The Ecology of Poole Harbour
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3. Salinity and Tides in Poole Harbour: Estuary or Lagoon?

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Notable features of Poole Harbour include its double high water and small tidal range. Due to the mixing of sea water with fresh water, surface salinity maxima and minima decrease while salinity range increases from the harbour entrance to its upper reaches. As far up as the Wareham Channel, salinity varies on a semi-diurnal basis in line with the tidal cycle. Salinity variation with depth is most pronounced in the Wareham Channel which is categorized as partially mixed, while the main body of the harbour is more or less vertically homogeneous. Depending on location, interstitial water in the mudflats may be of higher or lower salinity than the overlying water at high tide. Assertions in the literature that Poole Harbour is a lagoon are examined in the context of its tidal and salinity regimes. It is concluded that it is sufficient in explanatory terms to regard the harbour as an estuary.

The tidal range

The coastal waters of north-west Europe rise and fall twice a day under the dominant gravitational influence of the moon. Superimposed on this lunar tidal cycle is a lesser solar tide and while both are semi-diurnal, they are not of exactly the same period, the lunar day being 50 minutes longer than the solar day. Every 2 weeks, however, around the time of the new and full moon, the two tidal cycles are synchronized and spring tides occur which are of relatively large amplitude. Halfway between spring tides, the solar and lunar effects are opposed to produce reduced amplitude neap tides. So while the times of high and low water correspond with the lunar period, the predicted level to which tides rise and fall are determined over a 28 day period by an interaction of lunar and solar effects. In practice, however, whilst these gravitational cycles are relatively simple, actual tidal behaviour is more complex, due to other astronomical cycles associated with the seasons and weather conditions.

Were Poole Harbour to be an isolated water mass, its size is such that direct gravitational effects on it would be negligible. In fact, the tides of the harbour are transmitted into it from the adjacent sea. The coastal waters of Britain are set in oscillation by the rise and fall of Atlantic tides, and the English Channel effectively represents a basin in which the tides can be likened to a standing wave exhibiting greater amplitude in some locations with very little in others. The latter component of the standing wave is referred to as the nodal line. In the sea, the nodal line is reduced to a point or 'amphidrome' due to the rotation of the earth. In the northern hemisphere, the tidal oscillation rotates anti-clockwise round the amphidrome and tidal range increases with distance from it.

In contrast to the North Sea, there are no amphidromes in the English Channel. However, the flood tide does show a tendency to rotate anti-clockwise as it progresses west to east from the Atlantic. This behaviour has been described in terms of a degenerate amphrodromic system, the tide acting as if there would be an amphidrome inland of Bournemouth if the sea extended that far (Green, 1940; Tait, 1981). Consistent with this is the conspicuous contrast between the spring tide range at Poole Bay (around 2 m) and on the opposite French coast at St Malo (around 12 m). As a consequence, the tides in Poole Harbour are also of small amplitude, around 1.8 m for spring tides and only 0.6 m for neaps. Poole Harbour is, therefore, categorized as microtidal, i.e. of tidal range less that 2 m (McClusky and Elliot, 2004). Despite this, it is estimated that during a spring tide ebb up to 71.346 x 10^6 m^3 of water leaves the harbour, this being around 45% of the total spring high water volume (i.e. tidal prism ratio for spring tides = 0.45). For neap tides, 22% of the neap high water volume leaves on the ebb (Riley, 1995; Falconer, 1984). The geomorphology is such that around 80% of the harbour bed falls within the intertidal zone (i.e. between the extreme high and extreme low water levels for spring tides) and is, therefore, exposed periodically by the ebb tide (Gray, 1985).

The double high water

In a low amplitude tidal regime, local effects which would otherwise be masked become relatively pronounced. Consequently, on that part of the south coast of England between Portsmouth and Lulworth, a particular local tidal phenomenon known as a double high water occurs. This feature is transmitted into Poole Harbour. Figure 1 shows typical spring and neap tide cycles at Poole Bridge. The main low water is followed by a main flood tide which generates the first high water. A ‘fore-ebb’ generates a subsidiary low water, which is brought back up by a second flood tide (the ‘half-flood’) to a second high water which precedes the next main ebb and main low water. It can also be seen from Figure 1 that for spring tides the first high water is higher than the second, while for neap tides the reverse is true. It appears that the spring pattern is more common. Green (1940) reported that of 27 tides measured between April and May, in only seven was the second high water higher than the first. In any event, the detail of tidal behaviour in the harbour is more unpredictable than such generalizations imply, not least due to the effects of wind and barometric pressure. The double high is, however, a consistent and significant phenomenon.

Because of the double high tide, there is in Poole Harbour always a relatively long stand of high water such that for about 16 out of 24 hours, the water level is above mean tide level. This is of ecological significance as it limits the availability of mudflats as feeding grounds for important wader populations, while conversely increasing the feeding time for many of the filter feeding invertebrate animals of the mudflats which contribute to the diet of waders and also provide local fisheries. Effects on the distribution of saltmarsh plants have also been reported (Ranwell *et al.*, 1964).

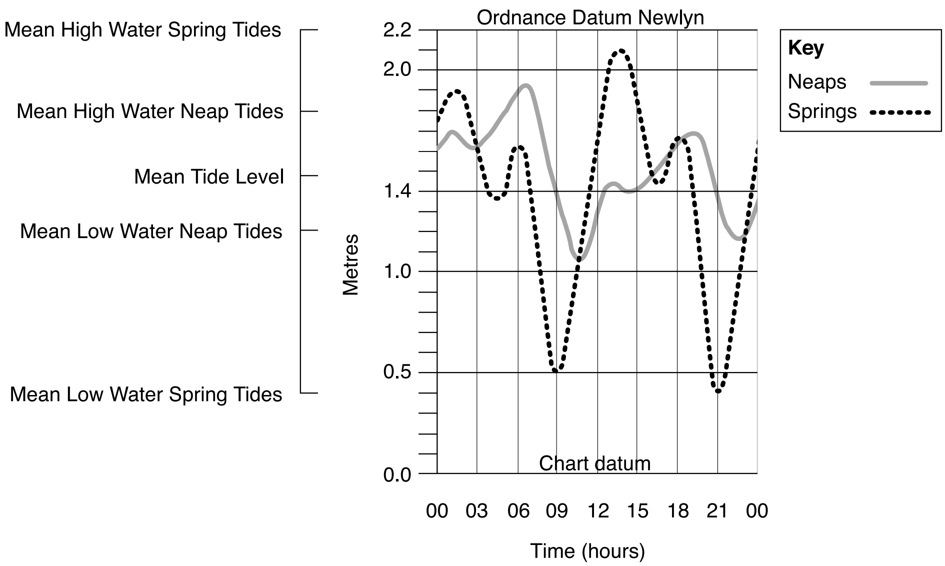

Figure 1 Typical tidal curves at Poole Bridge (modified from Gray, 1985).

Salinity

Classic definitions of salinity refer to the amount of dissolved inorganic matter expressed as grams per kilogram of water. In the open ocean, the salinity of sea water approximates to 35 g kg^{-1}. Normally, over 30 of the 35 g kg^{-1} of inorganic matter is made up of sodium and chloride – these being the main chemical components of salt. In contrast, the salinity of river water is generally less than 0.5 g kg^{-1} and the mixing of fresh water with sea water as a river approaches the sea is a defining feature of estuaries (Pritchard, 1960).

For aquatic organisms the salinity of the water in which they live is of considerable physiological significance. Most marine taxa have body fluid concentrations essentially the same as the surrounding sea water, consequently there is no tendency for them to gain or lose water by osmosis. Such osmotic equilibrium is not a feature of freshwater organisms, which in order to survive must maintain their internal concentration above that of the surrounding water. In this sense, fresh water is a more physiologically demanding medium than sea water, with the consequence that a lesser number of species have yet achieved the adaptations necessary to live in it.

Notwithstanding these challenges, rivers at least have the merit of being relatively stable in terms of the concentration of the water – a feature that freshwater environments share with the open sea. In contrast, the mixing of river and sea water in an estuary creates an environment of peculiar severity in which salinity varies considerably on seasonal and indeed shorter time-scales, mainly according to the amount of fresh water coming downstream. Superimposed on these variations, estuarine salinity also fluctuates in relation to the tidal movement of water.

Below, Poole Harbour salinity records from a number of published sources are reviewed, while original unpublished data, made available by the Environment Agency, are also reported. These sources have used various routine methods for the determination of salinity involving the measurement of a parameter relating to salinity such as chloride content or conductivity, and indeed, recent technical definitions of salinity reflect the method of determining it – nowadays conductivity in particular. However, since our present focus is on gross salinity variations from < 1 to > 34 across time and space, variations in the methods of determination in the source publications need not concern us. Therefore, converting from original sources as necessary, here salinity is expressed on the international Practical Salinity Scale (UNESCO, 1981), in which for standard sea water in defined conditions, S = 35. While the Practical Salinity Scale has no units, the salinity data as reported here can be considered to correspond numerically with reasonable approximation to a measure of grams per kilogram.

Surface salinity

There is a surface water salinity gradient in Poole Harbour from its mouth to its upper reaches from higher to lower salinity, respectively. Table 1 shows this gradient for seven sites, whose position is illustrated in Figure 2. This information is derived from an extensive data-set established by the Environment Agency using corresponding field and laboratory determinations spread over many years and at all states of the tide.

The relative consistency of salinity maxima across all sites from the harbour mouth deep into the Wareham Channel indicates the extent to which water of marine origin can, especially at high water of spring tides in the summer season, predominate. In contrast, salinity minima decrease much more markedly upstream from the harbour mouth. This phenomenon relates to the fact that salinity minima generally occur at low water when river flow makes up a greater proportion of a water mass much reduced in volume by the ebb tide. Nevertheless, the conspicuous increase in salinity range (maximum – minimum) with progress upstream represents an environmental gradient which will limit the penetration of organisms of both marine and freshwater origin. Between such limits, classic estuarine conditions will exclude all but the genuinely estuarine (euryhaline) species adapted as they are to cope with such a volatile environment.

Salinity variation within the depth

Sea water, with its load of dissolved salt, is denser than fresh water which will, consequently, tend to float above it in the water column. The degree of mixing between

Table 1 Poole Harbour surface salinity characteristics

Site	Maximum salinity	Minimum salinity	Range	Median
1. Harbour entrance	34.7	24.9	9.8	29.8
2a. North Channel	34.5	26.3	8.2	30.4
2b. South Deep	34.1	23.2	10.9	28.65
3a. Poole Bridge	33.9	19.2	14.7	26.55
3b. Hutchins Buoy	34.2	14.2	20.0	24.2
4. Lytchett Bay entrance	30.7	10.6	20.1	20.65
5. Wareham Channel	30.4	1.0	29.4	15.7

Source: Environment Agency.

distinct fresh and salt water masses entering an estuary depends on such factors as the relative volume of river and tidal flows, depth and wind-induced turbulence. Highly stratified estuaries with little mixing exist where large rivers flow into seas with low tidal amplitude. Conversely, where tidal flow dominates, the water column is normally fully mixed and the estuary is classified as vertically homogeneous, i.e. with no variation of salinity with depth. These two conditions represent the ends of a continuum between which lies the partially mixed condition in which, while there is no sudden transition from fresh to salt water, there is nevertheless an increase of salinity with depth (Dyer, 1997).

On the basis of such considerations, Poole Harbour (excluding Holes and Lytchett Bays for which I have been unable to find data) can be considered to consist of two distinct zones: a more or less vertically homogeneous zone in the main body of the harbour, and a partially mixed zone in the Wareham Channel. A July salinity profile as reported by Green (1940) is shown as Figure 3. The partially mixed condition of the Wareham Channel is explicable on the basis that it is through this channel that the main freshwater river flow into the harbour occurs. This, combined with the distance from the harbour mouth, indicates that the freshwater inflow is at its highest in the harbour relative to tidal flows. Conversely, in the main body of the harbour where tidal flows dominate, greater mixing produces a more or less homogeneous salinity profile.

More recent work supervised by Antony Jensen at Southampton University (Barkas, 2001), while confirming this general pattern, provides further information from a series of readings reported over the period April to August 2001. This work shows the extent to which salinity gradients can vary at any one place and includes April data for the Wareham Channel showing a salinity differential from surface to bottom in excess of 10.

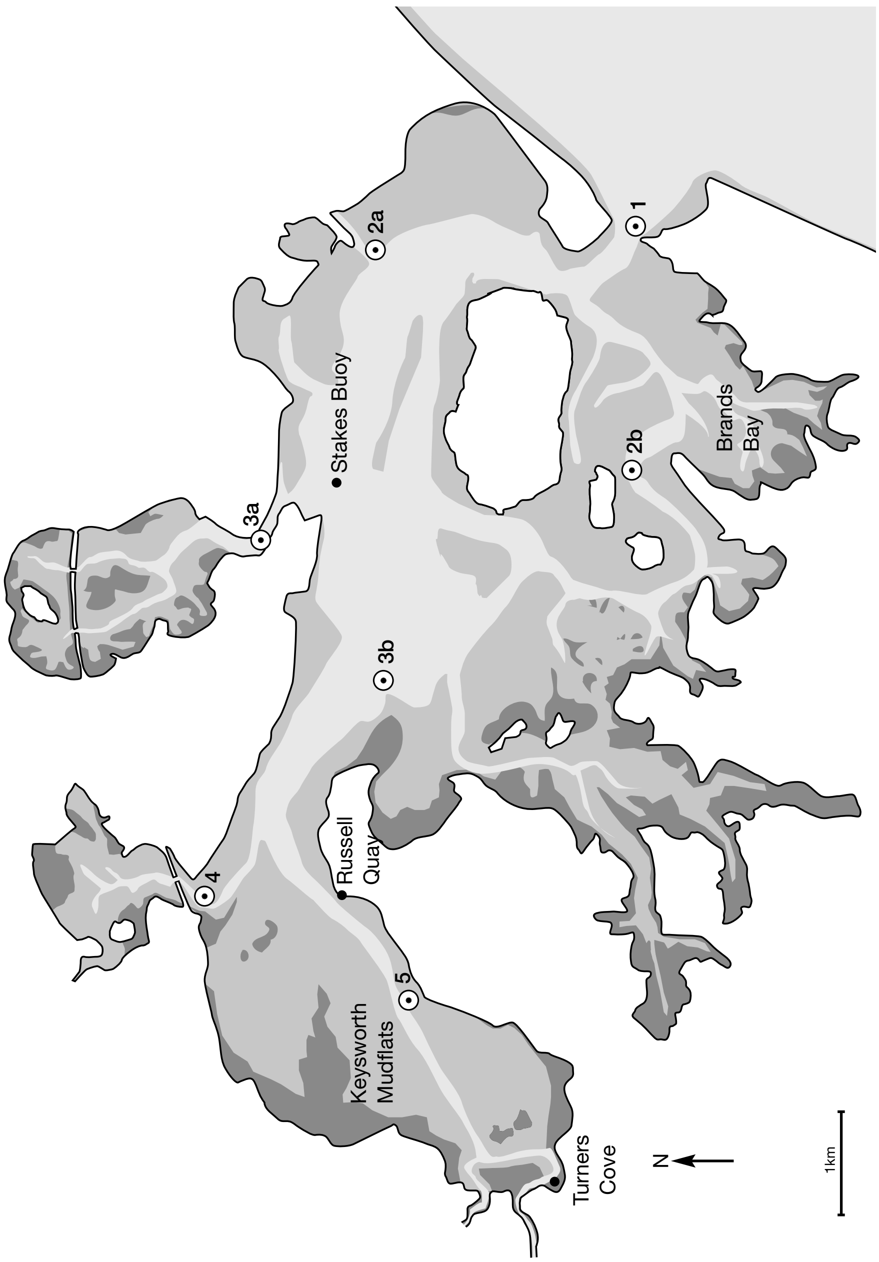

Figure 2 Positions of sampling sites for Tables 1 and 2 and Figure 3.

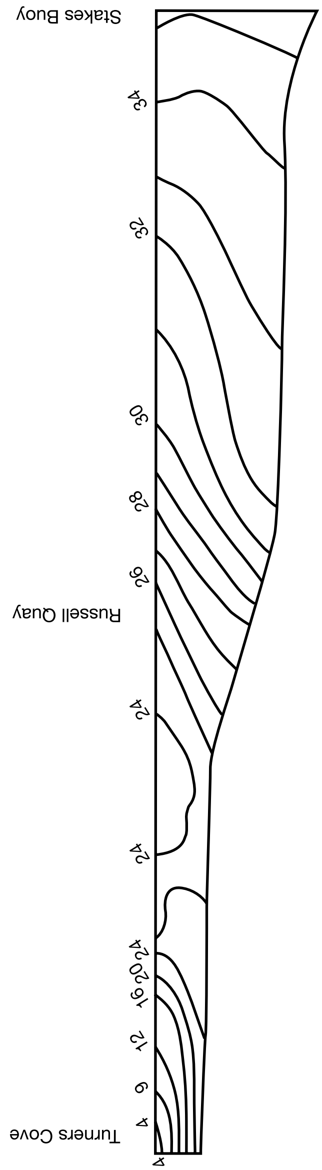

Figure 3 An example of salinity variation with depth from Stakes Buoy along the Wareham Channel (see Figure 2 for site locations).

Interstitial salinity

For many of the animals in Poole Harbour, the ambient salinity (at least at low tide) is that of the interstitial water between the particles of the sediment within which they live. The relationship between the salinity of interstitial water and the water overlying the sediment is known to be dependent on particle size and the slope of the shore. Fine sediments on mudflats are widespread in Poole Harbour and are particularly effective at moderating salinity fluctuations occurring in the overlying water. Through phenomena related to capillary action, fine deposits will tend to retain water and also attenuate evaporation to the air when exposed at low tide (Webb, 1958). This effect combined with the fact that intertidal mudflats are only covered by the higher salinity flood tide, can result in interstitial water of higher mean and lower salinity range than overlying waters (McClusky, 1971). In Poole Harbour, however, factors other than tidal submergence can determine interstitial salinity.

Data from Ranwell *et al*. (1964) shown in Table 2 indicate a general trend of decreased interstitial salinity with increased distance from the harbour mouth – a feature which confirms the importance of tidal submergence. However, superimposed on this pattern are local factors. Measurements on the Arne Bay *Spartina* marshes over a 1 year period showed a seasonal pattern linked to rainfall and connected to the discovery of a water table 20 cm below the marsh surface. This, combined with groundwater seepage, provides the sediment with a steady freshwater supply. In such circumstances as Smith (1955) first showed, the moderating effect of the fine sediment can work to maintain a lower salinity than the prevailing flood tide water.

The ecological effects of such phenomena relate in particular to the distribution of organisms for whom interstitial salinity is important, notably invertebrate infauna and marsh plants. Ranwell *et al*. (1964) for instance, were able to show how, in Poole Harbour, interstitial salinity limited the invasion of *Spartina* marshes by the reed

Table 2 Comparison of interstitial and surface water salinity in *Spartina* marsh at three sites in Poole Harbour

	Straight line distance from harbour mouth (km)	Interstitial water	Surface water	Difference	Date
Brands Bay	2.4	31.0	29.4	+1.6	19.7.62
Arne	6.4	26.7	24.4	+2.3	14.10.62
		25.2	26.4	-1.2	19.7.62
Keysworth	9.3	17.6	20.1	-2.5	19.7.62

Adapted from Ranwell *et al.* (1964).

Phragmites communis and Sea Club Rush *Scirpus maritimus*. However, this work on the saltmarshes is the only information I have been able to find on Poole Harbour interstitial water salinity and there seems to be no published data available on the mudflats despite their significance in terms of invertebrate macrofauna and consequent value to important wader populations and local fisheries. Nevertheless, patterns of invertebrate distribution reported by Caldow *et al.* (this volume, chapter 7) are suggestive of salinity as a limiting factor for various species in Poole Harbour.

Poole Harbour: Estuary or lagoon?

Scientific definitions of an estuary are numerous and varied, and it is not intended to review them here. Fortunately for our purposes, however, there are certain recurring defining attributes in the literature which represent a degree of consensus. These attributes characterize an estuary as: (i) a body of water of mixed origin, part from a discharging river system and part of an adjacent sea which is; (ii) partially enclosed by land, but with; (iii) free connection to the sea and consequently; (iv) subject to the tidal cycles of that sea (e.g. Pritchard, 1967; Barnes, 1974; Fairbridge, 1980). These features collectively have the additional merit of a good alignment with the common understanding of the word.

This chapter so far has examined Poole Harbour in estuarine terms applying, for example, Dyer's (1997) classification of estuaries on the basis of vertical salinity profiles. However, Poole Harbour has also been categorized as a coastal lagoon (Barnes, 1980, 1989, 2000). Insofar as estuaries and lagoons are, in essence, distinct categories of coastal feature – and arguably to be useful scientific concepts they must be – it is worth briefly commenting on which best applies to Poole Harbour.

The literature on coastal lagoons suggests that the concept has proved difficult to define. As for the term estuary, various definitions have been articulated, physical manifestations of which range from relatively small pools to the whole of the Baltic Sea (Jansson, 1981). In any event, coastal lagoons like estuaries are commonly referred to as partially or semi-enclosed bodies of water connected to the sea (e.g. UNESCO, 1980). While they may contain water of mixed origin, this is not a defining attribute as it is with estuaries. Arguably the definitive distinction between the two lies in the nature and extent of the connection with the adjacent sea. While estuaries are partially enclosed they have, by definition, free connection to the sea. Conversely, for lagoons, this connection is restricted with the consequence that the exchange of water between a lagoon and its adjacent sea is attenuated. While such exchange may occur only by percolation through a complete sediment barrier, lagoons may alternatively have one or more entrance channels. However, such channels are sufficiently small in relation to the size of the lagoon that its water body is effectively 'semi-isolated' (Barnes 1980).

Clearly then, in order to decide whether Poole Harbour should be considered a lagoon, we must make a judgement on whether its waters are sufficiently isolated to merit that status. Whilst we know that Poole Harbour has a narrow channel connecting it to the adjacent sea, this does not necessarily mean that the waters of Poole Harbour are to any significant degree isolated from that sea. If the entrance to the harbour, whatever its shape is sufficient to provide free connection to the sea, it should more accurately be considered an estuary. Since these various coastal features represent positions on a continuum, it is understandable that different authorities make different judgements on this, especially if these judgements are based primarily on geomorphology (narrow entrance occluded by sandy spits), rather than more ecologically significant attributes like the degree of isolation of the water mass. In the case of Poole Harbour, it is the latter as evidenced by tidal flows and the salinity regime that resolves the issue.

On tidal coasts, semi-isolation of a lagoonal water mass is taken to mean that much of the water is retained within the lagoon at low tide in the adjacent sea (McClusky and Elliot, 2004). For a lagoon with a river inflow, like an estuary, there will be a longitudinal salinity gradient from high at the seaward end to low at river end. However, in a lagoon, except in the vicinity of the entrance, this gradient is stable in the short term, that is to say it does not fluctuate on a semi-diurnal basis with the tide (Barnes, 1980). This feature contrasts with estuaries within which, due to their open connection to the sea, salinity fluctuates with the ebb and flow of the tide.

Now consider Poole Harbour: does the longitudinal salinity gradient fluctuate with the tide suggesting the ‘free connection’ that characterizes an estuary or is it stable suggesting a lagoon? Figure 4 shows continuous salinity readings over a 24 hour period juxtapositioned with predicted tide level over the same period. These graphs show that, as far up as the Wareham Channel, salinity varies on a diurnal time-scale which closely matches the tidal cycle.

This feature of Poole Harbour indicates that its entrance while narrow, nevertheless functions as a relatively free connection to the adjacent sea. In this respect, it is worth noting from Admiralty charts, the depth and current speeds of the channel at its narrowest point which, at over 18 m (compared with an average depth for Poole Bay of around 12 m (Riley, 1995)) and up to 2.6 m second^{-1} (Bird and Ranwell, 1964) on the ebb, provide an explanation as to why such a narrow channel does not significantly isolate the harbour’s waters from the waters of Poole Bay. On this basis, there appears to be no compelling argument for characterizing Poole Harbour as a lagoon. Conversely we can attribute to it all four of the defining attributes, as outlined above, of an estuary.

If, as I have argued, Poole Harbour is best regarded as an estuary, it is worth reflecting on why it has sometimes been regarded as a lagoon (Barnes, 1980, 1989, 2000) or less definitively as ‘lagoon-like’ (Gray, 1985), ‘lagoonal in character’ (English Nature, 1994) or resembling a lagoon (Bird and Ranwell, 1964). The geomorphology of the harbour with its two opposing spits forming a narrow entrance are certainly reminiscent of genuine lagoons but this, as we have seen, is misleading. More relevant to this question is the water level which in Poole Harbour is, as we have observed, above mean tide level

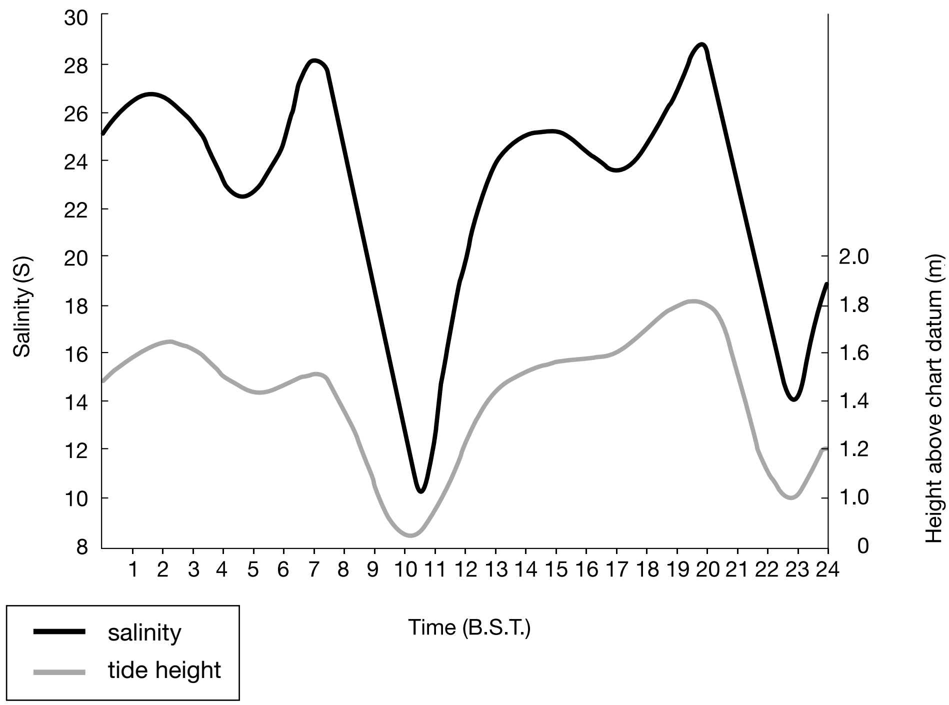

Figure 4 Surface salinity (S) in the Wareham Channel (site 5, Figure 1) over a 24 hour period (24 July 2000) shown in relation to predicted tidal level at Poole Bridge. Sources: Environment Agency; Poole Harbour Tidal Planner 2000.

for about 16 hours a day. However, while this also is reminiscent of lagoons, its cause is classically estuarine. Rather than being due to the retention of water as in a lagoon, the prolonged high is, in contrast, transmitted into the harbour from the adjacent sea.

Finally, it is worth noting that depressions in the sediment surface within the harbour can retain water at low tide to form shallow pools. An example of this is Holton Mere which is known to have persisted for 150 years in the mudflats on the north-western shore of the Wareham Channel disappearing in the first quarter of the twentieth century (although it remains marked on Admiralty charts). This feature, which at one time covered an area of 40 ha, has been described as a transitory shallow lagoon by Hubbard and Stebbings (1968). Arguably, there is a better case for considering such features as small coastal lagoons than for the harbour as a whole, since the water retained in them from a preceding high tide would normally be of relatively high salinity compared with the low tide salinity of the adjacent main channels (although there appears to be no data to support this assertion). Consequently, short-term salinity variations could well be moderated somewhat. However, such pools cannot be considered in any real sense semi-isolated and in any event their existence cannot be persuasively used to argue that the harbour as a whole is a lagoon.

Therefore, while the double high tide effect combined with a microtidal regime can reasonably be described as providing a somewhat lagoon-like environment, such references are misleading, at least insofar as they imply genuine lagoonal characteristics for the harbour. Rather, it is accurate to characterize Poole Harbour as an estuary, and in doing so recognize that estuarine phenomena prevail and provide sufficient explanation for its nature and ecology. With its great size, narrow entrance, double high water, small tidal range and other features of considerable interest, Poole Harbour may be a unique feature of the UK coastline, but it is nonetheless an essentially estuarine feature.

Acknowledgements

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