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II. SOME OBSERVATIONS ON THE WATERS OF THE RIVER BURE AND ITS TRIBUTARIES.

By ROBERT GURNEY, M.A.

THE East Norfolk rivers are, as is well known, the shrunken remains of what was in historic times a great estuarine system. The mouth of the estuary, which, in Roman times, extended from Caister in the north to Burgh Castle in the south, became blocked by the southerly drift of sand, and with the consequent narrowing of the estuary, the tidal scour was checked, and the great flats then covered by salt water at high tides were reclaimed by embankment, and the rivers confined within their present courses. Their history, their proximity to the sea, and the fact that their evolution is even now proceeding, renders a study of the waters of the broads and of the river Bure of special importance. Realizing this, the Sutton Broad Laboratory has regarded the analysis of the waters and the study of the tides as within the province of its work since the year 1903. In 1906 two expert chemists, Mr. H. Peel and Mr. A. G. Innes, spent some months working continuously at the analysis of the water. Observations have accumulated, but it was not thought advisable to work them up for publication until 1908. Mr. Innes then took the work in hand, and in April, 1910, completed a paper on the subject. This paper will be published in the Transactions of the Norfolk and Norwich Naturalists' Society, but I have been kindly permitted to present here the main results of the work.

The Tides.

It is well known that the action of the tide can be traced many miles up the river Bure, but exact observations appear to have been hitherto wanting. The following facts, excepting those relating to Yarmouth, are the results of work carried out by us by means of recording tide gauges. A full account will be published elsewhere.

The range of tides off Yarmouth amounts to about 6 feet at springs and 4 feet at neaps. At Southtown bridge, below the confluence of the Yare and the Bure, but about $2\frac{3}{4}$ miles above the harbour mouth, the range, taking the average for two complete years, is 4 feet 7 inches at springs and 3 feet 7 inches at neaps. About 12 miles above this point, at Acle bridge, the range of tide is found to be 13-15 inches at springs, and 7-9 inches at neaps. Above Acle the range of tide continues to decrease and the difference between spring and neap tides becomes difficult to detect without prolonged observation, since the variations due to other causes are liable to obscure it. A definite tide of an average range of about 5 inches can be traced at St. Benet's Abbey, about 16 miles from Yarmouth, but above that point the rise and fall of water is increasingly difficult to connect with the period of ordinary tides.

Leaving the Bure and proceeding up the Thurne river, a tide of about 5 inches may be detected at Potter Heigham bridge, and an irregular oscillation of about $1\frac{1}{2}$ inches is found in Heigham Sounds, about $1\frac{1}{2}$ miles from Potter Heigham bridge. Beyond this point our own evidence and that of others is in agreement, namely, that no tide, in the usual sense, can be traced.

This short sketch of the nature of the tides in the Bure and its tributary, the Thurne river, is necessary in order fully to understand the significance of the analysis of the water from the point of view of salinity.

* Research Department, December 15, 1910.

Salinity of the Water.

In ordinary circumstances a great body of salt water passes up the Bure at every tide, and the water at the Yacht Quay in Yarmouth is usually of a very high salinity, and contains a marine fauna. Of course the salinity is variable, and samples have been analyzed, which showed salinities varying from 416 to 1684 grains of chlorine per gallon. On the other hand, there may be occasions on which so much fresh water is being discharged that the water may have a salinity of as little as 34*, and the fauna may be that of fresh water.

Proceeding up the Bure, it can be proved that the salinity normally remains high for several miles, but that there is a point at which there is a sudden drop, and this point is the limit to which salt water normally penetrates. It has been proved that no tidal change of salinity can be detected in normal circumstances higher than Acle Bridge, about 12 miles from Yarmouth, and this fact is in accordance with theoretical expectations. For example, a series of seven analyses were made at various times between June 7 and 9, 1906, in the Bure at Muckfleet, and in each case the salinity was found exactly the same, namely 9·8.

This conclusion, namely, that Acle bridge marks the limit of range of sea-water, was stated by us in 1904, and is established both by the evidence of Mr. Innes and by that of Dr. Otto Hehner, and Mr. C. Hawksley for the Yarmouth Waterworks Bill of 1906.

Above Acle the salinity of the water is still somewhat above that of pure fresh water, and this salt must be derived from some source other than the sea. In order to make the explanation clear the waters of the Thurne river must be examined. If one proceeds up the river, taking samples of the water on the way, it is found that the salinity increases the further one proceeds from the mouth.

For example, on September 12, 1906, Mr. Innes found the salinity at the mouth 5·73. At Potter Heigham bridge it had risen to 23·67, at Candle dyke to 28·57, and in Hickling Broad to 46·2. In Horsey Mere the salinity was 53·8. These and many other analyses taken at other times prove that the Thurne river is salt at its source. There is clearly a large amount of salt water finding its way by percolation through the soil into Hickling Broad and Horsey Mere, and the salinity of these broads may be as great as 78·4 and 164 respectively. As a consequence of their high salinity these broads contain species of Crustacea, which are usually found only in brackish water. These species are *Neomysis vulgaris*, *Gammarus duebeni*, and *Corophium grossipes*. I have recently found the prawn *Palæmon squilla* in Heigham Sounds, and it is probable that both it and *Palæmonetes varians* occur in Hickling and Horsey.

We have here, then, an isolated group of broads having a highly saline water which is drained into the Thurne river. This water passes down, becoming less salt as it receives the fresh water drained off the marshes, and finally mingles with the water of the Bure itself. The latter, before it reaches Thurne mouth, is a fresh water containing about 5 grains of chlorine per gallon, and is characterized by the great quantity of floating microscopic vegetation in the form of Algæ and Diatoms contained in it. At Thurne mouth, however, it receives a large volume of saline water, so that the water below this point is of a higher salinity than that above it. Owing to the oscillation of bodies of water to and fro caused by the tide the contrast is not always clear, since the mixed water is of course driven back by the flood tide to some distance above its entry. A true picture of the *régime* of the waters of the Thurne river can only be presented by

* All references to salinity must be read as so many grains of chlorine per gallon.

means of tables and figures, but it must be stated that the conclusions given above could be fully substantiated in that way.

Coming now to the waters of the Ant, which enter the Bure by St. Benet's Abbey, about 16 miles from Yarmouth, it is found that the salinity, though never very high, presents certain problems which still await solution. For above Barton Broad, in the river, and in Sutton Broad, the salinity is normally very low, namely, 3-4 grains per gallon; yet in Barton Broad there is a rise to 6-7 grains, and, below that point, the river water has a salinity of 7-8. Mr. Innes concludes that there is a percolation of sea water into the broad as there is at Hickling, but the point seems to require further research. The high salinity cannot be due in normal circumstances to a reflux of water from the Thurne river, since the water of the Bure at Ant mouth is generally of a lower salinity than that of the Ant. The salinity, both of Barton and of Sutton Broad, is variable, and that of Sutton may reach 7 grains without apparent cause.

It is worth noticing here that the water of the broads of the Ant does not contain the rich plankton fauna of the broads of the Bure itself. There is a noticeable scarcity of Diatoms and Algæ, and the planktonic *Daphnia cucullata* has only been obtained on one or two occasions. These broads agree with those of the Thurne river group in the abundance of Chara, a plant which is rarely found in the Bure system, and this fact seems to point to a possible community of origin of the water of both. It is true that of late years the great beds of Chara, which used to luxuriate in Hickling, for example, have to some extent disappeared, but this seems to be due to the invasion of that broad by a green alga allied to *Zygnema* in the first instance, and later by a species of *Cladophora*, which covers the bottom with a thick carpet which must smother all other vegetation.

In normal circumstances, then, we may state that the pure waters of the upper Bure receive on their passage by Ant mouth a slight access of salt water. At Thurne mouth they receive a great volume of highly saline water, and the mixed water is driven back by the flood tide nearly as far as Horning, the excess of salinity over that of pure fresh water from Horning down to Acle being due to the discharge of the Ant and the Thurne river. At some point below Acle the river takes the character of an estuary in the sense that it receives water from the sea.

Abnormal Tides.

The tides on the East Coast are well known to be largely affected by wind, and exceptionally high tides may be expected when strong northerly winds prevail. On such occasions the water is prevented from ebbing, and the next flood tide comes in with the water already standing at or near the level of ordinary high water. High tides so caused, rising occasionally as high as 12 feet in place of the usual 6 feet, naturally drive an immense body of salt water up the rivers. One such tide occurred on March 13, 1906, and raised the salinity at Horning to 287, which is equivalent to 22 per cent. of sea-water. Normal conditions were not restored till after March 22 at Horning, and the effect was traceable up the Ant as late as March 30.

It seems probable that the effect of such tides on the river depends a good deal on the level of water in the river at the time, the effect being the greatest when the level is lowest. For this reason much smaller tides than that above mentioned may drive salt water up. An 8-foot tide at Yarmouth suffices to influence the salinity of the Bure in the summer as much as an 11- or 12-foot tide at other times. Thus, on July 7, 1903, the tide reached 8 feet 3 inches on the gauge at Yarmouth. On July 13 the salinity at Sutton Broad was 9.8, about a mile below Barton 112.6, and at Ludham bridge 384.4. On the other hand,

in the Bure at Ant mouth it dropped to 191, showing that normal conditions are more rapidly restored in the Bure than in the Ant. At Thurne mouth the salinity was 538·7, and here the fauna, while comprising a few specimens of fresh-water Crustacea, was composed of marine species, such as *Centropages hamatus*, *Acartia discandata*, and the Ctenophore *Hormiphora*.

As showing how suddenly such changes may occur, I may give as an instance the tide of September 4, 1910. Unfortunately no chemical analyses were made, so that the evidence is almost wholly zoological.

At Stokesby on September 3, at 12.45 p.m., the floating fauna was that of pure fresh water, including even the rotifer *Conochilus volvox*. On the other hand, twenty-four hours after, at 12.30 p.m. on September 4, high water being at 8.30 a.m. at Yarmouth, not a single living specimen of a fresh-water species could be found, their place being taken by a rich marine fauna, including the Tunicate *Oikopleura* and numbers of marine Copepods. The water the following night was brilliantly phosphorescent owing to the presence of *Noctiluca*. Faunistic conditions remained the same till I left the place on September 7, when the salinity of a sample taken at 10 a.m. was 705, but it was evident that the influence of fresh water had begun to re-establish itself on the previous day, since fresh-water weed was found drifting down the river.

These conditions show the unstable conditions which prevail in the Norfolk broads, and that though, as a general rule, they are entirely beyond the direct influence of sea-water, yet at certain times the old estuarine conditions re-establish themselves.

The CHAIRMAN, Prof. MYRES (before the paper): The paper this evening is by Miss Marietta Pallis, of Newnham College, on the "Cause of the Salinity of the Broad of the River Thurne," and I will ask Miss Pallis if she will be good enough to give us a brief verbal account of the principal points contained in the paper, and indicate to us the questions on which she would most desire that the discussion should turn.

The CHAIRMAN (after Miss Pallis's paper): Since Miss Pallis's paper was circulated, we have received from Mr. Robert Gurney a paper on "Some Observations on the Water of the River Bure and its Tributaries," which I think will come in very appropriately here, and I should like to ask Mr. Gurney to give us the substance of those observations of his before we come to more general discussion.

Dr. C. E. Moss: The problem that has been put before us can be approached from various standpoints. I do not pretend to speak from the geological or engineering standpoint, but only from the botanical point of view. It appears to me that Miss Pallis has given a very satisfactory explanation of some difficult and curious facts with regard to the distribution of maritime species in the Thurne district. The maritime species in this district are quite different from those that occur locally on mountain-tops in various parts of North Britain, not merely because they are far more general in the Thurne district, but because the species which occur here are much more thoroughly maritime. Several of the species that occur throughout the Thurne district are, so far as this country is concerned, otherwise absolutely limited to the vicinity of salt marshes. Miss Pallis, in her investigations on the distribution of these species, has been led into a study of the cause; and it does seem to me that her explanation carries conviction. There is one question I should like to ask Miss Pallis. I gather from what she says that the salt-water table sinks underneath the sand-dunes. Now, we often