404	998
6	396	1,013

CONDITION OF THE OYSTERS OF THE YORK AND PIANKATANK RIVERS

The condition of the oysters in the York River was carefully followed throughout the time of investigation. There were, of course, fluctuations in the condition of all the oysters at the different seasons of the year and in different years. Determinations of the glycogen content and of the percentage of water in the meat confirmed the general impression, gained by inspection, that, regardless of the season, the oysters of the York River above Claybank were poor, while those below it and in the Piankatank River were generally good. The oysters on the right shore of the York River were usually in better condition than those on the left shore, and in some respects the oysters in the vicinity of Bell Rock and above were a little better than those just below. The poorest oysters were found on the grounds from just below Bell Rock Lighthouse to a point just above Claybank Wharf, and particularly on grounds off Poropotank and Purtan Bays.

The meats of the poor oysters were found to be watery and emaciated, with brownish or greenish discoloration of the mantle, gills, and labial palps. The shells of these oysters were very thin and fragile and often contained mud vesicles. Aside from the poor quality of the meat, the shell condition was a factor that made the oysters of this area unmarketable, or marketed with great difficulty. In many instances there was a failure of gonad development.

SHELLS OF THE YORK RIVER OYSTERS

The majority of oysters from the upper part of the York River had thin, fragile shells. In various degrees of intensity this condition prevailed among the oysters grown above Claybank, and was especially pronounced in the specimens taken at stations 9 (at Goff Point), 22 (Purtan Bay), and 23 (between Allmondsville and Claybank). Similar conditions were observed in the oysters brought by J. E. Scanlon and other oyster growers to the shellfish laboratory in Washington in the spring of 1934, before the initiation of the present investigation.

Adult York River oysters varied from 3½ to 4¾ inches in length and from 1¼ to 3½ inches in width. Long and narrow oysters were more abundant in the upper part of the river, whereas wide and rounded specimens predominated in its lower part (fig. 29).

So thin were the shells of many specimens obtained from the upper part of the York River that the valves, when examined in a transmitted light, were transparent. The shells of these oysters were so fragile that they crumbled under a slight pressure of a finger. Cases of infestations by mudworms (*Polydora*) and boring sponge were frequent. In several instances, the shells of live oysters were almost completely destroyed by the boring sponge. There were, however, many specimens that were entirely free from infestation, yet had extraordinarily fragile and thin shells. This abnormal condition of the shells suggested either a deficiency of calcium in the sea water or some morbid state of the organism, which might have resulted from a functional disturbance or an infectional disease interfering with the calcium metabolism.

The first possibility was explored by determining the amount of calcium in the sea water. It was considered possible that sulfates and lignin, found in considerable quantities in the pulp-mill effluent discharged at the head of the river, had a tendency to precipitate calcium carbonates and upset the ionic equilibrium of sea water. If this were the case, the analyses of samples of sea water collected from the upper and lower parts of York River would have revealed the relative degree of Ca depletion. Determinations made according to the method of Meloche and Setterquist (1933) gave the following results:

Station	*Calcium Milligrams per liter*	*Chlorine Milligrams per liter*	$\frac{Ca}{Cl}$
16 (upper part)	102.1	4,610	0.02215
14 (lower part)	204.0	8,630	.02363

The difference in the concentration of Ca in the two sets of samples depends, of course, on the salinity of water, but the ratio of Ca:Cl does not show a significant difference between the upper and lower parts of the river. The values of Ca:Cl ratios, representing the averages of four samples, are slightly greater than the Ca:Cl ratios calculated from the data available for various parts of the ocean. The latter vary from 0.02112 to 0.02266 (Th. G. Thompson and R. J. Robinson 1932:119), the "best" value according to Lyman and Fleming (1940) being 0.02106. Since the calcium-chlorinity ratio in the York River did not significantly differ from the values usually encountered under normal conditions, further observations along this line were discontinued.

FIGURE 28.—Cross section of the left shell of an oyster from the upper part of York River. The section is made at the level of the muscle scar; the cloacal side is on the left. Notice the large cavities either empty or filled with loose chalky deposit; magnified 3½ times.

There was no evidence that defects in the calcification of shells of York River oysters could be correlated with the disturbance of the calcium equilibrium in the water; it is reasonable to suspect that they were due to the functional failure of the lime-depositing organs.

Shape, Area, and Weight of Shells

Field examinations of a large number of samples from the upper part of the river indicated that the poorest oysters were invariably those with long, narrow, and very thin shells (fig. 29). It was therefore of interest to compare the areas and weights of shells of the oysters from the polluted area with those from the lower part of the river and from the adjacent areas which are free from pollution. Obviously, such a comparison should be made between oysters of the same age that grow for the same length of time in the river. This, however, presented considerable difficulty because of the changes in the oyster populations on various grounds caused by oyster-farming operations. During the time of observations, and in the preceding years, oystermen were transplanting their stock from one ground to another and occasionally were bringing in oysters from the outside. Fortunately, there were several areas of abandoned bottoms which still contained fairly large numbers of oysters. By making a thorough inquiry, the authors were able to avoid the bottoms that were recently planted and take samples from the areas which contained only so-called native oysters. The latter term is used here only for the sake of convenience and denotes oysters which remained in the York River not less than four years. Undoubtedly, some oysters grew from local set, but the majority were planted as seed from the James River. On October 11 and 12, 1938, samples of these oysters were collected from eight stations in the upper part of the York River above Claybank. Three weeks later, on October 31, samples were obtained at five stations distributed in the lower part of the York River, in its mouth, and in the Piankatank River. Oysters comprising the second group were taken from waters not affected by pulp-mill pollution and appeared to be in every respect normal. Unfortunately, the exact age of these oysters could not be ascertained. Examination of planting records of local oystermen convinced us, however, that oysters collected from various stations in the lower part of the York River and vicinity were at least 5 years old. Oysters from the upper part of the river, where planting operations ceased long ago, were probably not less than 6 or 7 years old.

The purpose of our comparison was to determine whether there was a significant difference in the weight of the shells in oysters from different stations which may have suggested that the deposition of calcium carbonate and growth of shell was affected by local conditions. Unfortunately, a number of specimens obtained at various stations had to be rejected because their shells were riddled by the boring sponge and the determination of their weight would have been misleading. This so reduced the number of oysters available for measurements that no more than eight specimens could be accepted from each station. The comparison has to be made, therefore, only between the two larger groups of shells, one from the upper York River (group B) and one from the lower York and Piankatank Rivers (group A). After removing the encrusting organisms and dirt, the shells were dried at 60° C. for 24 hours and both valves of each oyster weighed to the nearest decigram. The area of the shell then was determined by placing the left valve, which is usually the largest, on a sheet of thin paper and obtaining its contour and measuring the area with a planimeter. The results were expressed as total areas, in square inches, and as a weight of both valves per square inch of shell area. Fortunately, oysters of this section have rather flat shells without the pronounced ridges which sometimes are conspicuous in the shells from other sections of the coast. Consequently, it has been assumed that an error due to the unevenness of the shell surface was insignificant.

There appears to be no significant difference in the areas of shells in the two groups of oysters, the means for groups A and B being 7.38 ± 1.68 and 7.64 ± 2.28, respectively.

The test of significance and the necessary statistics given in table 30 show that the "*t*" value is 0.722 and the difference between the two means is, therefore, entirely within the probability of random sampling.

TABLE 30.—*Comparison of the means of surface areas of shells of oysters from the upper York River (B), and the lower York River and the Piankatank River (A)*

Group	Number of shells	Degrees of freedom	Mean of surface area	Sum of squares
			Square-inches	
A	49	48	7.38±1.68	159.816
B	60	59	7.64±1.28	235.980
Difference			0.26	
Total		107		395.796

The weight of shell per square inch of area is significantly higher in the oysters from the unpolluted section (group A) than in those from the polluted area of the York River (group B), the means being 13.43 ± 0.50 and 10.40 ± 0.28, respectively. The test of significance (table 31) gives the value of $t = 5.63$ showing that the difference far exceeds the probability of random sampling.

TABLE 31.—*Comparison of the means of weight of shells per square inch of oysters of the upper York River (B) and the lower York River and the Piankatank River (A)*

Group	Number shells	Degrees of freedom	Mean weight per square inch	Sum of squares
			Grams	
A	49	48	13.43±0.50	594.369
B	60	59	10.40±0.28	271.317
Difference			3.03	
Total		107		865.686

From the analyses of areas and weights of shells, an inference can be made that, with respect to the mean area of shells, the two groups of oysters do not differ from each other, although they can be easily distinguished by their shape. As to the weight of shells, oysters from the upper part of York River are unquestionably lighter than those from its lower part and from the Piankatank River. It is natural to suppose that the difference is brought about by a slower rate of calcium deposition in these oysters. Light weight of oyster shells from the upper part of the York River is due to their thinness, and to the presence of large cavities filled with loose chalky material instead of more compact, and therefore heavier, layers of crystalline calcium carbonate. Very often adult oysters were found in which the thickness of the shell varied from 0.5 to 1.50 millimeters. The prevailing thickness of shell in the oysters of the lower part of the river was usually from 4 to 10 millimeters. As oyster shell is not of uniform thickness, considerable difference always can be noticed in the same valve. However, no oysters with thin, transparent shells were found except in the upper part of the York River.

It also has been observed that the central parts of the shells of group-B oysters (upper York River) were the thinnest, and that the thickest portion of the shells, was at the edge. This is readily seen in figure 28 representing the cross-section of the right valve of an oyster from station 5. It seems that the deposition of shell material along the central part of the valve was inhibited. The tendency to deposit more shell material at the edges than at the central portion of the valve frequently can be found in oysters from Long Island Sound, Louisiana, and Texas. Some of the very heavy shells, more than 1-inch thick, collected by Galtsoff in Louisiana, showed increased thickness at the edges. In some of these specimens the thickening was restricted to the left valve only, while in others it was pronounced on both sides of the body. It is therefore probable that irregularity in the deposition of shell material frequently occurs in oysters and attracts no attention if the valves remain fairly thick. So little is known, however, about the physiology of shell formation in the oyster and other lamellibranchs that interpretation of these observations must wait until the underlying biological processes are better understood.

Presumably, the shell material of the oyster acts as a buffer. Part of it dissolves in the shell liquor when the valves are closed and through the accumulation of CO_2 the acidity of the liquor increases and the inside of the shell is corroded. Dugal and Irving (1937) have demonstrated this for the clam, *Venus*. Marks of etching on the nacreous layer are easily noticeable in the clam but cannot be observed on the oyster shell deprived of true nacre. The possibility that in the oyster a certain portion of the inorganic part of the shell material may be lost through dissolution in the shell liquor does, however, exist. The dissolution of salts may become more pronounced the longer the mollusk remains closed. Whether this condition is responsible for the thinness of the York River shells has not been ascertained, for the evidence of such an occurrence is rather difficult, if not impossible, to obtain. Yet it appears desirable to indicate this possibility, for it will be shown later that the presence of pulp-mill pollutant increases the duration of closure of shells in York River oysters.

PATHOLOGICAL STUDIES

Structure of Shell

In view of the pronounced abnormality in the consistency and thickness of shells of many oysters taken from the upper part of the York River, it was considered desirable to study the shells in a more detailed manner and to determine whether the microscopic structure of these shells would reveal any pathological condition. Thin transverse sections of shells were made by grinding small pieces that were mounted on glass slides with heated Bakelite varnish. For grinding to the desired thickness, a motor-driven silicon-carbide resinoid wheel was used. After grinding, the preparation was air-dried and mounted in Canada balsam.[5] The presence of large pockets of chalky material presented considerable difficulty, and many preparations were lost before the grinding was completed. Several satisfactory preparations, however, were made and used for comparison with the normal-shell structure.

The literature on the composition and structure of mollusk shells comprises many papers written by zoologists, mineralogists, and chemists. Because of the different points of view from which shell studies were made, it is difficult to correlate the microscopic structure of shell with its crystallographic characteristic and with its chemical composition. A review of the extensive literature, scattered in zoological, mineralogical, and geological publications, and which frequently contained contradictory statements, is not necessary for the present discussion. It suffices to mention that in accordance with the present views, lamellibranch shell consists of three layers: (*a*) an outer layer of horny substance, conchyolin, secreted by the epithelium of the groove at the free edge of the mantle; (*b*) an underlying prismatic layer, also formed at the edge of the mantle; and (*c*) an internal nacreous layer which is secreted by the epithelial covering of the body and mantle. The described arrangement is typical for fresh-water Unionidae and marine Aviculidae and Mytilidae. In other lamellibranchs it occurs with certain modifications. In

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[5] For the details of the technique and suggestions regarding the necessary equipment, the authors are grateful to Dr. L. G. Henbest of the U. S. National Museum who perfected this method.

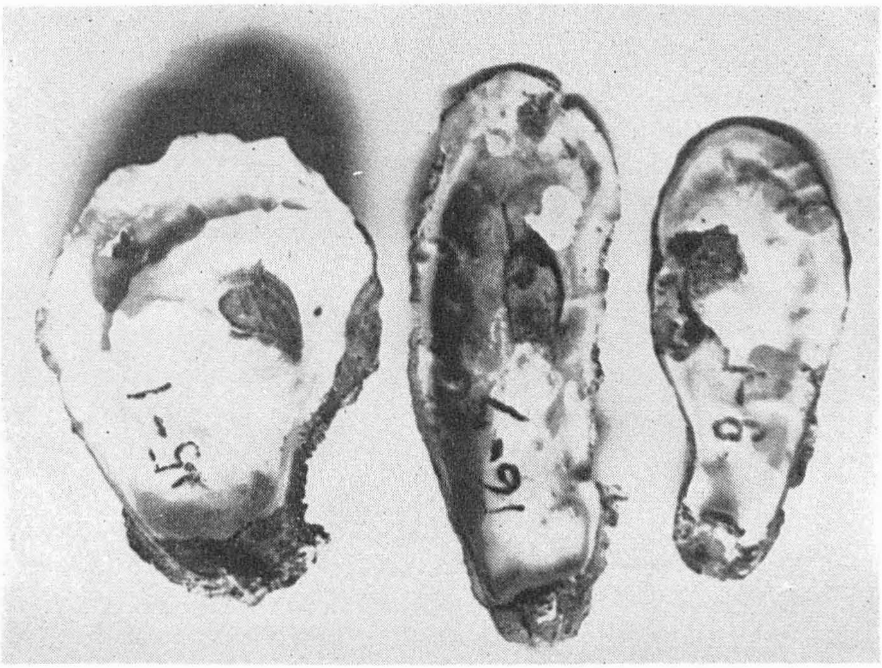

FIGURE 29.—Shells of adult York River oysters. The two shells on the right are from the upper part, and the shell on the left is from lower part of the river.

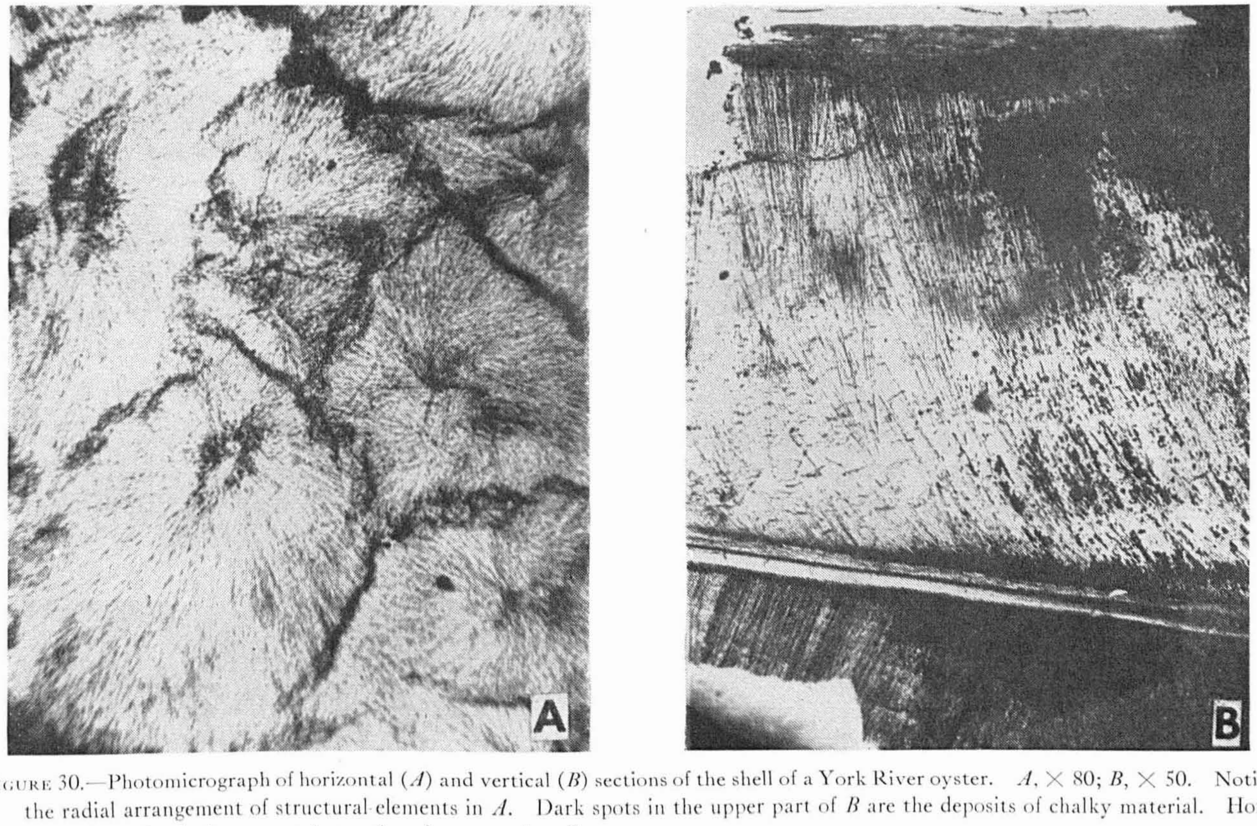

FIGURE 30.—Photomicrograph of horizontal (*A*) and vertical (*B*) sections of the shell of a York River oyster. *A*, × 80; *B*, × 50. Notice the radial arrangement of structural elements in *A*. Dark spots in the upper part of *B* are the deposits of chalky material. Horizontal layer in the lower part is a series of compact lamellae.

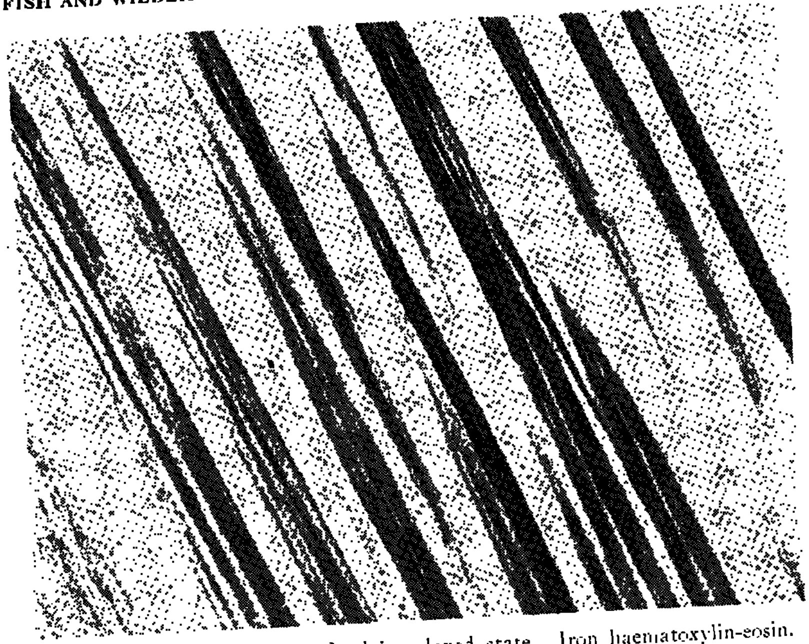

FIGURE 31.—Photomicrograph of the adductor muscle fixed in relaxed state. Iron haematoxylin-eosin. Vertical section. Note slightly swollen dark areas. × 250.

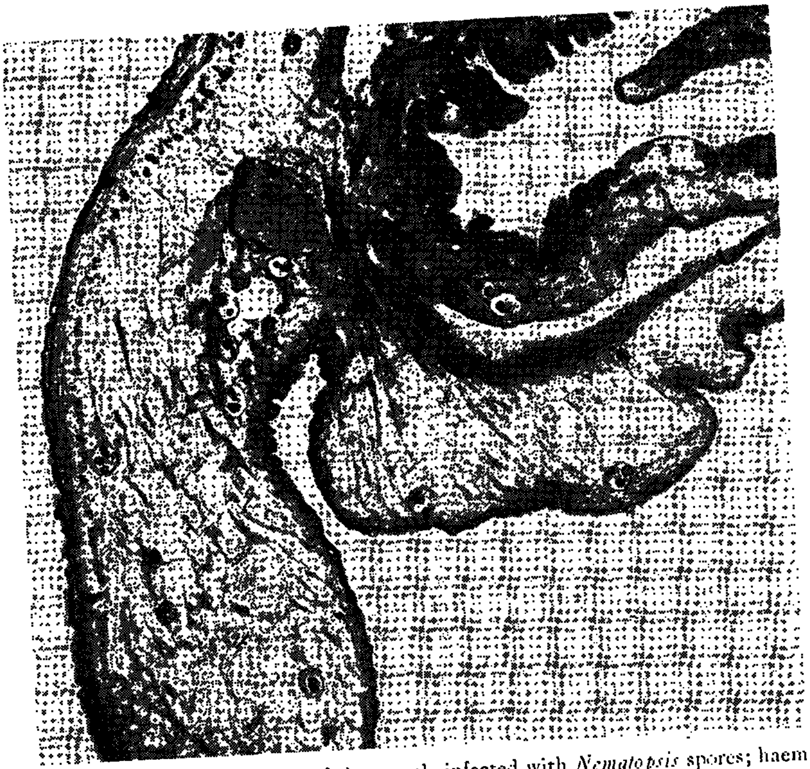

FIGURE 32.—Photomicrograph of a cross section of the mantle infected with *Nematopsis* spores; haematoxylin-eosin. × 125.

Ostrea the outer horny layer (periostracum, or epidermis of many authors) is not well developed and its existence is doubted by some of the investigators. In our preparations a very thin homogeneous layer, not impregnated with calcium salts, can be seen over the prismatic layer of the shell. It is, however, very poorly developed.

The prismatic layer, as the name implies, consists of regular and distinct prisms of calcified material embedded in conchyolin substance and oriented normally to the surface of the shell. It often can be found as a scale-line formation on the exterior of the shell and at its edges. This layer is rather thin and often absent in old shells.

The inner layer of the shell consists of a substance different from the true nacre of other lamellibranchs, and is characterized by a very irregular arrangement of structural elements, oriented horizontally, obliquely, and sometimes even vertically (at right angle to the surface of shell). In preparations ground parallel to the surface of the shell, this layer is seen to consist of large alveoli with vertical laminae radiating from their centers (fig. 30A).

Typical for the genus *Ostrea* (Böggild 1930) is the fact that the layers of normal consistency may alternate with more or less loosely packed layers of chalky substance, placed vertically, and oriented at all possible angles around the normal (at right angle to surface) axis of the shell (fig. 30B). The chalky deposits (called in French *chambrage*, chambering) were investigated by Orton and Amirthalingam (1927), who advance a theory that they are caused by the shrinkage of the body after spawning or when the oyster is transferred from high to low salinity. Subsequent automatic secretion of material by the surface of the shrunken body, destined normally for thickening of the shell, seals the liquid which percolates between the oyster's body and the shell and forms a chamber. Further deposition of the nacreous layer serves to conceal the chamber permanently. If we accept this explanation, which requires further corroboration, an inference must be made that chalky material is precipitated from the liquid sealed in the chamber and is not secreted by the mantle epithelium. More detailed observations are necessary to settle this interesting point. Chambering has also been observed in *Ostrea* (*Gryphaea*) *angulata* and in several fossil forms such as *Gryphaea vesicularis*, *Ostrea hippopodium*, and *Ostrea reflexa*. Presence of large cavities filled with calcite crystals are typical for the shells of these species. These facts lead us to infer that chambering is a normal tendency in various species of oysters. There is no reason, therefore, to regard it as a symptom of pathological conditions.

Examination of preparations made from fragile and thin shells of York River oysters discloses the presence of the same structural elements as are found in normal shells. The only noticeable difference is in the thickness of the shell, not in its component parts. We conclude from these observations that the functioning of shell-secreting organs was proceeding normally except that the rate of deposition of calcium salts was reduced, probably by environmental conditions. The experience of local oystermen, who claim that oysters transplanted from the upper part of the river to its mouth or to Mobjack Bay resume good growth and develop stronger shells, corroborates this inference.

Microscopic Examination of the Tissues

Oysters of poorest quality, i. e., watery with emaciated and discolored tissues and thin transparent shells, were selected and preserved in Bouin III, Fleming, and 10 percent formalin solutions. Some of the material, after a brief immersion in 10 percent formalin, was sectioned by using the freezing-microtome technique and stained with Sudan III, IV, and haematoxylin. Other specimens were embedded in paraffin and stained with Heidenhain iron haematoxylin, Delafield haematoxylin, and counterstained with eosin, safranin, and mallory. All the organs, namely the mantle, gills, heart, digestive gland, intestine, gonads, adductor muscle, viscera, ganglia, and circumpallial nerve, were examined. These studies revealed no pathological conditions in these organs with the exception of the occasional occurrence of abnormal fibers in the adductor muscle. Both in smooth and striated portions of the muscle, fibers were found which were abnormally swollen, and in some instances surrounded by very thin capsules. Although the homogeneous and transparent substance of the fiber had no increased affinity for eosin, it somewhat resembled the first stages of hyaline degeneration found in mammalian tissues (Vines 1934: 210). In the latter cases the degenerated mass is usually eosinophilic. The affected muscle fibers of the oyster had, however, strong affinity for iron haematoxylin and retained black color in the preparations in which other parts of the muscle remained almost completely unstained (fig. 31). This condition has been observed by Prytherch (1940) in the muscles of oysters infected by *Nematopsis*. In our preparations, abnormal muscle fibers were found both in the infected and non-infected specimens. Muscular degeneration in weak, European oysters (so-called "hockley" oysters) was described by Orton (1924), who found microscopic spindle-shaped bodies throughout the tissues remote from the adductor muscle. His experiments with healthy oysters, the shells of which were bored and the adductor muscles pierced, showed that the spindles could be produced artificially. He thinks that these spindles may arise from the degeneration of the muscles of the mantle. No spindles answering Orton's description were found in the York River oysters. The abnormal fibers of York River oysters were much longer and wider than those described by Orton and were found only in the adductor muscle. So little is known about the muscular degeneration in mollusks, and in lamellibranchs in particular, that no interpretation of the observed condition is at present possible.

Careful examination of other tissues, i. e., mantle, gills, labial palps, digestive gland, nervous ganglia, intestines, heart, and excretory organs, revealed no pathological or degenerative conditions. The connective tissue of the body wall and mantle contained large numbers of pigment granules insoluble in alcohol and xylol, but similar granules, although in smaller number, occur in other oysters. In the preparations fixed with osmic acid, large black globules were abundant in the mantle and in the body wall, occupying almost the entire space inside the vesicular cells. Sections of fresh material, made with the freezing microtome and stained with Sudan III and IV, proved without any doubt the fatty nature of the globules. No traces of these globules could be found in the preparation treated with ethyl alcohol or other fat solvents. Similar globules were found in healthy oysters from Onset, Mass., Milford, Conn., and Beaufort, S. C. Apparently infiltration of connective tissue with fat is a normal phenomenon not noticeable in the preparation dehydrated with alcohol.

Infection with Nematopsis Spores

In the course of the histological examination, it was noticed that many specimens were infected with spores of a gregarine *Nematopsis*. This microorganism was first described by European protozoologists (Schneider, 1892, Leger and Duboscq, 1903, 1913; and Hatt, 1931) who found it in various lamellibranchs, such as *Cardium*, *Mytilus*, *Anomia*, *Tapes*, *Solen*, and *Ostrea*. In the United States the spores of *Nematopsis* were first reported in 1930 by Prytherch (1940) in the oysters of Mobjack Bay, Va., and later recorded by him from North Carolina and Louisiana. The life cycle of this protozoan was described by Kudo (1939) and Prytherch (1940). Since the initiation of the York River investigations, the distribution of *Nematopsis* in the lower Chesapeake Bay and adjacent waters was studied by Galtsoff and Engle, who were able to extend their observations to other coastal States including Connecticut, New York, Delaware, Alabama, and Texas. In 1941 Galtsoff (unpublished report, Fish and Wildlife Service) found that Texas oysters from Aransas Pass, Mesquite Bay, Karankawa Reef, Lap Reef, Jordan's Pass, and Borup Reef were heavily infected with *Nematopsis* spores. In some instances, oyster tissues contained countless numbers of cysts, especially in the mantle, gills, and in the heart. There was no unusual mortality among the infected oysters and the appearance of their bodies varied from fair to good. Only in cases of extremely heavy infection were oyster meats poor. In 1941 the Louisiana Department of Conservation (unpublished data collected by Gowanloch and Kavanaugh) reported that *Nematopsis* was present on nearly all oyster grounds within the State's waters, in many instances, infecting all the oysters on the reef. The State investigators were unable to find any correlation between the intensity of *Nematopsis* infection and the mortality which occurred at that time on some of the grounds.

Oysters heavily infected by *Nematopsis* were collected in 1943 by Engle (1945) in Mobile Bay in the area of Dauphin Island (Mississippi Sound). The infection was so heavy that the gills of the specimen examined by Galtsoff appeared to be full of cysts which could be easily washed off by shaking the tissues in water. Although these oysters were in poor condition, they were not dying, and no reports were received later of any noticeable mortality among them.

In 1942–43 Galtsoff found that oysters on public seed-grounds and on planted bottoms in the Delaware Bay were infected with *Nematopsis* cysts. Since it was known that during the preceding year some of the infested seed oysters were shipped to Connecticut and New York for planting in Great South Bay and in Long Island Sound, attempts were made to locate them. Some of the oysters grown from this seed were collected for examination and found lightly infected. Planters reported no unusual mortality among this stock which grew and fattened in a normal way.

The range of distribution of *Nematopsis*, as shown by these observations, extends from Texas to Delaware Bay with occasional infection of oysters in Great South Bay and Long Island Sound. So far *Nematopsis* has not been found in waters of Rhode Island, Massachusetts, New Hampshire, or on the Pacific coast.

Infection with this microorganism can naturally be suspected as one of the possible causes of the pathological condition of York River oysters. An answer to this question is given by the results of a systematic examination of oysters collected at various sections of the river. At each sampling station, 20 oysters were obtained for microscopic examination of their organs and tissues. Each specimen was dissected and preparations were made of the mantle, gills, labial palps, heart, and both parts of the adductor muscle. The highest infection was found to occur in the mantle.

Examination of 200 oysters collected at various times during the year of 1936 at 10 different stations between West point and Yorktown shows that 86 specimens, or 43 percent of them, were not infected. In this examination the following technique was used: a piece of tissue or organ, about 1 centimeter square, was cut from the body and placed between two slides which were strongly pressed together and held in that position with a pair of self-closed forceps. Very strong illumination and a magnification of 250 were employed. By using a mechanical stage, the entire slide, representing 1 square centimeter of the original section of the tissue, was examined and the total number of cysts found in it recorded. No counts were made when the number of cysts exceeded 200 per field. In several cases of very heavy infection of the mantle, the number of cysts per square centimeter was estimated to exceed 5,000. In other organs it varied from 0 to 30. In order of the frequency of infection, the organs can be listed as follows: mantle, adductor muscle, heart, labial palps, and gills. No cysts were found in the digestive gland, gonads, and excretory organ. A summary of these examinations is given in table 32.

In 29 percent of those with infection of the mantle, the number of cysts was very great, exceeding 200 per square centimeter. Next in the frequency of infection was the adductor muscle (41.2 percent), in which the number of cysts was always small. The gills were found to be infected only in 10.5 percent of parasitized oysters. This low percentage is rather surprising, for one may have expected that the organs engaged in the pumping of water in which the gymnospores of *Nematopsis* are suspended would have a greater opportunity to be invaded by the micro-organism.

TABLE 32.—*Frequency of occurrence of* Nematopsis *in various organs of 114 infected oysters from York River*

Infected organs	Number of oysters in which infection was found	Percentage
Mantle	69	60.5
Adductor muscle	47	41.2
Heart	29	25.4
Labial palps	15	13.2
Gills	12	10.5
Digestive gland	0	0
Gonads	0	0

The infection with *Nematopsis* can naturally be suspected as one of the possible causes of the poor condition of York River oysters. An attempt to answer this question was made by recording the condition of oysters examined for the presence of *Nematopsis* spores. The results of the observations are summarized in table 33, which shows the date of collection, the distance of the station from West Point, condition of the oysters, percentage of infected specimens in the sample, and intensity of infection. The latter is expressed in the following arbitrary terms: heavy—widespread infection, number of cysts in the mantle exceeding 1,000 per square centimeter; medium—cysts in two or three organs, number of cysts in mantle less than 1,000 per square centimeter; light—occasional cysts in one or two organs.

TABLE 33.—*Infection of York River oysters with* Nematopsis

[20 oysters were examined at each station]

Station No.	Approximate distance from West Point	Date	Condition	Percentage infected	Intensity of infection
	Miles	*1936*			
9	2.0	July 31	Poor	88	Heavy.
8	4.5	Aug. 17	Very poor	56	Medium.
17	5.5	June 19	Poor	71	Light.
16	6.5	Aug. 5	do	16	Do.
6	8.5	Nov. 10	Very poor	12	Do.
22	10.5	July 16	Poor	96	Do.
22	10.5	Nov. 24	do	56	Do.
		1937			
22	10.5	July 6	do	100	Heavy.
		1936			
15	16.5	Aug. 27	Good	87	Medium.
14	23.0	July 27	do	48	Light.
20	29.0	June 2	do	0	

If the infection of oysters with *Nematopsis* is the primary cause of their poor condition, one should expect the poorest oysters to be those the most heavily infected. Observations, however, do not support this conclusion. The poorest oysters of the entire section, found at station 6 (table 33), showed a rather low percentage of infection, and those found in fairly good condition (station 15) were more heavily infected. Furthermore, a decrease in the percentage of infected oysters from 96 to 56, as observed at station 22, was not accompanied by any noticeable improvement in their quality. Convincing evidence that the primary source of trouble is not a parasitic infection was the observation that the condition of the meats of the heavily infected oysters from stations 6 and 22 was not worse than the condition of the meats of the noninfected specimens collected at the same time from the same stations. This observation eliminates *Nematopsis* as a factor responsible for the poor quality of the York River oysters and indicates that their pathological condition is due to some other cause. This inference is further corroborated by the fact that spores found in tissues are inactive, i. e., they do not propagate within the body of the oyster.

Microscopic examination of infected tissues (fig. 32) reveals no inflammatory or other pathological processes in the infected organs. The mesenchyme tissue of the mantle and the pallial nerve in the immediate vicinity of the encapsuled cysts were normal. Likewise, no pathological conditions were observed in the adductor muscle infected with cysts. As stated, abnormal muscle fibers were found both in the infected and noninfected muscles and therefore the condition could not be attributed to the presence of the parasite. It would be reasonable to expect some pathological reaction if the tissue were suffering from the presence of spores. From the microscopic study one may conclude that the encapsuled spores do not affect the host organism, except possibly in extreme cases, such as encountered by the authors in only two Alabama oysters, where the water tubes and passages of the gills were clogged with millions of spores. Even in this case there was no mortality among infected oysters.

METAL CONTENT OF THE YORK RIVER OYSTERS

The presence of blue or greenish discoloration in the tissues of oysters suggests the accumulation of an excess of copper. In order to determine this, analyses were made during the summer of 1937 of copper, iron, manganese, and zinc content of oysters collected at station 22 in the upper part and station 14 in the lower part of the York River. In preparing the samples for analyses, the following procedure was followed; one to two grams of the dried sample were weighed into a silica crucible, charred over a low flame, and then ashed in the muffle at a temperature of 500° C. for 3 to 4 hours. The sample was cooled, and moistened with water. Then 1 milliliter of concentrated HNO_3 was added, and the sample evaporated to dryness on the hot plate and returned to the muffle for one hour at a temperature of 400° C. Ashing was usually completed after one application of HNO_3. The cooled ash was dissolved in 15 milliliters of 1:1 HCl. Then 10 drops of 30 percent H_2O_2 were added to the solution, which was then heated until the oxygen ceased to be liberated. The sample was then transferred to a 100-milliliter volumetric flask and diluted to the mark. The water used in solutions and reagents was redistilled in pyrex containers and was frequently tested for copper and iron and found to be free from traces of these metals.

Copper was determined as a thiocyanide-pyridine compound using Biazzo method with modifications described by Elvehjem and Lindow (1929) and Elvehjem and Hart (1931). Kennedy's thiocyanate method (1927) was used for Fe determination. Manganese was determined by the periodate method of Willard and Greathouse, modified by Richards (1930). All colorimetric determinations were made by comparing the unknown with standards in a Duboscq colorimeter. Zinc was determined as potassium zinc ferrocyanide using a Duboscq nephelometer for turbidimetric estimation (Birckner 1919).

The results of the analyses (table 34), expressed in milligrams of metal per kilogram of dry meat, show considerably higher content of all four metals in the oysters of the upper part of the river than those taken from its lower section. The last three lines of the table are introduced for comparison to show the metal content of the three samples of oysters collected

TABLE 34.—*Metal content of York River and Norfolk oysters in milligrams per kilo, dry basis*

Source	Date	Iron	Copper	Manganese	Zinc
Station 22	July 23, 1937	1,210	782	59.9	9,240
Station 14	do	452	326	25.7	6,120
Near Norfolk	October 1931	495	299	19.5	------
Do	do	322	164.3	14.9	------
Do	do	1,040	135.6	22.4	------

in October 1931 in the vicinity of Norfolk and analyzed by E. J. Coulson.

In general, there is no significant difference in the metal content of the York River oyster and those from the vicinity of Norfolk. (The latter samples were taken from commercial plantings and their exact origin is not known). Slightly higher figures for manganese are undoubtedly due to the presence of ripe ovaries in the July samples. It has been shown by Galtsoff (1942) that ovaries store a relatively large amount of manganese and seasonal fluctuations of this metal in oysters coincide with their sexual cycle.

Greenish discoloration of tissue is probably associated with increased copper content, which may be responsible for their disagreeable and somewhat bitter taste. It is, however, of interest to note that green oysters of Long Island Sound have a much higher copper content, often exceeding 2,000 milligrams per kilo. In comparison with these oysters, the copper content of the York River oysters is rather low. The reason for the greater accumulation of metals by the oysters in the upper York River, as compared with those from its lower part, is not clear. There is apparently no excess of heavy metals in the pulp-mill effluent and it is, therefore, doubtful whether the increased amount of metals in the oyster meats comes from the pulp-mill wastes. Their accumulation is probably the result of the metabolic disturbances which interfere with the excretion of metallic salts. This problem requires, however, special study which could not be undertaken in the course of the present investigation.

QUALITY OF YORK RIVER OYSTERS AS DETERMINED BY THE SO-CALLED CONDITION FACTOR

The quality of oysters can be measured by determining the ratio between the dry weight of the meat and the volume of the cavity (in milliliters) of the shell. The idea was originated by Caswell Grave (1912), who expressed the "fatness of oysters" by determining the percentage of the shell cavity filled with meats. Hopkins in 1937 (Higgins 1938) showed that the ratio

$$\frac{100\times\text{dry weight in grams}}{\text{Volume of cavity in milliliters}},$$

is a very useful index of the quality of oyster meat. Since that time this index has been extensively used by shellfish investigators on the west coast and in Canada.

In order to determine the relationship of shell cavity to total volume of shell, and of the meat to shell cavity, of oysters in the York River, samples of 100 oysters each were collected from station 20 in the lower York and station 16 in the upper York. Observations were made during the last of May and the first of June 1937.

After the oysters were scrubbed clean with a wire brush, they were weighed individually to the closest tenth of a gram. Each oyster was placed in a celluloid box partly filled with water, having a glass-tube side arm, and the displacement was measured. This container was 5 by 4.5 by 9.5 centimeters, and the glass tube at the side was of 6 millimeter bore, graduated in 10 cubic centimeter units. The oysters were then opened carefully and the meats dried individually in an electric oven at 50° C. for 4 days, and at 100° C. for 1 day, and the weight of the dried material determined. The weight of the two valves of each oyster was determined, as was also the volume by displacement. The shell-cavity volume was then determined by finding the difference between the volume of the whole oyster and the volume of its shell. The results were averaged for each sample of 100 oysters and are presented in table 35.

From these observations it is apparent that the shell comprises 80 percent of the total weight of the oysters of the lower York and 73 percent of the total weight of those of the upper York. The shell cavity constitutes 34 percent of the total volume of the lower river oysters and 47 percent of the total volume of those of the upper. However, there is

TABLE 35.—*Relationship of volume and shell cavity of oysters in the lower and upper York River*

[Results are averages from 100 oysters at each locality]

Locality	Total weight in grams	Shell weight in grams	Total volume, cubic centimeters	Shell volume, cubic centimeters	Cavity volume by difference, cubic centimeters	Dry weight of meats, grams	Condition factor
Lower York River	147.6	118.5	81.9	53.8	28.1	2.34	8.32
Upper York River	75.6	55.1	45.5	24.1	21.4	1.26	5.88

29 percent more meat in the cavity of the oysters of the lower York, if we compare the factors obtained by dividing the dry weight by the volume of the cavity, thus:

$$\text{Lower York River: } \frac{\text{Dry weight of meats}}{\text{Volume of cavity}} = 0.08318 \text{ gm./cc.}$$

$$\text{Upper York River: } \frac{\text{Dry weight of meats}}{\text{Volume of cavity}} = 0.05885 \text{ gm./cc.}$$

These data confirm the observations that the shells of the upper York River oysters are thinner than the shells of those from the lower part of the river. The shell cavity of the oyster of the upper York River is, however, greater than that in the oyster of the lower part, but the greater volume of shell space contains less meat because of the higher water content of the oysters in the upper part of the river.

GLYCOGEN CONTENT OF OYSTERS

The glycogen content of the oyster fairly expresses the quality of its meat and furnishes a possibility of evaluating the condition of the oyster in definite quantitative terms. The purpose of the observations described in this section was, first, to study the glycogen cycle in native oysters found at different stations in the York and the Piankatank Rivers; second, to determine the effect of transplantation of James River oysters, known to be in good condition and growing in areas of good environment, to the York River; and third, to determine the effect of the removal of oysters from the badly affected areas of the upper York River and their transplantation to areas in the lower part of the York and the Piankatank Rivers, known to be favorable to good oyster production. It was expected that the proposed studies, if carried on over a sufficiently long period, would provide definite answers to the following questions: Is the upper York River environment decidedly adverse to newly planted healthy oysters? Will removal from the upper part of the York River to a better environment restore the normal conditions of the affected oysters?

Cycle in the Oysters of the York and Piankatank Rivers

For a study of the glycogen cycle of the oysters of the York River, a sample of 25 oysters was taken each month from native beds at designated stations. These stations were selected as being more or less evenly spaced up and down the river and were located on both sides. From November 1935 to April 1937 samples were procured from stations 20, 14, 5, and 9 in the York River and from stations 55 and 53 in the Piankatank River. After July 1936, samples from stations 23, 6, and 8 in the York River were added.

After the oysters were brought to the laboratory, they were carefully opened and the meats allowed to drain on a double thickness of paper toweling for 15 minutes. The meats were then passed twice through a food grinder, and a sample of approximately 10 grams of the ground meats was taken and carefully weighed in a covered dish. The glycogen content was then determined according to the method of Pflüger (1906), as described in detail in the handbook of methods, Association of Agricultural Chemists (1935) and with the titration of sugar according to the method of Hagedorn and Jensen (1923). Computation of the glycogen from the sugar titration was made by the usual conversion factor of 0.9. The results were expressed in percentage of glycogen of the sample on a wet-weight basis.

During the course of these studies the method of glycogen determination in oysters was critically studied by Calderwood and Armstrong, who suggested several valuable modifications that greatly expedite the procedure and increase the accuracy of the results. The suggested modifications are described in a separate paper (Calderwood and Armstrong 1941).

In table 36 are shown the results of the analyses for nine stations in the York and the Piankatank Rivers. During the winter of 1936–37 it was impossible to obtain certain samples in January and February because of the extremely cold weather and the fact that much of the upper parts of the rivers were covered with ice.

The data for three stations in the York River were selected for graphic presentation in figure 33. Station 20 represents the lower York River, station 5 the middle York River, and station 9 the upper York River. Seasonal fluctuations in the glycogen content of the oysters of the Piankatank River at stations 53 and 55 are shown in figure 34.

It will be seen that the curves for the York and Piankatank Rivers follow the same trend, differing only quantitatively. The data show that throughout the year the oysters of the Piankatank River maintained a higher glycogen content than those of the York River. Curves in figure 33 show also that the glycogen content of the York River oysters decreases from the mouth of the river toward its head. The process is reversed in the Piankatank, where oysters from the upper part of the river are richer in glycogen than those from the lower part,

TABLE 36.—*Glycogen content of oysters in the York and the Piankatank Rivers*

[Glocogen in percentage is on a wet-weight basis]

Date	York River							Piankatank River	
	Station 20	Station 14	Station 23	Station 5	Station 6	Station 8	Station 9	Station 55	Station 53
1935									
November	4.95	3.66	----------	3.30	----------	----------	3.01	5.05	4.64
December	4.88	----------	----------	----------	----------	----------	3.58	4.92	6.25
1936									
January	----------	----------	----------	----------	----------	----------	----------	4.70	6.03
March	2.67	2.84	----------	2.22	----------	----------	1.48	3.65	4.44
April	2.59	2.62	----------	2.78	----------	----------	1.52	5.59	4.83
May	4.35	3.88	----------	3.26	----------	----------	1.50	3.93	5.11
June	3.80	2.20	----------	1.91	----------	----------	1.79	2.90	6.04
July	3.04	2.29	1.12	1.56	1.03	0.68	1.38	1.70	3.00
August	2.15	2.26	1.53	1.15	1.83	.89	1.27	.67	1.69
September	2.40	1.49	.44	.67	1.25	----------	.41	1.31	1.54
October	2.91	2.58	1.48	----------	1.43	.56	.73	2.25	2.82
November	2.75	2.69	1.67	----------	2.09	.61	1.12	2.72	4.13
December	3.95	2.77	1.02	1.45	----------	----------	1.21	4.06	5.21
1937									
January	----------	2.85	2.52	2.59	2.12	1.47	1.88	----------	----------
February	4.06	3.74	2.10	2.84	2.17	1.98	1.76	5.94	5.44
March	3.70	4.61	----------	2.67	1.60	1.11	1.73	2.40	3.83
April	5.28	2.79	----------	2.35	----------	1.43	1.65	2.84	2.97
Average	3.56	2.88	1.49	2.21	1.69	1.12	1.63	3.35	4.24

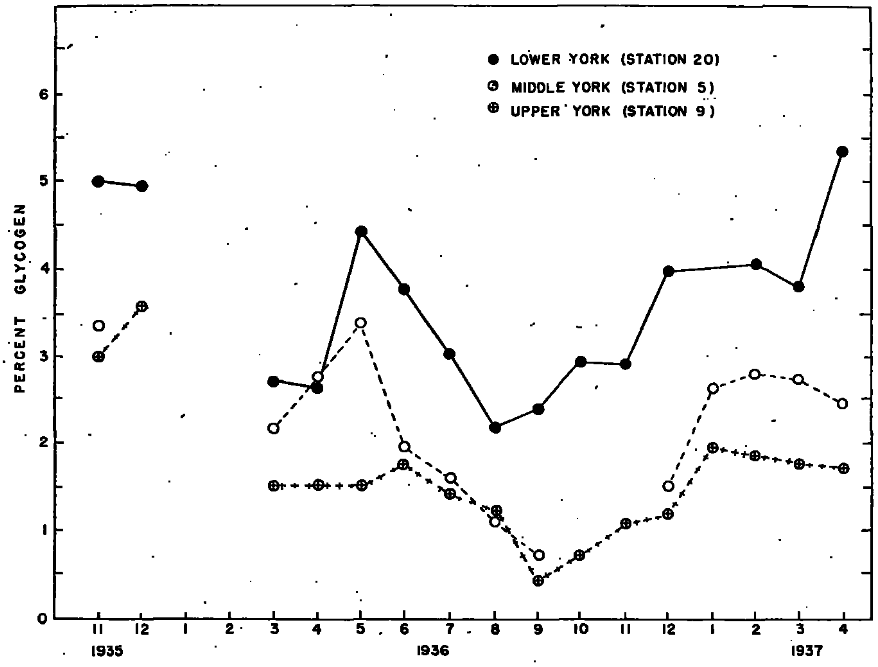

FIGURE 33.—Glycogen content of York River oysters from the lower, middle, and upper parts of the river. Glycogen in percentage is on a wet-weight basis.

although the difference is less pronounced than in the York River.

A direct correlation between the distance from West Point (upper part of the river) and the increase in glycogen content can be seen also in figure 35, which represents a 9-months' average (July 1936 to March 1937) of the glycogen content of oysters at various stations in the York and Piankatank Rivers.

Despite the fact that the average figures used in this diagram tend to diminish the extent of vertical fluctuations of the curve, it is quite apparent that oysters in the upper half of the river, above Claybank, are decidedly lower in glycogen. Marked improvement in oyster-quality occurs in the York River at stations 14 and 20 and in the Piankatank River.

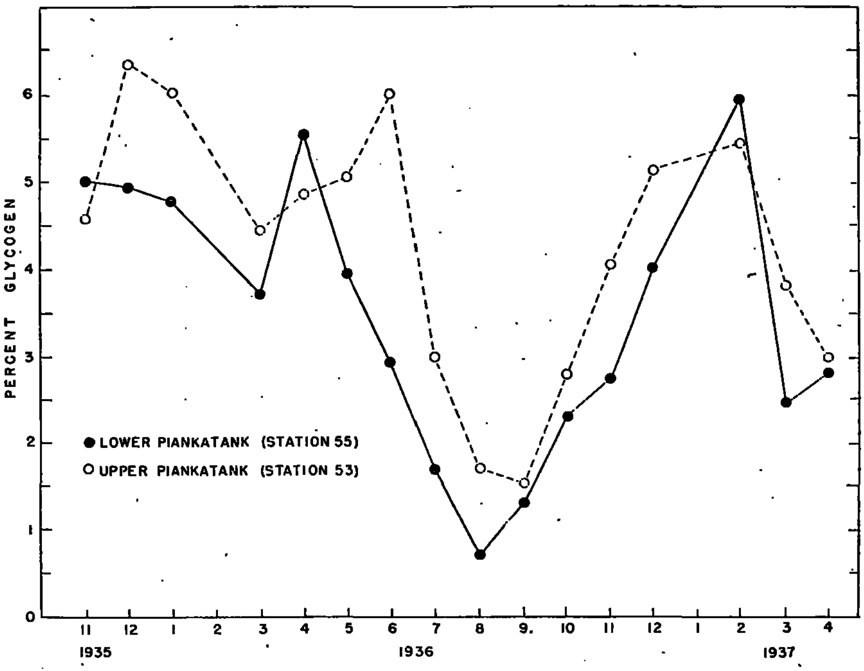

Figure 34.—Glycogen content of oysters from the lower and the upper Piankatank River. Glycogen in percentage is on a wet-weight basis.

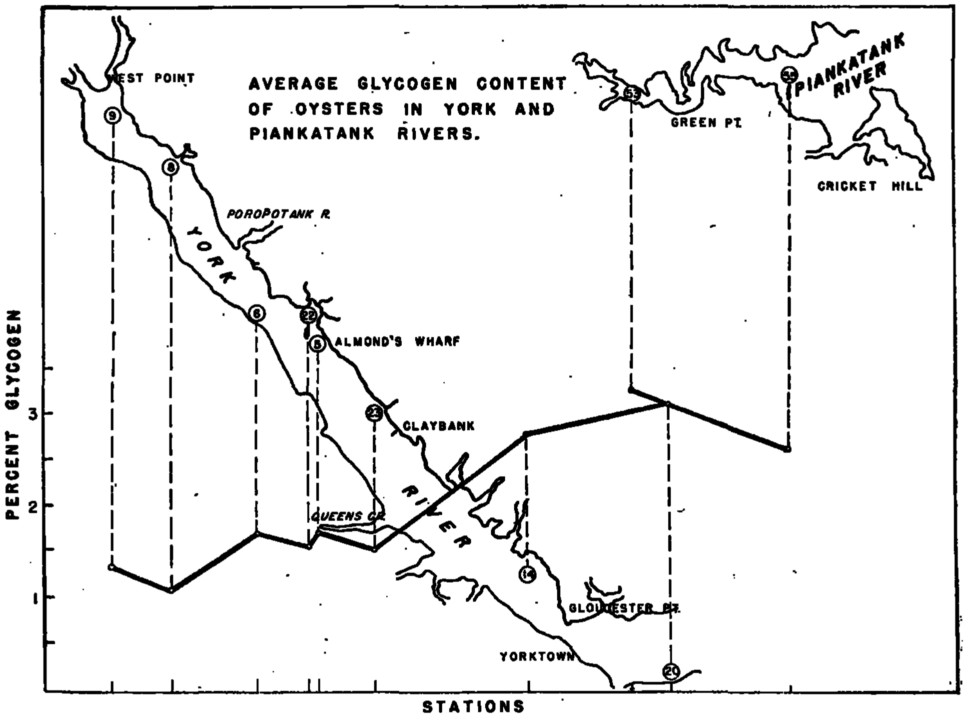

Figure 35.—Average glycogen content of the oysters at the various stations in the York and the Piankatank Rivers from July 1936 to March 1937, inclusive. Glycogen in percentage is on a wet-weight basis.

Changes in the Glycogen Content of James River Seed Oysters Transplanted to the York and Piankatank Rivers

James River seed oysters were selected for transplanting experiments for their good quality and because they are generally used by the oyster growers in Virginia for planting on private bottoms. In December 1935 and January 1936 these oysters were planted at stations 20, 14, 15, 5, 16, 17, and 9 in the York River and at stations 55 and 53 in the Piankatank River. At monthly intervals 10 oysters were tonged from each station and analyzed for glycogen content. The results of these determinations for the various stations are shown in table 37.

Differences in the trend of the glycogen cycles of these oysters became apparent only 6 months after planting. This is clearly evident in figure 36, representing the seasonal changes in glycogen content of James River seed oysters transplanted to the lower York River (station 20), to the upper York River (station 9), and to the upper Piankatank River (station 53). The low glycogen content at the upper York River station during the winter of 1936–37 stands in contrast to the high glycogen level attained by oysters planted in the lower part of the York and Piankatank Rivers.

A direct correlation between the increases in glycogen content of the planted oysters in the York River and the distance from West Point is apparent in figure 37, which represents averages for 15 months at the different stations. The curve is almost identical with that based on the analyses of native oysters (fig. 35), with the difference that decided improvement in the condition of oysters becomes apparent at station 15, near Queens Creek. The difference may be easily attributed to the different locations of stations used in the two sets of observations. In contrast with the York, we again find the highest glycogen content at the upper station in the Piankatank River.

Glycogen Changes in Oysters Transplanted from the Upper York River to the Lower York and the Upper Piankatank Rivers

Low glycogen values, as illustrated by analyses of the upper York River oysters, suggested a transplanting experiment to determine whether the glycogen content would increase and reach a normal level when the oysters are removed from the unfavorable environment. If the poor condition of the oysters in the upper part of the river is primarily the result of their weakened or diseased state, one would expect them to remain poor for some time after transplanting. On the other hand, marked improvement in the meats upon transplanting the oysters to good waters would indicate that the cause of their poor condition is the unhealthy environment.

In March 1936 oysters were tonged at station 22 in Purtan Bay and transplanted downstream at station 20 at the mouth of the river, and at station 53 in the upper Piankatank River. Monthly samples consisting of 10 oysters each were taken

TABLE 37.—*Glycogen content of James River seed oysters transplanted to the York and the Piankatank Rivers*

[Glycogen in percentage is on a wet-weight basis]

Date	York River							Piankatank River	
	Station 20	Station 14	Station 15	Station 5	Station 16	Station 17	Station 9	Station 55	Station 53
1935									
December	[1] 2.70	[1] 2.70	----------	[1] 2.70	----------	----------	[1] 2.70	----------	----------
1936									
January	2.24	2.18	[1] 2.33	----------	[1] 2.33	[1] 2.33	----------	[1] 2.60	[1] 2.60
February	2.87	2.88	2.99	3.42	2.85	----------	1.78	2.96	3.39
March	2.21	2.07	1.71	2.74	1.76	1.97	2.21	2.74	3.20
April	2.30	1.70	2.66	2.68	2.34	2.28	2.41	2.80	3.12
May	1.98	1.63	2.18	2.44	1.78	3.26	1.97	2.76	3.32
June	1.85	1.41	2.06	----------	2.34	3.26	1.49	3.72	3.38
July	2.62	2.68	3.89	1.64	.40	.97	1.51	1.20	1.79
August	2.62	2.13	1.85	.89	1.06	.99	1.24	2.04	2.19
September	2.40	2.36	2.02	.88	1.34	.46	.41	1.45	1.43
October	2.60	2.64	2.46	2.34	2.47	2.00	1.77	1.88	----------
November	4.31	2.83	3.90	----------	1.69	1.92	1.17	3.21	3.70
December	5.27	2.20	----------	1.40	1.32	1.45	1.86	2.60	5.93
1937									
January	3.50	----------	3.10	2.07	1.47	1.00	1.32	3.90	4.42
February	5.66	4.20	4.24	2.78	2.50	1.92	2.43	----------	3.67
March	4.32	4.85	3.86	----------	----------	----------	----------	----------	4.07
April	4.35	2.98	4.76	3.71	2.26	3.44	1.65	----------	3.03
Average	3.16	2.58	2.97	2.24	1.82	1.95	1.66	2.60	3.29

[1] At time of transplanting.

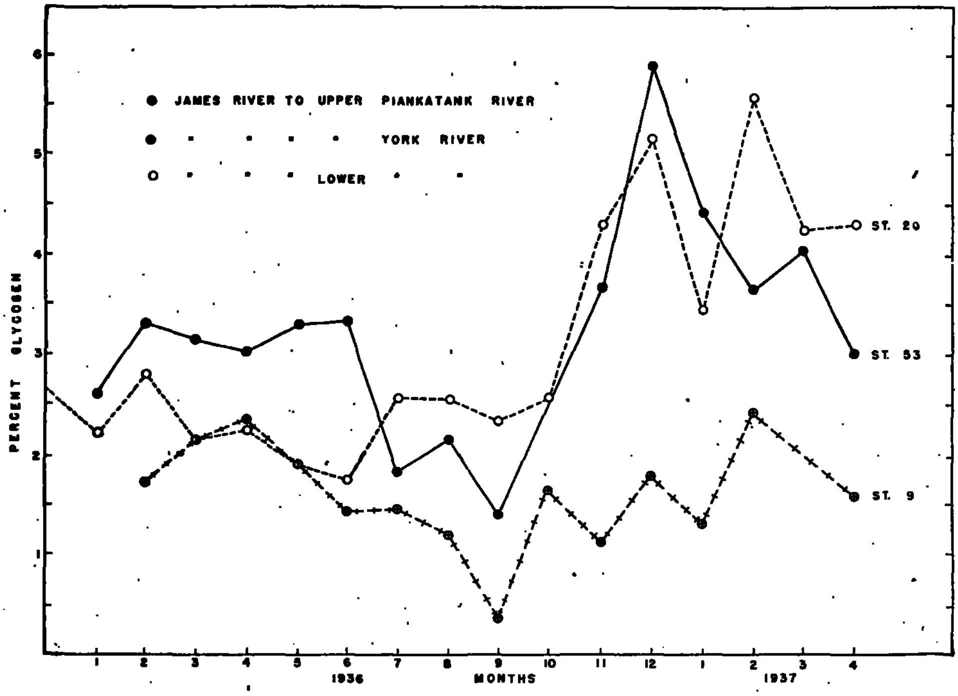

FIGURE 36.—Glycogen content of James River seed oysters transplanted to the upper Piankatank River and to the upper and lower sections of the York River. Glycogen in percentage is on a wet-weight basis.

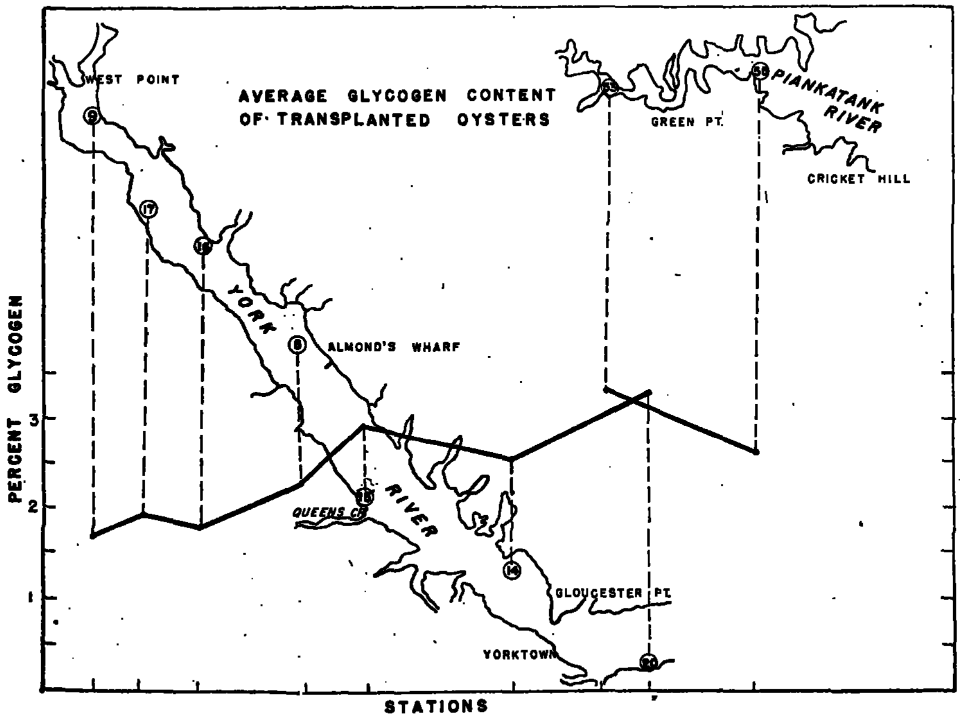

FIGURE 37.—Average glycogen content of James River seed oysters planted at various stations in the York and Piankatank Rivers. Glycogen in percentage is on a wet-weight basis.

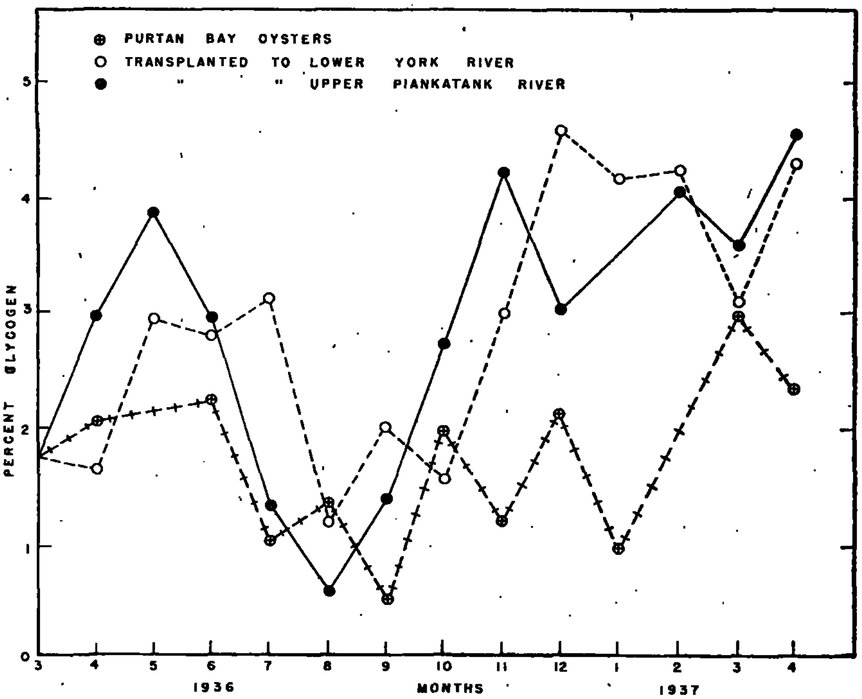

Figure 38.—Glycogen content of Purtan Bay oysters transplanted to the lower York and the upper Piankatank Rivers. Glycogen percentage is on a wet-weight basis.

from all 3 localities for analysis. The results of the observations extending from March 1936 to April 1937 are shown in figure 38. Almost an immediate improvement is noticeable in the condition of the oysters after their removal from Purtan Bay. During the summer months the difference disappears, only to become more pronounced in the following fall and winter.

The results of the experiments show definitely that the factors that retard glycogen formation in the York River oysters inflict no permanent injury to the organism. The action is that of a general depressant inhibiting the carbohydrate metabolism. Apparently there is no accumulation of toxic substances in the body and no irreparable injury is inflicted on the oysters kept in the upper York River, for recovery after transplanting is very rapid. The improvement in the condition of the oyster is not restricted to the increase in glycogen content; it is accompanied by an increased rate of growth, the deposition of shell material, and the disappearance of both the greenish color and the strong or acrid taste of the meat.

From the practical point of view, the results of the transplanting experiments point to the possibility of a partial solution of the oyster-cultural problem in the upper York River.

WATER CONTENT OF THE OYSTERS OF THE YORK AND THE PIANKATANK RIVERS AND OF THE VARIOUS TRANSPLANTED OYSTERS

As samples of oyster meats were being prepared for glycogen determination, a portion of the ground meats was dried and the percentage of water determined. As previously mentioned, the meats, after removal from the shell, were allowed to drain for 15 minutes on a double thickness of paper toweling and then passed twice through a food chopper. Approximately 30 grams of the ground meats were placed in a previously weighed container and the weight of the meats computed. Then, they were dried in an electric oven at 50° C. for 24 hours and at 100° C. for another 24 hours. The sample was allowed to cool in a desiccator and then reweighed.

The water content of the oysters of the York and the Piankatank Rivers was determined from the ground meats of 25 oysters taken each month from native beds at designated stations. From November 1935 to April 1937 samples were obtained from stations 20, 14, 5, and 9 in the York River and stations 55 and 53 in the Piankatank River. After July 1936, stations 23, 6, and 8 in the York River were added. The results of these observations are presented in table 38.

TABLE 38.—*Percentage of water in oyster meats from different stations in the York and the Piankatank Rivers*

Date	York River							Piankatank River	
	Station 20	Station 14	Station 23	Station 5	Station 6	Station 8	Station 9	Station 55	Station 53
1935									
November	81.6							82.5	82.0
December	80.8						83.8	81.7	79.3
1936									
January								81.1	79.2
March	82.7			80.6				81.5	79.8
April	84.1	83.1		87.0			88.8	81.4	82.9
May	82.2	82.2		83.1		87.7	87.4	83.3	80.9
June	82.6	79.7		81.7			79.0	82.8	79.3
July	77.9	78.9	78.9	82.4	81.6	79.6	82.0	83.3	82.0
August	79.9	79.0	84.8	85.1	87.9	86.5	84.0	86.2	82.2
September	81.5	86.3	86.1	86.2			86.6	86.4	84.7
October	80.7	81.4	84.5		85.2	85.7	85.3	81.0	82.8
November	83.4	82.3	85.7		84.9	87.2	85.1	81.2	77.4
December	82.6	78.9	70.3	86.1	86.7	86.4	83.6	80.7	79.0
1937									
January	88.3	83.2	84.3	91.2	91.6	85.5	83.6	83.9	79.1
February	83.4	83.0	84.1	83.3	85.2	84.2	83.7	81.7	83.0
March	83.7	82.3	86.5	86.1	87.8	87.0	86.9	83.6	82.1
April	83.1	86.2	88.7	85.7	86.5	88.5	86.8	84.1	82.8
Average	82.4	82.0	83.4	84.9	86.4	85.8	84.8	82.7	81.1

It can readily be seen that the oysters of the upper York River were more watery than those of the lower, the oysters in the lower averaging about 82 percent water and those of the upper about 86 percent. It will be noticed that the oysters of the upper Piankatank had a slightly smaller water content than those of the lower river, but the upper Piankatank River (station 53) oysters were very much less watery than those of the upper York (stations 5, 6, 8, and 9).

These analyses of water content of the oysters of the various localities are in harmony with the general observations of oyster conditions at the various places and with the "fatness" of the oysters as measured by their glycogen content. The areas having oysters of higher glycogen content also had oysters with a smaller water content.

The percentage of water found in the James River oysters transplanted to the various stations in the York and the Piankatank Rivers is given in table 39. These analyses are based on samples of 10 oysters each taken monthly from January 1936 to April 1937.

It will be seen that the water content of the oysters varied in accordance with the location in which they were planted. The oysters planted at the various stations in the York and the Piankatank Rivers be-

TABLE 39.—*Percentage of water in James River seed oysters transplanted to various stations in the York and the Piankatank Rivers*

Date	York River							Piankatank River	
	Station 20	Station 14	Station 15	Station 5	Station 16	Station 17	Station 9	Station 55	Station 53
1935									
December	[1]82.5	[1]82.5		[1]82.5			[1]82.5		
1936									
January	85.0	87.6	[1]87.2		[1]87.2	[1]87.2		[1]87.4	[1]87.4
February	88.1	83.9	86.9	88.7	86.5		88.6	84.6	84.5
March	83.1	84.5	83.3	86.4	88.4	88.7	88.7	85.3	85.7
April	90.7	84.8	85.9	88.6	88.6	88.6	86.3	85.6	85.8
May	85.0	89.0	85.4	85.4	86.5	86.7	86.3	85.3	83.8
June	92.6	83.2	81.5	81.1	88.3	88.6	86.4	82.1	86.6
July	73.0	78.7	80.3	78.4	84.7	82.2	83.7	76.5	84.9
August	80.7	81.5	78.4	84.6	86.1	84.2	83.2	84.9	82.9
September	79.1	81.4	81.2	86.6	85.7	85.4	86.5	86.4	85.1
October	81.5	83.5	84.2	80.4	83.0	83.6	84.2	87.7	81.7
November	79.8	78.5	79.7		84.9	85.2	82.2	80.2	79.6
December	80.9	81.3	80.1	85.2	84.5	87.2	81.9	84.0	79.4
1937									
January	87.3	81.7	82.7	90.9	85.3	86.7	91.2	84.2	81.0
February	80.9	82.4	84.5	83.3	84.0	86.0	83.7		83.8
March	80.7	81.1	81.8	85.3	86.1	84.6	86.2		83.2
April	82.5	84.3	82.2	84.4	86.5	85.4	86.5		82.8
Average	83.2	83.0	82.5	85.0	85.9	86.0	85.7	83.9	83.4

[1] At time of transplanting.

came similar in water content to the oysters already there. The oysters planted in the upper York River became much more watery than the oysters planted elsewhere. It will be noticed that in the Piankatank River the oysters had nearly the same water content as those in the lower York, and that the oysters of the lower Piankatank were slightly more watery than those from the upper part.

In order to observe the effect of transplanting poor oysters to areas known to produce good oysters, the following experiment was carried out. In March 1936, oysters were tonged from station 22 in Purtan Bay and transplanted downstream at station 20 at the mouth of the river and at station 53 in the upper Piankatank River. Monthly samples consisting of 10 oysters each were taken from all 3 localities for analyses. The results of observations of water content from March 1936 to April 1937 are shown in table 40.

The results show an improvement in the water content of the oysters after their removal from Purtan Bay. Those remaining in the original bed were much more watery throughout the time of observations than those removed to a different environment. This improvement is in line with the improvement in general condition and in glycogen content as previously noted.

Transplanting experiments show that with respect to general condition, water content, and glycogen content, the transplanted oysters within a short time acquire the characteristics typical of native oysters.

TABLE 40.—*Changes in water content of oysters transplanted from station 22 in the upper York River to the lower York and the upper Piankatank Rivers*

Date	Not transplanted Upper York (station 22)	Transplanted	
		Lower York (station 20)	Upper Piankatank (station 53)
1936			
March	86.9	[1] 86.9	[1] 86.9
April	85.6	83.4	86.5
May	84.1	83.8	83.6
June	83.3	82.9	83.7
July	82.5	77.5	84.6
August	84.5	81.0	83.2
September	87.7	82.1	86.5
October	85.3	81.2	81.4
November	85.6	81.4	78.5
December	83.4	81.4	79.5
1937			
January	91.8	88.5	81.0
February	89.8	83.0	83.0
March	85.9	83.2	83.1
April	82.0	----------	82.8
Average	85.5	82.4	82.9

[1] At time of transplanting.

BIOLOGY AND CULTIVATION OF THE OYSTER IN THE YORK RIVER

Studies of the biology and cultivation of the oyster in the York River were carried out in 1936 and 1937 for the purpose of determining practical procedures that might be helpful in overcoming the increasing difficulties of the oyster growers. The history of the industry of this area indicates that the York River is primarily an oyster-growing area that produces but little natural set. The many bushels of market-oysters harvested in the past from this river came principally from planting seed oysters obtained elsewhere, mostly in the James River. The density of planting varied from 500 to 1,500 bushels an acre, depending on the type of bottom and the size of the seed. According to statements made by local oystermen still engaged in the business of growing oysters in the York River, the yield in the upper part of the river prior to 1918 varied from 1 to 3 bushels for each bushel planted. Most of the grounds at the time of this investigation did not produce more than one-half bushel for each bushel of seed planted. The period required to grow the seed to marketable size varied from 18 months to 3 years, depending on the location of the planting and the size of the seed when planted.

The continued poor condition of the oysters and their unmarketability had discouraged the planting of seed, with the result that, at the time of these studies, old oysters were predominant on the grounds with only small numbers of spat or seed present.

The last set of oysters of commercial value, according to the planters, occurred in 1933. Marketable oysters were harvested only in the lower part of the river where some planting operations were still continued.

GONADS

Observations on the development of the gonads were started at the end of June 1936 and continued to June 1937. Oysters in the lower part of the river ripened earlier than those above. During June 1936, from 80 to 100 percent of the oysters examined at stations 14 and 20 had fully developed and ripe sex products, while the oysters at the stations farther up the river showed a lesser degree of ripeness. In 1937 an examination made during the last week of May disclosed, in general, the same situation, with 60 to 80 percent of the oysters of the lower part of

Table 41.—*Condition of the gonads in oysters in the York River during 1936 and 1937*

[Stations arranged from lower to upper river]

Station No.	June 26, 1936				Sept. 26 to Oct. 1, 1936				Nov. 4 to 6, 1936				Mar. 4, 1937				May 24 to June 7, 1937			
	Number examined	Undeveloped	Partly developed	Ripe	Number examined	Undeveloped	Partly developed	Ripe	Number examined	Undeveloped	Partly developed	Ripe	Number examined	Undeveloped	Partly developed	Ripe	Number examined	Undeveloped	Partly developed	Ripe
20	10	0	0	10	14	0	6	8	10	1	0	9	10	9	1	0	15	0	4	11
14	10	0	2	8	13	0	10	3	10	0	3	7	10	4	6	0	20	1	7	12
15	10	4	2	4	0	------	------	------	10	3	1	6	10	10	0	0	22	2	4	16
23	10	2	8	0	0	------	------	------	0	------	------	------	10	7	3	0	20	3	16	1
5	10	0	5	5	15	10	4	1	0	------	------	------	10	9	1	0	20	1	18	1
6	10	0	7	3	11	4	4	3	0	------	------	------	10	10	0	0	0	------	------	------
17	0	------	------	------	0	------	------	------	7	0	4	3	0	------	------	------	0	------	------	------
16	10	5	5	0	0	------	------	------	0	------	------	------	0	------	------	------	0	------	------	------
22	0	------	------	------	0	------	------	------	0	------	------	------	10	8	2	0	20	0	13	7
8	10	0	9	1	14	7	2	5	0	------	------	------	0	------	------	------	0	------	------	------
9	10	1	4	5	15	3	5	7	13	3	7	3	7	6	1	0	0	------	------	------
24	10	0	9	1	0	------	------	------	0	------	------	------	0	------	------	------	0	------	------	------
Total	100	12	51	37	82	24	31	27	50	7	15	28	77	63	14	0	117	7	62	48
Percentage	------	12	51	37	------	29	38	33	------	14	30	56	------	82	18	0	------	6	53	41

the river containing ripe gonads, while in the upper part of the river only 5 to 30 percent of the oysters were ripe. Throughout the summer and fall some oysters with ripe gonads always were present and only during the winter and early spring were oysters found without functional gonads. Of the oysters examined in March 1937, 82 percent had no gonad material discernible with the naked eye and no specimen contained mature sex products, although 18 percent of the oysters were found to have small amounts of sex products. These could be considered either as the beginning of the development for the coming spawning season or as the remnants of sex products not yet absorbed (table 41).

SPAWNING AND OCCURRENCE OF LARVAE

In 1937 fully ripe gonads were first observed during the latter part of May. Judging by the subsequent changes in the appearance and consistency of the gonad tissues, it may be concluded that spawning started during the same time. Straight-hinge oyster larvae were found in plankton from June to November. Using their number as a criterion of the intensity of spawning, it was found that reproductive activities of oysters were more pronounced in the lower part of the river than in its upper section, although some spawning took place on all the grounds of the river bottom.

During the spawning season of 1936, frequent plankton samples were taken by means of a 45-liter plankton trap. The sample was concentrated to 10 cc., preserved in 10 percent formaldehyde, and the oyster larvae counted in a Sedgwick-Rafter cell. In sampling the river, 3 or 4 days were usually required to complete a cruise. For convenience in summarizing these data the river was arbitrarily divided into three sections, lower, middle, and upper. In recording the abundance of oyster larvae, the straight-hinge larvae were considered as recently spawned, the umbo larvae represented those which had passed about two-thirds of the larval period, and the "eyed" larvae were those of the very late stage, immediately preceding the setting.

Straight-hinge larvae were present in all the samples taken from June 16 through November 3, 1936, but the eyed larvae were scarce, and in most samples absent. This is an occurrence frequently noted by American biologists engaged in oyster studies.

The mean number of larvae per 45-liter sample taken at each of the stations in York River showed a greater abundance in the lower section of the river and a gradual diminution as one proceeds upstream (table 42). This can be easily seen in figure 39, which shows the results of counts made of samples collected during one cruise at station 14, lower section, station 5, middle section, and station 9, upper section. Three major peaks of intensity of spawning occurred during this season: the first, of the longest duration, was noticed during the first half of July, the second, of short duration, occurred about the middle of August, and the last, also of brief duration, took place about the first of October. Oyster larvae disappeared from the plankton early in November.

It was apparent from the examination of plankton samples that the number of oyster larvae rapidly decreased as one proceeded from the mouth of the river upstream. This condition is clearly shown in

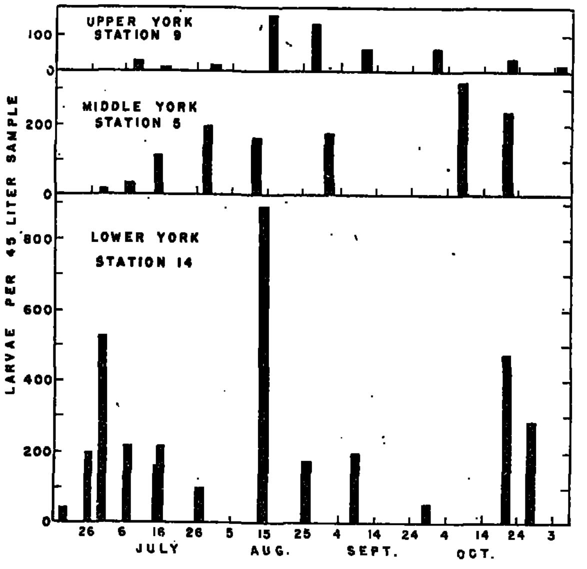

FIGURE 39.—Seasonal occurrence of oyster larvae at three stations in the York River, 1936

figure 40 representing the mean number of larvae in samples collected throughout the season at three sections of the river. The number of samples collected at each section was as follows: in the lower part, 31 samples at 3 stations; in the middle part, 32 samples at 4 stations; and in the upper part, 37 samples at 4 stations. The decrease in the number of oyster larvae was probably due to some abnormal condition of the environment in the upper part of the river because spawning and setting in tidal waters frequently takes place in water of reduced salinity.

TABLE 42.—*Mean number of free swimming larvae per 45-liter sample in the York River*

Lower river			Middle river			Upper river		
Station No.	Number of samples	Number of larvae	Station No.	Number of samples	Number of larvae	Station No.	Number of samples	Number of larvae
20	9	648	23	8	165	16	9	52
14	13	273	5	9	163	17	9	90
15	9	230	22	8	175	8	8	78
			6	7	50	9	12	50
						18	[1] 7	14
						19	[2] 7	38

[1] Pamunkey River.
[2] Mattaponi River.

SETTING OF OYSTERS IN 1936

During the summer and fall of 1936, wire bags filled with shells were placed at several stations in the York River to obtain information on the period and intensity of oyster setting. The shells, obtained from a local shucking house, had not been used previously as cultch. It was certain, therefore, that any spat, or scars showing the place of the attachment of spat, had attached or been formed during the period of exposure of the shells at the selected stations. Bags were taken out and replaced by new ones at intervals of 2 to 4 weeks. Fifty shells, taken from each of the bags, were examined with a dissecting microscope and the number of spat on the inner surface of the shalls counted. From the data thus obtained, the number of spat per bushel of shells was computed. Because the interval between the observations sometimes was too long to determine the exact time of setting, the approximate time was estimated by measuring all spat found on the shells, and plotting an age-distribution curve for the period of the exposure of the bag of shells. Using this method, first suggested by Hopkins (1931), the approximate times of major setting-periods were determined and plotted (fig. 41).

The first collectors were placed on June 11 at several stations in the lower and middle parts of the river. The first set appeared about July 15 at station 14 opposite Yorktown. After this date, setting of varied intensity occurred throughout the summer until October 19. In the lower part of the river, two periods of relatively heavy setting were recorded (fig. 41), the first during the last half of July and the early part of August, and the second about the middle of September. The latter setting was the heaviest and was almost of commercial importance. Each of the two peaks of heavy-setting periods occurred approximately two weeks after the corresponding periods of abundance of the oyster larvae.

The setting of oysters in the upper section of the

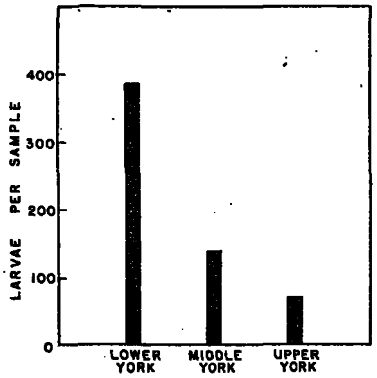

FIGURE 40.—Comparative abundance of oyster larvae in the three sections of the York River. The columns represent the mean number of larvae per sample, for the period from June 16 to November 4, 1936.

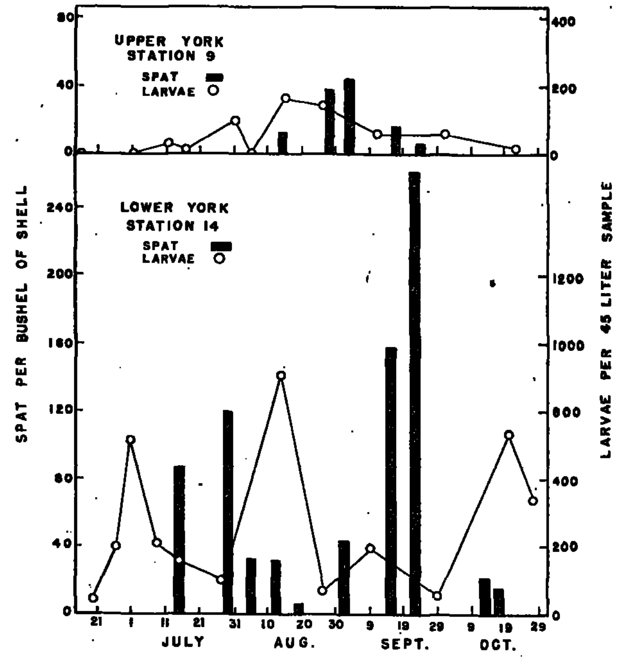

FIGURE 41.—The occurrence of larvae and setting of oysters at two stations in the York River, June to October 1936.

York River during 1936 was considerably less than that in the lower part, and of shorter duration. The first setting was recorded during the early part of August and extended through September. Station 9, near West Point, Va., was the uppermost location where shell bags were placed. Some of them were lost but enough were recovered to show that the intensity of setting was insignificant and could not provide a natural replacement of oyster populations on the bars used for commercial fishing. At station 9 scattered setting occurred during August and September and the period of heaviest setting took place during the latter part of August and early in September (fig. 41). Again the peak of larval occurrence preceded the heaviest setting by about 2 weeks. At station 14 the total number of spat per season per bag was 1,402; at station 22, near Purtan Bay, 660; and at station 9, only 226.

Data resulting from the examination of shell bags show that the setting in the York River decreased from the mouth to the head of the river. A different result was obtained, however, from an examination of natural shells and oysters on the bars of the river. In checking the number of spat per bushel of bottom material, it was found that the mortality among the spat in the lower part of the river was so great that the advantage of heavier setting in the lower part was lost. Consequently, by the end of the setting season there was no material difference between the number of spat in the two parts of the river (fig. 42).

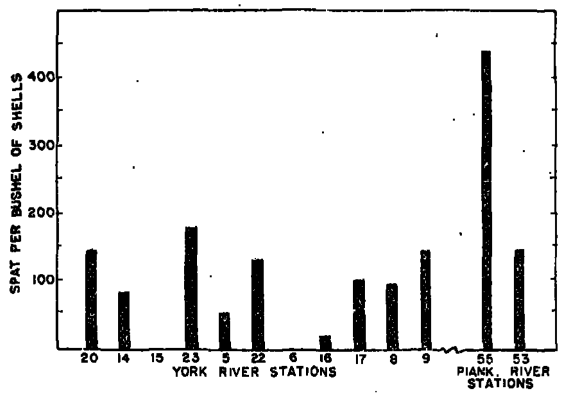

FIGURE 42.—Number of oyster spat per bushel of oysters and shells taken from the bars in the York and the Piankatank Rivers at the end of the setting season, 1936.

Although the spat survived better in the upper part of the river, the intensity of setting there was too low to be of commercial value. The loss of spat in the lower part was primarily caused by the depredations of the screw borers or oysters drills, *Urosalpinx* and *Eupleura*, which abounded on the bars of the lower section of the river but were not found in its upper part. Production of seed oysters on a commercial scale appears to be feasible in the lower part of the river only if effective drill control measures are employed.

Piankatank River

The condition of gonad development, spawning, and setting in the Piankatank River resemble those in the lower and middle York River. The number

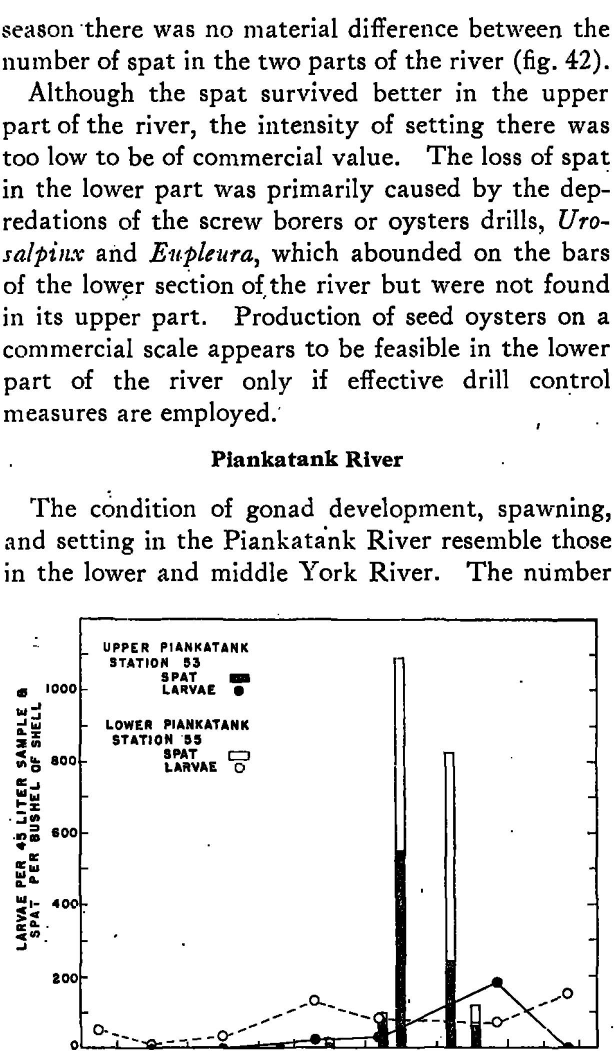

FIGURE 43.—The occurrence of larvae and setting of oysters at two stations in the Piankatank River, June to October 1936.

of larvae found in the plankton samples was smaller and varied less than in the York River. The larvae reaching setting stages were more numerous with the consequent higher rate of setting (fig. 43).

Examination of plankton samples and of shell bags were conducted at station 55, near the mouth of the river, and station 53, several miles from the mouth. The setting of oysters at each of these stations could be considered of commercial value.

ORGANISMS FOUND IN ASSOCIATION WITH OYSTERS IN THE YORK RIVER

No attempt was made to collect and identify all the forms that may be inhabiting the York River. Attention was paid, however, to the presence and abundance of organisms intimately associated with the oyster or constituting a definite danger to the oyster industry.

Sponges most common on the oyster beds in the York River were the sulfur sponge, *Cliona celata*, red bearded sponge, *Microciona prolifera*, and one unidentified species of siliceous sponge occurring in the lower part of the York River. The sulfur or boring sponge was very thickly spread in the lower river and caused considerable damage to oysters by weakening the shells. It was found as far up the river as station 9, which was probably the extreme range of its distribution in brackish water. The range and abundance of *Microciona* was the same as that of the sulfur sponge. *Microciona* constituted a nuisance to the oystermen because occasionally it caused a painful rash on the hands and arms of the men handling oysters.

Hydroids, *Thuiaria* sp., called by local watermen "moss," were abundant in the lower and middle parts of the York River.

Among other coelenterates the most common were the three genera of jellyfish, *Dactylometra quinquecirrha*, the most abundant, the red-colored *Cyanea* sp.; and *Aurelia* sp. The first two species, found only occasionally, were distributed throughout the whole river, while the last was confined mostly to the middle and lower parts. Sea anemones were seen on many of the shells and oysters brought in from all parts of the river.

Several species of Ctenophores were present, sometimes in enormous numbers. The identity of only one of them was established as *Mnemiopsis gardeni*.

An unknown turbellarian worm was found in rather great numbers on oyster shells and on oysters in the middle and lower parts of the York River.

The nemertean worm, *Cerebratulus lacteus*, was common in the river below Yorktown. It was found both in the shallow waters inshore and among the oysters in deeper water, fragments being brought up frequently in the oyster dredge.

Bryozoan colonies encrusted the shells of oysters and other animals in all parts of the river. They fouled the shell surfaces to such an extent that space available for setting of oyster larvae was greatly reduced. Undoubtedly, they were responsible in part for the light set of oysters during the summer of 1936.

The clam worm (*Nereis limbata*, Ehlers) was common throughout the river. The tubes of another annelid, tentatively identified as *Hydroides hexagonus*, often were found on the shells of oysters from all parts of the river. One planter reported that in 1935 the tube worm was thick enough to form a crust on the oysters in certain parts of the upper river. Another annelid frequently found on oyster shells was a bright red terebellid, *Polycirrus exinuis* Leidy.

The shells of the oysters contained numerous mud blisters, averaging five per shell, made by various species of *Polydora*. Live *Polydora* could be found frequently. Examination of the large number of oysters collected on July 25, 1940, along the entire length of the river showed that about one-third of the blisters contained live worms which were identified by Dr. Olga Hartman as *Polydora ligni* Webster, most common in the sample, *Polydora calca* Webster, and *Polydora* sp., probably *anaculata* Moore. Since *Polydora* blisters were found both in good and very poor oysters, it was impossible to correlate their presence or absence with the condition of the oyster.

In view of the reports by Kudo (1939) and Prytherch (1940) that mud crabs are primary hosts of the gregarine *Nematopsis* and are responsible for the distribution of this parasite on oyster beds, a survey was made of the occurrence of these crabs (family Xanthidae) in the York River. The distribution of the various species,[6] is presented in table 43, which shows the stations and the number of specimens found in a bushel of bottom debris.

The blue crab, *Callinectes sapidus*, which also may be one of the hosts of *Nematopsis*, occurred in all parts of the York River, but was more abundant in the lower section.

Filling the shells of gastropods were many hermit crabs. Their distribution was limited to the middle

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[6] Dr. Mary J. Rathbun kindly identified these species.

Table 43.—*Distribution of mud crabs (Family Xanthidae) in York River, Va.*[1]

[Number of crabs found per bushel of bottom debris]

Station	Eury-panopeus dissimilis	Panopeus herbstii		Neo-panope texana texana	Rhithro-panopeus harrisii
		Typica	Simpsoni		
20	15	1		17	
14	31	1	10		
15	1				3
23	7				15
05	20				
22	23				
06	8	1			5
16	8				
08	2				14
09	6				7

[1] The samples were collected in the fall of 1936 from Oct. 7 to Nov. 6. An oyster dredge catching about ½ bushel to a drag, and a pair of tongs catching about ½ of a bushel to a grab, were used to gather the bottom material. The number of crabs were counted in the material brought up and the amount of material closely estimated.

and lower parts of the river. Spider crabs, *Libinia dubia*, and *L. emarginata* were often seen in the dredge loads taken in the lower parts of the York. Along the low banks from the mouth to the head of the river were fiddler and sand crabs. The sand crab, *Ocypode albicans*, was more abundant on the shores below Yorktown than in the upper part of the river.

Barnacles were widely distributed the length of the river and in many places completely encrusted the shells of oysters. However, they did not constitute any serious menace to the oyster industry.

The oyster crab, *Pinnotheres ostreum* Say, was observed many times in the mantle cavity of oysters opened in the course of the investigation. These crabs were found on all oyster grounds, but were more abundant in the lower part of the river. On one occasion 575 oysters were examined and 17 were found infested by crabs.

Gastropods were numerous with the greatest variety of species found in the lower part of the river. The mud snail, *Nassa* sp., abounded in the river predominating in its lower half. On the pilings and sides of moored barges in the vicinity of West Point, periwinkles, *Littorina* sp., were occasionally seen. These may have been brought in by the barges carrying pulp wood to the Chesapeake Corporation plant at West Point. No oyster drills, *Urosalpinx* sp. or *Eupleura* sp., were found in the upper river, but both species were present and constituted a serious menace in the lower part of the river. Other gastropods common in the lower part included the sand collar, *Polynices* sp., the conchs, *Busycon carica*, and *B. canaliculatum; Purpura* sp.; and several species of *Crepidula*. One of the horse mussels, *Modiolus demissus*, was abundant on the oyster beds from the mouth to the head of the York River. The edible mussel, *Mytilus edulis*, was common in the lower part of the river. Fairly abundant in the vicinity of Yorktown was the razor clam, *Ensis directus*. Several shells of oysters dredged from the lower river were found drilled by boring clam *Diplothyra* sp. This clam only rarely was found and did not constitute an oyster menace in Virginia waters.

It might be mentioned that only one specimen of starfish, *Asterias forbesi*, was taken within the lower part of the river. At the mouth of the river, however, starfish occurred in exceptional abundance in the spring of 1937 and later disappeared.

The tunicate, *Molgula* sp., occurred throughout the river. It was found growing in such thick clusters at some locations in the lower river that it completely hid the oysters to which it was attached.

In résumé, ecological observations failed to disclose the predominance of any predatory or commensal organisms which might have been responsible for the poor quality of the oysters. The animals found in York River frequently occur on oyster bottoms and can be considered as constituting a normal community of organisms inhabiting these bottoms.

EXPERIMENTAL STUDIES

Pulp-mill effluents emptied into the upper York River in large quantities constitute the only industrial pollution of the river. Physiological experiments carried out at the Yorktown laboratory were, therefore, primarily concerned with the effect of these wastes on oysters and on oyster food-organisms. Simultaneously with these observations, studies were made on the chemical nature of polluting effluents and their fractions. Physiological effect of each of the effluents and later on various fractions of them, prepared by the chemist, were tested individually or in combinations. These studies included observations on the effect of pollutants on the adductor muscle (determination of the number of hours the shells remain open), studies of the changes in the activity of the ciliated epithelium of the gill (drop-counting method), and determinations of the rate of water filtration of oysters kept in various concentrations of pollutants.

Although the literature on water pollution by pulp- and paper-mill wastes is very voluminous, the effluents from the sulfate pulping process have often been dismissed with the statement that sulfate mills do not discharge a waste liquor to pollute water

(Kobe 1937). As early as 1908 European workers began studies on the toxicity of sulfate pulp-mill effluents upon fish life (Ahlin 1908) and within the past decade extensive studies have been made upon the resin acids present in sulfate pulp-mill effluents. This recent work (Ebeling 1930, 1931, 1932; Vallin 1935; Hagman 1936; Järnfelt 1936; Bergström and Gederquist 1937; Vestergren 1938; Erdtman 1939) has been carried out chiefly in Sweden and Finland upon the finned fishes inhabiting fresh waters. All of the work has been upon the wash waters from the sulfate pulping process which contained a sufficient quantity of the resin acids to be injurious to the animals tested.

In the United States some toxicity studies have been made with the alkyl mercaptans (Cole and Warrick 1935; Cole 1935) known to be formed in the sulfate pulping process. These studies were also conducted on fresh-water fishes.

With possibly a single exception (Anon., 1910) no record was found of the effect of sulfate pulp-mill effluents upon either marine fishes or sea water. The publication in question was confined to a report on the study of the toxicity of alkali metal sulfides on fishes.

As far as could be ascertained no investigations other than the work reported here and presented in a preliminary report (Galtsoff, Chipman, Hasler, and Engle, 1938) has been made with reference to the effect of sulfate pulp-mill effluents upon oysters.

DESCRIPTION OF THE PROCESSES EMPLOYED BY THE CHESAPEAKE CORPORATION AND LOCATION AND DESCRIPTION OF THE VARIOUS SEWER OUTLETS

A description of the processes employed in manufacturing pulp and paper appears to be essential for an understanding of the nature of the effluents entering the York River and of the samples used in testing.

The mill makes its pulp from wood by the sulfate process using chiefly loblolly pine (*Pinus taeda* L.). In this process the pine chips are cooked at elevated temperatures and pressures in a water solution containing sodium sulfide and caustic soda. These chemicals dissolve the noncellulosic portion of the chip leaving the cellulose as a fibrous pulp which is separated from the cooking liquor and then purified. The separated liquor, after being fortified with chemicals from the recovery house, is reused in the cooking operation.

Before going to the paper-making machine the raw pulp from the digester is purified by counter-current washing in a diffusion apparatus. This method reduces the volume of water needed and gives increased recovery of the chemicals used for cooking the chips. The first wash water, richest in chemicals, is designated "weak-black liquor" and is sent to the recovery house for reclaiming. The last wash water, although dark in color, is too poor in chemicals for profitable recovery and is discharged into the river. The intermediate wash waters are reused, being finally withdrawn from the circuit as weak-black liquor. After removal from the diffusers the pulp is subjected to screening and further washing with paper-machine waste water, which contains very small amounts of chemicals.

The weak-black liquor, after filtration to remove suspended fibers, is concentrated in multiple effect vacuum evaporators until the "sulfate soap" begins to separate. After removal of the soap, concentration of the liquor is continued until it becomes combustible and it is then sent to the incinerators. Prior to incineration the chemicals lost in the pulp wash waters are replaced by the addition of "salt cake," sodium acid sulfate. If the sulfate soap, removed during concentration of the black liquor, cannot be sold, it also goes to the incinerator.

During incineration the noncellulosic constituents of the wood, present as soluble substances in the black liquor, burn and pass out of the smokestack as gases and vapors, leaving an ash composed chiefly of water-soluble substances, sodium carbonate and sodium sulfide, derived from the sodium compounds present originally in both the black liquor and the salt cake. The ash is dissolved and this solution is treated with quicklime which changes the sodium carbonate of the ash to caustic soda and leaves the sodium sulfide unaltered. The quicklime changes to calcium carbonate, which being insoluble, settles out as a sludge and is removed, leaving the clear solution of caustic soda and sodium sulfide to be used for cooking the wood chips.

The calcium-carbonate sludge contains appreciable amounts of the above-mentioned chemicals which are removed by a system of counter-current washing and filtration. These wash waters are used for dissolving the ash, while the washed calcium carbonate is converted into quicklime. Prior to 1935 the calcium-carbonate sludge was pumped into a fresh-water swamp, now about one-third to one-half mile from the Pamunkey River, but since then all of the calcium-carbonate sludge, after being washed, has been reburned to quicklime, supplying from 90 to 95 percent of the quantity needed for causticizing the ash.

Due to the limited supply of process waters the fiber losses, as reported by the mill chemist, are very small. With a daily output of 350 tons of pulp, the losses are usually less than 300 pounds per day, and only rarely exceed 500 pounds per day.

The effluents from the mill are carried in various sewer lines. Their location, size, and nature of material carried have been given in figure 4, and described in pages 97–99.

Based on the nature of the chief effluent carried, the samples taken from the ditch receiving effluents from pipes *J* and *H* are spoken of in this paper as pulp-mill effluents, those taken from the ditch receiving the effluents from pipes *A*, *B*, *C*, and *D*, as paper-mill effluents, and those taken from the ditch draining the sludge pond as sludge-pond effluent.

PHYSIOLOGICAL EFFECT OF RIVER WATER CONTAINING PULP- AND PAPER-MILL WASTES

The first problem encountered in a study of the effect of industrial wastes on aquatic organisms is the determination of the concentration of the pollutant in the water. This presents little difficulty in cases of metallic salts, acids, or other substances which can be detected and quantitatively determined by available chemical methods. In the case of pulp-mill effluents, consisting of a complex mixture of various organic compounds and mineral salts, such a direct approach is impossible because of the absence of specific reactions. The situation is further complicated by the fact that the chemical nature of the toxic component or components of the sulfate-mill effluents is not known.[6]

In search of some method, it was first thought possible to apply the Folin-Dennis reaction for phenol, as many phenolic compounds in sulfate pulp-mill waste produce a blue color when allowed to react with this reagent. Many tests were made on samples of water collected at various distances from the pulp-mill in the York River, at many locations in the Piankatank River, and from a number of places throughout the general area of the lower Chesapeake Bay. The procedure used was that of Vorce (1925), who applied this test to water analysis. The results were, however, inconsistent and unreliable for an estimation of the concentration of sulfate-mill waste in the sea water because it was apparent, and confirmed by supplementary tests, that besides lignin and other components of pulp-mill waste, the waters of the river contain a number of other substances, not derived from the industrial waste, which give a blue color with the Folin-Dennis reagent.

Although it was impossible by chemical determination to obtain accurate measurements of the amount of pulp-mill effluents present in the York River, it was obvious that the upper river contained this material in considerable amounts. The presence of the physiologically active material of the effluents in the river in relatively high concentrations was demonstrated in two types of biological tests and observations on oysters. One of these showed the effects of river water of the upper York River on the rate of water filtration of oysters and the other the effect of this water on the time oysters remain open.

Frequently, pulp-mill effluents containing large amounts of black liquor were discharged into the Pamunkey River off the city of West Point. On the morning of the sampling, the river was brown with the effluent and a large area was covered with foam and froth. At this time two 5-gallon bottles of river water were taken at the bridge across the Pamunkey River just above its junction with the Mattaponi River to form the York.

After being brought to the laboratory, the sample was filtered through a double thickness of cheesecloth to remove the larger pieces of fiber. In order to avoid subjecting the oysters to sudden changes in salinity, the samples were adjusted to the approximate salinity of the laboratory supply of sea water by the addition of sea salts. These salts were obtained by evaporation of laboratory sea water after centrifuging with the Foerst highspeed centrifuge to remove the larger plankton forms, and drying the residue. The salinity of the sample was found to be 10.28 parts per thousand and the laboratory sea water 21.28 parts per thousand. Sea salt was added to the sample so that the salinity, when tested, was 21.94 parts per thousand. The difference between the sample and the laboratory sea water in which the oysters were acclimated was less than normal daily fluctuations in the salinity of the water at Yorktown.

The observations consisted in determining the rate of water filtration by the gills of normal oys-

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[6] A nitrosolignin test, Pearl and Benson (1940), successfully used by Benson, Kobe, and Scott (1941) in determining the concentration of sulfite waste liquor in sea water, had not been published at the time the York River studies were made.

ters using the drop-counting method described by Galtsoff et al. (1935). Oysters were placed both in the laboratory supply of sea water and in the sea water collected in the upper York and adjusted to Yorktown salinity. The method, in general, consists of measuring the amount of water pumped by an oyster in a flowing salt water system. By means of an electric drop counter, the amount of water is recorded automatically on a kymograph drum. Because of the limited amount of test material, the solution was recirculated. In analyzing the kymograph records, the average number of drops per second was determined for each 10-second interval during the entire period of counting, which usually lasted from 2 to 2½ minutes. For convenience in plotting, the figures thus obtained were multiplied by 60 to represent the mean number of drops per minute. The results of these tests are presented in figure 44. The periods preceding and following the treatments may be considered as controls, indicating the rate of filtration in unpolluted river water.

The findings clearly show that, at times, the river water at West Point contained sufficient pulp- and paper-mill wastes to exert a very strong physiological action on oysters. When the normal oysters were exposed to this water containing large amounts of these wastes, they immediately changed their rate of pumping, the rate dropping to a very low level, or they stopped pumping completely. Even when this water was diluted 10 times with unpolluted sea water, there was a marked reduction in the ciliary activity of the oysters exposed to it. The effects were not permanent and the oysters filtered water at their normal rate once the test material was removed.

As the live oyster must keep the shell open a considerable part of the time, any agent in the water that would reduce the hours per day open must be regarded as injurious to the oyster, for it would interfere with its feeding and respiration. For a study of the possible effect of pulp-mill effluents in the water in the upper York River on oysters, observations were made of the time oysters in the river remained open at West Point below the pulp mill, at Allmondsville which is about half way between West Point and Yorktown, and at Yorktown.

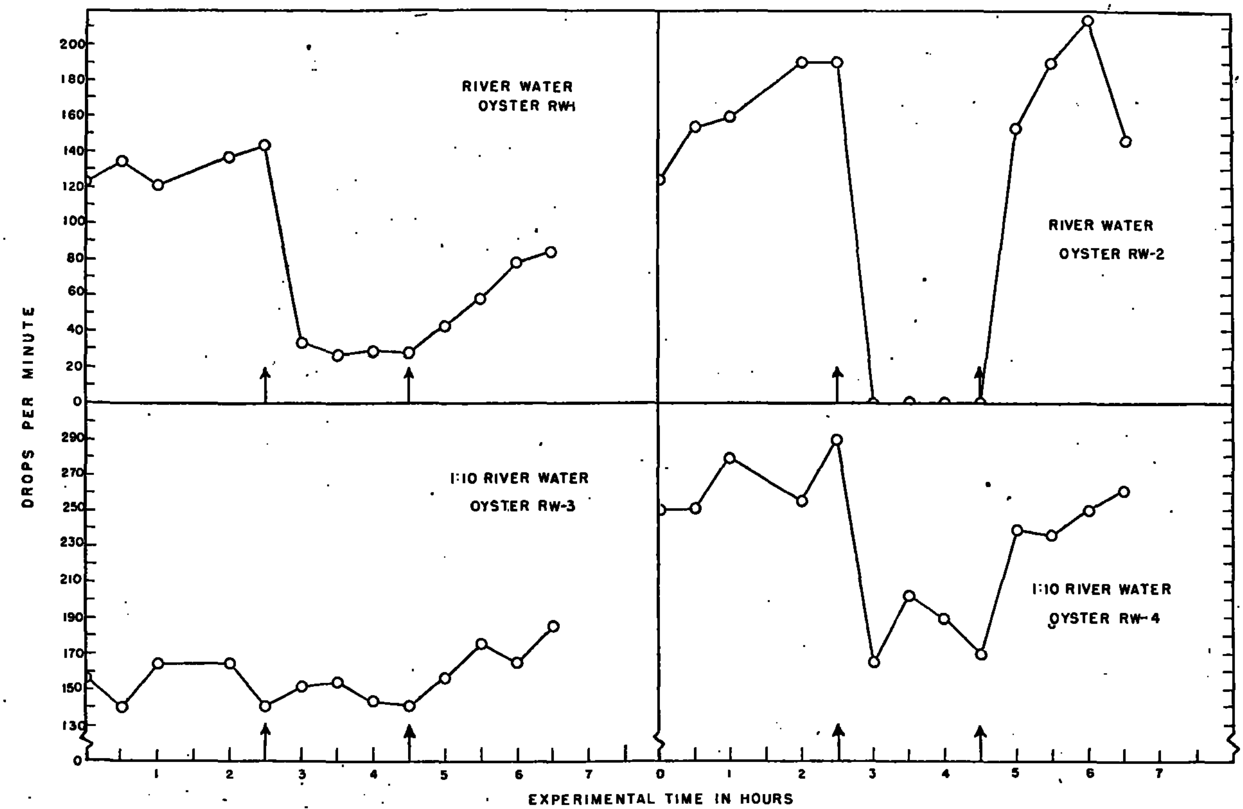

FIGURE 44.—Effect of river water polluted with pulp-mill effluents on the rate of pumping of water by the gills of the oyster. Drop-counting method. Samples of water used in this experiment were collected at the Pamunkey River Bridge.

TABLE 44.—*Time oysters remain open at various locations in the York River*

Location	Dates of observation (inclusive)	Days observed	Water temperature range, C°	Salinity range parts per thousand	Mean hours per day open
West Point	Aug. 15–Sept. 13, 1936	30	24–28	10.3–15.9	14.3
	Oct. 14–Nov. 24, 1936	42	10. 21	11.6–16.5	21.8
	Apr. 2–28, 1937	28	11–18	0.2–7.5	12.3
	Aug. 20–Oct. 17, 1937	59	[1] 23–30	[1] 4.4–12.6	16.8
	Nov. 6–29, 1937	24	8–14	0.6–7.2	11.0
Allmondsville	Aug. 13–26, 1937	12	26–28	14.7–17.9	21.3
	Aug. 21–30, 1937	10	26–28	15.9–17.9	21.5
	Sept. 16–Oct. 5, 1937	17	19–22	13.9–17.1	20.8
	Sept. 25–Oct. 5, 1937	11	19–21	15.1–17.1	21.8
Yorktown	Aug. 18–Sept. 9, 1936	19	25–28	21.3–23.2	20.3
	May 10–26, 1937	17	18–23	12.0–16.2	21.7
	Aug. 21–Sept. 10, 1937	21	26–27	18.5–23.0	21.1

[1] Represents observations made Aug. 20 to Sept. 16. Temperature and salinity were not observed from Sept. 17 to Oct. 17.

For these observations oysters were selected from the locality near the place of testing so as to avoid changes in their environmental conditions during the period of observation. They were mounted on their left valve in blocks of a mixture of plaster of paris and cement and a small hook was attached to the movable right valve. The blocks with the oyster partially imbedded were securely fastened to a small wooden platform to which was attached a wooden upright lashed to the end of a section of pipe in such a way that the oyster to be observed was just below the pipe opening and the pipe lowered in position in the water. A light chain, attached to the hook on the right valve of the oyster, was led through the pipe and attached at the upper end to a recording lever, counterbalanced to compensate for the weight of the chain, and to give a slight pull on the oyster, a pull just sufficient to allow the lever to fall as the oyster opened. In most instances the lever ended in a writing tip in contact with the smoked paper of a kymograph drum, but at Allmondsville the lever was connected to a motion recorder marking with ink on a revolving paper clock-face. A similar arrangement for recording the shell movements of clams is fully described and pictured by Loosanoff (1939). At all the locations, the apparatus was placed in adequate housing to protect it from the weather.

Recordings were made of the activities of 5 oysters at West Point, 4 oysters at Allmondsville, and 3 oysters at Yorktown for periods ranging from 10 to 59 days from August 1936 to December 1937. Conditions of temperature and salinity during observation were recorded. The results of the observations on the time the oysters remained open are summarized in table 44.

In all cases but one, the oysters in the river at West point were open considerably less time than oysters at Allmondsville and Yorktown. Even in the instance when the hours open were not reduced, the kymograph tracings of the behavior of the adductor muscle showed a physiological reaction to the presence of pulp-mill effluent in the river. It consisted in a series of repeated and rapid shell movements followed by periods of extended closure. This abnormal behavior took place at those times when the observer reported marked discoloration of the water with effluent. Similar response of oysters to the presence of pulp-mill effluent in sea water was often observed in the laboratory (figs. 45–46), and was used in certain work as a bioassay method to determine the presence of the physiologically active material on pulp-mill effluents in test samples. A more complete description of the nature of the shell activity of oysters exposed to pulp-mill effluent in sea water is described later in connection with certain laboratory experiments.

From the foregoing it definitely can be stated that the river water of the upper York River contained the physiologically active material of the pulp-mill effluent in sufficient amount to produce an effect on oysters. The laboratory experiments described in the following sections serve to explain more fully the nature of the physiological effects of mill effluents in sea water at various concentrations under controlled conditions.

EFFECT OF PULP- AND PAPER-MILL EFFLUENTS ADDED TO SEA WATER ON THE TIME THAT OYSTERS REMAIN OPEN

The measurement of the hours per day that oysters remain open under controlled conditions gives an easy physiological method of determining the injuriousness of materials in the surrounding water, as the oyster normally keeps the shell open a considerable part of the time for feeding and respiration. Any agent reducing the hours open would eventually injure the oyster.

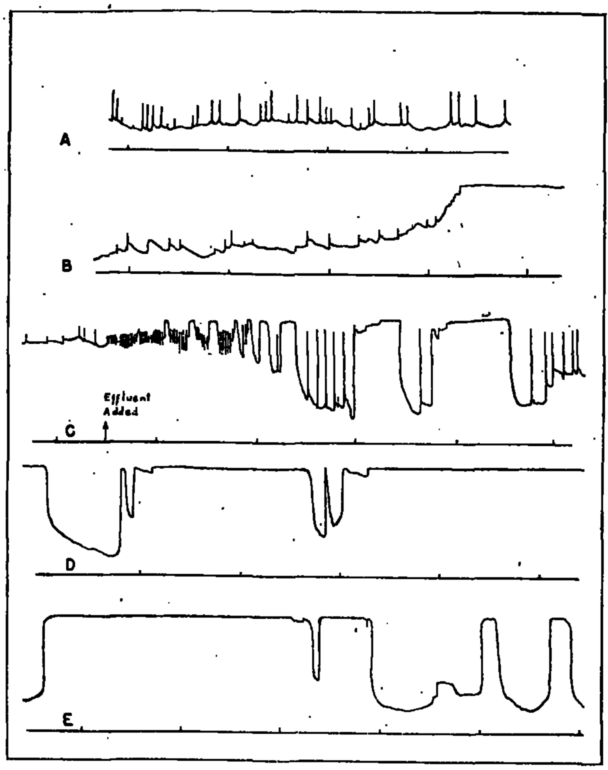

FIGURE 45.—Kymograph records showing the shell movement of normal oysters and an oyster exposed to pulp-mill effluent at a concentration of 1:10. The base line is marked in 1-hour intervals. A and B demonstrate normal activity of oysters in sea water. C shows the immediate response to the addition of pulp-mill effluent, which is followed by extended periods of shell closure. D and E present tracings showing continued shell closure with brief periods in which the oyster is open and a weakening of the adductor muscle. The writing pen is in the uppermost position when shells are closed.

The oysters employed for these tests were obtained from the lower York River. They were from 3 to 4 years old and in good condition. Preparatory to the experiments, they were brought into the laboratory and held for several days for acclimatization in tanks of running sea water.

The equipment used for the observations of the shell movement was essentially similar to that employed by Hopkins et al. (1931). The oysters were fastened to small cement blocks by their left valves. Light threads, attached to their right valves, were connected to levers which recorded the opening and closing of the shells on a slow motion kymograph. The oysters were placed in chambers receiving sea water, or a mixture of sea water and test material, running in from mixing chambers having a series of baffle plates. Test solution was added to a mixing chamber through a siphon tube connected to a container floating in the constant-level sea water supply. In this way the uniform rate of delivery of the solution was maintained. By controlling the rates of flow of sea water and of test solution supplied to the mixing chambers, it was possible to adjust the dilution of the material in the floating chamber so that the desired concentration would reach the oysters. In each test one oyster, used as a control, was kept in a chamber receiving unpolluted laboratory sea water delivered at the same rate as the water containing the known concentration of pollutant was delivered to two experimental oysters kept in an adjoining chamber. Thus, during each test, the control oyster was kept in identical conditions of temperature, salinity, and rate of flow as the two experimental specimens.

The kymograph tracings of shell movements of

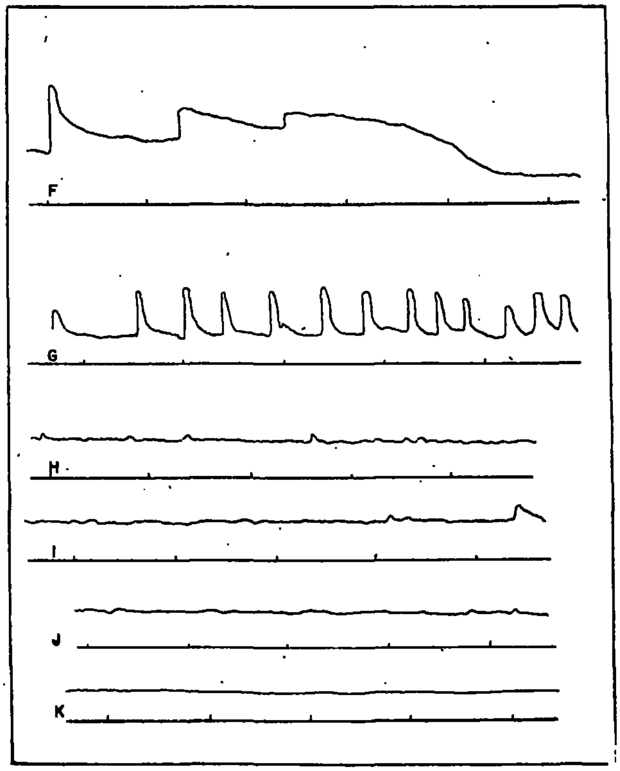

FIGURE 46.—Kymograph records showing the effects of prolonged exposure to pulp-mill effluent on the shell movement of an oyster. The tracings represent later periods in continuation of figure 45. F and G show the weakening of the adductor muscle with the oyster unable to hold the shell closed. H, I, and J give the record of the gaping of the shell with feeble attempts of the oyster to close the valves. K represents the final gaping of the shell with the death of the oyster. The writing pen is in the uppermost position when shells are closed.

the oysters were marked off into hours and analyzed as to the number of hours during each day the oysters were open. The duration of the experiments varied from 6 to 30 days during which shell movements were recorded continuously. Because each of the tests required many days, the experiments were made during the entire year at different ranges of temperature and salinity. The temperature of the solution in which the oysters were immersed was observed and recorded every morning and night. The salinity of the laboratory sea water was measured daily.

In analyzing the tracings of shell movement of the oysters, one must bear in mind that strong poisons frequently produce complete paralysis of the adductor muscle which results in the cessation of movements and gaping of the valves. Thus the number of hours per day the oyster remains open can be considered as an index of a normal behavior only if the curve of shell movement remains normal. Figures 45 and 46 representing normal behavior and the shell movements of an oyster affected by toxic substance illustrate this point. One can notice in the experiments with high concentrations of effluent (1:10), that after several days of treatment, the adductor muscle of the oyster became paralyzed and the shells remained completely open. The muscular contraction of these oysters were similar to those described by Hopkins et al. (1931) in his work on the effect of sulfite liquor on *Ostrea lurida.* In analyzing the data, the records that showed paralysis of the adductor muscle were not taken into consideration for determining the time the oysters remained open. The tests are summarized in table 47 which gives in a condensed form the conditions of each experiment and presents the results as the means of the number of hours per day the oyster remained open. The ranges of temperature and

TABLE 45.—*Effect of pulp-mill effluent on the time the oysters remain open*

Concentration of effluent	Oyster No.	Hours per day open		Dates of test (inclusive)	Water temperature range °C.	Salinity range parts per thousand	Eufflent No.	Specific gravity at 17.5° C.	Date collected
		Control	Experimental						
1 : 10	15-1	21.7	2.3	Nov. 6 to 12, 1936	12.5 to 17.1	23.32 to 22.74	6	1.0012	Sept. 8, 1936.
	15-2	21.7	7.8						
1 : 100	CB-5	22.3	8.0	May 11 to 17, 1936	15.4 to 23.6	15.17 to 16.08	3	1.0029	May 11, 1936.
	CB-6	22.3	9.0						
1 : 200	CB-1	22.4	8.6						
	CB-2	22.4	12.8						
	1-1	23.1	14.8	May 25 to 30, 1936	16.4 to 23.8	14.81 to 16.20			
	1-2	23.1	10.5						
	1-3	21.9	11.2						
	1-4	21.9	14.8						
	8-3	19.2	14.2	July 30 to Aug. 6, 1936	20.5 to 27.1	20.43 to 21.62	4	1.0021	June 14, 1936.
	8-4	19.2	15.3						
1 : 400	5-1	21.3	10.8	July 5 to 12, 1936	24.1 to 28.2	19.27 to 20.10	3	1.0029	May 11, 1936.
	5-2	21.3	17.4						
	5-4	20.5	15.9						
	5-5	20.5	14.9						
	7-1	20.0	14.1	July 16 to 25, 1936	25.3 to 27.2	19.72 to 20.68	4	1.0021	June 14, 1936.
	7-2	20.0	12.4						
	7-3	24.0	14.4						
	7-4	24.0	10.0						
1 : 1,000	2-1	21.3	9.8	May 25 to 30, 1936	16.4 to 23.8	14.81 to 16.20	3	1.0029	May 11, 1936.
	2-2	21.3	10.7						
	2-3	21.2	11.4						
	2-4	21.2	14.0						
	12-1	21.2	22.2	Oct. 19 to 27, 1936	17.3 to 20.7	22.83 to 23.57	6	1.0012	Sept. 8, 1936.
	12-2	21.2	17.5						
	12-3	21.3	13.0						
	12-4	21.3	15.7						
	18-1	20.4	10.5	Mar. 10 to 19, 1937	3.8 to 10.6	16.20 to 17.29	11	1.0039	Feb. 25, 1937.
	18-2	20.4	9.2						
	104	20.7	14.6	June 15 to 27, 1938			51	1.0014	June 13, 1938.
1 : 2,000	6-1	18.7	16.4	June 16 to 25, 1936	25.3 to 27.2	19.72 to 20.68	4	1.0021	June 14, 1936.
	6-2	18.7	19.1						
	6-3	18.8	17.1						
	6-4	18.8	18.8						
1 : 4,000	4-1	21.9	22.3	June 7 to 17, 1936	21.2 to 25.2	17.41 to 17.90	3	1.0029	May 11, 1936.
	4-2	21.9	21.7						
	4-3	22.7	22.3						
	4-4	22.7	15.8						
1 : 5,000	14-1	21.7	21.0	Nov. 7 to 27, 1936	6.3 to 16.1	21.00 to 23.75	6	1.0012	Sept. 8, 1936.
	14-2	21.7	22.7						
	19-1	21.3	19.1	Mar. 12 to 26, 1937	4.2 to 11.1	15.37 to 17.77	11	1.0039	Feb. 25, 1937.
	19-2	21.3	13.1						
	25-1	22.4	19.7	Apr. 26 to May 5, 1937	12.6 to 16.2	15.46 to 18.57	17	1.0053	Apr. 20, 1937.
	25-2	22.4	19.8						
1 : 10,000	3-1	22.1	22.0	June 2 to 29, 1936	19.4 to 27.0	16.09 to 19.94	3	1.0029	May 11, 1936.
	3-2	22.1	22.8						
	17-1	20.1	18.1	Mar. 12 to Apr. 11, 1937	4.2 to 13.3	15.37 to 17.90	11	1.0039	Feb. 25, 1937
	17-2	20.1	20.5						

salinity are written in the order of their occurrence to indicate the trend of the change experienced during the tests.

Physiological factors controlling the spontaneous muscular movements of the oysters are not well understood. It is known, however, that under normal conditions the oyster has a tendency to keep its shell open for very long periods of time, frequently exceeding 24 hours (Galtsoff 1928).

A summary of these data referring to the conditions under which each set of observations were conducted, as well as the nature of the test effluent, are shown in table 45. The observations were made using samples of mill effluents flowing into the river from the pulping process (sewers *J* and *H*), from the paper mill (sewer *A*), and from the sludge pond. The specific gravity and the color of the effluents were noted immediately upon collecting and the sample was stored in 5-gallon bottles which were well-corked and kept in the laboratory room.

Records of shell movement were obtained for 74 oysters. Of these, 49 oysters were treated with various concentrations of the mill effluents and 25 were used as controls. The results of all the experiments are given in figures 47 to 50 which show the hours per day that each oyster was open during the periods of observation.

The effectiveness of the various samples of effluent,

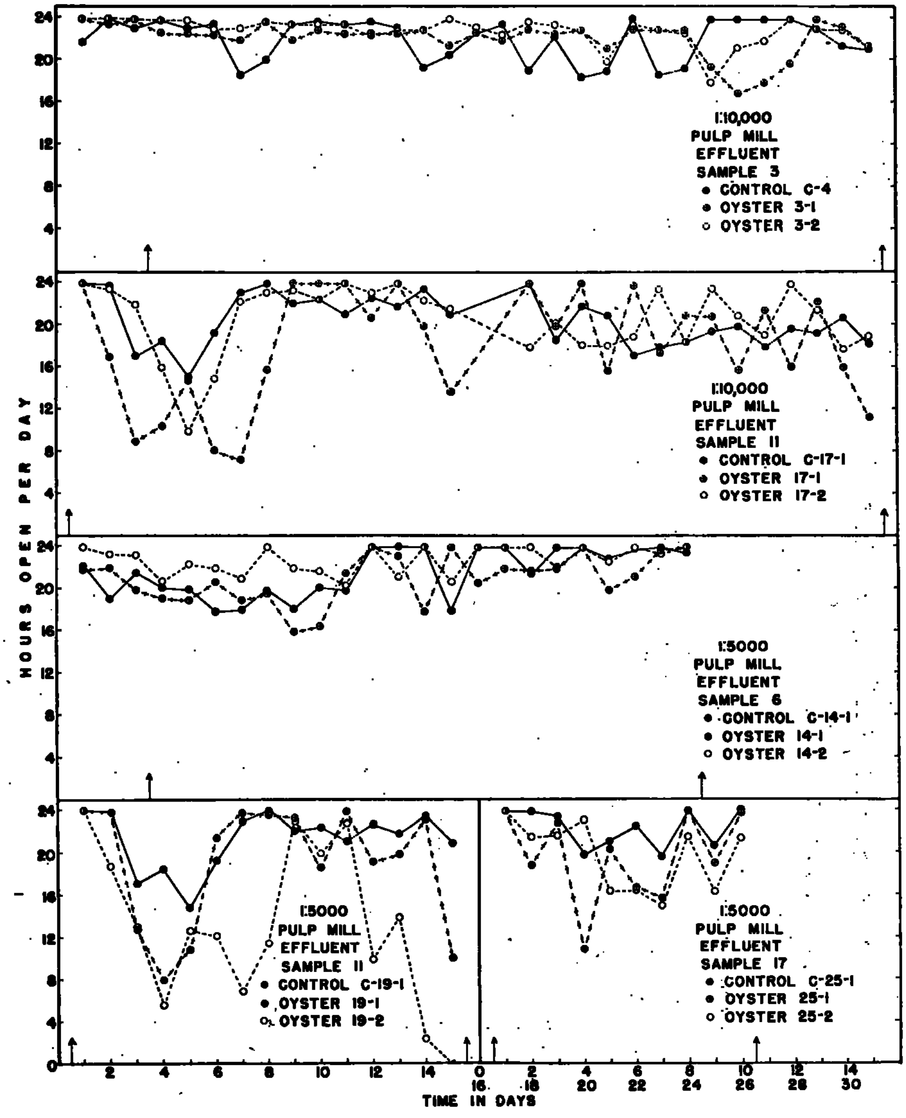

FIGURE 47.—Effect of pulp-mill effluent on the time the oysters remain open. Concentrations: 1 : 10,000 and 1 : 5,000.

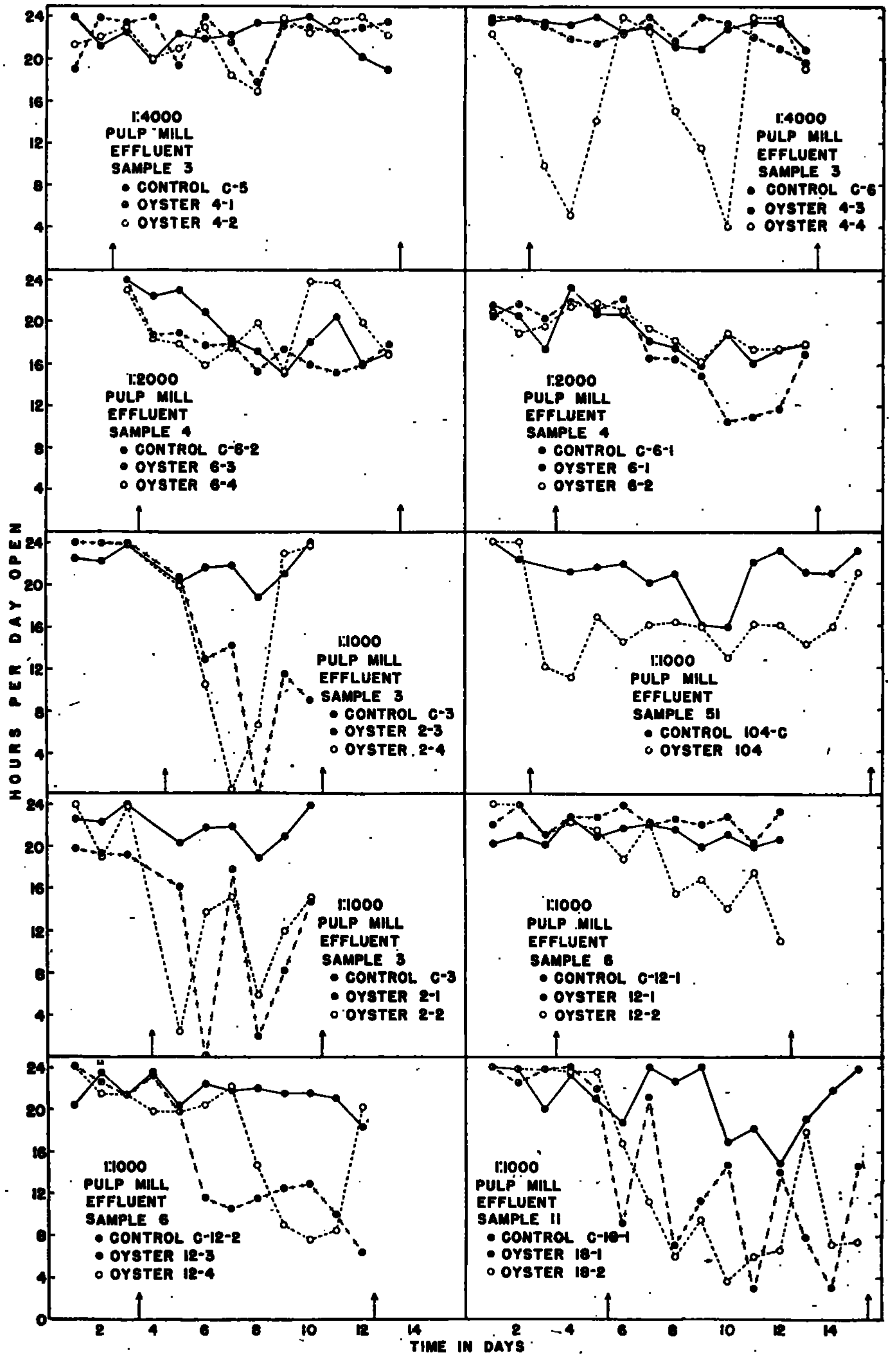

FIGURE 48.—Effect of pulp-mill effluent on the time the oysters remain open. Concentrations: 1 : 4,000, 1 : 2,000, and 1 : 1,000.

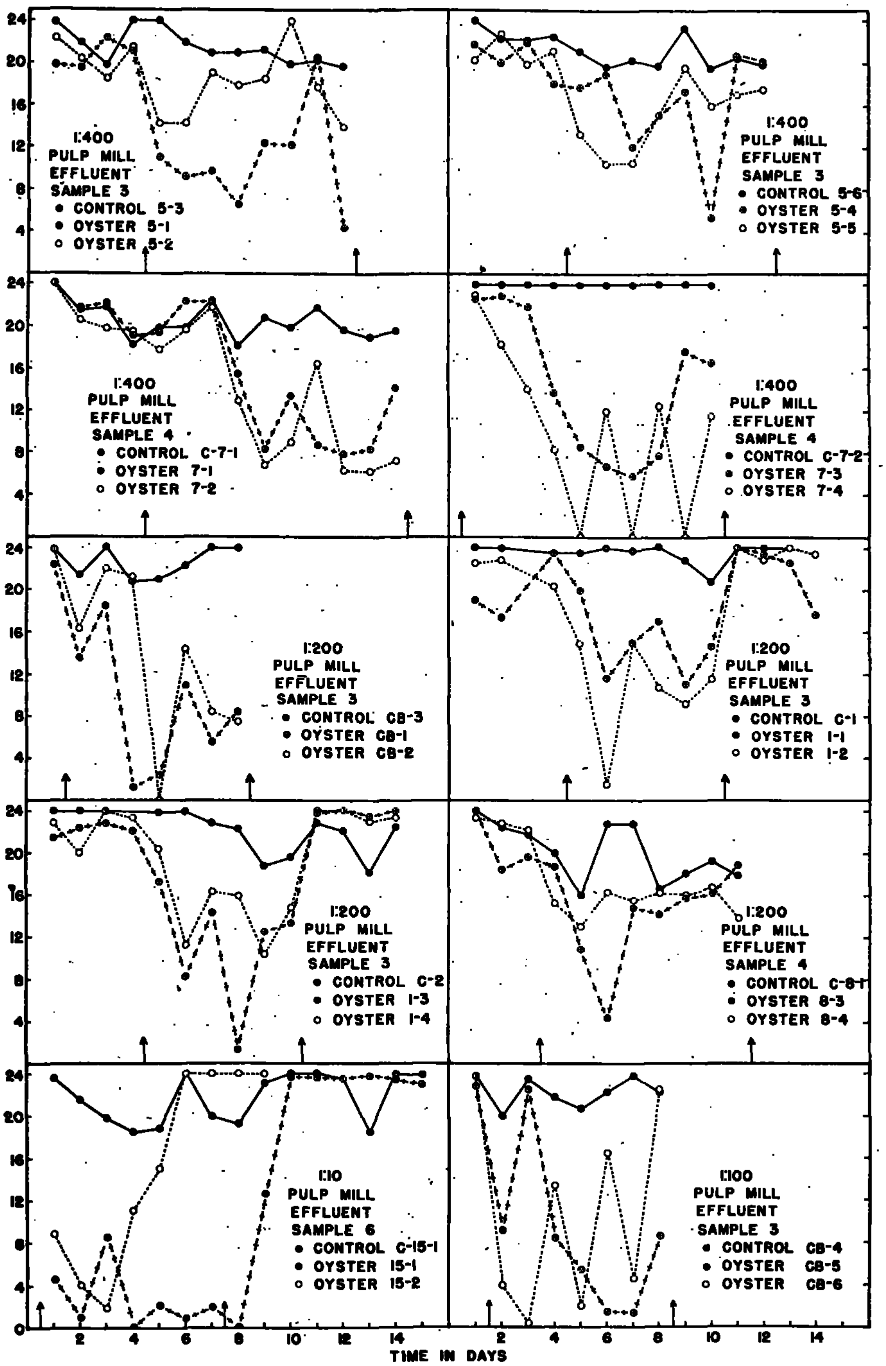

FIGURE 49.—Effect of pulp-mill effluent on the time the oysters remain open. Concentrations: 1 : 400, 1 : 200, 1 : 100, and 1 : 10.

collected at different times from the same sewer outlet, did not remain constant but was subject to change, associated with variations in the degree of dilution of the effluent, and changes in its character. The latter depended on conditions within the mill and also were associated with different stages of the manufacturing process. As these changes occurred suddenly and frequently, the time of flow of an effluent having a particular specific gravity, color, and other characteristic was of brief duration. For this reason the material used for testing consisted always of composite samples of the effluent collected at 15-minute intervals over a period of 5 hours.

Experiments reported later (pp. 159–163), showed changes in the physiological effectiveness of the effluents after storage and oxidation and after varied forms of treatment. There is no doubt, therefore, that the effectiveness of the effluent used in the experiments on the shell movements of oysters varied depending on its specific gravity, chemical composition, and age. Because the chemical nature of the physiologically active component of the effluent was unknown, it was decided not to adjust the effluent to an arbitrary specific gravity by evaporation. Such an adjustment, it was thought, might have produced changes in the effectiveness which would invalidate the tests. The various concentrations used in the experiments were prepared from the composite samples of effluent regardless of their specific gravity. There is no doubt that fluctuations in the composition of the effluent to a certain extent were responsible for the variability in the results, especially in the experiments in which low concentrations of the effluent were used. It is our opinion, however, that despite this variability, the experiments clearly show that the presence of the effluent in the river water causes the reduction in the number of hours the oyster remains open.

Laboratory experience shows, however, that in a sample of an oyster population several oysters are always present which, when placed in water and adjusted to the new environment, remain open for a much shorter period of time than the others. Because of this situation single tests are of little significance. It is necessary to have a large number of observations and make comparison between the means computed for each series of tests. A glance through table 45 shows that the daily mean number of hours the control oyster remained open under different temperature and salinity ranges varied from 18.7 to 24.0. Analyses of individual records made for each day separately shows that occasionally some were open only from 12 to 15 hours per day but, in the majority of cases, the oysters stayed open from 21 to 24 hours a day. It can be noticed easily that the addition of pulp-mill effluent reduces the number of hours open as the concentration of the effluent is increased. This negative correlation is apparent from examination of table 46 showing the frequency distribution of the number of hours open in various concentrations. Vertical columns give the total number of days the oysters were open for the specified number of hours indicated in the first column. The totals given at the bottom of the table cannot be used for direct comparison because the number of days for which the muscular activity was recorded in the controls and for the two lowest concentrations (1:10,000 and 1:5,000) were much greater than for other dilutions of the effluent. Experiments with the lower concentrations were continued for longer periods of time with the expectation that an adverse effect of a pollutant may be cumulative and would become apparent only after a prolonged exposure. On the other hand, in the tests with higher concentrations (1:100 and 1:10), pronounced toxic action was noticeable in a few days. In several

TABLE 46.—*Frequency distribution of "hours open" in various concentrations of pollutant*

Figures in the body of the table indicate the number of days during which oysters remained open for a number of hours shown in the first column. Total number of oysters used: in controls (0 concentration)—24; in tests—49. Duration of the experiments from 6 to 30 days; for details see table 45]

Hours open	Concentrations of pollutant in sea water									
	0	1/10,000	1/5,000	1/4,000	1/2,000	1/1,000	1/400	1/200	1/100	1/10
21–24	145	80	51	31	8	15	4	4	2	
18–21	94	16	18	5	9	10	9	5		
15–18	19	11	9	3	19	9	12	20	1	
12–15	3	2	5	1	1	11	10	17	1	
9–12		3	5	2	3	14	6	11	1	1
6–9		3	2			9	9	7	2	2
3–6			1	2		4	2	2	3	2
0–3			2			7		6	4	6
Total	261	115	93	44	40	79	52	72	14	11

cases, oysters used in the latter experiments were dead or dying by the end of the experiment. The experiments with the dilutions of pulp-mill effluent thought likely to occur in the York River were performed on a greater number of oysters and for longer periods of time than those with stronger concentrations.

Summary of observations of the time the oysters were open in various concentrations of the effluent are given in figures 47 to 49, while temperature and salinity data, referring to these experiments, together with the specific gravity of the samples of pulp-mill effluent can be found in table 45. In the concentration of 1 : 10,000 no significant reduction in the hours open was noticed by the end of the test lasting 30 days (fig. 47) and the shell movements of the oysters remained normal. In oysters 3–1 and 3–2, slight reduction in hours open occurred on the twenty-fifth day and continued for 4 days. It was, however, of temporary nature. We may infer from these data that a continuous exposure to the concentration 1 : 10,000 lasting for one month produces no noticeable effect in the number of hours the oysters remain open. It is, of course, possible that an adverse effect may become apparent later, but because of the lack of space in the temporary laboratory at Yorktown, it was impractical to prolong a single experiment beyond the 31-day period.

Of the six oysters used in the tests with the concentration of 1 : 5,000, two oysters exposed for 25 days were not affected by the pollutant; in three oysters the mean number of hours open during an 11-day period was slightly reduced, namely from 21.7 and 21.3 in the controls to 19.1 and 19.8 in the experiments, and one oyster was open only 13.1 hours as compared with 21.3 hours for the control. It is reasonable to assume that the toxicity of the effluent, sample 6, used in treating the first pair of oysters was less than that of samples 11 and 17 used in the other tests, because the specific gravity of sample 6 was only 1.0012 as compared with 1.0039 and 1.0053 of samples 11 and 17, respectively.

With the increase of concentration to 1 : 1,000 (fig. 48), the effect of the effluent is apparent within 1 or 2 days after the beginning of the test and becomes more and more pronounced as the concentration increases.

Variability in the results of the test can be attributed chiefly to the changes in the toxicity due to the dilution of the effluent by wash water and its degree of oxidation. Despite these conditions, the general tendency of the oyster to reduce the number of hours open as the concentration increases is quite clear.

High concentrations varying from 1 : 400 to 1 : 10 have a more pronounced effect as can be easily seen from the examination of figure 49. In the case of the latter concentration (see lower left of figure) rapid increase in the hours open recorded after the fourth day of exposure was due to the paralysis of the adductor muscle.

Relationship between the number of hours the oysters are closed and the concentration of the effluent can be seen clearly by plotting the mean number of hours the oysters stay closed against the log of concentration of the effluent. In making this plotting, the mean values were computed for each concentration used in the experiments listed in table 45. The values of means with their standard deviation and standard errors are given in table 47. For convenience in plotting, the concentrations are expressed in parts per 10 liters. The line was fitted by inspection. As can be seen from figure 50, there is a definite relation between the number of hours closed and log-concentration. As the plot of (x, log y) approximates a straight line, the set of the experimental data may be represented by an exponential equation of the form of $y=ae^{bx}$. Constants a and b, determined by the method of averages, are as follows: $a=0.2814$ and $b=0.4234$. The numerical value of e is, of course, 2.718. Thus, the equation representing the mean number of hours the York River oysters remained closed in a given concentration of the effluent can be written in the following form:

$$x=\frac{\log y+0.5504}{0.1839}$$

TABLE 47.—*Mean values of hours open (M) and closed (M ¹) in various concentrations of pulp-mill effluent*

[N=number of oysters under observations, N^1=number of oyster-days, x=number of hours closed computed from equation $y=ae^{bx}$ when y=is concentration in parts per 10 liters, a=0.2814, b=0.4234, Δ=difference between the observed and computed values, σ=standard deviation of hours open, S.E.=standard error]

Concentration in parts per 10 liters	M	σ	S.E. ±	M^1	N	N^1	x	Δ
1,000	5	------	--------	19.0	2	11	19.3	−0.3
100	8.5	------	--------	15.5	2	14	13.9	+1.6
50	12.8	2.40	0.85	11.2	8	72	12.2	−1.0
25	13.7	2.52	0.89	10.3	8	52	10.6	+0.3
10	13.5	3.89	1.17	10.5	11	79	9.0	+1.5
5	17.9	1.29	0.65	6.1	4	40	6.8	−.07
2.5	20.5	3.15	1.57	3.5	4	44	5.2	−1.7
2.0	19.2	1.63	0.67	4.8	6	93	4.6	+0.2
1.0	20.9	2.06	1.03	3.1	4	115	3.0	+0.1
0	21.3	1.29	0.26	2.7	25	261	------	------

TABLE 48.—*Effects of paper-mill and of sludge-pond effluent on the time the oysters remain open*

Concentration of effluent	Oyster No.	Hours per day open		Dates of test (inclusive)	Water temperature range ° C.	Salinity range parts per thousand	Effluent No.	Specific quantity at 17.5° C.	Date collected
		Control	Experimental						
Paper-mill effluent									
1 : 200	8-1	19.9	12.2	July 29 to Aug. 6, 1936	20.5 to 27.1	20.43 to 21.62	5A		July 14, 1936
	8-2	19.9	14.7						
1 : 500	22-1	22.1	22.2	Mar. 24 to Apr. 3, 1937	6.5 to 11.1	9.85 to 13.73	13		Mar. 12, 1937
	22-2	22.1	22.2						
	103	20.8	19.4	June 15 to 27 1937			52	1.0013	June 3, 1937
1 : 1,000	20-1	22.1	21.7	Mar. 10 to 19, 1937	5.8 to 9.8	16.20 to 17.29	12	1.0018	Feb. 25, 1937
	20-2	22.1	21.7						
	101	22.1	22.3	June 3 to 10, 1938			49	1.0049	May 31, 1938
Sludge-pond effluent									
1 : 500	105	17.2	18.3	June 18 to 22, 1938			53		June 13, 1938

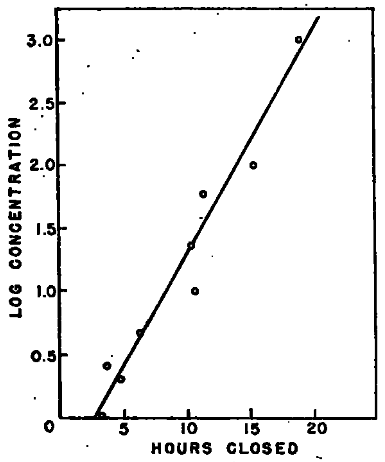

FIGURE 50.—Relation between the hours the oysters are closed and log concentration of pulp-mill effluent discharged into York River.

The reliability of the equation can be judged by comparing the observed and the computed value of x in table 47.

Physico-chemical basis of the equation cannot be evaluated at present because of the lack of understanding of the chemical nature of the physiologically active component of the pulp-mill effluent and of its effect on the neuromuscular system of the oyster. The type of the exponential equation suggests, however, that probably the mass law is involved and the reactions responsible for the prolonged contraction of the adductor muscle depend on the effective concentration of the reacting materials.

Physiological effect of the pulp-mill effluent is shown also on the type of muscular activity of the oysters. There was a marked change in the shell movements of oysters subjected to solutions containing pulp-mill wastes in concentrations of 1 : 1,000 or stronger. Irritating effect of the effluent was characterized by rapid and frequent shell closures at the time the effluent was added. These changes are clearly noticeable on the kymograph records reproduced in figure 45C.

The periods of high activity were followed by long periods in which the oysters remained tightly closed. In the stronger concentrations, the periods of closure became less frequent and as the adductor muscle weakened, the oysters were unable to hold the valves together for any length of time. In a concentration of 1:10 the amplitude of the movement of the adductor muscle, during the brief periods of attempts to close the shell, became less and less, and finally the shell remained open and the oyster died (fig. 46J and K). Under the conditions of the experiment, death of the oysters occurred only in concentrations in 1:10.

In comparison with the pulp-mill waste, the paper-mill effluent is much less toxic. Tests performed with the latter show that its effect becomes noticeable only in the concentration of 1:200 (table 48). Only one experiment was performed with the effluent from the sludge pond. No effect was observed in the dilution of sludge water at 1 : 500 (fig. 51).

EFFECT OF PULP- AND PAPER-MILL EFFLUENTS ON THE WATER FILTRATION OF OYSTERS

Pumping of water by the oyster for feeding and respiration is dependent on the combined activities of the ciliated epithelium of the gills, the adductor muscle, and the mantle. The ciliated lining of the gills provides a mechanical force which drives the water through a system of water pores and tubes, whereas the contractions of the adductor muscle and the mantle control the flow of water by regulating the opening and closing of the mantle chamber

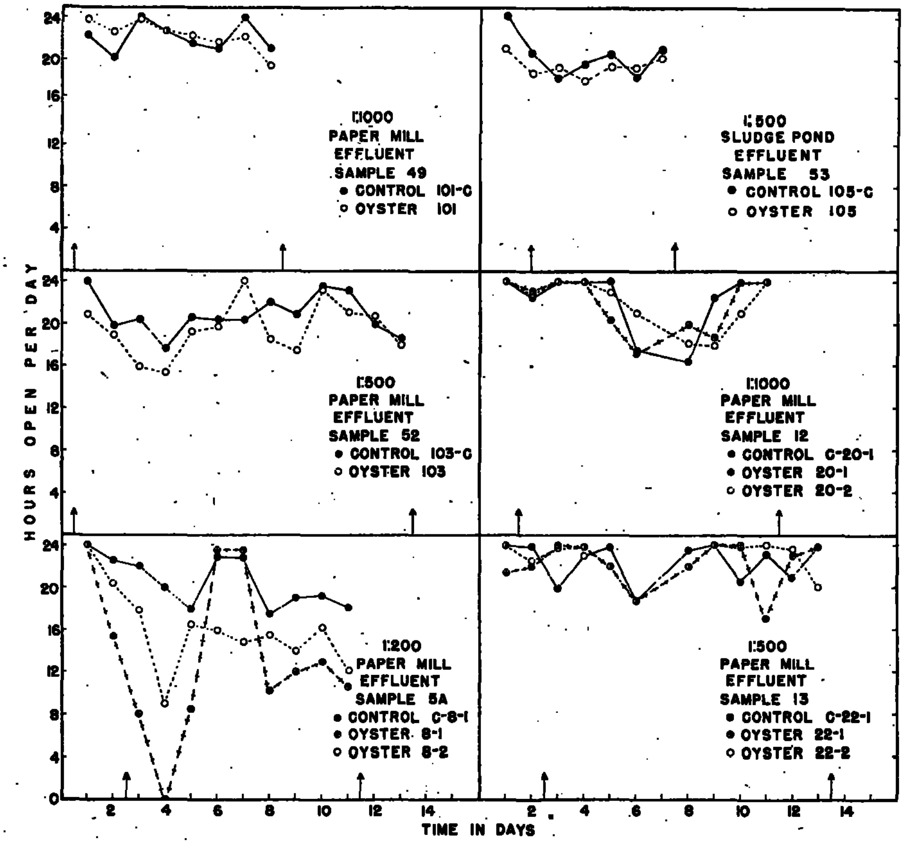

FIGURE 51.—Effect of paper-mill and sludge-pond effluents on the time the oysters remain open.

to provide for a greater or lesser access of the outside water to the gills. To obtain a clear understanding of the functions of these organs in the presence of the pollutant, three sets of experiments were conducted.

The effect of various concentrations of the pulp-mill effluents on the ciliated epithelium of the gill was studied by using the two methods previously developed by Galtsoff (1928, 1935) generally known as the carmine-cone method and the drop-counting method. For a study of the effect of pollutants on the entire feeding mechanism of the oyster a combination of Nelson's apron method (Nelson 1936) and Galtsoff's constant-level tank (1928), employed in the drop-counting method, was used. In the apron method continuous records of the pumping of the water by the intact oyster were obtained for periods lasting from several days to about a fortnight.

Experiments Using the Carmine-Cone Method

Normal adult oysters, collected from the vicinity of the laboratory, usually from the lower York River, were employed. They were brought to the laboratory in lots of a half to 1 bushel as needed and stored in a tank of flowing laboratory sea water.

On the morning of testing, oysters were selected from the stock supply and the valves carefully pried ajar without injuring the adductor muscle and a small glass rod inserted. The valves were then wired to prevent any further opening. A small rubber tube was then inserted into the cloaca and the remaining space berween the valves on the excurrent side filled with wet cotton. After removing any air bubbles trapped in the valves and tube by means of a bulb pipette, the oyster was placed in an enamelware tray containing 8 liters of sea water. A stream of bubbles passing through a tube in the tray circulated the water. The rubber tube was then connected to one arm of a glass "⊥" tube onto which had been attached a glass tube marked with two marks 15 centimeters apart. The upright arm of the "⊥" tube was connected to a small thistle tube containing a light carmine suspension held in the tube by a Day's pinchcock clamp. By releasing a small amount of carmine by slight pressure on the clamp, the suspension joining the water being pumped by the oyster formed a red cone, the tip of which was timed by a stop watch as it passed between the two marks.

After allowing the oyster time to recover from shock, the rate of pumping in plain sea water was determined, 10 readings in succession being averaged. Usually one investigator could test three oysters, two experimental and one control. After readings at half-hour intervals had shown the oyster to be pumping at a regular rate, the test solution was added from a pipette in an amount sufficient to bring the concentration to the desired strength. An electric stirrer was then turned on for 10 minutes. Using this technique two sets of experiments were performed. In the first series of tests, the concentration of the effluent was gradually increased and readings were made 15 minutes after each addition of effluent. In the second series, oysters were kept for several hours in a given concentration of effluent: during the first 2 hours readings were made every half hour, then at greater intervals.

In the tests which were conducted in the summer of 1936, oysters were subjected to gradually increasing concentrations of a composite sample of effluent taken from sewers *J* and *H*. The specific gravity of sample No. 3 was 1.00285. To eliminate variations of salinity and temperature in any one experiment, the tests were designed to be completed within a 24-hour period. In no experiment did the temperature vary more than 2° C. Moreover, there was no appreciable change in salinity in any experiments except in those where the concentration of effluent exceeded 30 parts per thousand and the sea water was noticeably diluted by the pollutant. The hydrogen-ion concentration was taken into consideration. Significant increase in pH varying from 0.3 to 0.4 occurred only when the concentration of the effluent reached 30 parts per thousand and above.

Each experiment was adequately controlled, i. e., control was observed simultaneously with two experimental oysters. The percentage of the depression was computed by considering as 100 percent the rate of flow of each test oyster before the addition of the effluent. The controls served as a check against any possible decrease in the rate of flow resulting from fatigue, changes in temperature, and other factors. Since there was no actual distinction in the controls between the periods before and during treatment, separation has to be made arbitrarily on a time basis. One hour prior to treatment, at least two series of readings were made at 30-minute intervals. A similar number of readings was made at the end of each test period which, on different occasions, varied from 5 to 26 hours. An inspection of the rates of flow of the controls showed that 12 out of 13 oysters increased their rate of pumping during the test period. This indicated that any depressive effect observed in the test oyster could not be attributed to the condition of the experiment and was due to the presence of pollutant. The pulp-mill effluent was added in gradually increasing amounts that resulted in the following concentrations: 5, 10, 20, 30, 40, and 50, parts per thousand. The results, computed as means of all the observations for a given concentration, are presented in figure 52. They show a definite relationship between the increase in the concentration of the pulp-mill effluent and its physiological effect on ciliated epithelium. Using the same technique, numerous tests were made in 1937 and 1938 with different samples of pulp-mill and paper-mill effluents. The results of some of these experiments, presented in figure 53, show considerable variation in the physiological effectiveness of various samples, a fact already noticed in other tests (pp. 137–140). If, however, the same sample of the pollutant was used to test

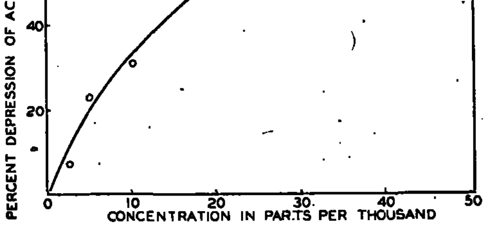

FIGURE 52.—Effect of increased concentration of pulp-mill effluent (sample 3, specific gravity 1.00285) in depressing the activity of the ciliated epithelium of the gill measured as a velocity of the cloacal current. Carmine-cone method. Each point represents mean of observations on nine oysters. Samples collected May 11, 1936. Tests performed between May 14 and 20, 1936.

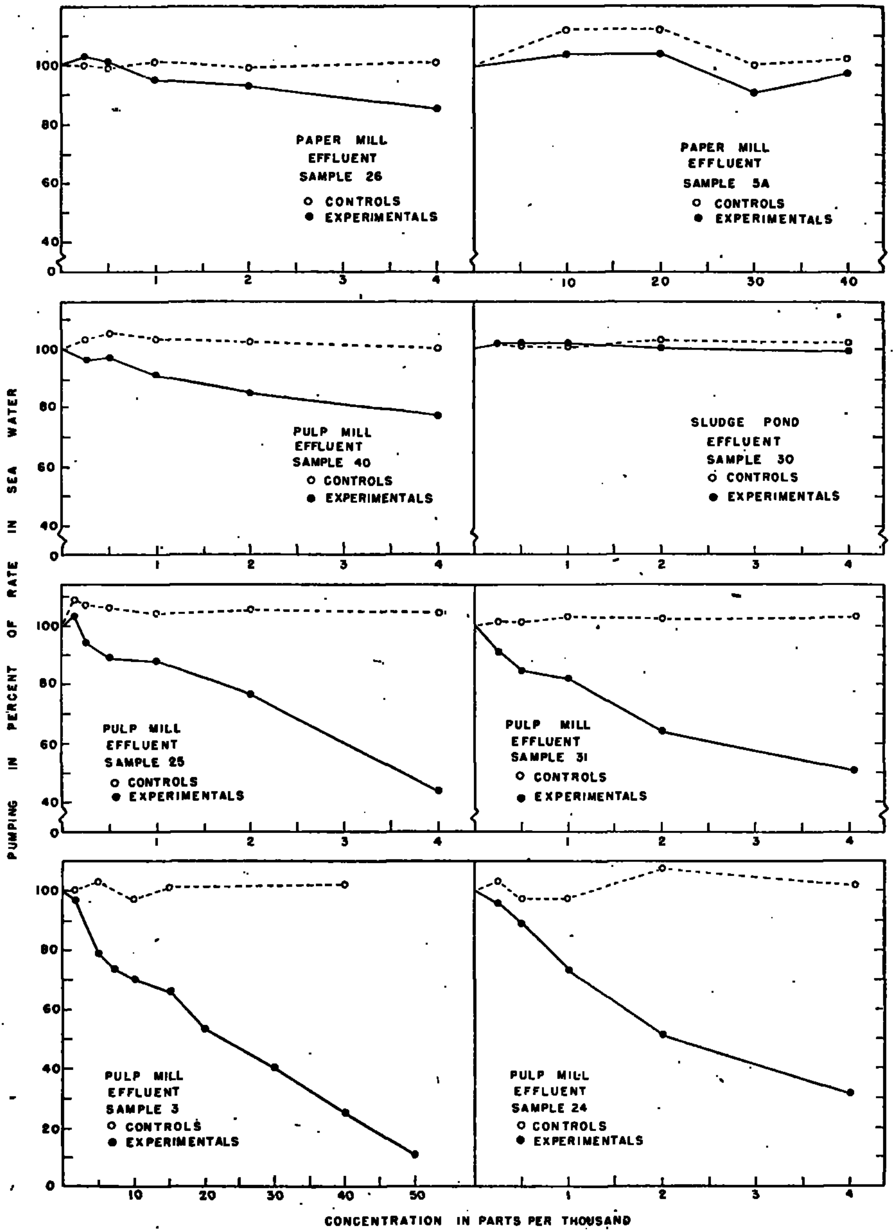

FIGURE 53.—Effects of increasing concentrations of pulp- and paper-mill effluents and sludge-pond effluent on the ciliary motion of the gill epithelium as measured by the carmine-cone method. Each point on the curves represents the average of five or more oysters. Exposure time was a half hour after the desired concentration was attained except for sample 3 in which a 15-minute exposure was used.

its effectiveness in various concentrations, the relation between the degree of depression of the rate of pumping and concentration followed the same general trend shown in figure 52.

From the point of view of toxicological studies, the method in which the concentration of toxic material is being gradually built up is open to criticism because under this condition the response of the organism may result from prolonged exposure to low concentration of a physiologically active substance plus the additional effect of stronger concentrations. On the other hand, oysters located near the source of pollution are frequently subjected to gradually increasing concentrations of pulp-mill effluent, which is being discharged at a greatly variable rate. The laboratory tests to a certain extent reproduce these conditions.

The results of tests in which a given concentration of the effluent was kept constant are shown in figure 54 which summarizes the observations made with various samples of pulp- and paper-mill effluents. From the examination of the curves, it is apparent that physiologically active material, which depresses ciliary activity of the gills, is present in varying amounts in different samples. Thus, sample 5 was effective only in a relatively high concentration of 1:100, samples 3 and 6 were effective in dilution of 1:200, and the effect of samples 23 and 24 was very pronounced in rather low concentrations of 1:2,000 and even 1:4,000. Details of these and other

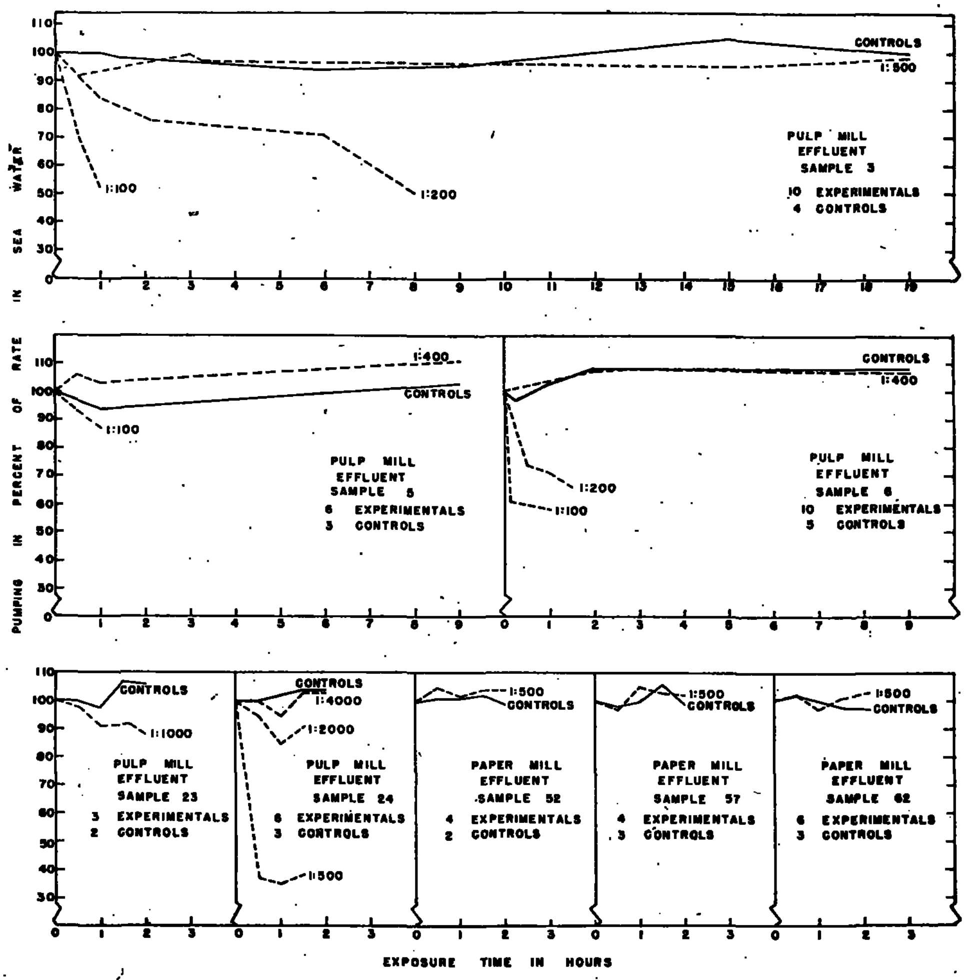

FIGURE 54.—Effects of exposure to various concentrations of pulp- and paper-mill effluents on the ciliary motion of the gill epithelium as measured by the carmine-cone method. The plotted points represent the averages for the number of oysters indicated in each block of the graph. During each test the concentration of effluent indicated on the graphs remained unchanged.

TABLE 49.—*Conditions of the experiments using the carmine-cone method with fixed concentrations of the pulp- and paper-mill effluents.* (*See figs. 54 and 56*)

Sample No.	Specific gravity at 17.5° C.	Concentration tested	Date of test	Salinity, parts per thousand	Water temperature range, ° C.	Sea water pH	Solution pH
Pulp-mill effluent							
3	1.0029	1:100	June 4, 1936	16.0	17.6 to 19.2	8.1	8.1
			July 27, 1936	17.7	27.6 to 27.9	7.8	----------
		1:200	May 28, 1936	14.1	24.9 to 19.6	7.9	7.9
			May 25, 1936	14.1	24.9 to 19.6	7.9	7.9
		1:500	May 26, 1936	15.3	21.3 to 23.0	7.9	7.9
5	1.0013	1:100	Aug. 21, 1936	21.3	27.7 to 28.8	7.8	----------
		1:400	Aug. 17, 1936	21.4	27.3 to 27.6	7.8	7.8
6	1.0016	1:100	Oct. 15, 1936	----------	21.5 to 21.9	----------	----------
		1:200	Oct. 20, 1936	22.8	18.5 to 20.4	7.9	----------
		1:400	Oct. 21, 1936	22.8	20.1 to 20.7	7.9	----------
23	1.0035	1:1,000	Sept. 3, 1937	19.9	26.6 to 28.4	8.1	8.1
			Sept. 8, 1937	19.6	23.2 to 23.4	7.9	7.9
24	1.0043	1:500	Sept. 16, 1937	17.0	22.0 to 23.2	8.1	----------
		1:2,000	Sept. 24, 1937	21.7	20.3 to 21.3	8.1	----------
		1:4,000	Sept. 27, 1937	21.1	18.3 to 19.7	8.1	8.1
[1] 24	1.0043	1:500	Sept. 29, 1937	29.7	18.2 to 19.5	8.0	----------
			Oct. 6, 1937	----------	23.9 to 24.8	8.1	8.1
		1:1,000	Sept. 30, 1937	28.8	19.0 to 20.4	7.9	7.9
			Oct. 1, 1937	28.5	20.7 to 21.0	7.9	7.9
			Oct. 2, 1937	25.7	21.6 to 22.5	7.9	7.9
			Oct. 3, 1937	25.7	22.3 to 22.8	7.9	7.9
			Oct. 4, 1937	25.5	22.6 to 23.0	7.9	8.0
			Oct. 5, 1937	----------	22.8 to 24.9	7.9	7.9
		1:2,000	Oct. 7, 1937	----------	24.1 to 24.9	7.9	7.9
			Oct. 8, 1937	25.1	20.1 to 19.6	7.9	7.9
Paper-mill effluent							
52	1.0013	1:500	June 14, 1938	17.9	21.7 to 22.4	7.9	7.9
			June 15, 1938	18.6	22.6 to 23.5	8.0	8.0
57	----------	1:500	June 16, 1938	18.9	21.2 to 22.2	7.9	8.0
			June 17, 1938	19.5	23.8 to 24.8	8.0	7.9
62	----------	1:500	June 22, 1938	18.5	24.0 to 24.6	7.9	7.9
			June 23, 1938	18.7	24.8 to 24.4	8.0	----------
			June 24, 1938	18.3	25.3 to 26.4	7.9	7.9

[1] Tests at Beaufort, N. C.

experiments in which fixed concentrations of pulp- and paper-mill effluents were used are given in table 49. All samples of paper-mill effluent tested contained no physiologically active material.

Analysis of the experimental data shows that with the exception of high concentrations of 1:100 and 1:200 the depression caused by a given concentration of pollutant remains fairly constant for several hours and does not increase with the duration of the test (fig. 54). The inference can be made that, under the conditions of these tests, there was no cumulative effect of the pollutant on the ciliary mechanism of the oyster. Neither was there any indication that oysters become adapted to a given concentration and develop greater tolerance. This is of interest because it has been shown that, in chlorinated water, oysters easily develop tolerance to relatively high concentrations of free chlorine (Galtsoff 1946).

In order to obtain a better understanding of the relationship between the depressing effect of the pulp-mill effluent and its concentration and to avoid the difficulty caused by wide fluctuation in the specific gravity and toxicity of various samples, a series of tests was made using one sample (No. 24) which proved to be highly toxic. The sample was collected on September 19, 1937, and was stored in well-stoppered bottles. Its specific gravity was 1.0043 and the color of the liquid was dark brown. In conducting the tests, each oyster was exposed only once to a given concentration, in which it was kept for one and a half hours, and the velocity of the cloacal current measured at half-hour intervals. The rate of pumping before the pollutant was added was considered as representing the normal rate. Thus, the conditions of these tests were entirely different from those of the experiments summarized in figure 52. Namely, each oyster was left in the pollutant for one and a half hours instead of 15 minutes and was subjected to only one concentration instead of being exposed to the cumulative effect of gradually increasing concentrations.

The results, expressed in percentages of the normal rates of pumping, show a definite relationship between the concentration of the sample and its depressing effect (table 50). This relationship approximates a straight line (fig. 55). A comparison with the results of other tests summarized in figure 52 shows that the depressing effect of sample 24 was more than ten times greater than that of the samples used in previous experiments.

TABLE 50.—*Depression of the rate of filtration caused by pulp-mill effluent (sample 24)*

[Specific gravity 1.0043. Carmine-cone method. Figures express means of percentages of normal rate. Each oyster was exposed to one concentration of the effluent for 1½ hours. Three sets of readings were made at half-hour intervals]

Concentration, parts per liter	Number of oysters	Percentage of normal rate	Standard deviation	Percentage of depression
0	21	100		0
.25	6	99.2	4.37±0.87	0.8
.5	18	89.2	8.21±1.90	10.8
1.0	27	77.8	5.83±1.12	22.2
2.0	15	36.5	5.65±1.46	63.5

It was thought that oysters in the lower part of York River, being exposed for a long time to very low concentrations of pollutant, may have developed a certain degree of tolerance and become less sensitive to pulp-mill effluents than oysters living in unpolluted water. To test this possibility sample 24 of the pulp-mill effluent was divided into two portions and a series of bioassays was made simultaneously at Yorktown, Va., and at the United States Fisheries laboratory at Beaufort, N. C. Details of

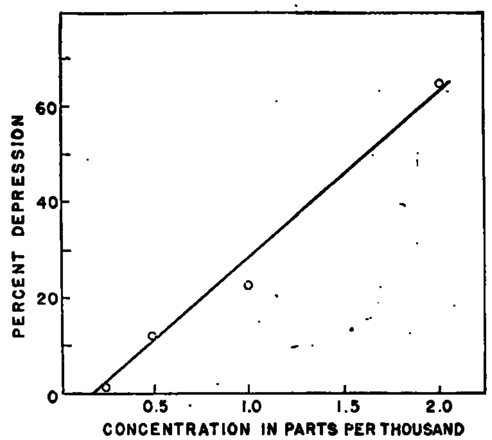

FIGURE 55.—Percentage of depression in ciliary motion of the gill epithelium, as measured by the carmine-cone method, caused by various concentrations of pulp-mill effluent (sample 24, specific gravity 1.0043).

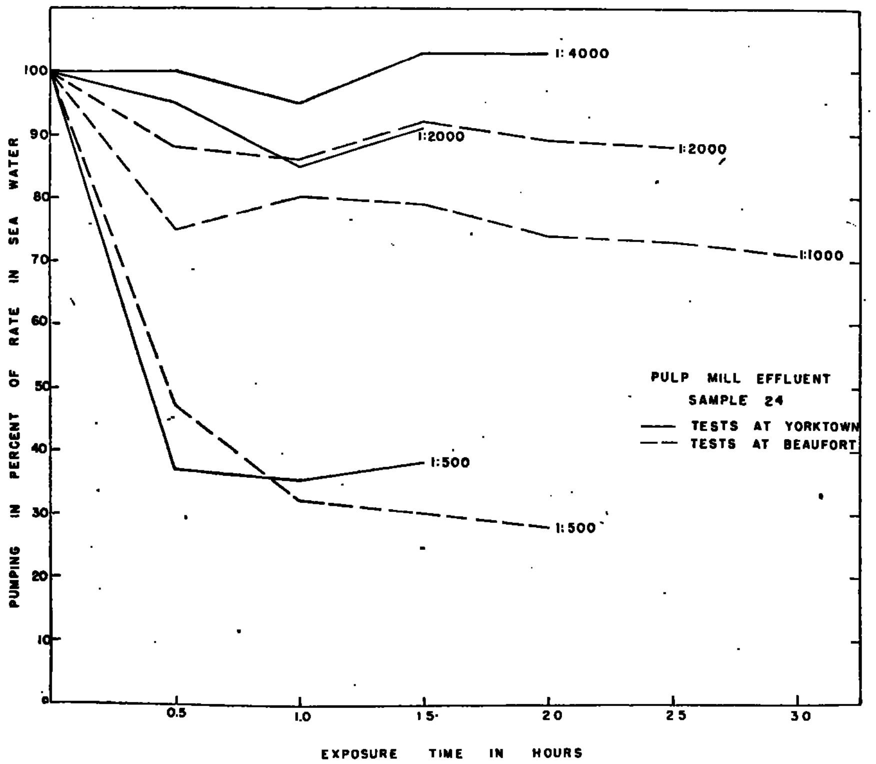

FIGURE 56.—Comparison of the effects of time of exposure of various concentrations of pulp-mill effluent on the rate of water filtration of oysters in tests carried on at Beaufort, N. C., and at Yorktown, Va. Tests were run at the same time at each locality and with the same sample of effluent. Two oysters and a control were observed for each concentration.

the two sets of experiments are given in table 49. As can be seen from figure 56, the behavior of the oysters from Beaufort, that had not been in contact with pulp-mill waste, was no different from the behavior of the oysters from the lower part of the York River, which for several years might have been subjected to very low concentrations of the pollutant.

From numerous observations with the carmine-cone method, we conclude that the presence of pulp-mill effluent exerts a definite depressing action on the ciliary epithelium of the gill and reduces its efficiency, the reduction in rate being proportional to the concentration of the physiologically active components of the pollutant. The effect is, however, temporary and the normal rate is restored soon after fresh sea water is supplied the oyster. There is no evidence that several hours of exposure to the concentrations used in the tests produce irreparable changes in the gill epithelium.

Experiments Using the Drop-Counting Method

This method (p. 133), differs from that of the carmine cone in two essential points. First, the oyster is kept in running sea water, which prevents the accumulation of the products of metabolism and, second, the rate of flow of the current produced by the gill epithelium is recorded automatically without disturbing the animal. It was therefore possible by using this method to obtain numerous records of the activity of the oyster in natural sea water and in various concentrations of test materials. As in the experiments previously discussed on the effects of river water of the upper York River on the ciliary activity of oysters, the kymograph records showing the number of drops of water discharged through the cloaca were analyzed for each 10-second interval of the period of recording, which usually lasted from 2 to 2½ minutes. The average figure thus obtained was multiplied by 60 to give the number of drops per minute. The temperature, pH, and salinity of the sea water were observed during the periods of testing and are recorded in table 51. Each experiment lasted from 4½ to 6 hours. In these experiments there was no recirculation of the test material as there was in the experiments described on page 133 in which the amount of test material available was small.

Material for testing comprised 11 different samples of pulp-mill effluent collected from sewers *J* and *H* and one sample of the material draining from the sludge pond. The results of the experiments are presented graphically in figures 57, 58, 59, and 60. They confirm the findings obtained with the carmine-cone method that the effluents arising from the pulping process depress the ciliary activity of the gill epithelium. The drop-counting records clearly show that, in physiologically active solutions, the effect is immediate. As the water containing pulp-mill effluent is turned on, the number of drops of water discharged through the gills decreases almost immediately. The normal rate is restored, however, as soon as the delivery of the pollutant is stopped. This can be easily noticed in figures 57 to 60 in which the beginning and end of each treatment are indicated by vertical black arrows.

Recovery after treatment is complete and, in many instances, the rate of pumping of water through the gills after the removal of the effluent is greater than it was before the treatment. We may conclude that the ciliated epithelium of the gills suffers no irreparable damage due to the presence of pulp-mill effluent, which apparently acts as a depressing or narcotizing agent. As soon as the latter is removed from the environment, normal function of the ciliated epithelium of the gills is fully restored.

Effect of Pulp- and Paper-Mill Effluents on the Rate of Pumping of Water by Intact Oysters (Rubber-Apron Method)

The object of employing this method was to observe the effect of pulp- and paper-mill effluents on the pumping activity of intact oysters exposed over long periods to various concentrations of the pollutants. While the carmine-cone and drop-counting methods are well adapted for the study of one isolated mechanism of feeding, the rubber-apron technique is suitable for determining the combined action of all the mechanisms which control the rate of water filtration by the oyster, namely, that of the ciliated epithelium of the gills and their ostia, the mantle, and the adductor muscle.

By using a constant-level tank (Galtsoff 1928) simultaneous records were obtained of the water output of experimental oysters subjected to pulp- and paper-mill effluents and of the control oysters in unpolluted sea water. Nelson's method (Nelson 1936) for preparing an oyster for such observation was used with modifications which permitted the gathering of continuous records of the rate of pumping and the shell movements. A piece of rubber dam was patterned to form a conical shape when wrapped around an oyster, the cone leading away

TABLE 51.—*Effect of pulp-mill effluent (sewers J and H) and sludge-pond effluent on the rate of discharge of water through the gills (drop-counting technique)*

[See figs. 58, 59, 60, and 61]

Sample No.	Specific gravity at 17.5° C.	Concentration	Effect on rate of pumping	Experiment No.	Date	Temperature °C.	Salinity °/00	pH
Pulp-mill effluent					*1936*			
3	1.0029	1:200	Depressed	8c	June 5	23.3	16.7	8.2
6	1.0012	1:400	do	13c	Nov. 12	15.6	22.3	8.0
19	1.0028	1:200	do	RF12 [1]	Aug. 12	21.4	31.2	
		1:500	do	RF 8 [1]	Aug. 18	21.2	36.9	
					1937			
24	1.0043	1:1,000	Depressed	15c	Sept. 19	24.2	18.6	8.0
			do	1	Nov. 1	15.0	14.6	8.1
			do	2	Nov. 2	16.1	16.9	8.1
			do	3	Nov. 3	15.2	16.8	8.1
			do	6	Nov. 5	15.4	17.4	8.1
		1:2,000	Depressed	7	Nov. 7	15.3	18.2	8.3
			do	9	Nov. 9	15.6	17.2	8.1
			do	12	Nov. 12	15.6	18.1	8.1
25	1.0025	1:500	do	17	Dec. 13	20.7	19.1	7.8
		1:1,000	Depressed	19	Dec. 14	20.5	18.8	7.8
			do	21	Dec. 15	20.7	18.6	7.9
			do	22	do	20.7	18.6	7.9
		1:2,000	Depressed	13	Dec. 9	20.3	15.1	7.9
			Not depressed	16	Dec. 10	20.1	17.6	7.9
					1938			
35	1.0038	1:500	Depressed	25	Feb. 15	21.4	19.4	8.1
			do	24	do	21.3	19.4	8.1
40	1.0040	1:500	Depressed	40	Mar. 8	22.5	20.5	8.0
			do	41	do	22.7	20.5	8.0
			do	42	Mar. 9	22.4	21.0	8.1
			do	43	do	22.4	21.0	8.1
			do	44	Mar. 10	22.2	20.4	8.0
			do	45	do	22.1	20.4	8.0
			do	46	Mar. 11	21.8	20.0	8.0
42	1.0020	1:500	Depressed	74	Apr. 20	20.8	17.1	7.9
			Not depressed	72	Apr. 11	20.1	16.6	7.9
			do	73	do	20.2	16.6	7.9
			do	75	Apr. 20	20.6	17.1	7.9
50	1.0022	1:500	Not depressed	90	June 6	22.5	18.1	8.0
			Depressed	91	June 7	24.1	17.4	8.1
			do	92	do	24.2	17.4	8.1
			do	93	June 8	22.9	17.4	8.1
			do	94	do	22.8	17.4	8.1
			do	95	do	22.8	17.4	8.1
			do	96	do	22.9	17.4	8.1
51	1.0014	1:500	Depressed	100	June 14	22.4	17.9	7.9
			do	101	do	22.2	17.9	7.9
			do	102	do	22.2	17.9	7.9
63	1.0013	1:500	Depressed	112	June 24	25.6	18.3	7.9
			Not depressed	113	do	25.6	18.3	7.9
Sludge—pond effluent					*1938*			
56	1.0026	1:500	Depressed slightly	105	June 15	23.0	18.6	8.1
			do	106	do	23.0	18.6	8.1
			Not depressed	107	June 17	23.5	19.5	8.0
			Depressed slightly	109	do	23.5	19.5	8.0
			Not depressed	110	June 21	23.5	17.4	7.9
			do	111	do	23.5	17.4	7.9

[1] Tests at Woods Hole.

from the out-current side. The rubber dam was cemented tightly to the oyster with sufficient slack at the posterior end to allow the valves to part freely and without obstruction. Into this slack region was inserted a plug of cotton to prevent any water escaping to the in-current side. The oyster, equipped in this manner, will, when feeding, discharge all water into the apron.

The oyster was then placed in a constant-level chamber and the end of the rubber cone firmly attached to an outlet trough about 1½ inches in diameter. The water pumped by the oyster was collected and measured by means of a dumping vessel which automatically discharged when the water reached the desired level. Each dumping was recorded on a slow-motion kymograph. Full description of this method with detailed diagrams is given in the paper of Galtsoff (1946), Reaction of Oysters to Chlorination.

By using this method, the rate of water filtration was measured in oysters kept in various dilutions of pulp-mill effluents for a period of time varying from 1 to 13 days. In each experiment two oysters were observed: one of them was kept in unpolluted water and served as a control, the other was placed in a known concentration of the pollutant which was

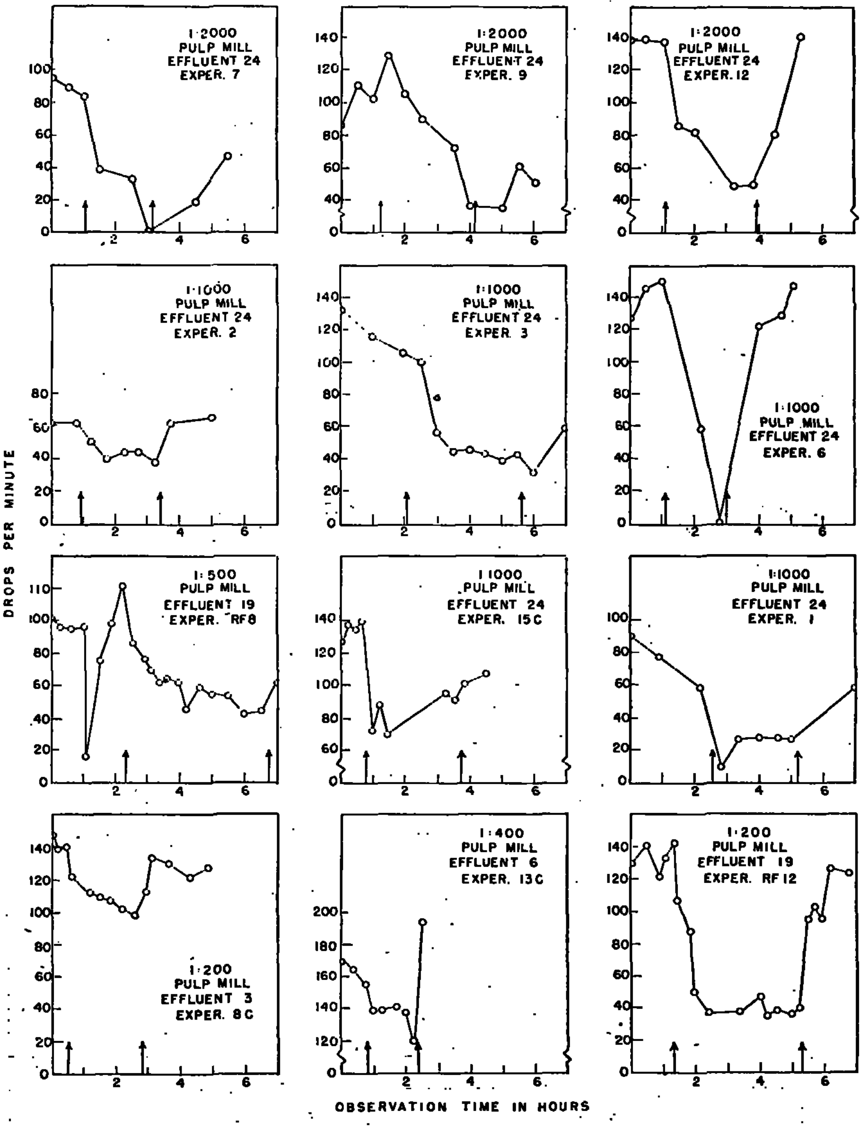

FIGURE 57.—Effect of various samples of pulp-mill effluent on the rate of filtration of water by oyster gills measured by the drop-counting method. Concentrations: 1:2,000; 1:1,000; 1:500; 1:400, and 1:200.

flowing through the chamber at the same rate as the unpolluted water that was delivered to the control. Records of the temperature and salinity of water were maintained. In every respect the control and test oysters received identical treatment except that the water supplied the control contained no pollutant. All of the oysters used were normal healthy specimens taken, in most cases, from the lower York River.

Before the beginning of each test, continuous record of the rate of pumping and of muscular movement of both oysters were obtained. In the majority of cases, this preliminary period lasted 2 or 3 days. Only in one instance was the test started 24 hours after the oyster was placed in the tank and in two instances the oysters were kept for 4 and 6 days before the pollutant was added. Numerous observations performed by Galtsoff at the Woods Hole laboratory in connection with a study of the physiology of feeding show that oysters wrapped in rubber-dam aprons and kept in constant-level tanks suffer no ill effects caused by their abnormal situation. If temperature and other conditions of water remain unchanged, the rate of pumping proceeds at a very constant rate. This can be seen also from the fact that by the end of the tests, some of which lasted as long as a fortnight (fig. 62), the rate of

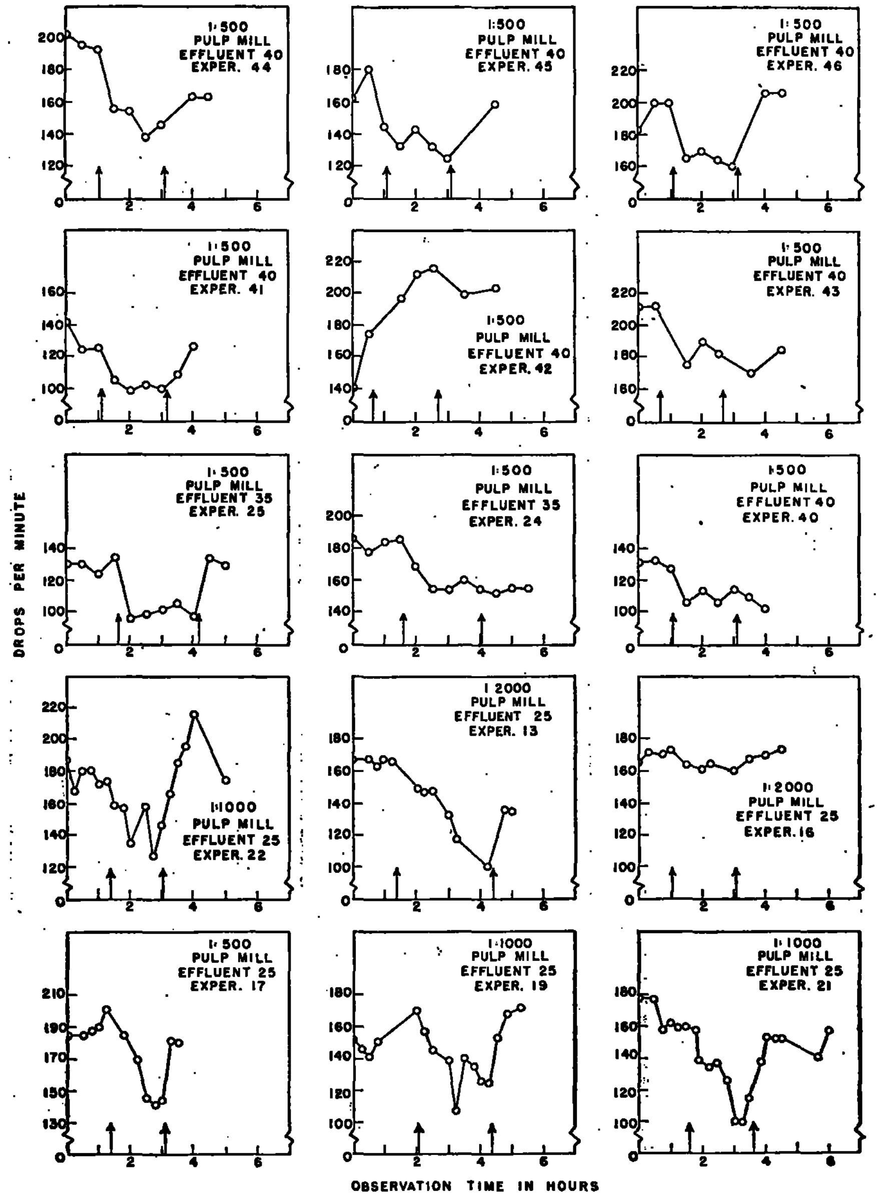

FIGURE 58:—Effect of various samples of pulp-mill effluent on the rate of filtration of water by oyster gills measured by the drop-counting method. Concentrations: 1:2,000; 1:1,000; and 1:500.

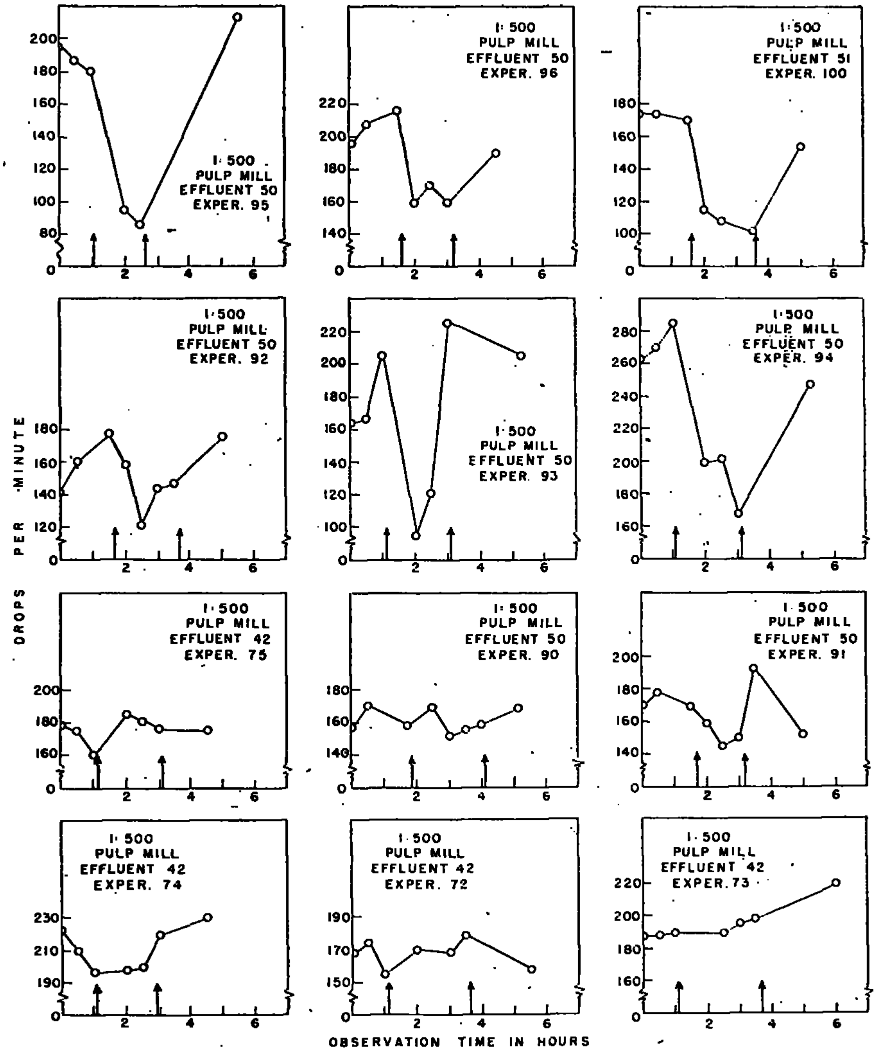

FIGURE 59.—Effect of various samples of pulp-mill effluent on the rate of filtration of water by oyster gills measured by the drop-counting method. Concentration 1:500.

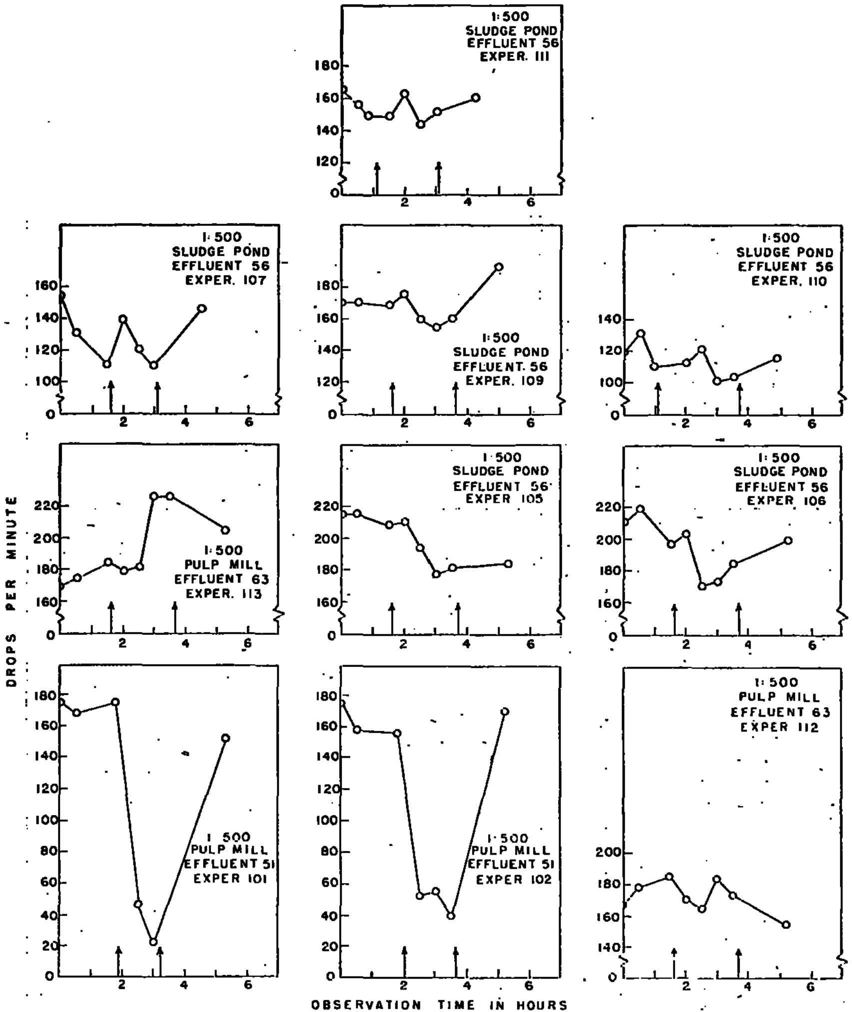

FIGURE 60.—Effect of various samples of pulp-mill and sludge-pond effluents on the rate of filtration of water by oyster gills measured by carmine-cone method.—Concentration 1:500.

pumping of water in the control oyster was approximately at the same level as at the beginning of the experiment.

Obviously, the larger oysters pump greater amounts of water than smaller ones, but besides the differences in size, the rate of pumping is dependent also on the physiological conditions or the needs of the organism. These conditions cannot be ascertained in advance. A study of the effect of an external factor on the rate of pumping must be made, therefore, by determining this decrease or increase in comparison with a certain known level of activity. This basic rate of pumping, which was considered as 100 percent, was determined for each experimental oyster by analyzing its record of activity during the preliminary period, i. e., when the test specimen was kept in plain sea water. Duration of these periods are given in column 8, table 52. From kymograph records the rate of pumping was determined for each hour the shells of the oyster were open and the mean rate for the entire period when the oyster was active was considered its basic rate. The mean rate of pumping in various concentrations of pollutant was computed in a similar way for the entire period of exposure, counting only the hours when the shells were open, and compared with the basic rate of the same specimen. Figures in the last column of table 52 give the percentages of the basic original rates. As can be seen from the examination of figures 61 and 62, the initial rates of pumping in the majority of oysters varied from 6 to 12 liters per hour. The purpose of the control oysters was to demonstrate that no significant variation in the rate of flow could be attributed to some unexpected change in the sea water or to the injury of the oysters caused by the conditions of the experiment. Examination of the curves, marked in figures by solid circles, shows that the rate of pumping in the control remained fairly constant and, in many instances, was higher at the end of the test than at its beginning.

Concentrations of 1:200 and 1:400 of the pulp-mill effluent gave immediate and marked effects, depressing the water output to a small fraction of its rate observed before treatment. In the tests employing the concentration of 1:200 of samples 3 and 5, oysters filtering originally over 10 liters per hour, decreased the rate to a fraction of a liter (fig. 61). The effect of this effluent in concentrations of 1:770 and 1:1,000 was less pronounced. Some of the oysters were almost unaffected while others showed a marked drop in the rate of flow. Sample No. 6 decreased the pumping activity of one oyster at a concentration of 1:770 but did not appreciably alter the rate of another oyster kept in the same concentration. Of the six samples of the effluent tested at a concentration of 1:1,000, sample No. 6, which had the lowest specific gravity of the group, was the only one that did not produce a reduction in the rate of flow.

There was no change in the rate of pumping in the tests in which the paper-mill effluent (sewer *A*)

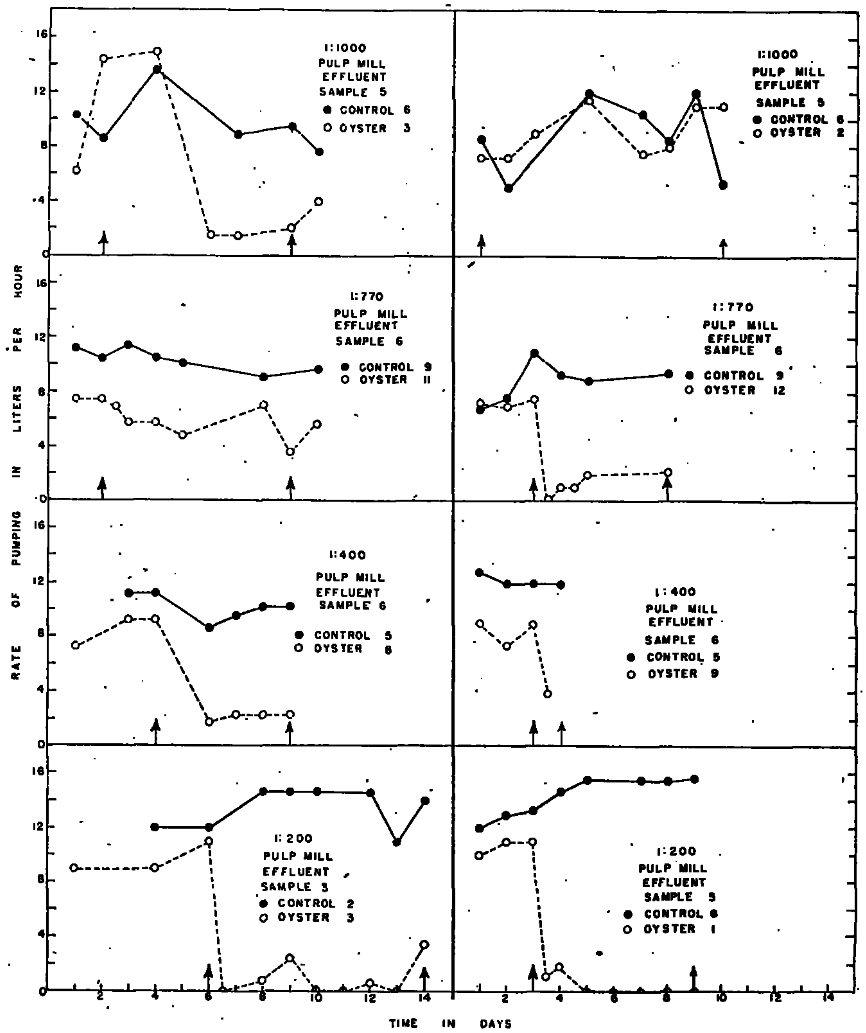

FIGURE 61.—Effect of the pulp-mill effluent in concentrations from 1 : 200 to 1 : 1,000 on the rate of water filtration of oysters. Rubber-apron method. The period between arrows represents the period of treatment. Conditions of the experiments are given in table 52.

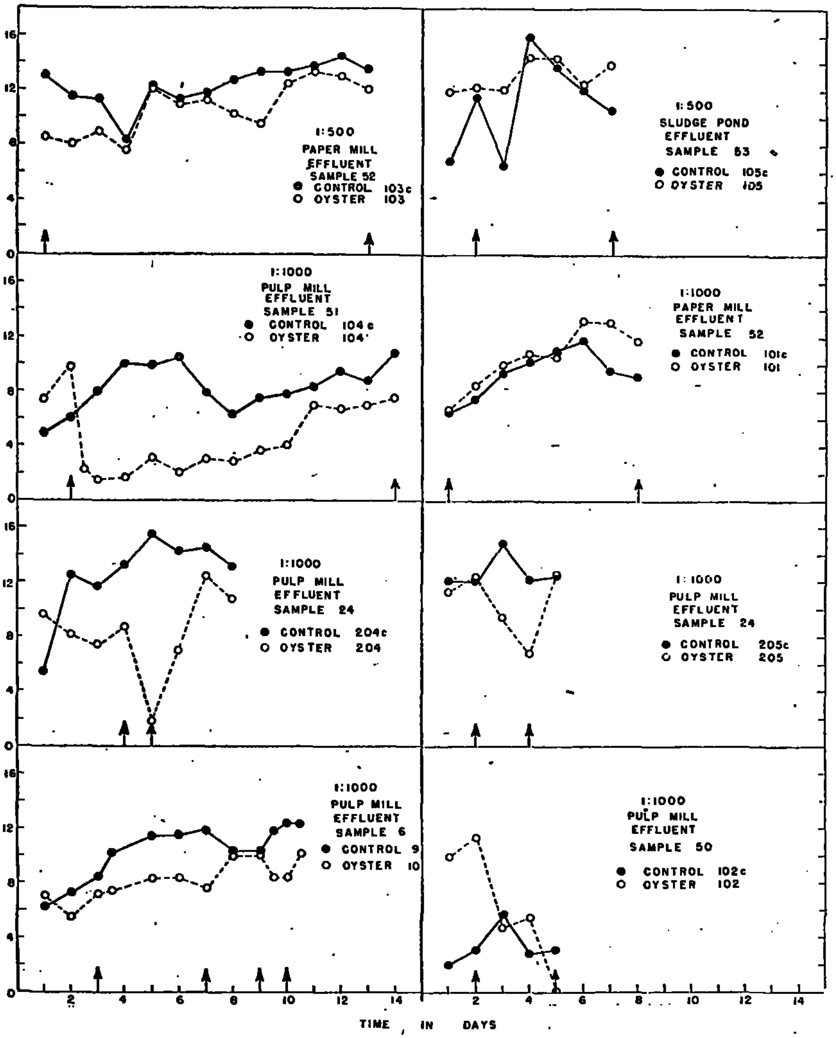

FIGURE 62.—Effect of pulp-mill effluent in concentrations of 1:1,000, paper-mill effluent in concentrations of 1:500 and 1:1,000, and sludge-pond effluent in concentrations of 1:500 on the rate of water filtration of oysters. Rubber-apron method. The period between arrows represents the period of treatment. Conditions of the experiments with pulp-mill effluent are given in table 52.

was used at concentrations of 1:1,000 or 1:500, nor with the sludge-pond effluent at a concentration of 1:500 (fig. 62).

It may be added that, in the tests with pulp-mill effluent, there was a noticeable change in the character of shell movement, consisting of a series of rapid and forceful closures (fig. 45) immediately after the addition of the pollutant. This reaction of the adductor muscle already has been described in a previous section. It was readily noticeable in the concentrations of 1:1,000 and stronger.

In several instances, when the pumping of water by experimental oysters stopped, the shells remained open, and the shell movement became irregular. These observations clearly show that the opening of the shell does not necessarily indicate that the oyster is feeding.

Experiments using the apron method clearly indicate that the physiologically active material was present in appreciable amounts only in the effluent coming from the pulping process (sewers *J* and *H*). They also corroborate the conclusion made from the tests using the carmine-cone and drop-counting methods that the amount of active material in different samples of pulp-mill effluent greatly varies.

So far, for the sake of convenience in presenting the experimental data, the various effects of pulp-mill effluent on oysters were considered separately.

TABLE 52.—*Effects of pulp-mill effluent (sewers* J *and* H) *on rate of pumping of oysters, (rubber-apron method)*

[Rate of pumping of test oysters is expressed in percentage of basic rate determined from records obtained during the number of days these oysters were kept in sea water before pollutant was added. Basic rate for control has been determined for the same periods of time. The order of figures of temperature and salinity indicates the trend of change during the test]

Concentration	Sample No.	Effluent specific gravity at 17.5° C.	Oyster No.	Dates of test (inclusive)	Temperature range °C.	Salinity range, parts per thousand	Days in sea water	Days in effluent	Rate of pumping in percent of original rate	
									Control	Test
				1936						
1:200	3	1.0013	1	Aug. 25–Sept. 2	29.0–24.2	21.9–23.2	3	6	119.1	4.4
1:200	3	1.0013	3	July 7–23	25.8–30.4	19.5–20.6	3	8	107.5	9.4
1:400	6	1.0012	9	Sept. 15–18	24.0–25.2	23.0–23.8	3	1	97.5	46.4
1:400	6	1.0012	8	Sept. 5–9	26.4–20.4	22.5–23.0	3	4	93.9	25.6
1:770	6	1.0012	12	Nov. 16–23	11.3–9.3	22.4–22.9	3	5	105.1	16.2
1:770	6	1.0012	11	Nov. 3–12	15.0–12.2	----------	2	6	92.4	84.2
1:1,000	5	1.0013	3	Aug. 3–13	28.9–25.1	20.6–21.1	2	4	99.5	114.6
1:1,000	5	1.0013	2	Aug. 8–22	28.5–25.9	20.6–21.5	1	6	111.6	125.7
1:1,000	6	1.0012	10	Oct. 15–24	18.1–21.3	22.8–24.0	6	5	125.1	102.5
				1937						
1:1,000	24	1.0043	204	Oct. 22–29	17.5–13.0	20.7–19.9	4	1	128.2	22.1
1:1,000	24	1.0043	205	Nov. 7–11	14.9–12.3	17.2–18.4	2	2	110.4	70.7
				1938						
1:1,000	50	1.0022	102	June 8–12	22.6–25.3	17.1–18.8	2	3	156.0	39.9
1:1,000	51	1.0014	104	June 11–27	23.4–25.3	17.9–19.6	2	13	161.6	46.6

It has been demonstrated that the pollutant reduces the number of hours oysters remain open and depresses their rate of feeding. Either of these reactions reduces the amount of water filtered by the oyster. Their combined effect can be evaluated by determining from the kymograph records the total volume of water filtered by the oyster during each day of the exposure to the pollutant. As an illustration of such effect, we have selected the data from the test with oyster No. 104 which was kept for 12½ days in a concentration of pulp-mill effluent of 1:1,000. The specific gravity of the effluent was 1.0014 and the experiment was run from June 14 to June 27, 1938. During this time the temperature and salinity of water varied between 23.4° to 25° C. and 17.9 to 19 parts per thousand. The data are given in table 53.

TABLE 53.—*Effect of pulp-mill effluent (sample 51) diluted 1:1000 on the rate of pumping per hour and the total amount of water filtered by the oysters during each day in the experiments made June 14 to 27, 1938*

[Difference between control and experimental=1,499.2 liters]

Day of observation	Experimental			Control		
	Time open	Rate of pumping	Total water filtered	Time open	Rate of pumping	Total water filtered
	Hours	*Liters per hour*	*Liters*	*Hours*	*Liters per hour*	*Liters*
1	24.0	7.4	177.6	24.0	4.8	115.2
2 [1]	[1] 12.0	[1] 9.8	[1] 235.2	[1] 11.1	[1] 6.0	[1] 133.2
2 [2]	[2] 6.1	[2] 2.2	[2] 26.8	[2] 11.2	[2] 6.0	[2] 134.4
3	11.1	1.4	15.5	21.2	7.9	167.5
4	16.8	1.6	26.9	21.6	10.1	218.2
5	14.5	3.1	45.0	21.9	9.9	216.8
6	16.2	2.1	34.0	20.2	10.4	210.1
7	16.4	3.1	50.8	20.9	8.1	169.3
8	15.9	2.8	44.5	16.1	6.2	99.8
9	12.9	3.7	47.7	15.8	7.3	115.3
10	16.2	4.1	66.4	22.1	7.7	170.2
11	16.0	7.0	112.0	23.2	8.2	190.2
12	14.3	6.7	95.8	21.2	9.4	199.3
13	15.8	6.9	109.0	21.0	8.7	182.7
14	12.1	7.4	99.3	23.2	10.9	252.9
Total for 12½ days of test	--------	--------	760.3	--------	--------	2,259.5

[1] Observations made 12 hours before addition of test material to experimental chambers.

[2] Observations made 12 hours after adding of test material to experimental chambers.

During the first day and a half, when both the test and the control oysters were kept in plain sea water, the rate of pumping by the test oyster was slightly greater than that of the control. Both specimens were open for about the same number of hours. The rate of pumping and the total daily amount of water filtered was immediately reduced after the supply of the effluent was turned on. In the control oyster, the rate of pumping was gradually increasing and by the end of the test (fourteenth day of observation) this oyster pumped more than double the volume of water filtered during the first day. There was possibly some common factor present during the last 4 to 5 days of the test which was responsible for an increase in the rate of pumping of both oysters. The total result was that, during the 12½ days, the test oyster filtered 760.3 liters against the 2259.5 liters filtered by the control oyster, a difference of nearly 1,500 liters. Similar data computed for other tests show that the total amount of water filtered by the oyster is materially reduced when sea water in which they are kept contains small amounts of pulp-mill effluent.

PHYSIOLOGICAL EFFECTS OF VARIOUS MATERIALS CONTAINED IN THE PULP-MILL EFFLUENT

As all the pulp- and paper-mill effluents which exert a marked physiological effect on oysters were obtained from the outlet of the sewer connected with the pulping process, the physiological action of the various materials entering this sewer-ditch were made the object of investigation. The effluent of this ditch contains the following mill wastes: the last diffuser wash; sea water from the condensers; blow-down condensate; weak-black liquor; sulfate soaps; and "burnt cooks."

The first three are the normal components discharged through this sewer, while the last three enter at irregular intervals because of errors in the operation of either the digester house or of the recovery house. Before describing the manner in which these latter wastes find access to the sewers it is necessary to clarify the designations applied to some of these wastes.

The character of both the last diffuser wash and the weak-black liquor were given in connection with the description of the mill and its process, while the sea water is self explanatory.

The blow-down condensate arises as follows: after the cooking process has completely disintegrated the chips in the digester, the liberated cellulose fibers are released with the digester contents to the first cell of the diffusion battery. As the cooking liquor passes from the elevated temperature and pressure of the digester to the atmospheric pressure of the diffusion cell, it liberates great quantities of steam. This steam, which carries with it a large volume of vapors of volatile substances that are either liberated from or derived from the chips during the cooking process (Klason 1908; Klason and Segerfelt 1910; Bergström and Fagerlind 1909; Rinman 1911) is passed through a condenser in order to recover the turpentine present. After separation of the latter, the condensed water, or blow-down condensate, is discharged as a waste product into the weir.

The sulfate soaps may be described as follows: the species of wood used by this mill contain oleoresins (Herty and Dickson 1908) together with a certain quantity of the true fats (Carpenter 1937). During the pulping process the alkali of the liquor reacts with both the fats and the resin acids of the oleoresin, converting them into their respective sodium salts, which are ordinarily called soaps. These soaps, being but slightly soluble in the alkaline cooking liquor, tend to separate as an upper layer. That formed on the weak black liquor is known as "weak soap" while that separated in the process of concentrating the black liquor for incineration is called "strong soap." Despite their strong detergent power, these soaps are of little market value because of their dark color and disagreeable odor.

In most pulp mills there are occasions when, through some faulty procedure, the charge of chips in the digester undergoes, at the cooking temperature, a partial charring that results in a product called a "burnt cook," which makes the pulp obtained difficult to purify. Whenever the amount of charred material present is so great that the cost of purification exceeds the value of the usable pulp, the entire contents of the digester are usually discarded.

As black liquor, sulfate soap, and burnt cooks do not enter the sewer when the mill is operating properly, a description of their mode of entry is necessary, as all of them contain substances which exert a physiological effect upon oysters. Located in the area between the chip conveyor and the recovery house, but not shown in the plant lay-out in figure 4, are several covered steel tanks of different sizes which are used for the storage of black liquor during the various stages of its recovery. In the largest tank, about 30 feet in diameter, the filtered weak-black liquor is stored as feed for the evaporators. The air vent of this tank is connected to a 15-inch cast-iron pipe emptying into a weir in ditches *J* and *H*. The liquid in this tank is usually covered with a froth of weak soap which sometimes, if the tank is nearly full, can be seen escaping through the vent and flowing into the weir. On some occasions the weak-black liquor has been collected at the outlet of this pipe. Another, even more frequent, mode of entry of weak soap into the sewers *J* and *H* is the froth from the weak-black-liquor filter. This filter is on top of one of the smaller steel tanks located just outside the north end of building 9 in figure 4. This filter is fully enclosed, but fitted with a 4-inch vent pipe which discharges into an open sump beneath it. The position of this sump is about at the place in figure 4 where sewer *J* changes from a due north to a northwesterly direction. On almost every visit to the mill during the time of this investigation, this vent pipe was discharging a mixture of weak-soap froth and pulp fibers into the sump.

The strong sulfate soap gets into the sewers only at very infrequent intervals, but the quantity entering at such a time is usually quite large. This strong soap, having been skimmed from the black liquor during concentration of the latter, is stored in one of the steel tanks previously mentioned. Steam coils in this tank keep the soap liquid so that it can be pumped to either the shipping dock or to the incinerators. The latter means of disposal requires high pressure in the pipe-line and occasionally there occurs a break in the line spilling the soap on the ground in the vicinity of these tanks. Between July 1 and November 1, 1938, no less than three such accidents occurred. Each time the spilled soap covered an area of more than a thousand square feet to an average depth of about 6 inches and extended to the sump. This soap, having very little value, is left on the ground until washed into the sump by rains, finally getting into the river. In the three cases observed it was apparent that at the time of the accident a large amount of soap had flowed into the sump.

Notwithstanding the claim that burnt cooks are not discarded, appreciable quantities of pulp are frequently found on the ground adjoining the weirs of sewers *J* and *H*. On one occasion, after the ditch carrying effluents from these sewers had been changed to a covered aqueduct, a pile of pulp 2 or 3 feet in diameter and 18 to 20 inches in height was found on the plank cover of the aqueduct where it connected with the weirs. The position of this pile of pulp in relation to the 15-inch cast-iron pipe which entered the weir, and the distance of the pile, more than 6 feet from the end of the pipe, indicated that the pulp had been discharged from the pipe with considerable force. These particles had a charred appearance typical of burnt cook, and were too black to be the shives usually found.

A few hours before this pile of pulp was examined, two 5-gallon samples of water, collected at the highway bridge over the Pamunkey River, about one-half mile down stream from the location of the outlet of the aqueduct carrying the effluent from this pipe, showed a marked physiological effect upon oysters and also contained considerable quantities of very black pulp.

For examination of the physiological effect, tests were made of strong soap, weak soap, weak-black liquor, last diffuser wash, and blow-down condensate, from samples collected as these materials actually were being added to the effluent of the pulp mill. For these tests the changes in the rate of pumping of sea water by oysters were observed using the carmine-cone technique as previously described, with increasing concentration of test material. The results are presented in figure 63.

From these results it will be seen that the materials effective in reducing the pumping activity of oysters are contained in the black liquor and soaps. These same materials, of course, are present in the last washings of the diffusers but here they are present in greater dilution and in only one of the experiments was this effluent sufficiently strong to produce a slowing down of the rate of pumping. It must be borne in mind, however, that the method of bioassay was such that the effective materials must produce their action within a 30-minute exposure time. No answer has been obtained, as to what action these physiologically active materials would exert on the oyster in dilute concentrations over a period of time. It will be readily seen, however, that these active materials do enter the river at times in very high concentration as a result of faulty operation of the equipment used in the recovery process. Some of the variations in the characteristics of both the pulp-mill effluents and mill liquors are given in table 54.

TABLE 54.—*Variations in mineral constituents of mill effluents and mill liquors*

Sample No.	Density 25° C. / 25° C.	Percentage by weight			Source of sample
		NaOH	Na_2CO_3	Na_2S	
70A	0.999	0.013	0.15	0.068	Outlet of 15-inch pipe (east weir of ditches *J* and *H*); weir full of froth.
71E	1.018	1.54	.54	.251	Weak-black liquor.
73	1.078	1.49	.64	.078	Do.
75	1.092	1.4	.67	.112	Do.
88	0.998	0.73	.12	.045	Outlet of 15-inch pipe (east weir of ditch *J* and *H*).
89L	1.056	0.57	.20	.13	Vent of 30-foot weak-black-liquor tank.
90	1.079	1.89	.60	.11	Weak-black liquor.
92	1.099	2.74	.98	.15	Do.
94	1.007	0.57	.23	.57	Outlet of 15-inch pipe (east weir of ditches *J* and *H*).
95	1.086	1.53	.44	.57	Weak-black liquor.
97	1.193	4.41	1.08	1.65	Concentrated black liquor.
98	1.083	1.86	.62	.74	Weak-black liquor.
99	1.015	2.20	.095	.071	Effluent of west weir of ditches *J* and *H*.

CHANGES IN EFFECTIVENESS OF PULP-MILL EFFLUENTS UNDER STORAGE AND OXIDATION

The usual effluents from the sulfate process freshly collected have been shown to contain substances having a marked physiological action on oysters and contain substances toxic to finned fishes (Hagman 1936). Since the materials are known to be oxidized (Bergström and Trobeck 1937) exposure of the pulp-mill effluents to the air for any appre-

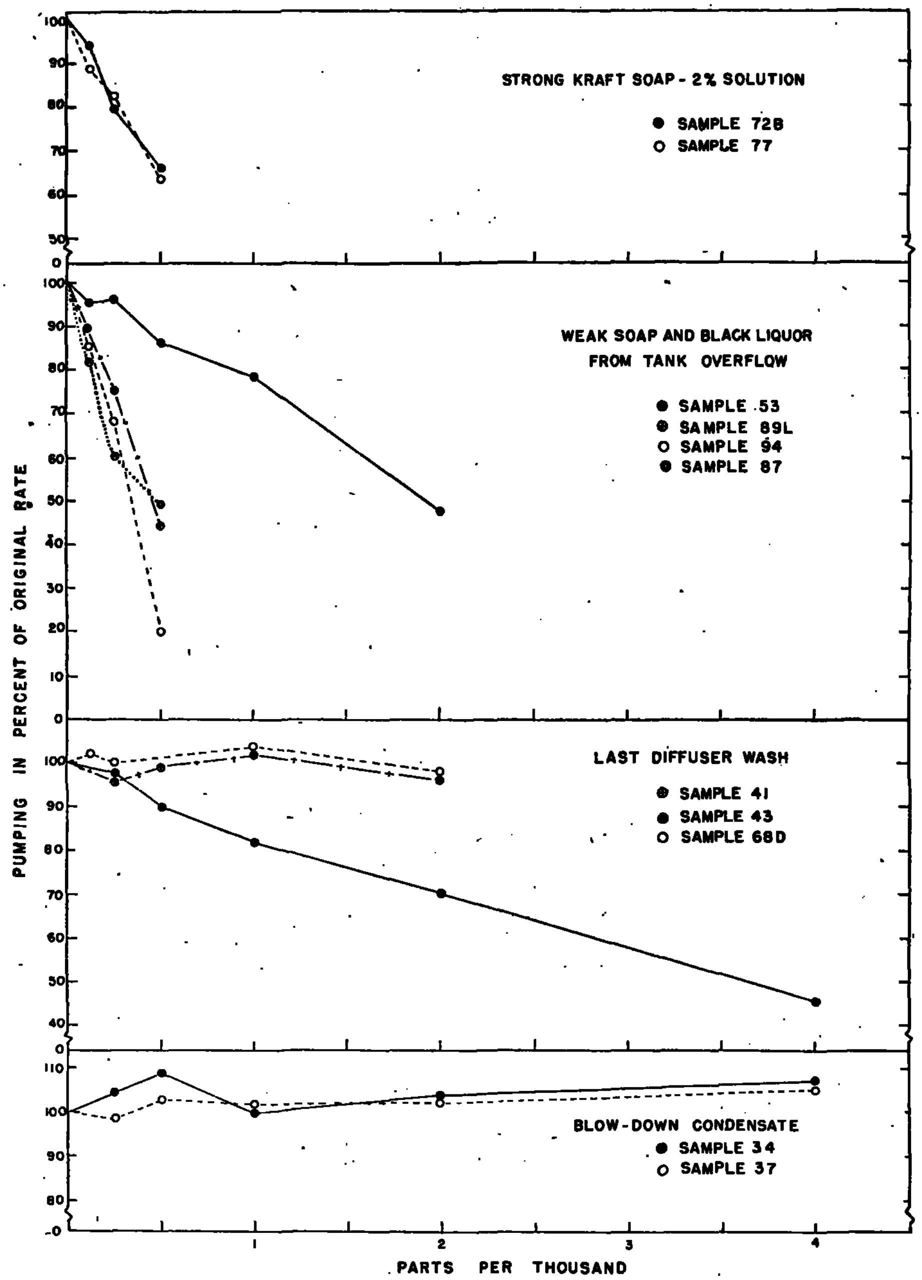

FIGURE 63.—Effect of various waste materials composing the pulp-mill effluent on the rate of water filtration of oysters. The exposure time was 30 minutes in each increasing concentration. Carmine-cone method.

ciable length of time might be expected to alter the character of the constituents present. As a consequence, experiments were performed to determine the changes in physiological effectiveness caused by the storage of the effluents and the effect of gases upon their toxicity.

A sample of effluent from pulp-mill sewers *J* and *H* was tested as to its effectiveness in reducing the rate of pumping of water by oysters. One portion of this sample was kept in a stoppered bottle and another in an unstoppered bottle open to the air for a period of 4 weeks. At the end of this period the stored portion was tested as to its action on oysters. The results, given in the curves of figure 64, show that storage under these conditions did not appreciably alter the physiological action of this sample.

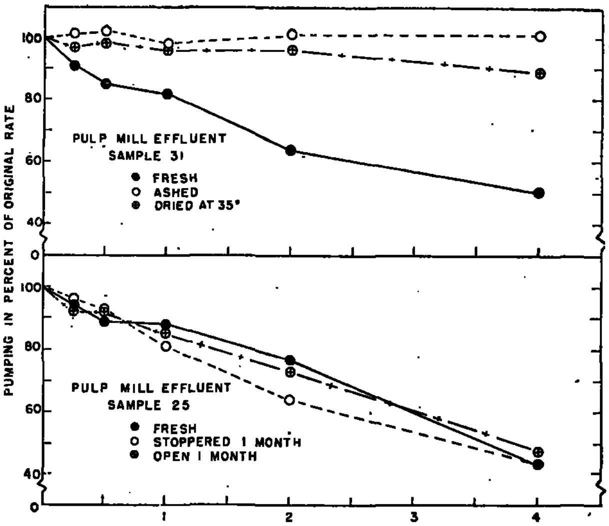

FIGURE 64.—Effect of storage and drying of pulp-mill effluent on its effectiveness in changing the rate of water filtration of oysters. Carmine-cone method with increasing concentrations at half-hour intervals.

Another sample of effluent from pulp-mill sewers *J* and *H* was collected and tested as to its action on oysters. One portion of this sample was dried at 35° C. in an open dish in an electric oven, and another portion was evaporated to dryness over a bunsen burner and then ashed. Both of the treated portions were then taken up in distilled water to their original volume and tested as to their physiological activity on oysters. The results are shown in the upper part of figure 64. Within the limits of these experiments, drying the sample greatly reduced its potency and ashing completely destroyed its activity.

Since the toxicity of the mill effluents was seen to be correlated rather definitely with the amount of weak-black liquor present, samples of weak-black liquor taken directly from the line supplying the evaporators were tested. The samples were collected into hydrogen-filled flasks. The flasks were completely filled with the hot liquor; then a rubber stopper connected to a hydrogen reservoir was inserted. After the stopper had been tied in place the connection to the hydrogen reservoir was opened. In this series of experiments, the stock samples were kept under hydrogen and for all withdrawals the liquid removed was displaced by hydrogen.

On the day of its collection a portion of this material was withdrawn in the manner described and tested as to its effectiveness in reducing the rate of pumping of oysters with increasing concentrations of the test material. At intervals, samples from the supply kept under hydrogen were withdrawn and tested. In the case of sample 90 (fig. 65), storage under hydrogen completely prevented the loss in effectiveness of the sample for a period of 14 months. In sample 71E the loss in effectiveness was somewhat reduced, but the toxicity of the liquor was still pronounced after 14 weeks of storage (fig. 66).

In like manner, tests were made at intervals using portions of one of these samples stored in the laboratory in open vessels. The loss in potency with storage of the sample exposed to the air is seen in the different curves of figure 67.

On the day of its collection, a 250-milliliter portion of one of the samples was placed in a 500-milliliter flask; the superincumbent air was displaced with oxygen (99.5 percent purity) and the closed flask attached to a reservoir containing a known volume of oxygen. The flask and its contents were shaken for 90 hours. The absorption was at a pressure of 1 meter, water gage, and the oxygen consumption, not corrected to standard conditions, was 2,750 milliliters. Physiological tests with this portion showed that the potency had been completely destroyed by the treatment with oxygen. A graphic presentation of these data is given in figure 68.

From all the experiments performed, it is evident that by oxidation a great part of the active material of the effluent can be rendered physiologically ineffective. This material, however, is not readily oxidized. Storage in air for periods as long as eight

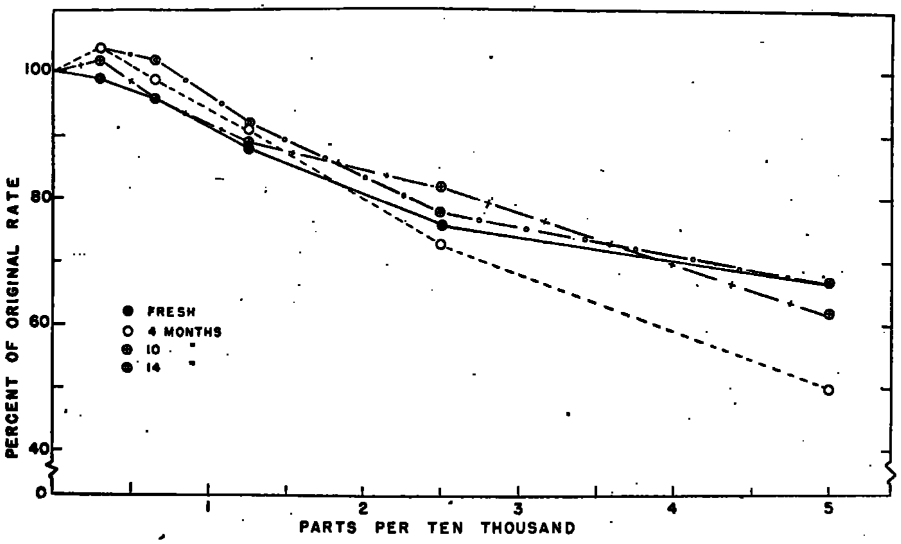

Figure 65.—Effect of storage under hydrogen on the effectiveness of weak-black liquor (sample 90) in reducing the rate of water filtration in oysters. Carmine-cone method; half-hour exposures to each of the increasing concentrations.

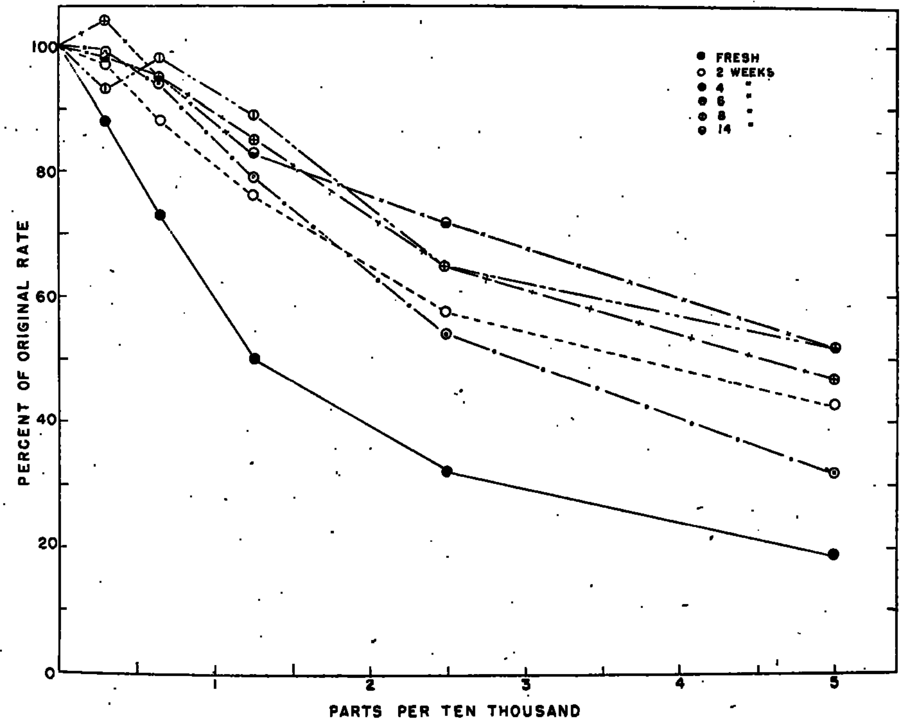

Figure 66.—Effect of storage under hydrogen on the effectiveness of weak-black liquor (sample 71E) in reducing the rate of water filtration in oysters. Carmine-cone method; half-hour exposures to each of the increasing concentrations.

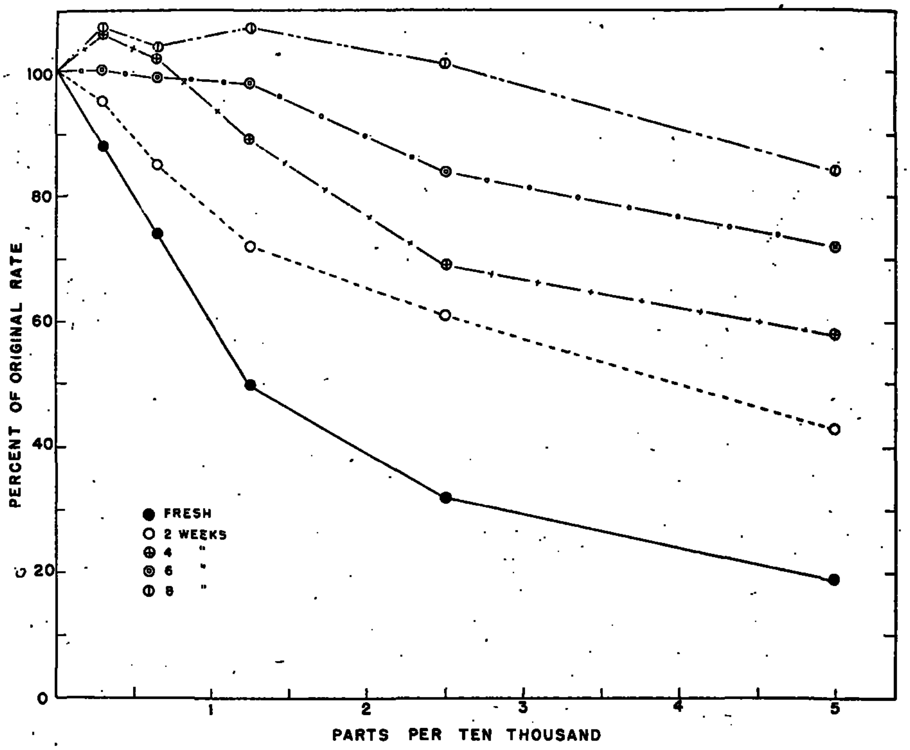

Figure 67.—Effect of storage in open vessels on the effectiveness of weak-black liquor (sample 71E) in reducing the rate of water filtration in oysters. Carmine-cone method; half-hour exposures to each of the increasing concentrations.

weeks did not completely destroy its effectiveness in reducing the rate of water filtration of oysters under the experimental conditions.

CHEMICAL NATURE OF WEAK BLACK LIQUOR AND KRAFT SOAPS AND RESPONSE OF OYSTERS TREATED WITH FRACTIONS OF THESE MATERIALS

Despite an extensive literature on sulfate black liquor very little of it deals with a careful determination of the organic constituents. Most of the publications are devoted to technical discussions of the processes advocated or in use for recovery of the alkali values from the liquor. The most frequently cited publications (Klason, 1893; Klason and Segerfelt, 1910) report lignin, ether solubles, formic, acetic, resin, and lactone acids together with phenols as the organic components. A similar paper (Klein, 1908) adds to the list but does not mention any sulfur compounds. In a discussion devoted chiefly to an improved pulping process, Rinman (1911) proposes a new classification of the gross organic constituents. In some fractionation experiments (Cirves, 1930) a relationship is sought between the pentose and hexose sugars and the oxyacids and humic acids of the black liquor. In a fairly recent paper (Heath, Bray, and Curran, 1933) attention is called to black liquor undergoing changes on storage.

A search (Holzer 1934) by the color-curve absorption method for the black-liquor constituents responsible for the dark color of sulfate pulp revealed a single, sulfur-containing, primary unit, which showed the reactions of phlobotannins, as being the source of the color. While the sulfur compounds in the stack gases from the incineration of the concentrated black liquor have given rise to numerous publications, there is only one (Kress and MacIntyre, 1935) in which attempts to prepare a sulfur balance for the sulfate-pulping process was made, but this paper gives no information about organic sulfur compounds in the black liquor.

The literature on sulfate soap is in a condition similar to that for black liquor, the principal topics being the development of refining processes which will enable the sulfate soap to be marketed in competition with soaps from the usual sources. The sulfate soaps from European sulfate mills have been studied by several workers, but; because of the difference in the tree species, the European data are

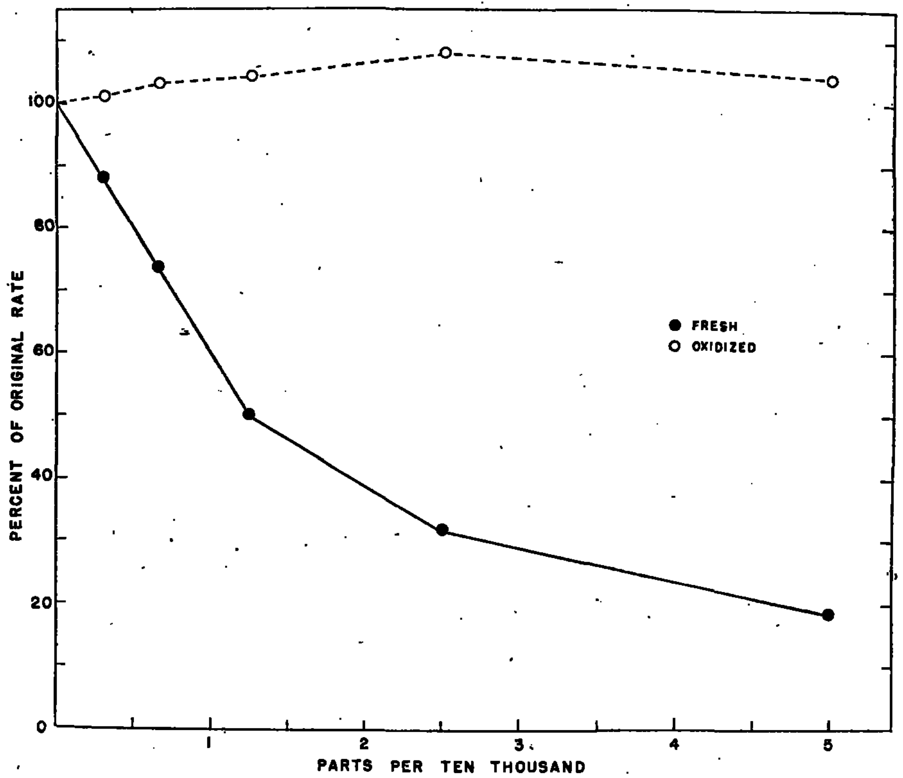

FIGURE 68.—Effect of treatment with pure oxygen on the effectiveness of weak-black liquor (sample 71E) in reducing the rate of water filtration in oysters. Carmine-cone method; half-hour exposure to each of the increasing concentrations.

of little value to the present problem. Three publications (McKee and Blengsli, 1936; Wallach, 1937; and Pollak, 1938) dealt with the composition of the sulfate soaps obtained in pulping American wood. The most comprehensive paper was that of McKee and Blengsli, who isolated from the soap acids a gasoline-insoluble substance which was not examined further than its classification as an organic acid produced by oxidation of the resin acids.

During the course of the present investigations fractionation was made of a sample of strong sulfate soap (sample 77) scooped from the ground in the area between the structures designated by the numbers 5, 9, and 10 in figure 4. During the night of October 30, 1939, the pipe line carrying the melted soap to the incinerators broke and spilled the soap on the ground. The total quantity of material spilled cannot be determined, but at 6 a. m. on October 31 the material covered an area of about 1,200 square feet and was still dropping to the ground from the broken pipe. At 11 a. m. the break had been repaired but the layer of soap had an average depth of about 8 inches over the area and remained there until rains carried it into the sump emptying into sewers *J* and *H*. At the time of the accident an unknown amount of this soap had also entered sewers *J* and *H* through the sump, for two sides of it were bordered by the spilled material. As shown in figure 63, a 2-percent solution of this soap produced a marked physiological action on oysters when added to the sea water in increasing concentration from 1 : 32,000 to 1 : 2,000. The sample was fractionated using methanol and ethanol in accordance with the scheme shown in figure 69, and the various fractions tested at like concentrations as the original sample 77 as to their effectiveness in reducing the rate of water filtration of oysters using the carmine-cone technique. The results of the bioassays of each fraction are indicated in figure 69. In control experiments it was learned that at the concentrations used with the sulfate soap fractions, both methanol and ethanol were found to have no physiological effect upon the oysters.

A study of the results shows that toxic substances are in that portion of the soap having the greater solubility in these solvents. The separation obtained even with repeated fractionation was not capable of isolating the toxic substances in a highly concentrated form.

While treatment with strong alkali caused improvement in the color of the sulfate soap in agreement with the findings of Wahlberg (1924), it did not remove the toxic substances. Control experiments showed sodium hydroxide was physiologically ineffective except when present in high concentrations.

Although the strong sulfate soap contains material which has a physiological effect upon oysters, the concentrated black liquor after removal of the soap was found to be also effective.

As sulfate soap rarely flowed into the sewers its examination was discontinued in order to investigate materials that were discharged into sewers with greater frequency.

During the collection of the sample of soap just discussed a thick froth was being discharged from the vent and overflow of the weak black-liquor storage tank. Part of this material was dropping from the vent onto the ground and part was flowing from the outlet of the 15-inch cast-iron pipe in one of the weirs of sewers *J* and *H*. Two 10-quart pails were filled with material dropping from the vent (sample 89) and a 10-gallon tub was filled with the froth coming from the 15-inch pipe (sample 87). After standing, the greater part of the froth had liquefied. Sample 89 yielded about 1 liter (89L) and sample 87 about 6 liters. Each of these liquids when added to sea water in increasing concentration from 1:32,000 to 1:2,000 caused a physiological response in oysters as shown by a reduction in the rate of pumping.

Because of the small quantity available no attempts were made to fractionate sample 89L, but sample 87 was given an extensive examination which is recorded in figure 70. The various fractions obtained were tested at like increasing concentrations as to their effectiveness in reducing the rate of water filtration by oysters. The results of these observations are included in figure 70.

From each of these samples there remained a certain quantity of froth which had not liquefied even after standing for 48 hours. In the case of sample 87 this noncondensable foam when compacted

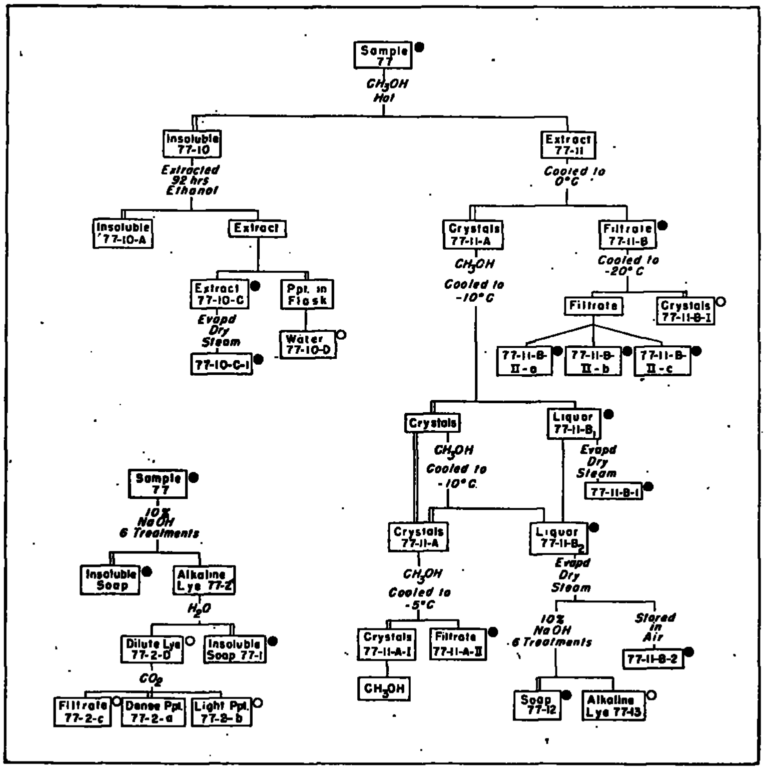

FIGURE 69.—Scheme of fractionation of strong Kraft soap (sample 77). The physiological effectiveness of the fractions is indicated by solid circles. Noneffective fractions are marked by open circles.

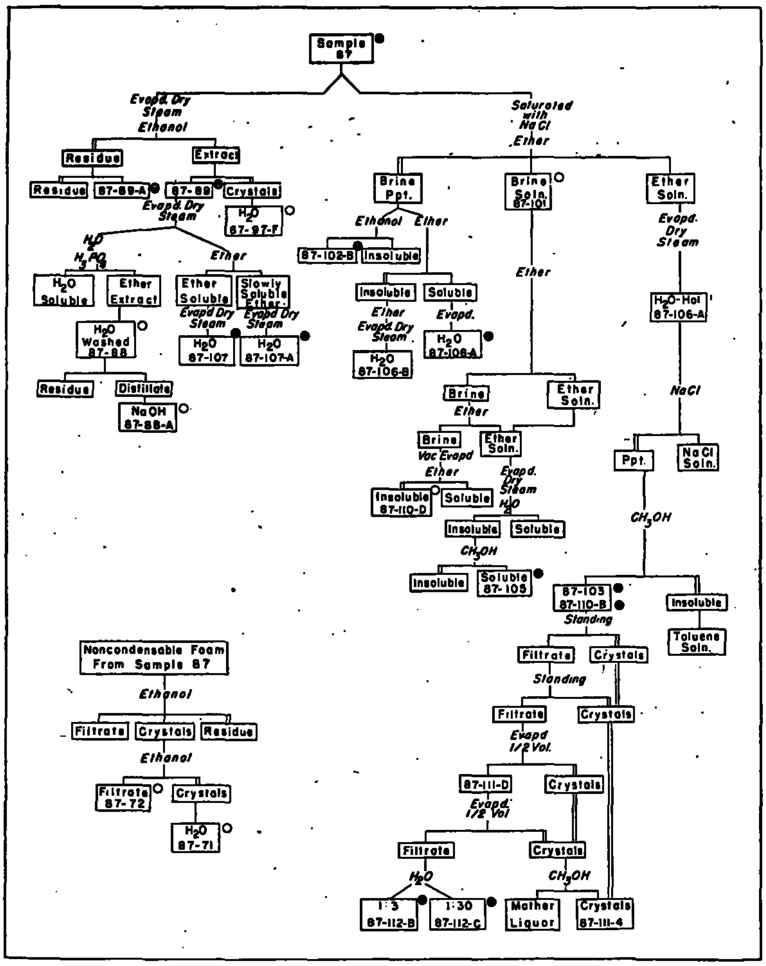

FIGURE 70.—Scheme of fractionation of weak soap (sample 87). The physiological effectiveness of the fractions is indicated by solid circles for effective, and empty circles for noneffective.

amounted to over 30 grams. This powder was extracted with ethanol in a Soxhlet apparatus. The sample was largely fine fibers and the extract did not yield fractions that were physiologically active. This fractionation, and its results when tested on oysters, is shown in the lower left section of figure 70.

Since concentration in vacuo of the liquefied portion of sample 87 was prevented by the excessive foaming due to the sodium soaps present, some of the liquid portion was evaporated to dryness in open vessels on a steam bath. The evaporation residue was then subjected to the fractionation shown in the upper left section of figure 70. It was shown in a preceding section that treatment of physiologically active mill effluents with gaseous oxygen destroyed the active principle and there was considerable likelihood that exposure of the original liquid material of sample 87 to air during evaporation might also bring about some oxidation of the active principle. This exposure to air during evaporation occurred with only the original material. All extractions of the evaporation residue and all subsequent evaporations as shown in the diagrammatic outline were carried out under hydrogen.

A portion of the liquefied material from sample 87 was saturated with salt in order to precipitate the soaps present and thereby enable evaporation to be carried out under reduced pressure and with the exclusion of air. The salt treatment precipitated the soaps as a finely divided suspension, but the addition of sulfuric ether caused them to concentrate in the upper layer. The products obtained as a result of the combined salt and ether treatments of the liquefied portion of sample 87 were then fractionated in accordance with the scheme shown diagrammatically in the right-hand section of figure 70. As the results obtained supplied an important clue to the nature of the physiologically active materials present in the mill liquors, a detailed discussion of this fractionation will be given. Whenever possible the manipulations were performed in an atmosphere of hydrogen.

The combined treatments with salt and ether yielded three fractions. The precipitate consisted largely of soaps but it also contained other substances and some fine fibers. The ether layer was dark brown and contained the physiologically active materials, while the aqueous layer, besides being saturated with salt, contained materials which imparted a deep-red color to the liquid. The aqueous layer, after removal of the precipitate and the ether solution, was given two additional extractions with ether and was then concentrated without difficulty, under reduced pressure, to about one-third of its original volume. This concentration precipitated a large quantity of the salt, which was removed by filtration and washed twice with ether. These ether washings were now used to extract the residual liquor from the concentration of the aqueous layer and then combined with the other ether extractions of that layer. This residual aqueous solution and the original aqueous layer were bioassayed as fractions 87–110D and 87–101, respectively. The various ether extracts of the aqueous layer (87-101) and its fractions were combined and evaporated to dryness leaving a slight amount of a dark brown residue. When the residue from the evaporation of the ether extracts was treated with water, a small quantity of an insoluble oil arose to the surface. Filtration through a moistened filter separated the oil from the aqueous solution. Salt was the only material that could be isolated from the latter. The oil was treated with methanol giving an insoluble portion too small for further work and the fraction 87–105 of figure 70.

The salt precipitate, labeled "brine precipitate" in figure 70, was filtered from the ether required for coagulation and then given two additional extractions with ether. These two latter extractions, 87–106A and 87–106B in figure 70, were later combined with the ether solution from the coagulation treatment and the entire mixture was bioassayed as fraction 87–106A. The ether insoluble portion of the salt precipitate was now extracted with ethanol in a Soxhlet apparatus. After this treatment, there remained a small quantity of insoluble material consisting of fine wood-fibers. The ethanol extract was bioassayed as fraction 87–102B of figure 70.

When treated with water the ether residues 87–106A and 87–106B formed a light-gray emulsion. After some preliminary titrations a 10 percent salt solution was added in the proportions 6:10 breaking the emulsion and forming a gray precipitate which was separated and then leached with boiling methanol, leaving a grayish-brown residue soluble only in boiling toluene. Due to the insolubility in water of both the fraction and the solvent no bioassays were made. The methanol leachings were clear at first but on standing deposited a few crystals. As filtration and further standing yielded a few more crystals, the methanol solution was evaporated to about one-half its original volume and cooled, whereupon another small crop of crystals appeared. Filtration and further concentration of the filtrate gave a fourth deposit of crystals. These last were yellow whereas the earlier deposits had been white, but a recrystallization from methanol yielded a product similar to the others. These four deposits had a total weight of 0.09 grams, an amount too small for bioassay.

When the mother liquor from these crystals was diluted to four volumes with water, 87–112B, it caused a pronounced physiological action on oysters. Even after a further ten-fold dilution this material, 87–112C, still greatly reduced the rate of water filtration of oysters. The quantities of these samples remaining after the biological and chemical tests had been made were insufficient for further refining and testing, and the quantity of sample 87 on hand was too small to permit a repetition of the fractionation.

The method of salt precipitation used so successfully for separating the toxic portion of sample 87 met with several obstacles when applied to samples of weak black liquor. Due to the black liquor containing larger percentages of the constituents insoluble in the salt brine, the use of even larger volumes of ether did not effect a distinct separation between the brine and the precipitate. Filtration of such a mixture, using air-tight vessels filled with hydrogen, required several days and resulted in the loss of much of the ether from evaporation. Drying the material by storage over calcium chloride in hydrogen-filled desiccators required several weeks and caused the material to lose its physiological activity. When

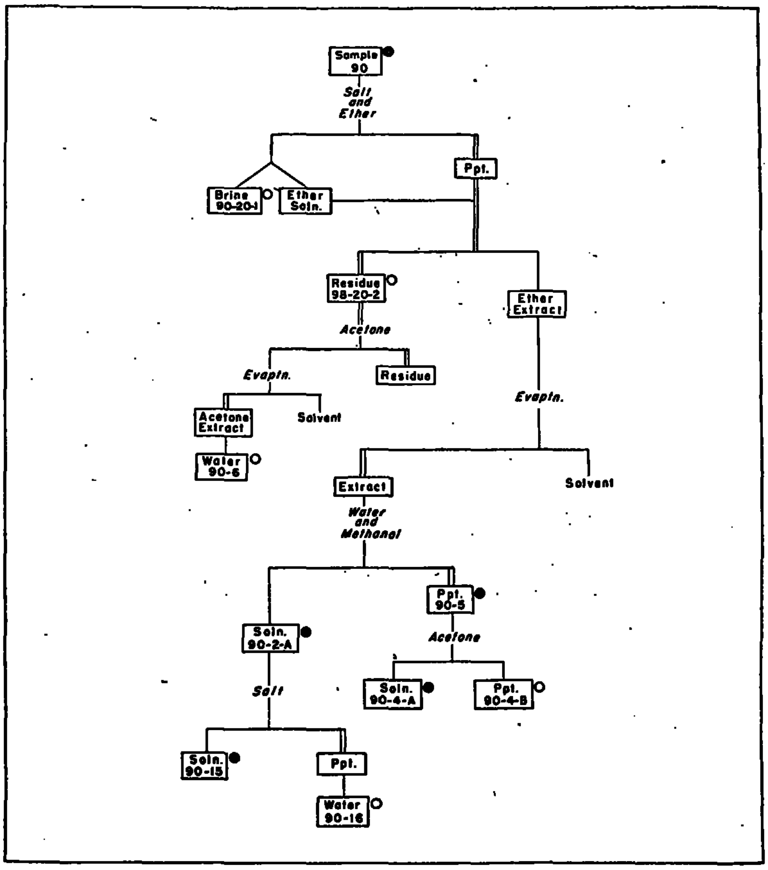

FIGURE 71.—Scheme of fractionation of weak-black liquor (sample 90). The physiological effectiveness of the fractions is indicated by solid circles for effective and open circles for noneffective.

placed in an evaculated desiccator the freshly precipitated material at once overflowed its container and filled the entire desiccator with froth. Partial drying over calcium chloride in a hydrogen-filled desiccator followed by the application of suction caused a sudden efflorescence of the precipitate and its loss by dispersion throughout the vessel. Despite continuous and vigorous shaking for 48 hours with much more salt than was needed to completely saturate the black liquor, a single treatment did not fully precipitate the toxic substances. After filtration, two further shakings with salt, each followed by filtration, were required to obtain a nontoxic filtrate from weak black liquor. These precipitates always retained a considerable quantity of the original black liquor taken for treatment because of their gelatinous character.

In view of the difficulties described, the following procedure was used in preparing precipitate for extraction. The weak liquor was shaken for 24 hours with salt and ether, then, filtered as rapidly as possible under hydrogen. This process was repeated for a total of three treatments. It was necessary to have ether present during the precipitation because the precipitates formed in its absence were so hydrophilic that the solvent could not "wet" them enough to effect solution of the toxic substances. The toxic materials in these precipitates were isolated by continuous ether extraction for seven days in a hydrogen-filled Soxhlet apparatus. The details of the fractionation and the results of the bioassays of the various fractions isolated from weak sulfate black liquor are given in figure 71. Increasing concentrations from 1 : 32,000 to 1 : 2,000 were employed in the physiological tests on oysters.

No extensive discussion will be given of the various fractions since it would parallel very closely that already given for sample 87. Only the fraction 98–20–2 needs comment. To conserve time this fraction was prepared from black liquor sample

98 and tested while the corresponding fraction of sample 90 was undergoing the further fractionation shown. While the results obtained with the weak black liquor are not as clear cut as those obtained with sample 87, they do lead to the same general conclusion.

CHEMICAL NATURE OF THE PHYSIOLOGICALLY ACTIVE MATERIALS IN SULFATE PULP-MILL EFFLUENTS

A study of the specific sulfate pulp-mill products which exert a physiological effect upon oysters leads to the conclusion that the toxic material tends to concentrate in the soap portion of the mill products. European investigators (Ebeling 1930, 1931, 1932; Bergström and Cederquist 1937; Bergström and Trobeck 1937; Bergström and Vallin 1937; Hagman 1936, 1937; Järnefelt 1936; Vallin 1935; Vestergren 1938) have arrived at similar conclusions concerning the toxicity of sulfate pulp-mill wastes to finned fishes, ascribing the toxic action to the resin acids and their sodium and calcium salts.

It has been found, however, in the work reported here that the sulfate soaps precipitated from mill liquors by salt were not toxic after treatment with ether, whereas the ether extracts of these soaps did contain the harmful material. This indicated that these soaps, when precipitated from aqueous solution by salt, adsorbed the toxic substance of the mill liquors. The necessity of repeated treatment of the black liquor with salt, before complete removal of the toxic substance was effected, is a further indication that its presence in the soap is due to adsorption by the latter of material "salted out" of the black liquor by the treatment with salt.

The sodium compounds in the black liquor will produce an effect similar to the action of the salt. Sample 87 also gave corresponding results, although to a lesser degree, in that the ether extract (87–105) from the concentrated salt brine also contained toxic material.

The exact nature of the toxic material has not been determined, but the readiness with which ether removes it from the soap leads to the opinion that we are dealing with a constituent of the unsaponifiable portion. It has been shown definitely by Erdtman (1939) that the toxic substance in the case of the European pine, *Pinus sylvestris*, is a dioxystilbene present in the heartwood of the tree. No such work has ever been undertaken upon the loblolly pine, *Pinus taeda*, although the durability of its heartwood has been recorded by Mohr (1897).

DISCUSSION AND CONCLUSIONS

Studies of the cycles of temperature, salinity, currents, oxygen content, pH, and plankton, described in the first part of this report, show that from an ecological point of view, the conditions in the York River follow the seasonal changes commonly encountered in tidal waters of the Atlantic coast. No abnormal deviation in these factors has been noticed during the course of the studies. It is true that the oxygen content was somewhat diminished in the upper part of the York River but the decrease was insignificant and cannot be considered as affecting oysters which are known to tolerate low oxygen tension (Galtsoff and Whipple 1931). The potential food supply for oysters, measured by the total production of plankton, was greater in the York River than in the Piankatank River. Thus, an assumption that the lack of food for oysters was responsible for their failure to fatten in the York River cannot be corroborated by the evidence and, therefore, must be discarded.

Observations on glycogen cycles in the York River oyster and field experiments in transplanting oysters from the upper part of the river to its lower part and (pp. 118–123) indicate the existence in the upper part of York River of an environment decidedly harmful to oysters. This harmful effect is manifested in the failure of oysters to accumulate glycogen, in a generally emaciated condition of their meat, and in the disturbance of the calcium metabolism which results in the abnormal condition of the shell.

Further proof that the upper part of York River provides an unhealthy environment is given by the results of the field tests in which the James River seed oysters, planted simultaneously in the upper and lower York River and in the Piankatank River (fig. 36), fattened much more rapidly in the last two localities.

Recovery of oysters taken from the upper part of the York River and transplanted to other waters indicates the presence of some toxic factor in the upper York River which does not occur in adjacent localities. If the poor condition of the oysters in the upper part of York River was due to infection by *Nematopsis* spores, disease, or to degeneration of the stock, one would not expect their rapid recovery after they were removed from the grounds and planted in the lower part of the York River or in the Piankatank River. The question naturally arises whether the presence of foreign substances introduced in large quantities with the pulp-mill effluents at the head of the river at West Point is responsible for the pathological condition of the oysters. Direct evidence of the harmful effect of the pulp-mill effluent is provided by the physiological experiments which prove its toxicity. The deleterious action of the effluent is manifested by its effect on the adductor muscle, on the ciliary epithelium of the gills, and on the complex pumping mechanism of the oyster. By decreasing the number of hours the oyster stays open, the presence of the effluent in the water reduces the time normally used by the organism for feeding. Furthermore, the rate of feeding is also decreased because of the depression of the ciliary movement and reduction in the pumping capacity of the organism, due to the presence of the pulp-mill effluent.

The toxic agent in the effluent of the pulp mill produces a general depressing effect which inhibits the principal functions of the organism and results in its failure to accumulate glycogen and probably is responsible for the stunted growth of the oysters in the polluted area. This effect is apparently noncumulative, since under the conditions of the experiments, the oysters showed remarkable recovery immediately after their removal to unpolluted water. Their glycogen content increased to the normal level, shells were strengthened by deposition of lime, and growth was resumed.

The second question is whether the pulp-mill effluent occurs in York River in concentrations which were found to be effective in laboratory experiments. No chemical test is available at present for the detection and quantitative determination of the pulp-mill waste in natural waters. A nitrosolignin reaction developed by Pearl and Benson (1940) for sulphite waste liquor was not known at the the time the investigations were carried on in York River. Even if this method were known, its application in determining the concentration of pulp-mill effluent in York River would be of doubtful help because of the possibility that some of the nitrophenols which produce specific color reaction may be normally present in river water. Direct proof that harmful substances are present in the water of the York River was obtained by collecting samples of water in the upper part of York River at the time when a considerable area of the river was discolored by waste products discharged from the sewers of the pulp-mill plant at West Point, and using these for bioassays (p. 132).

Judging by the condition of the oysters in the lower part of York River and their ability to accumulate substantial amounts of glycogen, the deleterious effect of pulp-mill effluent extends down the river as far as Allmond's Wharf. It is, of course, of great interest to determine what concentration of pulp-mill effluent may actually occur in the upper half of the river and whether this concentration is of the same degree of magnitude as that which proved effective in the laboratory experiments. The problem presented considerable difficulties because of the great fluctuations in the rate of the discharge of the pulp-mill effluent and the changes in its specific gravity, presumably as a result of the degree of its dilution, chemical composition, and age. Using a conservative figure for the rate of discharge, based on personal observations, and knowing the resulting rate of flow of the river, it was possible to compute this concentration. Calculations made by using Hotteling's formula or employing the formula proposed by Tuckerman (p. 101) gave comparable results showing that either formula may be applied in such a problem.

In order to arrive at the mathematical solution of the problem, it was necessary to assume that the pulp-mill effluent is being discharged at a uniform rate, that it is rapidly and thoroughly mixed with the water, and is uniformly distributed in the river. It is realized that these assumptions deal with a more or less theoretical case and that, under natural conditions, the pulp-mill effluent is not discharged at a uniform rate and is not thoroughly mixed in the river but probably follows a definite path along the river axis. The above-mentioned assumptions have to be made, however, in order to solve the mathematical problem. It appears significant that theoretical calculations of the final concentration of the pulp-mill effluent in the polluted part of York River give a figure of 0.0004 or 1 : 2,500, which is of the same degree of magnitude as the threshold concentration determined by various laboratory tests. Thus, it has been shown that with the existing flow of the river and the observed rate of discharge of pulp-mill effluent effective concentration of the effluent may be expected to occur in the York River. Furthermore, the computations show that with a given rate of discharge of pulp-mill effluent at about 4.26 acre feet per day, this final concentration is reached within 100 days.

Laboratory tests, consisting in a study of shell movements of oysters, the efficiency of the ciliated epithelium of the gills, and the rate of pumping of water by the intact oysters, have demonstrated that pulp-mill effluent exerts a general depressing effect on the physiology of the oyster. It reduces the number of hours the oyster remains open and therefore decreases the time which could be used for feeding. It also reduces the rate of pumping of water by the gills. The depression of the rate of filtration is proportional to the concentration of the effluent. In case of the shell movement of the oysters and their ability to keep their valves open, the relationship between the concentration of the effluent and the mean number of hours the oysters remain closed can be expressed by an exponential equation (p. 141). The threshold concentration of the effluent, as determined by laboratory tests, is about 1 : 2,000. Because of considerable variation in the specific gravity and chemical composition of the effluent, this concentration does not remain constant and therefore could not be determined with accuracy.

Chemical studies of the pulp-mill effluent show that a physiologically effective fraction of black liquor which is found in the pulp-mill effluent can be separated by the method of salt precipitation. It was found that separation between the brine and the precipitate was rather difficult and that the toxic material had a tendency to concentrate in the soap portion of the mill products.

Sulfate soaps precipitated from mill liquor by salt, contained toxic material which apparently was adsorbed by them from the black liquor. Treatment with ether rendered these soaps harmless, whereas the ether extract was toxic. We may infer from these results that when black liquor is present in sea water a portion of it may precipitate as a soap and carry with it a certain portion of the toxic component. It is, therefore, quite possible that a certain portion of toxic material is carried down the river as precipitate and is deposited in the areas of sedimentation. This possibility provides a clue for explaining the rather puzzling fact that the poorest oysters were found not in an extreme upper section of the York River, close to the source of pollution, but several miles downstream on the grounds of Purtan Bay. Studies of the sedimentation process in the York River made by the Soil Conservation Service at the request of the Chesapeake Corp. (Brown, Seavy, and Rittenhouse, 1939) throw light on the problem. This investigation shows convincingly that:

> Between 1857 and 1911, there were two main areas of heaviest sediment accumulation, one at the head of the estuary between ranges 6 and 8, and one in the upper middle estuary between ranges 10 and 14. These areas of excessive accumulation were separated by an area of scour near range 9. A second and larger area of scour was located below range 14. Between 1911 and 1938 there were still two areas of filling and two of scour. These areas, however, coincide only partially with the areas of scour and fill between 1857 and 1911. The point of most rapid accumulation migrated downstream from range 13 to range 14, and sedimentation was also rapid at ranges 15 and 17, where, between 1857 and 1911, pronounced scouring occurred [fig. 23].

It is reasonable to infer that toxic material precipitated by sea water is carried by the currents and is deposited in the areas of the accumulation of sediment ("fill areas"). According to the report of the Soil Conservation Service, since 1911 the area of most rapid accumulation of silt has migrated further downstream and is now located in the section of Purtan Bay. Thus, sedimentation data provide reasonable explanation for the fact that the poorest oysters are found at some distance from the place of discharge of the pollutant.

The cultivation of oysters in the York River was conducted by the oystermen according to the methods generally employed in Virginia. It consisted in planting seed and growing it to marketable size. As in other sections in the tidewater of Virginia, James River seed was used principally for planting, although there is no doubt that a certain percentage of marketable oysters grew from the local seed. Our observations show that the propagation of oysters in York River has not completely stopped. The setting in the upper part is insignificant but in the lower part it is still of sufficient intensity to produce a set of commercial value. Unfortunately, the mortality among the small oysters in the lower part of the river is very great due to depredation by drills, which in Virginia inflict serious damage to oyster beds located where the salinity of sea water exceeds 15 parts per thousand. In this respect, the York River is no different from Hampton Roads, James River, and other oyster-producing sections of the lower Chesapeake Bay.

A theory has been advanced by representatives of the Chesapeake Corp. (Bailey 1941) that the decline of the oyster industry was "the direct result of poor methods of oyster farming, combined with silting." According to Bailey (loc. cit.) the York River oystermen had tonged most of the oysters and had failed to return to the river any appreciable amount of shells. Because of this practice, the level of the existing oyster bars was lowered and increased silting of the river covered them with soft mud.

Silting and poor management of oyster reefs is often responsible for the destruction of productive oyster grounds. Examples of such conditions can be found in the depleted natural oyster grounds in South Carolina, Georgia, and Texas. If the failure of the York River oyster industry resulted from a combination of these conditions one would expect to find a gradual decrease in the acreage available for cultivation. We know, however, that the principal difficulty in the York River was the poor quality of oysters, very low yield in pints of shucked oysters per bushel, discoloration of oyster meats, and unpleasant flavor. These conditions are not found on the grounds depleted through overfishing. It is reasonable to expect that they are due to some abnormal condition of the environment and are not the result of mismanagement or defects in the methods of oyster culture.

There is no doubt that because of deforestation and cultivation of land, soil erosion has greatly increased with the corresponding increase in sedimentation of our rivers. The condition is general for the Atlantic coast and is not unique for the York River. We know, however, that oyster grounds in James River continue to produce good oysters and up to the present provide the principal source of seed for Virginia oyster growers. Likewise, there are no signs that oysters in the Piankatank River are abnormal or poor. Observations and experiments described in this report show that the difficulty was confined to the upper part of the York River and that there was a rapid recovery of York River oysters after removal from the polluted waters. Bailey's report fails to mention the peculiar condition of oysters or the fact that the York River receives large quantities of pulp-mill effluents, but blames the oyster industry for its poor practices and lack of conservation. He also states that "the freshets that brought down the silt also caused fluctuations in the salinity of the upper river, and with this change in salinity and silt conditions came new conditions as well as new pests." Some of the pests he mentions, namely, the oyster drill (*Urosalpinx cinerea*) and the starfish (*Asterias forbesi*) are so sensitive to lowered salinity of water that the latter constitutes a barrier protecting the upstream oyster grounds against the depredation by these pests. It is a well established fact that the lowered salinity cannot be responsible for bringing these enemies to the oyster grounds.

In order to demonstrate that low oyster-production is not the result of pollution, the Chesapeake Corp. acquired a large percentage of the leases and put into operation a plan of growing oysters on trays suspended or placed above the bottom. The grounds selected for this purpose are located in the lower part of the river below Claybank wharf and at the mouth of Queens Creek. As shown in the preliminary report (Galtsoff *et al.*, 1938), and in the present paper, these grounds have not been affected by pulp-mill pollution. The results of raising oysters on platforms have not been disclosed by the Chesapeake Corp. in detail with the exception of Mr. Bailey's statement (p. 7, loc. cit.) that "While the primary purpose of the experiment was to demonstrate that an abundance of oysters of high quality could be produced in the York River when planted on hard bottoms or raised above the smothering silt deposits that prevail over a greater portion of the river bottom, the tray project, as carried on by the Chesapeake Corp., is on a practical basis in which money is only invested with the prospect of a fair return." As the method requires a large investment of capital and can be carried out only in the localities well protected against strong wind and waves, it obviously cannot be used by local oystermen lacking large financial support and having leases in the exposed areas of the river and in the bay. Furthermore, the method in which oysters are exposed at low tide is unsuitable for Virginia waters and in other localities where low winter temperature might kill them by freezing. To be applicable to Chesapeake Bay and other waters north, the platform should be placed below low-water level.

During the course of the present studies, the Chesapeake Corp. carried on a parallel investigation of the physiological effect of pulp-mill effluent on oysters. The results of these studies were not described in detail in any technical journal but a brief summary was published in a popular article by May (1943) which appeared in the February 1943 issue of the magazine *Travel.* According to the description given in this article, the Corporation conducted a series of tests in which a number of trays containing 2-year-old oysters were placed at seven stations over a distance of 19 miles along the river, from 1½ miles below West Point to Queens Creek. At each of these stations four trays with 2-year-old oysters were placed on the bottom and four trays suspended 18 inches above the bottom. The experiment lasted 11 months. How often the trays were examined is not known, but May states (p. 90, loc. cit,) that "these guinea-pig mollusks were watched almost breathlessly by the experimenters."

At the end of the eleventh month it was found that the oysters placed at the four stations located in the areas of greater sedimentation ("fill" areas) showed a "composite" survival of 65 percent in suspended trays and 22 percent survival on the muddy bottom. At the three stations in the "scour" areas the mortality was about the same for both the top and bottom baskets. (Unfortunately, the author fails to disclose the exact figures of mortality.) The investigators of the Chesapeake Corp. draw from these data a conclusion that "the entire test shows that silt caused 40 percent death in the 'fill' areas, against practically no mortality because of silt in the 'scour' area." In the absence of a detailed description of the experiment and because of the omission of essential data showing separately the mortality at each of the stations, it is difficult correctly to evaluate the results of the test. One fact, however, appears to be significant. The reported cumulative mortality of 35 percent of the oysters in the suspended baskets, and of 78 percent of those in bottom baskets, placed in the fill areas, far exceeds the normal annual mortality of the oyster population which, according to our observation, usually does not exceed 10 percent. It is obvious that either the experimental technique was defective or the conditions in York River were deleterious to oysters. Probably the latter assumption is correct; certainly, it is in accord with the findings of this report which have demonstrated the toxic effect of the pulp-mill effluent on the physiology of the oyster. High mortality rate among oysters, reported by the Chesapeake Corp. and not observed by the authors of this report, was probably due to the crowded condition of oysters kept in trays suspended in polluted water, to injuries caused by transplanting them, and in taking up and lowering the trays for inspection, and, possibly, to other factors involved in the experiment. The fact that the death rate was higher among the oysters placed in mud than among those suspended above it is not surprising. Soft mud is not a healthy habitat for oysters. In the York River this environment is even less favorable because the toxic fraction of the black liquor is probably precipitated in part by salt water and is deposited in the areas of the fill.

To prove that pulp-mill effluent has no deleterious effect on oysters the Chesapeake Corp. conducted a survival experiment, the details of which are not disclosed. It is stated, however, by May (p. 30, loc. cit.) that the experiment conducted from November 9, 1938 to May 18, 1939, consisted in keeping oysters in glass tanks filled with water from Piankatank River to which the pulp-mill effluent was added in doses "beginning with the average percentage for York River and increasing up to 77 times. The latter concoction was the color of creamless coffee." Three duplicate tanks with pure sea water were used as controls. It is not stated how often the water was renewed. At the conclusion of the experiment, writes Mr. May, "there was a momentous oyster opening attended by all the important personnel of the mill. There was also present Mr. J. R. Nelson who had spent much of his life in oyster culture who presided as an official observer." Death of one oyster in the control was recorded.

Final conclusion from the experiment conducted by the Chesapeake Corp. is formulated as follows:

> The experiment proved that 77 times the normal percentage would not bring death to a York River bivalve, probably because the carbohydrates or other sugary compounds, the salty compounds such as sodium carbonate and the ordinary vegetable matter in effluent are natural shellfish foods although little of them might reach down river oysters in the widely flowing and rather deep York * * *. In general the more effluent in the test tanks the fatter and happier the oysters appeared.

It is not clear whether this was only a personal conclusion of May or that he expresses a concensus of opinion of all who were present at a "momentous oyster opening." Professional scientists would not venture to ascertain the "happiness" of the oyster and therefore disregarded this part of the conclusion. As to the effect of the pulp-mill effluent on fattening of oysters the results of the experiment, if they are correctly presented, contradict all the observations described in detail in the present report. If May's statement be considered seriously, one would be tempted to infer that increased pulp-mill pollution of water in the York River should be encouraged for it would cause oysters to fatten and make them "happy."

It has been shown in the present study that the specific gravity and toxicity of the pulp-mill effluent were subject to great fluctuations. A certain decrease in toxicity took place after considerable improvement in the disposal of the effluent was made at the pulp-mill plant. Furthermore, chemical and toxicological studies described in the report showed that the toxicity of the pulp-mill effluent could be greatly reduced by oxidation (p. 164, fig. 68). This suggests a method of treating the effluent which would render it harmless before it is discharged into tidal waters. It is considered, however, that working out a purely technical problem of the process of treatment to be used at the mill is beyond the scope of the present investigation. The data obtained by the authors demonstrate that the physiological effect of the pulp-mill pollutant can be made harmless through oxidation. It must be pointed out, however, that oxidation proceeds rather slowly since the physiological effectiveness of the samples of pulp-mill effluent was destroyed only after vigorous treatment with pure oxygen. One may expect, therefore, that oxidation in the river may be a slow process and that the depressive action of pulp-mill effluent may remain effective for a long time. Experiments with samples of river water collected at West Point (p. 132) corroborate this inference.

The results of several years of intensive study, carried out by the authors and described in detail in this report, have been presented here with the hope that they will be useful to the pulp-mill industry and to State conservation agencies in working out a practical solution to the problem of treatment and safe disposal of pulp-mill wastes. It is the authors' strong belief that the cause of the conservation of our seafood resources in coastal waters can best be served by preventing further inroads from pollution and that through cooperation and mutual understanding of the problems involved a way may be found for the coexistence of the pulp mill and the shellfish industries, both valuable and necessary for the welfare of our Nation.

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TABLE 6.—*Hydrographic data for station 20 in the lower York River off Sandbox*

[Average depth 10.5 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature		Salinity		pH		Phosphorus		Percentage saturation with dissolved oxygen	
					Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
1935				*Meters*	° *C.*	° *C.*	*Parts per thousand*	*Parts per thousand*			*Milligrams per cubic meter*	*Milligrams per cubic meter*		
Dec. 6	10:30 a. m.	4	LE	1.7	6.6	6.5	20.23	20.37	7.9	7.9	--------	--------	94.2	92.2
12	1:45 p. m.	5	½E	1.7	6.7	6.8	20.59	20.84	8.0	8.0	--------	--------	96.2	90.5
23	2:40 p. m.	6	LE	1.7	3.4	3.6	21.53	21.49	7.9	7.9	--------	--------	110.8	96.8
1936														
Jan. 4	9:20 a. m.	7	LE	1.1	1.6	1.6	21.08	21.08	7.9	7.9	--------	--------	95.1	94.1
21	10:25 a. m.	8	FE	1.7	2.4	2.4	11.56	11.60	7.7	7.7	[2] Tr.	Tr.	--------	--------
Feb. 19	10:35 a. m.	9	LE	.8	.5	.7	13.35	15.68	7.9	7.9	16.0	16.0	94.5	93.9
28	9:55 a. m.	11	FF	1.1	2.6	2.5	14.83	14.96	7.9	7.9	Tr.	Tr.	--------	--------
Mar. 4	1:50 p. m.	12	½E	1.8	4.9	3.9	12.93	12.39	7.8	7.7	Tr.	Tr.	--------	--------
16	10:30 a. m.	14	½E	1.3	8.8	7.1	12.88	15.70	8.1	8.1	3.0	Tr.	101.2	104.7
23	3:10 p. m.	16	FE	1.0	8.6	8.3	13.66	13.98	--------	--------	Tr.	--------	--------	--------
30	3:45 p. m.	17	LF	1.1	12.7	12.1	11.26	12.29	8.2	8.1	Tr.	Tr.	114.4	114.6
Apr. 8	9:10 a. m.	18	HWS	1.0	10.3	10.1	12.70	12.68	8.1	8.1	Tr.	Tr.	--------	--------
14	9:45 a. m.	20	LE	.8	11.6	11.1	10.28	10.54	8.0	8.0	0	0	99.7	96.5
May 1	9:20 a. m.	21	LE	.7	15.9	15.4	13.01	13.84	8.4	8.4	Tr.	Tr.	--------	--------
12	9:45 a. m.	22	½F	1.5	19.7	19.2	13.87	14.09	8.3	8.3	Tr.	Tr.	--------	--------
28	10:30 a. m.	23	½E	1.1	21.5	21.4	15.25	--------	--------	--------	3.0	1.0	94.3	--------
June 27	9:20 a. m.	28	LE	1.2	--------	22.5	--------	13.89	--------	--------	--------	--------	--------	--------
30	2:05 p. m.	29	LWS	1.1	25.3	24.9	17.63	18.22	8.3	8.4	--------	--------	106.9	115.5
July 6	1:40 p. m.	29a	½E	1.1	25.5	25.8	18.50	--------	--------	--------	Tr.	Tr.	--------	--------
15	10:45 a. m.	30	LE	1.1	26.7	26.5	19.96	19.96	7.8	7.8	6.2	6.2	--------	--------
27	10:30 a. m.	32	LE	1.8	26.4	26.1	21.00	21.08	7.7	7.9	4.0	3.1	110.2	101.1
Aug. 14	12:30 p. m.	33	LE	1.5	27.3	27.0	20.82	20.82	7.9	7.9	6.2	6.2	--------	--------
26	2:30 p. m.	34	½F	1.8	29.3	28.3	21.92	21.92	8.1	8.1	6.2	6.2	105.3	101.0
Sept. 14	10:15 a. m.	35	HWS	1.5	25.2	25.3	23.39	23.42	7.6	7.7	--------	--------	84.8	88.4
Oct. 2	9:45 a. m.	36	LF	1.5	21.4	21.3	23.64	23.68	7.8	7.9	30.0	24.8	93.8	97.7
20	9:30 a. m.	37	½F	1.7	20.1	20.0	23.40	23.51	8.1	8.1	12.4	12.4	74.2	88.5
Nov. 6	8:45 a. m.	38	LWS	1.9	14.9	14.6	23.13	23.22	8.1	7.8	12.4	12.4	92.0	95.6
24	2:20 p. m.	39	FF	2.0	9.7	9.7	22.94	20.14	8.0	8.1	30.0	18.6	--------	--------
Dec. 8	10:30 a. m.	40	LWS	1.6	5.1	5.2	22.65	22.66	8.0	8.0	Tr.	Tr.	--------	--------
14	10:30 a. m.	42	FE	--------	5.7	5.7	21.91	21.96	7.9	7.9	6.2	Tr.	--------	--------
1937														
Jan. 4	2:25 p. m.	43	LF	2.0	7.7	7.4	21.02	21.13	7.9	7.9	Tr.	Tr.	--------	--------
25	2:30 p. m.	45	LE	1.8	10.5	10.1	16.82	17.14	8.1	8.1	Tr.	Tr.	99.6	95.4
Feb. 15	10:50 a. m.	46	HWS	1.2	5.5	5.5	18.37	18.37	7.8	7.9	--------	--------	--------	--------
Mar. 5	9:45 a. m.	47	LWS	1.9	4.4	4.2	16.83	17.48	8.1	8.1	15.0	20.0	101.8	94.8
31	9:45 a. m.	49	LF	.7	7.7	7.7	17.21	17.21	8.4	8.4	Tr.	Tr.	105.5	104.0
Apr. 26	3:35 p. m.	50	LE	1.0	13.6	13.3	18.30	18.57	8.1	8.1	6.2	6.2	96.8	90.7

[1] LWS=Low water slack; HWS=High water slack; LE=Last of ebb; LF=Last of flood; FF=First of flood; etc.
[2] Tr.=Trace.

TABLE 7.—*Hydrographic data for station 14 in the York River below Carmines Islands*

[Average depth 8.3 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature		Salinity		pH		Phosphorus		Percentage saturation with dissolved oxygen	
					Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
1935				*Meters*	° *C.*	° *C.*	*Parts per thousand*	*Parts per thousand*			*Milligrams per cubic meter*	*Milligrams per cubic meter*		
Dec. 2	10:30 a. m.	4	LE	--------	9.3	9.2	20.63	20.46	7.7	7.7	--------	--------	92.5	93.0
12	12:45 p. m.	5	FE	1.2	6.4	6.6	20.26	20.30	8.0	8.0	--------	--------	95.8	96.4
1936														
Jan. 3	2:40 p. m.	7	FF	.7	2.4	2.2	20.70	20.77	8.0	8.0	--------	--------	96.8	97.4
21	12:10 p. m.	8	LE	1.0	3.2	3.2	13.12	13.57	7.7	7.7	[2] Tr.	Tr.	--------	--------
Feb. 19	12:50 p. m.	9	LWS	.7	--------	.7	--------	10.03	--------	7.7	--------	12.4	--------	93.4
27	4:00 p. m.	11	½E	--------	3.8	3.6	13.44	13.30	7.9	7.9	Tr.	--------	96.6	85.6
Mar. 4	3:15 p. m.	12	LE	1.3	6.2	6.1	10.23	10.32	7.7	7.7	Tr.	Tr.	--------	--------
18	11:45 a. m.	14	FE	1.2	8.7	8.4	13.68	14.76	8.1	8.1	--------	--------	103.5	109.0
24	8:50 a. m.	16	½F	.6	8.8	8.5	16.22	12.52	7.9	8.0	Tr.	Tr.	--------	--------
Apr. 8	11:45 a. m.	18	FF	.7	10.5	10.4	12.16	12.09	7.9	7.9	Tr.	Tr.	--------	--------
14	10:45 a. m.	20	LWS	.7	12.3	11.9	7.83	9.54	7.8	8.0	0	0	92.3	100.0
27	10:00 a. m.	21	FF	.7	--------	12.7	--------	14.16	--------	8.6	--------	Tr.	--------	117.5
May 12	10:50 a. m.	22	LF	1.1	21.1	20.1	12.77	13.78	8.2	8.2	Tr.	Tr.	--------	--------
28	1:20 p. m.	23	FF	.7	--------	22.9	--------	15.26	--------	--------	--------	Tr.	--------	--------

[1] LWS=Low water slack; HWS=High water slack; LE=Last of ebb; LF=Last of flood; FF=First of flood; etc.
[2] Tr.=Trace.

TABLE 7.—*Hydrographic data for station 14 in the York River below Carmines Islands*—Continued

Date	Time	Cruise	Tide [1]	Turbidity-disc reading	Water temperature		Salinity		pH		Phosphorus		Percentage saturation with dissolved oxygen	
					Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
1936				*Meters*	° *C.*	° *C.*	*Parts per thousand*	*Parts per thousand*			*Milligrams per cubic meter*	*Milligrams per cubic meter*		
June 8	3:45 p. m.	24	½E	1.0		22.9		17.18		8.3				
11	2:00 p. m.	25	FF		23.4	22.8								
19	2:15 p. m.	26	½E	.9		24.8		17.36		8.0				
25	2:40 p. m.	27	HWS	1.2	22.7	22.7	17.61	17.72	7.5	7.7				
26	9:05 a. m.	28	LE	.8	21.9	21.9		17.56		7.7				
30	12:10 p. m.	29	LWS	.9		25.8		17 07		7.9		[2] Tr.		100.3
July 8	9:30 a. m.	30	FF	.8	25.2	24.9								
15	2:45 p. m.	31	½F	.7	27.9	27.9		19.43			6.2	6.2		
27	2:00 p. m.	32	FF	.8	27.3	27.3	20.35	20.44	7.9	7.9	3.1	3.1	109.2	107.6
Aug 14	10:30 a. m.	33	LE	1.8		28.0		20.68		7.9		6.2		
26	12:15 p. m.	34	LW	1.5	29.0	28.7	21.02	21.29	7.8	7.8	6.2	6.2	86.8	87.4
Sept. 9	2:15 p. m.	35	½F	1.1		25.6		22.34		7.5		3.1		101.1
29	9:40 a. m.	36	HWS	1.1	22.5	22.6	23.51	23.51	8.0	7.8	6.2	18.6	83.3	82.1
Oct. 20	2:45 p. m.	37a	½E	1.3	20.0	20.0	22.68	22.74	8.1	8.0	12.4	12.4	115.5	120.2
27	8:45 a. m.	37	FE		17.6	17.0					12.4			
Nov. 5	9:15 a. m.	38	FF			15.8		22.50		7.7		12.4		92.5
24	12:45 p. m.	39	FF	1.7		9.0		22.23		8.1		18.6		
Dec. 3	10:40 a. m.	40	LF	1.4	6.1	4.3	22.56	22.45	7.9	7.9	12.4	12.4		
14	12:30 p. m.	42	½E	1.8	5.8	5.8	21.67	21.92	7.7	7.9	6.2	12.4		
1937														
Jan.	2:15 p. m.	43	LF	1.6		7.2		18.95		7.9		Tr.		
26	1:00 p. m.	45	FE	1.1		9.6		7.91		7.6		Tr.		87.9
Feb. 12	9:00 a. m.	46	LF	.6	4.8	4.7	16:91	16.83	7.8	7.7				
Mar. 4	11:45 a. m.	47	FF	.7	5.2	5.3	14.99	15.03	8.0	8.2	20.0	20.0	91.7	92.4
22	10:25 a. m.	48	E			7.5		15.61				3.1		
31	11:00 a. m.	49	LF	1.0	8.0	8.1	16.60	16.55	8.4	8.4	Tr.	Tr.	105.4	107.2
Apr. 23	11:45 a. m.	50	FE	1.0	15.4	15.2	16.28	16.38	8.3	8.1	6.2	6.2	100.2	102.1
June 16	5:00 p. m.	51	FF			24.9		17.86				6.2		

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[1] LWS=Low water slack; HWS=High water slack; LE=Last of ebb; LF=Last of flood; FF=First of flood; etc.
[2] Tr.=Trace.

TABLE 8.—*Hydrographic data for station 15 in the York River just above Queens Creek*

[Average depth 3.4 feet]

Date	Time	Cruise	Tide [1]	Turbidity-disc reading	Water temperature	Salinity	pH	Phosphorus	Percentage saturation with dissolved oxygen
1935				*Meters*	° *C*	*Parts per thousand*		*Milligrams per cubic meter*	
Dec. 2	12:20 p. m.	4	FF	0.5	8.7	18.66	7.7		103.2
12	11:40 a. m.	5	HWS	.6	6.5	18.42	7.9		109.0
1936									
Jan. 3	1:35 p. m.	7	FF	.6	3.0	18.80	8.0		97.6
21	1:45 p. m.	8	LE	.4	2.9	8.60	7.5	[2] Tr.	
Feb. 19	2:05 p. m.	9	FF	.2	2.0	5.93	7.7		90.8
Mar. 5	9:25 a. m.	12	FE	.8	3.2	12.70	7.7	Tr.	
16	2:15 p. m.	14	FF	.8	10.7	8.48	8.2	Tr.	104.7
24	10:10 a. m.	16	½F	.6	9.4	10.30	8.0	Tr.	
30	10:35 a. m.	17	FF	.8	12.4	8.96	7.8	Tr.	108.9
Apr. 8	2:45 p. m.	18	LE	.2	11.3	6.35	7.5	Tr.	
14	11:45 a. m.	20	FF	.2	13.6	7.83	8.2	0	94.9
27	11:00 a. m.	21	FF	.1	13.9	11.74	8.1	Tr.	95.2
May 12	11:45 a. m.	22	LF	.5	21.6	12.63	8.0	Tr.	
28	11:00 a. m.	23	½F	.3	22.9	13.53		Tr.	101.1
June 11	1:15 p. m.	25	FF		25.4				
26	10:45 a. m.	28	FF	.6	21.8	15.55	7.6		
30	11:15 a. m.	29	LE	.5	25.7	16.49	7.7	Tr.	104.0
July 8	10:30 a. m.	30	FF	.4	25.8				
16	9:45 a. m.	31	½E	.7	27.6	18.71	7.5	6.2	
27	3:00 p. m.	32	½F		28.4	18.75	7.9	3.1	108.3
Aug. 14	9:30 a. m.	33	LE	1.0	27.0	19.63	7.7	12.4	
26	10:30 a. m.	34	LWS	.3	28.8	19.85	7.7	6.2	82.0
Sept. 9	2:40 p. m.	35	LF	.7	27.1	20.88	7.7	6.2	106.0
29	11:30 a. m.	36	FE	.3	22.7	22.23	7.7	12.4	88.0
Oct. 20	4:00 p. m.	37	LE	.5	19.9	22.03	7.7	18.6	83.0
Nov. 5	1:45 p. m.	38	LF	.2	15.4	20.63	7.7	12.4	93.7
24	11:45 a. m.	39	LE	1.1	8.4	20.14	8.1	18.6	
Dec. 3	11:35 a. m.	40	LF	.6	5.9	20.44	7.9	6.2	
14	1:00 p. m.	42	½E	.6	5.7	20.19	7.7	6.2	
1937									
Jan. 6	3:15 p. m.	43	LF	.5	7.0	15.97	8.1	Tr.	
26	12:10 p. m.	45	FE	.6	9.7	11.83	7.6	Tr.	90.8
Feb. 12	9:30 a. m.	46	LF	.3	5.0	16.00	7.7		
Mar. 4	12:45 a. m.	47	FF	.7	6.2	14.60	8.1	20.0	98.1
22	2:00 p. m.	48	FF		9.6	12.34		6.2	
31	12:00 m.	49	LF	.6	8.4	12.67		Tr.	103.9
Apr. 23	12:30 p. m.	50	½E	.4	17.3	14.94	8.1	6.2	111.8

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[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, LF=Last of flood, FF=First of flood, etc.
[2] Tr.=Trace.

TABLE 9.—*Hydrographic data for station 23 in the York River above Claybank*

[Average depth 4.6 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature	Salinity	pH	Phosphorus	Percentage saturation with dissolved oxygen
				Meters	° *C.*	*Parts per thousand*		*Milligrams per cubic meter*	
1936									
June 26	11:05 a. m.	28	FF	0.5	22.9	14.40	7.5		
July 8	11:40 a. m.	30	½F	.5	26.1				
16	10:30 a. m.	31	FE	.6	27.3	18.44	7.6		
29	10:50 a. m.	32	LWS	.5	28.1	17.11		3.1	91.5
Aug. 13	10:15 a. m.	33	½E	.8	26.9	18.01	7.9	12.4	
31	2:20 p. m.	34	LE	.9	26.3	19.16	7.7	12.4	92.8
Sept. 9	3:15 p. m.	35	LF	.8	25.3	20.41	7.6	6.2	90.6
29	12:40 p. m.	36	FE	.3	22.7	21.71		6.2	82.9
Oct. 21	10:00 a. m.	37	FF	1.0	19.4	20.01	7.8	12.4	91.2
Nov. 5	10:45 a. m.	38	FF	.5	15.6	20.72	7.7	12.4	91.0
24	11:10 a. m.	39	½E	1.1	8.1	19.79	7.9	18.6	
Dec. 3	12:30 p. m.	40	LF	.9	6.0	20.88	7.7	12.4	
14	1:40 p. m.	42	½E	1.1	5.8	21.55	7.9	6.2	
1937									
Jan. 6	4:00 p. m.	43	LF	1.2	7.2	16.18	7.8	[2] Tr.	
26	11:30 a. m.	45	FE	.7	9.6	12.54	7.6		89.1
Feb. 12	10:10 a. m.	46	LF	.3	4.7	14.13	7.6		
Mar. 4	1:15 p. m.	47	½F	.4	5.9	9.94	7.9	15.0	96.3
31	12:45 p. m.	49	LF	.8	8.3	15.12	8.3		106.7
Apr. 23	1:10 p. m.	50	½E	.5	16.4	12.95	8.3	6.2	107.3
June 7	12:00 m.	51	½E		26.8				

[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, LF=Last of flood, FF=First of flood, etc.

[2] Tr.=Trace.

TABLE 10.—*Hydrographic data for station 5 in the middle York River just above Allmonds Wharf*

[Average depth 3.9 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature	Salinity	pH	Phosphorus	Percentage saturation with dissolved oxygen
				Meters	° *C.*	*Parts per thousand*		*Milligrams per cubic meter*	
1935									
Oct. 17	2:30 p. m.	1	LF		17.9	18.28			
Nov. 11	1:20 p. m.	2	FE		16.8	17.21			
Dec 6	1:35 p. m.	4	LE	0.5	5.8	14.96	7.8		91.7
12	10:40 a. m.	5	LF	.6	6.2	16.51	7.8		88.6
1936									
Jan 3	12:35 p. m.	7	FF	.6	1.2	17.63	7.9		94.1
23	12:15 p. m.	8	FE		.9	7.79	7.4		
Feb. 20	10:30 a. m.	9	½E	.8	.3	8.98	7.6		95.0
27	2:35 p. m.	11	FE	.9	4.2	7.47	7.3	[2] Tr.	93.5
Mar. 5	10:30 a. m.	12	FE	.7	7.0	6.93	7.5	Tr.	
18	2:10 p. m.	14	LE	.4	11.2	7.29	7.9		101.1
24	11:15 a. m.	16	LF	.6	10.6	5.81	7.8	Tr.	
30	11:50 a. m.	17	FF	.4	13.2	3.80	7.5	Tr.	90.7
Apr. 8	3:30 p. m.	18	LE			6.64	7.5	Tr.	
14	1:00 p. m.	20	FF	.4	13.8	5.64	7.6	0	89.1
27	1:00 p. m.	21	LF	.6	15.2	9.54	8.1	Tr.	113.8
May 12	12:45 p. m.	22	HWS	.3	22.6	10.64	7.6	Tr.	
June 1	11:40 a. m.	23	½E	.2	21.6	11.35		3.0	107.0
8	2:15 p. m.	24	FE	.3	23.0		7.8		
11	12:00 m.	25	FF		26.0				
26	11:25 a. m.	28	FF	.5	22.9	13.89	7.5		
30	10:20 a. m.	29	½E	.3	25.2	13.31	7.7	Tr.	91.8
July 8	12:30 p. m.	30	LF	.4	26.3				
16	10:50 a. m.	31	FE	.5	27.9	17.32	7.5	6.2	
29	12:00 m.	32	FF	.5	28.1	16.33		3.1	90.6
Aug. 13	2:45 p. m.	33	LE	.8	28.6	16.58	7.9	6.2	
30	12:00 m.	34	LE	.4	26.0	18.08	7.7	12.4	88.2
Sept. 10	11:15 a. m.	35	LE	.8	25.3	18.98	7.7	6.2	96.5
29	1:15 p. m.	36	½E	.7	22.7	21.11	7.9	6.2	88.2
Oct. 21	10:45 a. m.	37	FF	1.2	18.6	19.24	7.9	18.6	104.8
Nov. 5	1:00 p. m.	38	LF	.5	15.4	19.04	7.9	18.6	102.8
24	10:00 a. m.	39	FE	.4	8.4	19.18	7.9	18.6	
Dec. 3	1:00 p. m.	40	HWS	.3	5.7	19.98	7.7	12.4	
14	2:10 p. m.	42	½E	1.0	5.8	18.78	7.7	6.2	
1937									
Jan. 8	3:45 p. m.	43	FF	.7	8.9	9.38	7.8	Tr.	
26	11:15 a. m.	45	FE	.6	9.9	7.88	7.4	Tr.	87.3
Feb. 12	10:45 a. m.	46	LE		4.3	13.57	7.7		
Mar. 4	1:45 p. m.	47	½F	.5	7.2	10.86	7.9	5.0	96.0
22	11:45 a. m.	48	LE		8.2	11.44		3.1	
30	10:20 a. m.	49	LF	.3	8.4	12.47	8.3	Tr.	99.4
Apr. 23	1:30 p. m.	50	½E	.6	17.0	12.39	8.3	6.2	105.9
June 7	2:00 p. m.	50a	LE		29.2			12.4	
16	2:15 p. m.	51	½E		26.7	13.17			

[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, LF=Last of flood, FF=First of flood, etc.

[2] Tr.=Trace.

TABLE 11.—*Hydrographic data for station 22 in the York River inside Purtan Bay*

[Average depth 4.1 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature	Salinity	pH	Phorphorus	Percentage saturation with dissolved oxygen
1936				*Meters*	° *C.*	*Parts per thousand*		*Milligrams per cubic meter*	
Apr. 8	3:45 p. m.	18	LE	0.2	10.8	--------	7.6	--------	--------
30	3:55 p. m.	21	FF	.4	19.9	7.70	8.1	--------	--------
June 19	12:30 p. m.	26	FE	.4	24.9	13.87	7.7	--------	--------
July 8	1:15 p. m.	30	FF	.3	26.8	--------	--------	--------	--------
16	11:30 a. m.	31	½E	.5	28.3	16.35	7.7	--------	--------
29	1:45 p. m.	32	FF	.3	28.5	16.53	7.7	3.1	90.3
Aug. 13	11:30 a. m.	33	LE	.6	27.8	17.27	7.8	8.1	--------
31	1:25 p. m.	34	LE	.7	26.4	18.26	7.9	12.4	106.0
Sept. 10	11:35 a. m.	35	LE	.7	25.4	18.89	7.7	6.2	98.3
Oct. 1	3:45 p. m.	36	½E	.4	22.3	21.22	7.7	62.0	84.0
21	11:10 a. m.	37	FF	--------	19.3	19.29	7.9	30.0	96.8
Nov. 5	12:45 p. m.	38	LF	.3	15.3	19.89	7.7	18.6	93.2
24	10:15 a. m.	39	FE	.4	8.4	18.91	7.9	18.6	--------
Dec. 4	4:35 p. m.	40	½E	.4	6.2	19.45	7.7	12.4	--------
14	2:30 p. m.	42	½E	.6	5.8	19.61	7.9	6.2	--------
1937									
Jan. 8	3:25 p. m.	43	LWS	.6	8.6	8.55	7.8	[2] Tr.	--------
26	10:45 a. m.	45	HWS	.5	10.0	7.68	7.3	Tr.	85.5
Feb. 12	11:00 a. m.	46	HWS	.3	3.9	13.41	7.6	--------	--------
Mar. 4	2:00 p. m.	47	LF	.4	6.4	9.33	7.8	15.0	94.8
22	12:30 p. m.	48	LE	--------	9.3	11.09	--------	3.1	--------
30	10:35 a. m.	49	LF	.6	8.4	12.16	8.3	Tr.	100.0
Apr. 23	1:45 p. m.	50	½E	.6	16.5	12.11	8.3	6.2	112.3
June 7	2:15 p. m.	50a	LWS	--------	28.4	--------	--------	--------	--------

[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, LF=Last of flood, FF=First of flood, etc.

[2] Tr.=Trace.

TABLE 12.—*Hydrographic data for station 6 in the York River just below Taskinas Creek*

[Average depth 5.2 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature	Salinity	pH	Phosphorus	Percentage saturation with dissolved, oxygen
1936				*Meters*	° *C.*	*Parts per thousand*		*Milligrams per cubic meter*	
June 19	12:00 m.	26	LF	0.4	24.8	14.72	7.8	--------	--------
26	12:00 m.	28	FF	.3	22.6	12.56	7.7	--------	--------
July 10	1:15 p. m.	30	½F	.2	27.7	--------	--------	--------	--------
16	12:15 p. m.	31	FE	.2	28.8	15.81	7.4	--------	--------
29	12:50 p. m.	32	FF	.4	28.3	15.61	7.8	6.2	87.6
Aug. 13	2:30 p. m.	33	LE	.5	28.5	16.06	7.8	6.2	--------
Sept. 10	1:15 p. m.	35	FF	.6	26.0	17.41	7.7	6.2	115.1
Oct. 1	10:15 a. m.	36	HWS	.4	21.6	22.45	7.9	6.2	93.5
21	11:30 a. m.	37	FF	.6	18.2	19.24	7.9	12.4	97.4
Nov. 5	11:20 a. m.	38	FF	.1	14.8	17.83	7.6	18.6	96.3
24	10:40 a. m.	39	FE	.3	8.3	18.30	7.9	--------	--------
Dec. 4	4:00 p. m.	40	FE	.3	5.6	18.93	7.7	--------	--------
23	11:40 a. m.	42	LE	.3	--------	12.72	7.7	[2] Tr.	--------
1937									
Jan. 8	3:00 p. m.	43	LE	.4	8.2	8.12	7.8	Tr.	--------
26	10:15 a. m.	45	HWS	.5	9.9	6.96	7.4	Tr.	86.4
Feb. 11	2:15 p. m.	46	½E	.2	4.6	9.85	7.4	3.2	--------
Mar. 4	2:20 p. m.	47	LF	.3	6.2	10.30	7.7	10.0	93.1
30	11:00 a. m.	49	LF	.2	8.1	10.52	8.3	3.1	91.3
Apr. 23	2:20 p. m.	50	LE	.3	17.4	9.60	8.1	6.2	99.2

[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, LF=Last of flood, FF=First of flood, etc.

[2] Tr.=Trace.

TABLE 13.—*Hydrographic data for station 16 in the York River off Roanes Point*

[Average depth 4.2 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature	Salinity	pH	Phosphorus	Percentage saturation with dissolved oxygen
				Meters	° *C.*	*Parts per thousand*		*Milligrams per cubic meter*	
1935									
Dec. 6	2:45 p. m.	4	LE	0.5	6.4	12.11	7.7	----	98.9
13	12:25 p. m.	5	LF	.3	6.6	16.60	7.8	----	80.5
1936									
Jan. 7	12:00 m.	7	FE	.4	2.0	7.34	7.7	----	95.3
23	11:20 a. m.	8	FE	----	1.6	5.97	7.2	----	----
Feb. 21	11:10 a. m.	9	FE	.3	0.2	6.19	7.4	[2] Tr.	88.3
Mar. 5	12:45 p. m.	12	LE	.3	5.3	6.29	7.3	Tr.	----
18	3:25 p. m.	14	LWS	.3	11.1	----	7.2	----	100.6
24	12:45 p. m.	16	FE	.6	11.1	3.53	7.3	Tr.	----
30	12:50 p. m.	17	FF	.6	14.5	1.96	7.3	Tr.	90.1
Apr. 9	10:20 a. m.	18	½F	.3	11.4	3.51	7.4	----	----
16	12:00 m.	20	LE	.2	15.7	3.21	7.5	Tr.	92.6
29	11:05 a. m.	21	LWS	.3	18.0	5.41	7.8	Tr.	95.1
May 14	10:45 a. m.	22	½E	.3	20.8	7.30	7.4	Tr.	----
June 1	12:30 p. m.	23	LE	.5	22.5	10.41	----	Tr.	101.7
19	11:15 a. m.	25	½F	.3	25.6	13.10	7.6	Tr.	----
25	1:30 p. m.	26	LE	.4	25.7	12.67	----	----	----
26	12:20 p. m.	28	FF	.6	23.3	11.82	7.5	----	----
30	1:15 p. m.	29	½E	.3	25.9	13.06	7.4	Tr.	76.0
July 17	2:30 p. m.	31	FE	.3	29.0	14.79	7.3	3.1	----
31	11:50 a. m.	32	FE	.3	25.5	17.32	7.5	6.2	66.9
Aug. 13	1:30 p. m.	33	LE	.5	28.3	14.89	7.9	12.4	----
28	10:45 a. m.	34	FE	.7	27.0	17.81	7.7	12.4	85.0
Sept. 10	12:20 p. m.	35	LE	.5	25.8	16.46	7.6	6.2	96.1
Oct. 1	10:40 a. m.	36	HWS	.5	21.9	20.91	7.8	12.4	69.8
21	12:50 p. m.	37	LF	.5	20.0	17.55	7.8	12.4	92.5
Nov. 4	1:15 p. m.	38	FF	.1	15.8	18.15	7.7	3.1	83.3
19	4:35 p. m.	39	FE	.7	8.3	17.20	7.7	----	----
Dec. 4	3:30 p. m.	40	½F	.3	5.6	18.33	7.7	18.6	----
Dec. 13	11:30 a. m.	42	LE	.4	3.9	12.43	7.7	Tr.	----
1937									
Jan. 8	2:05 p. m.	43	LE	.4	8.1	6.51	7.6	Tr.	----
27	10:30 a. m.	45	LF	.3	9.1	5.88	----	93.0	83.6
Feb. 11	1:30 p. m.	46	FE	.3	5.2	10.77	7.5	----	----
Mar. 3	3:35 p. m.	47	LF	.2	5.4	9.80	7.9	6.2	84.2
22	1:00 p. m.	48	LWS	----	10.2	8.35	----	----	----
30	11:20 a. m.	49	LF	.4	9.0	11.35	8.5	Tr.	98.5
Apr. 27	12:20 p. m.	50	LF	.4	15.5	9.65	7.6	3.2	90.9
June 16	12:30 p. m.	51	LWS	----	26.4	10.05	----	12.4	----

[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, FE=First of ebb, FF=First of flood, etc.
[2] Tr.=Trace.

TABLE 14.—*Hydrographic data for station 17 in the York River off Ware Creek*

[Average depth 3.9 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature	Salinity	pH	Phosphorus	Percentage saturation with dissolved oxygen
				Meters	°C.	*Parts per thousand*		*Milligrams per cubic meter*	
1935									
Dec. 6	3:15 p. m.	4	LWS	0.4	6.2	11.67	7.7	-----	97.5
1936									
Jan. 7	11:40 a. m.	7	FE	.6	2.2	7.72	7.7	-----	87.7
23	10:30 a. m.	8a	HWS	-----	0.6	3.87	7.2	-----	-----
Feb. 21	10:30 a. m.	9	HWS	.5	.1	6.91	7.4	-----	-----
Mar. 6	1:45 p. m.	12	FE	.2	5.9	5.21	7.2	7.0	-----
19	11:30 a. m.	14	½E	-----	10.3	3.75	7.6	3.0	73.8
25	10:25 a. m.	16	½F	.1	11.3	2.61	7.3	[2] Tr.	-----
Apr. 1	10:00 a. m.	17	½E	.1	13.2	2.86	7.5	Tr.	82.3
9	10:40 a. m.	18	½F	.3	11.2	4.29	7.4	-----	-----
16	3:30 p. m.	20	FF	.2	15.2	3.04	7.4	Tr.	100.8
29	11:45 a. m.	21	FF	.1	18.2	6.31	7.9	Tr.	108.3
May 14	10:55 a. m.	22	½E	.0	21.0	6.55	7.4	Tr.	-----
June 1	1:30 p. m.	23	LE	.2	22.6	11.40	-----	Tr.	109.4
11	11:00 a. m.	25	FF	-----	25.0	-----	-----	-----	-----
19	10:45 a. m.	26	½F	.4	25.0	12.86	7.6	-----	-----
July 2	12:30 p. m.	29	½E	.1	25.6	13.21	7.4	Tr.	84.5
17	2:20 p. m.	31	FE	.2	29.1	14.90	7.4	3.1	-----
31	12:10 p. m.	32	FE	.3	25.3	15.95	7.5	3.1	77.9
Aug. 17	2:10 p. m.	33	FE	.3	28.1	15.97	7.7	30.0	102.6
28	11:30 a. m.	34	LE	.5	26.9	16.62	7.8	6.2	89.8
Sept. 10	12:45 p. m.	35	LE	.4	25.8	15.97	7.7	6.2	100.5
Oct. 1	11:10 a. m.	36	FF	.5	22.0	20.81	7.8	6.2	96.6
21	1:10 p. m.	37	LF	.3	22.0	15.90	7.8	12.4	84.3
Nov. 4	12:45 p. m.	38	FF	.1	15.6	17.48	7.7	3.1	88.2
19	4:20 p. m.	39	FE	.3	8.4	16.89	7.6	-----	-----
Dec. 4	2:50 p. m.	40	½F	.4	5.7	17.56	7.7	24.8	-----
23	11:20 a. m.	42	½E	.1	4.3	12.88	7.7	Tr.	-----
1937									
Jan. 8	1:45 p. m.	43	LE	.4	7.6	7.07	7.7	Tr.	-----
27	10:50 a. m.	45	LF	.2	9.3	4.65	7.4	93.0	84.7
Feb. 11	1:15 p. m.	46	FE	.2	5.3	10.57	7.3	-----	-----
Mar. 3	3:10 p. m.	47	½F	.2	5.4	8.31	7.6	6.0	88.2
30	12:05 p. m.	49	LF	.3	8.4	-----	-----	Tr.	-----
Apr. 27	12:40 p. m.	50	LF	.5	15.0	9.06	7.3	3.1	107.9

[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, FE=First of ebb, FF=First of flood, etc.

[2] Tr.=Trace.

TABLE 15.—*Hydrographic data for station 8 in the upper York River inshore of Bell Rock Lighthouse*

[Average depth 13.6 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature		Salinity		pH		Phosphorus		Percentage saturation with dissolved oxygen	
					Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
				Meters	°C.	°C.	*Parts per thousand*	*Parts per thousand*			*Milligrams per cubic meter*	*Milligrams per cubic meter*		
1936														
Apr. 29	12:25 p. m.	21	FF	0.2	15.9	15.3	3.69	4.43	7.3	7.3	-----	-----	86.1	82.0
June 26	12:50 p. m.	28	FF	.6	-----	23.9	-----	12.92	-----	7.5	-----	-----	-----	-----
July 10	12:00 m.	30	FF	.3	-----	27.7	-----	-----	-----	-----	-----	-----	-----	-----
17	2:00 p. m.	31	FE	.3	-----	29.1	-----	14.22	-----	7.5	-----	-----	-----	-----
31	12:50 p. m.	32	½E	.3	-----	26.0	-----	16.02	-----	-----	-----	3.2	-----	78.2
Aug. 17	2:00 p. m.	33	FE	.3	-----	27.8	-----	13.33	-----	7.9	-----	-----	-----	99.8
Sept. 11	11:50 a. m.	35	½E	.4	-----	26.2	-----	16.96	-----	7.7	-----	6.2	-----	101.1
Oct. 1	1:00 p. m.	36	FE	.5	-----	21.7	-----	20.73	-----	7.7	-----	6.2	-----	83.3
22	11:00 a. m.	37	FF	.5	19.2	19.3	-----	19.24	-----	7.9	-----	12.4	81.4	65.0
Nov. 4	12:00 m.	38	FF	.7	15.7	15.6	-----	17.83	-----	7.6	-----	3.1	85.5	82.9
19	4:10 p. m.	39	FE	.7	8.5	8.6	17.03	18.03	7.5	7.7	-----	-----	-----	-----
Dec. 4	2:30 p. m.	40	FF	.4	5.3	5.2	17.65	17.54	7.7	7.7	12.4	18.6	-----	-----
23	11:05 p. m.	42	½E	.8	4.2	4.3	11.31	12.03	7.7	7.7	[2] Tr.	Tr.	-----	-----
1937														
Jan. 8	12:30 p. m.	43	LE	.4	7.0	7.1	5.73	11.60	7.6	7.7	Tr.	Tr.	-----	-----
27	11:20 a. m.	45	LF	.3	9.0	9.3	5.12	6.35	7.2	7.2	93.0	93.0	84.7	81.1
Feb. 11	12:45 p. m.	46	FE	.4	5.6	4.9	13.55	14.05	7.6	7.6	Tr.	Tr.	-----	-----
Mar. 3	2:00 p. m.	47	FF	.4	5.4	4.6	7.11	7.85	7.5	7.5	8.0	-----	85.1	83.8
30	12:40 p. m.	49	LF	.4	8.9	8.5	-----	-----	-----	-----	Tr.	Tr.	-----	-----
Apr. 27	12:55 p. m.	50	LF	.6	15.6	14.3	8.17	9.78	-----	-----	3.1	3.1	87.3	81.7

[1] LWS=Low water slack; HWS=High water slack; LE=Last of ebb; LF=Last of flood; FF=First of flood; etc.

[2] Tr.=Trace.

TABLE 16.—*Hydrographic data for station 9 in the upper York River on the middle ground just below West Point*

[Average depth 12.4 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature		Salinity		pH		Phosphorus		Percentage saturation with dissolved oxygen	
					Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
				Meters	° *C.*	° *C.*	*Parts per thousand*	*Parts per thousand*			*Milligrams per cubic meter*	*Milligrams per cubic meter*		
1935														
Oct. 22	10:20 a. m.	P2	FE	--------	19.1	18.0	9.89	12.61	--------	--------	--------	--------	--------	--------
29	8:55 a. m.	P3	FF	--------	16.9	16.6	11.13	13.02	--------	--------	--------	--------	--------	--------
Nov. 8	9:15 a. m.	2	LF	--------	16.4	16.4	14.34	14.47	--------	--------	--------	--------	--------	--------
Dec. 3	3:50 p. m.	4	½E	0.7	8.1	8.2	11.53	13.89	7.6	7.5	--------	--------	--------	--------
13	11:30 a. m.	5	¼F	.5	6.4	6.3	13.04	13.04	7.7	7.7	--------	--------	89.0	89.7
1936														
Jan. 7	10:45 a. m.	7	HWS	.4	1.9	1.8	3.87	8.62	7.4	7.6	--------	--------	88.8	90.3
22	12:45 p. m.	8	¼E	.4	3.2	3.0	5.01	8.13	7.4	7.5	--------	--------	--------	--------
Feb. 20	2:05 p. m.	9	LE	.2	.4	0.3	1.96	7.83	7.1	7.3	--------	--------	87.9	86.0
27	12:15 p. m.	11	HWS	.3	2.9	2.7	0.86	2.30	6.9	7.1	[2] Tr.	Tr.	85.2	72.3
Mar. 5	2:00 p. m.	12	LE	.3	5.2	4.8	3.35	5.55	7.2	7.3	Tr.	Tr.	--------	--------
19	12:00 m.	14	½E	--------	10.8	10.9	1.21	3.95	7.3	7.3	8.0	Tr.	80.2	86.2
25	11:00 a. m.	16	½F	.2	11.2	11.3	1.64	1.42	7.2	7.3	Tr.	Tr.	--------	--------
Apr. 1	10:45 a. m.	17	½E	.2	12.2	12.9	2.54	5.01	7.1	7.3	Tr.	Tr.	76.7	80.3
9	11:15 a. m.	18	½F	.2	11.7	11.7	--------	2.11	7.2	7.3	6.2	Tr.	--------	--------
16	1:00 p. m.	20	LWS	.2	13.2	13.2	.39	2.50	7.1	7.4	12.4	Tr.	94.3	106.8
29	1:40 p. m.	21	FF	.2	16.3	15.6	2.02	2.88	7.1	7.3	6.2	6.2	85.2	83.9
May 14	11:30 a. m.	22	½E	.3	21.7	21.6	4.51	5.73	7.3	7.3	Tr.	0	--------	--------
June 3	11:45 a. m.	23	LF	.5	23.1	22.8	10.72	10.73	--------	--------	3.0	2.0	114.9	108.7
8	12:00 m.	24	LF	.5	23.1	23.2	11.98	11.49	7.9	7.9	--------	--------	--------	--------
16	12:15 p. m.	25	½E	.6	24.8	24.2	11.24	12.30	--------	--------	Tr.	0	--------	--------
19	10:10 a. m.	26	¼F	--------	24.8	24.8	11.55	11.78	7.5	7.5	--------	--------	--------	--------
26	1:30 p. m.	28	FF	.6	23.1	--------	18.15	--------	7.4	--------	--------	--------	--------	--------
July 2	11:45 a. m.	29	½E	.6	25.2	24.6	11.78	14.09	7.6	7.4	13.0	Tr.	97.1	87.1
10	11:00 a. m.	30	FF	.6	28.3	27.2	--------	--------	--------	--------	--------	--------	--------	--------
17	1:30 p. m.	31	FE	.8	29.9	28.2	13.35	12.94	7.4	7.5	6.2	12.4	--------	--------
31	1:15 p. m.	32	½E	.6	26.3	26.1	13.77	16.28	--------	--------	6.2	3.2	83.4	57.2
Aug. 17	1:00 p. m.	33	LF	.5	27.7	27.5	14.33	14.49	7.9	7.8	30.0	12.4	96.7	89.1
28	12:30 p. m.	34	LE	.8	28.0	27.9	15.90	17.11	7.5	7.5	12.4	6.2	59.0	62.3
Sept. 11	12:30 p. m.	35	LE	.5	26.0	25.9	15.44	16.49	7.7	7.7	3.1	3.1	90.2	87.3
Oct. 1	1:30 p. m.	36	FE	.4	21.7	21.5	18.93	18.86	7.8	7.8	6.2	6.2	86.6	91.7
22	11:45 a. m.	37	FF	--------	20.2	19.6	14.65	14.11	7.8	7.8	12.4	12.4	83.6	81.6
Nov. 4	11:30 a. m.	38	LWS	.6	15.7	15.6	14.52	15.23	7.4	7.5	3.1	3.1	81.4	76.8
19	3:40 p. m.	39	HWS	.6	8.7	8.7	17.07	17.09	7.6	7.7	--------	--------	--------	--------
Dec. 4	1:30 p. m.	40	FF	.6	5.4	5.2	15.81	15.99	7.7	7.7	30.0	12.4	--------	--------
15	3:35 p. m.	42	½E	1.0	5.0	5.0	14.76	16.51	7.8	7.8	6.2	6.2	--------	--------
1937														
Jan. 5	12:35 p. m.	43	LE	.4	6.6	7.0	4.85	8.77	7.3	7.4	Tr.	Tr.	--------	--------
27	11:45 a. m.	45	LF	.3	8.9	9.4	2.54	4.24	7.2	7.2	93.0	93.0	74.8	70.6
Feb. 11	12:10 p. m.	46	HWS	.4	5.6	4.1	11.17	12.12	7.6	7.6	Tr.	Tr.	--------	--------
Mar. 3	11:40 a. m.	47	LWS	.4	5.3	4.6	3.26	4.78	7.2	7.3	6.2	3.1	78.3	75.2
30	1:00 p. m.	49	LF	.4	8.5	8.3	10.86	10.73	8.3	8.4	Tr.	Tr.	96.9	95.3
Apr. 27	1:35 p. m.	50	LF	.4	15.1	14.3	7.47	8.73	--------	7.4	6.2	6.2	84.5	77.9
June 16	10:50 a. m.	51	LE	--------	23.4	23.4	6.40	9.06	--------	--------	12.4	12.4	--------	--------

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[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, LF=Last of flood, FF=First of flood, etc.

[2] Tr.=Trace.

TABLE 17.—*Hydrographic data for station 18 in the Pamunkey River above bridge at West Point*

[Average depth 29.5 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature		Salinity		pH		Phosphorus		Percentage saturation with dissolved oxygen	
					Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
				Meters	° *C.*	° *C.*	*Parts per thousand*	*Parts per thousand*			*Milligrams per cubic meter*	*Milligrams per cubic meter*		
1935														
Dec. 3	1:35 p. m	4	FF	0.2	8.4	8.4	1.17	6.26	7.3	7.3	--------	--------	--------	--------
13	10:25 a. m	5	FF	.6	6.4	6.3	7.12	9.07	7.6	7.6	--------	--------	80.9	80.8
1936														
Jan. 6	2:35 p. m	7	LE	.2	1.3	1.3	.53	1.28	7.1	7.1	--------	--------	76.0	77.1
22	3:15 p. m	8	LE	.2	3.4	3.2	.26	2.09	6.9	7.1	--------	--------	--------	--------
Feb. 20	3:15 p. m	9	LE	.2	.2	.2	.14	.11	6.7	6.7	--------	--------	87.1	87.1
Mar. 6	10:05 a. m	12	LF	.2	5.4	5.3	1.31	1.67	7.0	7.0	[2] Tr.	Tr.	--------	--------
19	1:15 p. m	14	LWS	--------	10.7	10.5	.25	.17	7.1	7.2	6.0	--------	55.1	52.7
25	12:45 p. m	16	HWS	.2	11.8	11.7	.25	.23	6.9	6.9	Tr.	Tr.	--------	--------
Apr. 1	12:30 p. m	17	½E	.0	13.6	13.5	.23	.21	7.0	7.0	Tr.	Tr.	77.6	71.3
9	12:55 p. m	18	LF	.2	12.2	12.2	.05	.12	7.1	7.0	43.4	6.2	--------	--------
16	2:30 p. m	20	FF	.2	13.5	13.5	.05	.12	7.1	7.0	12.4	12.4	87.1	99.2
29	4:45 p. m	21	FF	.1	15.8	15.5	.28	.28	7.0	7.0	8.0	--------	80.3	77.0
May 14	12:25 p. m	22	½E	.3	21.9	21.8	.52	.61	7.2	7.1	Tr.	--------	--------	--------
June 3	12:50 p. m	23	FE	--------	24.7	22.9	6.04	8.28	--------	--------	Tr.	2.0	101.6	86.6
July 2	10:45 a. m	29	FE	.5	25.5	25.3	10.12	11.12	7.1	7.2	6.2	6.2	78.3	72.3
17	12:40 p. m	31	FE	.5	29.3	28.3	11.08	12.94	7.0	7.1	3.1	3.1	--------	--------
31	2:30 p. m	32	LE	.6	27.1	26.9	9.69	10.61	7.1	7.1	6.2	6.2	89.4	78.4
Aug. 17	12:20 p. m	33	LF	.2	27.6	27.2	11.35	12.27	7.7	7.7	30.0	30.0	78.3	64.2
28	2:15 p. m	34	FF	.7	28.3	28.4	11.58	11.43	7.4	7.1	12.4	12.4	95.6	83.3
Sept. 11	2:20 p. m	35	LE	.6	26.2	25.6	11.44	12.57	7.2	7.2	3.1	3.1	84.6	69.0
Oct. 22	12:20 p. m	37	FF	.8	20.2	19.7	9.58	10.03	7.8	7.8	12.4	12.4	76.4	68.6
Nov. 4	10:15 a. m	38	LWS	.5	15.8	15.7	10.28	10.73	7.1	7.2	3.1	3.1	75.1	74.9
19	3:10 p. m	39	LF	.5	9.3	9.1	14.25	14.38	7.6	7.5	--------	--------	--------	--------
Dec. 4	12:15 p. m	40	LWS	.6	5.8	5.7	10.63	11.56	7.5	7.5	6.2	Tr.	--------	--------
5	2:30 p. m	42	FE	.6	5.0	4.7	12.29	14.20	7.7	7.7	6.2	12.4	--------	--------
1937														
Jan. 5	2:45 p. m	43	FF	.1	6.3	6.5	.60	3.32	7.2	7.3	68.2	Tr.	--------	--------
27	1:00 p. m	45	HWS	.1	8.5	8.5	.21	.58	6.9	7.0	12.4	12.4	57.7	54.7
Feb. 11	10:40 a. m	46	LF	.2	5.8	5.0	4.45	6.83	7.3	7.3	Tr.	Tr.	--------	--------
Mar. 3	1:20 p. m	47	FF	.2	5.0	5.0	.15	.24	7.1	7.1	8.0	8.0	68.3	77.0
30	2:50 p. m	49	HWS	.4	9.3	8.3	7.34	8.77	8.2	8.2	Tr.	Tr.	95.0	89.4
Apr. 27	2:30 p. m	50	HWS	.3	15.7	15.0	3.19	4.89	7.2	--------	Tr.	Tr.	71.1	75.0
May 17	3:00 p. m	50a	LF	--------	19.7	19.9	.12	.12	6.7	6.8	--------	--------	65.8	65.3

[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, LF=Last of flood, FF=First of flood, etc.
[2] Tr.=Trace.

TABLE 18.—*Hydrographic data for station 19 in the Mattaponi River above the bridge at West Point*

[Average depth 15.0 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature		Salinity		pH		Phosphorus		Percentage saturation with dissolved oxygen	
					Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
1935				*Meters*	*° C.*	*° C.*	*Parts per thousand*	*Parts per thousand*			*Milligrams per cubic meter*	*Milligrams per cubic meter*		
Dec. 3	2:50 p. m	4	FF	0.6	8.3	8.1	3.91	4.78	7.3	7.3	--------	--------	--------	--------
13	9:25 a. m	5	FF	.7	6.3	6.2	4.29	6.96	7.3	7.6	--------	--------	82.3	82.9
1936														
Jan. 6	3:35 p. m	7	LE	.2	1.2	1.1	.07	.07	7.2	6.7	--------	--------	82.3	71.3
Mar. 6	11:10 a. m	12	FE	.2	5.7	5.3	1.69	1.98	7.0	7.0	[2] Tr.	Tr.	--------	--------
19	12:30 p. m	14	LE	--------	10.8	10.5	.04	.04	7.1	7.2	--------	--------	86.1	85.7
25	12:00 m	16	LF	.1	11.7	11.6	.10	.08	6.7	6.7	8.0	Tr.	--------	--------
Apr. 1	11:35 a. m	17	½E	.2	13.8	13.7	.10	.10	7.0	6.9	Tr.	Tr.	91.7	78.8
9	11:50 a. m	18	LF	.2	12.2	12.2	--------	--------	6.9	6.9	92.4	12.2	--------	--------
16	1:30 p. m	20	LWS	.4	13.1	13.0	.07	.07	6.9	6.9	15.0	12.4	94.0	103.5
29	2:40 p. m	21	FF	.2	16.3	15.5	.10	.10	6.8	6.7	12.4	12.4	90.0	82.9
June 3	12:30 p. m	23	HWS	.6	24.1	22.8	6.46	6.73	--------	--------	Tr.	Tr.	81.1	87.9
July 2	10:00 a. m	29	FE	.6	25.5	25.4	9.49	10.14	7.1	7.3	6.2	6.2	83.8	76.8
17	11:25 a. m	31	FE	.6	28.7	27.9	12.14	12.52	7.1	7.3	3.1	3.1	--------	--------
31	3:30 p. m	32	LE	.6	27.1	26.7	7.23	9.86	--------	--------	12.4	0	86.7	64.4
Aug. 17	11:15 a. m	33	LF	.5	27.2	27.2	10.75	11.35	7.8	7.7	30.0	30.0	93.5	69.7
28	3:00 p. m	34	FF	.8	28.5	28.1	11.76	11.91	7.2	7.2	12.4	12.4	76.8	77.0
Sept. 11	1:05 p. m	35	LE	.5	26.2	25.9	11.33	11.82	7.0	7.2	3.1	3.1	86.5	83.8
Oct. 22	1:40 p. m	37	FF	.7	19.9	19.7	12.25	12.32	7.9	7.8	12.4	12.4	79.3	78.4
Nov. 4	9:30 a. m	38	LWS	.6	15.7	15.5	9.81	10.55	7.2	7.1	3.1	3.1	84.4	83.4
19	2:45 p. m	39	LF	.7	9.2	9.2	13.44	14.02	7.6	7.6	--------	--------	--------	--------
Dec. 4	11:25 a. m	40	LWS	.7	5.7	5.5	10.48	11.91	7.6	7.6	6.2	6.2	--------	--------
15	3:15 p. m	42	FE	1.1	5.2	4.9	11.98	12.86	7.7	7.6	6.2	6.2	--------	--------
1937														
Jan. 5	2:00 p. m	43	FF	.3	6.4	6.3	.96	1.56	7.1	7.1	74.4	12.4	--------	--------
27	12:15 p. m	45	HWS	.2	8.9	8.9	.19	.40	6.9	6.8	12.4	12.4	62.8	68.8
Feb. 11	10:00 a. m	46	LF	.2	4.9	4.5	3.57	4.87	7.2	7.3	Tr.	Tr.	--------	--------
Mar. 3	12:30 p. m	47	LWS	.2	5.2	5.0	.12	.12	6.9	6.8	8.0	8.0	69.1	53.4
30	2:15 p. m	49	HWS	.4	9.1	8.7	6.17	7.29	8.2	8.2	Tr.	Tr.	91.5	89.6
Apr. 27	3:00 p. m	50	FE	.3	16.1	15.9	2.67	3.73	--------	--------	Tr.	Tr.	75.5	70.6

[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, LF=Last of flood, FF=First of flood, etc.
[2] Tr.=Trace.

TABLE 19.—*Hydrographic data for station 55 in the lower Piankatank River off Iron Point*

[Average depth 4.2 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature	Salinity	pH	Phosphorus	Percentage saturation with dissolved oxygen
1935				*Meters*	*° C.*	*Parts per thousand*		*Milligrams per cubic meter*	
Dec. 10	1:50 p. m	2	½E	[2] B	6.6	17.56	8.1	----------	101.4
1936									
Jan. 11	12:25 p. m	3	FF	B	2.2	13.75	7.9	----------	97.0
Mar. 3	1:30 p. m	4	FF	B	4.3	11.17	8.1	----------	108.6
12	2:00 p. m	5	FE	----------	7.0	11.73	7.9	[3] Tr.	73.1
Apr. 3	10:15 a. m	6	LE	B	11.9	10.14	8.3	Tr.	102.9
16	10:30 a. m	7	LE	B	13.2	8.42	8.4	Tr.	106.7
May 6	9:25 a. m	8	LF	B	18.8	8.06	8.3	Tr.	103.3
June 4	11:00 a. m	9	FE	B	23.2	10.86	----------	92.0	90.3
16	10:00 a. m	10	FE	B	24.5	11.73	7.7	3.0	----------
July 1	10:00 a. m	11	½E	B	25.0	12.67	8.1	3.0	91.9
21	10:40 a. m	12	FE	B	27.2	14.22	7.4	6.2	----------
Aug. 3	10:30 a. m	13	½F	B	25.7	16.04	7.8	8.0	87.7
21	10:15 a. m	14	LF	----------	28.0	16.46	7.9	12.4	106.5
Sept. 3	9:15 a. m	15	HWS	----------	25.2	18.01	7.7	6.2	96.0
Oct. 6	10:30 a. m	17	HWS	B	21.0	18.57	7.9	3.1	97.6
26	11:45 a. m	18	½F	B	19.0	19.05	7.9	3.1	96.4
Nov. 10	10:30 a. m	19	FE	B	13.7	19.40	8.0	----------	112.2
Dec. 1	10:15 a. m	21	HWS	B	5.3	19.67	8.0	3.1	----------
1937									
Jan. 12	10:30 a. m	22	FE	B	8.1	17.32	8.1	Tr.	----------
Feb. 2	10:10 a. m	24	LE	B	6.7	13.64	7.6	Tr.	99.2
16	9:45 a. m	25	½F	----------	5.4	12.43	7.8	----------	99.2
Mar. 2	10:30 a. m	26	LE	B	3.9	12.57	7.9	24.8	----------
23	9:30 a. m	27	FE	B	8.1	11.35	----------	3.1	----------
Apr. 6	10:15 a. m	28	FE	B	10.7	13.15	8.6	5.0	113.6
21	9:45 a. m	29	HWS	B	15.1	13.37	8.6	----------	111.4

[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, FE=First of ebb, FF=First of flood, etc.
[2] B=On the bottom.
[3] Tr.=Trace.

TABLE 20.—*Hydrographic data for station 53 in the upper Piankatank River off Ferry Creek*

[Average depth 7.3 feet]

Date	Time	Cruise	Tide [1]	Turbidity disc reading	Water temperature		Salinity		pH		Phosphorus		Percentage saturation with dissolved oxygen	
					Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
				Meters	° *C.*	° *C.*	*Parts per thousand*	*Parts per thousand*			*Milligrams per cubic meter*	*Milligrams per cubic meter*		
1935														
Nov. 13	2:40 p. m.	1	½E	--------	17.4	16.8	13.33	14.51	--------	--------	--------	--------	--------	--------
Dec. 10	11:30 a. m.	2	HWS	2.2	7.1	7.1	13.33	13.73	8.0	8.0	--------	--------	97.4	100.7
1936														
Jan. 11	11:20 a. m.	3	FF	1.8	3.0	2.5	7.48	12.00	7.8	7.8	--------	--------	91.2	92.4
Mar. 3	11:40 a. m.	4	FE	2.2	--------	5.1	--------	6.11	--------	7.5	--------	--------	--------	99.4
12	12:45 p. m.	5	HWS	1.3	9.2	9.1	7.21	7.27	7.6	7.6	[2] Tr.	Tr.	75.8	75.7
Apr. 3	12:10 p. m.	6	LE	1.3	--------	12.9	--------	7.18	--------	7.9	--------	Tr.	--------	97.8
16	11:45 a. m.	7	LE	--------	--------	14.9	--------	5.63	--------	8.1	--------	Tr.	--------	98.4
May 6	11:00 a. m.	8	LF	1.2	20.2	19.7	5.54	6.00	8.0	8.0	Tr.	Tr.	91.4	93.9
June 4	12:30 p. m.	9	½E	1.2	24.3	24.4	9.60	9.43	--------	--------	6.2	3.0	96.1	76.0
16	11:00 a. m.	10	FE	--------	--------	25.3	--------	9.65	--------	7.5	--------	6.2	--------	--------
July 1	11:30 a. m.	11	LE	--------	--------	25.8	--------	10.75	--------	7.6	--------	Tr.	--------	77.9
21	12:40 p. m.	12	FE	.8	27.7	27.9	12.48	12.70	7.2	7.2	6.2	6.2	--------	--------
Aug. 3	12:00 m.	13	LF	.5	27.3	26.3	14.16	14.67	7.5	7.5	4.0	6.2	79.8	82.6
21	11:20 a, m.	14	LF	--------	28.6	27.5	13.26	15.25	7.9	7.7	12.4	12.4	110.3	66.8
Sept. 3	11:45 a. m.	15	LE	--------	26.0	25.4	16.04	16.26	7.7	7.8	6.2	6.2	100.4	101.6
Oct. 6	12:00 m.	17	FF	1.0	20.8	21.3	16.80	17.09	7.9	7.8	3.6	6.2	105.8	97.4
26	1:00 p. m.	18	LF	--------	18.9	18.9	17.45	17.34	7.9	7.8	3.1	3.1	92.6	94.0
Nov. 10	11:45 a. m.	19	FF	2.0	14.1	14.1	17.90	17.88	7.9	7.9	--------	--------	98.1	100.8
Dec. 1	12:30 p. m.	21	FE	1.6	4.2	4.3	17.57	17.57	8.0	7.9	3.1	3.1	--------	--------
1937														
Jan. 12	2:30 p. m.	22	LWS	1.7	8.9	8.9	12.25	12.47	7.9	7.9	Tr.	Tr.	--------	--------
Feb. 2	11:50 a. m.	24	LE	.7	6.2	6.1	7.14	7.05	7.5	7.1	Tr.	Tr.	86.7	78.0
16	11:00 a. m.	25	½F	1.7	5.9	5.7	8.33	8.28	7.5	7.7	--------	--------	106.2	101.8
Mar. 2	12:00 m.	26	FF	1.8	--------	3.8	--------	7.85	--------	--------	--------	24.8	--------	--------
23	10:45 a. m.	27	FE	2.0	8.9	8.8	9.16	10.23	--------	--------	3.1	6.2	--------	--------
Apr. 6	12:00 m.	28	½E	1.0	13.1	12.7	9.02	9.07	8.4	8.4	5.0	5.0	105.3	105.0
21	10:45 a. m.	29	FE	1.4	16.1	14.1	10.35	13.46	8.6	8.6	--------	--------	117.7	113.5

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[1] LWS=Low water slack, HWS=High water slack, LE=Last of ebb, LF=Last of flood, FF=First of flood, etc.

[2] Tr.=Trace.

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