EFFECT OF WIND ON SALINITY DISTRIBUTION IN AN ESTUARY[1]

By

JOHN P. BARLOW[2]

ABSTRACT

The distribution of salinity in a small tidal estuary, Great Pond, through a period of over a year is described. The numerous important variations in salinity, both seasonal and short-term, cannot be attributed to tides or to day-to-day changes in the supply of fresh water. It is shown that they are related to day-to-day changes in wind force and direction and that the general seasonal change in average salinity is related to a general seasonal change in prevailing winds.

INTRODUCTION

Of the important time and space variations in properties of estuaries, the most striking are those of salinity. Salinity variations are of particular significance since they may represent marked changes in both the accumulation and distribution of fresh and salt water. Some variations in salinity can clearly be attributed to climatic and seasonal changes in the fresh water supply from land drainage; others are of such short duration and irregular occurrence that their causes are not immediately apparent.

These salinity variations appear to be especially marked in the smaller and shallower estuaries, such as those dissecting the southern shore of Cape Cod. Ketchum (1951) has discussed the circulation and tidal exchanges in one of these small estuaries, Great Pond, near Woods Hole, Massachusetts, and the purpose of this paper is to present the results of a year's study of the variations in salinity of this same estuary. The salinity data have been collected during seasonal surveys of biological and chemical properties of this pond (Barlow, 1955; Hulbert, 1956) and during several detailed hydrographic studies. These data give an exceptionally detailed description of the salinity variations in this estuary and provide the basis for an understanding of their causes.

[1] Contribution No. 752 from the Woods Hole Oceanographic Institution.

[2] Present address: Department of Conservation, Cornell University, Ithaca, New York.

METHODS AND SOURCES OF DATA

Great Pond (Fig. 1) is the drowned mouth of a small river, the Coonamessett, which now provides the principal source of fresh water for the pond. Great Pond's northern portion, the arm, is shallow and muddy and is surrounded by high banks and trees which shelter it from most winds. The narrows and main pond are deeper, sandier, and more exposed to winds from all directions. The extensive shallows in the southern end were apparently formed by sand drifting into the pond from Vineyard Sound. The narrow entrance from Vineyard Sound is maintained in the barrier beach by a set of stone revetments and jetties.

Twenty-eight regular surveys of the plankton, salinity, phosphate, and temperature were made between March 20, 1950 and July 7, 1951. Surface and bottom salinity samples were usually taken at

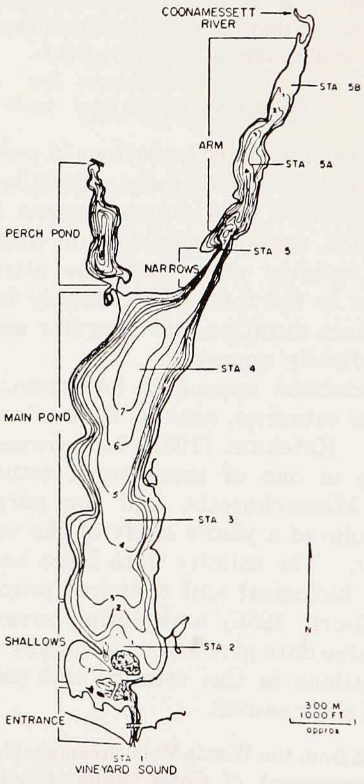

Figure 1. Chart of Great Pond. Depths in feet

all of the stations shown in Fig. 1. During spring and summer of 1950, observations were taken at about 10 to 15 day intervals, but during the following winter and spring they were less frequent and less detailed. Intensive surveys during which the salinity distribution was studied in greater detail throughout several stages of the tide were made on June 3 and 26 and August 29, 1950.

Rainfall measurements near the pond were provided by Mr. Wilfred Wheeler of Falmouth, Mass. Wind velocity and direction were recorded on each sampling day; wind measurements recorded at Nantucket Lightship and published by the U. S. Weather Bureau have also been used. River flow just north of Great Pond was measured at irregular intervals.

THE SALINITY DISTRIBUTION AND ITS VARIATIONS

A number of samples taken across the pond have shown only small east-west salinity differences, seldom exceeding 3‰. However, since the river water tends to flow over the mixture which it forms with Vineyard Sound water, there may be large differences at the surface and bottom in parts of the pond. Discussion of the salinity will therefore be limited to the vertical distribution along the land-sea axis of the pond.

Several typical salinity distributions are shown in Fig. 2. The distribution observed on August 29, 1950 is of special interest because the meteorological conditions were then so typical of the most frequent conditions during summer. Vertical and horizontal gradients were strongest in the arm and narrows. In the arm, the surface salinity ranged from zero at the river mouth to over 20‰ at the narrows and was from 10 to 15‰ less than the salinity of the bottom water. The gradients were much less in the main pond.

There were many temporary variations. Sometimes, when the pond was everywhere nearly isohaline from surface to bottom, the salinity gradients were horizontal and were strongest between the pond and the arm, as on June 3. At other times, as on June 26, there were only small and irregular horizontal salinity differences; at such times the gradients were predominantly vertical.

The seasonal distribution at the surface is shown in Fig. 3. It is seen that there were large and abrupt changes in the extent and freshness of the brackish surface layer, which was most pronounced in summer when it usually extended far down the arm into the main pond. In winter, however, the brackish layer seldom extended far from the river. The mean surface salinities in the arm and northern end of the main pond were therefore higher in winter than in summer,

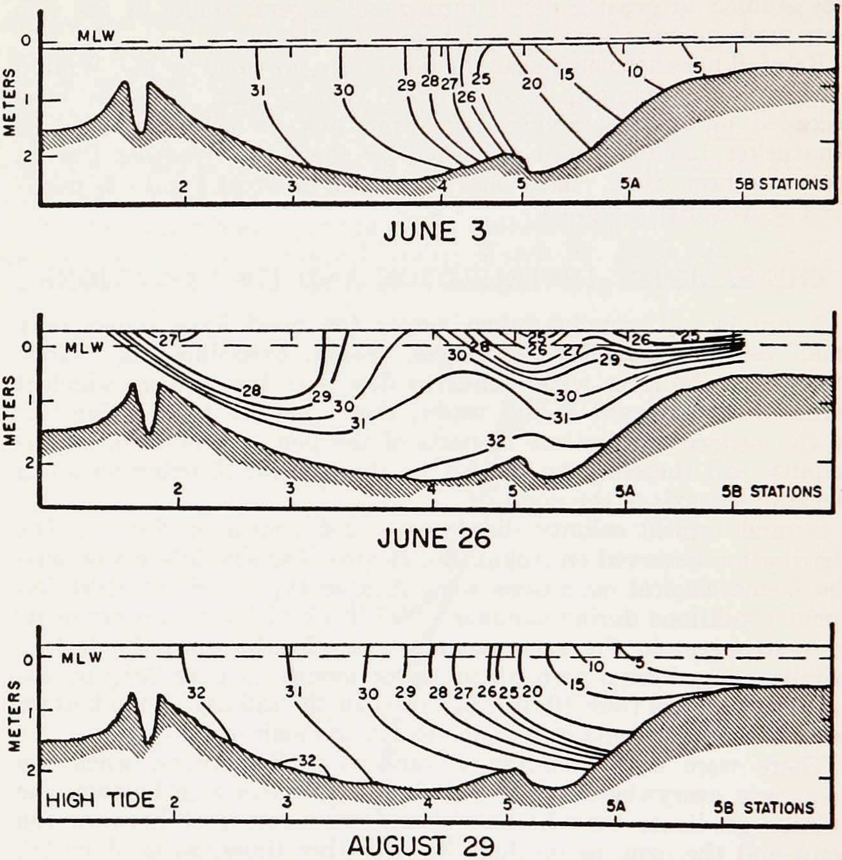

Figure 2. Vertical distribution of salinity (°/₀₀) on June 3, June 26, and August 29 at high tide. Station 1 at left of diagram. Broken line represents mean low water.

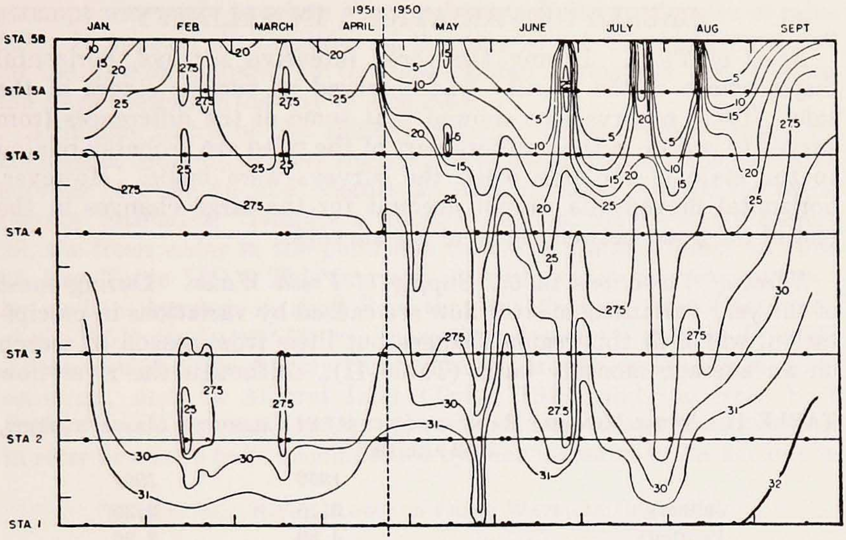

Figure 3. Seasonal distribution of surface salinity (°/₀₀). Closed circles indicate observations.

as shown in Table I. The deeper water in most of the arm and main pond and the surface water in the southern part of the main pond had but small variations seasonally or within seasons.

TABLE I. MEAN SALINITIES (°/₀₀) AND THEIR RANGES IN GREAT POND

Summer: May 4–August 23, 1950

Winter: Sept. 18, 1950–Apr. 22, 1951

Station	*Summer*			*Winter*		
	Mean	Min.	Max.	Mean	Min.	Max.
1, surface	31.68	31.48	32.09	31.73	31.29	32.32
2, surface	30.56	27.30	31.89	29.11	26.11	32.23
3, surface	27.84	23.08	31.36	29.23	27.18	31.30
4, surface	24.49	14.45	28.83	29.61	27.66	30.01
bottom	30.87	27.99	32.09	30.58	29.22	31.31
5, surface	14.42	3.59	24.47	25.09	11.08	29.85
bottom	29.82	25.99	31.51	29.59	26.87	31.11
5a, surface	10.02	2.35	28.00	25.43	16.00	30.62
bottom	27.92	21.44	30.97	29.02	25.02	30.84
5b, surface	7.21	0.02	25.49	17.60	0.39	29.36
bottom	23.92	1.51	30.77	23.87	3.23	30.37

CAUSES OF VARIATIONS IN SALINITY

Effect of Tides. During the three intensive surveys, horizontal displacement of the salinity was observed at various stages of the tide. These observations showed that some of the differences from survey to survey in the southern part of the pond are probably related to the state of the tide when the surveys were made. However, horizontal movements cannot account for the large changes in the rest of the pond between some of the surveys.

Effect of Variations in the Supply of Fresh Water. During most of the year variations in river flow are caused by variations in precipitation, which in this region changes but little from season to season on an average monthly basis (Table II). Although the river flow

TABLE II. Total Monthly Rainfall (inches) at Falmouth, Massachusetts, 1950 and 1951*

	1950	*1951*
January	3.15	3.39
February	4.39	3.26
March	4.47	4.16
April	3.98	2.54
May	2.67	3.96
June	3.83	1.35
July	1.90	1.47
August	4.13	5.43
September	3.24	1.24
October	1.04	2.95
November	6.25	4.20
December	3.08	4.87

* Recorded by Mr. Wilfred Wheeler, Falmouth, Mass.

may change as much as five-fold in two days when large volumes of water stored in reservoirs are released into the valley in spring and fall for the benefit of local cranberry culture, none of the salinity surveys was made when the river flow was so markedly changed. On the basis of our observations seasonal differences in the salinity distribution are evidently not caused by seasonal changes in the supply of fresh water. In fact, in winter and spring, when surface salinities in the pond are highest, precipitation is greater than the yearly average, and in summer, when surface salinities are lowest, the rainfall is lower than average.

Heavy rainstorms, however, may cause immediate but temporary increases of from two to six times in the river flow, and since the surface of the arm is likely to be effected most by these increases, an attempt was made to relate changes in its salinity to changes in rainfall. It appears that salinity of the arm is not effected by rainfall on the day of sampling or by total rainfall during the two, five, or ten days preceding the day of sampling.

Although many of the salinity changes are doubtless caused by changes in total amounts of fresh water in the pond, only the intensive surveys of June 26 and August 29 were detailed enough for satisfactory estimates. Despite a smaller flow in the river on August 29, the fresh water in the pond was twice the amount found on June 26 (see Table III). This increase in fresh water was accompanied by such a decrease in river flow that the flushing time (Ketchum, *et al.*, 1951) on August 29 was more than five times that on June 26. These results differ sharply from those of circulation studies in other estuaries, such as Alberni Inlet (Tully, 1949) and the New York Bight (Ketchum, *et al.*, 1951), where it has been shown that increases in river flow tend to be accompanied by such increases in the accumulation of fresh water that the flushing time remains relatively little changed.

TABLE III. River Flow and Fresh Water in Great Pond

	River flow per hour	*Total fresh water*	*Flushing time*
June 26, 1950	$1.8 \times 10^3 M^3$	$114 \times 10^3 M^3$	2.66 days
August 29, 1950	$0.75 \times 10^3 M^3$	$230 \times 10^3 M^3$	12.7 days

Effect of Variations in Wind. In Great Pond, variations in wind force and direction are the principal cause of variations in the distribution of fresh and salt water, both vertically and horizontally.

When the wind force is 0, the river water flows seaward in a shallow surface layer that is only gradually mixed with salt water. When this condition obtained on May 25 there was a shallow brackish layer extending far down the pond (Fig. 3); only in the shallows and at the southern entrance to the pond was tidal turbulence adequate to produce mixing from surface to bottom. On the other hand, strong winds may increase the vertical mixing so much so that the salinity in the pond is everywhere nearly homogeneous from top to bottom, as on June 3, when the wind was southeast and its force 4.

Though the wind plays an important part in vertical mixing, it has its most marked and probably its most important effect on horizontal distribution, particularly in the arm.

We have examined the relation between the salinity and the wind component parallel to the long axis of the pond, the latter being computed from the mean wind force and direction observed at Nantucket Lightship in the 24 hours preceding sampling. Wind directions at Nantucket Lightship were nearly the same as those at the pond at the time salinities were measured.

In Fig. 4a it is seen that, in the arm, winds directed seaward along its axis are associated with high surface salinities, while winds directed landward are associated with low surface salinities. Hence changes in wind direction are accompanied by abrupt changes in the salinity

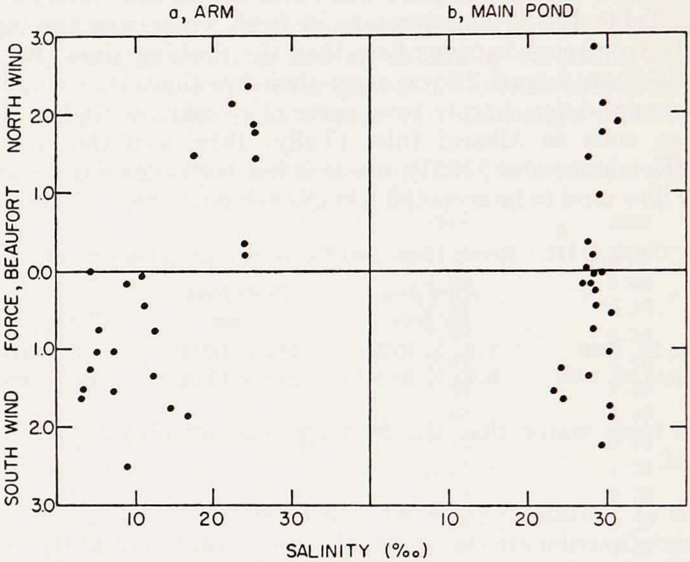

Figure 4. Wind force and direction relative to salinity of the arm and of the main pond. Wind force is north or south component of average Beaufort wind force reported at Nantucket Lightship in 24 hours preceding sampling. Salinities are mean surface salinities.

of the arm. For example, a shift in wind from south on August 11 to north on August 12 caused rapid increases in surface salinity; on August 11 the wind had a component of 0.8 from the south and on August 12, 2.4 from the north (Fig. 3). Inversely, when the wind changed from north on April 21 to south on April 22 there was a rapid decrease in surface salinity; on April 21 the wind had a component of 1.8 from the north and on April 22, 1.8 from the south (Fig. 3).

In the main pond, however, winds seem to have much less effect on the salinity than in the arm (Fig. 4b), probably due in large measure to differences in the topography of the land around the arm and the pond. While the arm is effectively shielded from all winds but those directly landward or seaward, the main pond is exposed about equally to winds from all directions. Nevertheless, on the three occasions when the mean surface salinity in the main pond was below 25‰ there were strong southerly winds.

During the intensive surveys of June 26 and August 29 both current and salinity at the entrance were measured at half-hourly intervals. From these data, volumes of flow and exchanges of fresh water were estimated (see Table IV). Unfortunately the observations did not

TABLE IV. Exchange of Water Between Great Pond and Vineyard Sound as Affected by Wind Direction

Date	June 26	August 29
Wind direction	Northerly	Southwesterly
Period of Ebb (southerly)	0950–1430 4.7 hours	1148–1300; 1430–1900 5.9 hours
Period of Flood (northerly)	1430–1900 4.5 hours	0745–1148; 1300–1430 5.5 hours
Total Flow, Ebb	$438 \times 10^3M^3$	$470 \times 10^3M^3$
Total Flow, Flood	$756 \times 10^3M^3$	$411 \times 10^3M^3$
Net Loss	$-318 \times 10^3M^3$	$59 \times 10^3M^3$
Fresh Water Loss, Ebb	$59 \times 10^3M^3$	$2.91 \times 10^3M^3$
Fresh Water Gain, Flood	$15 \times 10^3M^3$	$1.14 \times 10^3M^3$
Net Loss	$44 \times 10^3M^3$	$1.77 \times 10^3M^3$
Net Loss per Hour	$4.8 \times 10^3M^3$	$0.15 \times 10^3M^3$
River Flow per Hour	$1.8 \times 10^3M^3$	$0.75 \times 10^3M^3$
Fresh Water Content of Pond	$114 \times 10^3M^3$	$230 \times 10^3M^3$

include a complete tidal cycle, but the periods of ebb and flood observed were about equal. With northerly winds of force 3 and with the flood into the pond greatly exceeding the ebb, the fresh water content of the pond was relatively low; $44 \times 10^3m^3$ of fresh water escaped from the pond. With southwesterly winds of force 2 only $1.77 \times 10^3m^3$ of fresh water escaped. Thus, with northerly winds the net loss of fresh water per hour of observation was three times greater than the rate of river flow whereas with southwesterly winds the loss was only 1/5 the river flow. Obviously, then, northerly winds facilitate the loss of fresh water from the pond while southerly winds retard it.

Seasonal changes in salinity distribution have been summarized in Table I, which shows that all of the average surface salinities in the arm in summer were 10 to 15‰ lower than surface salinities in winter. In the main pond, however, there appear to be no significant seasonal changes in surface salinity.

As would be expected from the foregoing discussion, these seasonal changes in salinity in the arm are also associated with changes in wind direction and force. The northerly or northwesterly winds that prevail in fall, winter and spring allow relatively little fresh water to accumulate in the arm; obviously this results in higher salinities there in winter. Of the seven winter surveys (January through April 1951) which were detailed enough to show the salinity of the entire pond, only two (January 10, April 22) were made on days when the wind had components from the south, and it was only on those days that surface salinities were as low as those which are usual during summer when southwesterly winds prevail.

From May through August in 1950 and 1951 the wind had components from the south on 15 of the 18 days it was observed at the pond. These southerly winds allowed more fresh water to accumulate in the arm, hence surface salinities were generally lower than those found in winter. On the remaining three of those 18 days (June 26, July 22, and August 12, 1950) the wind had components from the north, and on those days the surface salinities in the arm were as high as usual during the winter.

ACKNOWLEDGEMENTS

These studies were suggested by Dr. Alfred C. Redfield, to whom the author is indebted for his continued encouragement and advice. The author has also benefited from discussion of this problem with Dr. Bostwick H. Ketchum.

The observations reported here have been made by a group of investigators from the Woods Hole Oceanographic Institution which included Dr. J. C. Ayers, E. M. Hulburt, D. Norton, F. A. Richards and Messrs. J. A. Posgay, H. J. Turner Jr., and C. Wheeler. Of these, Dr. Hulburt has made a special contribution through his original evaluation of the relation between wind direction and salinity, and Dr. Richards has analyzed fresh water exchange between the Pond and Sound.

REFERENCES

Barlow, J. P.

1955. Physical and biological processes determining the distribution of zooplankton in a tidal estuary. Biol. Bull. Woods Hole, *109* (2): 211–225.

Hulburt, E. M.

1956. Distribution of phosphorus in Great Pond, Massachusetts. J. Mar. Res., *15* (3): 181–192.

1956. The phytoplankton of Great Pond, Massachusetts. Biol. Bull. Woods Hole, *110* (2): 157–168.

Ketchum, B. H.

1951. The exchanges of fresh and salt water in tidal estuaries. J. Mar. Res., *10:* 18–38.

Ketchum, B. H., A. C. Redfield and J. C. Ayers.

1951. The oceanography of the New York Bight. Pap. Phys. Oceanogr. Meteorol., *12* (1): 4–46.

Tully, J. P.

1949. Oceanography and prediction of pulp mill pollution in Alberni Inlet. Bull. Fish. Res. Bd. Can., *83:* 1–169.