Observations of nutrient release into semi-enclosed macrotidal lagoons

S. B. Mitchell
School of the Environment, University of Brighton, Lewes Road, Brighton BN2 9UF, UK

Abstract
Sections of the densely populated southern and eastern English coasts are characterised by a sequence of semi-enclosed macrotidal lagoons. Periodic release of nutrients (nitrate/phosphate) from sewage treatment plants and agriculture into these areas has caused concern to environmental managers in terms of possible eutrophication problems and excessive growth of macrophytic algae (enteromorpha/ulva). It is therefore important to investigate the patterns of distribution of nutrients within these lagoons in order that this effect may be better predicted and mitigation measures undertaken. Results of nitrate and phosphate concentrations are shown, measured both over individual tidal cycles and over longer term deployments at Pagham Harbour, West Sussex, UK, a site of great importance as a nature reserve and a home for several rare species of plants and animals. In particular, the effects of fresh water-salt water stratification over 2 tidal cycles will be presented. It is shown how obtaining periodic vertical profile measurements during the tidal cycle helps to quantify the flux of nutrients from the tidal limits into the main body of the lagoon. Also of key interest is the interaction between sediment bound nutrients with the surrounding water in which the sediment is suspended during parts of the tidal cycle. Synthesis of these results with existing knowledge about sediment-water-nutrient interactions reveals how it is possible for nutrients to become trapped at the muddy tidal limits of the lagoon.

Keywords: macrotidal, lagoon, nutrients, nitrate, phosphate, stratification.

1 Introduction

Increases both in the use of fertilizers for agriculture and of detergents in industrial and household use have led to increasing concern about the fate of
nitrates and phosphates in natural rivers and estuaries [1], and on possible increases in the occurrence of eutrophication problems in estuarine areas. Much of the recent literature [2,3,4] has highlighted the importance of understanding the nutrient balance in estuaries in identifying the root causes of eutrophication problems.

In estuaries and coastal waters, eutrophication appears generally to be nitrate-limited [1]. The sheltered nature of these harbours makes them very susceptible to problem growths of macrophytic algae such as Enteromorpha and/or Ulva green seaweeds, which are symptomatic of eutrophication problems worldwide [5]. In the Great Ouse estuary, UK, removal of nutrients due to phytoplankton activity, has also been suggested [6]. Thus an understanding of the factors influencing nitrate concentrations, including a description of the major sources and sinks within natural harbours, is essential, in order that decisions can be made on the necessary infrastructure required to treat the effluent before it enters the natural environment.

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In addition, cohesive sediments found on intertidal areas within estuaries also act as a sink for organic material. The role of cohesive sediments as a source of nutrients for primary production by algae and other plant life is outlined in [7]. In particular, the presence of nitrates in the sediment has been demonstrated as having a seasonal influence, due to the dependence of the processes of nitrification and denitrification on the presence of certain bacteria within the sediments, related to the abundance of oxygen within the sediments [8]. Enteromorpha/Ulva seaweed mats on intertidal mudflats in Langstone and Chichester harbours have been shown to control changes in oxygen levels in the sediment underlying the mats, leading to seasonal changes in the nature of these sediments as sources and sinks of nutrients [9]. The implications for the overall nitrate budget in the estuary system are therefore dependent to some degree on the sediment transport processes.

A better understanding of the role of estuarine processes on controlling the nutrient budget is thus required for estuaries of this type. The relative importance of saline stratification [10], fresh-saltwater mixing, and sediment water exchange are at present unclear, and a primary aim of this paper is to present a simple conceptual model to assist in the understanding of these phenomena. The results and analysis of this work will help researchers and managers to gain insights into the processes of flow and nutrient transport in the light of likely changes in and around the lagoon by a better understanding of the effects of, for example:

- nutrient removal at sewage treatment works,
- local sea level rise,
- increased fresh water inputs into the lagoon, for example by construction of new flood relief channels.

2 Study site and methods

Along the heavily populated stretch of coastline between Portsmouth and Chichester, there exist the 4 semi-enclosed harbours of Portsmouth, Langstone, Chichester and Pagham, all of which are affected by issues relating to
eutrophication and the nutrient balance. The smallest of these, Pagham Harbour (Figure 1) has an area of approximately 5 km² and is located at 0° 45’ W, 50° 48’ N. Local tides are semi-diurnal with a mean tidal range of between approximately 3.0 m (Neaps) and 6.5 m (Springs). Fresh water enters through a network of rifes, indicated as Q1-Q4 on Figure 1, the largest of which are located at the Ferry Pool and the Salthouse. Owing to its elevation, however, the tidal cycle within the harbour is asymmetrical, with seawater inundation occurring only during the 6-8 hours over high water. Thus, for that period of the tidal cycle around low tide, Pagham Harbour consists of a network of drainage channels surrounded by mudflats and areas of salt marsh. At high water the mudflats are covered, and surrounding land is protected from flooding by a series of flood banks and tidal flap gates. At the Ferry Pool site, however, fresh water inflow to the harbour is controlled by means of a large pump that discharges nutrient-laden, fresh water at varying intervals throughout the tidal cycle [11].

Figure 1: Pagham Harbour. Q1 – Q4 indicate location of fresh water inputs.

Measurements of nitrate and phosphate concentrations, made at approximately monthly intervals, were obtained at the two significant tidal limits of Ferry Pool and Salthouse, and also at the Harbour Entrance. These data were obtained from the UK Environment Agency. However, since the timing of these long-term measurements does not allow for investigation of variations of concentrations of determinands within individual tides, a more intensive
sampling regime was also used. In this case, a battery-operated submersible pump was attached to a Valeport conductivity-temperature-depth (CTD) probe and deployed at the Ferry Pool site for the morning tides of 14 July and 25 September 2003. The CTD-pump assemblage was raised and lowered manually by means of a pulley suspended above the middle of the channel at a frequency of between 10-30 minutes. Both tides selected were spring tides of a similar height (Table 1). Fresh water inflow to the harbour was similarly low on both sampling days. The pump supplied water samples to individual 250-ml sample bottles at a rate of 1.5 litres per minute, with simultaneous water depth and salinity readings being taken at each sample. The samples were later analysed (within 24 hours) for concentrations of nitrate and phosphate using hand-held Hach colorimeters. Simultaneous measurements of water depth at roughly 20-minute intervals were obtained by visual inspection at the Ferry Pool site.

Table 1: Tide conditions for the 2 deployments.

<table>
<thead>
<tr>
<th>Date &amp; Time GMT</th>
<th>Predicted Peak Tidal Height (m, Shoreham)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 July 2003 11:36</td>
<td>6.1</td>
</tr>
<tr>
<td>25 Sep 2003 10:31</td>
<td>6.3</td>
</tr>
</tbody>
</table>

3 Results

Long term variation in nitrate and phosphate concentrations at the three sites sampled by the UK Environment Agency are shown in Figures 2-3. Although detailed analysis is not possible due to the low sampling frequency and the lack of consistency of tidal state, it is possible to identify some key features that may assist in elucidation of the mechanisms affecting the nutrient balance. A pattern of nutrient concentrations may be observed that increases during the summer months, when fresh water inflows are lower. This is particularly apparent during the long drought period during 1995. Additionally, it may be seen that the concentration of nutrients is generally higher at the Ferry Pool than at the Salthouse, even though both carry water away from small-scale sewage treatment works, where concentrations of nitrates and phosphates may be expected to be high. In general, the concentration of N and P at the seaward limit of the harbour is much lower (generally <1 mg/l), although for the case of N, one or two instances exist where nitrate levels are higher, during winter months (Figure 2).

Results from the two intensive campaigns of 14 July and 25 September 2003 are shown in Figures 4-5. Although both the tidal height and the fresh water inflow to the harbour were the similar on both days, small variations in nutrient inputs can be seen. On all 4 plots shown in Figures 4-5, a period of flow of nutrients is observed prior to the arrival of the flood tide, when the salinity is zero and effectively only fresh water originating from the land is present. Thus at these times the observed nutrient concentrations reflect the concentrations of nutrients entering the tidal system at this point. The magnitudes of N and P concentrations entering the harbour on 14 July and 25 September 2003 may thus
be observed in general to be similar to those obtained from the Environment Agency recording programme. With the arrival of the flood tide at 0930 on 14 July and 0800 on 25 September, a change can be seen in the observed concentrations of N and P. Saline water of a greater density arrives at the site and underlies the less dense, more nutrient-laden water originating from the land as the water column stratifies. With the arrival of high water and the subsequent ebb, the stratification may be observed to start to break down as the water becomes better mixed.

Figure 2: Nitrate concentration (as N) by year at Ferry Pool (triangles), Salthouse (squares) and Harbour Entrance (diamonds).
Discussion

Results shown in Figures 2-3 indicate a generally predictable pattern of concentration of nutrients within Pagham Harbour as recorded by monthly survey. The ratio of N:P ranging between approximately 1:1 and 2:1 is much less that the Redfield ratio of 16:1 and points strongly towards eutrophication being nitrate limited, in common with many UK riverine systems [1]. There is little evidence of seasonal limitation by P as described in other estuaries [2]. This is almost certainly due to the high local concentrations of phosphorus being...
continuously discharged from small-scale sewage treatment works, and possibly also from agricultural practices.

Figure 4: Vertical profiles of nitrate N (top panel) and phosphate P (bottom panel) 14 July 2003. x-axis: time in hours GMT. y-axis: water depth.

The fact that concentrations of N and P are generally higher at the Ferry Pool site than at the Salthouse almost certainly points to the importance of dilution by other sources of fresh water that are in greater supply at the Salthouse site. Also, as indicated elsewhere [11], it is likely that the timing and magnitude of fresh water events as controlled by intermittent pump discharge at the Ferry Pool leads to a greater concentration of nutrients here than at the Salthouse, where the flow is controlled by tidal flap gate. A final observation from the monthly monitoring is related to the occurrence of elevated levels of N at the Harbour entrance (Figure 2) during some winter months. As observed elsewhere [12], it is possible that this is due to the contribution of the relatively nitrate-rich waters of the Solent at certain times of year. The possible existence of a link between the condition of the Solent and the presence of nutrients in Pagham Harbour raises important questions about the mitigation measures necessary for the treatment of eutrophication in harbours of this type.
Figure 5: Vertical profiles of nitrate (as N, top panel) and phosphate (as P, bottom panel) 25 Sep 2003. x-axis: time in hours GMT. y-axis: water depth.

In this system, it is unlikely that significant phytoplankton growth could occur, due to the high degree flushing that occurs during each tidal cycle. Thus the nutrient removal as suggested by [6] seems unlikely in this case. However, inspection of the stratification observed with the arrival of saline water at the Ferry Pool site (Figures 4-5) suggests an alternative means of nutrient uptake. A reasonable degree of stratification with respect to N and P persists throughout much of the tidal cycle. Even at the end of each deployment the surface waters are still significantly more nutrient-rich than the water near the bed. This is a particularly interesting feature as the salinity stratification has generally broken down by this time [11]. However, the importance of this phenomenon is that the muddy inter-tidal areas that surround the tidal channels are thus exposed to water of a higher concentration of nutrients that they would be in the absence of significant stratification. Since inundation of the mudflats generally only occurs for 5-6 hours of each tidal cycle, it is suggested that the nutrient stratification that
is observed during each flood tide controls the degree to which nutrients pass into the estuarine sediments present. It is therefore suggested that this is part of a mechanism by which nutrients become preferentially trapped at the muddy tidal limits of lagoons of this type.

5 Conclusions

Monthly surveys have been carried out at three locations at Pagham Harbour, UK, of nitrate and phosphate concentrations. These, together with the results of detailed ‘vertical profiling’ surveys carried out at one of the three sites, have revealed patterns of nutrient transport that can help explain some of the mechanisms that lead to eutrophication in harbours of this kind. The main preliminary conclusions of this work to date are:

1. Ratios of N:P of between 1:1 and 2:1 lead to the view that eutrophication in the harbour is nitrate limited. The occurrence of relatively high levels of P are consistent with the effluent waters from small-scale sewage treatment processes nearby.

2. Concentrations of nutrients are generally higher at the Ferry Pool site than at the other main freshwater input site at the Salthouse, by a factor of about 2. This is almost certainly due to a greater dilution effect at the Salthouse, and due to the effect of intermittent pumping of fresh water at the Ferry Pool.

3. Vertical profiles of N and P during 2 similar tidal cycles reveal a pattern of salinity-induced stratification that could help to promote nutrient transfer from the overlying water to the muddy inter-tidal sediments. Nutrients could then become preferentially trapped at the muddy tidal limits of the system.

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References


