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Effect of freshets on Passamaquoddy plankton

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Summary—Sudden or heavy discharge into Passamaquoddy Bay, from streams at its head, works out through the 10-mile long Bay and through the 8-mile long Head Harbour Passage, its main connection with the Bay of Fundy, in less than 10 days, as shown by the salinity of the water. Through the Bay, the outflow is more or less superficial and carries certain elements of the plankton out into the Passage. But, in the latter, strong tidal mixing prevents stratification, although the water is deeper. Under these circumstances, working of the freshet outward has a double effect, first a carrying out of the well-mixed plankton, and then an indraft of deep plankton from without. The latter provides an abundance of planktonic animals in the Passage at all depths.

Forty years ago, Dr. Johan Hjort, of Norway, brought Henry B. Bigelow and me together in the expedition (Hjort, 1919), which he was organizing for the Biological Board of Canada. It was for me a marvellous introduction to the oceanographic problem in our waters. The methods used were those with which Hjort had been concerned in north European waters and Bigelow in waters off the New England and Nova Scotian coasts. In the picture that was developed, the Bay of Fundy, which I was investigating for quite a few years from the Atlantic Biological Station at St. Andrews, New Brunswick, stands out like a sore thumb, in the peculiarity of both its plankton and its hydrography. This is in association with very heavy tidal action. There is also a striking peculiarity in the wealth of fish as well as of zooplankton near the surface in the Passamaquoddy region near the mouth of the Bay (Huntsman, 1927). When the Passamaquoddy Power Project made the explanation of this condition desirable, Bigelow asked me whether temperature explained this, and, if not, what could the explanation be. This paper gives part of the answer to his question and is offered as a tribute to the stimulating effects of long and most enjoyable association with him in oceanographic investigations.

The herring is by far the most abundant fish in the Passamaquoddy region (Fig. 1). Its food consists mainly of Crustacean zooplanktons of the orders Copepoda and Euphausiacea, which are known to the local fishermen as " red feed " and " shrimp " respectively, as seen in herring stomachs. The distribution of such zooplankton both vertically and horizontally determines its availability to the herring, which take these forms individually as silhouetted against the sky when a matter of inches above them. The herring have their own peculiar vertical and horizontal distribution, and vary in condition in accordance with the food available at the place and the time (Battle, *et al.*, 1936). Freshets in the rivers that discharge into Passamaquoddy Bay shift the herring about from one place to another (Huntsman, 1934), as do other factors that bring about movements of the water. Also, mixture over shoals under tidal action of the water of this Bay, which is stratified from river discharge, concentrates the herring and their planktonic food together for effective feeding (Battle, *et al.*, 1936). There has been need for elucidation of any effects of freshets in shifting the zooplankton from place to place.

ESTUARIAL CIRCULATION OF ZOOPLANKTON

The typical circulation of water in a river estuary is movement oceanward of the fresher and lighter surface water, and movement riverward of the salter and heavier deeper water. This is dependent upon tidal mixing of the fresh river water with the salt sea water. It will depend upon the depth from the surface to which particular

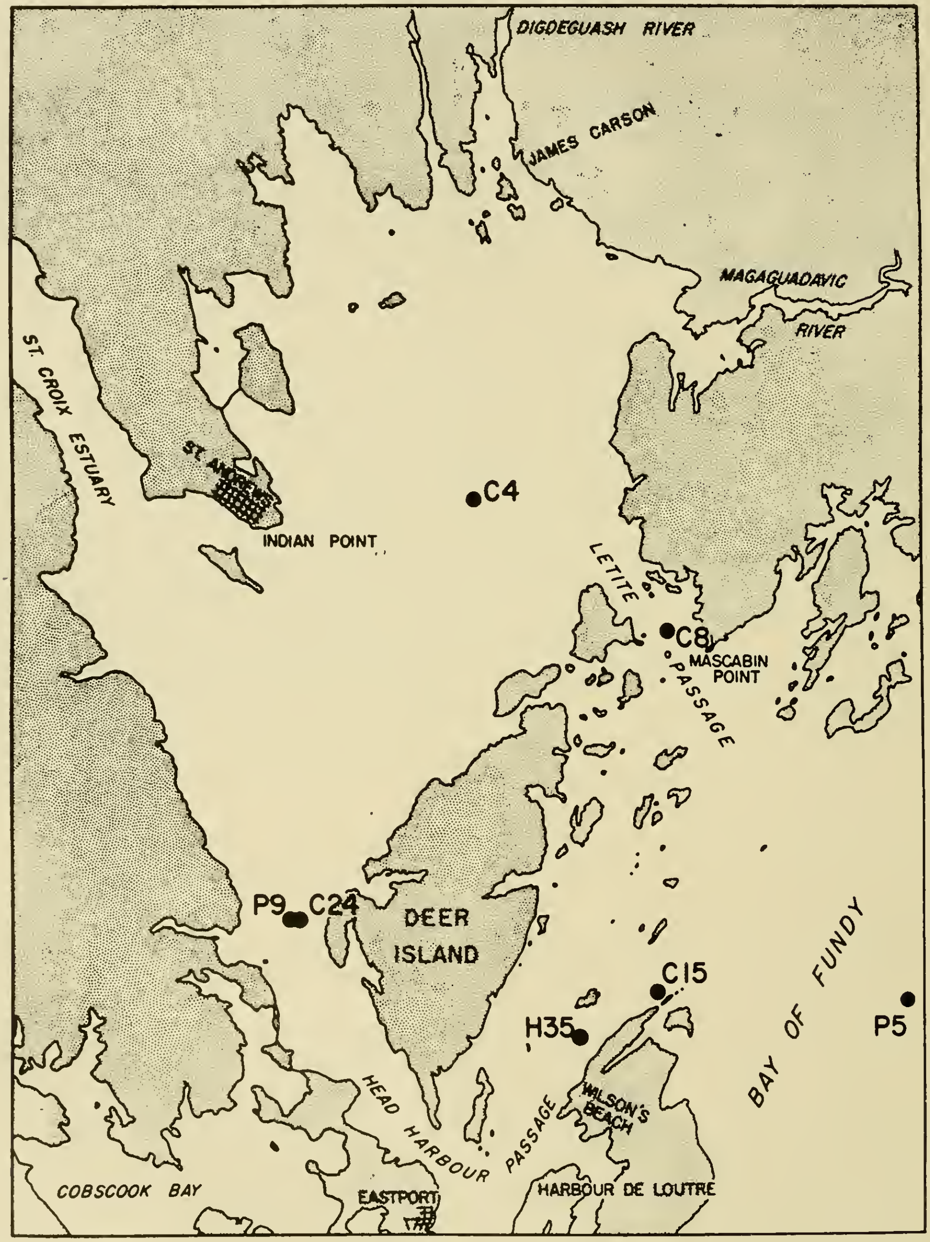

Fig. 1. Passamaquoddy Bay, New Brunswick, showing principal rivers, passages to Bay of Fundy and positions of the stations mentioned.

zooplanktonts keep, and upon the depths of the two movements, as to whether these will be carried oceanward out of the estuary or riverward to be concentrated at the head of the estuary. The strengths and depths of the movements will depend, not only upon the degree of tidal mixing, but also upon the amount of river water. Any estuarial concentration of zooplankton there may be, will be increased by freshets in the river.

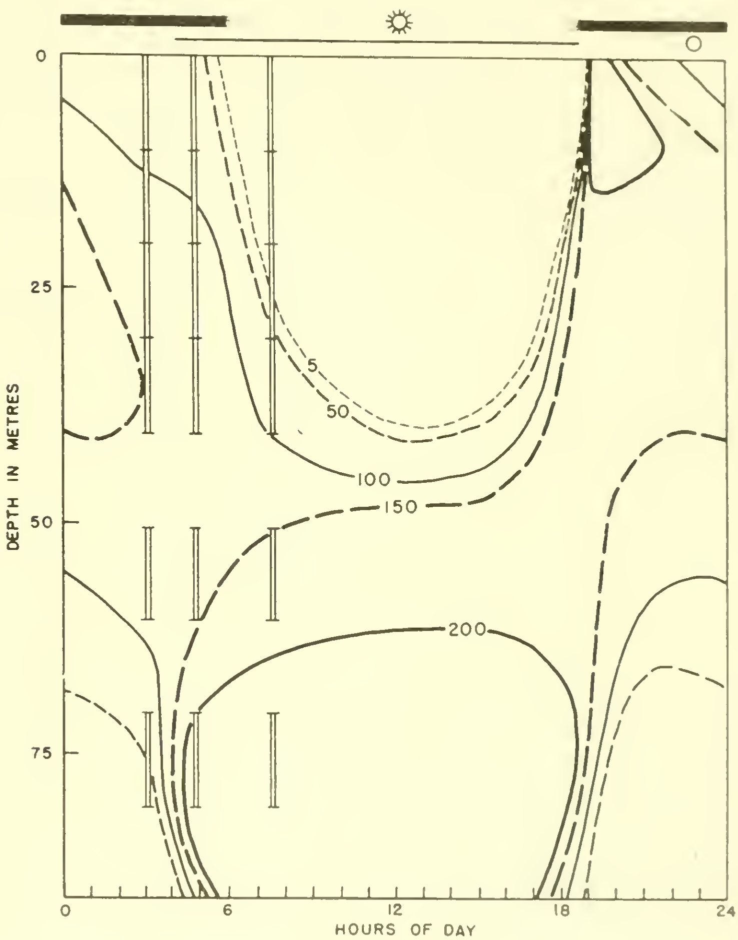

Fig. 2. Vertical distribution of *Calanus* throughout the 24-hr. day at Prince station No. 5 in the Bay of Fundy, as inferred from vertical tows made on September 20, 1926, through ten metres of water at different depths on three occasions: (1) between 2.50 and 3.55 hr., (2) between 4.35 and 5.25 hr. and (3) between 7.15 and 7.55 hr., as shown by vertical lines. Periods of sunlight and moonlight are shown at the top, and numbers of *Calanus* are per tow.

While the zooplanktonts may be at the proper depth during the day for transport riverward, their migration towards the surface at night may well result in their being carried oceanward. So complex is the situation that, as yet, only their actual distribution can be depended upon to show in which direction particular zooplanktonts have moved.

DIURNAL MIGRATION OF *CALANUS*

The principal zooplanktont for food of Passamaquoddy herring is the copepod, *Calanus finmarchicus*. Its vertical migrations are so complex (Esterly, 1919; Russell, 1926; Clarke, 1933; and Cushing, 1951) that local and temporal data seem necessary to show its vertical distribution that may determine how it will be shifted in the Passamaquoddy circulation. Fig. 2 gives an interpretation of the vertical distribution of this species throughout an entire day at Prince Station No. 5, in water about 90 metres deep in the Bay of Fundy just outside the main passage leading to Passamaquoddy Bay. It is believed that this is sufficiently representative of the times and places dealt with, except as altered by vertical movements of the water. The interpretation is based, as shown, mainly upon data obtained on September 20, 1926, in closing vertical tows through six different strata at three different times with rapidly increasing light intensity in the morning. It will be evident that these copepods were on the whole more heavily concentrated near the bottom, and least heavily near the surface.

CHARACTERISTICS OF THE REGION

Passamaquoddy Bay (Fig. 1) is about five miles wide and ten miles long. On its east side, it is connected with the Bay of Fundy through the relatively short and shallow Letite Passage, and also through the still shallower Little Letite Passage. The main connection, however, is at the south end through the long and tortuous, as well as deep, Western or Head Harbour Passage (also called " Quoddy River "), which virtually forms its mouth. The Passages have very rough, irregular and rocky bottom. The Bay inside is of rather uniform depth, from 20 to 35 metres, but it is still deeper near the Passages.

Fresh water is discharged into the Bay mainly from the St. Croix, Magaguadavic and Digdeguash Rivers. The St. Croix River discharges into the west side of the Bay near its mouth somewhat more than 2,000 sec/ft from a drainage basin of over 1,300 square miles. It is controlled for power purposes, so that in summer the discharge is comparatively steady, ranging for the most part from 500 to 2,000 sec/ft. The Magaguadavic River discharges on the average around 1,000 sec/ft from more than 600 square miles into the Bay on its east side near its head, and it is similarly controlled for power purposes. The Digdeguash River, together with other uncontrolled streams, discharges into the head of the Bay the drainage from about 300 square miles. The volume and availability of this discharge may be judged from records made on the Magaguadavic River at Elmcroft (above the level of storage) with a drainage area of about 350 square miles. From 2 to 6 inches of rain fell over the drainage basin on August 26 and 27, 1924, and the rates of discharge on successive days, beginning on August 25, were: 85; 246; 2,890; 2,520; 2,030; 518; 339; 276 sec/ft. Therefore, with heavy rains, the principal increase in river discharge is a day or so after the rain. With other rivers controlled, this is into the head of the Bay. It is to be noted that the discharges of the St. Croix and Magaguadavic Rivers reach the Bay only after having been mixed with sea water in estuaries, which are fifteen and four miles long respectively. The estuary of the Digdeguash River is about two miles long.

The tides of the region are very heavy, the amplitude ranging from 20 to 25 feet. The rough character of the bottom near shore and in the Passages makes the strong tidal currents very effective in mixing the light river water with the heavy sea water. This is evident for the Bay itself in that near the mouth the salinities at the surface and at 50 metres depth, which is deeper than the Bay in general, were for example on October 12, 1933: 30·99 and 31·73 ‰ respectively. Also, the salinities at the same depths on the same day at Station No. 5 outside Head Harbour Passage were: 31·98 and 32·32 ‰ respectively. KETCHUM and KEEN (1953) have calculated that in August of 1951 the mixed water moving out of the Bay near its mouth was over 100 times as great as that of the discharge from rivers, and that outside the Passages it had increased to nearly 600 times.

Owing to their shallowness, the Letite Passages do not permit much movement of water through, so that the principal outlet for mixed water and the principal inlet for salt water is Head Harbour Passage. Also, movement through the Letite Passages is more inward than outward, as determined through a complete tidal cycle in 1951. But, there is very definite passage out of mixed water through Letite and passage in of salt water, as well as very heavy mixing of the two.

RAINFALL AND PLANKTON INDRAFT

Calanus is not produced to any particular extent in the Passamaquoddy region, but is there as an immigrant from the Gulf of Maine (WRIGHT, 1929; FISH, 1936). It was very abundant at Prince Station No. 5 just outside Passamaquoddy Bay in the late summer of 1933. Vertical hauls with the No. 0 (bolting cloth measure) net from 90 to 0 metres gave the following quantities in cubic centimetres of settled plankton (chiefly *Calanus*) on the dates indicated: 13 on July 10; 9 on August 11; 22 on September 15.

The quantity of *Calanus* at Station No. 5 varied greatly from September 23 to October 3. Deep tows were made on the former date, giving large quantities at from 100 to 50 metres and at about 90 metres. On October 2, a vertical haul gave only 2 cu.cm. Yet, deep tows made the next day revealed even greater abundance than on September 23.

During the night of September 17–18 there was a very heavy rainfall over the basin that drains into the head of Passamaquoddy Bay, over 5 in. falling at St. Andrews and 4·81 in. at St. George on west and east sides of the Bay, and 3·25 in. at McAdam at the head of the drainage into the Digdeguash River. Three days later, another inch of rain fell over the area. It is estimated that these rainfalls more than doubled the amount of fresh water being discharged into the Bay.

KETCHUM and KEEN (1953) have calculated that the mean flushing time for the removal from Passamaquoddy Bay of fresh water discharged into it is 15·8 days, and they conclude that " it seems probable that a flushing time of about 15 days should be approximately correct ". In late summer of 1933, there were three heavy rainfalls recorded, on August 25, September 18 and October 7. Weekly determinations of bottom salinity in the middle of Passamaquoddy Bay showed that higher salinity returned between 5 and 13, 9 and 16, and 11 and 18 days respectively. If such return has a constant period, it will, therefore, lie between 11 and 13 days after the rainfall. After the freshet of September 18, salinities were measured for Prince Station No. 9, which is off Clam Cove Head at the mouth of Passamaquoddy Bay where it joins Head Harbour Passage, on September 23, 26 and 29, and on October 3. The values at 50 metres depth were 31·78 ‰, 31·67 ‰, 31·85 ‰ and 31·89 ‰ respectively. This shows that salter water was entering the mouth of the Bay 11 days after the rainfall. What relation this has to the flushing time is not clear. It may represent merely the beginning of heavy interchange at the mouth of the large mass of fresh water.

In Head Harbour Passage, particularly the outer part, heavy tidal action and irregular bottom keep the water quite thoroughly stirred, so that the plankton present can easily be obtained in tows at any depth. Tows were made at two Stations (H.F. 50 and 35) in the outer part of the Passage on September 18 (at 50 only), 23, 26, 29 and October 3. The quantities (cu.cm. after settling) of plankton (chiefly *Calanus*) were: 12; 8 and 16; 18 and 12; 180 and 95; and 80 and 27 respectively. There was thus a very marked increase in quantity between 8 and 11 days after the rainfall. It would seem to be possibly significant that, following the heavy indraft of *Calanus* into the Passage, as found on September 29, there was a low amount outside on October 2, but not on October 3. The movement outward of the mixed water from the freshet might be expected to have such temporary effect in carrying outward much of the plankton.

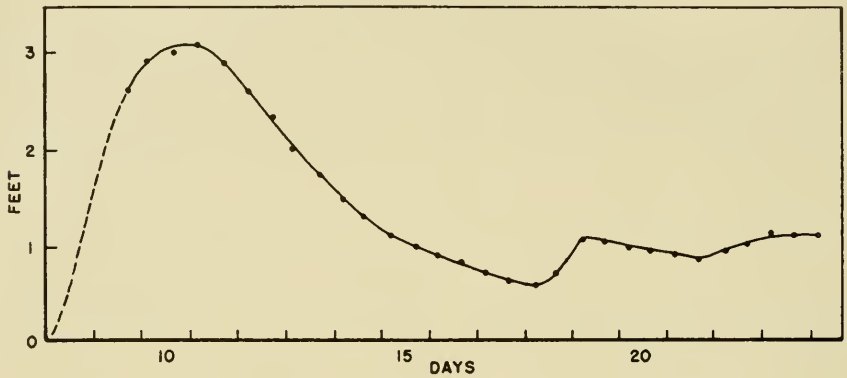

Fig. 3. Height above low water of surface of Digdeguash River at the Stillwater bridge in August, 1951.

The very definite result was that a dearth of *Calanus* in Head Harbour Passage was changed to abundance when the water from the freshet worked its way out. *Calanus* had been abundant in deep water outside, but the freshet made it abundantly available to birds and to herring and other near-surface fishes by bringing it into the Passage, where vertical currents lift it rather steadily toward the surface, overcoming its tendency to descend from daylight. As far as the facts went, this was coincident with entrance of quite salt water into the Passage, presumably from the depths outside where *Calanus* was known to be abundant.

RAINFALL AND SHIFTING OF PLANKTON

On August 8 and 9, 1951, heavy rain (4·66 to 1·39 in.) fell over the drainage basin of the Digdeguash River. The course of the discharge from the River into the head of Passamaquoddy Bay was measured with a gauge at the first bridge above the point where the River falls into the tidal Digdeguash Basin (Fig. 3). The heaviest discharge was on August 10.

The progress of the outflow of fresher water was determined, beginning at different points on August 12, 13 and 14, by getting the salinities of surface samples taken daily at high water at four different points: (1) near the mouth of the Digdeguash estuary (James Carson's shore); (2) Indian Point at St. Andrews; (3) Mascabin Point in the outer part of Letite Passage; and (4) Wilson's Beach in the outer part of Head Harbour Passage. The results (Fig. 4) showed that the greatest effect at St. Andrews was on August 14, and that there was a clear effect at Wilson's Beach only on August 18. On that same day, the most marked effect appeared at Mascabin Point. But there was a complexity, which seems to have been owing to the facts that there is on the whole more inward than outward movement through Letite Passage, and that the outflow is largely through the main Head Harbour Passage. Along such

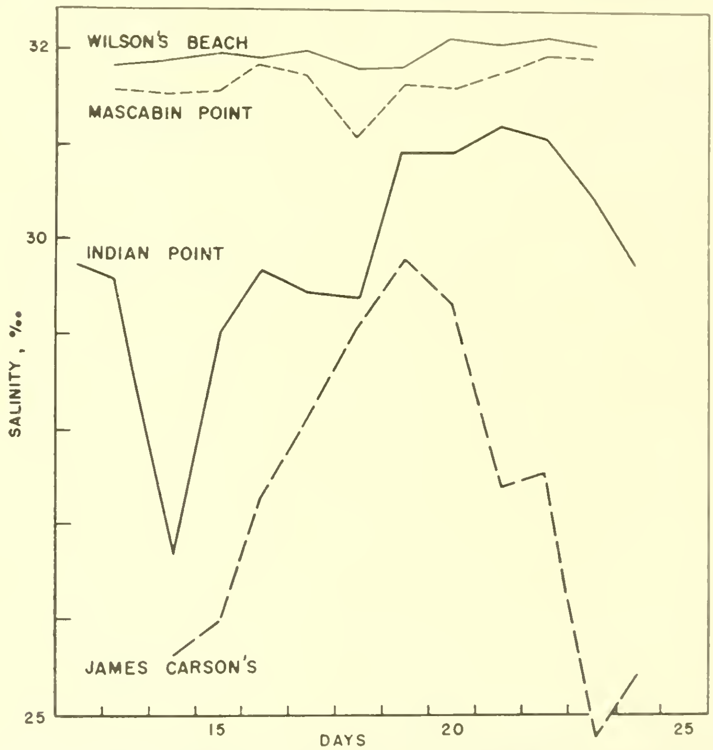

Fig. 4. Shore salinity at high water at four different points in Passamaquoddy Bay and in the related Passages on successive days in August, 1951, following freshets on August 10 and 19.

course, Letite Passage and St. Andrews are on opposite shores of the half-way point. When the fresher water was most noticeable at St. Andrews four days after the heaviest discharge, there was very slight freshening at Mascabin Point in Letite Passage. But, another four days later, when the freshening was definite at Wilson's Beach, there was a more marked freshening at Mascabin Point. This is evidence that the outflow through Head Harbour Passage, which would be with the ebbing tide, was being carried with flooding tide north to the entrance into Letite Passage. At high tide, therefore, the latter showed a greater effect from this than did Head Harbour Passage itself. The slighter drop at Mascabin Point on August 17 indicates that the fresher water was issuing from Head Harbour Passage on that day. Entrance of fresher water into the Bay through Letite Passage on August 17 and 18 serves to explain the otherwise anomalous slight drop in salinity at St. Andrews on those days. This would mean that the fresher water was in part making a circuit around Deer Island in its position between the two Passages.

It will be noted in Fig. 4 that the crest of the fresh water flood was sharp and lasted about a day only, at St. Andrews, while at Wilson's Beach it lasted for two days and was little pronounced. The definite return of salter water to Head Harbour Passage was on August 20, that is, 11 days after the rainfall of August 9. This is in agreement with the data for the rainfall of September 17–18, 1933, which gave no increase in deep salinity at the inner end of Head Harbour Passage until 11 days or more later.

At the time of the freshet in 1951, August 9–10, *Calanus finmarchicus* was abundant in the passages leading out of Passamaquoddy Bay. There was also a most unusual plankton in the Bay, namely large numbers of Salps, mainly *Salpa fusiformis* and a few *S. zonaria*. *Salpa* seemed to be largely concentrated in the Bay, as *Calanus* certainly was in Head Harbour Passage. Such differential distribution was shown in tows made at 15 metres depth with a net of No. 5 mesh on August 8 at four stations, which were in the centre of the Bay (C_4), in the middle of Letite Passage (C_8), at the inner end (C_{24}) and at the outer end (C_{15}) of Head Harbour Passage. At these stations in the order given, the numbers of large *Calanus* and of *Salpa* respectively were as follows: C_4, 0 and 5; C_8, 28 and 0; C_{24}, 0 and 1; C_{15}, 347 and 1. The Salps must have come from the " Gulf Stream " water of the open Atlantic outside the continental slope, but they were, as near-surface forms, concentrated in the Bay, as was the locally produced *Aurelia*, which is quite in evidence in calm, clear weather. In contrast, *Calanus* was, as a deep-living form, concentrated in the Passages, as was also *Sagitta elegans*, another immigrant from the depths of the Gulf of Maine.

Surface tows were taken daily at Wilson's Beach in the outer part of Head Harbour Passage with net of No. 0 mesh from August 11 to 23. The numbers of *Calanus* in hundreds on successive days were: 347; 312; 712; 125; 372; 108; 34; 23; 6; 21; 104; 78; and 525. It will be noted that the number was definitely down by August 17 and lowest on August 19, with marked recovery by August 21. The numbers of *Sagitta*, although small, show a similar course: 9; 3; 18; 10; 14; 1; 2; 1; 0; 2; 2; 5; 17. The freshet seemed to exert an effect in removing *Calanus* and *Sagitta* from the Passage, beginning perhaps on August 16, reaching a peak on August 19, and passing away by August 23 with full return of these planktonts. The freshet would thus have worked out of the Bay through Head Harbour Passage during a period of six days, centred on the 10th day after the rainfall, or the 9th day after the peak of the discharge into the head of the Bay.

Euphausiid Crustaceans, of the genera *Meganyctiphanes* and *Thysanoessa*, are also indicative of deep indraught from the Gulf of Maine. Like *Calanus* and *Sagitta*, they were to be found in Head Harbour Passage at the time of the freshet. They occur in schools and more or less avoid the net, which made their numbers in the plankton hauls less representative of their distribution. The numbers of individuals of those two genera respectively in the hauls of successive days from August 11 to 23 were: 1 and 0; 0 and 0; 10 and 4; 1 and 1; 14 and 0; 4 and 0; 5 and 1; 0 and 0; 451 and 3; 29 and 110; 85 and 22; 15 and 4; and 24 and 0. There was thus a marked increase in their numbers on August 19, at the very beginning of the strong resurgence of salter water as shown at St. Andrews and at Mascabin Point, rather than at Wilson's Beach. It may be inferred that they had been in much greater abundance in deep water outside the Passage than in the Passage. The Amphipod Crustacean, *Euthemisto compressa*, another immigrant from the Gulf of Maine, was present in quite small numbers which for the successive days were: 0; 0; 3; 6; 2; 8; 1; 2; 7; 7; 22; 26; 17. Its numbers definitely increased on August 21.

Salpa fusiformis and *S. zonaria* were taken in the hauls on successive days in the following numbers respectively: 44 and 18; 28 and 0; 34 and 0; 71 and 1; 54 and 0; *214* and 0; *73* and 0; *22* and 0; 45 and 2; 23 and 1; 181 and 1; 25 and 2; 44 and 0. Since the more abundant species was in the aggregated stage, in which the individuals are attached together in rather long strings of as many as 18 individuals, there is considerable variation in its numbers, which will, therefore, not reflect very well its general abundance at the time and place. However, the numbers in italic mean that on August 16, 17 and 18 the individuals were in poor condition. It is to be expected that such open ocean forms as these would be injured by exposure to low salinity, and indeed those concentrated in the Bay were to be found in considerable numbers dead on the beaches as left by ebbing tide. It may be inferred that individuals that had been damaged by low salinity in the Bay were being carried out as the freshet worked out through the Passage. On this basis, the outflow occurred on August 16, 17 and 18, and the resurgence of salter water began on August 19. This agrees with the behaviour of the Euphausiids.

DISCUSSION

The passage of fresh water through Passamaquoddy Bay and Head Harbour Passage from the Digdeguash River to the Bay of Fundy may be expected to vary in time with the forces that effect it. One of these variable forces is the hydrodynamic effect of lighter water at the head of Passamaquoddy Bay than in the Bay of Fundy outside. This will vary with the amount of warm and fresh, and thus relatively light, water discharged by the Digdeguash River. The freshets of September 18, 1933, and of August 9, 1951, would provide a strong force to drive the water through the Bay and the Passage. Correlatively, the heavy outside water would be driven inwards. This force would operate at the outer end of the Passage only when the fresher water reached that far.

Following the 1933 freshet, the greater force set in motion was clearly acting in the Passage between 8 and 11 days after the rainfall, as shown after 11 days by high salinity at the inner end and a great abundance of *Calanus* in the outer part. Following the 1951 freshet, the fresher water was in the Passage 7 days after the rainfall, as shown by drop in abundance of *Calanus* and *Sagitta* and by appearance of many *Salpa* in poor condition. The greater force had clearly acted through the Passage by 10 days after the rainfall, as shown by *Salpa* in good condition, as well as by increased numbers of Euphausiids and *Euthemisto*. By that same time, there were sharp rises in surface salinity at Mascabin Point and at St. Andrews.

It would seem to have taken in 1951 9 days, with the main discharge one day after the main rainfall, for the peak of the freshet to pass from Digdeguash Basin to the outer part of Head Harbour Passage. What relation this has to the calculated average flushing time of about 15 days for the Bay alone is uncertain. The latter is based upon average conditions, and certainly not upon the conditions following a freshet, as the authors clearly state (KETCHUM and KEEN, 1953).

Whatever may be the complex conditions in Passamaquoddy Bay, it seems clear that a freshet, in working out through the heavily stirred Head Harbour Passage to the Bay of Fundy, at first carries plankton into the Passage from within and also out from the Passage. Then, with a reflux of outer water, it brings deep-water forms into the Passage from without. The latter is of particular importance for providing food for herring. The fattest herring of the whole region are those in this Passage and its associated waters, namely Harbour de Loutre and Cobscook Bay (Battle, *et al.*, 1936).

ACKNOWLEDGEMENTS

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