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WOODS HOLE OCEANOGRAPHIC INSTITUTION
Woods Hole, Massachusetts

THE DISTRIBUTION OF SALINITY IN THE ESTUARY OF THE DELAWARE RIVER

Supplementary report

Prepared by
Bostwick H. Ketchum, Scientist in charge

December, 1952

APPROVED FOR DISTRIBUTION Alfred C. Redfield
Associate Director

WOODS HOLE OCEANOGRAPHIC INSTITUTION
WOODS HOLE, MASSACHUSETTS

December 30, 1952

Board of Water Supply
City of New York
120 Wall Street
New York 5, New York

Gentlemen:

A report concerning the distribution of salinity in the estuary of the Delaware River prepared by Dr. Bostwick H. Ketchum is transmitted herewith. The principal conclusions of our study are summarized in the introduction to the report.

The basic data we have used for determining the salinities within the bay are given in tabular form in Mr. Terenzio's Second Report, which also includes charts and detailed descriptions of the surface distributions. These data are not presented again in this report. We agree with his description and interpretation of these data.

It is significant that, while our methods of treating and interpreting these data was independent and different from Mr. Terenzio's, we have arrived at substantially the same conclusions wherever similar subjects are considered in both reports. Although the basic data are incontrovertible, interpretations of data may be subject to question. It is, consequently, gratifying that our conclusions and his are mutually confirmatory.

Respectfully yours,

Alfred C. Redfield

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Associate Director

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DISTRIBUTION OF SALINITY IN THE ESTUARY OF THE DELAWARE RIVER

INTRODUCTION

The Woods Hole Oceanographic Institution has been asked by the New York City Board of Water Supply to study and review recent observations on the distribution of fresh and salt water in the Estuary of the Delaware River. The objective was to determine the relationship between river flow and the salinity in various parts of the estuary so that the effects of the proposed diversion of Delaware River water on the distribution of salinity could be evaluated.

The study has included a review of data on the distribution of fresh and salt water in the coastal water immediately outside the Delaware Capes. It had been alleged that a pool of fresh water accumulates in this area which is returned to the bay on the flood tide and thus decreases the salinity of Delaware Bay. While it is true that the water immediately outside every river mouth is fresher than the surrounding sea water it must be realized that this fresh water is constantly being exchanged. New fresh water is supplied on each tidal cycle from the estuary, and old fresh water is being mixed with sea water on the outskirts of the freshened area. The problem becomes, therefore, one of determining how long any given increment of fresh water can be expected to remain in the area, and influence the subsequent salinity within the bay. Analysis of the non-tidal currents and estimation of the volume of fresh water derived from the Delaware River Watershed which is accumulated in the area indicate that the water outside the Capes will be swept away in a period of two to five days. The belief that the large spring flows of the Delaware River will be accumulated and retained for long periods of time in the area of the sea outside the bay thus appears to be unfounded.

The distribution of salinity within the estuary of the Delaware River has been derived from the data of nine surveys conducted during 1951 and 1952. For any location within the estuary there is a natural variation of salinity which is greatest at a location near the head of the Bay. The range of salinity at this location exceeds fifteen parts per thousand at comparable stages of the tide, and exceeds eighteen parts per thousand if extreme conditions at low water slack and high water slack are compared. The effects of diversions on the salinity of the bay should be evaluated with reference to these variations which are observed under the natural conditions prevailing at present.

The total volume of river water accumulated within the Delaware River and Bay Estuary increases with increasing river flow. The length of time required for the river to contribute a volume of water sufficient to replace the volume of fresh water accumulated within the estuary has been defined as the Flushing Time. For river flows about equal to the mean annual flow (11,770 cfs. or one billion cubic feet per day) the flushing time for the entire estuary, between Trenton and the Capes, is about 100 days. For low river flows, nearly four months are required for the rivers to replace the volume of fresh water which accumulates under this condition. For flows about double the mean annual value, the time is reduced to about sixty days. The large Spring flows of the Delaware River can, therefore, be expected to have an important influence on the salinity of the bay for a period of about two months, but they will be swept through the bay by the end of that time and effects over longer periods cannot be expected.

In order to evaluate the proposed diversion of Delaware River water the relationship between river flow and the salinity conditions at various locations in the estuary has been studied. At any location within the estuary the salinity is inversely related to river flow; the higher the river flow the lower the salinity. It is possible to predict from this relationship the effect of the diversion at various river flows. At low rates of river flow (2,157 cfs. at Trenton) the natural salinity would be unusually high throughout the estuary. The release of water required by the proposal, as shown by the Hydrographs, would reduce these salinities at most by 0.37 parts per thousand for the 440 mgd. diversion and 1.08 parts per thousand for the 800 mgd. diversion. For river flows about double the average rate (28,900 cfs. at Trenton) the unusually low salinities occurring under natural conditions would be increased at most by 1.69 parts per thousand for the 440 mgd. diversion and 3.20 parts per thousand for the 800 mgd. diversion.

These predicted changes are the greatest to be expected in any part of the estuary for the conditions considered. The maximum effect is not expected to occur at the same locality under all conditions. It will be found further downstream during high river flows and further upstream during low flows.

Under present natural conditions the range of variation of salinity expected for the two rates of river flow given above would be greatest at a location near the head of the bay, where it would equal 16.46 parts per thousand. It is calculated that this range would be reduced to 14.73 parts per thousand by the 440 mgd. diversion and further reduced to 12.85 parts per thousand by the 800 mgd. diversion. Both of these estimates, of course, take account of the release of water during periods of low river flow.

The proposed diversions of Delaware River water will thus increase the unusually low salinities in the estuary because of retention of water, and will reduce the unusually high salinities, because of the releases of water during periods of low flow. The extreme variation of salinity in the estuary will be somewhat reduced.

Biologically, the important conditions which limit the viability or success of populations are generally the extreme conditions to which the populations are exposed. The proposed diversions should, therefore, be beneficial to the populations within the estuary.

OFFSHORE CONDITIONS

We have been asked to discuss the salinity of the sea outside the Delaware Capes and to reach conclusions concerning the volumes of Delaware River water accumulated in this area,and the length of time this accumulated fresh water remains in the area and can be expected to influence the salinity of Delaware Bay. The non-tidal currents, salinities of the water, and the river flow are the data we have used in reaching our conclusions which may be summarized as follows.

1. The non-tidal currents would be expected to carry the water opposite the entrance to Delaware Bay southward and away from the entrance in a period of two to five days.
2. The fresh water attributable to the Delaware River and its tributaries is spread over wide areas of the sea (2000-3500 square miles in the two surveys analyzed), outside and to the south of the entrance to Delaware Bay.
3. The volume of Delaware River water in these large areas corresponds to little more than two weeks flow of the Delaware and its tributaries to the Capes.

4. The belief that the heavy spring flows of the Delaware River may have a prolonged effect on the offshore area and on the salinity of water returning to Delaware Bay on the flood tide appears to be unfounded.

Off the coast of eastern United States is an area known as the Continental Shelf which ranges in width from 20 to 150 miles between Cape Cod and Cape Hatteras. The seaward boundary is the 100 fathom (600 ft.) depth contour. Beyond this the depth increases rapidly to 1000 fathoms.

The waters over the Continental Shelf are diluted by precipitation and drainage from the land. Undiluted sea water which is found just over the edge of the Continental Shelf has a salinity of 35.00 $^{o}/_{oo}$.[a] Most of the water on the Shelf has lower salinities which range from about 31.5 $^{o}/_{oo}$ to 35.0 $^{o}/_{oo}$. Immediately opposite the mouths of the various rivers which enter this area, the salinity is still further reduced. The amount of the reduction varies with the time of year and the associated changes in the volume of the water produced by the rivers.

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[a] The symbol $^{o}/_{oo}$ is used for parts of sea salt per thousand parts of solution, on a weight basis.

Currents on the Continental Shelf outside Delaware Bay.

The currents over the Continental Shelf flow in a general southerly direction largely paralleling the shore. The Current Atlas of the North Atlantic Ocean published by the Hydrographic Office of the U. S. Navy Department (H. O. Miscel. No. 10688, First Edition, 1946) shows that throughout the year the currents off the mouth of the Delaware flow southerly to southeasterly with velocities of two to six miles per day. These currents were obtained by averaging all available navigational data from ships over many years and were generally based on several hundred observations. The analysis of such a large number of observations produced the resultant current or non-tidal drift. This general rate of circulation has been confirmed by drift bottles released in this area, which also indicate that the non-tidal drift in the offing of Delaware Bay is in the neighborhood of four or five miles per day. (A. R. Miller, Woods Hole Oceanographic Institution Report 52-28)

Current measurements made by the U. S. Coast and Geodetic Survey indicate that the non-tidal current at Overfalls Lightship in the entrance to Delaware Bay flows S 17°E at 0.12 knots, or 2.88 nautical miles per day, and at Five Fathom Bank Lightship, about twenty miles east of the entrance, the non-tidal current flows S, 75°E at 0.11 knots or 2.64 nautical miles per day. (Zeskind and Lacheur, Dept. of Commerce, U. S. C. and G. Survey Sp. Pub. 123, 1926, p. 68-75.)

These current observations indicate that the fresh water contributed by the Delaware River to the offshore area will be transported southward or southeastward, and away from the mouth of the bay. Since the mouth of the bay is about ten miles wide, non-tidal drifts of two to five miles per day would carry water from the northern end of the entrance to the southern end in two to five days. The current measurements thus indicate that large masses of fresh water from the Delaware Estuary will not remain opposite the entrance to the bay for long periods of time.

Salinity on the Continental Shelf Opposite Delaware Bay.

The surface salinity distribution observed in May, 1951 immediately outside Delaware Bay is shown in Figure 1. (A. R. Miller, Woods Hole Oceanographic Report 52-28). These data were obtained from a continuous record of salinity made by the STD (salinity, temperature, depth recorder) as the ship followed the course track shown by the fine, zigzag line. The pattern shows that the freshened waters leaving Delaware Bay turn southward along the coast, where they are gradually mixed with sea water to give higher and higher salinities. This distribution is to be expected from the non-tidal currents in the area. The results of five other surveys conducted for the U. S. Navy Hydrographic Office in recent years also indicate that the water leaving Delaware Bay is carried southward along the coast. The patterns differ in details and in complexity, but all show this same basic feature.

The average salinity of the waters over the Continental Shelf from the coast out to the 20 fathom (120 ft.) depth contour have been determined to aid in evaluating the offshore effect of the Delaware. On the average, between Cape Cod and Cape Hatteras, the water within the 20 fathom depth contour has a salinity of 32.55$^{o}/_{oo}$. If we take 35.00$^{o}/$oo as the salinity of undiluted sea water, this corresponds to 7.1% fresh water in the entire area. Bigelow and Sears (Pap. Phys. Oceanog. & Meteorol. 4(1), 1935) found that off the mouth of the Delaware River the "vernal freshening of the water reaches its climax about a month after the discharge of the Delaware River passes its peak". The salinity at their station closest to shore off Cape May ranged from about 30.9 to 32.4$^{o}/_{oo}$ in 1929 and from

30.4 to 32.4$^{o}/_{oo}$ in 1930. Fresher water was found directly in the mouth of the bay where the surface salinity dropped to 24.58$^{o}/_{oo}$. At times, therefore, the water near the mouth of Delaware Bay is only slightly fresher than the average along the entire coast from Cape Cod to Cape Hatteras. At other times the salinity is substantially reduced by the Delaware flow.

The salinity of the waters off the mouth of the Delaware is changed, not only by the Delaware River, but also by the fresh water contributed by the Hudson, Connecticut and other rivers to the north. The large amounts of fresh water from these rivers is carried to and past the mouth of Delaware Bay in the southward Continental Shelf current. In order to evaluate the relative effect of the Delaware River on the salinity of the waters on the Continental Shelf, the size of the drainage areas may be compared. We have determined the drainage area supplying the Continental Shelf between Cape Cod and Cape Hatteras to be 116,000 square statute miles. The surface water area over the Continental Shelf measures an additional 37,000 square miles. Of the total area of 153,000 square miles, the Delaware River and Bay system contributes 13,628 square miles or 8.9%. Its effect on the salinity of the waters of the Continental Shelf would be expected to bear a similar relationship to the total effect.

The flushing time of the area outside Delaware Bay.

The length of time required, on the average, to transport river water through an estuary or a limited part of the sea has been defined as the Flushing Time. Where sea water is diluted by river water, the proportion of each type of water present can be determined from the salinity. The total quantity of river water in the area considered is determined, and the Flushing Time is the length of time required for the river to produce an equivalent volume. A study of the accumulation of river water in an area of 500 square miles off the mouth of the Hudson River has been reported by Ketchum, Redfield, and Ayers (Pap. Phys. Oceanog. & Meteorol. 12(1), 1951). It was found that the average time for the transport of river water through this area, regardless of the rate of river flow, was about ten days.

A similar analysis has been made for the area off the mouth of Delaware Bay. It was based on data obtained for the U. S. Navy Hydrographic Office on two surveys made by the U. S. Coast & Geodetic Survey Vessel STIRNI in cooperation with Dr. Harold Haskin of Rutgers University. These two surveys were made on

22 October - 13 November 1951 and on 29 February - 18 March 1952. The results are shown in Table I.

During the October - November cruise the survey discovered freshened water over a sea surface area of approximately 2000 square statute miles. It will be shown below that a period of two to three months is required for the transport of river water through the Delaware Estuary. The average monthly rate of flow for the third month prior to the survey is, therefore, used to determine the flushing time of the offshore area. The flow measured at Trenton is multiplied by 1.57 to account for the additional drainage downstream (see Figure 6). The mean river flow in August, used for the October - November survey, was relatively low and a flushing time for the offshore area of 17.4 days was obtained. Prior to the February - March survey the river flow had been large. The sea water which was freshened by the water discharged through Delaware Bay was found to extend over a sea surface area of about 3500 square statute miles. The flushing time of the offshore area for this period was 16.4 days.

These results show that, on the average, the fresh water discharged from the mouth of Delaware Bay is rapidly diluted with sea water over extensive areas. The transport of fresh water through these large areas requires only a little more than two weeks, and is independent of the river flow.

It appears from these results that the conditions off the mouth of the Delaware are not substantially different from those off the mouth of the Hudson, and that the circulation rapidly removes the fresh water issuing from Delaware Bay so that its effect on the salinity of the bay will be limited to a short period of time. The time will be even shorter than the two week period given above since these estimates include the effect of fresh water far removed from the mouth of the bay.

The belief that the heavy spring flows of the Delaware have a prolonged effect on the offshore area and on the salinity of the water returning to the Delaware Bay on the flood tide thus appears to be unfounded. Although, as it will be shown in the next section, it takes about two months for the transport of these large flows through the river and bay, they are dispersed within a very few days after passing the Capes and entering the sea.

SALINITIES AND FLUSHING TIMES WITHIN DELAWARE BAY.

We have been asked to study recent observations on the distribution of salinity in Delaware Bay, and to determine the volumes of fresh water within the bay at various times, and the length of time required for the transport of river water through the estuary. Our conclusions may be summarized as follows:

1. The salinity increases along the length of Delaware Bay, following a sigmoid curve, from salinities of nearly zero at the river end to salinities which approach 32.00 parts per thousand at the seaward end.
2. At any location within the bay a considerable range of variation of salinity may be expected as a result of variations in river flow. For comparable stages of the tide this variation exceeds 15.00 parts per thousand of salinity near the head of Delaware Bay.
3. The total volume of river water accumulated in the bay increases with increasing river flow.
4. The flushing time for the river part of the system (where the water is 99% or more fresh water) varied from 7.2 to 36.5 days, the shorter time corresponding to the higher river flow.

5. The flushing time for the estuary (where the water present contains less than 99% fresh water) varied from 40.9 to 89.5 days. The flushing times were shortest for high flows and longest for the low flows of the river.

The distribution of salinity within Delaware Bay has been derived from observations made during nine periods between September 1951 and July 1952. The observations were made for the U. S. Navy Hydrographic Office by Dr. L. Eugene Cronin of the University of Delaware and Dr. Harold Haskin of Rutgers University. The series of observations used are listed in Table II.

Mid-Channel Salinity Distribution.

The samples were taken at various stages of the tide. To obtain a comparable distribution pattern the location of the sampling point has been adjusted to its presumed high water slack postion using for this purpose the direction and velocity of tidal currents given by the current tables published by the U. S. Coast and Geodetic Survey. The stations which were, after adjustment, in a mid-channel position were combined for each cruise to provide a mid-channel salinity distribution. The results show the change in salinity with length of the estuary and are presented in Figure 2.

The salinities in this figure are the highest salinities one would expect at each location at any stage of the tide for the particular conditions existing at the time of the observations. At other stages of the tide the salinities in the channel would be lower than those recorded. The magnitude of the salinity change with the ebbing tide can be approximated from the curves in Figure 2 by the assumption that the salinity at any locality at low water slack will be equal to the salinity at high water slack 30 channel stations upstream. This assumption is based upon the fact that the excursion on the ebb tide is about 30,000 feet or five nautical miles. Such a displacement downstream indicates that the maximum change during the tidal cycle would occur where the plot of salinity vs. distance is steepest and would amount to about six parts per thousand. Some observations were made available by Dr. Haskin which show such a variation of salinity during the tidal cycle and indicate that the range may, at times, be greater than six parts per thousand. This data may be summarized as follows:

Salinities (parts per thousand) at various stages of the tide.

Ship John Light	maximum	minimum	range
April 1952 Surface	7.4	2.1	5.3
Bottom	17.2	8.9	8.3
February 1952 Surface	15.2	<10.4	>4.8
Bottom	16.8	<11.1	>5.7
Miah Maull			
April 1952 Surface	19.2	10.8	8.4
Bottom	23.2	18.2	5.0
February 1952 Surface	21.6	15.0	6.6
Bottom	24.4	21.8	2.6

The mid-channel salinities are also higher than can be expected on either side of the channel. The surveys indicate that at high water slack the water on both sides of the channel at the surface is somewhat fresher than the water in mid-channel. It may also be noted that the channel includes the deepest water in the bay, which is also generally the most saline.

The data in Figure 2 make it possible to determine the range of variation of salinity to be expected at various locations under natural condtions. The salinities have been read from Figure 2 for mid-channel locations 300, 350, 400,450, and 500. The first three of these are within the area occupied by the seed oyster beds; the last two are within the oyster planting bed area. The results are given in Table III. The greatest range of salinity observed any place within the estuary was found at Channel Station 300, where the difference between the highest and lowest salinity at high water slack was 15.2$^o/_{oo}$. Above this location the lowest salinities quickly approach zero and the highest salinities were never greater than 15.2$^o/_{oo}$ above Station 267. Downstream from this location the minimum salinities are never low enough to produce a greater range. If the highest salinity at high water slack is compared with the lowest salinity expected at low water slack the range of variation at this location increases to 18.6$^o/_{oo}$. It is clear that successful oyster culture is now carried on in the stretch of the river where the variations in salinity are relatively large.

Distribution of fresh water in Delaware Bay.

The fresh water distribution can be derived directly from the salinity. From the distribution of fresh water and river flow the Flushing Times can be calculated. To permit direct comparison of these times the bay has been divided into sections. The sections selected, and the weighted mean salinity for each section for each of the nine surveys is shown in Table IV. These mean salinities were derived from the data given in Figure 2. In some cases there was a considerable stretch of the river where no observations were available between the bay determinations and the river observations made for the New York City Board of Water Supply. In these locations the probable trend of salinity change was assumed as shown by the dashed lines in Figure 2, and the corresponding salinities are given in parentheses in Table IV.

The proportion of fresh water has been computed from these mean salinity values using a salinity for the source mixing water of 32.00°/oo. Reference to Figure 2 shows that all of the seaward salinities are approaching this value, and the observations in the offshore area indicated that water of this salinity was always in the immediate offing of the bay. The proportions of fresh water in each of the sections of the estuary are given in Table V.

The volume of fresh water within the bay has been computed from the fresh water proportions and from the high tide volume of the river and bay. The volume data used were provided by U. S. Army Engineers and were based on the following surveys:

Trenton to Philadelphia	1951
Philadelphia to New Castle	1942
New Castle to Ship John Light	1946
Ship John Light to the Capes	1931

These data were presented for the mid-tide conditions (+3.0 feet referred to Delaware River Datum). They were corrected to mean low tide to give the low tide volumes. To these low tide volumes were added the intertidal volumes. Because the tidal wave in the Delaware River and Bay system is a progressive one it is not possible to use the range of tides at each location in computing the intertidal volume. The method of computing the intertidal volume is as follows:

From the tide tables of the U. S. Coast and Geodetic Survey the height of the tide throughout a lunar tidal cycle at various locations was computed. The tide stations used were so selected that a given stage of the tide occurs an hour later at each up river station. For each of these stations a tide curve was prepared, with the result shown in Figure 3. The progressive wave up the river can be clearly seen by comparing the times of low water at successive stations.

For each of the twelve lunar tidal hours the height of tide at each station was determined, and the resultant heights were plotted against the length of the estuary.

Four of the curves thus obtained are shown in Figure 4. Distances in this and the next figure are expressed in nautical miles from Cape Henlopen, so that Cape Henlopen is at zero miles, Trenton at 120 miles. Each of these curves shows, on a vastly exaggerated vertical scale, the contour of the water surface above mean low water. It will be seen that there is about half a wave in the river at any time. When it is high tide half way up the river it is approaching mid-tide at both ends, and conversely, when it is high tide at one end it is approaching low tide at the other. It is clear that the intertidal volume of the Delaware Estuary can not be calculated by simply multiplying the range of tides by the surface area, as can be done for an estuary having a standing tidal wave.

The intertidal volume in the river has been computed for each of the twelve lunar hours during a tidal cycle. The maximum and minimum enclosed volumes at any time during the tidal cycle are thus obtained for each of the nine tidal stations. In Figure 5 these enclosed volumes are plotted against distance. The difference between the maximum and minimum enclosed volumes at any distance gives the volume which must enter any part of the estuary during a tidal cycle to produce the observed change in water level -- that is, it is the enclosed intertidal volume for that part of the river.

The sum of the intertidal volumes computed in this way and the low tide volumes derived from the U. S. Army Engineers data gives the high tide volume of the river and estuary. The results are presented in Table VI for the various stretches of the river.

The product of these volumes and the proportion of fresh water in the appropriate stretch of the river, gives the total volume of fresh water present. These volumes are given in Table VII.

The Flushing Time.

The data presented in Table VII, when combined with the appropriate river flow, can be used to compute the flushing time of various parts of the estuary. Two factors, which must be considered, make the determinations of the appropriate river flow difficult. First, only part of the fresh water in the area is contributed by the Delaware River at Trenton, since the fresh water inflow is augmented downstream by additional rivers and drainage areas. Second, the river flow is variable and the fresh water found in any part of the estuary may have been contributed at a time when the flow was quite different from that which obtained at the time of the survey. The following discussion shows how these factors have been treated.

1) Augmentation of river flow.

The drainage area of the entire Delaware River and Bay system is more than twice as great as that part which lies above Trenton. Figure 6 shows the relationship between drainage area and length of the system. In spite of the two fold increase in drainage area, the increase in river flow has been estimated by Mr. Terenzio of the New York City Board of Water Supply to be only 1.57 times the Trenton flow. The ratio of river flow at various downstream stations is given by the lower line in Figure 6. It seems possible that the difference between river flow and drainage area in the lower part of the bay may be partially compensated for by direct inflow of ground water into the lower bay. However, we have used the river flow curve in determining the factors by which the Trenton flow is augmented downstream.

2) Variation in river flow.

To take account of variations in river flow, the cumulative volume of water contributed by the Delaware River at Trenton has been computed for a period prior to the date of the surveys, as listed in Table II. This is done for a long enough period of time to account for the total volume of fresh water (corrected for augmentation) found within the estuary. The cumulative volumes of river water produced by the Delaware River at Trenton prior to each survey are given in Figure 7.

An example of the actual calculation of Flushing Time is shown in Table VIII. The volume of fresh water in each section was obtained from Table VII. The river factor (column 3) was read from the lower curve in Figure 6. The observed volume of fresh water in each section divided by the appropriate river factor shows that part of the fresh water which was contributed by the Delaware River at Trenton. The length of time for the river to produce this volume was, then, read from Figure 7. This is equivalent to the flushing time for the part of the Delaware River and Bay considered. The cumulative Flushing Times between Trenton and various cross sections of the estuary and the appropriate Trenton river flows are presented in Table IX for each of the nine surveys.

One of the striking characteristics of the Delaware River is the fact that the total volume of river water in the upper regions (above Channel Station 100) is independent of river flow. This part of the river is always 99% or more fresh water whether the river flow is large or small. As a result the flushing time of this part of the river flucutates greatly. Because of fluctuating river flow the flushing time of this part of the river varies from 2 to 30.5 days.

At times of high river flow the water which is practically fresh extends downstream beyond Channel Station 100. The part of the river which is more than 99% fresh is indicated by the underlined numbers in Table IX. The mechanism for the flushing of this part of the river must be quite different from the mechanism involved where the tides are mixing fresh and salt water. The flushing times for the river part of the system below Trenton vary from 7.2 days to 36.5 days.

In all parts of the estuary the flushing times are inversely related to river flow, that is high flows result in low flushing times and vice versa. The computed flushing times between Trenton and various boundaries in the estuary are plotted against river flow in Figure 8. Four of the surveys provided adequate data to evaluate the flushing time from Trenton to the Capes. The times varied from 53.9 to 99.5 days. For low flows the times will be even longer, as shown by the flushing times of 103 days to Station 450 obtained for Survey B, and 109 days to Station 500 obtained for Survey C. Both of these surveys were conducted when the river flows at Trenton were about 0.5 billion cubic feet per day (5700 ft^3/sec.). Survey D was made following a period of rapidly increasing river flow, and indicated a flushing time of nearly 108 days to Station 450.

To summarize these results, it appears that for river flows about the annual mean value (1.0 billion cubic feet per day) the flushing time of the Delaware River and Bay system between Trenton and the Capes is about 100 days. For greater flows, about 2.0 billion cubic feet per day, the flushing time is reduced to about sixty days. For low flows, about 0.5 billion cubic feet per day, the flushing times increase. Although the surveys available at the times of low flow do not permit calculation to the Capes, it appears that a flushing time of four months would be approximately correct for these conditions.

It has been alleged that the large spring flows of the Delaware River may have a prolonged effect on the salinity of the bay and compensate to some extent for the lowest flows in mid-summer. The flushing times indicate that these large flows will have an important influence for about two months, but will be transported through the bay by the end of this time, and longer influences cannot be expected.

The accumulation of pollution in the estuary is also intimately related to the accumulation of fresh water, since much of the pollution is introduced in the "river" end of the system. The amount of pollution in the estuary, or any part of it, would thus be equivalent to the rate of introduction times the flushing time.

At times of low river flow, therefore, almost four months' contributions of pollution can be expected in the estuary, whereas the accumulation at high river flows would be equal to about two months of contributions.

EFFECT OF DIVERSIONS

We have been asked to estimate the effect on the distribution of salinity in Delaware Bay to be expected from the proposed diversions, with the associated releases of water at times of low river flow. The conclusions we have reached may be summarized as follows:

1. The salinity at any location in the estuary is an inverse exponential function of river flow. Practically all of the salinities predicted from this relationship agree with observed salinities within 10%. In contrast, the natural variations associated with fluctuating river flow may be several hundred percent, and exceed 100% throughout most of the estuary.
2. The diversions will have the maximum effect in the part of the bay where the gradient of salinity is greatest -- i.e. where the curves in Figure 2 are the steepest.
3. At the average rate of river flow (11,770 cfs. at Trenton) the maximum effect is predicted

between Channel Stations 300 - 350, where the diversion of 440 mgd. is expected to increase the salinity by 0.43 parts per thousand. For the diversion of 800 mgd. the predicted increase in salinity is 0.85 parts per thousand.

4. At low rates of flow the salinities will be decreased by the release of water as shown by the hydrographs. For 440 mgd. diversion a maximum decrease of 0.37 parts per thousand is predicted at Stations 200 - 250. For 800 mgd. a maximum decrease of 1.08 parts per thousand is predicted for the same location.

5. For flows of about double the average rate, with impounding of water as shown by the hydrographs, the salinity in the estuary will increase. The effect will be greatest between Stations 350 - 400, where the 440 mgd. diversion is expected to increase the salinity by 1.69 parts per thousand and the 800 mgd. diversion is expected to increase the salinity by 3.20 parts per thousand.

6. The range of variation of salinity as a result of fluctuating river flow is expected to be reduced by the proposed diversion. Under natural conditions the range of salinity variation is greatest, 16.46 parts per thousand, between

Stations 300 - 350. It is calculated that this range of variation would be reduced to 14.73 parts per thousand by the 440 mgd. diversion, and further reduced to 12.85 parts per thousand by the 800 mgd. diversion. These reductions result because the lowest salinities would be increased by retention of water during high flows, and the highest salinities would be reduced by releases of water during low flow periods.

7. The reduction of the range of variation of salinity by the proposed diversions of Delaware River water is expected to be beneficial to biological populations inhabiting the estuary.

Salinity - River flow relationship

In order to evaluate the possible effect of New York City's allowed and proposed diversions of Delaware River water, the relationship between salinity and river flow must be determined. It is shown that the salinity at various locations within the estuary is an inverse exponential function of river flow. This relationship was predicted on purely theoretical grounds by Arons and Stommel (Trans. Amer. Geophys.Union, 32, 419-421, 1951).

The demonstration that this relationship is applicable to the Delaware Estuary makes it possible to predict the changes of salinity to be expected from modifications of river flow.

Arons and Stommel proposed a theory which describes the distribution of salinity in a hypothetical estuary of uniform cross section. Their fundamental equation may be written

$$S_x = \sigma e^{\mathcal{F}\left(1 - \frac{L}{x}\right)} \qquad (1)$$

in which S_x is the salinity at any position in the estuary, x, σ is the salinity of the source sea water, L is the total length of the estuary, e is the base of the natural logarithms (2.718), and F is the flushing number which is a compound term including river flow and various characteristics of the estuary which are constant for any given location in any given estuary. For our purposes we will define the flushing number as:

$$\mathcal{F} = \mathcal{R}\mathcal{F}' \qquad (2)$$

in which R is the river flow at Trenton in cubic feet per second. Substituting RF' for F in equation (1) makes it possible to solve for the relationship between salinity and river flow. Although F' is a compound term which takes account of such characteristics of the estuary as depth, excursion of the water due to the tide, and the intensity of the mixing of salt and fresh water, it is unnecessary to know the values of the component parts if the value of the whole can be determined. The value of F' has been determined empirically from the observations made during the nine surveys listed in Table II.

According to above equations the salinity at any location within the estuary should be related to river flow as follows:

$$\ln S_x = \ln \sigma + R F'\left(1 - \frac{L}{x}\right) \qquad (3)$$

The term $(1 - \frac{L}{X})$, which establishes the location within the estuary, is always negative since L, the total length always exceeds x, the partial length. The predicted relationship would thus show a decrease of salinity with increasing river flow.

The salinity data from the nine available surveys have been plotted on a logarithmic scale against the appropriate river flow in accordance with this relationship. The results are shown in Figure 9, which illustrates that the salinity in each segment does decrease in a regular way with increasing river flow. There is some variation of the observations from the correlation lines drawn, but the variations are much less than might be expected from the magnitude of the fluctuation in river flow. In plotting the points the average river flow applicable to the flushing time for each part of the estuary has been used. These averages commonly include individual flows that vary from one another by a factor of 2 or more - in one case the river flow had increased over the total flushing time by a factor of 15. Much smaller adjustments of the river flow for the points in Figure 9 would place all of the observations directly on the appropriate correlation line.

In order to solve equation (3) for salinity it is necessary to know the value to be assigned to the salinity of the source sea water σ, and the value of $F' (1 - \frac{L}{X})$ for each of the locations in the estuary considered in Figure 9. Substitution of these values, and of any given river flow at Trenton (in cubic feet per second) into equation (3) gives a solution for the salinity to be expected at that location and river flow. The values for these constants are listed below for eight locations in the estuary.

Location	σ	$F' (1 - \frac{L}{X})$
100 - 200	6.5	-1.65×10^{-4}
200 - 250	14.25	-1.52×10^{-4}
250 - 300	19.5	-0.727×10^{-4}
300 - 350	25.0	-0.492×10^{-4}
350 - 400	28.0	-0.353×10^{-4}
400 - 450	30.0	-0.191×10^{-4}
450 - 500	31.0	-0.084×10^{-4}
500 - 550	32.0	-0.0725×10^{-4}

The salinity expected at each of these locations has been determined for the river flows applicable at the time of each of the nine surveys listed in Table II. To compare the predicted values with observations these results have been plotted in Figure 10 against the salinity values listed in Table IV for the same locations. The two lines forming an envelope for the points on this figure correpsond to equality plus or minus 10%. It is clear that practically all of the observed salinities are predicted from river flow at Trenton with at least this accuracy. In contrast, the variation which resulted because of fluctuations in river flow was 770% between Stations 250 and 300, and exceeded 100% throughout most of the estuary. The errors of prediction are, consequently, small in comparison to the natural variations.

Predictions of the effects of Diversions.

The average flow of the Delaware River at Trenton, based on 34 years of record is 11,770 cfs. The diversion of 440 million gallons per day would reduce this mean flow to 11,089 cfs., and the diversion of 800 million gallons per day would reduce it to 10,530 cfs. The average distribution of salinity and the effects of this diversion on the average can be determined from the correlations in Figure 9 for the various sections of the bay. The results are given in Table X. The maximum effect would be in the region lying between Stations 300 and 350 where the increase in salinity is predicted as 0.43$^{o}/_{oo}$ for the 440 mgd. diversion and 0.85$^{o}/_{oo}$ for the 800 mgd. diversion.

In accordance with the release formula, the Trenton flows will be augmented during low flow periods. The lowest weekly average flow in 1949 as shown on the hydrographs was 2157 cfs. during the week of August 27. This would be increased to 2404 cfs. according to the release formula for diversion of 440 mgd. and to 2893 cfs. for a diversion of 800 mgd. The expected salinity distribution with the unmodified flow and with flow modified by the two diversion formulae are shown in Table XI. As a result of this low river flow the salinity throughout the river would be considerably higher than would be expected under the average flow conditions. Because water would be released at this low river flow, the effect of the diversion would be to decrease the salinity throughout the river. The maximum decrease is predicted between Stations 200 - 250 where the diversion of 440 mgd. is expected to reduce the salinity by 0.65$^{o}/_{oo}$. For the 800 mgd. diversion the maximum effect is predicted at the same location where the salinity would be expected to decrease by 1.08$^{o}/_{oo}$.

As an example of the effect of the diversion of moderately high river flows, the week of January 4, 1949 has been selected. The natural flow of the Delaware at Trenton during this week averaged 28900 cfs. The 440 mgd. diversion would reduce this to 24471 and the 800 mgd. to 21095 cfs. The effect of these reductions are shown in Table XII. With this river flow the salinity throughout the bay would, of course, be much less than under the average flow conditions. For the 440 mgd. diversion the maximum effect is predicted between Stations 350 - 400 where the unusually low salinity would be increased by 1.69$^{o}/_{oo}$. In the same range the 800 mgd. diversion would produce its maximum effect by increasing the salinity by 3.20$^{o}/_{oo}$.

In the text above we have selected the location where the maximum effect is predicted. The data in the table show that the effect of the diversion will decrease both landward and seaward of the point of maximum effect. The location of the maximum effect in every case is in the zone of the maximum gradient of salinity -- where the curves in Figure 2 are the steepest. This zone moves downstream with increasing river flows, and the maximum effect is, therefore, not always expected at the same locality.

Biologically, the important conditions which may limit the viability or success of populations are generally the extremes to which these populations are exposed. The proposed diversions are expected to reduce the annual range of variation of salinity in all parts of the estuary. The ranges observed during 1951 and 1952 have already been presented in Table III. From Tables XI and XII the ranges at the indicated low and high river flow can be listed for the natural conditions and two diversion proposals. Since the diversion increases the lowest salinities by impounding water at times of high river flow and decreases the highest salinities by releasing water at times of low river flow, the range of salinity to be expected will be decreased by the proposed diversions. The ranges of salinity variation expected are shown in Table XIII.

Under natural conditions the maximum range of variation would be expected between Stations 300 -350. For the high river flow the salinity at this location is predicted as $6.03^{o}/_{oo}$; for low flow periods it would increase to $22.49^{o}/_{oo}$ -- a salinity range of $16.46^{o}/_{oo}$. The 440 mgd. diversion is predicted to decrease this range to $14.73^{o}/_{oo}$ by increasing the low salinity to $7.50^{o}/_{oo}$ and decreasing the high salinity to $22.23^{o}/_{oo}$. The diversion of 800 mgd. would further decrease the range to $12.85^{o}/_{oo}$ by increasing the low salinity to $8.85^{o}/_{oo}$ and reducing the high salinity to $21.70^{o}/_{oo}$. Similar, but smaller modifications of the range of variation of salinity would be expected in other parts of the estuary.

If the extreme conditions of salinity variation in the estuary of the Delaware River limit the viability or growth of populations within the estuary, the retention and releases of water under the proposed plans will be beneficial because they will decrease the range of variation of salinity in all parts of the estuary.

Table I

Accumulation of River Water and Flushing Time of an Area of the Continental Shelf Opposite the Entrance to Delaware Bay.

Date of Survey	Oct-Nov 1951	Feb-March 1952
Area Surveyed Sq. St. Miles	3,820	3,620
Area Freshened Sq. St. Miles	2,000	3,460
Total Volume $10^9 ft^3$	11,483	11,015
Volume Fresh $10^9 ft^3$	15.81	43.77
Mean River Flow[1] $10^9 ft^3$/day	0.91[a]	2.67[b]
Flushing Time Days	17.4	16.4

[1]The average river flow two months prior to the survey (cf Table IX) has been used. The Trenton gaged flow (cfs.) is multiplied by 1.57 to account for downstream increments (See Figure 6) and by 86,400 seconds per day.
a: August: 6710 x 1.57 x 86,400 = 0.91 x $10^9 ft^3$/day.
b: December: 19,700 x 1.57 x 86,400 = 2.67 x $10^9 ft^3$/day.

Table II

Sources of Data for the Determination of the Distribution of Salinity in Delaware Bay.

Code No.	Date	Source
A	6 Sept. 1951	USN - Dr. Haskin
B	26-27 Sept. 1951	USN - Dr. Haskin
C	9 Oct. 1951	USN - Dr. Haskin
D	9 Nov. 1951	USN - Dr. Haskin
E	30 Nov. - 3 Dec. 1951	USN - Dr. Cronin
F	1-5 Feb. 1951	USN - Dr. Cronin
G	22-29 May 1952	USN - Dr. Cronin
H	28 July 1952	USN - Dr. Haskin
I	18-22 Aug. 1952	USN - Dr. Cronin

Table III

Maximum and Minimum Salinities and Salinity Range (parts per thousand) observed at Various Locations during the Surveys listed in Table II.

Location	High Water Slack Maximum	High Water Slack Minimum	High Water Slack Range	Low Water Slack* Minimum	Maximum Range
300	18.9	3.7	15.2	0.3	18.6
350	22.2	9.6	12.6	6.0	16.2
400	25.8	13.8	12.0	11.3	14.5
450	29.1	21.7	7.4	15.7	13.4
500	30.6	25.8	4.8	24.0	6.6

*Assuming a 30 station downstream displacement on the ebbing tide.

Table IV

Observed Mean Salinity (parts per thousand) in Various Stretches of Delaware River and Bay.

Location Chan. Sta.	Surveys A	B	C	D	E	F	G	H	I
Tr. - 100	(.007)	(.01)	(.01)	(0)	.14	.13	.06	(0)	(.02)
100 - 200	(.18)	(1.85)	(2.1)	(.01)	1.20	.17	.12	(.11)	.63
200 - 250	(1.85)	(6.30)	(7.20)	(.29)	3.45	.45	.17	(1.20)	4.06
250 - 300	10.50	13.91	15.72	7.24	7.19	1.17	3.27	7.65	8.85
300 - 350	18.71	18.47	20.77	14.18	14.41	6.65	8.62	15.20	14.09
350 - 400	23.15	22.57	24.03	18.71	21.19	11.94	13.48	19.98	17.82
400 - 450	26.95	26.48	27.49	23.09	24.76	17.18	19.60	24.63	23.76
450 - 500			29.92		27.46	24.19	24.82	28.33	27.49
500 - 550					28.94	27.88	26.96		29.50

Note: Salinities in parentheses were estimated from the dashed lines in Figure 2.

Table V

Percent Fresh Water in Various Stretches of Delaware River and Bay, Reference Salinity 32.00 parts per thousand.

Location Chan. Sta.	Surveys A	B	C	D	E	F	G	H	I
Tr. - 100	99.99	99.97	99.97	100.00	99.56	99.59	99.81	100.00	99.94
100 - 200	99.44	94.22	93.44	99.97	96.25	99.47	99.62	99.66	98.03
200 - 250	94.22	80.31	77.50	99.09	89.22	98.59	99.47	96.25	87.31
250 - 300	67.19	56.53	50.87	77.37	77.53	96.34	89.78	76.09	72.34
300 - 350	41.53	42.28	35.09	55.69	54.97	79.22	73.06	52.50	55.97
350 - 400	27.66	29.47	24.91	41.53	33.78	62.69	57.87	37.56	44.31
400 - 450	15.78	17.25	14.09	27.84	22.62	46.31	38.75	23.03	25.75
450 - 500			6.50		14.19	24.41	22.45	11.47	14.09
500 - 550					9.56	12.87	15.75		7.81

Note: The underlined numbers identify the extent of the "river part" of the estuary referred to in the text.

Table VI

The Total Volumes of Water (billions of cubic feet) in Various Stretches of Delaware River and Bay

Location Chan. Sta.	Low Tide Volume $10^9 ft^3$	Intertidal Volume $10^9 ft^3$	High Tide Volume $10^9 ft^3$
Tr. - 100	11.7	3.70	15.4
100 - 200	12.5	2.60	15.1
200 - 250	9.7	2.20	11.9
250 - 300	13.2	3.20	16.4
300 - 350	18.9	5.30	24.2
350 - 400	34.0	11.0	45.0
400 - 450	61.0	20.0	81.0
450 - 500	102.0	23.0	125.0
500 - 550	161.0	21.4	182.4
Total	424.0	92.4	516.4

Table VII

Volume of Fresh Water (billions of cubic feet) in Various Stretches of Delaware River and Bay

Location	Surveys								
Chan. Sta.	A	B	C	D	E	F	G	H	I
Tr. - 100	15.40	15.40	15.40	15.40	15.33	15.34	15.37	15.40	15.39
100 - 200	15.02	14.23	14.11	15.10	14.53	15.02	15.04	15.05	14.80
200 - 250	11.21	9.56	9.22	11.79	10.62	11.73	11.84	11.45	10.39
250 - 300	11.02	9.27	8.34	12.69	12.71	15.80	14.72	12.48	11.86
300 - 350	10.05	10.23	8.49	13.48	13.30	19.17	17.68	12.70	13.54
350 - 400	12.44	13.26	11.21	18.69	15.20	28.21	26.04	16.90	19.94
400 - 450	12.78	13.97	11.41	22.55	18.32	37.51	31.39	18.65	20.86
450 - 500			8.12		17.74	30.51	28.06	14.34	17.61
500 - 550					17.44	23.47	28.73		14.25
Total to 450	87.92	85.92	78.18	109.70	100.01	142.78	132.08	102.63	106.78
Total to 550					135.19	196.76	188.87		138.64

Note: See Table V.

Table VIII

Example of the Calculation of Flushing Time for Delaware River and Bay.
Survey of 1-5 Feb. 1952 (F)

Location Chan. Sta.	Volume Fresh $10^9 ft^3$	River Factor	Trenton Equivalent Local $10^9 ft^3$	Trenton Equivalent Total $10^9 ft^3$	Total Time Days	Trenton Mean Flow $10^9 ft^3/day$
Tr. - 100	15.34	1.365	11.2	11.2	4.0	2.81
100 - 200	15.02	1.455	10.3	21.5	7.2	2.99
200 - 250	11.73	1.470	8.0	29.5	10.0	2.95
250 - 300	15.80	1.486	10.6	40.1	15.8	2.54
300 - 350	19.17	1.502	12.8	52.9	23.7	2.23
350 - 400	28.21	1.518	18.6	71.5	36.0	1.96
400 - 450	37.51	1.534	24.5	96.0	48.0	2.00
450 - 500	30.51	1.551	19.8	115.8	60.0	1.93
500 - 550	23.47	1.570	14.9	130.7	64.0	2.04

Table IX

The Cumulative Flushing Time (days) between Trenton and Various Boundaries in Delaware River and Bay, and the Applicable Trenton Mean River Flow (billions of cubic feet per day) for the nine surveys listed in Table II.

Survey	A		B		C	
Boundary	Flow	Time	Flow	Time	Flow	Time
100	.49	23.0	.37	30.5	.38	29.5
200	.59	36.5	.44	47.5	.40	53.0
250	.61	48.0	.49	56.5	.43	63.0
300	.60	61.5	.53	64.0	.46	71.5
350	.61	70.5	.54	75.0	.50	77.5
400	.62	83.0	.56	88.4	.51	89.6
450	.63	95.0	.57	103.0	.53	101.2
500	--	--	--	--	.54	109.0
550	--	--	--	--	--	--

Survey	D		E		F	
Boundary	Flow	Time	Flow	Time	Flow	Time
100	5.69	2.0	1.12	10.1	2.81	4.0
200	3.94	5.5	1.26	16.8	2.99	7.2
250	2.05	14.5	1.38	20.6	2.95	10.0
300	1.25	30.5	1.60	23.1	2.54	15.8
350	0.84	56.5	1.76	26.0	2.23	23.7
400	0.71	84.0	1.93	29.0	1.96	36.0
450	0.69	107.7	1.71	39.7	2.00	48.0
500	--	--	1.22	65.0	1.93	60.0
550	--	--	0.91	99.5	2.04	64.0

Survey	G		H		I	
Boundary	Flow	Time	Flow	Time	Flow	Time
100	2.25	5.0	.90	12.5	.58	19.5
200	2.35	9.2	1.27	17.0	.66	32.7
250	2.25	13.0	1.20	24.5	.74	38.5
300	1.97	20.0	.93	40.8	.81	45.0
350	1.96	26.0	.93	49.5	.82	55.5
400	1.99	34.2	1.04	55.0	.82	71.6
450	2.08	42.5	1.15	60.7	.92	78.8
500	2.22	48.0	1.22	64.5	1.00	83.7
550	2.32	53.9	--	--	1.06	87.1

Table X

Effect of diversions on the mean salinity (parts per thousand) to be expected in various reaches of the Delaware River and Bay at mean river flow.

	No Diversion	440 mgd		800 mgd	
River Flow, Trenton, cfs.	11,770	11,089		10,530	
Location	Salinity	Salinity	Change	Salinity	Change
100 - 200	0.94	1.04	+.10	1.14	+.20
200 - 250	2.41	2.64	+.23	2.87	+.46
250 - 300	8.33	8.72	+.39	9.07	+.74
300 - 350	14.05	14.48	+.43	14.90	+.85
350 - 400	18.54	18.96	+.42	19.29	+.75
400 - 450	24.00	24.27	+.27	24.54	+.54
450 - 500	28.08	28.24	+.16	28.37	+.29
500 - 550	29.39	29.54	+.15	29.66	+.27

Table XI

Effects of diversions and release on the mean salinity (parts per thousand) to be expected in various reaches of the Delaware River and Bay at low river flow.

	No Diversion	440 mgd		800 mgd	
River Flow, Trenton, cfs.	2,157	2,404		2,893	
Location	Salinity	Salinity	Change	Salinity	Change
100 - 200	4.55	4.37	-.18	4.04	- .51
200 - 250	10.26	9.89	-.37	9.18	-1.08
250 - 300	16.67	16.36	-.31	15.81	- .86
300 - 350	22.49	22.23	-.26	21.70	- .79
350 - 400	25.96	25.72	-.24	25.28	- .68
400 - 450	28.80	28.65	-.15	28.38	- .42
450 - 500	30.44	30.38	-.06	30.26	- .18
500 - 550	31.49	31.46	-.03	31.33	- .16

Table XII

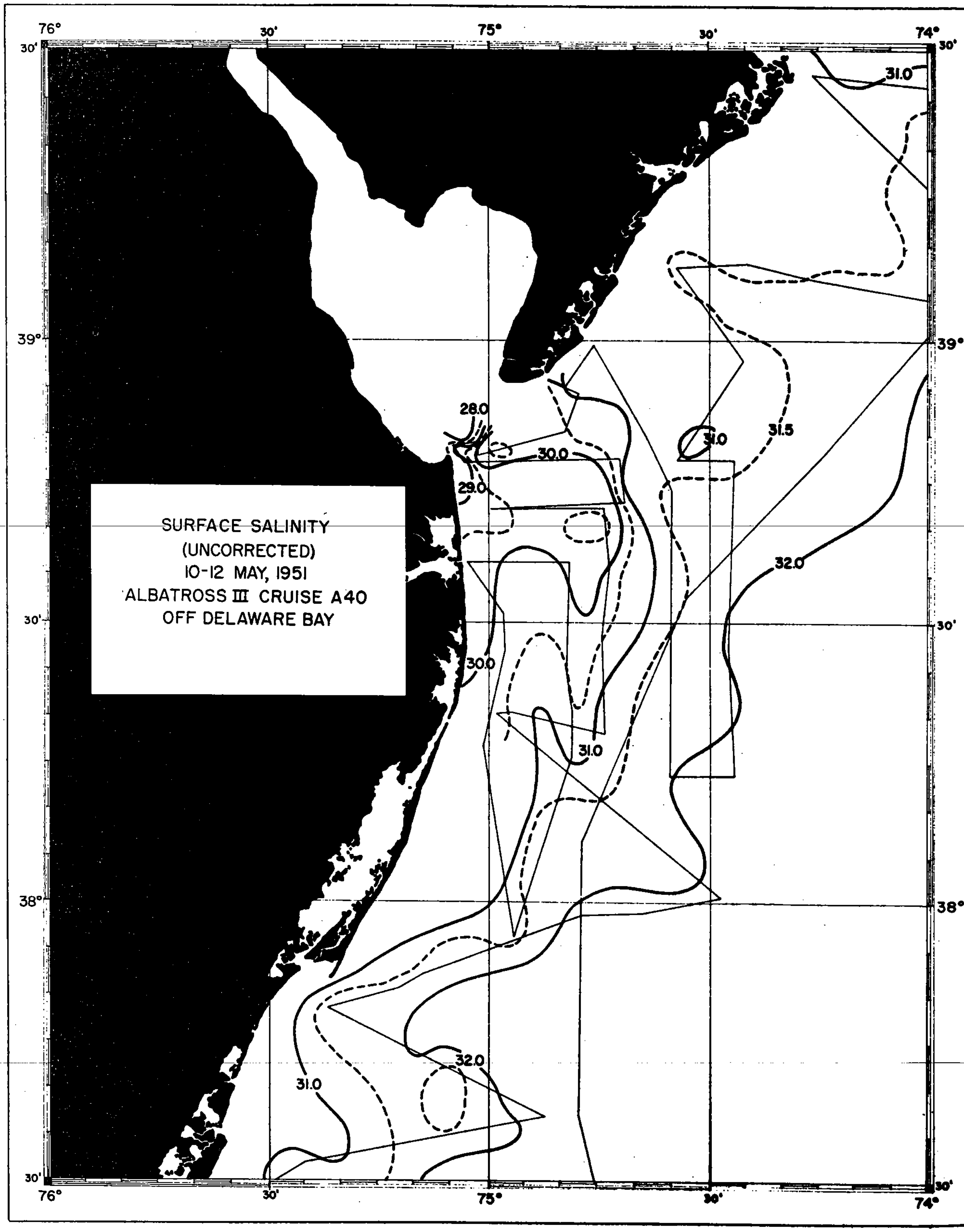
Effects of diversions on the mean salinity (parts per thousand) to be expected in various reaches of the Delaware River and Bay at high river flow.

	No Diversion	440 mgd		800 mgd	
River Flow, Trenton, cfs.	28,900	24,471		21,095	
Location	Salinity	Salinity	Change	Salinity	Change
100 - 200	0.05	0.11	+ .06	0.20	+ .15
200 - 250	0.18	0.34	+ .16	0.58	+ .40
250 - 300	2.38	3.30	+ .92	4.21	+1.83
300 - 350	6.03	7.50	+1.47	8.85	+2.82
350 - 400	10.10	11.79	+1.69	13.30	+3.20
400 - 450	17.28	18.81	+1.53	20.04	+2.76
450 - 500	24.27	25.23	+ .96	25.95	+1.68
500 - 550	25.94	26.82	+ .88	27.46	+1.52

Table XIII

Range of Salinities (parts per thousand) to be expected in various reaches of the Delaware River and Bay.

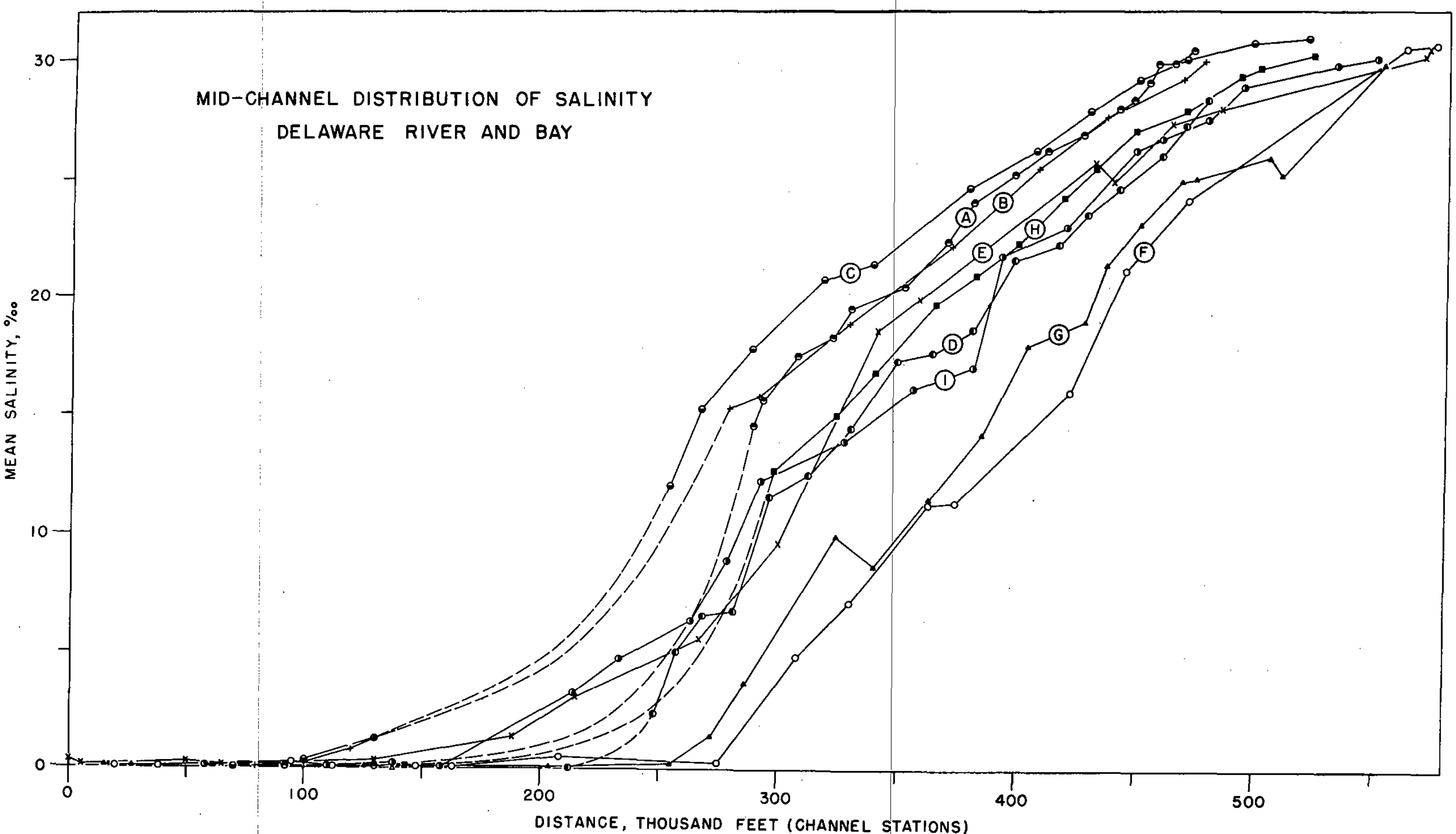
Location	No Diversion	440 mgd	800 mgd
100 - 200	4.50	4.26	3.84
200 - 250	10.08	9.55	8.60
250 - 300	14.29	13.06	11.60
300 - 350	16.46	14.73	12.85
350 - 400	15.86	13.93	11.98
400 - 450	11.52	9.84	8.34
450 - 500	6.17	5.15	4.31
500 - 550	5.55	4.64	3.87



SURFACE SALINITY
(UNCORRECTED)
10-12 MAY, 1951
ALBATROSS III CRUISE A40
OFF DELAWARE BAY
76°
30'
75°
30'
74°
39°
38°
28.0
29.0
30.0
31.0
31.5
32.0

FIG. I

FIGURE 2



The mean mid-channel salinity observed in Delaware River and Bay on nine surveys (see Table II) conducted during 1951 and 1952.

FIGURE 3

The height of the tide at nine tide gaging stations in Delaware River and Bay at various times during a tidal cycle.

FIGURE 4

The height of the water surface above mean low water at various locations in Delaware River and Bay at four stages of the tide, separated by three lunar hours. Distances are expressed in nautical miles from Cape Henlopen.

FIGURE 5

The maximum and minimum enclosed intertidal volumes in Delaware River and Bay. Distances are expressed in nautical miles from Cape Henlopen.

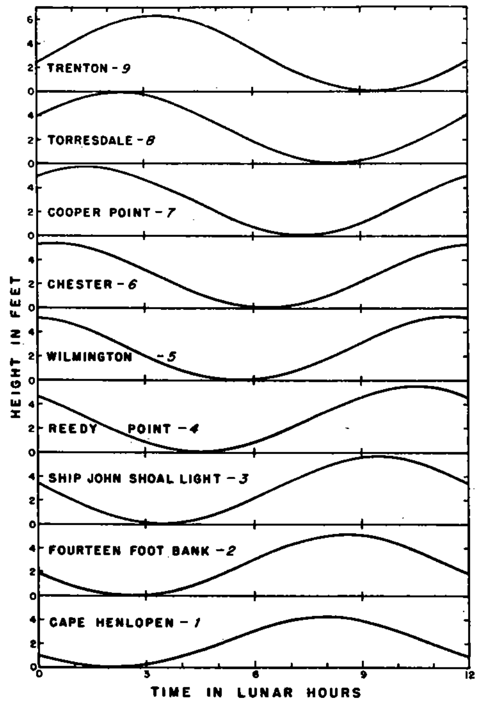


FIG. 3

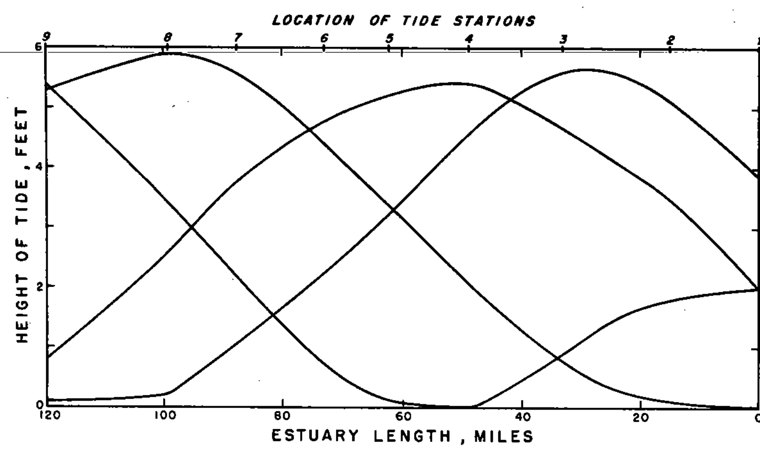


FIG. 4

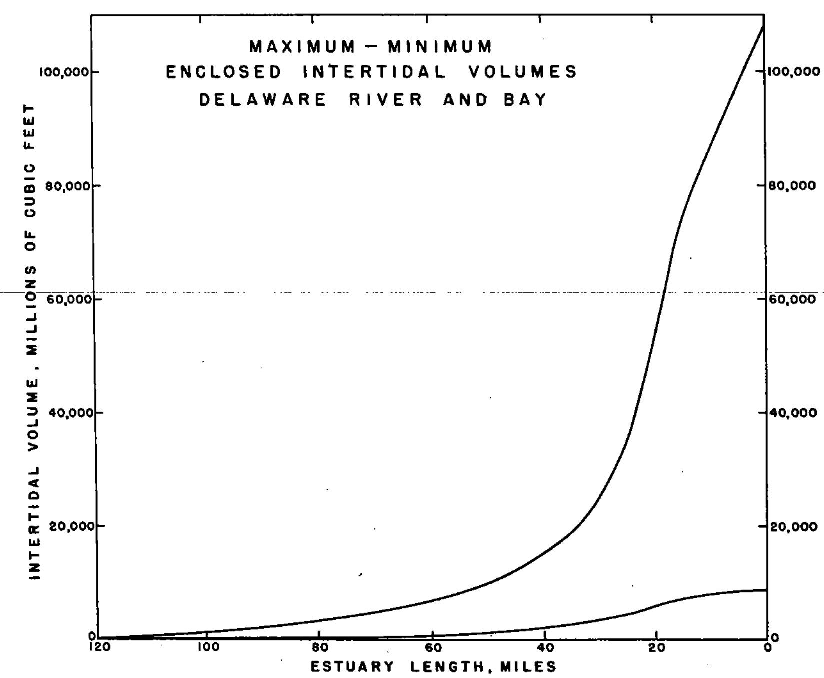


FIG. 5

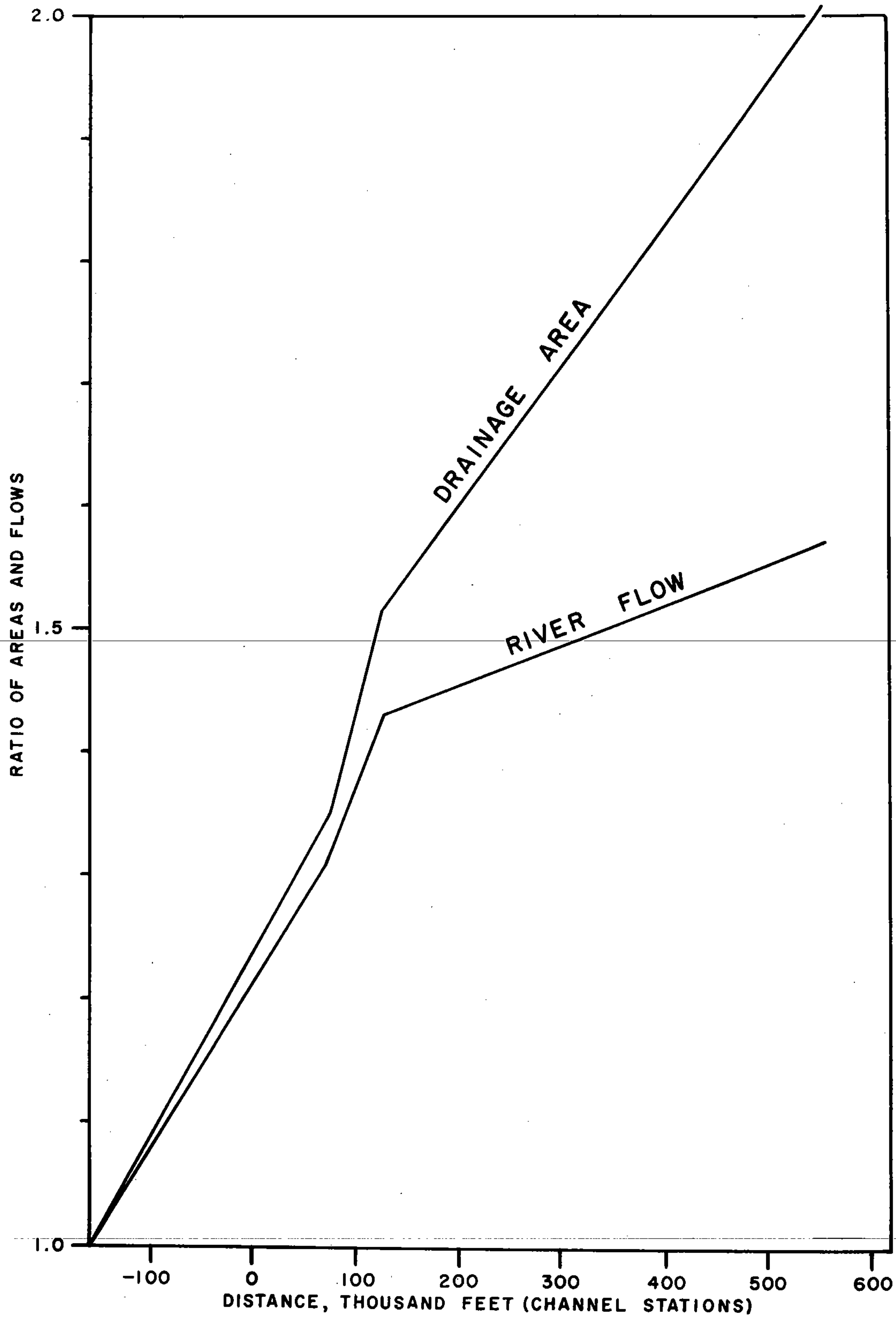


FIGURE 6

The change in total drainage area (upper curve) and in gaged river flow (lower curve) with length of the Delaware River and Bay Estuary.

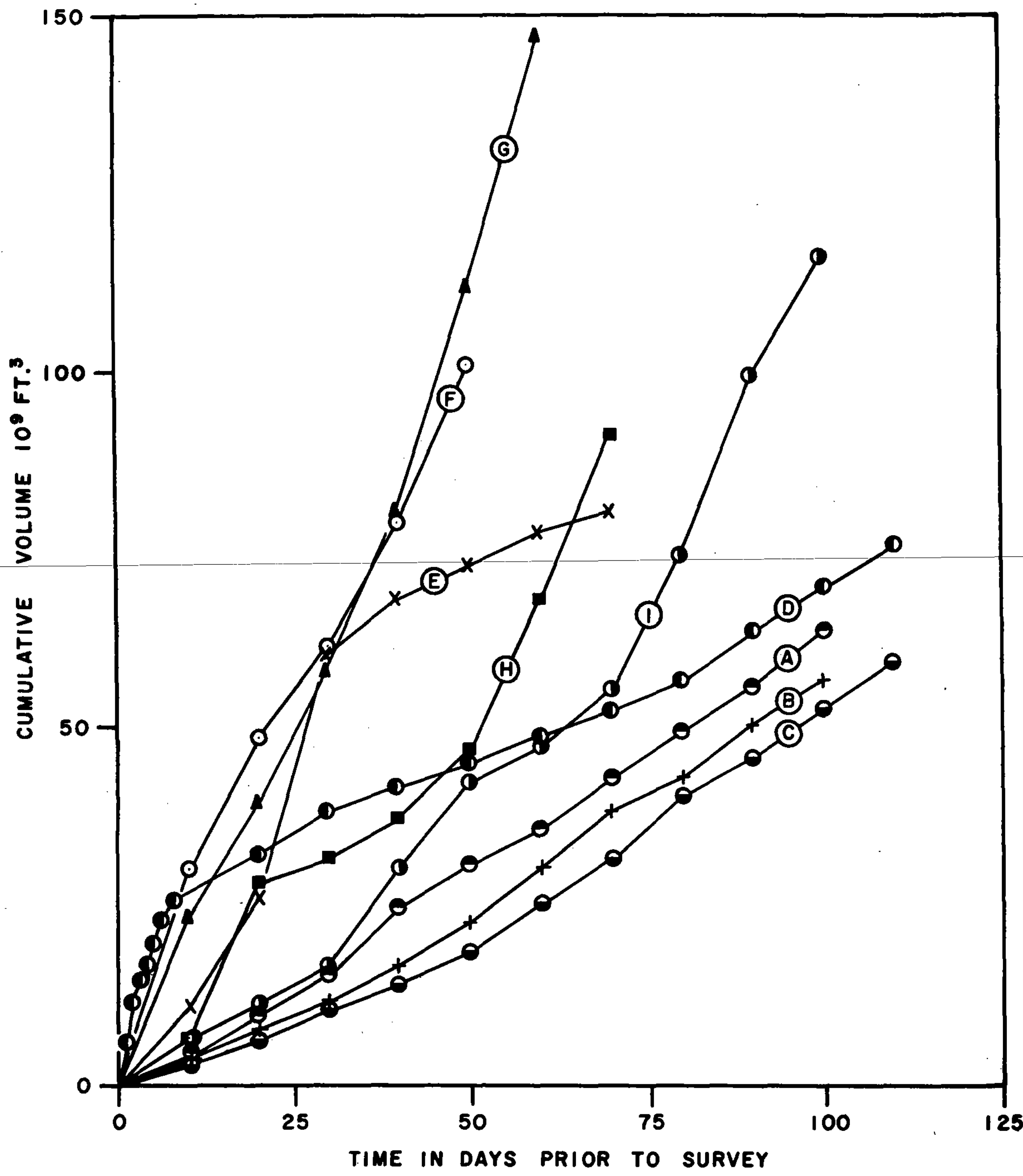


FIGURE 7

The cumulative volume of river water introduced by the Delaware River at Trenton for various times prior to the nine surveys listed in Table II.

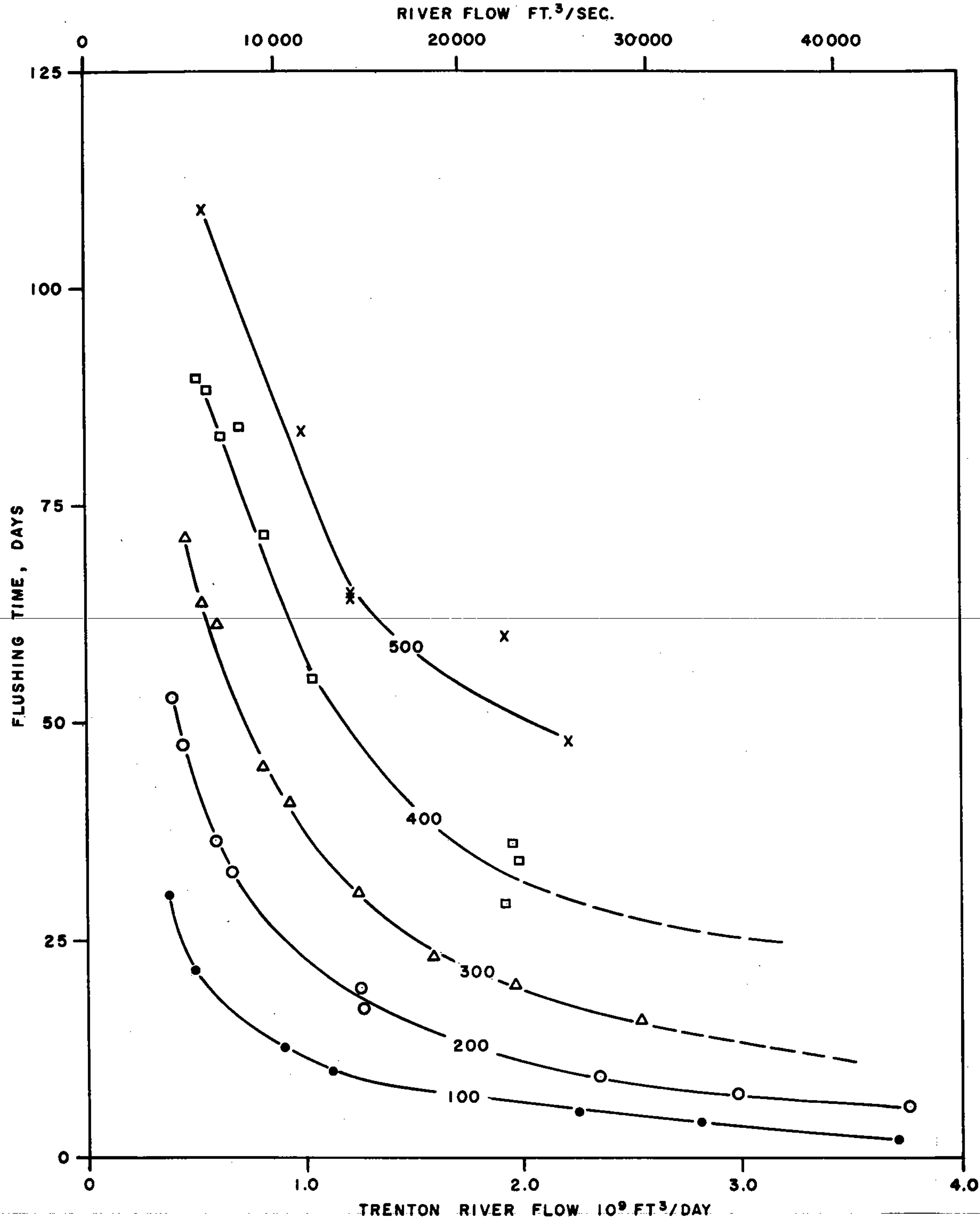


FIGURE 8

The cumulative flushing times between Trenton and various boundaries in the Delaware Estuary as a function of River flow at Trenton. The numbers on the curves represent the Channel Station at the outer boundary of the part of the estuary considered

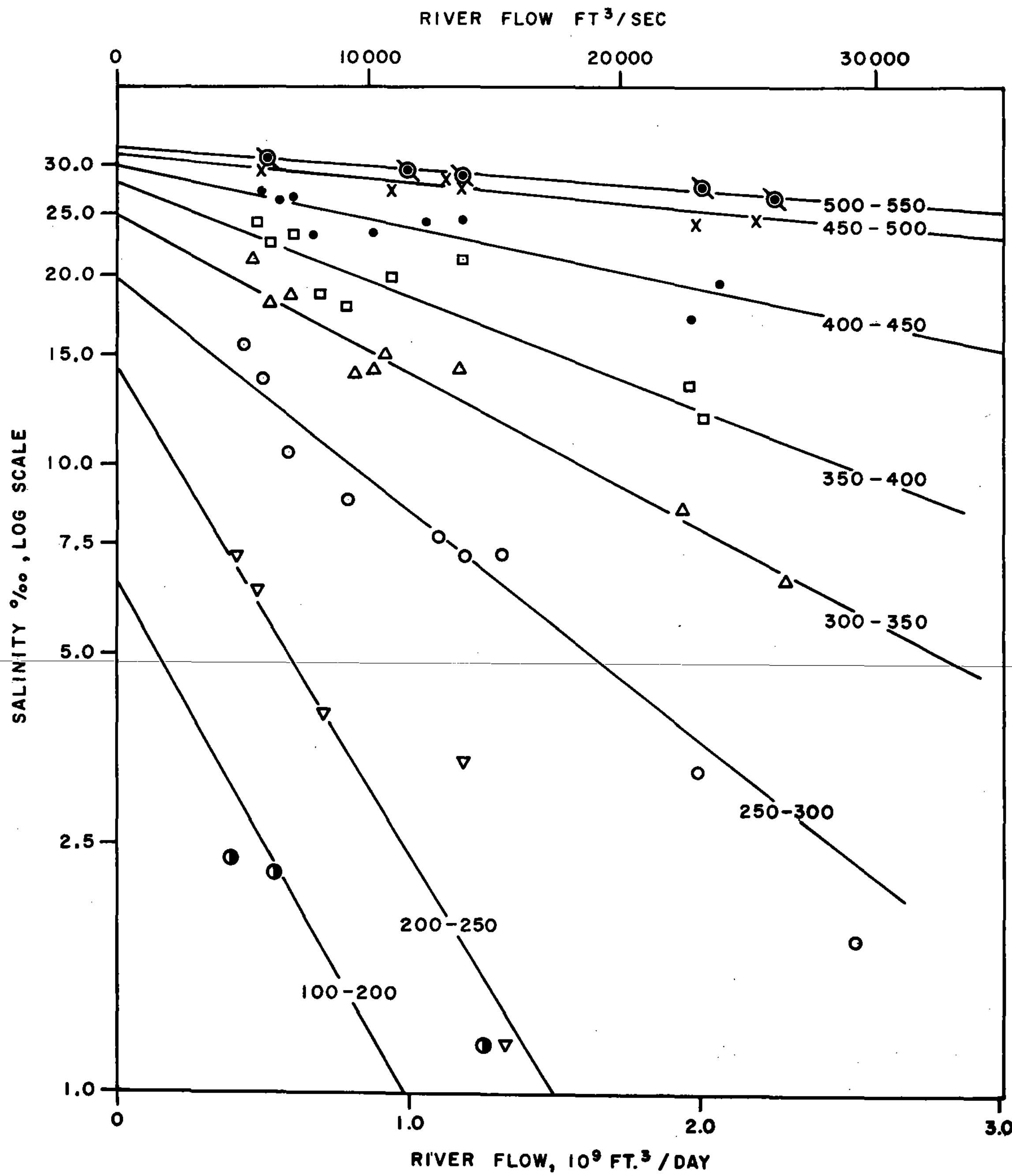


FIGURE 9

The mean, mid-channel salinity for various reaches of the Delaware River and Bay as a function of River flow at Trenton. The numbers on each line give the Channel Station location of the inner and outer boundaries of the region over which the salinities have been averaged.

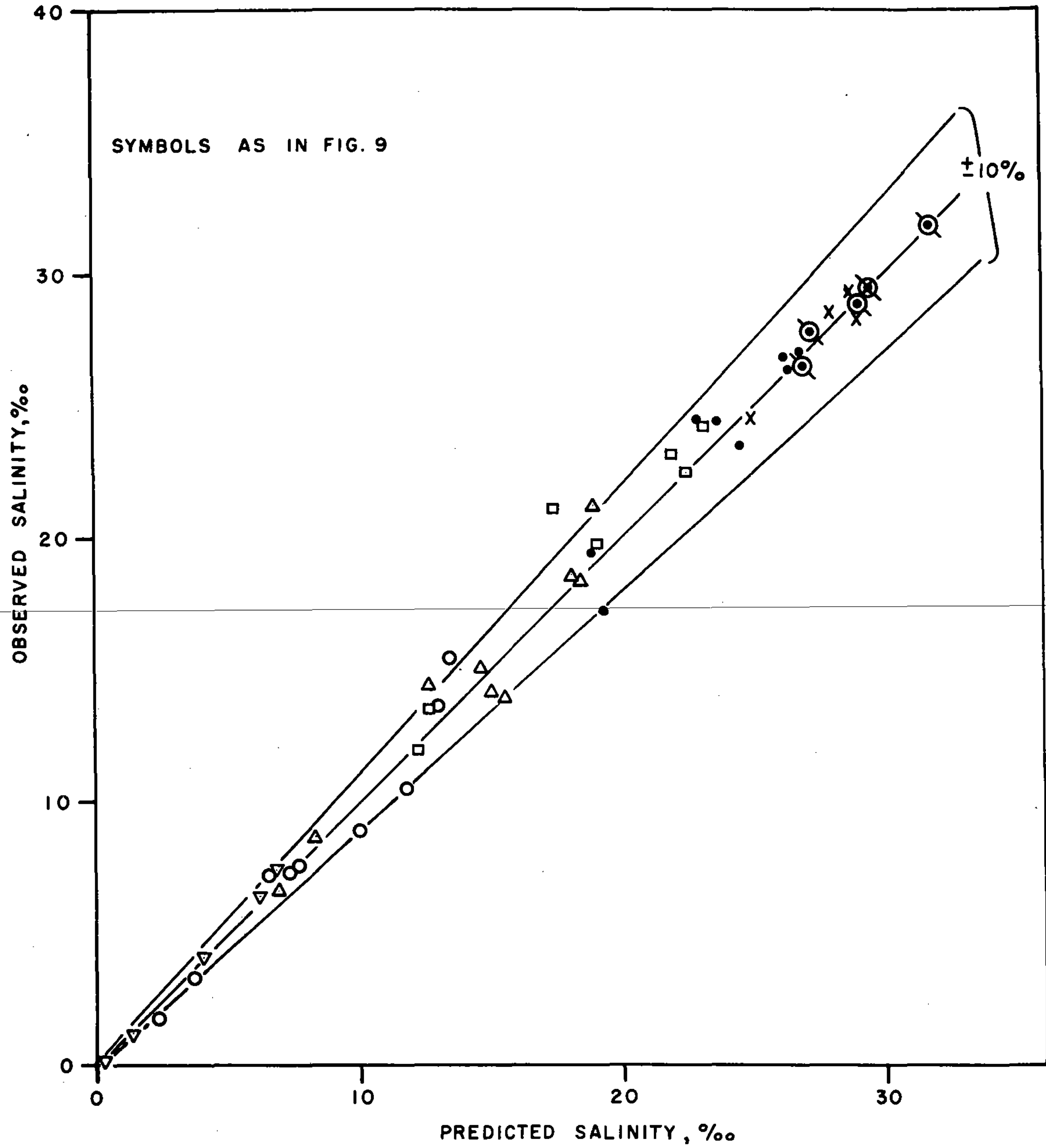


FIGURE 10

Comparison between the mean, mid-channel salinities predicted from the relationship shown in Figure 9, and the salinities observed at comparable locations during nine surveys in 1951 and 1952. The symbols used for each point are the same as in Figure 9, and identify the location of the observation.