Investigating and managing water quality in saline lagoons

based on a case study of nutrients in the Chesil and the Fleet European marine site

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Preface

The 1990s saw a "call to action" for marine biodiversity conservation. The global Convention on Biodiversity, the European Union's Habitats Directive and recent developments to the Oslo and Paris Convention have each provided a significant step forward. In each case marine protected areas are identified as having a key role in sustaining marine biodiversity.

The Habitats Directive requires the maintenance or restoration of natural habitats and species of European interest at favourable conservation status, with the management of a network of Special Areas of Conservation (SACs) being one of the main vehicles to achieving this. Among the habitats and species specified in the Annexes I and II of the Directive, several are marine features and SACs have already been selected for many of these in the UK. But to manage specific habitats and species effectively there needs to be clear understanding of their distribution, their biology and ecology and their sensitivity to change. From such a foundation, realistic guidance on management and monitoring can be derived and applied.

One initiative now underway to help implement the Habitats Directive is the UK Marine SACs LIFE Project, involving a four year partnership (1996-2001) between English Nature, Scottish Natural Heritage, Countryside Council for Wales, Environment and Heritage Service, Department of the Environment for Northern Ireland, Joint Nature Conservation Committee, and Scottish Association of Marine Science.

The overall goal of the Project is to establish management schemes on 12 of the candidate marine SAC sites. A key component of the Project is to assess the interactions that can take place between human activities and the Annex I and II interest features on these sites. This understanding will provide for better management of these features by defining those activities that may have a beneficial, neutral or harmful impact and by giving examples of management measures that will prevent or minimise adverse effects.

Seven areas where human activity may impact on marine features were identified for study, ranging from specific categories of activity to broad potential impacts. They are:

- port and harbour operations
- recreational user interactions
- collecting bait and shoreline animals
- water quality in lagoons
- water quality in coastal areas
- aggregate extraction
- fisheries.

These seven were selected on the grounds that each includes issues that need to be considered by relevant authorities in managing many of the marine SACs. In most cases, the existing knowledge is extensive but widely dispersed and there is therefore a requirement to collate it together. In the case of water quality in lagoons, it is apparent that there have been few site specific studies and therefore little material that can be reviewed. Accordingly, the first step has been to trial an approach on a demonstration site and use this to inform broader guidance for other sites as to the assessment and management of water quality in saline lagoons. Through a review undertaken by the Environment Agency, the site selected for this study was Chesil and the Fleet European marine site. Here there is a perceived water quality issue, a site of considerable nature conservation interest and some data on which to build.

The reports from all these studies are the result of specialist input and wide consultation with representatives of both the nature conservation, user and interest bodies. They are aimed at staff from the relevant authorities who jointly have the responsibility for assessing activities on marine SACs and ensuring appropriate management. But they will also provide a valuable resource for industry, user and interest groups who have an important role in advising relevant authorities and for practitioners elsewhere in Europe.

The reports provide a sound basis on which to make management decisions on marine SACs and also on other related initiatives such as the Biodiversity Action Plans and Oslo and Paris Convention. As a result, they will make a substantial contribution to the conservation of our important marine wildlife. We commend them to all concerned with the sustainable use and conservation of our marine and coastal heritage.

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Summary

Section 1 Introduction

The purpose of this report is to provide guidance to those involved in the management of saline lagoons on potential water quality impacts and on the investigation and management of potential impacts from nutrients drawing on a case study. The report brings together published and unpublished information on water quality issues which may affect the conservation interest of saline lagoons with particular reference to those identified as Special Areas of Conservation (SACs). As there have been few relevant site specific studies on which to base guidance there was a need to focus on a case study to inform generic guidance. An assessment of potential sites highlighted the Fleet as an obvious choice for the case study.

Section 2 Background

Saline lagoons are defined as areas of shallow, coastal saline water, wholly or partially separated from the sea by sandbanks, shingle or, less frequently, rocks. Five main sub- types have been identified in the UK: isolated lagoons, percolation lagoons, silled lagoons, sluiced lagoons and lagoonal inlets. These sub-types have been used in identifying and designating statutory sites including SACs and SSSIs. Due to a range of salinity conditions and substratum types, lagoons support a variety of biological communities as well as a number of species restricted to the habitat.

Lagoons are relatively uncommon in the UK (with concentrations in the south and east of England and in the Western and Northern Isles of Scotland) and in Europe. They are listed as a priority habitat under the EC Habitats Directive and under the UK's Biodiversity Action Plan. Ten sites (incorporating over 60 individual lagoon sites) have been identified as SACs for lagoons in the UK.

Section 3 Guidance on potential water quality impacts in saline lagoons

Although they may be naturally rich in, for example, nutrients, saline lagoons and the biological communities that they support are potentially very sensitive to changes in water quality particularly due to low water exchange with the sea. The degree to which a site is sensitive will depend on:

- The type of lagoon (i.e. nature of exchange with the sea) and its size;
- Communities and species present.

The type and size of lagoon suggest the following generalised order of sensitivity:

Least sensitive	Lagoonal inlets
↓	Silled and Sluiced lagoon
Most sensitive	Percolation and Isolated lagoons

However, those parts of larger sites, such as lagoonal inlets, furthest from seawater exchange and therefore poorly flushed are also likely to be sensitive. Equally, once impacted, larger lagoons may take longer to recover. Other factors affecting sensitivity include depth and substrate.

Biological features of lagoons, which may potentially be affected by changes in water quality in temperate areas, include:

- ! eelgrass beds (*Zostera* spp.);
- ! charophytes;
- ! other lagoonal aquatic plants (tasselweed, pondweed);
- ! lagoonal invertebrates;
- ! fish.

Very little information exists on the sensitivity of such features to changes in water quality. The report summarises what information there is. The following water quality (other than salinity) issues are identified in priority order:

- ! **nutrient enrichment**: including direct metabolic effects (for example the foxtail stonewort most frequently occurs at sites where soluble reactive phosphate is below 10 µg/l), increase in growth of epiphytic, floating, ephemeral, benthic and phytoplanktonic algae and associated competition with lagoonal vegetation of conservation interest, and indirect effects on lagoonal fauna;

- ! **turbidity**: including increase in light attenuation and smothering or inhibition of feeding of lagoonal invertebrates;

- ! **toxic contamination**: suggested contaminants of concern from studies outside lagoons include heavy metals, herbicides/pesticides and chronic oil pollution;

- ! **organic enrichment**: likely to be of limited concern given that lagoonal sediments are naturally high in organic material.

In addition, evidence from the few lagoon-specific studies undertaken and from similar systems suggests that once impacted (particularly by nutrient enrichment) lagoons may be slow to recover from impacts due to changes in water quality becoming self-perpetuating. This highlights the need to identify water quality impacts within lagoons as early as possible and suggests the need for a precautionary approach to interpreting and acting on information that may indicate an impact.

Section 4 Case study - The Fleet

The Fleet in Dorset is one of the largest and the best studied lagoons in the UK and has been identified as an SAC for this feature. It is a lagoonal inlet, with features of percolation lagoons. It can be divided into a western brackish section and an eastern, almost fully marine, section. It is considered the finest example of its physiographic type in the UK, and one of the most important in Europe. The site is of considerable importance for its biological communities and presence of a number of specialist lagoonal invertebrate species. It is also of conservation importance for its wildfowl, in particular for the number of wintering wildfowl, and a number of species of terrestrial importance are found on Chesil beach, which forms the barrier between the lagoon and the sea. It is of additional interest due to the presence of the Abbotsbury swannery in the western Fleet - the only colonial breeding site for mute swans in the UK. The conservation objective for the lagoon feature of the SAC highlights the following sub-features:

! seagrass bed communities
! tide-swept communities
! subtidal course sediment (gravel, cobble, pebble) communities
! intertidal sediment communities
! shingle spring line communities

Concern has been expressed that the Fleet may be subject to eutrophication. However, there was little recorded information to verify this. In order to determine the nutrient status of the Fleet and potential related impacts on the conservation interests of the lagoon, and to inform management of the site, a case study was undertaken involving a number of related projects:

1. **Historical information** (water quality and ecology): Review of historical information on the Fleet to collate any information on water quality, trends in water quality parameters or related biota;

2. **Water quality investigations**: Investigations by the Environment Agency into the current and recent water quality status of the Fleet and its inputs, including data collection on point sources, streams, diffuse sources, and receiving waters, to support nutrient budget modelling;

3. **Hydrology**: Modelling of tidal currents, salinity and solute distribution to determine flushing characteristics of the Fleet and assist prediction of the fate of nutrient inputs.

4. **Nutrient budget**: Modelling of the nutrient budget of the Fleet and its inputs to assist in identifying causal factors and determining priorities for future management of the site.

The report summarises the background, methods, results and implications of each of these four projects. The nutrient budget and associated water quality investigations indicate:

! Nitrogen: peak inputs in winter from adjacent agricultural land (fertiliser application) via streams;

! Phosphorus: peak inputs in winter from agriculture (livestock farming), peak inputs in summer from wildfowl feeding, and inputs in both winter and summer from sewage discharge.

It is suggested that both nitrogen and phosphorus limit plant growth to varying degrees at different times of the year. However, in practice, nutrients are unlikely to be limiting in the Abbotsbury embayment at present because concentrations are excessively high throughout the year; it can only be postulated as to whether this would be the case under natural conditions.

The hydrological studies show that, hydrodynamically, the Fleet may be divided into the western Fleet with poor flushing characteristics, particularly the Abbotsbury embayment at the extreme western end, and the eastern section which is well flushed.

In terms of the biological response to, and impact of, nutrient inputs, location and timing are critical. In summary, inputs to the western end of the Fleet during the spring and summer are potentially significant due to poor flushing and the fact that this is the main plant and algal growing season. Furthermore, inputs during winter, particularly of phosphorus, can be incorporated within lagoon sediments and subsequently taken up by plant growth during spring and summer.

There is little direct evidence from observations of the biota that nutrient inputs are having a detrimental effect on the conservation interest of the lagoon, except possibly *Lamprothamnium papulosum*, or that nutrient inputs have significantly increased in recent years and from which sources. Both of these conclusions are due to a lack of historical information rather than being based on available evidence. What evidence there is suggests a possible decline in the distribution and population of *Lamprothamnium papulosum* at the western end of the Fleet. Research on the species in the Fleet and elsewhere suggests a critical threshold of soluble reactive phosphate between 10 µg/l-P and 30 µg/l-P.

However, caution is required as there is insufficient information from which to draw conclusions with respect to other features. Taking account of the nutrient and hydrological studies, it is likely that any increases in nutrient inputs to the western Fleet are likely (if they have not already done so) to be detrimental to the health of:

- eelgrass and tasselweed beds by increased epiphyte and benthic algal growth, and increased water turbidity restricting light availability to the plants;

- foxtail stonewort (*Lamprothamnium papulosum*) due to increased competition from green algae and direct effects of increases in phosphate concentrations;

- lagoonal invertebrate and fish populations by increasing the likelihood of harmful anoxic conditions near the sediment surface and in the water column overnight due to increased green algal growth, and by algal blooms in warm conditions either being directly toxic to invertebrates or fish, or by reducing oxygen available to them during post-bloom decay of algal cells.

From a site management point of view, the following combination of points should be noted:

- there is some evidence for an impact on the foxtail stonewort and circumstantial evidence for increases in green and planktonic algae which would have an impact on several conservation interests including seagrass;

- circumstantial evidence suggests that nutrient inputs from anthropogenic sources have increased over time, i.e. the last few decades;

- nutrient budget and distribution studies indicate probable nutrient enrichment, the timing and location of which could cause eutrophication;

- several features of nature conservation importance in the Fleet are sensitive to impacts from nutrient enrichment;

- several features of nature conservation importance in the Fleet are therefore vulnerable to impacts from nutrient enrichment;

- lagoon features which may have been impacted or which could be impacted are of high (international and national) nature conservation interest as reflected in the conservation objectives for the site;

- based on studies elsewhere, a system such as the Fleet may enter a self-perpetuating condition of nutrient enrichment and eutrophication through internal recycling.

Taking these points together, a precautionary approach would suggest that, even though some further work is required, steps should be taken to reduce nutrient inputs to the Fleet that are proportionate to the likely costs of taking no action. Information to date clearly indicates that the priority is for reducing inputs to the western part of the Fleet. Whilst it is likely that phosphorus is of more concern than nitrogen, consideration should be given to reducing both nutrients. Taking account of nutrient sources identified thus far, management measures should address, in priority order, agricultural sources, Abbotsbury sewage treatment works, and the management (especially feeding practice) of the swannery.

The report outlines options for addressing these sources. Reductions in agricultural inputs of nutrients are recommended, involving implementation of Best Management Practices (BMPs) for farms to retain nutrients on the fields and reduce the amounts of nutrients entering the watercourses and the Fleet itself. Further investigation is required into the impact of the Abbotsbury sewage treatment works and best option for addressing this; there should be a presumption against any new discharges to the Abbotsbury embayment. Consideration should be given to reducing feed and faeces inputs to the Fleet from the Abbotsbury swannery and/or investigating the success of measures already being introduced. Use of the Cardiff University physical model of the Fleet is advised, to assist in prioritising which nutrient inputs should be targeted for remedial action.

A prioritised list of further work is recommended. Overall, the emphasis should be on establishing an adequate baseline against which changes can be assessed, including components of the community such as phytoplankton, and completing and refining our understanding of the nutrient budget in order to effectively target management measures.

Section 5 Guidance on investigating and managing water quality in saline lagoons

The final section of the report outlines more general guidance of relevance to other lagoons drawing on the Fleet case study. Although lagoons are a diverse type of habitat, a number of characteristics of the Fleet make it a suitable site from which to extrapolate the findings and experience of the case study to other lagoons. The main limitation to this is the poorer base of information and lack of active management on many other lagoons compared to the Fleet.

Investigation and management of water quality issues at other lagoon sites are likely to require:

- Co-ordinated investigations of features of conservation and biological importance, relevant water quality aspects, hydrological/physical regime, and human activities which may affect any of these, including a collation and review of historical information if required;

- Management strategies co-ordinated by a project group, using baseline information, and reviewed at regular intervals in the light of monitoring studies (the latter involving scaled down aspects of the baseline studies).

The report outlines the approach and methods for each of the lines of investigation, cross-referring to experience from the Fleet. The need to undertake all of these lines of investigation, and the associated resource implications, will partly depend on the sensitivity of the features, the degree to which they are vulnerable and the level of understanding of site specific issues. As such, there is a progression in investigating such issues from identifying whether there is an impact to clarifying the nature of the impact to inform management. All aspects of a relevant lagoon site may need to be extensively studied at the baseline level initially, especially where there is little or no historical information.

Concerning management of sites, a precautionary approach is emphasised because of the potential for impacts, particularly from nutrient enrichment, to become self-sustaining and therefore the chances of effective management measures to diminish. A number of options for addressing different causal activities, i.e. agriculture, point discharges and others such as wildfowl, are outlined. On European marine sites, the management scheme process provides the appropriate means for documenting and co-ordinating such management measures. Recommendations for monitoring, including which biological features and water quality parameters to consider, are described. Monitoring is likely to be required infrequently for hydrographic and physical studies, at more frequent intervals for biological features of importance - the frequency depending on their importance and sensitivity - and will probably be required more frequently for water quality monitoring. The scope of such frequent monitoring, however, should be much reduced compared to the baseline studies.

Suggestions for generic research on water quality and lagoons include:

- the sensitivity of features of conservation importance, e.g. seagrass, tasselweeds and foxtail stonewort. The Fleet would provide a suitable site for relevant autoecological studies;

- the nutrient dynamics of lagoons, including cycling between sediments, water column and biota, and hindcasting;

- hydrodynamic properties of large lagoons.

1. Introduction

1.1 UK Marine SACs Project

These guidelines have been prepared as part of the UK marine SACs (Special Areas of Conservation) Project. The overall aim of this Project is to promote the implementation of the Habitats Directive in marine areas through trialing the establishment of management schemes on twelve sites in the UK and by providing proven good practice and guidance to practitioners in the UK and Europe.

To support the establishment of these management schemes, the Project is undertaking a series of tasks to collate and develop the understanding and knowledge needed. One of the areas for providing guidance to those developing the schemes concerns the interaction between human activities and marine features. Human activities have an important role in the management of marine features and may have both beneficial and damaging impacts. This report is one of seven studies bringing together guidance on these impacts and promoting the means of avoiding significant damage to features. The seven studies concern:

- port and harbour operations;
- recreational user interactions;
- collecting bait and other shoreline animals;
- water quality in coastal areas;
- aggregate extraction;
- fisheries;
- water quality in lagoons - the subject of this report.

1.2 Scope and objectives of the study

From a nature conservation perspective, lagoons are considered to be important physiographic features and, together with lagoon-like habitats, support important biological communities. Lagoons are a rare habitat in the North East Atlantic biogeographic area. This is recognised by their inclusion under the Habitats Directive as a priority Annex I habitat and as a priority habitat under the UK's Biodiversity Action Plan.

Management of lagoons presents a number of issues including maintenance or restoration of the physiographic structure, e.g. physical barrier such as a shingle bar, and the hydrological regime, ie supply of both fresh and saline water inputs. Whilst these issues are not comprehensively understood sufficient is known for them to be addressed (see, for example, Bamber *et al* 1993).

Less well known is the role of the quality of the water entering and within a lagoon system and its effect on the ecology and biota (water quality is unlikely to affect the physiographic interest of the habitat). Although nutrient concentrations can vary naturally with the primary production cycle through the year, semi-enclosed and closed water bodies such as lagoons have low flushing rates and are therefore potentially sensitive to changes in water quality, including in relation to changed use around the periphery of the habitat. There is, therefore, a need to clarify the importance of water quality in the management of lagoon habitats and to provide guidance to site managers as to how the issue can be investigated and addressed.

It is apparent that there have been few site specific studies into water quality in saline lagoons and therefore little material that can be reviewed. The priority therefore was to initiate a demonstration study on a site with a perceived water quality problem, preferably a site with nature conservation interest and some data on which to build. Further to this, the Environment Agency has reviewed sites of recognised nature conservation interest in England to determine those with a perceived or known deterioration in water quality and/or where the EA have undertaken any surveillance or monitoring. The review highlighted two sites, the Fleet and Rye Harbour Lagoon, with the former subject to more detailed study. Whilst Rye Harbour is part of a Special Protection Area the Fleet was a more obvious candidate for the study not only because of the level of previous work but because: (a) it is a SAC (and one of the twelve demonstration sites within the UK Marine SACs Project), (b) there is a long standing, if not universally held perception of a water quality problem associated with nutrients which may be compromising the interests of the site, and (c) the biodiversity of the site is such that it supports a notably wide range of communities and species found in saline lagoons.

The study therefore focussed on investigating the Fleet system, building on previous work, to provide an understanding of water quality issues in the management of the site and to draw lessons from this for other sites.

The objectives of the study were therefore to:

- Determine the current understanding of the nutrient status of the Fleet lagoon, attempt to confirm whether the site is affected (polluted) by excess nutrients, identify sources of nutrients, and recommend management and monitoring options and further work in the light of the study results. The study would also provide baseline information for future monitoring and environmental assessment of any developments around the site.

- Provide generic guidance, derived from the Fleet study, on nutrient-related water quality issues in saline lagoons, covering the potential for impacts, their investigation and management, and subsequent monitoring.

1.3 Audience

The target audience for this document includes:

- managers of saline lagoon sites (in UK and Europe) - to provide a case study and more generic guidelines on how to investigate and manage adverse impacts arising from changes in water quality and particularly nutrients;

- relevant and competent authorities - to inform development of appropriate management measures and assist in carrying out statutory responsibilities on SACs.

1.4 Report structure

The report is structured as follows:

Section 2 - provides background on marine Special Areas of Conservation and on saline lagoons in the UK.

Section 3 - provides an outline of potential water quality issues for saline lagoons based on previous work and experience of those involved with this study

Section 4 - describes the site-based study on the Fleet lagoon including a summary of individual supporting projects which are written up in full detail in separate reports referenced herein.

Section 5 - sets out generic guidance drawing heavily on the lessons learnt from the Fleet case study.

The guidelines provide a source of generic guidance supported and illustrated by a detailed case study. The material has been laid out such that readers can turn to Sections 3 and 5 for generic points without needing to refer to Section 4. However, in Section 5, generic points are illustrated by inclusion of examples from the Fleet case study and cross-reference to relevant parts of Section 4.

2. Background

2.1 Background to European marine sites

2.1.1 Habitats and Birds Directives

In May 1992, the member states of the European Union adopted the 'Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora'. This is more commonly referred to as the Habitats Directive. The main aim of the Directive is to promote the maintenance of biodiversity and, in particular, it requires member states to work together to maintain or restore to favourable conservation status certain rare, threatened, or typical natural habitats and species. These are listed in Annex I and II respectively.

One of the ways in which member states are expected to achieve this aim is through the designation and protection of a series of sites, known as Special Areas of Conservation (SACs).

The Birds Directive (Council Directive 79/409/EEC on the conservation of wild birds) complements the Habitats Directive by requiring member states to protect rare or vulnerable bird species through designating Special Protection Areas (SPA's). Together, the terrestrial and marine SPAs and SACs are intended to form an coherent ecological network of sites of European importance, referred to as Natura 2000.

2.1.2 Habitats Regulations

The requirements of the Habitats Directive have been transposed into UK legislation through the Conservation (Natural Habitats &c.) Regulations 1994 and the Conservation (Natural Habitats &c.) (Northern Ireland) Regulations 1995, known as the Habitats Regulations, and, in England, also by the Conservation (Natural Habitats &c.) (Amendment) (England) Regulations 2000.

Unlike on land where SACs and SPAs are underpinned by Sites of Special Scientific Interest, there is no existing legislative framework for implementing the Habitats Directive in marine areas. Therefore the Regulations have a number of provisions specifically for new responsibilities and measures in relation to marine areas.

The Regulations place a general duty on all statutory authorities exercising legislative powers to perform these in accordance with the Habitats Directive. The term European marine site is defined to mean any SPA and SAC or part of a site that consists of a marine area, and 'marine' includes intertidal areas. The new duties in connection with the management of marine sites are summarised below.

2.1.3 Management schemes

In the UK, management schemes may be established on European marine sites as a key measure in meeting the requirements of the Habitats Directive. Each scheme will be prepared by a group of authorities having statutory powers over the marine area - the relevant authorities. The Regulations set out which authorities have responsibilities for managing these sites and how they are to be managed, as described below:

! Relevant authorities are those who are already involved in some form of relevant marine regulatory function and would therefore be directly involved in the management of a marine site, and may include the following:

  “ country conservation agency;
  “ local authorities;
  “ environment agencies;
  “ sea fishery committees;
  “ port and harbour authorities;
  “ navigation authorities;
  “ lighthouse authority.

! A scheme may be established by one or more of the relevant authorities. It is expected that one will normally take the lead. Once established, all the relevant authorities have an equal responsibility to exercise their functions in accordance with the scheme.

! Each site can have only one management scheme.

Whilst only relevant authorities have the responsibility for establishing a management scheme, government policy (DETR 1998) strongly recommends that other groups including owners and occupiers, users, industry and interest groups be involved in developing the scheme. To achieve this, it suggests the formation of advisory groups and a process for regular consultation during the development and operation of the scheme.

Within the Regulations, the nature conservation bodies have a special duty to advise the other relevant authorities as to the conservation objectives for a site and the operations that may cause deterioration or disturbance to the habitats or species for which it has been designated. This advice forms the basis for developing the management scheme.

The scheme will encourage the wise use of an area without detriment to the environment, based on the principle of sustainability. European marine sites have been selected with many activities already taking place and it is recognised that these are normally compatible with the conservation interest at their current levels. Only those activities that would cause deterioration or disturbance to the features for which a site has been designated need to be subject to restrictions under a management scheme.

The primary focus of a management scheme is to manage operations and activities taking place within a European marine site, promoting its sustainable use. However, it may also provide guidance for the assessment of plans and projects particularly those of a minor or repetitive nature. A plan or project is any operation which requires an application to be made for a specific statutory consent, authorisation, licence or other permission. Not all types of plan or project fall within the statutory functions of relevant authorities, but are consented or authorised by other statutory bodies, termed competent authorities (e.g. central government departments).

2.1.4 UK marine SACs

In the UK, candidate SACs have been selected for ten of the marine features listed in Annex I and Annex II of the Habitats Directive and are shown in Table 2.1. There are presently 42 sites that have been forwarded to the European Commission as candidate SACs (Figure 2.1).

Table 2.1 Annex I habitats and Annex II species in UK candidate marine SACs

Annex I habitat	Annex II species
Estuaries Large shallow inlets and bays Sandbanks which are slightly covered by seawater at all times Mud and sandflats not covered by seawater at low tide Lagoons Submerged or partially submerged sea caves Reefs	Bottlenose dolphin Common seal Grey seal

2.2 Background to saline lagoons in the UK

2.2.1 Definition

Saline lagoons are defined as areas of shallow, coastal saline water, wholly or partially separated from the sea by sandbanks, shingle or, less frequently, rocks (Brown *et al* 1997). Five main sub-types have been identified in the UK, on the basis of their physiography, as meeting the definition of the habitat type, and these sub-types have been used in identifying and designating statutory sites including SACs (Brown *et al* 1997) and SSSIs (JNCC 1996):

i. Isolated lagoons: these are separated completely from the sea by a barrier of rock or sediment. Seawater enters by limited ground water seepage or by over-topping of the sea barrier. Salinity is variable but often low. Isolated lagoons are often transient features with a limited life-span due to natural processes of infilling and coastal erosion. Isolated lagoons may have less water exchange than percolation lagoons and consequently a more impoverished biota.

ii. Percolation lagoons: these are normally separated from the sea by shingle banks. Seawater enters by percolating through the shingle or occasionally by over-topping the bank (e.g. in storms). The water level shows some variation with tidal changes, and salinity may vary. Since percolation lagoons are normally formed by natural processes of sediment transport, they are transient features, which may be eroded and swept away over a period of years or decades or may become infilled by movement of the shingle bank.

iii. Silled lagoons: water in silled lagoons is retained at all states of the tide by a barrier of rock (the 'sill'). There is usually little tidal rise and fall. Seawater input is regular and frequent and although salinity may be seasonally variable, it is usually high, except where the level of the sill is near to high tide level. These lagoons are restricted to the north and west of

Scotland and may occur as sedimentary basins or in bedrock (where they are called ‘obs’). Muddy areas are dominated by filamentous green algae, amongst which may be colonies or rare charophytes, such as foxtail stonewort *Lamprothamnium papulosum*. Beds of tasselweeds, *Ruppia* spp. and, in the deeper, most stable lagoon, eelgrass *Zostera marina* may be present.

iv. Sluiced lagoons: sluiced lagoons develop where the natural movement of water between the lagoon and the sea is modified by human mechanical interference such as the construction of culverts under a road or valved sluices. Communities present in sluiced lagoons vary according to the substrate type and salinity but may resemble those of silled lagoons.

v. Lagoonal inlets: seawater enters lagoonal inlets on each tide and salinity is usually high, particularly at the seaward part of the inlet. Larger examples of this sub-type may have a number of different basins, separated by sills, and demonstrate a complete gradient from full salinity through brackish to fresh water. This salinity gradient significantly increases the habitat and species diversity of the sites in which it occurs.

The water in lagoons can vary in salinity from brackish (due to dilution of seawater by fresh water) to hypersaline (i.e. more salty than sea water as a result of evaporation). Lagoons can contain a variety of substrata but most commonly include soft sediments. The plant and animal communities of lagoons vary according to the physical characteristics and salinity regime of the lagoon, and therefore there are significant differences between sites. Although a limited range of species may be present compared with other marine habitats, many of these species are specifically adapted to conditions of varying salinity and some are found only in lagoonal habitats. The vegetation may include beds of eelgrasses *Zostera* spp., tasselweeds *Ruppia* spp, the alga *Chaetomorpha*, pondweeds *Potamogeton* spp. or stoneworts such as foxtail stonewort *Lamprothamnium papulosum*. In more rocky lagoons, communities of fucoid wracks *Fucus* spp., sugar kelp *Laminaria saccharina* and red and attached green algae are also found. The fauna is often characterised by mysid shrimps and other small crustaceans, worms which burrow into the sediment, prosobranch and gastropod molluscs and some fish species. Species that are particularly found in lagoons and consequently have restricted distributions in the UK include starlet sea anemone *Nematostella vectensis*, lagoon sandworm *Armandia cirrhosa*, lagoon sand shrimp *Gammarus insensibilis* and foxtail stonewort *Lamprothamnium papulosum*. Lagoons may also provide important habitat for waterfowl, marshland birds and seabirds.

2.2.2 Distribution and conservation importance

Lagoons are localised in Europe and on the Atlantic coast have a restricted distribution. They are listed as a priority[1] Annex I habitat in the Habitats Directive. The habitat type is complex, and a wide range of physical types and origins can be included in the broad definition. The habitat is also relatively uncommon in the UK (and consequently is listed as a priority habitat under the UK's Biodiversity Action Plan (UK Biodiversity Group 1999)). However, in the UK there is a range of

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[1] Priority habitats: those considered in danger of disappearance and for the conservation of which the European Community has particular responsibility. Sites submitted for priority habitats to the European Commission are automatically classed as Sites of Community Importance (one step on from being identified as a candidate SAC in the SAC selection and designation process).

geographical and ecological variation in the habitat type, and some of the types of lagoon found in the UK are rare elsewhere in Europe. Therefore, a high proportion of the sites identified as meeting the definition of the habitat type have been selected as Special Areas of Conservation (SACs). Only sites on natural substrata have been selected as SACs. Sites that are entirely artificial in origin, e.g. some docks, have been excluded from the definition, even though, in some cases the communities present may be similar to those of more natural sites. Ten sites (incorporating over 60 individual lagoon sites) have been identified as SACs for lagoons in the UK (see Figure 2.1 and Table 2.2). As a priority habitat there are likely to be numerous lagoon SACs in other EU Member States but no information was available at the time of writing on sites selected.

Table 2.2 Summary of UK lagoon SACs and component individual lagoons. Data for England based on Bamber 1997, for Scotland on Thorpe 1998 and Thorpe *et al* 1998

SAC	Individual lagoon site, type (and size/ha)
North Norfolk coast and Gibralter Point Lagoons	Broadwater (4.5), Holkham Salts Hole (0.5), Abraham's Bosom (1.5), Half Moon (0.1), New Moon (0.1), Seahorse (1.4), Arnold's Marsh (3.4), Salthouse Broad (3.0), Little Eye (0.2), W. Gramborough Hill (0.2), E. Gramborough Hill (0.2). All percolation lagoons.
Benacre to Easton Bavents Lagoons	Percolation: N.W. Denes Pool (2.1), N.E. Denes Pool (0.7), Easton Broad (1.7). Isolated: Benacre Broad (8.0), Covehithe Broad (0.8).
Orfordness to Shingle Street	Aldeburgh P8 (0.3), Shingle Street #p1 (0.5) #p3 (0.3) #p4 (0.5) #p5 (0.0003) #p6 (0.1) #p7 (0.25) and Shingle street Cobb #0 (1.1). All percolation lagoons.
Solent and Isle of Wight Lagoons	Lagoon inlet: Shut Lake (2.3) Sluiced lagoons: Fort Gilkicker Moat (4.3), Normandy Farm (5.0), Eight Acre Pond (3.0), North and South Salterns Lagoons (1.9), Oxey (0.93), Pennington (1.54), Keyhaven (0.62) Isolated lagoons: Farlington Marshes (0.02), Bembridge Harbour Lagoon (3.0), Harbour Farm #1 (3.9) and # 2 (3.7).
Chesil and the Fleet	Lagoonal inlet (with characteristics of percolation type to a small degree) (480)
Loch Roag Lagoons	Tob Valasay (30.0), Loch Shader (7.0). Both silled lagoons.
Obain Loch Euphoirt	Loch Obisary (300.0), Oban nam Fiadh (41.0), Oban Sponish (15.0), Bagh Uaine (2.0). All silled lagoons.
Loch nam Madadh	Sluiced: Loch an Duin (43.0), Alioter lagoon (15.0), Loch an Strumore (60.0), Bagh Ostram (2.0). Silled: Bac-a-stoc lagoon (2.0), Loch Minish lagoon (1.0), Oban nan Stearnan (10.0). Lagoonal inlet: Loch Houram (37.0), Loch na Ciste and Strom Ban (12.0), Leiravay Bay (9.0).
Loch of Stenness	Lagoonal inlet (860.0).
The Vadills	Lagoonal inlet (with basins separated by sills) (61.0)

Figure 2.1 Location of candidate Special Areas of Conservation for marine interests.

3. Guidance on potential water quality impacts in saline lagoons

3.1 Introduction

A range of water quality issues may be of concern in saline lagoons. The most obvious and critical water quality parameter in saline lagoons is salinity. This parameter helps to define the habitat and changes in salinity outside of normal variation for a site (tidally, seasonally) can have significant effects on the characteristics and biota of a site. Whilst it has not been comprehensively studied, sufficient is known about the importance of salinity and the factors which govern it in saline lagoons in the UK to enable management measures to be identified (see Bamber *et al* 1993, Bamber *et al* in prep.). The following section therefore considers other water quality issues of possible concern for lagoons.

In order to determine changes in water quality, and whether these lead to an impact, it is necessary to understand the natural condition of a site. For example, lagoons are naturally rich in organic material. It is evident that lagoons may also exhibit naturally elevated nutrient levels (see, for example, Taylor *et al* 1995) as a result of their low flushing characteristics and nutrient cycling within them, eg between biota and sediments.

However, due particularly to their restricted exchange with the sea and concomitant reduced flushing of dissolved or suspended materials, saline lagoons are potentially sensitive to changes in water quality or inputs of such material. The degree of sensitivity of a site to changes in water quality will be determined by:

- the type of lagoon (i.e. nature of exchange with the sea) and its size;
- communities and species present.

3.2 Sensitivity of different lagoons

Potentially, percolation and isolated lagoons are likely to be most sensitive to changes in water quality because of their very limited water exchange (flushing) with the sea or fresh waters. Silled and sluiced lagoons will be less sensitive, but generally still have very restricted water exchange. Overall, lagoonal inlets may be expected to be the lagoon type least sensitive to changes in freshwater quality or anthropogenic inputs, as seawater enters on each tide. However, inlets are still potentially sensitive, as tidal flushing to some parts of a site is usually poor, and the site as a whole is still sensitive to changes in water quality of marine inputs.

Given that larger sites may be able to withstand or respond more readily to water quality changes, it is worth noting the comparative size of the different lagoon types (see Table 3.1). Average size reinforces the general order of potential sensitivity from isolated and percolation types to lagoonal inlets. Note, however, that there is a large size range for each type. In addition, it is likely to be the case that once an impact does occur on a site it may be more difficult to reverse that change or restore conditions on larger rather than smaller sites.

Table 3.1 **Size of different lagoon types in the UK** (data from Bamber *et al* 1999, Covey 1999, Covey *et al* 1998, Smith and Laffoley 1992, Thorpe 1998 and Thorpe *et al* 1998)

Lagoon type	Number of sites	Average size/ha	Size range/ha
Isolated	48	4.89	<0.1 - 44.0
Percolation	44	2.99	<0.1 - 21.0
Sluiced	132	12.26	<0.1 - 850.0
Silled	54	16.20	0.3 - 300
Inlet	50	45.54	0.1 - 860

Stratification, and factors affecting this, will also influence the response of a lagoon system to various inputs, particularly nutrients. The nature of the isolating barrier can lead to stratification, e.g. sills can favour faster exchange and circulation of surface water at the expense of deeper water. The potential for stratification is greater in relatively deep lagoons, ie more than 2 metres, although transient stratification has been reported at shallower depths (Hodgkin & Birch 1986); deeper sites tend also to be larger sites. In considering factors affecting nutrient retention in estuarine systems, Scott *et al* (1999) noted that sills can play a part in trapping nutrients particularly where the sill is shallower than the photic depth. In such conditions the bottom water nutrients cannot leave the system without first entering the photic zone where nutrients can be utilised by phytoplankton.

Owing to their hydrodynamic properties many lagoons are characterised by finer sediments. Certain introduced contaminants to lagoons, such as phosphorus and organic material, will bind to, or be stored within, fine sediments such as mud more than other substrata such as sand or rock.

3.3 Sensitivity of lagoonal communities and species

Biological features of lagoons, which may potentially be affected by changes in water quality in temperate areas, include:

- eelgrass beds (*Zostera* spp.);
- charophytes;
- other lagoonal aquatic plants (tasselweed, pondweed);
- specialist lagoonal invertebrates;
- fish.

Very little information exists on the sensitivity of such features to changes in water quality, in particular to changes in nutrient levels. For an understanding of the known impacts of specific toxic and non-toxic contaminants in saline waters, the reader is recommended to consult a complementary report produced as part of the UK Marine SACs Project (Cole *et al* 1999). What information could be found relevant to saline lagoons is summarised below.

3.3.1 Eelgrass beds (*Zostera* spp)

Davison and Hughes (1998) conducted a review of information on eelgrass beds, including their sensitivity to a number of water quality factors (see Annex B for summary).

Nutrient enrichment: Whilst in some cases local increases in sediment nutrient content may have favourable consequences for *Zostera* growth (presumably where sediment nutrient content is poor), Davison and Hughes (1998) conclude that nutrient enrichment is more often cited as a major cause of decline, or the lack of recovery, of *Zostera* beds. Five different harmful effects have been identified, which are not mutually exclusive and several or all of them may apply in any given situation:

- high internal nitrate concentrations may cause metabolic imbalance in Zostera;
- *Zostera* may be more susceptible in conditions of nutrient enrichment to infection by wasting disease (*Labrinthula macrocystis*);
- increased growth of epiphytic algae as a result of eutrophication is correlated with seagrass loss;
- increased growth of blanketing or floating algae as a result of eutrophication may cause severe shading of *Zostera*;
- phytoplankton blooms resulting from nutrient enrichment can increase water turbidity, reducing ability of *Zostera* to photosynthesise;

High nitrate concentrations (daily levels of 3.5 and more µM NO_3^- - N) have been implicated in the decline of mature *Zostera marina* (Burkholder *et al* 1992), due, it is suggested, to high internal concentrations causing a metabolic imbalance. *Zostera marina* was found to be more sensitive than *Ruppia maritima*, and the effect was exacerbated by heavy epiphyte growth.

Levels of phenolic compounds were found to be lowered in *Zostera* under conditions of nutrient enrichment, possibly due to a reduction in available carbon within the plant. Phenolic compounds play an important role in providing *Zostera* with defence against infection, including wasting disease. Burkholder *et al* 1992 found that plants from enriched mesocosms succumbed to infection by *Labrinthula macrocystis*, while plants in the control mesocosm remained healthy. 'Wasting disease' is quoted as the single most important naturally occurring cause of *Zostera* decline. It should be noted that *Labyrinthula* (the fungus which causes wasting disease) does not appear to cause disease in conditions of low salinity.

Eelgrass leaves provide a substratum for the growth of many species of epiphytic algae. Data suggest that epiphyte density on seagrasses (and macroalgae) is a key factor in determining the maximum depth at which such plants can successfully grow; Burt *et al* (1995) found that light availability to seagrass plants was reduced by between 2 and more than 80% by epiphyte growth, independent of water depth, with the greatest decrease occurring during the main growing season. Epiphytes may also smother the *Zostera* plants unless kept in check by the grazing activities of gastropods and other invertebrates. Healthy populations of epiphytic grazers are therefore beneficial to the maintenance of *Zostera* beds.

Other studies have correlated seagrass loss with increased growth of blanketing or floating, as well as epiphytic algae, often as a result of nutrient enrichment (see Davison and Hughes 1998). Blanketing algae such as *Enteromorpha*, *Ectocarpus confervoides* and *Ceramium rubrum* may cause severe shading of *Zostera*.

Turbidity: Highly turbid water inhibits *Zostera* growth by reducing the amount of light available for photosynthesis. Phytoplankton blooms, resulting from nutrient enrichment, can increase turbidity and have been shown to reduce the biomass production and the depths to which *Zostera marina* can grow (Dennison, 1987).

Non-toxic contamination other than nutrient enrichment: The effects of other water quality parameters are less researched. It appears that *Zostera* can tolerate sea surface temperatures ranging from about 5 to 30EC, with an optimum growth and germination range of 10 to 15EC (Yonge, 1949 in Davison and Hughes 1998). High temperatures (above 15EC) appear to be required for flowering and germination of seeds of *Zostera marina* (Davison and Hughes 1998). Subtidal populations of *Zostera marina* which are not subject to lowered salinity produce no or few reproductive shoots (Giesen *et al* 1990), with laboratory studies indicating that maximum germination of *Zostera marina* occurs at 1 ppt salinity. However, other field studies indicate that germination in *Zostera marina* occurs over a wide range of salinities and temperatures (Churchill 1983 and Hootsmans *et al* 1987). In extreme winter conditions, the formation of ice amongst the sediments of exposed intertidal (and shallow subtidal) eelgrass beds can lead to the erosion of surface sediments and the uprooting of rhizomes, as well as direct frost damage to the plant. Plants may be killed or defoliated by severe frosts.

Toxic contamination: Contamination of coastal waters by heavy metals or antifoulants has not been shown to significantly affect *Zostera* plants, but agricultural herbicides are known to be harmful. Eelgrass beds do not appear to be highly sensitive to chronic oil pollution, but major oil spills can inhibit growth of plants (Davison and Hughes 1998). In both cases, the associated fauna and flora seem to suffer more damage than the eelgrass itself, in particular where dispersants are also used, which may have repercussions on the *Zostera* later, owing to reductions in populations of epiphytic grazers and consequent shading of the *Zostera*.

Heavy metals (mercury, nickel and lead) and a number of organic substances (napthalene, pentachlorophenol, Aldicarb and Kepone) have been found to reduce nitrogen fixation in *Zostera* roots, which may affect *Zostera* viability. *Zostera marina* was found to accumulate Tributyl Tin (TBT), but other studies found that TBT had not caused any observable damage to *Zostera* plants in the field (Davison and Hughes 1998).

Research on the triazine herbicide Irgarol, used in antifouling paints, on *Zostera marina* showed that this herbicide is present in the roots and shoots. Triazine herbicides are specific inhibitors of photosynthesis and sublethal effects have been detected (P. Donkin, pers. comm. in Davison and Hughes 1998). The terrestrial herbicide Atrazine has been implicated in declines of *Zostera marina* in Chesapeake Bay. In another study, exposure to 100 ng/l of this herbicide over 21 days resulted in growth inhibition and 50% mortality of *Zostera marina* (Delistraty and Hershner 1984).

The effects of pesticides on seagrass plants have also been found to be an important cause of their decline in southern England (Asmus & Asmus 1999).

3.3.2 Charophytes

Of the 33 charophyte species recorded from the UK and Ireland, 4 (*Chara baltica*, *Chara canescens*, *Lamprothamnium papulosum*, and *Tolypella nidifica*) have a strong affinity for brackish water habitats (Stewart and Church 1992). All four species are considered rare and threatened (UKBG 1999).

The most frequently recorded species in saline lagoons is the foxtail stonewort (*Lamprothamnium papulosum*) and it is considered a lagoonal specialist. It usually grows on sand, gravel or pebbles in less than 2 metres water depth, and is intolerant of strong water currents or wave action. Previous British and Irish work indicates that *Lamprothamnium papulosum* occurs within a salinity range of 10 ppt to 30 ppt, but studies elsewhere have found viable populations in up to 40 ppt whilst recent work in Britain has found the species in sites as low as 5 ppt (Martin 1999). It is often found where there is some disturbance from birds or animals, or in shallow water where fluctuations of water level result in more open vegetation (UK Biodiversity Group 1999). It usually occurs with tasselweed *Ruppia* spp., but does not compete well with dense vascular plant growth (Li 1997). It is a summer annual, germinating in spring, with oospores produced between July and September.

Charophytes such as *Lamprothamnium papulosum* are associated with clean, unpolluted water because most species cannot tolerate high levels of phosphates and nitrates (Bingham 1997), probably due to their inability to successfully compete with dense growths of filamentous algae such as *Cladophora* spp. Nutrient enrichment has been implicated in the decline of brackish charophyte species (Martin 1999). In Denmark, Sweden and Norway, *Lamprothamnium papulosum* populations have been severely reduced, with anthropogenic induced eutrophication and consequent competition for light and space suggested as the probable cause (Blindow and Langangen 1995, in Martin 1999) similar evidence has been found in the Netherlands (Coops and Doef 1996, in Martin 1999).

More recent research has found *Lamprothamnium papulosum* to be absent where soluble reactive phosphate (SRP) levels exceed 30 µg/l in the water column and total phosphates (TP) are about 100 µg/l (Martin 1999). These maximum values both come from the Fleet (at Herbury). Based on survey of 40 potential and known sites, *Lamprothamnium papulosum* most frequently occurs at sites with SRP of less than 10 µg/l and TP less than 50 µg/l (Martin 1999).

3.3.3 Other flowering aquatic plants (*Ruppia* spp *Potamogeton* spp)

Hodgkin and Birch (1986) note loss or reduced growth of *Ruppia* beds as a result of phytoplankton blooms and smothering by algae and epiphytes triggered by nutrient enrichment. Other references to the sensitivity of tasselweed to changes in water quality are contained within Davison and Hughes (1998) who report that *Ruppia* species appear to be less sensitive to metabolic imbalance caused by internal high nitrate concentrations than eelgrass (*Zostera*) species. Sheader & Sheader (1999) reiterate that *Ruppia* spp. require good light conditions and are therefore usually marginal in deeper lagoons, occurring as beds in up to about 0.5 m water depth.

Salinity tolerance is not well documented, but in England, dense beds of *Ruppia* spp. occur where seasonal salinity ranges from 10-40 psu (Sheader & Sheader 1999).

No information was found on the sensitivity of *Potamogeton* spp to changes in water quality in the Fleet Study Group archive or other references consulted as part of this project. However, a literature search was not conducted, and it is likely that information does exist, but relates to freshwater (rather than brackish) situations.

3.3.4 Lagoonal invertebrates

A range of invertebrates are found within saline lagoons in the UK including a number that are specialised to the habitat. Of these specialist lagoonal invertebrates, the small amount of information found on potential sensitivity to changes in water quality of concerns the starlet sea anemone *Nematostella vectensis*.

The starlet sea anemone *Nematostella vectensis* is a small edwardsiid anemone found in sheltered brackish habitats on the Atlantic and Pacific coasts of North America and on the south and east coasts of England. It is plentiful throughout its range in North America, but is considered vulnerable to extinction through habitat loss in England, where its distribution is restricted to brackish and saline ponds or lagoons. At present there is insufficient data to permit informed management of populations of the species and its habitat. It is found in shallow waters on fine sands and muddy sediments with shingle, where the mud has a high organic content. It occurs in shallow brackish waters, with low near-bottom flow rates, and where freshwater inputs are relatively low and regular seawater inflows occur. It is tolerant of conditions where the sediment surface may become anoxic, but where water column oxygen concentration remains high, as it can climb onto macrophytes (such as *Chaetomorpha* and *Ruppia* spp.) into oxygenated water. Salinity at the sites in England where it is found varies from 2-42 ppt, with the largest populations found where salinity varies between 16-36 ppt. *Nematostella vectensis* is eurythermal (-1EC to 28EC). It feeds on juvenile molluscs (*Hydrobia* and *Littorina*) and chironomid larvae, as well as ostracods and copepods. Populations at sites studied on the south coast of England reach their highest densities at the end of the year, falling in late winter back to previous spring/summer levels of abundance. These populations have been found to consist entirely of females reproducing asexually (Sheader *et al* 1997). No information is available on effects of nutrients on *Nematostella vectensis*.

No information was found concerning the sensitivity to changes in water quality of other specialist lagoonal species such as the polychaete *Armandia cirrhosa* or the amphipod *Gammarus insensibilis*. There is also a paucity of studies from saline lagoons of impacts on other invertebrates. However, a number of invertebrate species found in lagoons either occur in estuaries (or indeed are more characteristically estuarine), e.g. the surface feeding spionid worm *Streblospio shrubsolii,* or form species pairs with estuarine species, e.g. lagoonal cockle *Cardium glaucum* (*cf* the closely related common cockle *Cardium edule*). Observations from estuaries therefore provide an indication of likely effects within saline lagoons. For example, Scott *et al* (1999) provide an overview of impacts on benthic communities from nutrient enrichment (and/or organic enrichment as the effects of the two are often difficult to separate). Invertebrates are impacted by elevated nutrients particularly through oxygen depletion in the water column and sediments as a result of excessive benthic and planktonic algal growth and decay. Invertebrates may also be impacted by smothering of the sediment by macroalgal mats, as observed in the Ythan estuary where both

Corophium and *Cardium* were affected (Raffaelli *et al* 1989). Different taxonomic groups appear to exhibit different sensitivity to hypoxia, ie in order of increasing sensitivity from polycheates to molluscs/bivalves to echinoderms and crustaceans (Scott *et al* 1999).

Studies on the sensitivity of seagrass *Zostera* to oil pollution referred to above (see Davison and Hughes 1998) highlighted that the associated fauna, including epiphytic grazers, seem to suffer more damage than the eelgrass itself.

3.3.5 Fish

A literature search on the sensitivity of fish to changes in water quality has not been carried out. Lagoons with good tidal exchange (such as parts of the Fleet) are known to be important in particular as nursery areas for juvenile marine fish. The one example of impacts on fish in lagoons due to changes in water quality was disappearance of fish and crabs from areas in an estuarine lagoonal system in Western Australia where water became deoxygenated as a result of dense blooms of a blue-green phytoplankton species in response to nutrient enrichment (Hodgkin and Birch 1982, 1986). Information from estuarine systems indicates that fish are likely to be impacted by depletion in oxygen, either directly or indirectly through effects on their prey species, including as a result of nutrient enrichment (see Section 3.3.4 above and Scott *et al* 1999) and by toxic planktonic algal blooms.

Other features of interest which may be found in some lagoons, such as the rich and interesting invertebrate communities of tidal rapids and narrows, are not specifically lagoonal, although the species making up such communities in areas of reduced salinity may differ from those in fully marine areas. A full literature search for information regarding the sensitivity of such communities has not been carried out, but it is likely that such a search would not identify specific information on the sensitivity of such species to changes in water quality.

3.4 Summary of water quality issues

The following sections summarise water quality issues of concern for lagoons (other than salinity) in priority order. Note that there is more information on nutrient enrichment than other water quality issues.

3.4.1 Nutrient enrichment

Scott *et al* (1999) provide a useful overview of nutrients and related impacts in estuaries, much of which is relevant to lagoons.

It is evident that lagoons can be naturally rich in nutrients. In a review of lagoons (albeit of a wider definition than in the UK) from Europe and the Americas, it was found, in common with other near-shore brackish environments, that there is a summer phosphate maximum in contrast to the open sea (Nixon 1982).

There is some debate as to which nutrient is limiting in coastal waters (Taylor *et al* 1995, Cole *et al* 1999). Taylor *et al* (1995) undertook mesocosm experiments which indicated that the issue of nutrient limitation of lagoons is complex. Whilst their results suggested nitrogen limitation in coastal lagoons of the northeast United States, this depended on whether the entire lagoon system or plant communities within it were under consideration. They further concluded that lagoons will pass through successive shifts in limitation, ie a shift to phosphorus limitation following enrichment by nitrogen, and a concomitant shift in limitations on particular components of the system, i.e eelgrass and macroalgae shifting from nutrient to light limitation. Work in the Fleet reported herein did not indicate that either nitrogen or phosphorus was more limiting throughout most of the lagoon and that both may be limiting at different times of the year. It is apparent therefore that either nitrogen or phosphorus, or both nutrients, could be limiting in lagoons, depending on characteristics of the site, and that this may vary spatially, particularly in sites with a pronounced environmental gradient, or seasonally.

For the same reasons that they are naturally rich in nutrients, i.e. their restricted exchange with the sea and concomitant reduced flushing of dissolved or suspended materials, saline lagoons are also sensitive to nutrient enrichment. The fact that many lagoons may be naturally nutrient rich, even if only seasonally, may mean that relatively low additional inputs of nutrients could cause symptoms of eutrophication[2]. There are a number of potential sources of inputs of dissolved and suspended materials including freshwater and seawater inflows, groundwater, adjacent land by runoff, and even airborne sources, as well as from direct anthropogenic sources.

A number of effects may result from nutrient enrichment in lagoons including:

- direct physiological or metabolic effects as evident in charophytes in particular (in relation to phosphorus) but also in seagrass *Zostera* (at high concentrations of nitrates) with apparent lower sensitivity in tasselweed *Ruppia*;

- increased growth of epiphytic algae, particularly on seagrass and macroalgae, and associated competition for light. The importance of this relationship cannot be overstressed in terms of the effects of nutrient enrichment, since one of the classic symptoms of eutrophication in marine and freshwater ecosystems is a large increase in epiphyte standing crop (Parr *et al* 1998);

- increased growth of blanketing or floating algae, e.g. *Cladophora* spp, and reduced light to lagoonal vegetation including charophytes, seagrass, tasselweeds and macroalgae;

- increased growth of ephemeral benthic algae and associated competition for light and space with other lagoonal vegetation;

- increased phytoplankton standing crop with various effects:

    - in particular an increase in light attenuation and associated direct effects on lagoonal vegetation;

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[2] Defined by the Environment Agency (1998) as " the enrichment of waters by inorganic plant nutrients, which results in the stimulation of an array of symptomatic changes. These include the increased production of algae and/or other aquatic plants, affecting the quality of the water and disturbing the balance of organisms present within it. Such changes may be undesirable and interfere with water use.".

- effects on populations of invertebrates dependant on lagoonal vegetation. Bamber (1997) found distinct bias in types of lagoonal invertebrate communities present at different sites, in relation to the presence or absence of vegetation;

- lagoonal fauna, in common with other marine or freshwater fauna, are likely to be susceptible to the effects of harmful phytoplankton blooms. Fish in particular are susceptible to toxins produced by some phytoplankton, and to clogging of the gills when plankton are particularly dense in the water column;

- fish and benthic fauna and flora may be susceptible to reductions in oxygen content of the water when phytoplankton blooms or excessive algal growth decay.

> Hodgkin and Birch (1982) provide a good example of the complexity of the relationship between lagoons and nutrient inputs and the vulnerability of coastal lagoons to eutrophication in a study of two shallow (2 metre) coastal lagoons (essentially an enclosed estuarine lagoonal system) in Western Australia. In that case, excessive growth and accumulation of benthic green algae (principally *Cladophora* species) and dense phytoplankton blooms occurred, causing various impacts including loss of seagrass. The increase in algal and phytoplankton productivity was attributed to a great increase in the input of nutrients, especially of phosphorus, as a result of the enhanced use of phosphorus based fertilisers in the agricultural catchment. High freshwater drainage inputs during winter caused the influx and small tidal range and, therefore, water exchange with the adjacent sea was limited. Whilst low temperatures and light conditions limited benthic algal growth during winter, the nutrients were retained in the system by diatom blooms and recycled to detrital sediment to become available to benthic algae and phytoplankton in summer. At that time the most promising approach for addressing the problem was to decrease phosphorus inputs by modifying fertilizer practice. In order to effect a solution in an acceptable time frame, a more radical management measure was suggested, i.e. opening a new connection with the sea to increase tidal exchange (Hodgkin & Birch 1986), and subsequently implemented (Hodgkin & Hamilton 1993).

3.4.2 Turbidity

Increased turbidity may be perceived as a potential problem for lagoon sites due to:

- direct increase in light attenuation, affecting photosynthesis by eelgrasses and tasselweeds, as well as macroalgae;

- possible smothering or inhibition of feeding of fragile specialist lagoonal species (such as the starlet anemone *Nematostella vectensis*) by suspended inorganic matter settling out of the water column.

Turbidity may be caused by biotic growth (plankton) in the water column, or due to presence of suspended particles.

In some areas, e.g. peat areas in the catchment of some sites in Scotland, water colour will be a factor influencing light penetration and, therefore, photosynthesis of plants and algae. Whilst the vegetation at lagoon sites within these areas will be adapted to such conditions, consideration should be given to any factors that may change water colour and affect light penetration, e.g. increased peat erosion.

3.4.3 Toxic contamination

No examples were found of saline lagoons being affected by toxic contamination, whether by non-synthetics such as hydrocarbons or synthetics such as pesticides. However, such systems are potentially highly sensitive to such inputs given their poor to moderately poor flushing characteristics, and those adjacent to urban or industrial development are potentially most vulnerable. Studies from outside lagoons suggest the following toxic contaminants may be of concern:

- heavy metals and organic substances affecting physiology of seagrass *Zostera;*
- herbicides and pesticides inhibiting growth and causing decline of seagrass *Zostera*;
- chronic oil pollution and associated dispersant use affecting fauna, particularly epiphytic grazers.

3.4.4 Organic enrichment

Organic enrichment may be of less concern given that lagoonal sediments are naturally high in organic material. However, elevated organic inputs might be of concern in some cases because of low flushing rates in particular lagoons or parts of lagoons.

3.4.5 Recovery from impact

The characteristics of many lagoons (eg low flushing (or high retention times), fine sediments, stratification, species restricted to lagoons), suggest that once affected or impacted by inputs of contaminants, they may be slow to become clear of contaminants or to recover from associated impacts.

The few studies focussed on lagoons highlight that impacts as a result of changes in water quality can continue for some time or become self-perpetuating. Hodgkin and Birch (1982, 1986), for example, note complaints of excessive growth and accumulation of green algae from as early as the late 1960's. They describe a clear case of both recycling of nutrients from phyoplankton to benthic algae and a significant contribution from sediment stored phosphorus to growth of the main nuisance benthic algae. Furthermore, phytoplankton blooms had become progressively worse since the first major bloom without any corresponding increase in nutrient input. In terms of a management response, studies showed that even if the main source of inputs was removed (considered impractical anyway) the system would continue in a eutrophic state for 15 years (Hodgkin and Birch 1986). A management regime of harvesting excessive macroalgal growth was too late to address anything other than part of the symptoms and instead more radical and expensive management measures had to be considered (Hodgkin and Birch 1986).

In relation to nutrients, in particular, observations from estuarine systems are pertinent to lagoons. Scott *et al* (1999) note that a major concern with respect to the recovery of estuarine communities is that many of the responses to nutrient enrichment have been found to be self-perpetuating, i.e.

once they begin to occur they create conditions which further create deterioration. Thus once threshold levels of impact are reached, relevant processes and associated detrimental impacts will continue without necessarily any further increase in nutrient inputs. Taylor *et al* (1998) provide an overview of these issues and discuss results from two "eutrophic" estuarine case studies. In freshwater systems analogous to saline lagoons, internal cycling of nutrients, particularly phosphorus, may mean that accumulation within bed sediments can contribute to nutrient status of a lagoon after inputs have been reduced (see Moss *et al* 1986) and thus delay recovery from any impact once it has occurred. Mainstone *et al* 2000 discuss this phenomenon in rivers.

In lagoons the low flushing time means that internal processes (biological and geochemical) will have a significant effect. Biological processes will include increased phytoplankton growth in response to nutrient inputs, subsequent death and retention of the resulting organic particulate matter and retention of nutrients arising from breakdown of this organic material. Particulate nitrogen in the form of detritus, for example, from benthic and floating macrophytes that respond opportunistically to nutrient enrichment, is also likely to contribute to the internal source of nutrients for subsequent uptake by algae. Other examples of processes that contribute to a self-perpetuating state include reduction in benthic-pelagic coupling, changes to benthic food webs and the uncoupling of nitrification/dentrification (see Scott *et al* (1999) for estuarine case studies and references).

As a consequence of the few case studies of lagoons, and observations in similar systems to lagoons in conjunction with the characteristics of lagoons, it is concluded that many, if not most, saline lagoons would have a low recovery potential from water quality impacts, and particularly from eutrophication impacts, within accepted management and planning time frames. This highlights the need to identify water quality impacts within lagoons as early as possible and suggests the need for a precautionary approach to interpreting and acting on information that may indicate an impact.

4. Case Study - The Fleet

4.1 Background and objectives to case study

Concern has been expressed that the Fleet may be subject to eutrophication (see relevant references in Annex D for example). It is not known to what extent the extensive growth of benthic green algae that characterise the western basin of the lagoon in early summer may be due to direct or diffuse anthropogenic inputs, nor whether the planktonic algal blooms which have occurred have been due to natural events or to anthropogenic inputs. The difficulty is that some lagoons are naturally rich in nutrients, and a high green algal biomass and plankton blooms can typify unpolluted lagoons. However, as discussed in Section 3, research undertaken in other systems with seagrass beds has shown that nutrient enrichment can tilt the balance in favour of benthic, epiphytic and planktonic algal growth at the expense of the seagrass beds. This does not appear explicitly to have happened in the Fleet to date. However, due to the poor flushing and high retention times within the lagoonal basin, there is concern that even small additional inputs of nutrients could have deleterious effects, and that these effects may become self sustaining due to nutrient cycling within the lagoon system. This is reflected in statutory advice for the Chesil and the Fleet European marine site (English Nature 1999) which identifies nutrient enrichment as an operation which may cause deterioration of natural habitats or the habitats of species, or disturbance of species, for which the site has been designated[3].

In order to determine the nutrient status of the Fleet and potential related impacts on the conservation interests of the lagoon, and to inform management of the site, a number of specific studies have been undertaken. These studies were undertaken through both LIFE-Nature funding and contributions from the Environment Agency, Cardiff University and English Nature. The studies, which are summarised in the following sections of this report, are:

- review of historical information on the Fleet from the Fleet Study Group archive to collate any historical data on water quality, trends in water quality parameters and related changes in biota;

- investigations into the current and recent water quality status of the Fleet and its inputs, including data to support nutrient budget modelling (Environment Agency 1998a, 1998b; Mainstone and Parr 1999);

- modelling of tidal currents, salinity and solute distribution to determine the flushing characteristics of the Fleet and assist prediction of the fate of nutrient inputs (Westwater, Falconer and Lin 1999);

- modelling of nutrient budget of the Fleet and its inputs to assist in identifying causal factors and in determining priorities for future management of the site (Murdoch 1999).

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3 Advice on such operations has been developed using a three step process involving i) an assessment of the sensitivity of the interest features or their component sub-features, ii) an assessment of the exposure of each interest feature or their sub-features to operations, and iii) a final assessment of the current vulnerability of interest features or their component sub-features.

4.2 Introduction to the Fleet

4.2.1 General features

The Fleet lagoon (see Figure 4.1) lies between Chesil Beach, a large shingle barrier, and the impounded mainland Dorset shore, just west of Weymouth and the Isle of Portland. It is a natural lagoonal inlet with features of a percolation lagoon (see Section 2.2). The channel at Smallmouth connects the lagoon with Portland Harbour and the sea. The English Channel in this area is microtidal, with a tidal range of only approximately 1.5 m at spring tides. The Fleet has been described as the finest example of a lagoon of its type within the British Isles (Barnes, 1989), and is also one of the largest (480 ha) and best studied – hence its inclusion here as the case study. It is largely natural, with a predominantly rural catchment and adjacent shoreline, partly because the lagoon bed and the majority of the shore has been owned and managed privately by the Ilchester Estate for over 400 years.

The Fleet lagoon has evolved over the last 5000 years by impoundment of marine waters behind the shingle storm ridge of Chesil Beach. Originally, the lagoon was probably longer and wider than it is today. Its shape reflects the irregularities of the impounded mainland shore, with the broadest reaches (approx. 900 m wide) at Littlesea, and the shingle beach almost in contact with the mainland shore at the Narrows (minimum 65 m wide), where strong tidal currents erode back the shingle beach and prevent closure of the lagoon from the sea (Dyrynda 1997).

The shape and tidal regime of the Fleet result in two ecologically distinct zones within the lagoon (see Figure 4.2):

- the narrow inlet channel, with strong tidal currents, mostly fully marine salinity, good flushing characteristics and coarse sediments; and

- the lagoonal basin, with much weaker currents, lower and more variable salinity, considerably reduced seawater flushing and fine sediments (Dyrynda 1997).

4.2.2 Habitat, communities and species

The inlet channel extends from Smallmouth to the head of the Narrows. Tidal rapids are accompanied by coarse sediments and boulders, with slacker currents and finer sediments within the intervening section. The coarser sections of the channel bed support unusual and diverse assemblages of algae and sedentary invertebrates, particularly within the Narrows. A variety of unusual species are common here (eg the red alga *Gracilaria bursa-pastoris* and the sponge *Suberites massa*). Two southern species present in exceptional abundance are the snakelocks anemone *Anemonia viridis* which occurs in vast numbers on shingle and cobbles, and the sea squirt *Phallusia mamillata* which is abundant on stable bedrock and man-made structures. The southern black faced blenny *Tripterygion delaisi* occurs both at Ferrybridge and in the Narrows alongside a profusion of other small fish and crustaceans. Tracts of fine sand and mud are uncovered at low tide between Smallmouth and the Narrows. These sediment flats are not colonised by seagrasses, but resemble low-energy estuarine flats, with an abundance of the lugworm *Arenicola marina* and with algal mats in summer. Rarities found within this area include the specialist lagoonal polychaete worm *Armandia cirrhosa* (Dyrynda 1997).

Figure 4.1 Fleet lagoon - Location map including EA sampling points and known discharges

Figure 4.2 Ecological divisions within the Fleet lagoon (from Dyrynda 1997)

Upstream of the Narrows the lagoonal basin is divisible into three sections according to physical and biological factors (see Figure 4.2):

- Littlesea is the broadest and outermost section of the lagoonal basin, and is a transitional zone. Extensive platforms of seagrass-stabilised mud are dissected by relatively deep and steep-sided subtidal channels within which tidal currents are typically strong. Coarser sediments occur at the downstream end of Littlesea towards the Narrows. Towards the upstream end of Littlesea a declining tidal influence is reflected in the attenuation and ultimate phasing out of the low water channels and a transition to soft mud (Dyrynda 1997).

- Upstream of Littlesea from Moonfleet to Clouds Hill (west of Rodden Hive) the bed of the lagoon is level and shallow and dominated by deep soft organic muds mainly colonised by subtidal seagrass meadows. The shores in this section of the lagoon are very narrow due to much reduced tidal range. Moving westwards through the middle lagoonal basin seagrass *Zostera marina* is increasingly replaced by tasselweed *Ruppia cirrhosa*. *Zostera noltii* and *Ruppia maritima* occur in many parts of the lagoonal basin, and in some areas (eg close to Langton Hive Point) all four species occur together. *Zostera angustifolia* has been recorded in the Fleet as a separate species in the past, but it is now generally regarded as a narrow leaved form of the species *Zostera marina* (Davison and Hughes 1998). The rare foxtail stonewort *Lamprothamnium papulosum* is common towards the mainland shores of the lagoon (Dyrynda 1997).

- The Abbotsbury embayment forms the blind head of the lagoon, which is significantly different from the main sections of the lagoonal basin. The embayment is floored by soft organic mud, but the seagrass stands are thin and patchy. The green alga *Chaetomorpha linum* is common and in summer can be accompanied by tracts of the green sea lettuce *Ulva lactuca*. Much of the Abbotsbury embayment is permanently submerged, but the mud beds are partly exposed on rare occasions (Dyrynda 1997). *Phragmites* marsh is extensive along the mainland shore (where the Abbotsbury Swannery is located).

The coverage of vegetation on the bed of the lagoon is strongly seasonal. Seagrasses grow from late spring to autumn, accompanied by swards of green algae through to mid summer. During autumn, winter and early spring much of the lagoon bed features bare mud and plant debris (Dyrynda 1997).

A variety of lagoonal invertebrates, including some rarities, occurs within the lagoonal basin. Recent work indicates that some invertebrates are zoned in abundance both along and across the lagoon. In all areas a near-shore gradation of decreasing vegetation cover and invertebrate numbers was identified. The permanently submerged central areas supported the highest densities of vegetation and invertebrates. The fauna was found to be a mixture of both common and rare lagoonal specialists, and brackish species also found in estuaries. Well known lagoonal specialists that are widespread include the lagoonal cockle *Cerastoderma glaucum*, the crustacean *Idotea chelipes* and the gastropod molluscs *Hydrobia ventrosa*, *Rissoa membranacea* and *Littorina saxatilis*. A dwarf variety of the nudibranch mollusc *Akera bullata* (var. *nana*) is also common. Most of the common species were found to peak within specific areas of the lagoonal basin. Other lagoonal specialists were much more localised, e.g. the starlet anemone *Nematostella vectensis* and the crustacean *Gammarus insensibilis*, both of which were found to be centred within the upper, more brackish reaches of the basin adjacent to Clouds Hill. Generalist brackish species which are abundant in the Fleet, but which also occur within estuaries, include the polychaete worm *Scoloplos armiger* and the nemertine *Lineus viridis* (Dyrynda 1997).

The seagrass meadows are in summer frequented by adult grey mullet and eels, juvenile bass and by non-economic species such as sand smelt, 3-spined sticklebacks, deep-snouted pipefish and mud gobies (Dyrynda 1997).

Plankton communities are a little understood element of the lagoon system. The water is characteristically clear from spring to autumn, but is temporarily discoloured by intense green blooms in spring, and by short lived but often intense red/brown dinoflagellate blooms within the Abbotsbury embayment in summer. Little is known of zooplankton communities within the lagoon, except that mysids are very common and are likely to feature in the diet of many small fish such as juvenile bass and pipefish (Dyrynda 1997).

A variety of waterfowl and other aquatic birds feed upon vegetation, invertebrates and fish within the lagoonal basin. The most conspicuous herbivorous bird is the mute swan. A unique herd has been farmed at Abbotsbury Swannery since the 1300s. The birds nest within the Abbotsbury embayment in spring and early summer and otherwise forage along the length of the lagoonal basin consuming seagrasses or algae according to seasonal availability. Other common herbivorous grazers include wigeon, pochard, brent geese and coot, all of which are winter visitors. All of these birds feed on both seagrasses and green algae, depending on seasonal availability. In summer little terns (from the breeding colony on Chesil Beach) can be seen diving for small fish, and other common fish eaters include cormorants and mergansers (Dyrynda 1997).

4.2.3 Conservation objectives

Statutory advice on the Chesil and the Fleet European marine site includes a conservation objective for the lagoon feature (English Nature 1999). The role of conservation objectives is to set out what needs to be achieved to deliver the aims of the Habitats Directive in relation to the site. As such, they are the starting point from which a management scheme and a monitoring programme for the site are to be developed as they provide the basis for determining what is likely to cause a significant effect. The conservation objective for the lagoon feature is:

> "Subject to natural change, maintain the lagoon in favourable condition, in particular:
>
> - Seagrass bed communities
> - Tide-swept communities
> - Subtidal coarse sediment (gravel, cobble, pebble) communities
> - Intertidal sediment communities
> - Shingle spring line communities"

Details of how to recognise favourable condition are provided in Annex C.

4.3 Review of historical data and interpretation

The Fleet Study Group (FSG) was established in 1975 in recognition of the view that management and protection of the Fleet lagoon and Chesil Bank could best be achieved from a well informed position. The FSG has a diverse membership of academic and scientific practitioners, land managers and others. Its aim is to encourage research into all aspects of the Fleet (and more recently Portland Harbour), although until recently the emphasis has been towards biological, natural history, palaeoenvironmental and physiographical studies.

An accessible archive of work carried out by members of the Fleet Study Group and others is held at Weymouth College Library, Dorset. It includes over 250 reports, journal articles, letters, and other items of relevance to all types of studies on the Fleet from 1933 to present. The archive has been reviewed as part of the current project in order to extract any relevant information on current or past water quality, particularly in relation to nutrients. Other current and recent studies have also been reviewed as part of the project. A summary of the archive information in relation to understanding past and present water quality of the Fleet is presented here.

Information in the FSG archive concerns primarily the biological and historical interest of the Fleet. Few references contain any information on water quality, and those which do have very limited data relating to spot samples of a few sites, and none have reliable data on nutrients. There have been no comprehensive surveys of water quality in the Fleet prior to the Environment Agency investigations from 1996 onwards (see following report sections). Limited data on nutrient content of sewage effluent inputs to the Fleet exists from 1990 to present. It has, therefore, not been possible to identify the past nutrient status of the Fleet, nor to identify any reliable indicators of an increase or decrease in nutrient levels with time, due to lack of data. Data exist for temperature and salinity in the Fleet where measurements were made at the same time as biological studies. Review of other recent reports supplied by English Nature (several still in early draft form) which are not yet in the FSG archive has also been carried out, including the thesis (John, 1995) from which the following information on phytoplankton and nutrients was extracted. A list of references from the FSG archive which might have had information of relevance to water quality have been reviewed, and are listed and summarised in Annex D.

John (1995) measured salinity and temperature, and took samples for analysis for nutrients and plant pigments, together with enumeration of plankton species. Samples were taken during July-August 1995 from eight sites along the length of the Fleet. Two algal blooms occurred at Abbotsbury during the sampling period, the first at the end of July composed of the dinoflagellate *Oxyrrhis* sp., the second towards the end of August of the dinoflagellate *Glenodinium foliaceum*, which caused red colouration of the water. Elevated numbers of *Oxyrrhis* sp. were observed in samples from further eastwards to Moonfleet and Chickerell on days following the first bloom. The second bloom occurred on the last day of sampling at Abbotsbury, with high numbers of *Glenodinium foliaceum* also detected in the Clouds Hill sample. Lower numbers of *Glenodinium foliaceum* were recorded from samples taken eastwards in the Fleet as far as Chickerell Hive Point. Neither of these two dinoflagellates were detected in samples from the Narrows or further eastwards on any sampling occasion, and neither are known to be toxic or produce toxins which might harm fish or animals.

Measurements of plant pigments (including chlorophyll a) in the samples reflected the concentrations of phytoplankton found in the samples, with the exception of the bloom of *Oxyrrhis* sp., as this organism is not pigmented. On the day of the second bloom, a tributary entering the Fleet at Abbotsbury Swannery (referred to as Mill Stream (Abbey Barn) for EA sampling) was also sampled, and found to contain high numbers of single celled blue green algae.

Measurements of nutrient content of the water column indicated generally average concentrations for brackish waters of nitrate, phosphate and ammonium along the Fleet, ranging from 0-10 µM. However, peaks of nitrate were observed on one day at Abbotsbury and Clouds Hill (25 and 6 µM respectively, equivalent to 350 and 84 µg/l-N), on another day at Langton Herring (9 µM, or 126 µg/l-N) when dinoflagellates were found in the plankton samples, and again at Abbotsbury (10 µM, or 140 µg/l-N) on the last day of sampling when the bloom of *Glenodinium foliaceum* occurred. Extremely high levels of nitrate were also detected in the stream water on the day of the *Glenodinium* bloom, at a concentration of 266 µM (3724 µg/l-N), the concentration decreasing by an order of magnitude in the short distance from the stream to the Abbotsbury Embayment itself. Regression analysis indicated that the elevated total inorganic nitrogen levels observed at Abbotsbury were significantly correlated with the increased population density of *Glenodinium foliaceum* observed during the bloom in August.

An attempt was made to determine if phytoplankton populations were nutrient limited or not, by comparison of the ratios of different plant pigments (carotenoids and chlorophyll a). However, the ratio varied considerably, and did not correspond to variations in nutrient content of the water. The variation was attributed to the fact that the populations were of mixed species of phytoplankton, so no clear conclusions could be drawn from the comparison.

Whilst there are few references which contain information on water quality, several raise concerns about possible impacts on the Fleet including eutrophication, e.g. Elton (1991), Holmes (1983), John (1995).

4.4 Water quality monitoring and investigations

The review of historical information in the FSG archive has demonstrated that there is very little historical data on water quality of the Fleet itself prior to 1996. This is largely because, historically, there has been no national or statutory requirement for the Environment Agency (EA) or its predecessors to monitor water quality of inshore water bodies such as the Fleet. Data which exist have been obtained under the requirement for EA to monitor effluent discharges to freshwaters (i.e. sewage effluent discharges into the streams entering the Fleet). Unlike the General Quality Assessments (GQA) for rivers (see NRA 1994), there is no national surveillance programme for inshore waters such as lagoons.

The Fleet has now been put forward by the EA as a 'candidate polluted water (eutrophic)' to the European Community under the Nitrates Directive (91/676/EEC) for the review of such sites in 2001. The selection of the site was a result of concerns being expressed within the EA, but also by English Nature and the Fleet Study Group, over the nutrient status of the lagoon. Identification as a candidate site does not pre-judge the nutrient status or the key influences acting on it, but rather acts as a trigger for further investigation and monitoring to enable these questions to be answered with certainty. As a consequence, monitoring of the nutrient status of the Fleet and its inputs in future will have a statutory basis, ensuring routine monitoring takes place. The level of resources employed for monitoring and reporting will reflect EA regional priorities and the degree of the problem or potential problem of eutrophication at the site.

Table 4.1 provides an inventory of inputs to the Fleet. The following sections summarise the background, methods and results of monitoring or investigating several of these together with the Fleet itself in the following order:

- 4.4.1 Point sources (effluent discharges)
- 4.4.2 Streams (watercourses)
- 4.4.3 Receiving waters (the Fleet itself)
- 4.4.4 Additional monitoring of point sources, streams and the Fleet to support modelling
- 4.4.5 Estimation of inputs from diffuse sources (including land run-off and wildfowl)

Table 4.1 Inventory of inputs to the Fleet lagoon (based on table 4 from EA 1998a)

Sources	Direct	Indirect
Sewage Treatment Works		Abbotsbury STW
		Langton Herring STW
		Swannery Restaurant
	Moonfleet Manor Hotel	
	RETC Chickerell (now revoked)	
	RETC Bridging Hard (now revoked)	
Watercourses	East Fleet stream	
	West Fleet Stream	
	Rodden Stream	
	Portesham Mill Stream	
	Coward’s Lake	
	Abbotsbury Mill Stream	
	Herbury Stream	
Other	Wildfowl	
	Portland Harbour	
	Land Run-off	Land Run-off
	Groundwater flow	
	Saline Intrusion	
	Aerial deposition	

4.4.1 Effluent discharges

There have been six sewage effluent discharges to streams feeding the Fleet and to the Fleet itself, listed below in order from west to east (and shown on Figure 4.1) and with level of treatment indicated:

- Abbotsbury Swannery Restaurant (private) secondary;
- Abbotsbury sewage treatment works (STW) (Wessex Water plc) secondary;
- Langton Herring STW (Wessex Water plc) secondary;
- Moonfleet Manor Hotel STW (private) secondary;
- Royal Engineers Training Camp (RETC) Chickerell STW (private, managed by Wwplc) secondary **(now revoked)**;
- RETC Wyke Regis (Bridging Hard) (private) **now revoked**.

Discharges of sewage effluent have been monitored by the Environment Agency from 1990 to present. Frequency of monitoring is, however, low, due to the small size of the discharges involved. The sampling regime followed national criteria based on dry weather flow (DWF) of each works involved (EA 1997a). All concentrations below are expressed as µg/l-N or µg/l-P.

Although sparse, data obtained from 1990 to 1997 have been examined for trends in water quality. Due to the lack of long term data and infrequency of sampling, analysis for statistical significance was not performed, and the conclusions reached are therefore tentative.

Abbotsbury Swannery Restaurant has a DWF of 10.3 m^3/day and is therefore sampled four times per year. It discharges into Abbotsbury Mill Stream (called Mill stream (Abbey Barn) in other EA reports), and has consent limits of 20 mg/l BOD, 10 mg/l ammonia and 30 mg/l suspended solids. No trend analysis of effluent monitoring results was carried out as this was a new consent, effective from February 1996.

Abbotsbury STW is the largest input, with a dry weather flow (DWF) of 140 m^3/day, and is therefore sampled 12 times per year. It discharges into Portesham Mill Stream above Horsepool (called Mill Stream (Horsepool) in other EA reports). From 1990 to '96 a general decrease in concentrations of ammonia, nitrate, nitrite, TON and ortho-phosphate was observed in the final effluent from Abbotsbury STW.

Langton Herring STW has no numeric limits associated with its discharge consent, with an estimated DWF of <100 m^3/day, and is therefore sampled four times per year. It discharges into Rodden Stream below Langton Herring village. Despite infrequent sampling, its effluent also showed a general decline in ammonia and ortho-phosphate concentrations from 1990 to '96. Nitrate concentrations have remained relatively constant.

Moonfleet Manor Hotel has a private STW with a DWF of 27 m^3d, and is therefore sampled four times per year. It discharges direct to the Fleet, and has a history of poor consent compliance. Its consent is 50 mg/l BOD, 40 mg/l ammonia, 60 mg/l suspended solids. A reed bed has now been installed, which should provide improved effluent quality. No trend analysis was carried out due to lack of data.

RETC Chickerell STW had a DWF of 64 m^3/day discharging direct to the Fleet, and is therefore sampled four times per year. Ammoniacal nitrogen concentrations of the effluent were very variable (probably due to short term variations in population at the camp). This discharge was incorporated into the mains sewer system by April '99.

RETC Wyke Regis was a small septic tank with a DWF of 9 m^3/day and entered the Fleet at the Narrows where there are strong tidal currents and dilution is large. No elevation of nutrients at this point was detected during the surveys. This discharge has also been eliminated by transfer of flows to mains sewerage.

The relative contributions of these effluent inputs to nutrient concentrations within the Fleet lagoon itself has been modelled. The results of the nutrient load modelling are considered below (section 4.5).

4.4.2 Streams entering the Fleet

There are seven freshwater inputs flowing into the Fleet draining a very small catchment of 28km^2 (see figure 4.1 for locations):

- East Fleet Stream;
- West Fleet Stream;
- Herbury Stream;
- Rodden Stream;
- Portesham Mill Stream;
- Mill Stream – Abbey Barn;
- Coward's Lake.

Of these, limited nutrient data from 1990 to the present exists for all inputs except Herbury Stream. Although sparse, data from 1990 to '97 has been subject to long term trend analysis (EA 1998a), the results of which are summarised below. However, because of the lack of long term data and infrequency of sampling, analysis for statistical significance was not performed, and the conclusions reached are therefore tentative.

Cowards Lake had a mean concentration for ammonia of 0.03-0.09 mg/l from 1990-96. This then increased to 0.4 mg/l for 1997, due to a suspected farm pollution incident skewing the data. Nitrate and TON also displayed a general increase in concentration over the period. TON lowest mean was 3.33 mg/l in 1992, highest mean was 7.80 mg/l in 1995. Orthophosphate ranged from low to high during the period with means of from 0.04 mg/l in 1992 to 0.18 mg/l in 1995.

Mill Stream - Abbey Barn showed a general increase in concentration of nitrate, TON and orthophosphate from 1990-97, with mean ammonia from 1990-96 remaining less than 0.16 mg/l. In 1997 mean ammonia increased to 0.68 mg/l, again, attributable to one sample skewing the data. This one sample with high ammonia was due to a farm pollution incident (enforcement action was taken by EA). TON lowest mean was 4.75 mg/l in 1992, highest mean was 7.78 mg/l in 1997. Orthophosphate ranged from moderately low to high during the period with means of from 0.08 mg/l in 1996 to 0.18 mg/l in 1991 and '95.

Portesham Mill Stream receives effluent from Abbotsbury STW, and has shown a general decrease in ammonia from 1990-97, except during 1995 when levels were elevated. Nitrate and TON showed a general increase in levels, ortho-phosphate was in equilibrium. TON was high, with lowest mean at 7.48 mg/l in 1994, highest mean of 14.55 mg/l in 1996. Orthophosphate was higher than all other stream inputs throughout the period with means of from 0.55 mg/l in 1995 to 0.94 mg/l in 1992.

Rodden Stream (which receives effluent from Langton Herring STW) showed a decline in ammonia and ortho-phosphate from 1990-97, with an increase in nitrate and TON (mirroring Langton Herring STW effluent trends). TON was high, with lowest mean of 9.65 mg/l in 1990, highest mean of 13.67 mg/l in 1991. Orthophosphate was also somewhat elevated for some of the period with means of from 0.04 mg/l in 1996 to 0.63 mg/l in 1990.

No nutrient data are available for Herbury Stream; its water quality is assumed to be similar to that of East Fleet stream.

West Fleet Stream is dry for 3-4 summer months of the year (a winterbourne). Ammonia concentrations were similar to those in the above streams, and exhibit a similar pattern with relatively stable low concentrations, with an occasional elevated peak. However, the nitrate and TON concentrations were much higher than those of other streams. The highest concentrations were recorded in 1997 (36.2 mg/l nitrate and 36.28 mg/l TON), at two to three times greater than East Fleet, Portesham Mill stream and Rodden stream (the other streams with high TON). Lowest mean TON was 12.00 mg/l in 1995, highest mean TON was 36.28 mg/l in 1997. Orthophosphate concentrations were moderate to high with lowest mean of 0.07 mg/l in 1996 and highest mean of 0.37 mg/l in 1991.

East Fleet Stream is also dry for 3-4 months a year, and exhibits a similar pattern to that of the West Fleet Stream, with somewhat lower concentrations of nutrients, but still with TON higher than either Portesham Mill stream or Rodden stream. TON lowest mean was 11.59 mg/l in 1994, highest mean was 17.33 mg/l in 1995. Orthophosphate remained relatively moderate to high throughout the period with means of from 0.08 mg/l in 1996 to 0.41 mg/l in 1990.

In terms of nutrient concentrations, without account being taken of flows of each stream, West Fleet stream had by far the highest nitrogen concentrations. East Fleet stream, Portesham Mill stream and Rodden stream also had high nitrogen concentrations, with Cowards Lake and Mill stream (Abbey Barn) being much lower. Both West Fleet and East Fleet streams are winterbournes (i.e. dry for several months of the year). In terms of phosphorus concentrations, Portesham Mill stream (which receives effluent from Abbotsbury STW) and Rodden stream (which receives effluent from Langton Herring STW) had highest concentrations of orthophosphate, followed by East and West Fleet streams, and, again, Cowards Lake and Mill stream (Abbey Barn) with the lowest.

The relative contribution of each of these streams to nutrient loads to the Fleet lagoon itself has been modelled, taking into account estimated flows for each stream as well as nutrient concentrations. The results of the nutrient load modelling are considered below.

4.4.3 Receiving waters

The lack of data on nutrient concentrations in streams, combined with concerns regarding the eutrophication status of the Fleet, led the Environment Agency to initiate a project to monitor water quality within the Fleet lagoon itself as part of its routine monitoring programme from 1996 to the present. Information obtained was intended to facilitate more informed decisions on the future management of the Fleet. Monitoring was also required in order to provide routine nutrient data to allow possible designation of the Fleet as a 'polluted water (eutrophic)' under the EC Nitrates Directive (91/676/EEC).

Two day surveys were undertaken, covering both spring and neap tides, four times a year, corresponding to spring, summer, autumn and winter. Five sites from within the lagoon itself were sampled from mid channel (see Figure 4.1):

- Abbotsbury Swannery;
- Langton Hive Point;
- Chickerell Hive Point;
- the Narrows;
- Smallmouth.

Seven freshwater input sites were sampled (see Figure 4.1):

- Cowards Lake
- Mill stream (Abbey Barn) (upstream of Abbotsbury Swannery restaurant discharge);
- Mill stream (Horsepool) (downstream of Abbotsbury STW discharge);
- Rodden stream (upstream of Langton Herring STW discharge);
- Rodden stream (downstream of Langton Herring STW discharge);
- West Fleet stream;
- East Fleet stream.

Herbury stream was the only stream input not sampled.

A number of water quality determinands was measured for each sample, including temperature, dissolved oxygen, pH, salinity, ammonia, nitrate, nitrite, orthophosphate, silicate, total organic nitrogen (TON) and chlorophyll a.

Summary data for nutrients for the Fleet sites are presented below (Table 4.2), although it should be noted that the data set is limited and figures should be treated with caution.

The data in Table 3.2 indicate that the Fleet off Abbotsbury Swannery has by far the largest nutrient concentrations, with concentrations reducing eastwards. The sites at the Narrows and Smallmouth had by far the lowest nutrient concentrations. Variations in results were high, in particular at the three sites with the highest concentrations (Abbotsbury Swannery, Langton Hive and Chickerell Hive).

Levels of orthophosphate from marine waters exceeded 10 µg/l-P at Smallmouth on all but one sampling occasion from 1995 to 1997, with much higher levels (well over 15 µg/l-P) further up the

Fleet measured on most sampling occasions. At Chickerell Hive and Langton Hive orthophosphate concentrations reached 45 and 68 µg/l-P respectively in 1997. Concentrations at Abbotsbury were much higher throughout this period (EA 1998a). The relevance of these observations to *Lamprothamnium papulosum* is explored in Section 3.9.

Concentrations of chlorophyll-a (as an indicator of planktonic algae) followed a similar pattern in distribution to nutrients, with high levels at the Abbotsbury end of the Fleet, and lower levels at the eastern end.

Elevated chlorophyll-a levels at Abbotsbury in August 1997 corresponded with high levels of planktonic algae. Water samples taken at this time showed bloom levels of the dinoflagellate *Prorocentrum micans*, which caused red discoloured water in the Abbotsbury area. *Prorocentrum lima* was also detected in samples in low numbers from Abbotsbury as well as Langton Hive and, to a lesser degree, at Chickerell Hive. The bloom duration lasted some time, at least four weeks (the interval between sampling occasions). Both the occurrence and duration of the bloom is of possible concern given the associated potential increase in light attenuation and the fact that *P. lima* can cause toxicity though the food chain above a certain level (>100 cells/l) including Diarrhetic Shellfish Poisoining (Environment Agency 1997b).

Table 4.2 Summary nutrient data for the Fleet, April 1996-August 1997

Site	Ammonia µg/l		Nitrate µg/l		Orthophosphate µg/l		TON µg/l		Salinity g/kg	
	Mean	st.dev.	Mean	st.dev.	Mean	st.dev.	Mean	st.dev.	Mean	st.dev.
Abbotsbury swannery	**14.83**	13.08	**1920**	1550	**135.67**	134.93	**1960**	1600	**15.51**	4.14
Langton Hive	**27.33**	45.03	**440**	680	**30.67**	26.15	**460**	720	**25.84**	2.91
Chickerell Hive	**9.57**	5.83	**310**	520	**21.00**	13.49	**320**	550	**26.87**	4.94
The Narrows	**8.14**	4.10	**180**	220	**16.43**	6.55	**190**	230	**29.00**	5.28
Smallmouth	**6.83**	3.35	**91**	72	**9.75**	5.72	**94**	76	**33.90**	1.37

Source: Environment Agency 1998a

Table 4.3 Summary data for chlorophyll-a for the Fleet, April 1996-August 1997

Site	Chlorophyll-a (µg/l)	
	Mean	st.dev.
Abbotsbury swannery	58.83	44.93
Langton Hive	9.50	5.68
Chickerell Hive	8.49	9.81
The Narrows	5.40	7.61
Smallmouth	2.94	2.70

Source: Environment Agency 1998a

4.4.4 Additional investigations of water quality within the Fleet

Additional investigations of the Fleet itself and inputs were carried out in 1998 (EA 1998b), to provide additional data, in particular for use in the nutrient budget modelling.

Chemical sampling of Fleet lagoon and stream inputs

Monthly chemical sampling (April to October 1998) in the Fleet lagoon (5 previous sites plus Cloud's Hill) and six freshwater input sites (excluding Herbury stream) (results not included in EA 1998b but used in nutrient budget modelling).

Stream flow measurements

Monthly flow measurements (March to September 1998) for six streams (excluding Herbury stream).

Diurnal variation of discharges

Investigation into diurnal variation of Abbotsbury and Langton Herring STW discharges over 24 hours 2-3rd August 1998 (BOD and nutrients).

Diurnal variations in nutrient concentrations from the two main sewage works discharging into streams into the Fleet (Abbotsbury and Langton Herring STWs) were investigated over two days. At Abbotsbury, little diurnal variation in concentrations of any of the determinands was observed. Approximate concentrations were:

- BOD 4-5 mg/l;
- ammonia 1-3 mg/l;
- TON and nitrate 20-25 mg/l;
- nitrite <1 mg/l; and
- ortho-phosphate around 7 mg/l.

At Langton Herring, diurnal variation was greater, in particular for BOD. Approximate concentrations were:

- BOD generally 3-6 mg/l;
- ammonia 7-12 mg/l;
- TON and nitrate 1 mg/l;
- nitrite <1 mg/l; and
- ortho-phosphate around 6 mg/l.

Whilst BOD was generally around 3-6 mg/l, there was an isolated peak of 19 mg/l around 18.30hrs on 2nd August, and from 7.00-9.00am on 3rd August BOD increased markedly to 168 mg/l. At this time ammonia concentration dropped, and TON and nitrate increased to around 6 mg/l. This latter noticeable change in determinand concentrations was attributed to the settlement tank being cleaned at the works at that time, and concentrations of all determinands were back down to their previous levels by between 19.00 and 23.00hrs on 3rd August.

The principal difference between the effluents from the two works was the higher nitrate concentration of Abbotsbury STW effluent, and the slightly greater diurnal variation in effluent quality at Langton Herring STW, in particular in terms of BOD and ammonia concentrations. Higher nitrate concentrations in the STW effluent indicate that the works is nitrifying, i.e. converting ammonia and nitrites to nitrate. The concentrations recorded are not particularly high for a sewage works effluent.

Continuous monitoring

Continuous monitoring of dissolved oxygen, salinity and turbidity in Fleet waters at Abbotsbury and Chickerell over 15 days in October 1998.

Continuous monitors for dissolved oxygen (DO) concentrations were sited in the Abbotsbury embayment and in the channel off Chickerell Hive Point to gather data on summer diurnal variations in DO. These results have not been interpreted in EA 1998b. However, preliminary examination of the continuous monitor trace indicates that at Abbotsbury, tidal variation is not seen in the trace for salinity, with levels for approximately 12 days at around 24 ppt, dropping to around 12 ppt on 25.10.98, and increasing to 15-18 ppt for the last 2 days of the record. This drop in salinity corresponds approximately to a series of peaks in turbidity on 25.10.98, and is assumed to be due to a rainfall event. For dissolved oxygen, there does appear to be some diurnal variation, but the trace is not regular, varying between <80% and well over 100%. Around 25.10.98 and for the following two days, diurnal variation was barely discernible, with DO consistently around 80% saturation.

At Chickerell, tidal influence can clearly be seen, with variations in salinity from around 34 to 35.5 ppt presumably corresponding to tidal influx of higher salinity water. Dissolved oxygen at this site does not vary with the tidal cycle, but there does appear to be diurnal variation, with higher levels (>100% saturation) during the middle of the day, and lower levels of 70-80% during the night. This variation is indicative of algal or plant photosynthesis increasing water oxygen concentrations during the day, with lower levels at night. Turbidity was fairly constant at a low level, with the exception of a few groups of peaks of up to 600 NTU (Nephelometric Turbidity Units). These groups of peaks corresponded to disruptions to the tidal and diurnal variations in salinity and DO. At the same time as some of the peaks in turbidity, salinity is reduced, and the diurnal variation in DO levels is less obvious. They may therefore be associated with rainfall events, however, there is no data on rainfall in the report (1998b).

Algal sampling

Algal sampling with corresponding chemical sampling (chemical results not included in EA 1998b).

Low numbers of diatoms were observed in samples taken during April and May 1998. No potential toxin or nuisance organisms were observed or reported during this time. In July, the sample from Abbotsbury Swannery showed the presence of bloom numbers of *Alexandrium* sp. (a toxin-producing dinoflagellate which can cause paralytic shellfish poisoning or PSP). The duration of this bloom was unknown, but a sample taken a month later was clear. Very low numbers of *Prorocentrum* sp. (a potential diarrhetic shellfish poison producer) were observed in a sample taken at Ferrybridge in July '98. CEFAS results showed the presence of ASP (amnesic shellfish poison) cells in April and August '98, and a sample taken by CEFAS in July showed the presence of PSP cells, with numbers lower at Ferrybridge than at Abbotsbury. No toxins were detected in shellfish flesh.

Sediment sampling

Sampling from mid channel at Abbotsbury Swannery, Langton Hive and Chickerell Hive to assess phosphate concentrations in surface sediments during October 1998. See Table 3.4 for results.

Table 4.4 Sediment nutrient data for Fleet samples, 15th October 1998

Determinand (mg/kg dry weight)	Abbotsbury Swannery	Langton Hive Point	Chickerell Hive Point
Orthophosphate	0.86	<0.35	<0.35
Total phosphorus	2.92	2.27	3.54
Total organic carbon	233	344	554
Total organic nitrogen	<4.8	<7.0	<7.0
Nitrite	1.06	0.227	0.392
Nitrate	3.74	6.77	6.61
Dry matter (%)	45.2	30.3	28

Source: Environment Agency 1998b

It should be noted that with respect to phosphorus, concentrations within surface sediments are meaningless because phosphorus is mobile within sediments and significantly affected temporally by redox reduction. To derive an indication of the importance of phosphorus and likelihood of uptake and release by sediments it would be necessary to measure the Equilibrium Phosphate Concentration within the Fleet, i.e. a measure of the propensity of the sediment to leach phosphorus (see Mainstone *et al* 1996).

4.4.5 Estimation of nutrient loadings to the Fleet lagoon from diffuse sources

Background and methodology

The objective for this investigation carried out by WRc for the Environment Agency was to 'estimate nutrient loadings from diffuse sources to the Fleet lagoon, including those arising from the swannery' (Mainstone & Parr 1999).

The topographical catchment of the Fleet is small (28 km^2), stretching along the length of the Fleet. Much of the catchment is under pasture, with sheep and dairy farming being important land uses. Arable farming is concentrated around the village of Langton Herring and in scattered areas largely to the south and east. At Abbotsbury Swannery, at the extreme western end of the Fleet, mute swans have been managed for around 600 years. This history of management has led to the development of a large breeding colony (around 150 pairs) in the 50 acre reed bed of the swannery, accompanied by a large flock (approximately 350) of non-breeding birds. In winter, numbers increase to around 1500 as birds from other areas fly in.

Freshwater inputs enter the Fleet from seven small streams, with further inputs from direct runoff along the lagoon shore. Groundwater seepage may also be a substantial though uncertain input given the presence of chalk and greensand aquifers (water bearing rock strata) underlying the whole area.

Any estimate of diffuse loads produced from export coefficients needs to be calibrated in some way against measured loads in the receiving waters. This requires that point source loads are also estimated and the sum of point and non-point source estimates are compared with observed loads entering the lagoon. Export coefficients may then need to be adjusted to provide a better fit with measured loads. Five stages to producing the nutrient budget may therefore be identified (Mainstone and Parr 1999):

! estimating point source nutrient loads;
! estimating diffuse nutrient loads;
! estimating nutrient loads in waters entering the Fleet;
! comparing nutrient loads estimated by export coefficients with loads estimated from receiving water monitoring;
! modifying export coefficients if necessary.

Annual nutrient budgets were constructed for both nitrogen and phosphorus. No assessment of the seasonality or bioavailability of the nutrient loads was made during this study (Table 4.5). MAFF agricultural census information on crop areas and livestock numbers for three parishes within the catchment area of the Fleet was used, and data on bird (particularly swan) populations and estimated loads were incorporated. The above estimates for diffuse sources of nutrients (combined with estimates for point sources) were calibrated against measured loads for the Fleet.

Point sources: Estimated loads for point sources (consisting of two public sewage treatment works at Abbotsbury and Langton Herring, and two private sewage treatment works at Moonfleet Manor Hotel and Royal Engineers Training Camp at Chickerell) were necessarily crude, due to a lack of sufficiently detailed information on flows and nutrient concentrations of sewage effluent from these works. The results indicated that the loads from the two private works were negligible, and that Abbotsbury sewage treatment works contributes a much larger load than that from Langton Herring (1.19-2.90 tonnes N per year and 0.38-1.19 tonnes P per year at Abbotsbury, compared to 0.35 and 0.10 per year respectively for Langton Herring).

Diffuse source loads estimated were from atmospheric deposition, agriculture, bird populations and groundwater. As with the estimations of loads from point sources, there were considerable sources of error for each of the estimates from diffuse sources.

Atmospheric deposition: Background nutrient loads from atmospheric deposition were estimated at 18.48 tonnes per year for nitrogen, and 0.42 tonnes per year for phosphorus (the latter is based on the whole catchment).

There are two possible methods for calculating the nitrogen loading using the information available, one assumes a fixed proportion of modelled atmospheric deposition is exported to surface waters whilst the other uses the proportion of rainfall which is lost to surface runoff. Partly because of the complex geology of the catchment, the two methods give estimates that are an order of magnitude apart. Therefore, a mean of the two values obtained has been used.

Agriculture: Data on agricultural land is typically only available for aggregated groups of parishes. In the case of the Fleet, the relevant aggregation covered a much larger area than the topographical catchment. Fortunately, three of the parishes constituted 80% of the catchment area of the Fleet, and MAFF was able to separate out data for these three parishes, although data for some crops and livestock was not provided on this basis due to commercial confidence constraints on its use. The catchment is predominantly under pasture (70%), supporting sheep and dairy farming. 24% of farm holdings were devoted to arable, with most of this under cereal crops (predominantly wheat, with significant amounts of winter barley and maize). Data on pig and poultry numbers were withheld. Estimations of nutrient inputs from the various types of agriculture were made using assumptions about fertiliser use for different crops and rates of loss to receiving waters. The calculations produced estimates of 64 tonnes of N and 0.8 tonnes of P per year exported to the Fleet from agricultural fertiliser use and 44 tonnes N and 1.5 tonnes P derived from livestock.

Bird populations: Colonial breeding in mute swans as occurs at Abbotsbury is traditionally accompanied by high juvenile mortality, as families leave the nest early, and cygnets fail to 'imprint' properly on the parents. To assist successful imprinting, swans are fed at the nest with grass clippings (from the swannery lawns) in floating dustbin lids. The non-breeding flock represents a threat to the breeding colony, as if these birds were to descend on the breeding colony, it is likely that the ensuing havoc would result in high juvenile mortalities. The flock is therefore distracted during nesting time by supply of wheat grain away from the reed bed. Wheat is delivered directly to the water and ingested by the birds off the lagoon bed. Feed is not normally supplied to the overwintering flock, except in exceptionally cold weather.

The inputs of nutrients to the Fleet from the swans were estimated by using the nutrient load delivered to the swans in feed (whole wheat, crumbs and pellets), and applying a conversion efficiency to estimate the loads generated in excreta. Figures of 0.25-0.29 tonnes N and 0.05-0.06 tonnes P per year from swan feeding were obtained by this method.

Loads from other bird species in the Fleet (Canada geese, Brent geese, and lesser black-backed, common, black headed and herring gulls) were estimated using monthly counts to obtain bird numbers, multiplied by figures for nutrients in faeces obtained from the literature. Inputs to the Fleet of 0.17 tonnes N and 0.06 tonnes P were obtained by this method for birds other than mute swans.

Groundwater: Figures for nutrient loads from groundwater could not be quantified due to lack of information on both nitrogen and phosphorus concentrations in groundwaters within the catchment. However, this source of nutrients is potentially significant and cannot be ignored, particularly for nitrogen as Environment Agency borehole data indicate that total inorganic nitrogen (TIN) concentrations from groundwaters to the north and west of the catchment are high (around 6 mg/l TIN).

Streams: Comparisons were made between the estimates of loadings obtained by the above methods with nutrient loadings measured for the Fleet. Unfortunately, there were no flow data for the seven small streams entering the Fleet, so flows had to be estimated using the Institute of

Hydrology's Micro Low Flow methodology[4]. Nutrient data for the streams were also sparse due to the fragmentation of the riverine load to the Fleet into a number of minor watercourses which would not normally receive much monitoring attention. There was a discrepancy between the calculated loads for phosphorus from the various sources and the calculated loads in the streams, which could be due to a number of reasons, but is probably due to the low accuracy of the methods for estimating both the theoretical inputs and the measured inputs from the streams. Agreement between the two methods for nitrogen was good.

Table 4.5 Summary of estimated annual nutrient loads to the Fleet

Source	Nitrogen		Phosphorus	
	Tonnes/year	%	Tonnes/year	%
Point sources (sewage works)	1.5-3.2	1 - 2.5	0.48-1.29	12 – 39
Livestock	44.4	34	1.54	37 – 47
Fertiliser application	64.4	49 – 50	0.75	18 – 23
Background load	18.5	14	0.42	10 – 13
Abbotsbury swannery	0.3	0.2	0.06	2
Other bird species	0.2	0.1	0.06	2
TOTAL	129.3 – 131.0		3.31 – 4.12	

Source: Mainstone & Parr 1999

Summary of results: Although there were concerns over the reliability of a number of aspects of the data on which the estimates were based, agricultural sources were found to be highly important for both nitrogen and phosphorus. Around 80% of the annual load of nitrogen, and over half, perhaps as much as 70%, of the annual total phosphorus load to the Fleet is estimated to come from agricultural sources. In addition, contributions from pigs and poultry were not included in estimations of inputs from livestock, which might make the agricultural load even more important to the annual budget. The two sewage works at Abbotsbury and Langton Herring may contribute as much as 40% of the annual phosphorus load to the Fleet, but this figure may be as low as 12%. Mute swans and feeding from the swannery and other bird species do not appear to be making a major contribution to nutrient loads entering the lagoon as a whole but they may be important in the Abbotsbury sub-catchment.

Further work: More detailed modelling was recommended to gain a better understanding of the spatial and seasonal distribution of loads and the effects on water quality within the Fleet. The immediate identification and implementation of practical control measures across the catchment, using catchment walk overs to identify critical practices and run-off pathways, was also recommended. Further modelling will eventually help to focus attention on high risk areas and will help to predict the likely effect of control measures on nutrient status and eutrophication risk.

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[4]Micro Low Flows is a piece of software developed by the Institute of Hydrology, particularly for catchments subject to artificial influences such as impoundment, discharges and abstraction, to allow the estimation of natural low flows at ungauged sites.

Improved information on the loads entering the Fleet via point sources, feeder streams, direct run-off and groundwater seepage is also recommended. It should be borne in mind, however, that the above studies are approximate calculations of annual nutrient inputs. The timing and availability of loads from different sources may alter the ecological importance ascribed to different human activities.

4.5 Nutrient load analysis and modelling

4.5.1 Background and Methodology

Nutrient load analysis and simple modelling of the Fleet lagoon was carried out by Environment Agency using data obtained during water quality monitoring studies from 1996 to '98 (Murdoch 1999) and information from Mainstone and Parr 1999. The relative contributions of point sources (sewage works discharges), freshwater and wildfowl contributions to the nitrogen and phosphate concentration levels in the lagoon was quantitatively assessed. The modelling attempted to assess input loads on daily and seasonal as well as annual timescales.

Before the modelling was carried out, nutrient sources were identified and their loads estimated. Two direct discharges from Wessex Water plc. sewage treatment works (STW) at Abbotsbury and Langton Herring discharge into streams entering the Fleet (Mill stream (Horsepool) and Rodden Stream respectively). Other smaller sewage effluent discharges were not included in the model as they are very small, and their input is not thought to be significant in overall terms (Mainstone & Parr 1999).

No continuous flow monitoring data were available for the streams, therefore flows were estimated from mean flow statistics using the Institute of Hydrology's Micro Low Flow methodology. Estimated daily stream flows are then calculated using flow data from the nearby Broadwey gauging station to estimate daily variations. Calculated flows were compared to spot gaugings of stream flows, with relatively good agreement between the two for all streams except Mill Stream (Horsepool) and Mill Stream (Abbey Barn). Flows for Mill Stream (Horsepool) were adjusted in the light of this comparison as it receives effluent from Abbotsbury STW which would not have been taken account of in the flow estimations. Nutrient monitoring data were available for six of the seven streams (inputs from Herbury stream were assumed to be similar to those of the nearby East Fleet stream).

Diffuse input flows (run-off from land into the lagoon directly) were estimated using Micro Low Flow methodology, and were assumed to be evenly distributed between Abbotsbury and East Fleet. Nitrogen concentration of diffuse sources was assumed to be 5 mg/l N, estimated from the concentration of nitrogen found in borehole water nearby. No data were available for phosphorus content of borehole water, and since phosphorus mobility is low, diffuse inputs of phosphorus were ignored for the purpose of this modelling.

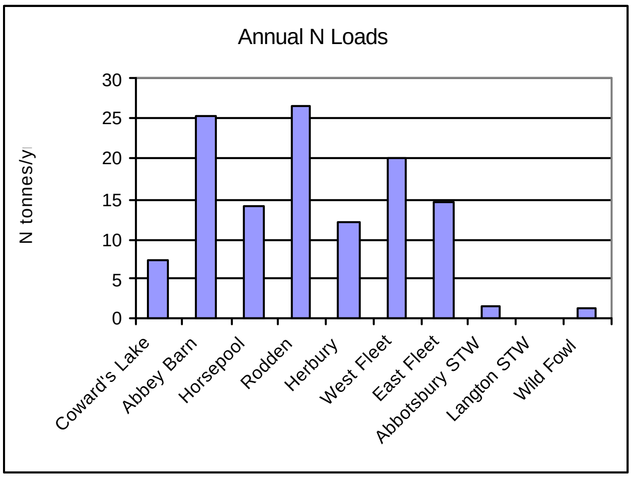
Estimated inputs from faecal matter of wildfowl, including swans, were put into the model using estimates based on monthly numbers of birds and the nitrogen and phosphorus content of faeces (see Section 3.3.5; Mainstone & Parr 1999). For the purposes of the modelling, the worst case of all wildfowl faeces input to the lagoon was assumed (rather than one third defaecated into the lagoon with two thirds onto land as estimated in Mainstone & Parr 1999).

The model (ECoS (2)) was used to obtain simulations of annual budgets. Use of this model means that short term accuracy is traded for the ability to do long simulations. Physical and tidal data required by the model were taken from Robinson's work (Robinson 1983; Robinson *et al* 1983). This model is much more approximate than that developed by Westwater, Falconer and Lin (1999), because of the level of accuracy of the bathymetry, tidal and flow data used, and the fact that it is a one dimensional model rather than two dimensional.

4.5.2 Results

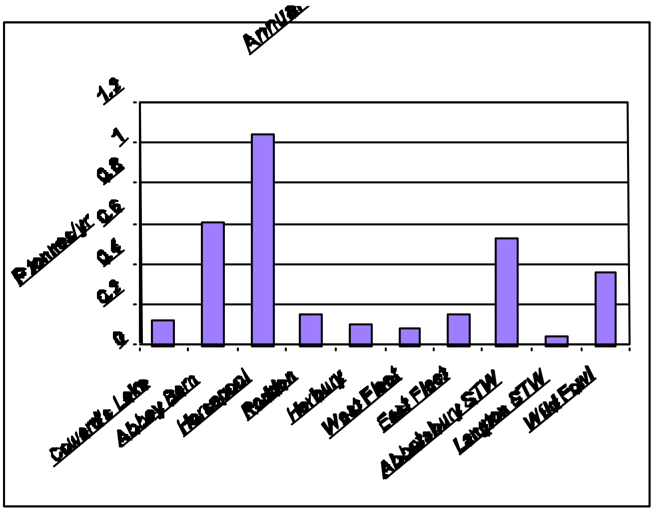
Nitrogen: For total inorganic nitrogen (TIN), the freshwater streams were found to dominate inputs to the system. Stream inputs showed a strong annual cycle with winter highs and summer lows. The inference is that winter runoff and flushing of nitrates is responsible for the winter peaks observed. Annual loads for three of the streams (Abbey Barn, Rodden and West Fleet) were around 20-25 tonnes N per year, with the other streams (Horsepool, Herbury and East Fleet) around 15 tonnes N per year and Cowards Lake lowest at 7 tonnes N per year. The loads for Mill stream (Abbey Barn) and for Rodden stream include the inputs from Abbotsbury and Langton STWs respectively, although both are shown separately in addition on the graph below. Abbotsbury sewage treatment works (STW) output and wildfowl had very low loadings (2 tonnes N per year). Input from Langton STW was negligible. Total inorganic nitrogen (TIN) loads were greatest at the Abbotsbury (western) end of the Fleet.

Figure 4.3 Annual nitrogen loads to the Fleet (from Murdoch 1999)



Phosphorus: The model showed a double annual cycle in phosphorus loads, with winter highs and summer highs. The winter highs appeared related to the stream inputs (particularly Mill stream (Horsepool) and Mill stream (Abbey Barn), but also Cowards Lake, Rodden stream and West Fleet stream). The stream loads from Mill stream (Horsepool) and Mill stream (Abbey Barn) are highest at about 8 kg/day in winter. Mill stream (Horsepool) load includes the effluent from Abbotsbury STW (which contributes approximately 2 kg/day). Other stream inputs were much lower with winter inputs of less than 2 kg/day. The summer highs appear to be related to the wildfowl inputs; the impact of wildfowl may be exacerbated owing to associated high organic loadings resulting in increased anoxia within sediments and enhanced phosphate release (Mainstone pers. comm.). However, there could be effects from Abbotsbury STW inputs entering the western Fleet and not being flushed out to the eastern Fleet and the sea.

Figure 4.4 Annual phosphorus loads to the Fleet (from Murdoch 1999)



4.6 Modelling tidal currents and solute distributions

4.6.1 Background and methodology

The objectives for this investigation carried out by Cardiff University School of Engineering (Westwater, Falconer and Lin 1999) were to produce an operational two dimensional model of the Fleet lagoon, calibrated against field data, and to establish the flushing characteristics of the lagoon using simulations of the transport of a conservative tracer. The model and tracer simulations could then be used to predict distribution of water quality indicators such as salinity and nitrogen distribution in the Fleet and from stream inflows.

The Fleet is characterised by unusual hydrodynamic properties, in that the velocities and depths at the head of the lagoon are very small which leads to low Reynolds number flows. This hydrodynamic phenomenon means that the effective bottom friction increases with decreasing Reynolds number (or reduced velocity x depth), thereby leading to increased headlosses. This effect is not currently included in numerical hydraulic models and was an important component of the current study. More extensive research is required in the future into studying the effects of this complex hydrodynamic phenomenon, particularly as it relates significantly to the transport of fluid mass and solute contaminant and water quality indicator fluxes in tidal wetlands.

The numerical model used for this part of the work is much more refined than that used for the initial budget modelling used by the EA. However, as with any model, there are still uncertainties included within the model which should be appreciated, including effects of turbulence and lagoon bed roughness on water flows in the lagoon, erosion and deposition of sediments, and chemical and biological processes relating to water quality parameters. The particular case of the Fleet, being very shallow with parts subject to tidal drying, and with highly variable width along its length, presents particular difficulties in developing a realistic hydrodynamic model. The model used did, however, provide reasonable agreement when calibrated against field data.

Bathymetric data obtained in 1998 for English Nature were used in the model, as the data originally used (from Robinson 1983) were found not to be sufficiently detailed. Data on bathymetry of the western part of the Fleet were, however, sparse, which compromises the accuracy of the model predictions somewhat. Tidal elevation data from Portland Harbour were initially used in the model, but were found not to give a good fit with the measured data on calibration of the model. Therefore the tidal elevation data from the 1960's reported in Robinson *et al* (1983) were used (Westwater *et al* 1999).

Difficulties in fitting the model to the measured data were also encountered due to the relatively great effects of flow resistance of the lagoon bed in such shallow waters as occur throughout the Fleet. This difficulty was overcome by adjusting the values for bed resistance in the model to better match the measured data.

4.6.2 Results

Flow velocities in the Fleet were found to be generally low (0.2 – 0.3 m/s) and one dimensional (i.e. along the axis of the lagoon), with the exception of around Smallmouth and the Narrows, where relatively high flows of around 1 m/s were observed. At Smallmouth just inside the Fleet there was a large eddy, which was apparent during both neap and spring tides. In the Littlesea area of the eastern Fleet there was also a more complicated flow regime, with transverse flows (i.e. across the Fleet) in all plots at low tide, corresponding to the tidal drying of large areas in this embayment with flows following deeper channels in the lagoon bed. At high tides the flow reverted to the predominantly one-dimensional flow along the Fleet as seen for other areas.

Tracer studies indicated that the eastern Fleet has good tidal exchange with Portland Harbour up to Chickerell Hive in the Littlesea area, particularly during spring tides. During neap tides, tidal exchange with the west Fleet was extremely weak, with very little tidal exchange from Littlesea westwards. Tracer studies simulating release of a tracer at Abbotsbury showed that over ten tidal cycles the tracer only travelled as far as the narrow section adjacent to Abbotsbury, and did not even reach Rodden Hive Point. Tracer studies simulating release of contaminants in streams also demonstrated that Abbotsbury is a potential problem area, as it has three streams (Coward's Lake, Mill Stream (Abbey Barn) and Mill stream (Horsepool) (also known as Portesham Mill Stream)) flowing into it, but with very little tidal exchange. Again, contaminants did not travel further than the narrow section adjacent to Abbotsbury over ten tidal cycles. The other streams appeared to have little effect on the gross water quality characteristics as their flows are lower, and they enter the Fleet further eastwards where tidal exchange is better. Some localised effects were seen in the Littlesea area.

4.6.3 Conclusions and further work

Hydrodynamically the Fleet may be considered as two separate sections:

- East Fleet, from Smallmouth through The Narrows and into Littlesea, where there is reasonable tidal exchange and good tidal mixing due to the narrowing of the channel. In this area the stream inputs appear to have little effect on gross water quality characteristics, with localised effects at low tides around the point where East Fleet stream enters the lagoon.

! West Fleet, from Littlesea westwards. This area has a significant lack of tidal flushing and circulation, with large areas of stagnant water, particularly at the Abbotsbury end of the Fleet. It appears that the western end of Littlesea, with its large areas drying out at low tide, acts as a barrier to tidal flushing from the east Fleet, resulting in low flows and lack of flushing, leading to high sensitivity to contaminant release, in the western section of the lagoon.

Recommended further work includes:

! simulations of salinity distributions and other water quality indicators such as dissolved oxygen, nitrates and phosphates;

! refinement of the model by further investigation of the influence of bed roughness, effects of lagoon bed vegetation and effects of tidal flooding and drying on the hydrodynamics of very shallow areas such as the Fleet;

! further refinement of the model by obtaining additional bathymetric data for the Abbotsbury area, including location of any channels which would affect flows, and to refine the grid area from 50m down to 33m or 25m, to better investigate two dimensional flows.

4.7 Relevant studies of parameters other than nutrients

Grimwood & Dixon (1997) reported on metal concentrations found by the Environment Agency in the water column, sediments and biota in 27 Sensitive Marine Areas (SMAs) in England, one of which was for Portland Harbour and the Fleet. Only data for water column concentrations of certain metals from two sites in Portland Harbour were available, relating to samples taken in 1994, '95 and '96. The limited data showed no increasing nor decreasing trend in metal concentrations at either site. Values given (in µg l^{-1}) were mostly within the following ranges: zinc (1.1-6.6), copper (<0.5-1.6), nickel (0.3-6.5), and arsenic (<1-<2.5). No data was available for lead, chromium, vanadium, boron and iron. A risk assessment exercise indicated that for Portland and the Fleet, isolated concentrations of zinc occurred at levels exceeding the Environmental Quality Standard (EQS) of 5 µg l^{-1}, and so could present potential risk of ecotoxicological effects to exposed organisms in the short term. However, in the long term, results indicated that levels of zinc were not at concentrations likely to pose significant risks to ecosystem structure and function, and limitations on the zinc EQS were highlighted in the report.

Parr *et al* (1998) reported on turbidity in English and Welsh waters, however, data were only available for sites at some distance to seawards of the Fleet. These results indicated that marine waters off Chesil Beach were in the highest category for light transmission (75-100%) in summer 1995, and the second highest (50-75%) in winter '95; and the lowest category for presence of chlorophyll a (0-1 µg l^{-1}) in both summer and winter 1995.

Figure 4.5 Distribution of tracer released to mimic inputs from the Abbotsbury swannery after 10 tidal cycles (C12 from Westwater, Falconer and Lin 1999)

Figure 4.6 Distribution of tracer released to mimic stream inputs after 10 tidal cycles (C20 from Westwater, Falconer and Lin 1999)

4.8 Summary and interpretation of nutrient budget, distribution and fate

The preceding studies, including mathematical modelling of nutrient budgets and diffuse inputs to the Fleet, indicate the following:

4.8.1 Nitrogen

For nitrogen inputs to the Fleet, the principal sources appear to be freshwater streams. Of the seven streams which discharge to the Fleet, Table 3.6 gives an indication of their relative annual contributions of nitrogen to the Fleet budget, compared to the estimated contribution from wildfowl.

Nitrogen inputs from streams are greatest during winter, with the source of nitrogen being principally from agricultural fertiliser use. The principal area for arable land cultivation in the Fleet catchment is around Langton Herring, between Roddon and West Fleet streams. Figure 4.1 indicates that all the stream inputs discharge into the Fleet west of Chickerell. However, tilled land is known to be concentrated around the village of Langton Herring and to the east, so it is likely that overall nitrogen loads to the eastern Fleet can be expected to be somewhat higher than those to the western Fleet (Mainstone & Parr 1999).

The Fleet from Chickerell westwards has been shown by the physical modelling exercise to have very poor flushing characteristics.

4.8.2 Phosphorus

For phosphorus inputs to the Fleet the situation is less clear. Table 4.7 shows the estimated annual contribution of phosphorus to the Fleet from the stream sources and wildfowl inputs. In contrast to the situation for nitrogen, the relative contributions of the sewage treatment works at Abbotsbury and the wildfowl are more important on an annual basis for phosphorus. It should be noted that the estimated input for wildfowl assumes a worst case of all wildfowl faeces entering the lagoon directly rather than only a third with two thirds being deposited on land (as estimated in Mainstone and Parr 1999). If the latter were the case, then the stream inputs (largely from run-off and sewage) would be likely to account for a greater proportion of the nitrogen and phosphorous budgets.

The principal source of phosphorus inputs into the freshwater streams is also estimated to be from agricultural sources, primarily livestock farming (concentrated in the western Fleet), but also from mixed fertiliser application and land runoff as well.

Table 4.6 Estimated nitrogen contribution of sources entering the Fleet (based on Murdoch 1999)

Source	Estimated contribution Tonnes N per year	% of budget
Rodden Stream	27	21.9
Mill stream (Abbey Barn)	25	20.3
West Fleet stream	20	16.3
East Fleet stream	15	12.2
Mill stream (Horsepool) (includes 2 t/yr from Abbotsbury STW)	14	11.4
Herbury stream	13	10.6
Cowards Lake	7	5.7
Wildfowl	2	1.6

Table 4.7 Estimated phosphorus contribution of sources entering the Fleet (based on Murdoch 1999)

Source	Estimated contribution Tonnes P per year	% of budget
Mill stream (Horsepool) (includes 0.5 t/yr from Abbotsbury STW)	1	37
Mill stream (Abbey Barn)	0.6	22.2
Wildfowl	0.4	14.8
Rodden Stream	0.2	7.4
East Fleet stream	0.2	7.4
Cowards Lake	0.1	3.7
Herbury stream	0.1	3.7
West Fleet stream	0.1	3.7

However, for phosphorus, in contrast to the situation for nitrogen, there are peaks in loads in both summer and winter. In summer, the principal source of phosphorus appears to be from wildfowl-related inputs but the Abbotsbury STW may also be contributing. The main sources of the winter peaks appear to be freshwater stream inputs, with greatest contributions from Mill stream (Horsepool) and Mill stream (Abbey Barn) at approximately 8 kg/day, but also contributions from Cowards Lake, Rodden stream and West Fleet at approximately 1-2 kg/day. Overall, phosphorus loads from agriculture (mostly dairy farming in the west Fleet) and the STW's (particularly the larger works at Abbotsbury) are both important, and both occur in the western Fleet (Mainstone & Parr 1999). Again, all these inputs discharge into the poorly flushed part of the Fleet west of Chickerell.

4.8.3 Distribution and fate of nutrients

Within the Fleet lagoon itself, there is a west-east trend in nutrients. This trend is due to:

- ! Higher overall nutrient loadings to the west Fleet than to the east, i.e. higher inputs of phosphorus and also potentially significant inputs of nitrogen (although the east Fleet receives relatively higher inputs of nitrogen);

- ! Greater flushing (and dilution) of the east Fleet. On average the western Fleet has residence times varying between 10 days during high runoff conditions and 40 days during drought, whereas the eastern Fleet is flushed clear over a few tidal cycles (Robinson 1983); see Section 4.6 for further assessment of flushing times. The weak tidal flushing over the western Fleet basin would result in ponding of freshwater inputs and associated dissolved and suspended substances.

Data obtained during surveys clearly shows freshwater influence waning from Abbotsbury eastwards and that nutrient concentrations decrease with increasing salinity when all the sites are plotted out (EA 1998a), but this is a mere correlation. Salinity might be of relevance as an indicator of which nutrient is limiting plant growth, but this is no longer considered to the case, i.e. nitrogen limitation is just more frequently associated with marine waters (Carvalho, pers. comm.). A more useful indicator is the ratio between nitrates and phosphates. Table 4.8 gives estimates of the N:P ratio based on the survey data from Table 4.2, using dissolved available nutrients. All the figures fall close to the critical ratio of between 15:1 and 10:1. Therefore it is uncertain which nutrient would theoretically limit growth first except perhaps at Smallmouth where it is more likely that nitrate is limiting. It is suggested that both nutrients may limit plant growth to varying degrees at different times of the year. However, in practice, nutrients are unlikely to be limiting in the Abbotsbury embayment at present because concentrations are excessively high throughout the year; it can only be postulated as to whether this would be the case under natural conditions.

Table 4.8 Estimated N:P ratios at sites within the Fleet using dissolved available nutrients. N is derived from TON plus ammonia. (Based on means from EA nutrient data for April 1996-August 1997.)

Site	N:P ratio
Abbotsbury Swannery	14.56
Langton Hive	15.89
Chickerell Hive	15.69
The Narrows	12.06
Smallmouth	10.34

4.8.4 Bioavailability

In terms of bioavailability of nutrients, and their possible effects on the lagoon in terms of potential for eutrophication, the timing and location of nutrient inputs, as well as their relative size, is vitally important. Inputs entering the Fleet at the western end during the spring and summer are potentially significant due to reduced dilution in summer because of lower rainfall in summer combined with the poor seawater flushing of the western end of the Fleet compared with the east, and the fact that spring/summer is the main plant and algal growing season. Inputs from agriculture may be considerable, but the main periods for nutrient inputs from such sources are in winter during periods of higher rainfall when agricultural ground may be bare and crops are not using up nutrients. However, such nutrients, particularly phosphorus, are likely to become incorporated within the lagoon sediments during winter and taken up by plant growth during spring and summer. It should be noted that whilst most algae (including benthic species as well as plankton and epiphytes) receive all of the nutrients from the water column, most other macrophytes, including charophytes, also utilise sediment sources (Carvalho pers. comm.).

4.9 Assessment of change in conservation interests in response to nutrient levels

4.9.1 Information from assessing biota

There appears to be no reliable historical evidence for a decline in either *Zostera*, *Ruppia*, or stonewort *Lamprothamnium papulosum* populations in the Fleet since the late 1960's. There appear to have been changes in *Zostera* and *Ruppia* distributions with time, but these appear to have been natural changes, associated with hard winters and ice damage, or recovery of *Zostera* from the wasting disease in the 1930's.

With respect to *Lamprothamnium papulosum*, however, it is possible that it was common in the Abbotsbury embayment during the last century, as samples from the Natural History Museum collected then are labelled as taken from Abbotsbury (L. Carvalho, pers.comm.). However, no published data are available to confirm whether this was the case: publications in the Fleet Study Group archive only indicate its presence along the northern shores of the lagoon further eastwards, where it was reported as thriving in 1991 (Holmes, 1993). Sampling in 1998 failed to find any *Lamprothamnium papulosum* at Abbotsbury (A.Martin, pers. comm.). If, however, the environmental requirements of *Lamprothamnium papulosum* are considered, it is likely that the species has been affected at the western end of the Fleet. Studies indicate that the species appears to be absent from potentially suitable sites when levels of soluble reactive phosphate are greater than 30 µg/l-P, and is most frequently found where levels are less than 10 µg/l-P (Martin, 1999). Mean levels of orthophosphate (approximately equivalent to soluble reactive phosphate) at Chickerell Hive, Langton Hive and in the Abbotsbury embayment exceeded 20 µg/l-P from 1996 to 1997, with mean levels below 10 µg/l-P found only at Smallmouth (EA 1998a).

There is little information on lagoonal invertebrate or fish populations in the Fleet, and certainly not enough to determine whether significant changes in their populations have taken place.

There is no reliable evidence either for increases in epiphytic or benthic green algal growth which might affect species of conservation interest. However, the lack of evidence appears primarily due to a lack of quantitative historical information on populations of green algae. The review of historic literature in the FSG archive suggests that lush spring and summer growths of epiphytic and benthic green algae on the *Zostera* and *Ruppia* beds in the Fleet, as well as in the Abbotsbury embayment where seagrass is sparse, have occurred certainly since the late 1960's and probably earlier. However, there have been no quantitative surveys to determine whether the species composition of such growths has changed or not, or whether the density of algal growth has increased or decreased over this time.

Furthermore, there is no reliable evidence for increases in phytoplankton growth which might also affect species of conservation interest, and might indicate nutrient enrichment. Again, the lack of evidence appears primarily due to a lack of quantitative historical information on plankton. Algal blooms have been recorded at the Abbotsbury end of the Fleet on a number of occasions since 1969 (Whittaker 1980, Saunders-Davies 1993, John 1995, EA 1998a), mostly during particularly warm dry summers. Blooms in 1969 and 1976 were associated with fish deaths, and possibly with farm pollution incidents, but it is not known which species of plankton were involved. The species involved in the later blooms varied, and some blooms were not of toxin-producing species (eg. that recorded by John (1995) mentioned above).

In conclusion, the only evidence from the Fleet of detrimental change in conservation interests in response to nutrient levels is:

! a possible decline in the distribution and population of *Lamprothamnium papulosum* at the western end of the Fleet. Research on the species in the Fleet and elsewhere suggests a critical threshold of soluble reactive phosphate between 10 µg/l-P and 30 µg/l-P.

However, caution is required as there is insufficient information from which to draw conclusions with respect to:

! increases in growth of epiphytic algae;
! increases in growth of benthic green algae;
! increases in phytoplankton blooms;
! impacts on fauna.

The known and potential impacts of the first three of these on conservation interests, particularly seagrass *Zostera,* are described in Section 3 although there is little evidence to identify critical thresholds of nutrient concentrations with respect to deleterious increased growth in epiphytic algae, benthic algae and phytoplankton. These impacts, and the lack of information, indicate that it is not possible to conclude whether there has or <u>has not</u> been an impact on conservation interests.

4.9.2 Information from assessing nutrients

Indications of intensification of agricultural land use around some parts of the Fleet led to concern that this might result in increased nutrient inputs to the Fleet from surface water run-off and thus more frequent algal blooms and increased green algal growth. The work by EA since 1996 on nutrient concentrations of inputs to the Fleet as well as the Fleet itself (EA 1998a and 1998b) has indicated that the Fleet and its freshwater inputs do have high nutrient concentrations. However, there is no clear evidence of increases in nitrogen or phosphorus concentrations, primarily due to a lack of sufficient data on past water quality to allow identification of trends. Nutrient concentrations found by John (1995) and the Environment Agency (EA 1998a) are broadly similar, with the exception of the very high nitrate concentration (372 mg/l-N) found by John (1995) on one occasion in Mill Stream (Abbey Barn). Because of the small number of measurements, no firm conclusions can be drawn as to whether nutrient concentrations have increased since 1995. It is also not clear whether algal blooms are increasing or decreasing in incidence or intensity.

However, it is unlikely that there will have been a major change in the short time since 1995. To consider trends in relation to changing agricultural practice we really need to estimate nutrient status over the last 50-100 years (see Section 4.10).

Considering the information that is available, different statements can be made about the eastern and western parts of the Fleet. There would seem to be no nutrient enrichment or potential for eutrophication of the eastern, more marine end of the Fleet. Primary sources of nutrient inputs to the Fleet do not appear to include seawater entering the Fleet. There are very few, or only minor, stream inputs into the eastern Fleet. Run-off from agricultural land is likely to result in nitrogen loading to the east Fleet. However, tidal flushing of this eastern part of the Fleet occurs regularly. It is likely that even if nitrates were not flushed out, they would have little biological effect. This is because the main inputs are in winter, the period during which problematic species, such as phytoplankton, are least able to utilise increased levels of nitrates.

By contrast, however, all the work undertaken during this study indicates that there is a potential problem with nutrient enrichment of the western part of the Fleet, in particular of the Abbotsbury embayment. The major sources of nutrient inputs occur to the western part of the Fleet, with the Abbotsbury embayment receiving diffuse inputs from agriculture, and direct inputs from three streams, two of which include treated sewage effluent, as well as being the location of the swannery. In addition, flushing of this part of the Fleet by seawater and, particularly during the summer months, by freshwater is very poor. There is also a peak in inputs (of phosphorus) during the summer. As a result of these factors, there is a high potential for plant and algal species of concern, such as phytoplankton, to increase in numbers due to these nutrient inputs. Furthermore, winter inputs of phosphorous may be indirectly utilised as a result of poor flushing, incorporation into the sediment and subsequent uptake by plant and algal growth during the spring.

It is likely that increases in nutrient inputs to the western Fleet have caused or will cause increases in epiphytic algae on seagrasses, green algal mats and phytoplankton populations. Any such increases are likely to be detrimental to the health of:

! eelgrass and tasselweed beds by increased epiphyte and benthic algal growth, and increased water turbidity restricting light availability to the plants;

! foxtail stonewort (*Lamprothamnium papulosum*) due to increased competition from green algae and direct effects of increases in phosphate concentrations;

! lagoonal invertebrate and fish populations by increasing the likelihood of harmful anoxic conditions near the sediment surface and in the water column overnight due to increased green algal growth, and by algal blooms in warm conditions either being directly toxic to invertebrates or fish, or by reducing oxygen available to them during post-bloom decay of algal cells.

4.10 Implications for management of the Fleet

4.10.1 Basis for management response

From the study of the Fleet there is little direct evidence that nutrient inputs are having a detrimental effect on the conservation interest of the lagoon, except possibly *Lamprothamnium papulosum*, or that nutrient inputs have significantly increased in recent years and from which sources. Both of these conclusions are due to a lack of historical information rather than being based on available evidence. There is, however, circumstantial evidence for both scenarios (see, for example, Dean 1996, Elton 1991, Holmes 1983, and John 1995), and there have been changes in land use around the Fleet, particularly intensification of agriculture, that would be expected to increase nutrient inputs (see Section 4.8.2). Furthermore, knowledge of lagoons and lagoonal biota indicate that features of conservation interest in the Fleet, as defined in the site's conservation objectives, are sensitive to nutrient enrichment.

From a site management point of view, the following combination of points should be noted:

- there is some evidence for an impact on the foxtail stonewort and circumstantial evidence for increases in green and planktonic algae (see references in previous paragraph and EA 1997c, EA 1999) which would have an impact on several conservation interests such as seagrass;

- circumstantial evidence suggests that nutrient inputs from anthropogenic sources have increased over time, i.e. the last few decades;

- nutrient budget and distribution studies indicate probable nutrient enrichment, the timing and location of which could cause eutrophication;

- several features of nature conservation importance in the Fleet are sensitive to impacts from nutrient enrichment;

- several features of nature conservation importance in the Fleet are therefore vulnerable to impacts from nutrient enrichment;

- lagoon features which may have been impacted or which could be impacted are of high (international and national) nature conservation interest as reflected in the conservation objectives for the European marine site;

- based on studies elsewhere, a system such as the Fleet may enter a self-perpetuating condition of nutrient enrichment and eutrophication through internal recycling.

Taking these points together, a precautionary approach would suggest that, even though some further work is required (see Section 4.11), steps should be taken to reduce nutrient inputs to the Fleet that are proportionate to the likely costs of taking no action. Other further work recommended in Section 4.11 is directed towards helping to identify appropriate management measures. The question then arises as to the priorities for management.

The studies thus far clearly indicate that the priority is for reducing inputs to the western part of the Fleet. Whilst it is likely that phosphorus is of more concern than nitrogen, consideration should be given to reducing inputs of both nutrients. Taking account of the sources of nutrients identified thus far, whether manifest as peaks in summer or winter, management measures should address, in priority order, agricultural sources, Abbotsbury STW and the swannery.

4.10.2 Management options

Point sources, i.e. STWs and to a lesser extent the swannery, are more amenable to control than diffuse sources such as from agriculture and wildfowl not based at the swannery. In all cases, it is recommended that use is made of the model developed by Cardiff University to determine the effects of changing inputs and to assist in verifying prioritisation of potential changes. This will also assist in assessment of the cost effectiveness of any such changes.

Agricultural sources: Since agricultural inputs of both nitrogen and, particularly phosphorus, have been found to be significant, at least in winter, implementation of agricultural Best Management Practices[5], as already advocated by the EA, is recommended as a first step. Effects of such changes in agricultural practices on nutrient inputs to the lagoon should be modelled by running the Cardiff University model developed for the Fleet under different scenarios, to determine the priorities for action. A mechanism for this may be to target agri-environment funds at the catchment, which would ease implementation of less intensive agricultural practices.

Abbotsbury STW: Options for nutrient reduction in the effluent from Abbotsbury STW should be considered as, although it is not the major source of phosphorus to the Fleet, it discharges to the most sensitive area, and provides bio-available nutrients during summer when algal and plant growth are at a maximum. The mechanism for achieving this is full appropriate assessment under the Habitats Regulations which is, therefore, recommended. The assessment should confirm whether nutrient reduction is required and the best option for achieving this. If required, there are a number of options for reducing phosphorous inputs which would need to take account of the fact that this is a small works (see Mainstone *et al* 2000).

In addition to addressing current sources of nutrient inputs, it is recommended that there should be a presumption against any new discharges to the Abbotsbury embayment. Any application for a new discharge should be subject to an appropriate assessment, as would normally be the case, during which due consideration should be given to the potential effects and precautionary approach set out herein.

Wildfowl: Consideration of any practical measures which might reduce nutrient inputs from the swannery should be made, as it was identified by the modelling as a significant source of phosphorus during summer. Such measures might include changing the location of feeding stations, collection of runoff from feeding and nesting areas, and simple treatment of runoff (e.g. by settlement) before discharge to the Fleet. It is not clear, however, how much of the phosphorus input to the lagoon

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[5] BMPs: aim to keep fertilisers on the field where they belong and out of watercourses where they may do harm. They include nutrient and pesticide management plans, conservation tillage, crop residue management, critical area planting, early establishment of winter cereals on high risk land, compaction management and careful positioning of field access points (M. Tucker, pers. comm.).

from wildfowl is derived from recycled phosphorus from herbivorous wildfowl feeding on the seagrass and algae, before excretion into the lagoon; this may merit further investigation. It is also apparent that swannery managers are already putting into place measures to reduce inputs as much as possible.

In addition to the above management measures, current monitoring of water quality parameters should continue and be adapted as appropriate.

A range of work is also recommended to further investigate relevant issues within the Fleet, to help determine other priorities for action, and to assist with management of the site. These are elaborated on below.

4.11 Further work recommended for the Fleet

The following outlines obvious areas of further work, prioritised where possible. It does not elaborate on work currently being undertaken, for example the water quality monitoring programme now in place and current research on environmental requirements of *Lamprothamnium papulosum*. The following should provide a steer to the management group for the statutory site and relevant authorities on priorities for further work but may also inform studies undertaken by members of the Fleet Study Group.

Overall, the emphasis should be on establishing an adequate baseline against which changes can be assessed, including components of the community such as phytoplankton, and completing and refining our understanding of the nutrient budget in order to effectively target management measures.

4.11.1 Biological features

Condition monitoring: As a priority, monitoring of the condition of biological features likely to have been affected and or to respond to inputs of nutrients, e.g. *Zostera*, *Ruppia* and *Lamprothamnium papulosum* and green algae, particularly in the western part of the Fleet, should be undertaken.

Monitoring should build on previous work, e.g. see Holmes (1993) for methods and sampling sites, but should also take account of developments in monitoring, e.g. the use of remote sensing methods (such as aerial photography and CASI (Compact Airborne Spectral Imager)), which may prove to be cost effective, and provide a permanent record which can be re-analysed in future if required. However, care should be taken that new methods allow comparison with existing data, or are carried out in parallel with methods used in the past. Where quantitative and qualitative surveys of biota of conservation interest have been carried out in the past, these should be continued at suitable intervals, with the aim of detecting any changes should they occur.

Current work will contribute to establishing the current distribution of foxtail stonewort *Lamprothamnium papulosum* throughout the Fleet and to use of CASI. The condition monitoring programme planned for the site is likely to cover all of these attributes (see Annex C; English Nature 1999).

Phytoplankton: There is a need to undertake a baseline survey of plankton over at least a year to determine frequency of algal blooms and type of organism causing the blooms. Samples should be collected for plankton and preserved using iodine for later counting. These samples could then be analysed in batches as convenient. Such a time series of samples would help to characterise the plankton of the Fleet, including detecting blooms, and help to identify, in conjunction with nutrient monitoring, whether planktonic populations are nutrient limited, and by which nutrients.

It is suggested that as a minimum monitoring of phytoplankton as part of on-going monitoring (as opposed to survey to characterise the site) is achieved through measuring the surrogate attribute of light attenuation.

However, if funds allow, direct monitoring of phytoplankton would be preferable to identify which species are involved. Corresponding monitoring of zooplankton populations may indicate how they affect phytoplankton distribution. Consideration should be given to undertaken such monitoring in parallel with periodic surveys of fish populations mentioned, as these will in turn affect zooplankton populations.

Research: A number of aspects of the biota of the Fleet relevant to conservation interests merit study and include, in suggested priority order based on the degree of effort required and application of the results obtained:

! **Green algae:** A review of Holmes' data from seagrass surveys carried out in 1983, '85 and '91 to look at spatial distribution and density of green algal growth on the seagrass beds in the Fleet may help in determining whether changes in green algal populations have occurred over recent years. When Holmes carried out his seagrass surveys, he recorded presence of benthic and epiphytic algae, but these data were not analysed fully for the reports in the FSG archive.

! **Historical data on *L. papulosum*:** Investigation into the historic distribution of foxtail stonewort *Lamprothamnium papulosum* by analysis of sediment core samples for oospores will help to ascertain whether there has been a decline in distribution of this species, in particular in the Abbotsbury embayment, since the last century. This must be accompanied by attempts to establish the past nutrient status, particularly of phosphorus, of the Fleet. Current research is likely to contribute significantly to this topic (see Martin 1999).

! ***Lamprothamnium* physiology:** If funds allow, distribution data for *Lamprothamnium* could be supplemented by quantitative survey of physiological performance along re-locatable transects so that trends can be more objectively assessed over time.

! **Historical data on phytoplankton**: Palaeoecological investigations by analysis of sediment core samples from the Abbotsbury embayment for past history of plankton populations may assist in determining if plankton blooms have always been a feature of this part of the Fleet, or if they are a more recent phenomenon. The shallowness of the Fleet may make such analysis difficult to interpret, as water currents will affect the distribution of planktonic remains (Li, 1997).

In the case of studies using cores, it would be preferable to date levels within the cores to as fine a resolution as possible.

4.11.2 Nutrient levels

The data on nutrient levels within the Fleet could be investigated further with the following identified as a priority:

- **Current nutrient levels:** It is suggested that it would be relatively easy and cost effective for Fleet Nature Reserve staff (and Swannery staff) to collect and freeze filtered and unfiltered water samples from one or two sites on a weekly basis over the summer months for later analysis of nutrients (nitrate, nitrite, ammonia, total nitrogen, soluble reactive phosphate and total phosphorus, with perhaps also silicate and carbon, and chlorophyll a). This could be undertaken in conjunction with the phytoplankton survey recommended above.

4.11.3 Nutrient sources

In order to address significant gaps in the nutrient budget and assist in focussing management measures, the following work should be undertaken in recommended priority order:

Sources not estimated

In situ (sediments): The role of sediments in nutrient flux with lagoon water is likely to be important and needs to be addressed, in particular for phosphates which tend to be bound onto sediments. Determining the sediment Equilibrium Phosphate Concentration around the Fleet, particularly in the vicinity of Abbotsbury, would be of value. There may also be considerable cycling of nitrogen between plant matter and the water column over any year as plant material dies back (and is eaten and excreted by wildfowl) over autumn and winter. It would also be of value to model the seasonality of the swannery inputs including the loadings to the sediment. Research work on these aspects is therefore recommended.

Groundwater: Groundwater movements and water quality could not be assessed during the current study, and were therefore excluded from the modelling process by EA. However, the study by WRc on diffuse sources of nutrient inputs to the Fleet identified this source as possibly significant. Study of groundwater movement and quality for the Fleet is therefore recommended, in order to either eliminate it as a significant source of nutrients, or include it in the modelling and consider whether management of groundwater quality should be considered.

With respect to sources that were estimated, more refined budget modelling, e.g. at the sub-catchment level, would be of value to verify where the nitrogen and phosphorus sources are and to understand the spatial and seasonal nutrient budget estimates of both diffuse (see section 4.3.5) and point source loads.

Sources estimated

Agriculture: Agricultural sources appear from the modelling done so far to be the most significant source of nitrates to the Fleet, particularly in winter, and also a significant source of phosphate, again particularly in winter. Further work involving analysis of remotely sensed images and field survey could be carried out to better refine the estimates of inputs from agricultural sources for the Fleet. This may need to be done in order to target particular areas for farming Best Management Practices (BMPs) as advocated by the EA. However, given that it has been demonstrated that agricultural sources of nutrients are significant for the Fleet, adoption of BMPs for the whole of the Fleet catchment, if not already in place, would be desirable. If this were the case, only limited further refinement of the estimates of inputs would be required.

Point discharges (STWs)

The modelling studies have indicated that Abbotsbury STW is the only point source discharge which is likely to be significant in terms of nutrient inputs to the Fleet. There is likely to be a summer increase in population served by Abbotsbury STW, as Dorset is a prime holiday area, but no information is available on this at present. Investigation of seasonal variation in nutrient concentrations with corresponding effluent flow data from Abbotsbury STW is therefore recommended. Information from this investigation can then be fed into the model developed by Cardiff University to further refine estimates of the significance of this source of nutrients and the likely ecological effect of decreasing discharges.

Wildfowl: Populations of wildfowl using the Fleet are already monitored on a regular basis. This monitoring should continue. In addition, further existing information on swan and other wildfowl populations should be obtained, as these appear to be a significant source of nutrients, in particular of phosphate, in the Abbotsbury embayment during summer. Have the summer populations of swans significantly increased in recent years? Has the spring/summer feeding regime changed? Could it be modified to reduce the quantities of feed and faeces entering the lagoon itself?

NB - It should be borne in mind, when devising a programme for, and considering results of, routine monitoring of water quality, that extreme events may be critical in influencing ecological issues for a system such as the Fleet, and may well be missed by routine monitoring. For example, exceptionally cold winters have had a profound influence on the distribution of *Zostera* spp. in the Fleet in the past. Storms may also reduce salinities and increase flushing on an irregular basis. Little can be done proactively to determine the effects of such events, but given a good baseline of survey data, *ad hoc* surveys following such events may help in determining their importance to the Fleet system.

4.11.4 Other aspects

Hydrographic modelling: To assist management, further testing and application of the hydrodynamic modelling is recommended (see section 4.6), particularly running simulations of nitrate and phosphate distributions and refinement of the model based on additional bathymetric data and influence of bed roughness including as a result of vegetation.

Hindcasting: One line of investigation not used in the Fleet which may be appropriate is that of hindcasting (see Johnes *et al* 1994 and Scott *et al* 1999). This could be undertaken using the technique of catchment nutrient export modelling. This requires determining the relationship between human activities and nutrient inputs from the catchment and then using historical information on changes in human activity, such as land use, to determine past inputs. Such an approach could build on the nutrient budget modelling undertaken thus far and further refinement of estimates of inputs as suggested above. However, such modelling does rely on good quality historical land-use data. It should be noted that there are concerns that the calibration method employed by Johnes *et al* is not statistically valid for hindcasting purposes (Carvalho pers. comm.).

Until current research is completed it is not possible to conclude whether the palaeoecological studies suggested above (section 4.11.1) could also contribute to hindcasting.

Use of a "reference" site:. Another line of investigation not used in the Fleet study which may be appropriate would be to compare the Fleet with a similar lagoon site that is largely free of anthropogenic impact. Finding such "reference" sites is notoriously difficult and in the case of the Fleet there are few lagoons of the same type and size (the most similar in physiographic terms is in northern Scotland). However, parts of the Fleet are likely to behave similarly to many lagoons and the Fleet supports communities and species found at other sites. It is recommended that monitoring data from other relevant lagoonal SACs is assessed in conjunction with data from the Fleet to assist in distinguishing between more global and more local changes to features of interest.

4.11.5 Other water quality issues

Pesticides: Investigation into use of terrestrial herbicides such as Atrazine on farmland adjacent to the Fleet should be carried out. Exposure to levels of Atrazine of 100 ng/l over 21 days has been found to result in growth inhibition and 50% mortality of *Zostera marina* in the US (Davison and Hughes 1998). Indications from the Environment Agency are that use of Atrazine may be significant for the Fleet, as it is used on maize crops, which are known to be cultivated in the Fleet catchment (M. Tucker pers.comm.). If this herbicide is used locally, literature study, followed if necessary by surveys, should be carried out with the aim of determining whether significant concentrations may enter the Fleet via run-off from agricultural land. Surveys should be carried out at a time when herbicides would be expected to leach into the Fleet or its freshwater streams, which will depend on timing of application, as well as on rainfall. Sampling of soils and Fleet sediments may also be advisable, if the herbicide is found to be likely to bind to particulate matter.

5. Guidance on investigating and managing water quality in saline lagoons

5.1 Introduction

The purpose of this section is to draw out lessons from the Fleet case study and to use these, together with other principles and practice, to help inform those involved with managing other lagoon sites for nature conservation as to what is required in understanding water quality issues, possible management options, and associated monitoring. Where appropriate particular learning points from the case study are included by way of illustration. Throughout, cross reference is made to sections within the case study where more detail on approaches, methods, etc can be found if required.

For information, the reader should refer to Cole *et al* (1999) for more detail on specific water quality issues, e.g. background on nitrates, in conjunction with the present report. That report (particularly section 7), together with guidance being drawn up by the Environment Agency, English Nature and Countryside Council for Wales (Applying the Habitats Regulations to new Environment Agency permissions and activities: draft procedures and technical guidance), provide guidance on assessing water quality impacts with respect to consents (e.g. for discharges) within the framework of the Habitats Regulations

5.2 Relevance of the Fleet to other lagoons

In considering and extrapolating the lessons from The Fleet study, it is prudent to note both the similarities and differences between the Fleet and other lagoons sites. Whilst every site is unique in some way there are also a number of characteristics of the Fleet which are common to a range of other lagoon sites.

Physiography and habitat: Whilst the Fleet lies near the mid-range for size of lagoons in the UK (from less than 0.1 ha to 860 ha) it is larger than most lagoons. As a consequence, the communities it supports may be less sensitive to change (natural and anthropogenic) than those of smaller lagoon sites. Conversely, where change does occur it may be more difficult to reverse the impacts of such change than in smaller lagoons. The Fleet is representative of the main lagoon type, by area, within the UK. However, because of the clear divisions across the site, the western part of the Fleet in particular has some characteristics of smaller and more enclosed lagoons such as percolation lagoons.

Biological communities: Larger lagoons tend to include a greater diversity of habitat types and, therefore, to support a more diverse community of species. In that sense, the Fleet is representative of larger lagoons. However, as a result, the site also includes many of the communities and species found in most lagoons in the UK, e.g. both UK species of *Zostera* and of *Ruppia,* 5 of the 10 lagoonal species protected under the UK's Wildlife & Countryside Act 1981. It therefore provides a useful model from which to extrapolate on the impacts of nutrients on particular communities and species such as *Lamprothamnium papulosum* (See Table 5.1).

Nutrient sources: The Fleet is bordered by agricultural land, with several freshwater stream inputs – many other lagoon sites are more isolated from agricultural land, and have more diffuse freshwater inputs (e.g. percolation, groundwater seepage), which may be much more difficult to measure and quantify, yet may be significant sources. Where the population is more spread out and not connected to mains sewerage there may be numerous septic tanks which may discharge to a lagoon. Where urban areas are adjacent to a lagoon, or border a stream input to a lagoon, there may be storm sewage outfalls whose location may not be known, and which may contribute significant amounts of nutrients sporadically during storm events. Whilst the presence of the swannery is unique in the UK**,** the work on the input from the swans is relevant to estimating inputs from wildfowl on other sites. On small sites, in particular, wildfowl populations may be relatively significant to the nutrient budget.

Level of study: The study of historical information from the Fleet has been greatly assisted by the existence of the Fleet Study Group and its archive at Weymouth College, which has meant that data relating to the Fleet from various sources is collected together and easily accessible. This situation is unlikely to exist for other lagoon sites. It is unlikely that much historical information exists for other sites, and what does exist may be difficult to identify and obtain as it is likely to be spread amongst different agencies and locations.

Concerning more current studies and identification of potential sources of nutrient inputs, this has been relatively easy as a result of the work carried out by the Environment Agency on sewage discharges and freshwater flows. For some lagoon sites, identification and measurement of potential sources may be much more difficult, for example where:

! groundwater may be a major source of water input to a lagoon, flows and nutrient content of such inputs may be difficult and/or expensive to measure;

! seawater percolation is a major source of water input to a lagoon, flows may be very difficult to trace, measure or estimate;

! significant water exchange only occurs during extreme events, e.g. storms affecting isolated lagoons, which is very difficult to predict and measure, but which may, nevertheless, bring in or export significant quantities of nutrients.

Management: In addition, most of the land bordering the Fleet has been owned and managed for many years by a private estate, which has meant that few significant changes in its management have occurred, and those that have, have been documented. It is likely that there have been minimal changes in management at many lagoon sites. It is less likely that on many other lagoon sites, such changes have been have documented, although the information is probably available for some sites in Scotland (Downie pers. comm.).

Table 5.1 Saline lagoons in which the foxtail stonewort *Lamprothamnium papulosum* is known to occur (based on DETR 1999, Thorpe *et al* 1998, Martin pers. comm. and authors' own information).
*** = sites within SACs**

Fleet (lagoonal inlet)*	Oban nan Stearnan (silled)*
Fort Gilkicker Moat (sluiced)*	Oban a' Chlachain (sluiced)
Harbour Farm lagoons (isolated)*	Oban nam Fiadh (silled)*
Great Deep (sluiced)	Oban na Curra (sluiced)
Normandy Farm (sluiced)*	Alioter Lagoon (sluiced)*
Eight Acre Pond (sluiced)*	Oban Honary (lagoonal inlet)
Ardmore lagoon (sluiced)	Lochan Sticir (sluiced)
Loch Ceann a' Bhaigh (sluiced)	Loch an Duin (sluiced)*
Loch a' Bharp (lagoonal inlet)	Loch Strumore (sluiced)*
Loch Ba Alasdair (silled)	

5.3 Guidance on investigating water quality impacts in saline lagoons

5.3.1 Process

The process of investigating water quality and its effects on saline lagoons should follow the principals of any risk assessment, i.e. determining the risk of exposure of features of interest (in this case of conservation interest) to factors or processes to which they are sensitive and identifying activities or operations which contribute to such factors. The degree to which all of these aspects are investigated will depend on the site but in most cases the process should begin with defining the features of interest; in the case of European marine sites this is done through the conservation objectives.

As an example, the process in investigating nutrients in the Fleet in relation to conservation features is shown in Figure 5.1.

5.3.2 Key studies

Different investigations, or studies, will be required to inform and support different stages in the investigation process. Good, quantitative and qualitative baseline surveys of the biological features of conservation importance are not enough on their own to be able to attempt to determine the causes of any changes in communities observed. It is essential to have corresponding data on important environmental variables (such as nutrients) and on other aspects of the biology of the system which may affect the features of conservation interest.

Studies required will include one or all of the following interrelated studies:

- features of conservation interest, including associated biota which might affect them;
- relevant aspects of water quality which might affect such features;
- collation and review of historical information;

- ! hydrological and physical regime of the lagoon, to better understand the observed pattern of, or what affects, both biological features and water quality;

- ! activities which might affect any of the above.

The need to undertake all of these studies, and the associated resource implications, will largely depend on the sensitivity of the features, the degree to which they are vulnerable and the level of understanding of site specific issues. At any stage in the process, should the available information indicate that there is no concern, e.g. that the features of interest do not coincide with the part of the site where elevated nutrients occur and that they are not vulnerable, then there is no need to undertake further detailed studies.

Case study: key studies
The project on the Fleet involved a number of related studies. Some of the work had already been undertaken, some was already planned, and other work was initiated. In effect, however, the site has been subject to a series of complementary studies in response to a succession of different questions (see **Figure 5.1**). There was some evidence that features of interest are sensitive to impacts due to nutrient enrichment and also evidence to suggest that the site may have low recoverability from such adverse impacts. Thus, there was a need to gather information to determine the vulnerability of the features. Again, there was sufficient evidence, but only when drawn from several sources, to indicate that the features were potentially vulnerable and to justify further work to elucidate more fully the nature and cause of the potential impact and to inform possible management measures. Figure 5.1 provides an overview of the links between the various studies on the Fleet and indicates the progression through studies that provide better resolution, and more confidence, in identification of the impacts, but with increasing cumulative costs.

The approach and methods to each of the studies listed above are described in detail in relation to the Fleet investigation in **Sections 4.3** to **4.6**, and guidance on each is outlined below.

5.3.3 Features of conservation interest

The purpose of any investigation is to define the conservation interest, their quality and distribution.

On any site there will almost certainly be a need to undertake a survey to at least identify, if not to characterise, the biological features present, and assess their conservation importance and sensitivity to particular water quality parameters. Such surveys should follow guidelines currently being developed by the UK Marine SACS Project (see Hiscock 1998), although the need for comparison with historical studies may require modification in some cases. Trials to develop monitoring techniques and strategies to inform these guidelines have highlighted that at some sites, e.g. Loch nam Madadh lagoons, survey work may be a relatively damaging activity particularly where the site is subject to little other activity (Downie pers. comm.). Any negative implications of a survey would need to be weighed against the benefits of undertaking such work.

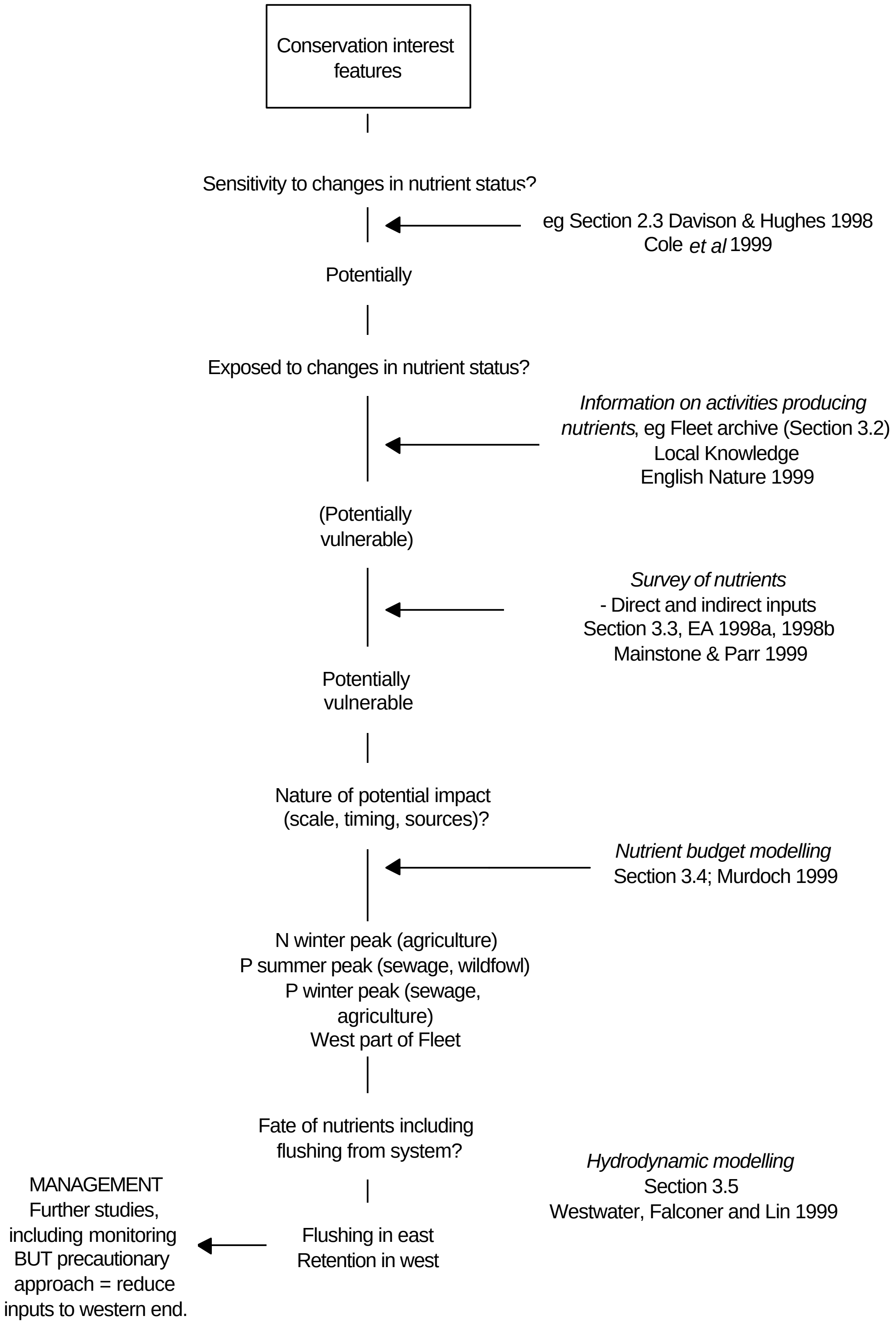

Figure 5.1 Steps in investigating impact of nutrients in the Fleet. Numbers refer to text within section 3, references are mainly studies reviewed and summarised in this report

Any survey undertaken must be quantitative as well as qualitative, in order to detect any changes which may occur. The scope of such surveys will be site dependent, but for example should include some or all of the following (in approximate priority order):

- spatial distribution (mapping), species composition and quality of vegetation, such as seagrasses, *Ruppia*, charophytes, pondweeds and reed beds;

- presence and distribution of specialist lagoonal invertebrates;

- distribution and species composition of other invertebrate communities;

- distribution and species composition of fish populations;

- spatial distribution (mapping) and species composition of algae (benthic and epiphytic) which may affect communities of conservation importance;

- spatial distribution (mapping) and species composition of grazing invertebrate populations which may affect communities of conservation importance;

- studies of bird populations which may affect communities of conservation importance (e.g. by grazing, preying upon other species, or nutrient input);

- distribution and species composition of plankton (phyto- and zooplankton), including frequency and species composition of blooms if relevant.

Timing, frequency and spatial extent (i.e. no. of sites surveyed) of the above surveys will vary for each component, and to some extent depend upon financial and time resources as well as the characteristics of the site. Seasonal variation in communities should be taken into account when planning such surveys.

There is a need to take account of information on the known sensitivity of biological features of interest. Such information, if available, is likely to be derived from studies elsewhere or from relevant reviews such as those undertaken as part of the UK Marine SACs Project (see, for example, Davison and Hughes 1998, Elliott *et al* 1998) as well as herein (**Section 3**).

Case study: conservation features affected
A number of conservation features of interest in the Fleet appear to have been, or potentially could be, affected by impacts from nutrient enrichment. In priority order these are:

- charophyte species - directly, i.e. physiological response, and indirectly, i.e. competition from opportunistic species;
- seagrass and tasselweeds - indirectly, i.e. competition from opportunistic species;
- fauna associated with charophytes, seagrass and tasselweed beds - indirectly through impacts on host vegetation.

There is a suggestion that another indirect impact is the exposure of fish species to toxic phytoplankton as a result of blooms caused by nutrient enrichment.

5.3.4 Activities

The purpose of studying activities around the site, or within its catchment, are two-fold. In the first instance, it is to determine whether there are any activities being undertaken which generate factors to which conservation features are sensitive, i.e. to determine potential vulnerability of those features, and therefore to assess whether further studies, particularly of water quality parameters, are required. Secondly, where further studies indicate there is a need for management, more detailed information on activities may be required to determine the most effective management measures; such information will be partly gathered by monitoring and modelling of relevant inputs to the site (see next section).

The degree to which contributing activities are differentiated, e.g. breaking down "agriculture" into different farming practices, will depend on the information available and the information required to implement effective management measures. Work around the Fleet, and review of potential water quality issues in lagoons, indicates that activities to be considered are likely to include some of all of the following:

- agriculture (direct run-off, via streams, via atmosphere, changes in land use) (see **Section 4.4.5**);
- point discharges - both direct and indirect via streams (sewage treatment works, storm overflows, private) (**Sections 4.4.1, 4.4.2, 4.4.4**);
- atmospheric discharges (**Section 4.4.5**);
- run-off or pollution incidents from adjacent urban or industrial development;
- dumping of waste;
- wildfowl (see **Section 4.4.5**);
- developments that affect or change the physical structure of the lagoon, including channels within it, leading to reduced flushing or seawater ingress, including percolation, e.g. coastal defence works;
- development/abstraction reducing freshwater input and subsequent effect not only on salinity but also flushing.

5.3.5 Water quality

The main purpose of these investigations is to make an initial assessment as to whether water quality is or may be having an impact on the conservation features, usually having ascertained that conservation features may be vulnerable (see previous section).

Survey of water quality parameters should ideally be carried out to coincide with biological surveys but will also need to be carried out more frequently to identify seasonal and annual trends as a minimum. Sampling or, where this is not possible, estimates of nutrient concentrations, for example, should include:

- ! the water body itself (at various points, depending on size of lagoon & hydrological regime) (**Section 4.4.3**);

- ! point source inputs - sewage treatment works and other discharges, storm overflows, marine inflow (for inlet, silled or sluiced lagoons), streams (**Sections 4.4.1, 4.4.2, 4.4.4**);

- ! diffuse source inputs - agriculture, atmospheric, groundwater, percolation, wildfowl, other (**Section 4.4.5**).

Which parameters?: Nutrients measured must be total nutrients in the waters (including those incorporated into planktonic biomass), as well as measured in the forms in which they are likely to be available for plant and algal growth. Suggested determinands include:

- ! total and bioavailable nutrients, i.e. total nitrogen, total phosphorus, nitrate, nitrite, ammonia, and appropriate measure of phosphate such as Soluable Reactive Phosphate (preferable to orthophosphate which is a theoretical parameter that is not analysable directly, Mainstone pers. comm.). Bioavailable nutrients should be measured on filtered water samples. Measurement of silica and carbon may also help in determining limiting nutrients, in particular for plankton growth;

- ! temperature, salinity, pH, turbidity, chlorophyll a;

- ! Sediment Equilibrium Phosphate Concentration (see Mainstone *et al*. 1996).

Flow data: Surveys or monitoring of nutrient concentrations of potentially significant inputs to lagoons **must** include quantification of flows of these sources, so that nutrient loads can be calculated. Inputs may have high concentrations of nutrients, but be of low flow, or vice versa. Concentrations alone are not adequate to be able to calculate nutrient budgets to ascertain the relative importance of each source to the lagoon. Estimated or modelled flows can be used at a crude level if necessary, i.e. where direct measurements are not available or costs preclude direct measurement. However, measurement of flows at the time of sampling for concentrations would be preferable and daily gauged flows even better.

Case study: estimation of flows
In the Fleet (see **Section 4.5**), a fairly crude model using existing data allowed rough prioritisation of sources of nutrients. Flows were estimated from mean flow statistics using the Institute of Hydrology's Micro Low Flow methodology (Murdoch 1999). However, use of calculated estimates of flows introduced error to the load estimates, which could be reduced if flow information for the sources were available.

Sampling frequency, intensity and timing: Nutrient concentrations of potential sources must be measured under a variety of different conditions, e.g. during summer and winter (particularly as time of year may be critical to bioavailability of nutrients and therefore biological response to nutrient enrichment), diurnally, and over a long enough period to characterise them (e.g. at least one year). Thus, frequency of survey is likely to be much greater than for biological components as rapid changes in water quality can occur.
There should be sufficient frequency of sampling to determine trends over several years. If resources permit, diurnal variations should also be investigated.

A balance should be struck between number of sites surveyed and frequency of sampling. A spread of sites sampled at low frequency, combined with a few of these sites sampled for fewer parameters, but much more often, will usually give the most useful results. An initial, wider spread of sites (for example, for Year 1) may then allow focussing in on fewer sites where effort should be directed. Where hydrological modelling has been undertaken it should be possible to better target sampling sites.

Estimating diffuse inputs: Sampling and measurement of diffuse inputs (of flows in particular) may be difficult or impossible. Where this is the case, estimation using available models or indirect measurement may be the best option. Even then, a significant amount of work may be required to produce sufficiently resolved data, e.g. to identify critical run-off pathways, e.g. to provide realistic estimates of atmospheric loads. The level of detail gone into will depend on the site and how necessary it is to target management measures effectively.

In the case of the Fleet, estimates of diffuse loads were produced from export coefficients. Such estimates need to be calibrated in some way against measured loads in the receiving waters (Mainstone and Parr 1999). This requires that point source loads are also estimated and the sum of point and non-point source estimates are compared with observed loads entering the lagoon. Export coefficients may then need to be adjusted to provide a better fit with measured loads. Five stages to producing the nutrient budget may therefore be identified (Mainstone and Parr 1999):

- estimating point source nutrient loads;
- estimating diffuse nutrient loads;
- estimating nutrient loads in waters entering the lagoon;
- comparing nutrient loads estimated by export coefficients with loads estimated from receiving water monitoring;
- modifying export coefficients if necessary.

Case study: diffuse inputs
The study to estimate diffuse inputs included atmospheric deposition, agriculture, wildfowl, groundwater and streams (and point sources) **see Section 4.4.5**. Although a number of concerns remain over the reliability of several aspects of the data on which estimates were made, the results provide an indication of the relative contributions from different sources.

Knowledge of cycling of nutrients between sediments and the water column in enclosed or partially enclosed systems such as lagoons may be critical. However, it is recognised that relevant data may difficult or expensive to obtain. As a consequence, it is suggested that in general this element of the nutrient budget is investigated only after other elements have been considered such as diffuse and point sources and the water body of the lagoon.

5.3.6 Review of historical information

A review of historical information on the site is suggested as an important study should assessment of biological features, activities, and water quality parameters, to which such features may be sensitive, give cause for concern or require further investigation. For most lagoon sites, there will be little or no published information (see **Section 4.3** for the Fleet). For unpublished information, the following should be contacted as a first step:

- for biological information on species or communities of conservation importance, as well as communities likely to affect them - local and national conservation agencies, local wildlife or naturalist groups, local authorities and in some cases information held at local and other Universities or Colleges or marine laboratories or institutes;

- for information on water quality and on hydrographic and physical aspects of the site - Environment Agency (EA) or Scottish Environment Protection Agency (SEPA), local authority or local water company, and in some cases information held at at local and other Universities or Colleges or marine laboratories or institutes.

5.3.7 Hydrological regime

The purpose of studying the hydrological regime is to determine the movement and fate of water quality parameters, e.g. nutrients, within the site and therefore to better understand the interaction between these and features of conservation interest, to help target monitoring or further survey, and to inform the development of management measures by providing a predictive tool.

Relevance: The hydrographic regime has a profound influence on the conservation interest of most lagoons, and the factors affecting such interests. Therefore, investigating the hydrographic regime of any lagoon will be crucial to many management measures intended to maintain its conservation interest. Models of annual nutrient budgets are useful at a coarse level to help determine the importance of different nutrient sources but are not sufficient to properly target nutrient sources for further study or reduction in flows or concentrations and predict the outcome of changing inputs through management measures. Deterministic models allow predictions of effects of changing concentrations or flows of all the sources included in them. It is therefore possible to target sources which will make a difference, and avoid ineffective action and use of funds. Use of such models is, however, unlikely to be able to incorporate the effects of extreme events such as storms etc. which may well be important in lagoons.

Type of model: Models which take into account the hydrographic conditions within the lagoon and incorporate seasonal variations (dependent on rainfall, inflow and flushing characteristics) have been shown by the Fleet study to be essential. The hydrographic conditions within many lagoons will be complex and difficult to ascertain, and will vary between different lagoon sites. Within a single, larger lagoon (such as the Fleet) the lagoon may be divided into different parts with very different hydrographic conditions (see **Section 4.6**). In terms of seasonal variation, in the Fleet, for example, seasonal growth of seagrass affects flows because the lagoon is so shallow.

Many saline lagoons, at least of the inlet type, will be similar to the Fleet in being characterised by unusual hydrodynamic properties. The case study has demonstrated the need to develop numerical hydraulic models more suitable to shallow, relatively low flow systems than many current models developed, for example, for estuaries. Therefore, use of appropriate models is recommended (see **Section 4.6** for detailed discussion). Such models will need to be adapted to each individual lagoon site, and should be capable of predicting the effects of changes in flows and nutrient inputs over a range of conditions.

Data required: Knowledge of tidal regimes and freshwater flows into and out of the lagoon (including via groundwater and percolation) will be required. Where separate lagoons are close together, their hydrological regimes may be interconnected (eg. by channels, percolation, or groundwater transfer), and knowledge of this will be required in order to determine sources of nutrients and possible remediation strategies if necessary.

At a coarse level, some of the above parameters can be estimated for inclusion in a crude model. However, in order to estimate better the importance of different sources of water and nutrients, further, more refined data and studies will usually be necessary. These may include studies of the local tidal regime, local bathymetry (especially if it is complex), freshwater, discharge and diffuse input flows (and their variation), percolation and groundwater quality and flows. Building of a more complex model may be expensive, but once constructed it may prove invaluable for future management of the site. Such models can be used to run scenarios and predict the effects of suggested changes to any of the parameters included in them.

Case study: data to underpin hydrological modelling
For the Fleet study, good hydrographical data were available from earlier studies (Robinson 1983 and Robinson *et al* 1983) which could be used for both crude and more detailed modelling. This is unlikely to be the case for other lagoon sites. Even with this existing data, due to the shallow nature of the Fleet lagoon and its complex shape, further bathymetric information was required in order to construct a reasonably accurate model of its flow regime. Problems were encountered with use of the new bathymetric data (location and depth of small channels were not fully represented), which could be avoided given better communication between the modellers and the surveyors or commissioning agency on what data were required and from where.

5.3.8 Co-ordination of studies and organisations

It is critical that any studies to investigate water quality are conducted in a coordinated way, For example, temporal co-ordination of biological, water quality and hydrographic surveys would help enormously in interpretation of data obtained.

Case study: co-ordination of surveys: In the Fleet, there was, perhaps surprisingly, little corresponding data. Reasonable data were available on the distribution and health of seagrass beds over time. However, there were no corresponding nutrient data, nor any suitable data on plankton or algal grazer communities which may affect the seagrass beds. Some data on green algae were available from the seagrass studies, but have not been analysed fully. **See Section 4.3**

Co-ordinating studies requires co-ordination between the various agencies and others involved in funding, survey, interpretation of data and lagoon management, such as has occurred latterly for the Fleet study. This level of co-ordination is essential for any similar project, to allow feedback of information and inform further survey and management of the site. It is likely, as found in the Fleet, that surveys and investigations involving <u>different</u> disciplines will probably be carried out by <u>different</u> agencies and/or contractors. In such cases, it is essential to form a project group to co-ordinate the work and facilitate interpretation of data as far as possible. It is recommended that the project group should include representatives of each of the agencies involved in management of the site, as well as representatives of each of the groups carrying out the different aspects of site survey and data analysis (including modelling) and perhaps those with a local specialist knowledge of the site.

Case study: co-ordination of relevant parties: In the Fleet further water quality data was collected by those undertaking the nutrient modelling that was not being gathered through routine monitoring. The project group for the Fleet study demonstrated good linkage between statutory authorities and the research community, as has been the case in relation other aspects of the Fleet through the Fleet Study Group. However, in relation to physical modelling it is apparent from the bathymetric survey that even closer liaison should have occurred between those undertaking the modelling and those actually collecting relevant data in the field.

5.3.9 Resources required

Funding and time constraints will determine the level of detail to which each of the following can be carried out, within what timescale, and by whom. As an indication of the order of costs required to undertake similar studies of other lagoon sites, approximate costs for each aspect of the Fleet case study are as follows:

Aspect of study	Approximate cost (excl. VAT)
Review of historical data, synthesis of modelling and monitoring studies carried out so far, recommendations (at commercial rates)	£7000
Water quality survey and monitoring studies (at Environment Agency internal rates)	£10,000
Nutrient budget modelling using existing data (at commercial rates)	£8000
Estimation and modelling of diffuse sources (at commercial rates)	£5000
Construction of physical model for the Fleet (CASE award studentship contribution)	£4000

Costs at full commercial rates for the survey and monitoring studies, and the construction of the physical model, will be several times higher than the costs given.

The Fleet is reasonably accessible. It is likely that costs for more remote sites, including many sites in Scotland, would be greater for those components of the study that involve field work.

5.4 Guidance on managing water quality impacts in saline lagoons

5.4.1 Basis for management response

Owing to poor water exchange in many lagoons or parts of lagoons, by the time a change in biota of conservation importance is detected, and the change is attributed to changes in nutrient inputs, it may well be too late for biological interests of the site to recover within the sort of time frame employed in management planning, e.g. five to twenty five years. This is because responses to nutrient enrichment in other systems similar to lagoons have been found to be self-perpetuating, i.e. once they begin to occur they create conditions which further create deterioration, and the few studies from lagoons support this (see **Section 3.4.5)**. Lagoons, such as isolated lagoons, or parts of lagoons such as the head end of lagoonal inlets where flushing is poor, are likely to be most susceptible to this. Stratification of the water column, if it occurs, will also affect what happens in terms of nutrient recycling within any lagoon.

As a consequence, it is recommended that a precautionary approach should be adopted for relevant lagoon sites, or parts of sites, taking account of the conservation objectives for the site, i.e. that proportionate management measures should be considered even where there is only limited evidence of an impact. In deciding upon management measures, it should be noted that the later these are initiated the more costly they may become.

Case study: basis of management response

In addition to evidence from the site, the recommendations for management measures in the Fleet take account of the importance and sensitivity of the biological communities and species concerned, e.g. environmental requirements of charophytes, and studies from elsewhere, e.g. nutrient recycling within other partially enclosed systems. In summary:

- There is (only) limited evidence for impacts on features of nature conservation importance from nutrient enrichment.
- Several features of nature conservation importance in the Fleet are sensitive to impacts from nutrient enrichment.
- There is circumstantial evidence that nutrient inputs have increased over the last few decades.
- There is therefore a potential risk that the impact to which features are sensitive will be realised, i.e. features of conservation importance are vulnerable.
- Studies elsewhere suggest that there is a low potential for recovery should such impacts occur and, indeed, that such impacts may be sustained in the long-term.

Taking these points together, particularly the latter, it is appropriate to act on the precautionary principle and recommend reducing inputs of nutrients. Given this precautionary approach, the cost of any management actions will need to be proportionate to the benefits gained.

5.4.2 Management options

Management strategies will depend on the conservation objectives for the site, financial resources, and the findings of the historical and baseline surveys. Some measures may need to be introduced before data collection is completed, depending on the findings of the surveys.

Management strategies are likely to involve various agencies and groups for different aspects. Ideally, they should therefore be coordinated by a single group. On European marine sites, this function would sensibly fall to the management group and be outlined in the management scheme document for the site. Management, monitoring and collection of additional baseline data will be closely interrelated and will feed back to each other. Regular reviews of management practices against monitoring data should be carried out, and both modified as appropriate depending on the findings of the reviews. *Ad hoc* reviews should also be undertaken as appropriate, as extraordinary events dictate (e.g. as particular development pressures arise or where unusual meteorological events may affect monitoring data).

Where excessive growth of macrophytes appears to be affecting features of conservation interest, including the system as a whole, consideration may be given to physically removing this material, as done in several cases (e.g. see Hodgkin and Birch 1986; e.g. semi-enclosed Cuckmere estuary in Sussex (Curzon pers. comm.)). Such an option should be assessed very carefully to determine that it will not cause other, potentially greater, impacts than the presence of the material being removed. Physical cropping will not address excessive growth of phytoplankton. More importantly, it only addresses a symptom and does nothing to tackle the cause(s) of the problem.

Where it is concluded that nutrients are or may be adversely affecting saline lagoon features of interest, there are a number of management measures that could be considered depending on the causal activity. These include:

- **Agriculture:** options range from voluntary to statutory mechanisms. Voluntary measures should be explored as a preference. In all cases, the success of proposed measures should be developed and implemented in close cooperation with the local (farming) community. Mainstone *et al* (2000) and Hodgkin and Hamilton (1993) provide overviews of tackling agricultural sources of nutrient loading and the latter discussed community involvement. Options include:

    - Best Management Practices (BMPs) for farming to retain nutrients on fields and reduce inputs to water courses or directly into the site; note that such an approach is consistent with codes of practice advocated for farming practice anyway, including both application of nutrients (see MAFF 1998) and soil erosion (MAFF 1999). The economic benefits of more effective fertiliser use should be highlighted;

    - in England and Wales, identification of contribution from agricultural sources of diffuse pollution within Local Environment Agency Plans (LEAPs);

    - considering the potential for adopting measures as part of an Environmentally Sensitive Area (ESA) status requirement, or, locally (and more readily), under Countryside Stewardship, e.g. use of buffer zones along field margins;

- identifying the catchment as a Nitrate Vulnerable Zone under UK legislation in fulfilment of the EC Nitrates Directive. Note, this measure does not address phosphates;

- other statutory mechanisms are potentially available and may merit investigation, such as the use of Water Protection Zones under the 1991 Water Resources Act.

- **Point discharges**

  - increased level of treatment at sewage works, e.g. tertiary treatment to remove phosphates or nitrates. In many cases, such as the Fleet, sewage works discharging to lagoons, or streams feeding the lagoons, are likely to be relatively small and this will therefore influence the chosen option for reducing inputs of phosphorus, e.g. phosphorus stripping is usually not recommended for small works for various reasons including difficulties in controlling the level of dosing (Bunting pers. comm.). See Mainstone *et al* (2000) for discussion of options for reducing phosphorus inputs from point sources;

  - timing of discharge, eg to coincide with optimum flushing period during tidal cycle;

  - relocation of discharges.

- **Other**

  - wildfowl: where these are managed through feeding, revise feeding regime to optimise food utilisation and minimise waste.

5.4.3 Monitoring

Monitoring is required to review and ensure the effectiveness of management measures and, in the case of statutory conservation sites, to report on the condition of features for which a site is designated. The actual monitoring programme will be site specific, depend on the resources available, and frequency will vary according to the attributes and parameters to be monitored. The above studies will highlight for any lagoon site those aspects of the environment which should be monitored, and give an indication of the frequency and extent required.

It is recommended that monitoring is undertaken to determine the condition of features of conservation interest including other biological features which indicate or affect these. Monitoring will also be required of relevant water quality parameters, both as an indication of attributes critical to the condition of conservation features, e.g. light attenuation, but particularly with respect to inputs where there is concern about these (some of which will be achieved by monitoring compliance with, for example, licensed discharges).

Guidance on methods for monitoring features of conservation interest are outlined in Hiscock (1998). Consideration should also be given to timing of monitoring surveys. For example, *Lamprothamnium papulosum* should be monitored in summer as it dies back in winter. Bamber *et al* (in prep.) discuss the required frequency of monitoring in detail. The requisite frequency of monitoring will partly depend on the sensitivity of different lagoons and/or species it supports, e.g. a small isolated lagoon is likely to be more sensitive to environmental impact than a large lagoonal inlet, the importance of the site, and site-specific aspects, e.g. is it exposed to a factor to which it is sensitive. Inevitably, funding will be another consideration and the monitoring programme will result from a compromise between this and other considerations. It is therefore important to provide guidance on a minimum standard for monitoring.

As a guide, for biological features, annual monitoring will certainly detect presence or absence, and may reveal changes in density or distribution, or species. More frequent (e.g. seasonal) monitoring may assist in understanding the life cycle of a species (for example timing of recruitment) and in identifying an optimum time(s) of year for monitoring, but the merit of the information gained would have to be balanced against the additional cost. In both cases any indication of a significant change would require a specific study to investigate cause and effect and help identify a management response.

It is suggested that for most biological features (with the exception of plankton studies), monitoring will need to be repeated at regular, but relatively infrequent intervals. On statutory nature conservation sites, including European marine sites, the minimum frequency is every 6 years (JNCC 1998). Where significant change is detected, or where the sensitivity or vulnerability of the sites merits it, the frequency may need to be greater.

A compromise option would be to take and preserve samples at additional times and archive them without sorting or analysis; then should a significant change be detected by less frequent monitoring, the archived samples can be retrospectively analysed to assist in determining cause and effect and its timing.

Depending on management issues, monitoring of water quality attributes will need to be carried out relatively frequently, and will need to take account of seasonal variation. For example, it is important to monitor for salinity conditions at times of highest and lowest salinity, normally late summer and mid-winter/early spring, respectively. It is recommended that, initially, monitoring is undertaken quarterly, and ideally monthly if possible, to build up a picture of the seasonal regime and to fully characterize the baseline for the site. Such monitoring should encompass both neap and spring tides. It is suggested that the scope of such surveys be reduced (i.e. select only a few sites to sample for only a few parameters), but that the frequency of sampling be maintained (e.g. monthly or weekly during summer, less frequently during winter). Periodic, more extensive surveys can then be coordinated with the less frequent biological monitoring surveys.

Guidance on methods for monitoring water quality parameters and/or modelling is provided in Scott *et al* 1999.

Hydrographical modelling, where undertaken, is likely to help determine effective location of sampling sites for monitoring of both biological features and water quality parameters.

For all aspects of lagoon systems, exceptional events (e.g. unusual meteorological conditions, or particular development pressures) or detected changes should trigger additional monitoring or baseline surveys, or may direct sampling to different areas or aspects of the lagoon system. Monitoring should be kept under regular review by the relevant management group.

5.5 Further research required on water quality in saline lagoons

5.5.1 Environmental requirements and sensitivity of biota

More information on the sensitivity of features of conservation interest to changes in water quality parameters, particularly nutrient concentrations is required. This should be information which could be extrapolated between lagoons of different types but with similar biological communities.

Scientific investigation into the optimum nutrient requirements of *Zostera* and *Ruppia* would be useful. Both appear to require moderate nutrient enrichment in order to thrive, but suffer from excessive competition and shading from algae in conditions with excessive nutrients. Little information has been found during the present study on what constitutes excessive nutrients for seagrasses and tasselweeds, or which nutrients may be crucial in this respect. Furthermore, much of the literature on seagrass and nutrients relates to seagrass beds on sand or muddy sand habitats, which tend to be naturally poor in nutrients (at least in terms of retention), whereas in most lagoons where they occur seagrass beds are associated with muddy habitats.

A limited amount of information is available on nutrient requirements of stonewort *Lamprothamnium papulosum*, and the species is subject to on-going research; depending on the results of such research further detail may be required, e.g. autoecological aspects such as oospore viability and germination conditions.

Controlled laboratory studies could contribute to an understanding of these issues. However, there is a risk in such studies of confounding effects as a result of laboratory, versus natural, conditions. Where appropriate field studies could be designed, it is suggested that the Fleet would provide a suitable site for undertaking autoecological studies in support of the above.

5.5.2 Nutrient budget

Further study of cycling of nutrients in lagoons between sediments, vegetation and the water column may be very important in terms of ascertaining the bioavailability of nutrients, and assessing the likely effectiveness of any management measures introduced to control nutrients in lagoons. This information should be able to be extrapolated to other lagoon sites with similar sediment characteristics.

Lagoons may often be systems with relatively high nutrient concentrations, but too little is known about what is natural/normal in terms of nutrients in lagoons. Baseline and monitoring studies of lagoonal SACs will assist in building up an information base on water quality in lagoons. Periodic reviews of such data from all lagoons in the UK (and elsewhere) would assist in formulating monitoring and management plans for individual lagoon sites.

One line of investigation not used in the Fleet study which may be appropriate is that of hindcasting (see Johnes *et al* 1994 and Scott *et al* 1999). The approach is based on catchment nutrient export modelling and involves determining the relationship between human activities and nutrient inputs from the catchment and then using historical information on changes in human activity, such as land use, to determine past inputs. Such an approach could be followed on the Fleet, building on work already undertaken for the case study.

Another approach might be to take contemporary measurements from a site largely free of anthropogenic impact as an indication of background (surrogate for "natural") levels. In the case study of the Fleet it is concluded that it would be difficult to find a comparable "reference" site; this is likely to be a limitation for many sites.

Depending on the feasibility of using lagoonal sediments, based for example on the results of the research on *L. papulosum* and attempts to derive a diatom-phosphorus model (Martin 1999), there may be merit in undertaking palaeoenvironmental studies of lagoon sites (hindcasting the biological response) to understand better the natural nutrient characteristics of lagoons. The diatom-phosphorus model will almost certainly require further development to provide more robust phosphorus reconstructions by increasing the number of sites used in the training set (Carvalho pers. comm.).

5.5.3 Fate of nutrients

The hydrodynamic properties of systems such as the Fleet have not been taken account of in numerical hydraulic models. More extensive research is required in the future into studying the effects of these complex hydrodynamic properties, particularly as it relates significantly to the transport of fluid mass and solute contaminant and water quality indicator fluxes in tidal wetlands including large lagoons.

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Annex A. List of saline lagoon Special Areas of Conservation in the UK

Lagoonal SACs in the UK are listed below in order around England and Scotland, starting in eastern England. There are no lagoonal SACs in Wales or Northern Ireland. Many of these SACs include a number of individual lagoons.

North Norfolk coast and Gibraltar Point Lagoons (Norfolk) A number of small percolation lagoons, eight between a shingle ridge (Blakeney Spit) and saltmarsh. The fauna of the lagoons includes nationally scarce lagoonal species the starlet sea anemone *Nematostella vectensis* and the lagoon shrimp *Gammarus insensibilis.* Other species of note include the relatively rare opossum shrimp *Paramysis nouveli.*

Benacre to Easton Bavents Lagoons (Suffolk) Percolation lagoons behind shingle barriers. They support a range of lagoonal vegetation types, including beds of narrow leaved eelgrass *Zostera angustifolia* in fully saline or hypersaline conditions, beds of spiral tasselweed *Ruppia cirrhosa* in brackish water and dense beds of common reed *Phragmites australis* in freshwater. The site supports a number of specialist lagoonal species including the anemone *Nematostella vectensis* .

Orfordness to Shingle Street (Suffolk) A series of percolation lagoons in a shingle bank. The fauna includes typical lagoonal species such as *Cerastoderma glaucum*, the ostracod *Cyprideis torosa* and the gastropods *Hydrobia ventrosa* and *H. neglecta.* The nationally rare starlet sea anemone *Nematostella vectensis* and lagoon sand shrimp *Gammarus insensibilis* are also found at the site.

Solent and Isle of Wight Lagoons (Hampshire & Isle of Wight) A series of lagoons at four locations mainly of isolated and sluiced types in coastal grazing marshes and behind sea walls. The lagoons have a range of salinities and substrata, ranging from soft mud to muddy sand with a high proportion of shingle. They support a diverse fauna including large populations of three notable lagoonal species: the nationally rare *Lamprothamnium papulosum*, the nationally scarce lagoon shrimp *Gammarus insensibilis* and the nationally rare *Nematostella vectensis*. Species diversity in these lagoons is high.

Chesil and the Fleet (Dorset) The Fleet is the largest example of a lagoon in England and has features of both lagoonal inlets and percolation lagoons. The lagoon is situated to landward of Chesil Beach, with a narrow entrance to the sea in Portland Harbour. It supports extensive populations of two species of eelgrass (*Zostera noltii* and *Zostera angustifolia*) and three species of tasselweed *Ruppia*, including the rare tasselweed *Ruppia cirrhosa*, and a diverse fauna that includes a number of nationally rare and scarce species. The eastern end of the lagoon is almost fully marine, with tidal narrows systems with rich and unusual fauna including sponges and anemones.

Loch Roag Lagoons (Lewis, Outer Hebrides) A complex of silled lagoons with a range of salinities, and a diverse range of habitats, including rocky outcrops, boulders and muddy sand, with softer mud in the inner basins, cobbles and shell gravel in the narrows. Beds of eegrasses *Zostera* spp. and tasselweeds *Ruppia* spp., turfs of marine algae and stands of large brown algae are present.

Obain Loch Euphoirt (Loch Eport obs, North Uist, Outer Hebrides) One of the most extensive and diverse systems of rock bound silled lagoons in the UK (with Loch nam Madadh). Consists of a complex of four lagoons, which together support the complete range of physical conditions and communities characteristic of this part of Scotland. Loch Obisary is unique among the brackish basins of the UK on account of its size, depth (over 40m), permanent hydrographic stratification and the range of communities it supports. Other lochs within the system support the nationally rare stonewort *Lamprothamnium papulosum*, beds of eelgrasses *Zostera* spp. and tasselweeds *Ruppia* spp.

Loch nam Madadh (Loch Maddy, North Uist, Outer Hebrides) Loch nam Madadh lagoons form the most extensive and diverse saline lagoon system in the UK, consisting of 10 lagoons, interconnected with freshwater lochans and the fjardic sea loch of Loch nam Madadh itself. There is a wide range of types from large, complex lagoons with several sills and basins, to single shallow lagoons, encompassing the full transition of salinity from freshwater to fully marine conditions. Rock bound silled lagoons in Europe are virtually restricted to the Outer Hebrides in Scotland. Most basins are floored with soft peaty mud, with boulders and cobbles, especially around the margins. At the entrances to some of the lagoons there are tidal rock and boulder waterfalls, or rock and coarse sediment rapids, or percolation barriers. There are beds of dwarf eelgrass *Zostera noltii*, small patches of *Zostera marina* and large quantities of the scarce green alga *Cladophora battersii*, and the scarce stonewort *Lamprothamnium papulosum*. Tidal rapids have kelps, calcareous maerl algae, and sea oak *Halidrys siliquosa* with rich epiphytic growths of sponges, ascidians and anemones.

Loch of Stenness (Orkney) A single basin with characteristics of silled lagoons and lagoonal inlets. It is the second largest brackish lagoon in the UK, and is of particular importance on account of its size, stability, reduced salinity regime and northern location. Lagoon bed is predominantly soft mud, with sand, gravel and pebbles around the margins. Mats of filamentous green algae occur, with large numbers of mostly marine/brackish infaunal and epifaunal species. Beaked tasselweed *Ruppia maritima*, the brackish fucoid alga *Fucus ceranoides*, filamentous green algae and the pondweed *Potamogeton* spp. occur in areas of lower salinity.

The Vadills (Shetland) A complex of eight interconnected shallow basins with characteristics of lagoonal inlets and rock-bound silled lagoons, encompassing fully marine to brackish conditions. Soft peaty mud forms the substratum in the basins, with narrows between basins with increased tidal currents supporting the calcareous alga maerl. Eelgrass beds *Zostera marina* and tasselweed *Ruppia maritima* occur in the sheltered basins, with rock tidal rapids supporting brown algae with rich associated epifauna. The site supports several unusual invertebrate species and communities, and the free living fucoid alga *Ascophyllum nodosum* ecad. *mackaii*, for which this is the northernmost record in the UK.

Annex B. Summary from Davison and Hughes (1998)

Davison, D.M & Hughes, D.J. 1998. Zostera biotopes *(Volume 1): an overview of dynamics and sensitivity characteristics for conservation management of marine SACs.* Scottish Association for Marine Sciences. (UK Marine SACs Project.)

Project context and study aims

A number of sites around the UK of high scientific and conservation importance have been designated as marine Special Areas of Conservation (SACs) under the terms of the EU Habitats and Species Directive. As a contribution to the development of management plans for marine SACs, scientific reviews have been commissioned of the dynamics and sensitivity characteristics of selected biotope complexes found at some or all of the sites. These reviews are intended to summarize the available information relevant to conservation management, including the ecological characteristics of each biotope complex, its conservation importance, its sensitivity to natural and human-induced environmental changes, and the monitoring options suitable for use in marine SACs. Attention is focused on 12 candidate SACs selected as 'demonstration' sites. This report covers biotopes characterized by eelgrasses (*Zostera* spp.). *Zostera* beds can occur in five of the seven broad habitats defined in Annex I of the Habitats Directive, namely 'Lagoons', 'Estuaries', 'Large shallow inlets and bays', 'Intertidal mud and sand banks' and 'Sandbanks covered by sea water at all times'.

Nature and importance of the biotope complex

Seagrasses are marine flowering plants found in shallow coastal areas around the world, typically on sheltered sandy or muddy substrata to a maximum depth of about 10 m. Seagrasses often grow in dense, extensive beds or meadows, creating a productive and diverse habitat that provides shelter and food for a wide variety of other plant and animal species. Seagrass beds thus constitute an important reservoir of coastal biodiversity. In addition, the beds provide food for wildfowl and for the juveniles of some commercially-important fish species. The dense root networks of the plants stabilize the underlying substratum and so act to reduce coastal erosion. Seagrass beds are therefore of considerable economic and conservation importance. Increasing human pressures on the coastal zone have led to losses of seagrass beds in many parts of the world. The importance and vulnerability of these biotopes therefore make them a high priority for management and conservation efforts.

In the British Isles, three species of eelgrass of the genus *Zostera* occur, common eelgrass *Z. marina*, narrow-leaved eelgrass *Z. angustifolia*, and dwarf eelgrass *Z. noltii.* It is possible that *Z. angustifolia* is a variety of *Z. marina* rather than a distinct species (and it is usually so regarded by authorities outside the British Isles). However, most of the UK literature makes a specific distinction between *Z. marina* and *Z. angustifolia*, a convention followed in this report. All three eelgrasses were once abundant and widespread around the British coasts, but serious declines have occurred, in particular as a consequence of a severe outbreak of 'wasting disease' in the early 1930s. Recovery of eelgrass beds since the 1930s has been slow and patchy, and all three *Zostera* species are now considered nationally scarce in the UK.

Distribution in the UK and elsewhere

Zostera marina is the largest of the three British eelgrasses and typically occurs in the shallow sublittoral down to about 4 m depth, in fully marine conditions and on relatively coarse sediments. The species is still patchily distributed around most of the British coastline, with concentrations of recent records in south-west England and the west coast of Scotland. Elsewhere, the species occurs throughout the Atlantic and Pacific coastlines. *Zostera angustifolia* is an intertidal plant found from mid- to low-tide mark, usually in poorly-draining muddy sediments. The species is typically found in conditions of variable salinity, often in estuaries. In Britian, *Z. angustifolia* has a more easterly distribution than *Z. marina,* with concentrations in the Solent, Thames Estuary, and Moray and Cromarty Firths. Narrow-leaved, intertidal forms of *Zostera marina* are known in Europe and North America, and probably correspond to the form designated as *Z. angustifolia* in the UK. Dwarf eelgrass, *Z. noltii* occurs higher on the shore than the other two species, typically on mixtures of sand and mud. In the UK, recent records are clustered in the Thames Estuary area, Moray and Cromarty Firths, and in Argyll. Outside the UK, *Z. noltii* occurs in the eastern Atlantic from southern Norway to the tropic of Cancer.

Eelgrasses can be found in several candidate or possible SACs around the UK, with one or more species occurring in 10 of the 12 'demonstration' sites considered by the UK Marine SACs Project. Two biotopes within the MNCR classification system are defined by the occurrence of *Zostera* beds, and two within the 'BioMar' Life Form classification.

Environmental requirements

All three British eelgrass species are found on sedimentary substrata, sheltered or extremely sheltered from strong tides and currents. In more exposed sites, beds tend to be smaller, patchier and more vulnerable to erosion. The plants flourish best where the local sediments are closely balanced between the forces of erosion and accretion. Excessive sedimentation can be harmful as it tends to smother the plants. Highly turbid water also inhibits growth by reducing the amount of light available for photosynthesis. *Zostera marina* usually occurs down to about 4 m, but has been recorded as deep as 13 m in water of exceptional clarity.

The optimum temperature range for growth and germination appears to be approximately 10-15°C, but plants can tolerate sea temperatures from 5-30°C. The intertidal *Z. angustifolia* and *Z. noltii* may be damaged by exposure to frost in severe winters. *Zostera marina* is intolerant of dessication. *Zostera angustifolia* occurs intertidally, but generally in areas of waterlogged sediment. *Zostera noltii* is the best-adapted to resist aerial exposure and consequently occurs higher up the shore than the other two species. Mature *Zostera* plants have a high tolerance to salinity changes. Although *Z. marina* is not normally found in brackish water, exposure to reduced salinity appears to be necessary to stimulate flowering shoot production.

Nitrogen is usually the most significant limiting nutrient. Moderate nutrient enrichment may stimulate growth, but excessive inputs are usually harmful (see below). *Zostera* leaves provide a substratum for the growth of many species of epiphytic algae. These epiphytes may smother the *Zostera* plants unless kept in check by the grazing activities of gastropods and other invertebrates. Healthy populations of epiphyte grazers are therefore beneficial to the maintenance of *Zostera* beds. The grazing activities of wildfowl may also play an important role in preventing excessive build-up of sediment among the eelgrass plants.

Biology and ecological functioning

Leaf growth in *Zostera* takes place in spring and summer. Detached shoots or rhizome fragments may be dispersed by currents and re-establish themselves, so allowing beds to expand vegetatively. *Zostera marina* is generally a perennial plant, and maintains its populations largely by this vegetative process. Sexual reproduction by seed production does not appear to play a significant role in the life history in northern latitudes. *Zostera angustifolia* populations may be either annual or perennial. Reproduction may occur by a combination of vegetative growth and seed set, of which the latter appears to be the more important. In the UK, beds of *Z. noltii* persist mainly by vegetative growth, despite prolific seed production. The differing levels of emphasis on sexual and vegetative reproduction can result in a complex genetic structure in populations of *Zostera*.

Subtidal eelgrass beds are one of the most productive of shallow-water coastal ecosystems. Relatively few species possess the capacity to digest eelgrass leaves directly, but the detritus formed by the decomposition of *Zostera* tissue fuels food-chains both within the beds and outside them. Eelgrass detritus dispersed by currents may make an important contribution to the energy supply of biotopes far removed from the beds themselves.

Zostera beds are highly species-rich, particularly the subtidal beds of *Z. marina.* A large number of algal species occur as epiphytes on *Zostera* leaves (some species are found only in eelgrass beds). Other algae grow amongst the eelgrass or occur as mats on the sediment surface. Complex communities of fish and invertebrate species are supported by the algae and *Zostera* detritus. *Zostera* is a highly important food source for several species of ducks and geese, as shown by parallel declines in eelgrass and some wildfowl populations. *Zostera marina* was formerly the most important food source for species such as Brent geese, but has now been supplanted by *Z. noltii* in this role.

Sensitivity to natural events

Zostera beds are spatially dynamic, expanding or receding at their edges. They are subject to a number of naturally-occurring factors which can cause changes in bed extent and plant density at a range of scales. Extreme weather conditions such as violent storms or heavy floods can destroy or damage beds over wide areas. Plants may also be killed or defoliated by severe frosts.

'Wasting disease' is the single most important naturally-occurring cause of *Zostera* decline. The most serious recorded outbreak of this disease took place in the 1920s-30s, and led to widespread loss of eelgrass beds throughout Europe and North America. Recovery from this event has still been only partial. The pathogen responsible for wasting disease is a fungus, *Labyrinthula macrocystis*. This organism is probably naturally present at low levels but undergoes occasional large-scale outbreaks for reasons which are still not fully understood. It is possible that severe eelgrass losses occur only when the plants are under stress from some other factor. *Labyrinthula* does not appear to cause disease in conditions of low salinity, and so tends to affect *Z. marina* far more severely than *Z. angustifolia* or *Z. noltii.*

Grazing wildfowl can remove a high proportion of the available biomass of *Zostera* (consumption of > 90% of standing stock has been estimated in some cases). However, it is believed that eelgrass beds are normally able to tolerate wildfowl grazing pressure unless under stress from some other factor.

The consumption of epiphytic algae by gastropods or other invertebrates can be important in maintaining the health of *Zostera* plants, so that any factors leading to a reduction in algal grazer populations may indirectly also affect the eelgrass itself.

Sensitivity to human activities

Zostera beds are vulnerable to the effects of many of the major human activities in the coastal zone, including coastal development, water pollution and physical habitat disturbance. Large-scale land reclamation can completely destroy eelgrass beds over wide areas. Other forms of coastal development (eg. construction of harbours or marinas, pipeline laying, channel dredging) can also adversely affect eelgrass beds by altering the local hydrographic regime and sediment balance. Depending on circumstances, rates of sedimentation or erosion may increase, with adverse consequences for bed viability. Many forms of coastal development also cause increases in water turbidity, which will cut down the light available for photosynthesis and reduce the depth to which plants can grow.

Contamination of coastal water by heavy metals or antifoulants has not been shown to significantly affect *Zostera* plants, but agricultural herbicides are known to be harmful. Eelgrass beds do not appear to be highly sensitive to chronic oil pollution (eg. from refinery effluent). Major oil spills can inhibit growth of the plants, but in both cases, the associated fauna and flora seem to suffer more damage than the eelgrass itself. The chemical dispersants used to treat major oil spills facilitate penetration of oil into the sediment. Oil-dispersant mixtures appear to cause more damage to *Zostera* biotopes than the oil alone, and consequently the use of dispersants should be avoided in these habitats.

Excessive nutrient enrichment arising from sewage, agricultural fertilizers or aquaculture can have a variety of harmful consequences for eelgrass beds. High nitrate levels appear to cause metabolic imbalances in *Zostera*. Nutrient enrichment is also likely to cause eutrophication - the proliferation of epiphytic, benthic or planktonic algae - all of which are potentially harmful to *Zostera* plants. Stress caused by excessive nutrient enrichment (or other factors) may also render *Zostera* more vulnerable to infection with wasting disease.

Eelgrass beds are not physically robust, and the plants are easily destroyed or damaged by trampling, digging, dredging, bivalve harvesting or other forms of physical disturbance. Human disturbance may also affect the movements of wildfowl, causing them to spend longer on *Zostera* beds, with resulting increases in grazing pressure.

Two non-indigenous plants, the cord-grass *Spartina anglica* and the brown alga *Sargassum muticum* have colonized eelgrass beds in the UK, mainly in the south of England. To date, neither species appears to be a serious threat to healthy *Zostera* beds, but both can take advantage of space in eelgrass beds created by other forms of disturbance.

Human-induced climate change may ultimately have serious consequences for eelgrass beds if predictions of sea-level rise and increased frequency of severe storms prove to be accurate.

Monitoring and surveillance options

Eelgrass beds possess a range of attributes which are potentially of use to an SAC monitoring scheme. For the purpose of detecting changes in the *Zostera* biotope, the most important parameters to monitor are probably the distribution and extent of eelgrass coverage, the *Zostera* standing crop and shoot density, the condition of the *Zostera* plants (eg. leaf length, sexual status, presence of wasting disease), the occurrence of characteristic and representative species in the associated community, and the local water quality (turbidity, nutrient levels).

Of the various available monitoring techniques, airborne or sublittoral remote sensing (the latter including side-scan sonar and RoxAnn™) can rapidly map the distribution of beds over large areas, but must usually be ground-truthed by some other method. Underwater video and field observers (diving or shore survey) must be used to provide information on *Zostera* plant condition and the associated biological community.

A standardized system for mapping intertidal and shallow subtidal *Zostera* beds (for use by field observers) has been developed following a workshop organized by English Nature in 1996.

Gaps and requirements for further research

Several aspects of *Zostera* biology are still relatively poorly-understood. Further information on these would make an important contribution to the conservation management of eelgrass biotopes.

Clarification of the taxonomic status of *Z. angustifolia* and more detailed information on the current UK distribution of all three *Zostera* types could be obtained by molecular genetic studies, and by re-examination of preserved specimens. Greater knowledge of the range of morphologic and life-history variability occurring within each form of *Zostera* would enhance the accuracy of field identifications and allow more detailed predictions of the responses of populations to environmental change.

In view of the potentially devastating effects of wasting disease on populations of *Z. marina*, it is essential to gain a more detailed understanding of the biology of the causative organism (*Labyrithula macrocystis*), the factors triggering large-scale epidemics and the role of other environmental stresses in determining rates of infection and recovery.

The success of attempts to preserve *Zostera* beds in the UK depends to a large extent on identifying the factors which limit or facilitate recovery following disturbance. Manipulation of these factors will be essential to the success of *Zostera* transplantation or re-introduction programmes. Considerable efforts have been made to artificially restore seagrass beds in several areas of the world, including some attempts in the UK, but long-term success has been very limited so far.

Synthesis and application to SAC management

The three key requirements for management of *Zostera* biotopes in an SAC are firstly, to ensure that the important environmental needs of *Zostera* are met (particularly with respect to sediment balance, water clarity and nutrient levels), secondly to review and manage human activities in and around the SAC to ensure that these are compatible with the maintenance of the biotope, and thirdly, to review and assess proposals for new activities to ensure that detrimental effects are avoided.

The human activities which are most likely to affect the integrity of *Zostera* biotopes are coastal development, nutrient input to coastal waters, and physical disturbance. These will be the most important factors to be considered in any SAC managment scheme. Management guidelines arising from the EU Habitats Directive and the UK Biodiversity Action Plan allow the compilation of a list of practical measures to be undertaken at National and SAC level.

Annex C. Extract from favourable condition table for Fleet and Chesil European marine site (from English Nature 1999)

NB - Many of the attributes will be able to be monitored at the same time or during the same survey. The frequency of sampling for many attributes may need to be greater during the first reporting cycle in order to characterise the site and establish the baseline.

Feature	Sub-feature	Attribute	Measure	Target	Comments
Lagoon		Extent	Area (ha) of lagoon basin, measured once per reporting cycle.	No decrease in extent from an established baseline, subject to natural change.	Extent is an attribute on which reporting is required by the Habitats Directive. The Fleet is a large lagoon, thus size (including the length:width ratio) will critically influence the hydrography of the site. Natural gradual reduction in area of the lagoon is inevitable, however, as a result of the natural progression of Chesil Bank.
		Salinity	Seasonal averages encompassing the east-west salinity gradient measured periodically throughout the reporting cycle (frequency to be determined).	Average seasonal salinity, and seasonal maxima and minima, should not deviate significantly from an established baseline, (to be derived from the Environment Agency monitoring programme), subject to natural change.	Salinity is a key structuring factor within lagoons and in the Fleet, the gradient from west to east is particularly notable. Note should be made of natural fluctuations that occur according to year on year variations in rainfall.
		Water clarity	Average light attenuation measured periodically throughout the reporting cycle (frequency to be determined).	Average light attenuation should not deviate significantly from an established baseline, subject to natural change.	Water clarity is important for maintaining the extent and density of algal and plant dominated communities. Clarity decreases through increases in amounts of suspended organic/inorganic matter.

Feature	Sub-feature	Attribute	Measure	Target	Comments
		Nutrient status - green algal mats	Extent across whole or parts of site, measured during summer months, annually.	No increase in extent of green algal mats from an established baseline, subject to natural change.	Nutrient status is important for the structure and functioning of the lagoon and its communities. The Fleet is probably naturally hypertrophic. Opportunistic green algae compete with other vegetation and affect the associated species. A late spring/early summer increase in filamentous green algae may be a related natural phenomenon or may indicate eutrophication.
		Characteristic species - *Rissoa membranacea membranacea*	Population size - average abundance (number of individuals/m^2), measured during the summer twice per reporting cycle.	Average numbers should not deviate significantly from an established baseline, subject to natural change.	Algal grazers (largely gastropods) affect the structure of the lagoon communities by consuming benthic and epiphytic growth. *R.membranacea* is the only species amenable to quantitative survey and can be used as a surrogate for grazers as a whole.
		Characteristic species - *Lamprothamnium papulosum* (foxtail stonewort)	Density (number of plants/m^2) and westward extent, measured during summer, twice per reporting cycle.	Average density should not deviate significantly from an established baseline (to be derived from Holme (in press), Martin (pers. comm.) and 1999 seagrass survey) subject to natural change. No eastward movement in westward limit.	The foxtail stonewort (*L. papulosum*) is a species characteristically found in lagoons which requires low nutrient conditions, particularly of phosphates, and therefore provides a possible indicator of nutrient status. It is a nationally scarce species.
		Fish species assemblage	Number of composite species measured during mid-summer from the inlet channel, once per reporting cycle	Average number of composite species should not deviate significantly from an established baseline, subject to natural change.	Diverse fish community characteristic of large, inlet type lagoons, the sheltered conditions providing a nursery for a number of species. The fish community as a whole provides an integrated measure of the quality and functioning of the Fleet as well as indicating populations of the main predators.

Feature	Sub-feature	Attribute	Measure	Target	Comments
	Seagrass bed communities	Extent	Total area (ha) of seagrass measured during peak growth period (Aug), twice per reporting cycle.	No decrease in extent from an established baseline (to be derived 1991 and 1999 surveys), subject to natural change.	Seagrass (including tasselweeds) contribute to the overall community structure within the Fleet and both are characteristic, to varying degrees, of lagoons. The area of seagrass provides a long-term integrated measure of environmental conditions.
		Characteristic species - density of *Zostera marina* and *Ruppia* spp.	Density (number of shoots/ m^2) measured during peak growth (Aug), twice per reporting cycle.	Average shoot density should not deviate significantly from an established baseline, subject to natural change.	Reduction in the density of plants is an early indicator of seagrass under stress and reflects changes in biomass. *Zostera marina, Ruppia cirrhosa* and *R. maritima* co-occur in many parts of the Fleet. Monitoring both *Zostera* and *Ruppia* may be justified as they have different salinity range preferences and therefore would provide an indication of conditions in different areas along the Fleet.
	Tide-swept communities	Tide-swept communities - species composition	Presence and abundance of composite species, measured during summer, once per reporting cycle.	Presence and abundance of composite species should not deviate significantly from an established baseline, subject to natural change.	Tide-swept communities are characteristic of inlet lagoons and are therefore integral to the structure of such lagoons. The bedrock biotope, which includes a number of rare or southern species such as the sponge *Suberites massa*, is the most notable part of the community and potentially provides a long-term integrated indication of tidal flow of the Fleet and therefore of a key functional process.
	Subtidal coarse sediment (gravel, cobbles, pebbles) communities	Extent	Area (ha) of submerged coarse sediment (gravel, cobbles & pebble) communities, measured once per reporting cycle.	No decrease in extent from an established baseline, subject to natural change.	Extent of sediments in this part of the Fleet indicates proportion of a habitat that adds to the structural diversity of the site and is likely to reflect hydrological conditions.

Feature	Sub-feature	Attribute	Measure	Target	Comments
		Characteristic species - density of *Anemonia viridis*	Density (number of animals/m^2), measured during summer once per reporting cycle.	Average density should not deviate significantly from an established baseline, subject to natural change.	The stability of the sediments enabling a diverse community to develop is notable. Monitoring of the community indicates condition of a distinct section of the Fleet and of water movement etc between the mouth and the Narrows. Unusually, the anemone *Anemonia viridis* occurs in high numbers and can therefore be readily measured. The species should be used as a surrogate for the community as a whole and indicator of a change in conditions.
	Intertidal sediment communities	Extent	Area (ha) of intertidal sediment between the Narrows and Smallmouth, measured once per reporting cycle.	No decrease in extent from an established baseline, subject to natural change.	Extent of sediments in this part of the Fleet indicates proportion of a habitat that adds to the structural diversity of the site and is likely to reflect hydrological conditions in the entrance to the Fleet.
	Intertidal sediment communities	Species composition	Presence and abundance of composite species, measured during summer once per reporting cycle.	Presence and abundance of composite species should not deviate significantly from an established baseline, subject to natural change.	The infaunal community, which includes a number of rare and/or lagoonal specialist species, eg *A.cirrhosa*, is indicative of sheltered, fully saline conditions and is likely to change in relation to a number of factors including hydrological conditions in the entrance to the Fleet.
	Shingle spring line communities	Extent and distribution	Frequency and distribution of shingle springline communities, measured during summer, once per reporting cycle.	No decrease in extent from an established baseline, subject to natural change.	The spring line community is unusual and reflects both the stability of, and percolation through, the shingle bank. The extent of the community (as measured by distribution) will be indicative of saline seepages along much of the Chesil Bank

Feature	Sub-feature	Attribute	Measure	Target	Comments
		Species composition	Presence and abundance of composite species, measured during summer once per reporting cycle.	Presence and abundance of composite species should not deviate significantly from an established baseline, subject to natural change.	The spring line community, which includes notable species such as *Caecum armoricum* (De Folins lagoon snail), is unusual and reflects both the stability of, and percolation through, the shingle bank. As such the community adds to the diversity (structure) of the lagoon and will reflect processes in relation to both the shingle and percolation of sea water into the lagoon.

NB .Extreme events (such as storms reducing or increasing salinities, exceptionally cold winters or warm summers) also need to be recorded as they may be critical in influencing ecological issues in the Fleet and may well be missed by routine monitoring

Glossary of terms used in the favourable condition table

Feature The habitat or species for which the site has been selected.

Sub-feature An ecologically important sub-division of the feature.

Attribute Selected characteristic of an interest feature/sub-feature which provides an indication of the condition of the feature to which it applies.

Measure What will be measured in terms of the units of measurement, arithmetic nature and frequency at which the measurement is taken. This measure will be attained using a range of methods from broad scale to more specific across the site.

Target This defines the desired condition of an attribute, taking into account fluctuations due to natural change. Changes that are significantly different from the target will serve as a trigger mechanism through which some further investigation or remedial action is taken.

Comments The rationale for selection of the attribute.

Annex D. List and summaries of relevant references from Fleet Study Group archive

List of references from Fleet Study Group archive of relevance to water quality, and consulted during this study

Authors	Date	Title	Source	No
Brenchley, J. & Probert, R.	n.d. (1997)	*Aspects of the biology of* Zostera *in the Fleet.*	Royal Botanic Gardens, Kew (unpubl. report)	1
Li, S.	1997	*Spatial variability in diatoms and charophyte oospores in a coastal lagoon, The Fleet, Dorset, England.*	MRes Research Dissertation, University College, London	2
Bingham, N.	1997	*The response of charophytes to salinity changes in a coastal lagoon.*	MRes Research Dissertation, University College, London	3
Dean, R.	1996	*The introduction of buffer strips to control agricultural pollution of the Fleet Lagoon.*	Report for Seal-Hayne Faculty of Agriculture, Food & Land Use, University of Plymouth. BTec Higher National Diploma in Agriculture	4
Dyrynda, P.E.J.	1997	*Seasonal Monitoring of the Fleet Lagoon Aquatic Ecosystem (Dorset, UK): 1995-1996.*	School of Biological Sciences, University of Wales, Swansea for WWF-UK	5
Environment Agency	1997	Local Environment Agency Plan - West Dorset – Consultation Report [also FSG letter with comments, 25 Jan 1998]	Environment Agency	6
Holmes, N.T.H.	1993	*The distribution of* Zostera *and* Ruppia *in the Fleet, 1991*	Report to English Nature	7
Holmes, N.T.H.	1983	*The distribution of* Zostera *and* Ruppia *in the Fleet.*	Report to the Nature Conservancy Council	8
Den Hartog, C.	1989	Letter to D. Seaward on *Zostera/Ruppia*, reporting on diseased specimen from the Fleet sent to him (September 1989)		9
Ladle, M. (ed.)	1986	The biology of the Fleet. (*Proceedings of the second Fleet Study Group Symposium.*)	Dorset County Council, Dorchester.	10
Robinson, I.S., Warren, L. & Longbottom, J.F.	1983	Sea level fluctuations in the Fleet - an English tidal lagoon.	*Estuarine, Coastal and Shelf Science*, 16:	11
Weymouth & Portland Borough Council	1995	Letter detailing water quality monitoring carried out by Environmental Health Services Section & Weymouth Port Health Authority in the Fleet and Portland Harbour (letter, 11 Aug 1995).		12
Bamber, R.N. & Henderson, P.A.	1985	*Diplostomiasis* in sand smelt, *Atherina presbyter* Cuvier from the Fleet, Dorset, and its use as a population indicator.	*Journal of Fish Biology*, 26:	13
Seaward, D. R.	1987	The marine molluscs of Portland Harbour		14

Authors	Date	Title	Source	No
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Fair, J.	1987	The Fleet Sanctuary Nature Reserve		16
Saunders-Davies, A.P.	1995	Factors affecting the distribution of benthic and littoral rotifers in a large marine lagoon, together with a description of a new species.	*Hydrobiologia* 313/314:	17
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Goudie, A.S. & Ireland, P.	1978	A preliminary investigation of the water chemistry of the Fleet, Dorset.	(Submitted to Proceedings of the Dorset Natural History & Archaeological Society)	19
Nunny, R.S.	1995	The Physical Environment: Hydrography.	*Lyme Bay Environmental Survey*, vol. 1. (Kerr-McGee)	20
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Nunny, R.S. & Smith, P.R.J.	1995	Environmental Quality: Existing Contaminant Levels.	*Lyme Bay Environmental Survey*, vol. 15. (Kerr-McGee)	22
Nunny, R.S.	1995	Environmental Quality: Contaminant Dispersion Modeling.	*Lyme Bay Environmental Survey*, vol. 16. (Kerr-McGee)	23
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Seaward, D. R.	1994	*Water temperature monitoring in the Fleet SSSI*	Report to Joint Nature Conservation Committee, ref. 99F2B003	25
Cooke. W.C.	1969	*The Fleet waters*		26
Whittaker, J.E.	1980	The Fleet, Dorset - a seasonal study of the watermass and its vegetation.	*Proceedings of the Dorset Natural History & Archaeological Society*, 100 (for 1978)	27
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Moore, J.A.	1987	*Lamprothamnium* - a pioneer in the conservation of the aquatic environment.	*Plant Press: Conservation News*, Conservation Association of Botanical Societies.	29
Saunders-Davies, A.P.	1993	letter re 'algal bloom' in the Fleet, due to sulphur bacterium; water quality data.		30
Institute of Hydrology	1992	Memo from Dr Gareth Roberts to F. M. Law	Remote sensed imagery of Fleet catchment	31

Authors	Date	Title	Source	No
Little, C., Morritt, D., Seaward, D.R. & Williams, G.A.	1989	Distribution of intertidal molluscs in lagoonal shingle (The Fleet, Dorset, U.K.).	*Journal of Conchology*, 33:	32
Barnes, R.S.K.	1991	European estuaries and lagoons: a personal overview of problems and possibilities for conservation and management	*Aquatic Conservation: Marine and Freshwater Ecosystems*, 1:	33
Barnes, R.S.K.	1989	The coastal lagoons of Britain: an overview and conservation appraisal	*Biological Conservation*, 49	34

1. Brenchley, J., & Probert, R. 1997 Aspects of the biology of *Zostera* in the Fleet.

Not directly relevant - primarily concerns investigations into the seed biology of Zostera populations in their natural habitat. Comment that in the Fleet, previous reports have listed two species of *Zostera*: *Z. noltii* and *Z. angustifolia*. Molecular investigation as part of this study indicated that *Z. angustifolia* is an environmentally induced phenotypic morph of *Z. marina*, and therefore the Fleet population should be referred to as consisting of *Zostera marina* only. It was noted that the *Z. angustifolia* morph plants tended to occur on shallow banks (higher light regime, higher temperatures), whilst those more typical of *Zostera marina* were found in deeper channels. The work concentrated around Langton Hive Point.

Water temperature at the sediment/water interface was measured continuously from April '96 to July '97 (data logger). <5EC in winter to >20EC in summer, fluctuating diurnally, but less than seasonal variation.

Salinity of subsurface water was measured at roughly monthly intervals. Higher in summer (~35ppt) than winter (~25 ppt).

Decreasing biomass in winter months - min. in March with near bare sediment surface. Seeds require cold stratification to germinate (8 weeks at #6EC), and will then germinate when temperatures are between 6 and 11EC - not higher. Salinity levels (equivalent to those observed) had no significant effect on germination in the laboratory. Seed germination was considerably faster with higher % germination achieved under anaerobic conditions than aerobic, in the laboratory. Field measurements confirmed that surface sediment was totally depleted in oxygen. *Zostera marina* seeds were found to be intolerant to drying, with best storage conditions found to be in the hydrated state in anaerobic conditions at a salinity of 30ppt at 2EC.

2. Li, S. 1997. Spatial variability in diatoms and charophyte oospores in a coastal lagoon, The Fleet, Dorset, England.

Diatom oospore population characteristics can be used to indicate past variations in salinity from cores taken in deep waters only. In shallow waters, water currents affect the distribution of diatom oospores, such that interpretation of past variations in salinity is affected.

Lamprothamnium papulosum mainly distributed in shallow water (10-40cm depth) around Langton Ferry and Herbury (eastern part of the West Fleet) on fine sand with relatively little water disturbance. Some adult plants also found between Top Ferry and Rodden Hive Point) during present study (full spatial study of distribution in Fleet not carried out - investigation based on distribution data from Holmes 1985 and '95).

Investigation of *Lamprothamnium papulosum* oospore distribution with depth and with distance from parent population centre & salinity (2.0 to 5.5 gl^{-1}).

No clear change in diatom population assemblages with longitudinal (E-W) salinity gradient observed. But gradient with depth observed - more fresh and fresh-brackish species found in shallow waters, more brackish and brackish-marine species found in deeper waters. Deeper channels in Fleet very organic-rich compared to shallower bays - accumulate fossil diatoms from both shallow and deeper waters, therefore diatoms will represent 'average' salinities for whole Fleet over time, not local variations. Most diatom species found in Fleet were euryhaline - therefore not much use for indicating salinity fluctuations.

Lamprothamnium papulosum is confined to four sites on the south coast of England in Dorset, Hampshire and the Isle of Wight, and one site in Scotland, on North Uist [Loch Maddy]. A substantial population occurs in the Fleet, but populations are small at the other sites (Church, 1992). It grows in natural and artificial brackish lagoons with salinities in the range 10-30 gl^{-1}, usually on sand, gravel or pebbles in <2m water depth, and is intolerant of strong water currents or wave action. It usually occurs with tasselled pond weeds (*Ruppia* spp.), but does not compete well with dense vascular plant growth. Often found where there is some disturbance from birds or animals, or in shallow water where fluctuations of water level result in more open vegetation (Round 1981).

Salinity gradient along Fleet under different precipitation conditions are described. Fleet is divided into two regions - East and West, with transition area between. East Fleet (approx.6.5km from Abbotsbury to Smallmouth) salinities are close to marine values, about 30-35 gl^{-1} . The transition zone is from approx. 4.5 - 6.5 km from Abbotsbury, where salinity drops dramatically from 30-15 gl^{-1} within 2km distance in average runoff conditions. West Fleet, from Abbotsbury to 4.5 km east, the salinity is quite stable from 13-15 gl^{-1} under average runoff, and 5-12 gl^{-1} under high runoff conditions (Robinson, 1992). Salinities recorded for this project varied along a transect in main part of lagoon from 2.0 gl^{-1} at Berry Knap, to 5.5 gl^{-1} at the west end of Herbury headland (east end of Langton Ferry bay).

3. Bingham, N. 1997 The response of charophytes to salinity changes in a coastal lagoon.

Tidal range 0.15m at Abbotsbury, to 2m at Smallmouth (Smith & Laffoley 1992). Charophytes are associated with clean, unpolluted water because most species cannot tolerate high levels of phosphates and nitrates. Levels in excess of 20 µg/l inhibit their growth [doesn't specify which nutrient or whether concentration expressed as phosphorus] whilst encouraging other plants (Stewart & Church 1992, Red Data Book, Stoneworts, JNCC). *Lamprothamnium papulosum* can tolerate near marine salinities of up to 35 gl^{-1} (Stewart, 1997, Stoneworts - connoisseurs of clean water, British Wildlife supplement). Its optimum salinity is 26 gl^{-1}, with a range of 8-18 gl^{-1} in Denmark (Olsen 1963, Danish Charophyta: Chronological, ecological and biological investigations, Khem: Copenhagen). It is a summer annual, germinating in spring. Oospores are produced between July and September.

Estimations of the historical marine-freshwater regimes of the lagoon are made from diatom species composition and *Lamprothamnium papulosum* oospore record of core samples with depth, but dating of sediment depths was not performed, so these estimations cannot be allocated to a time period. The work indicates that the Fleet has been brackish, but with marine intrusion similar to the present situation, for many years. Dominance by macrophytes is seen throughout the core, with more subtle changes in the balance of marine, brackish and freshwater diatoms attributed to such events as the construction of Portland Harbour, and the changes in channel morphology of Smallmouth when the new road bridge to Portland was constructed (1984). The overall salinity regime of the Fleet is, however, seen as relatively stable - neither becoming progressively more marine, nor rapidly progressing to a freshwater system.

4. Dean, R. 1996 The introduction of buffer strips to control agricultural pollution of the Fleet lagoon.

No evidence to suggest pollution from agricultural sources, but indicators to suggest it could be. Land use adjacent to the Fleet is mainly for dairy cattle grazing or arable rotations. Fleet hinterlands are mainly Oxford and Kimmeridge clays, cornbrash and Forest marble according to warden of Chesil and Fleet Nature Reserve). Fields have steep gradients leading down to the shores. Shoreline is colonised by gorse, blackthorn (*Prunus spinosa*), Hawthorn (*Crataegus monogyna*), bramble (*Rubus fruticosa*), Elder (*Sambucus nigra*) and many grasses. A few areas support saltmarsh vegetation. Land use varies along the Fleet from Ferry Bridge to the Tidmoor ranges (~5 km) are small fields for grazing of cattle and horses, some cut for hay, unchanged since the 19th century. Tidmoor ranges (MOD) are ungrazed and not managed for agriculture since the last century, the grassland being now encroached by gorse. From the ranges to Abbotsbury, the land is mainly used for intensive agriculture (arable and dairy). Non-intensively managed fields from Ferry Bridge to the western end of the Tidmoor ranges already have large areas between the fields and the edge of the lagoon. Intensively managed fields have been cultivated right to the margins of the Fleet. Dorset Heritage coastal footpath runs along the landward side of the Fleet.

No data on nutrient status of the Fleet, save NRA monitoring of tributaries. Reported pollution of tributaries of the Fleet, leading to loss of *Ruppia* and *Zostera* and occurrence of algal blooms, citing Elton, D 1991 (The Fleet and Chesil Beach Management Plan, Report to Ilchester Estate).

Mentions study by E.H. John, 1995 A study of the nutrient status, hydrographical features and phytoplankton composition of the Chesil Fleet, Dorset. University of Wales, Swansea (not in FSC archive). She suggests in this report that "the nutrient levels of the Fleet waters do have a significant effect on the plankton population, and that nutrient enrichment in the Abbotsbury embayment supported the development of two algal blooms". She expresses concerns that eutrophication within the Fleet is damaging the lagoonal fauna.

Buffer strips for reduction of nutrient inputs from agricultural sources to the Fleet are recommended as a secondary conservation practice (after reduction of inputs at source). Their effectiveness will need to be monitored. Many fields along the Fleet have tiled field drains installed [report does not say which ones do], which will reduce the effectiveness of the buffer strips and lead to nutrient input direct to tributaries of the Fleet

5. Dyrynda, P.E.J. 1997 Seasonal monitoring of the Fleet Lagoon aquatic ecosystem (Dorset, UK): 1995-1996.

Mentions two references not yet in FSG archive: Ladle & Young (in press) The Fleet lagoon and Chesil beach: Proceedings of the 3rd Fleet Symposium. Dorset County Council, Dorchester, and Bamber 1996 An assessment of saline lagoons within Special Areas of Conservation. English Nature research report No. 235 by Fawley Aquatic Research Laboratories Ltd.

Aim of seasonal monitoring study has been to generate information capable of distinguishing normal seasonal and year-to-year temporal variations from unnatural adverse trends caused by human activities. Monitoring strategy aims to record natural and man-induced changes to aquatic vegetation, invertebrates and fish within one section of the aquatic ecosystem (in a transect across the lagoon from Langton Hive Point).

Divides lagoon into two ecologically and physically different areas: the lagoonal basin, with weak currents and fine sediments, and the inlet channel, with strong tides and coarse sediments - both areas being very sheltered from wave action.

Lagoonal basin also divided into three sections: Littlesea - the broadest, outermost section characterised by fine sediments with seagrass beds intersected by deep fast flowing subtidal channels; from Moonfleet to Clouds Hill is a section where the lagoonal bed is level and shallow, dominated by deep, soft organic muds mainly colonised by seagrass meadows. *Zostera marina* is replaced upstream by *Ruppia cirrhosa* and *Lamprothamnium papulosum* is common towards the mainland shores; the Abbotsbury embayment forms the blind head of the lagoon. Although the embayment is floored by soft organic muds, the seagrass stands are thin and patchy. The green alga *Chaetomorpha linum* is common, and in summer can be accompanied by tracts of sea lettuce *Ulva lactuca*. Two small streams discharge into the embayment. *Phragmites* marsh is extensive along the mainland shore. The coverage of vegetation upon the bed of the lagoon is strongly seasonal. Seagrasses grow from late spring to autumn, accompanied by swards of green algae through to mid summer. During autumn, winter and early spring much of the lagoon bed features bare mud and plant detritus. The permanently submerged central areas supported the highest densities of vegetation and invertebrates.

The seagrass and algal meadows of the lagoonal basin are in summer frequented by adult grey mullet and eels, juvenile bass and by non-economic species such as sand smelt, 3-spined sticklebacks, deep-snouted pipefish and mud gobies. A variety of waterfowl and other aquatic birds feed upon vegetation, invertebrates and fish within the lagoonal basin. The most conspicuous herbivorous bird is the mute swan - a unique herd has been farmed at Abbotsbury since the 1300's. The herd currently stands at about 700 birds. The swans are fed, at a point within the recesses of the Abbotsbury embayment, grain and high protein pelleted feed, along with seagrass material gathered from the Fleet strandline. Winter visitors include widgeon, pochard, brent goose and coot. Plankton communities of the system are little known. The water is clear from spring to autumn, but is temporarily discoloured by intense green blooms in spring, and by short-lived but often intense red/brown dinoflagellate blooms within the Abbotsbury embayment in summer (John, E. 1995, J. Jamieson, EA pers. comm.). There is a suggestion that anthropogenic eutrophication may be exacerbating these blooms (EA, 1997). Little is known of zooplankton within the lagoon, except that mysids are very common.

An oyster purification plant was constructed on the mainland shore upstream of Smallmouth during the 1980's. Here, and in Littlesea immediately upstream of the Narrows, oysters (*Crassostrea gigas*) commenced in 1987 on a large scale. Due to concern as to whether this species could viably reproduce in UK water temperatures, seawater temperatures in the Fleet were monitored and searches made for settled spat. To date, spat searches have returned a negative result. Accumulation of organic waste under the oyster racks was another concern, but an impact study

(Collins & Byfield in press, Monitoring oyster farming in the Fleet. In Ladle & Young, in press) detected no evidence of an adverse effect beneath oyster racks in the Fleet.

6. Environment Agency 1997 Local Environment Agency Plan, West Dorset, Consultation Draft Nov. 1997.

Action plan (post consultation) due to be published summer 1998.

Average annual rainfall for the coastal area surrounding the Fleet is 701-750mm, rising to 800mm in the higher ground from which the tributaries which feed the Fleet at Abbotsbury and Roddon Hive originate. There is a tidal level monitoring station and current daily raingauge at Portland, and another daily raingauge at Weymouth just north of The Narrows.

The three streams which flow into the Fleet are all classed as RE1 (River Ecosystem Class 1 = Water of very good quality suitable for all fish species).

"Rivers, ponds and the ... Fleet and Portland Harbour may be suffering from diffuse inputs of nutrients and pesticides which are threatening the wildlife resource of the area. The water quality of the Fleet is being monitored quarterly; possible factors include agricultural activities and swan fouling".

EA will encourage landowners to establish buffer zones between intensive farmland and watercourses wherever possible.

The Fleet lagoon has priority status (under the EC Habitats Directive Regulations) "and there is evidence that its botanical interest is declining. We should work to establish the causes, develop plans to improve the habitat diversity of the hinterland, seek to restore ditch systems, establish sustainable inputs of nutrients and set target levels, and monitor the status of the chemistry and the animals and plants". "There is potential for restoration and enhancement of the river corridor, particularly to improve ... streams flowing into the Fleet, by restoring natural channel shape and reinstating meanders and side ditches". EA are working with the developers of Portland Harbour (Portland Ports Ltd) to ensure their operations can be carried out without detrimental impact on the sensitive habitats contained within the harbour itself and in the internationally protected lagoon of the Fleet whose only connection to the open sea is through the harbour. EA are undertaking quarterly surveys to ascertain any water quality impacts as a result of the redevelopment of Portland Harbour into a commercial port receiving fertilisers and molasses, and other commercial activities. Boat surveys will be undertaken in 1997 after which further monitoring will be reviewed.

The catchment of the Fleet is a narrow strip of undulating arable or improved pasture running northwest from Weymouth to the Abbotsbury swannery, backed by the steep slopes of White Hill and Portesham Hill. Fences or stone walls are more a feature of this open landscape than the hedges in the catchments to the west, and there are few trees or copses. The three short streams (Rodden, Portesham Mill stream, Cowards Lake) flowing into the Fleet have modified channels for much of their length and a number of the old ditches have been lost.

Two sites within Portland Harbour are monitored under the EC shellfish waters Directive (79/923/EEC) to protect shellfish waters from pollution. In 1996 the standards for copper and zinc were exceeded. A study is underway to identify any sources and long term trends in water quality or bioaccumulation in shellfish tissue. The EC shellfish hygiene Directive (91/492/EEC) defines standards for shellfish quality required in the end product, and classifies shellfish harvesting areas into 4 categories according to the concentration of bacteria found in the shellfish flesh. A site in the Fleet, and one within Portland Harbour have been classified within the area. In 1996 both achieved a B classification, a deterioration from an A classification in 1995.

Two Wessex Water Services consented STW discharges exist to tributaries of the Fleet, at Abbotsbury (DWF 101-1000 m^3/day) and at Langton Herring (no consented DWF, max. daily flow only). A further four private sewage treatment works with consented maximum discharge volume of >5 m^3/day discharge to the Fleet at Abbotsbury (<10 m^3/day), Langton Hive (26-50 m^3/day), Chickerell (>50 m^3/day) and the west end of the Narrows (<10 m^3/day).

The enclosed waters of Portland harbour are of high scientific interest for their marine communities and rare species with a southern distribution, such as an anemone (*Scolanthus callimorphus*), a rare sea slug (*Aeolidiella alderi*) and an ascidian (*Phallusia mammillata*). The rich sediment communities are considered to be of national importance and include the extensive eelgrass beds (*Zostera* spp) and mud plains dominated by the fragile sea pen (*Virgularia mirabilis*) and a Mediterranean polychaete (*Sternaspis scutata*). With the departure of the Navy, careful planning is essential to balance the development of industry and recreation with the needs of the precious marine biota. The consequences of a diesel spill or substantial pollution from a refuelling factory ship would be severe. The Fleet is the largest saline lagoon in England and a candidate SAC. Poor flushing leaves a fine substratum with good stands of all three eelgrasses (*Zostera* spp), both tasselweeds (*Ruppia* spp.) and a rare stonewort (*Lamprothamnium papulosum*). There are tidal rapids with rich sponge communities and many rare species within the lagoon; the lagoon sand worm (*Armandia cirrhosa*), de Folin's lagoon snail (*Caecum armoricum*), the starlet anemone (*Nematostella vectensis*), the gastropod (*Paludinella littorina*) and the lagoon sea slug (*Tenella adspersa*) are nationally rare and protected. The Fleet is a site of national importance for wildfowl and wetland birds. Redshank, as a breeding species, are almost restricted to the areas around the Fleet and Portland Harbour. The ringed plover, oyster catcher and little tern are similarly restricted in distribution. The Abbotsbury swannery is famous and with the gardens, is a major visitor attraction. The swan herd is believed to be increasing, resulting in excess nutrients entering the Fleet and overgrazing of the seagrass. There has been a decline in the botanical interest and algal blooms implying eutrophication but this has not been verified by a survey. Other potential threats are from silt, shellfish farming and Japanese seaweed (*Sargassum muticum*). The Chesil Beach is an exceptional geological feature and it supports extensive shingle habitats with rare plants such as the sea pea (*Lathyrus japonicus*) and breeding little terns. It is the only British site for two invertebrates, the scaly cricket (*Megoplistes squamiger*) and the darkling beetle (*Omophlus rufitarsus*). Babington's leek (*Allium babingtonii*) grows in substantial colonies at Abbotsbury.

The Fleet is a designated bass nursery area (SI 1156 1990) and fishing from boats is prohibited at all times. This prohibition does not apply to the shore and there is one fisherman using a tidal net for bass in this area, which is not abiding by the spirit of the designation. There is also a prawn fishery off the old Ferrybridge, known locally as the Billy Winter fishery. The private fish farm within the Fleet is not governed by the Sea Fisheries Committee restrictions. The EA issues eight licences (for 10 fyke nets each) annually for eel fishing on the Fleet. Reported annual catch varies from a minimum of <500 kg to over 2500 kg.

There is one groundwater abstraction licence for public water supply within the Fleet catchment, at Portesham on the upper Abbotsbury tributaries, of between 0.5 and 5.0 Mld.

7. Holmes, N.T.H. 1993 The distribution of *Zostera* and *Ruppia* in the Fleet, 1991. Report to English Nature SW region, from Alconbury Environmental Consultants.

This reports a 1991 repeat survey of that done in 1985, which followed a more extensive survey in 1983. All were carried out during August. *Ruppia cirrhosa*, *Zostera noltii* and *Z. angustifolia* were all thriving in the Fleet in very similar proportions to those reported in previous surveys. The nationally rare alga *Lamprothamnium papulosum* had extended its range and abundance.

The west-east and north-south zonation of species reported from previous surveys was confirmed. *Ruppia cirrhosa* was very dominant west of Rodden Hive Point, but then gives way gradually to *Zostera* eastwards down the Fleet. *Z. noltii* thrives best along the northern coves, whilst *Z. angustifolia* dominates along the shore in the shadow of Chesil and the main body of the Fleet. The decline of *Ruppia cirrhosa* recorded in 1985 has been shown by the 1991 surveys to be a temporary phenomenon. *Lamprothamnium papulosum* was found to be thriving better in 1991 than it had on previous surveys. In all surveys, this plant was always found associated with coarse sandy/gravel substrata where minimal amounts of organic matter were present.

[NB. *Z. angustifolia* is thought by other workers (den Hartog 1989, Brenchley & Probert 1997) to be an ecological/environmental variation of *Zostera marina*.]

The various recent potential threats to the seagrasses of the Fleet (invasion by Japanese seaweed *Sargassum muticum*, changes as a result of realignment of Smallmouth [in 1984?], and storms in 1989) do not appear to have had any adverse effect on *Ruppia*, *Zostera* and *Lamprothamnium papulosum* in the Fleet.

Whilst not directly mentioned in the text, records for % cover of algae *Cladophora* agg., *Enteromorpha* and *Ulva* are given for each of the 100+ quadrats surveyed in 1991.

8. Holmes, N.T.H. 1983 The distribution of *Zostera* and *Ruppia* in the Fleet. Report to Nature Conservancy Council, from Alconbury Environmental Consultants.

Report of base line distribution survey of *Zostera* and *Ruppia* in the Fleet. Whilst aquatic birds (including swans) may depend upon these grasses as a food resource, hence their importance, the populations of *Zostera* and *Ruppia* in the Fleet are of considerable significance in their own right. Such extensive mixed populations are virtually unknown from anywhere else in Britain [cf. recent surveys of Loch Maddy & other W. Isles/Orkney/Shetland lagoon sites]

Survey must be done in late July/August when weather & water clarity conditions are best, *Zostera* and *Ruppia* are growing healthily and at their greatest biomass, and flowers and fruit are at their most obvious to assist in identification, particularly of *Ruppia*.

The Abbotsbury basin was not surveyed rigorously, but appeared very sparsely colonised, and limited to *Ruppia* only. Algae such as *Ulva*, *Cladophora* and *Chaetomorpha* were abundant. Cladophoralean algae dominated the mud surface down to Rodden Hive Point, with their frequency diminishing to the east of this zone as *Zostera* spp. became more dominant. Rodden Hive is the most westerly point of the Fleet where a diverse flowering plant community was observed, and where the combined cover of these species far exceeded that of algae. Below Lynch Cove and the Narrows no aquatic flowering plants were recorded.

The upper and lower limits of distribution of *Zostera* and *Ruppia* were the same in 1983 as in 1968 (in Whittaker 1968). The report contains lengthy discussion as to possible changes in seagrass and algal populations over time, and possible mechanisms for such changes, as well as recommendations for future work. Concerns expressed by local residents about decline in seagrass are mentioned, and attributed tentatively to the wasting disease of the 1930's resulting in changes in species mix as well as decline in populations, and to subsequent declines in densities/extent due to hard winters. A recent increase in algae is reported, tentatively attributed to increases in nutrient inputs from domestic and agricultural sources, or to increases in the swan population over the previous decade.

9. den Hartog, C. 1989 Letter to D. Seaward.

The letter refers to a specimen of *Z. angustifolia*, which D. Seaward sent to den Hartog for analysis of disease. den Hartog mentions that *Z. angustifolia* is thought to be an ecological variant of *Zostera marina*. The specimen from the Fleet was diseased, with *Labyrinthula* lesions. This disease had been recorded from specimens from the Fleet on other occasions and in 1934 and the 1970's. Wasting disease (caused by *Labyrinthula*) has been found in eelgrass not subject to an epidemic of the disease, and it is thought that an epidemic could be caused by stress to the plants, such as too little light or too high temperatures.

10. Ladle, M. (ed) 1986 The biology of the Fleet - aspects of the flora and fauna of the lagoon. Fleet Study Group.

Includes the following papers:

Seaward, D.R. Ferrybridge reconstruction in relation to marine fauna

Holmes, N.T.H. Distribution of *Zostera* and *Ruppia* in the Fleet

Humphrey, E.C. A survey of the meiofauna of the Fleet

Dyrynda, P. Subtidal communities within the outer Fleet and Portland Harbour

Thompson, T.E & Seaward, D.R. Observations on the opisthobranch mollusc *Akera bullata* in the Fleet, Dorset

Ladle, M. The fishes of the Fleet with particular reference to the young stages of the bass (*Dicentrarchus labrax* L.)

Seaward, D.R. Ferrybridge reconstruction in relation to marine fauna. Short paper describing the changes observed during and after infilling of the old channel and construction of the new. The intertidal rare and local sea slug *Aolidiella alderi*, appeared to be unaffected by the development, but the local population (along with populations of other molluscs) was reduced by severe weather in January ‘85. A small area of interesting subtidal community with unusual fauna including the sea slug *Doto millbayana* under the old bridge was destroyed when the old channel was infilled - it was not known at this time whether this community would regenerate under the new bridge. Changes to the sand flats in Portland Harbour adjacent to the new channel were observed, but otherwise, no significant changes/impacts were observed.

Holmes, N.T.H. Distribution of *Zostera* and *Ruppia* in the Fleet. Report of the 1983 survey described above.

Humphrey, E.C. A survey of the meiofauna of the Fleet. Describes MSc project. Core samples were taken at low water at five sites within the Fleet, and analysed for macrofauna, meiofauna (i.e. retained on a 63µm sieve), temperature of sediment, particle size analysis and organic content, and salinity and temperature of the water. Water temperatures recorded during this survey were lower than those recorded by Whittaker in May 1968. Highest water temperatures were recorded at Moonfleet. pH measurements were higher than normal seawater (pH 8), as also recorded by Whittaker. It is suggested that this high pH may be contributory in the high preservation of empty *Foraminifera* tests. Greatest quantity of coarse material in sediments, with highest diversity and abundance of species was found at Moonfleet. High numbers of individuals were also recorded at Abbotsbury, where sediment sorting was greatest, although still relatively poorly sorted. The Fleet was shown to be a very rich area in terms of meiofaunal abundance and number of species, especially for *Harpacticoida* and *Foraminifera*.

Dyrynda, P. Subtidal communities within the outer Fleet and Portland Harbour. Summary of information included in Dyrynda 1984 and Dyrynda & Farnham 1985, covering surveys of the flora and fauna of sub tidal channels at the Narrows and Smallmouth (plus three stations in Portland Harbour for comparison).

Thompson, T.E & Seaward, D.R. Observations on the opisthobranch mollusc *Akera bullata* in the Fleet, Dorset. Paper describes the aspects of the taxonomy of *Akera bullata.* The variety *Akera bullata* subspecies *nana* of Jeffreys 1867 is the one found in the Fleet. It rarely exceeds 20mm in overall body length, swims only as a juvenile, has an obtusely rounded posterior pallial lobe, and lacks the ability to secrete offensive purple. It has existed in the Fleet since around 1850 at least. Densities of up to 120 m^2 were recorded by Seaward, 1978. As part of the studies into this species in the Fleet, temperature and salinity at the foreshore at Langton Hive Point were measured on a monthly basis from November 1984, and should continue until 1986. Salinity during 1985 varied widely, dropping to 22 ppt or lower in mid winter, rising to 35.5 ppt in summer (equivalent to open water in the English Channel). Temperature of the water was usually higher than that of the air, but this tended to reverse in the winter months.

The life cycle of *Akera bullata* in the Fleet is annual. Spawn masses are produced in April-June, spent adults die off in April-June to be replaced by newly settled young, which dominated the samples in June and July. Juveniles could swim until 2-3 months old. The benthic stages appear to be detritivorous. There was no evidence that *Akera* feeds on living *Zostera*, either the roots or the leaves. The Fleet population of *Akera bullata* is ecologically distinct from larger *Akera bullata* subsp. *farrani* found elsewhere, whether it should be considered a separate species was not concluded until completion of the sampling programme.

Ladle, M. The fishes of the Fleet with particular reference to the young stages of the bass (*Dicentrarchus labrax* L.). Paper reports a study to establish whether bass spawn within the Fleet, or whether eggs, larvae or post-larvae enter the Fleet with each tide, and to attempt to establish the age structure, distribution and relative growth rates of young bass within the lagoon. The surveys were conducted in May-October 1983. The study provided no evidence of bass spawning in the Fleet. It was generally believed that they spawn chiefly in offshore situations and that larvae migrate inshore, often to shallow brackish water. The status of the Fleet as a nursery area was confirmed, but it was not possible to estimate the size of the population except to say that it was substantial. The young fish were relatively quick growing for a species nearing the northern limits of its geographical distribution. Gobies were found to be the most abundant fish during the survey, with sandsmelt (*Atherina presbyter*) the second most abundant. Sandsmelt eggs attached to algal fragments (indicating that they are benthic rather than planktonic), rarely observed in other British waters, were found in the plankton at the end of May on the ebb tide.

11. Robinson, I.S. Warren, L. & Longbottom, J.F. Sea level fluctuations in the Fleet - an English tidal lagoon.

Tidal elevation data were presented for places along the Fleet (Abbotsbury, Morkham's Lake, Moonfleet, Chickerell, Bridging Hard, Smallmouth, Portland). Harmonic analysis of the data was not able to represent the observations adequately, particularly at the inner end of the lagoon. Careful inspection of the data shows that the tidal regime is capable of being understood in terms of non-linear propagation of long waves in very shallow water. Distortion of the tidal wave by unequal progression speeds of high and low water, and the set up of mean level by frictional effects, are shown to be the important physical mechanisms controlling the observed water level fluctuations. A one-dimensional numerical model which incorporates these processes is able to reproduce the observations satisfactorily. Whilst the model predicts strong effects of wind stress, the meteorological influences in the observed data appear to be largely due to external surges in the English channel which propagate into the lagoon through its entrance.

Although the sea level variations in the Fleet do not have the regular tidal oscillation pattern typical of most UK ports and estuaries, it has been possible to account for the observed pattern in terms of the non-linear propagation of long waves. The tidal regime in the East Fleet is typical of a shallow estuary with extreme tidal asymmetry resulting from the large range to depth ratio. The strong frictional effects result in a much stronger set-up of mean level at spring tides than at neaps, and consequently the tides of West Fleet have a strong fortnightly component. The semi diurnal tide propagates into the West Fleet only weakly when the mean level is high at spring tides, and not at all when the mean level is low at neaps. The very shallowness of the lagoon appears to damp all higher frequency oscillations, both tidal and wind driven, and acts as a low-pass filter enabling the longer period tides and external surges to penetrate to Abbotsbury. Viewed in this light, the apparently irregular tidal regime is much more comprehensible and more readily predicted.

12. Weymouth & Portland Borough Council. 1995 Letter detailing water quality monitoring carried out by Environmental Health Services Section & Weymouth Port Health Authority in the Fleet and Portland Harbour (11 Aug 1995).

Bathing water sampling (Total coliforms, faecal coliforms, faecal streptococci) by Weymouth and Portland Borough Council Environmental Health Dept. at bathing waters. Portland Harbour Castle

Cove, and Sandsfoot beach areas, May to September. Samples taken occasionally from Chesil Cove (not a designated bathing water). Results not given.

Weymouth Port Health Authority regularly samples mussel and oyster flesh in Portland Harbour and the Fleet [for bacteria?]. Annual sampling of shellfish flesh for MAFF for chemical contamination in the Fleet and Portland Harbour. No results given. [presumably available from MAFF?] Seawater and shellfish flesh are sampled on behalf of MAFF in the Fleet and Portland Harbour to monitor for algal blooms. Sampling frequency increased during spring and summer.

13. Bamber, R.N. & Henderson, P.A. 1985 Diplostomiasis in sand smelt *Atherina presbyter* Cuvier, from the Fleet, Dorset and its use as a population indicator.

The population of sand smelt, *Atherina presbyter*, breeding in the Fleet, Dorset, shows a high infection of diplostomiasis. The population was studied in 1983 to clarify aspects for this parasitic condition previously analysed for the sand smelt population at Fawley, Southampton Water. All age classes showed a higher percentage infection and mean number of metacercaria per fish than at Fawley. Analysis of postlarvae and juveniles showed that infection can occur at 1 week old, and verified the hypothesis that the scales of older fish inhibit cercarial settlement. Circumstantial evidence suggests that *Hydrobia ventrosa* may be the first vector host for this parasite, and the densities of this species and of nesting little tern colonies would account for the differential infection between these two sand smelt populations. The increase in infection of $2 fish at Fawley cannot be attributed to mixing with the Fleet population, and the different infection levels demonstrate population isolation. High levels of infection are limited to this part of the English channel; sand smelt samples from around the coasts of the British Isles show minimal infection rates elsewhere and suggest a southerly distribution of the parasite, away from Atlantic oceanic waters.

14. Seaward, D.R. 1987 The marine molluscs of Portland Harbour. Proceedings of the Dorset Natural History and Archaeological Society, Volume 108 for 1996.

Portland Harbour is under increasing recreational and developmental pressure and this paper was intended to place on record at least one aspect of its high marine biological importance. The shores and sublittoral are described, the present knowledge of its molluscan fauna is stated, and its 140 years of mollusc recording is summarised in relation to the history of enclosure of Portland Roads. The sandflats at Smallmouth and Sandsfoot are the only undisturbed sediment shores between Studland and Exmouth; they are particularly important for their unusually rich and diverse bivalve community, for several species normally sublittoral, and for a colony of a rare and local sea slug (*Aolidiella alderi*). The double low tide particular to Weymouth Bay is also mentioned.

15. Dyrynda, P. 1984 Investigations of the subtidal ecology of the Fleet Lagoon, Dorset. Report to the Nature Conservancy Council.

Good summary of conservation interest of the Fleet [see more recent references by Dyrynda].

16. Fair, J. 1987 The Fleet Sanctuary Nature Reserve.

800-900 swans in 1736. Swan numbers have varied from 500-1200 over the last 10 years [in 1986].

Increases in dairy herds occurred during the '70's and '80's, which has led to slurry and, occasionally, silage entering the Fleet at times. Corn is now planted on the extreme edges of the Fleet. Pesticide and fertilisers are sprayed in the Herbury area in recent years.

17. Saunders-Davies, A. 1995 Factors affecting the distribution of benthic and littoral rotifers in a large marine lagoon, together with a description of a new species. Hydrobiologia, 313-314: 69-74.

A significant population of rotifers living in the algae in the Fleet was investigated, including a description of a potential new species *Proales fleetensis* sp. nov. Measurements of salinity (conductivity), air and water temperature, nitrogen as nitrate and as ammonia were made at the time of sampling for rotifers on algae. pH values were high at the Abbotsbury end, probably due to photosynthesis by seagrasses. pH was lower and less variable towards Ferrybridge (8.3 to 8.9), possibly due to the buffering effects of seawater. Salinity around Ferrybridge was close to that of normal seawater (0.98 to 1.01 – units not given) and fairly constant. At Abbotsbury salinity was lower and much more variable (0.17 to 0.65). Nitrogen levels, both as nitrate and ammonia, were generally low, but variable.

Rotifer species richness and total abundance increased with decreasing salinity from Ferrybridge to Abbotsbury. During the period of the survey (June to Sept 1993) an explosive growth of the sulphur bacterium *Thiopedia roseola* occurred at Morkham's Lake. At this time rotifers disappeared from the benthic algae, which became covered in the bacterium, but were abundant in the mats of filamentous algae floating clear of the bottom.

18. Avon & Dorset River Authority 1970 Stream water analysis of stream below Portesham regarding a proposal for a trout farm, for E.B. Swaffield, Manor Farm, Portesham.

Chemical analysis results for the stream below Portesham are given as below:

Temp	12EC
pH	7.9
Total solids	296 ppm
Suspended solids	6 ppm
Dissolved solids	290 ppm
Free ammonia	None detectable
NO_2	No trace
NO_3	4.2 ppm
Cl-	29 ppm
Dissolved oxygen	11 ppm
O. Ab. 3min	0.1 ppm
O. Ab. 4 hrs	0.2 ppm
BOD	1.0 ppm

Comment is given that the water is clean, with good oxygen levels, low BOD and no detectable free ammonia indicating a lack of animal or plant waste in the water, which is therefore suitable for rearing trout (the subject of the proposal). Biological analysis supported this conclusion, though invertebrates were not sufficiently abundant to support a large population of fish, therefore if a trout farm were to be established, the fish would need to be fed.

19. Goudie, A.S. & Ireland, P. 1978 A preliminary investigation of the water chemistry of the Fleet, Dorset. Paper submitted to Proceedings of the Dorset Natural History and Archaeological Society.

Draft of paper giving water chemistry results (conductivity, pH, sodium, potassium, calcium, magnesium) for filtered water samples collected from 12 sites at hourly intervals from 11.00am to 18.00 on 23.3.78. Measurements were taken from six stream inputs (Rodden Bridge, Linton Hill, Abbotsbury, East Fleet Church, Langton Herring and Furzedown Farm) on the same day 23.3.78. Conductivity (salinity) measurements were also taken from 22 sites at 14.00 on 21.3.78. Results are not interpreted, save for mention that a narrow zone of higher conductivity (salinity) was observed along the length of the lagoon on the Chesil side, indicating seawater percolation through Chesil Beach.

20. Nunny, R.S. 1995 The Physical environment - Hydrography. Lyme Bay Environmental Survey. Vol. 1 Kerr-McGee.

Nothing of relevance to the Fleet.

21. Dyrynda, P. & Cleator, B. 1995 The Fleet Lagoon. . Lyme Bay Environmental Survey. Vol. 5 Kerr-McGee.

A comprehensive description of the marine biological interest of the Fleet [to 1995], in particular the subtidal communities of the Narrows and Ferrybridge area, and the extensive seagrass beds in the mid and western Fleet. Much of the information is summarised from previous work, but additional diver transects were performed in the 'link channel' (the Narrows to Ferrybridge) area, and core samples were taken in the seagrass/algal meadows for analysis for sediment particle size, hydrocarbon and macro invertebrate analysis. This paper provides a comprehensive summary of work to date [1995] on the marine biological interest of the lagoon, as well as a summary of hydrographic conditions.

22. Nunny, R.S. & Smith, P.R.J. 1995 Existing Contaminant Levels. Lyme Bay Environmental Survey. Vol. 15 Kerr-McGee.

Reports collection of sediments and shellfish from eastern Lyme Bay (including Portland Harbour) and their analysis for trace hydrocarbons and metals. Generally low levels of total organic material were found. Total hydrocarbon (THC) and polycyclic aromatic hydrocarbon (PAH) concentrations in sediments (total sediment samples) were, in general, equally low. Lyme Bay concentrations ranged from 0.56 to 29 µg/g TCH, with a slight increase eastwards in concentrations. Highest concentrations were found in Weymouth Bay and, in particular, Portland Harbour (200 µg/g TCH). The elevated levels in the vicinity of Portland Bill are attributable to past spills of fuel oil (now degraded), contamination from lubricating oils, or fallout from the incomplete combustion of fossil fuels. These will have been derived from shipping activity and from discharges, runoff and fallout from the urban areas of Weymouth.

Sediment metals analysis (on the <90 µm fraction) gave high concentrations of metals (copper, zinc, chromium, nickel, lead and arsenic) for the sample from Portland Harbour, but were not necessarily the highest encountered during the survey. The results suggested that sewage discharges were the source of metals in some areas of Lyme Bay.

23. Nunny, R.S. 1995 Contaminant dispersion modelling. Lyme Bay Environmental Survey. Vol. 16 Kerr-McGee.

This report contains little of relevance to the Fleet, with the exception that modelling studies demonstrated that in the event of an oil spill in Lyme Bay with winds of 7.7 m/s in a south westerly direction (not unusual), oil would be likely to be deposited along the eastern part of Chesil Beach and enter Portland Harbour

24. Robinson, I.S. 1983 A tidal flushing model of the Fleet - an English tidal lagoon. Estuarine, Coastal and Shelf Science, 16, 669-688.

25. Seaward, D.R. 1994 Water temperature monitoring in the Fleet SSSI. Report to Joint Nature Conservation Committee.

Reports water temperature monitoring carried out as part of an investigation into the possibilities of the introduced pacific oyster *Crassostrea gigas* breeding in British waters. Temperature recordings (data loggers) were obtained for one site (Oyster Hut, just W. of west end of Narrows) approximately 15 times per day from March 1993 to February '94, and from two other sites for shorter periods; Ferrybridge from November '93 to February '94 and Morkham's Lake from mid July to mid August 1993.

From March to August, Fleet water temperatures (at the Oyster Hut) were higher (by approx. 5EC) than those of mid channel (Channel Light Vessel), similar in September, then lower (dropping rapidly by 5-10EC) than mid channel from October to February. Fleet water temperatures were within the maximum-minimum range of Weymouth air temperatures throughout the year. Peak Fleet water temperature of 17-18EC occurred in June-August, and minimum water temperature of 6EC in February.

Other workers (Whittaker, 1978 and data from Abbotsbury Oyster Farm) indicate maximum water temperatures in other years of 26-28EC, and minima in January/February of below freezing, when the water surface has frozen. No evidence for vertical stratification has been found, and it is unlikely in such shallow open water, nor in the deeper Narrows-Ferrybridge area where tidal currents are strong.

Depending on the stage in the tidal cycle, highest and lowest temperatures were recorded during both night and day. In summer, when Fleet water temperatures are warmer than sea temperatures, warmer (during the day) or colder (during the night) water from the western Fleet flowed past the temperature sensor at the Oyster Hut. In winter, when sea temperatures are generally warmer than Fleet temperatures, the reverse is true. Temperature swings are greater further west in the Fleet (away from the buffering effects of seawater exchanged by the tide).

"Even on neap tides, there was usually some evidence of a second diurnal cycle at Morkham's Lake... this suggests that the statement by Robinson *et al* (1988, 668 [should be 1983, 668]) that 'the semidiurnal tide propagates into the west Fleet only weakly ... at spring tides, and not at all ... at neaps' may need some clarification. Robinson *et al* (1983, 659) recognise a 'fortnightly fluctuation of water level, related to the spring-neap cycle, which is strongest towards the western end', and state that at neap tide the water 'remains in West Fleet ... and for several days is virtually isolated from the tide'. The short record available from Morkham's Lake does not indicate an obvious fortnightly temperature cycle and ... even at neaps a semidiurnal variation is apparent".

The paper concludes that in 1993-94, temperature was not a limiting factor to spawning and settlement of *Crassostrea gigas,* but despite this, successful spawning of this species had not been observed to date.

26. Cook, W.C. 1969 The Fleet waters.

A typed manuscript describing all aspects of the Fleet. Of interest, are the descriptions of fish populations:

Around 200-350lb of adult bass were rod caught from the Fleet each summer from 1951-1954 [total weight of fish, not individual weights!], and in 1958 365lb was caught by the author on one rod. "it was normal for large numbers of bass to visit the higher reaches of the water about the middle of March to spawn, many of the larger fish saying in the gullies between the mud banks, but some also moving with the tides, July and August being the best months to find the big fish in the Narrows". Other fish reported include small wrasse (ballan, goldsinny and corkwing), three-spined stickleback, sand smelt throughout the year, a few lesser sand eel, 15-spined stickleback, greater, lesser and snake pipefish, butterfish, gunnel, blennies, gobies and short spined sea scorpion.

Also reported is the die-back of *Zostera* (quoted as *Zostera nana* in the Fleet) in 1929-30 and *Zostera marina* Weymouth Bay and Portland Harbour (where extensive beds existed). Over the "next couple of years the *Zostera nana* made a fair recovery and in recent years it has once again returned to its former density. In the open sea there has been no marked recovery of the larger species but during the last few years there have been signs that it might re-establish itself once again".

27. Whittaker, J.E. 1980 The Fleet, Dorset - a seasonal study of the watermass and its vegetation. Proceedings of the Dorset Natural History and Archaeological Society, 100 (for 1978).

Hourly water samples were taken, and measurements made of salinity, pH, calcium, magnesium, dissolved oxygen and temperature. Tidal measurements were made at half hourly intervals over 12-13 hours. A preliminary bathymetric map was also produced.

Seasonal pH ranges in the Fleet present a picture of high alkalinity of Fleet waters, especially in spring and summer months - pH mean of 7.8 in autumn and winter, but around 8.5 or higher in spring and summer (pH of seawater is 7.8-8.2). This is considered to be due to photosynthesis by *Zostera* in shallow waters - highest values occurred on *Zostera* flats, with lowest values around Abbotsbury in summer and autumn when water stagnates, and *Zostera* is rare. In august 1969 the water of West Fleet was dark brown with a lower pH than normal, with associated fish mortality. This was attributed to a phytoplankton bloom, possibly triggered by farm pollution. A similar occurrence was reported to have occurred during the severe drought of 1976.

Dissolved oxygen values of >200% saturation were recorded from the Fleet in spring and summer, assumed to be due to photosynthesis by *Zostera*. Values of >150%, however, were also recorded during winter when *Zostera* has died back. These were attributed to colder water being able to take up more oxygen.

Calcium and magnesium values showed a simple linear relationship with salinity.

Freezing of the Fleet was reported for winter 1963. Diurnal variations in water temperature of >5EC from early morning to late afternoon were reported.

"Marine algae and *Zostera* occur in luxuriant abundance in the Fleet for much of the year; only in winter and spring are there large tracts of bare mud. *Zostera* dies back by late June. Green algae are particularly common in the lower salinities of West Fleet where many species form dense mats of vegetation on the beds of *Zostera* and often cover large tracts of the water surface in spring. ... Epiphytic growth on all seaweeds and *Zostera* is very well developed". *Ulva* is reported as abundant from March to April, especially in the lower salinities, with 'flannel weed' (a number of filamentous species of mainly *Cladophora* and *Enteromorpha* species with some reds), which dies back in late autumn and may often be washed ashore in gales. *Chaetomorpha* spp. grows mainly in the low salinities around Abbotsbury, and, to a lesser extent, as far as Lynch Cove. It is most noticeable in late spring and summer. Two species of *Zostera* are recorded from the Fleet, the more common *Z. angustifolia*, and *Zostera nana*. "*Zostera marina* is not found in the Fleet, but it does occur in Weymouth Bay." "*Ruppia* also occurs in West Fleet".

28. Whittaker, J.E. & Farnham, W.F. 1983 The Fleet (Dorset), a preliminary biological study. In: The structure and function of brackish water and inshore communities. EBSA Heriot-Watt Symposium, Edinburgh.

"The algae have been studies by Burrows and Farnham (1980) and Burrows (1981); some 150 species have been identified. Their occurrence and distribution are mainly determined by salinity and available substrates. Some of these species have been rarely recorded; the stonewort *Lamprothamnium papulosum* is known from only three other brackish sites in the British Isles [now known to occur at more sites than this] but had been found in the Fleet since 1869. Alien seaweeds have also been discovered, namely *Grateloupia filicina* var. *luxurians*, *Solieria chordalis* and recently, *Sargassum muticum*. The latter two species occur within Weymouth Bay and have migrated into the Fleet on mobile substrates such as stones and shells. In the deeper channels (2-5m) of East Fleet many interesting sublittoral algae occur, including *Acrothrix gracilis*, *Cordylecladia erecta*, *Gloisiphonia capillaris* and *Gracilaria* (all three British species). Other algae grow as epiphytes on *Zostera* leaves, e.g. *Cladosiphon zosterae* or entangled around the bases e.g. *Entermorpha flexuosa* and *Cladophora* spp. *Ulva* usually forms massive growths in West Fleet, especially during the summer, perhaps in response to eutrophication.

29. Moore, J.A. 1987 *Lamprothamnium* - a pioneer in the conservation of the aquatic environment.

Included in this letter about *Lamprothamnium papulosum*, is the comment that "it is likely that, as with other charophytes, its growth is inhibited by the high phosphate levels (above 20 µg/l – not stated whether this concentration is as phosphorus) which result from contamination by human sewage or agricultural waste. Most charophytes, including *Lamprothamnium*, cannot tolerate prolonged disturbance of the sediments such as when motor boat traffic causes detrital matter to remain in suspension for longer periods than would occur naturally. ... *Lamprothamnium papulosum* has been found regularly in the Dorset Fleet since the 1890's, and my own investigations suggest that it is present throughout the year".

30. Saunders-Davies, A.P. 1993 Letter to John Fair, Abbotsbury estate, re. algal bloom in the Fleet.

This letter refers to sulphur bacteria found associated with decaying seagrass in the Fleet, sampled during a 'red infestation at Morkham's Lake'. Also contained are limited results from May to July 1993 from Abbotsbury and Morkham's Lake (and salinity and pH for MF and FB, assumed to be Moonfleet and Ferrybridge) on water temperature, pH, conductivity, salinity, nitrate and ammonia.

31. Institute of Hydrology 1992 Remote sensed imagery.

Memo relates to analysis of Landsat image of Fleet catchment taken on 26th April 1984, giving estimates of land cover within the Fleet catchment, and water temperature within the Fleet itself.

32. Little, *et al* 1989 Distribution of intertidal molluscs in lagoonal shingle (The Fleet, Dorset, UK). Journal of Conchology, 33, 225-232.

This paper describes the mollusc fauna found in springs on the landward side of Chesil Beach (i.e. seaward side of the Fleet), which contain a unique assemblage of mollusc species. The springs have similar salinity and temperature to that of seawater, suggesting their origin as seepage through Chesil Beach, and high oxygen content, suggesting a low retention time within the shingle.

33. Barnes, R.S.K. 1991 European estuaries and lagoons: a personal overview of problems and possibilities for conservation and management. Aquatic Conservation: Marine and Freshwater Ecosystems: Vol 1, 79-87.

Describes issues for conservation of estuaries and lagoons in Europe. No information of relevance to water quality in lagoons.

34. Barnes, R.S.K. 1989 The coastal lagoons of Britain: An overview and conservation appraisal. Biological Conservation, 49: 295-313.

Paper discusses the various definitions of coastal lagoons, and reports on surveys of lagoons carried out around the British mainland coast and the Isle of Wight, Anglesey, the Hebrides and the Western Isles [i.e. excluding Orkney and Shetland obs and 'isolated brackish/saline ponds', which do not fall within Barnes' definition of lagoons, as they are not retained by an 'isolating barrier beach, spit or chain of barrier islands']. Correlation and regression analysis of size of lagoon, number of specialist lagoonal species and species richness was performed using data from 52 lagoonal sites in Britain. The Fleet was 'by far the largest lagoon included in the analysis and it possesses the largest fauna and the greatest number of lagoonal specialists' [Loch Maddy lagoons, Loch Eport lagoons and Orkney and Shetland lagoons were not included in this analysis in the UK, although the Fleet's flora and fauna is still the best studied]. Overall species richness of lagoons was positively correlated with the number of specialist lagoonal species present (with and without the Fleet included in the analysis), and lagoonal area was marginally negatively correlated, less strongly when the Fleet was excluded from the analysis. The Fleet is listed as the 'best representative of its type'. [This analysis could usefully be repeated based on the now more extensive information on coastal lagoons, in particular from northern and western Scotland]. No information of relevance to water quality in this paper.