Journal of Coastal Conservation 8: 77-86, 2002

Mapping the intertidal vegetation of the harbours of southern England for water quality management

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Abstract. This paper discusses a research project dealing with the mapping of the intertidal vegetation of several harbours along the southern coastline of England. It describes in detail the methods used to map the vegetation and gives examples of the results from these studies. This paper then goes on to explain how these results are applied by the Environment Agency of England and Wales to improve water quality in the harbours. This type of vegetation mapping is useful in monitoring the development of the intertidal species including *Spartina, Zostera* and of particular importance to this study the green algae *Ulva* and *Enteromorpha*. The work was undertaken with funding from the Environment Agency and at present has taken place over a four year period. The data collected will be used by the Environment Agency to assess macro-algae cover values for the intertidal area of the harbours concerned. This forms part of the Agency's commitment to the EU Nitrates Directive and the Urban Waste Water Treatment Directive. Some of the species mapped act as suitable indicators of water quality and are symptoms of eutrophication. Other species are of interest for nature conservation and were recorded to provide a record for longer-term trends in vegetation patterns within the harbour. This paper aims to provide readers with an understanding of the techniques involved as well as an evaluation of the methodology.

Keywords: Eutrophication; Infrared photography; Intertidal; Green macro-alga; Photogrammetry; Remote sensing; Vegetation mapping.

Abbreviations: CIR = Colour Infrared; EA = Environment Agency; SSSI = Site of Special Scientific Interest; SPA = Special Protection Area; UWWT = Urban Waste Water Treatment

Introduction

The intertidal areas of the southern coast of England are important both in terms of their ecological value and for human related activities. These areas are under ecological, recreational and industrial pressure and it is important that they receive the correct stewardship if they are to be protected. One of the problems which has been growing ever more apparent in recent years is the problem of eutrophication in estuarine areas. An important symptom of eutrophication is the change in algae coverage of an area and subsequently in the flora and fauna. Increased pollution from sewage and agriculture has increased concentrations of nitrate in the water. This nutrient is the main limiting factor, along with climate, in algal growth in estuarine and coastal waters. To monitor the growth of the green algae a vegetation mapping project was carried out for the Environment Agency by the Department of Geography, University of Portsmouth from 1997-2001. This project concentrated on a number of harbours of the southern English coast from Portsmouth Harbour in Hampshire through to Pagham Harbour in West Sussex. The aim of the project was to create a set of 1:10 000 scale maps showing the vegetation cover in Pagham, Portsmouth, Langstone and Chichester Harbours (Fig. 1). From the maps produced, it would then be possible to calculate the intertidal area of the harbours covered by green macro-algae.

The macro-algae species found within the harbours are widely recognized as key indicators of eutrophication. These data in turn, would then be used with other biological indicators to assess the eutrophic condition of the harbours. Eutrophication is a condition in an aquatic ecosystem where high nutrient concentrations stimulate algal blooms. This research technique followed on from work carried out by Budd (1985) when he examined the feasibility of mapping the vegetation cover in Langstone and Chichester Harbours from aerial photographs. For the recent study, a methodology was developed which mirroring Budd's methodology closely, made appropriate use of more recent technology to improve the accessibility of the data and flexibility of the resultant maps.

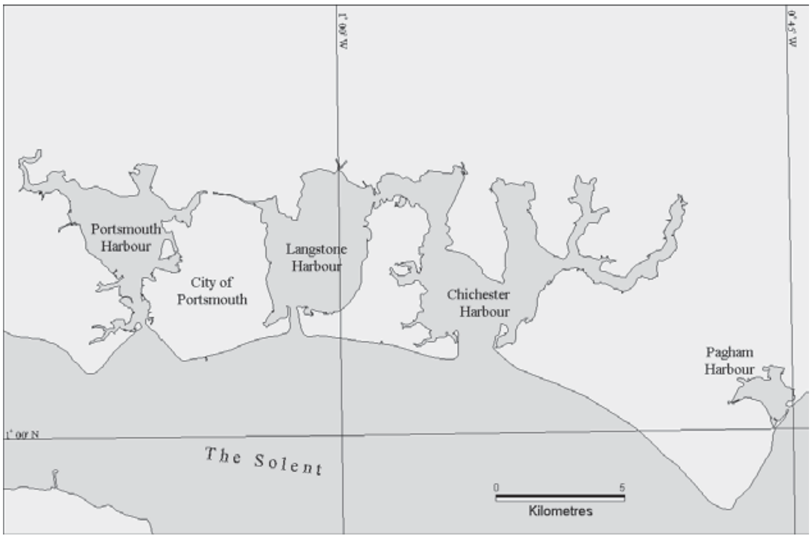

Fig. 1. Location map of the harbours mapped for the Environment Agency.

The Environment Agency (EA) is responsible for the management of the water quality within the harbour areas of England and Wales. The work on Langstone and Chichester was commissioned by the EA to comply with the conditions of the 1991 Urban Waste Water Treatment Directive (91/271/EEC). This requires that waters identified as being eutrophic, or at risk of becoming eutrophic and which receive discharges from qualifying sewage treatment plants, should be identified and designated as Sensitive Areas. Recommendations can then be made for the treatment of sewage from plants either directly into the harbours or into the catchment areas. The Urban Waste Water Treatment Directive requires that once identified the Sensitive Areas be reviewed every four years. Portsmouth and Pagham were not assessed under the provisions of the UWWT Directive as they do not have qualifying sewage discharges. Portsmouth and Pagham were however mapped for a review under the provisions of the Nitrate Directive (91/676/EEC). Under this directive the aim is to reduce water pollution caused or induced by nitrates chiefly from agricultural sources. Under the two directives by 2000, 62 rivers and canals (ca. 2500 km), 13 lakes and reservoirs and five estuaries had been designated as Sensitive Areas.

Remote sensing and vegetation mapping

The two principal methods employed to sample vegetation are either by ground sampling or by some form of remote sensing (Alexander 2000). In ground sampling, this may involve the use of quadrat sampling, whilst remote sensing may involve a range of increasing techniques from close range aerial photography through to the use of satellite based systems. Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation (Lillesand & Kiefer 1994). Remote sensing has long been established as a suitable tool for intertidal vegetation mapping (Schantz & Turner 1958; Moore & Chapman 1984; Burrough & McDonnel 1998). It offers a reliable, non-intrusive technique which allows large areas to be mapped to a high level of detail. One commonly used method for mapping vegetation is photogrammetry. This involves the use of stereo pairs of black and white or colour photographs. In this research, a photogrammetric technique has been used which employs colour infrared (CIR) film. Vegetation is clearly defined in CIR film due to the high reflectance in the near infrared due to the scattering and diffusion of the light by the different plant structures (Smith 1981). CIR film has been used widely in wetland studies and for tree species identification (see for example Budd 1985; Coppin & Bauer 1996; Ciesla 1990). Other forms of remote sensing available for vegetation mapping include the use of CASI (Compact Airborne Imaging Spectroradiometer) (Larsen & Erickson 1998). LANDSAT and SPOT (Gibson & Power 2000) and NOAA AVHRR (Hame et al. 1995). A comprehensive review of vegetation mapping techniques including mapping approaches, spatial scales and case studies is given by Alexander (2000). An introduction to remote sensing techniques and principles is given by Gibson (2000).

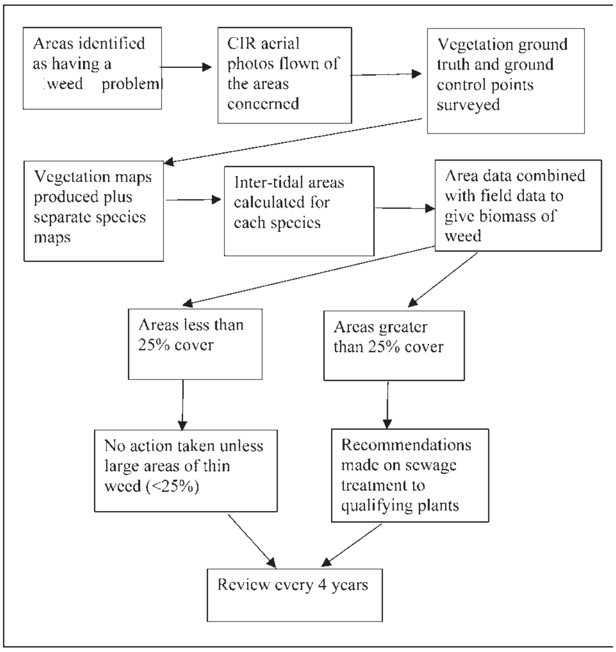

Fig. 2. Flow diagram of the methodological approach.

Undesirable disturbances of eutrophication

Mapping green algae is one of the methods employed by the Environment Agency to identify eutrophic areas. Eutrophication occurs naturally in the environment. However, due to increased human inputs of phosphorus and nitrate into the marine system higher concentrations of nutrients are available for algal growth. Algal blooms, oxygen deficiency deterioration of shell fisheries, reductions in fauna, widespread public complaints about scum and odours and excessive growth of weeds are all in part attributable to eutrophication (Montgomery et al. 1985; Lowthion et al. 1985). Excessive green weed can alter the invertebrate composition with a lower diversity found in thick weed areas. In particular, cockle (*Cardium edule*) numbers are greatest in lower algal cover. Green weed growth also affects the bird population, especially short-billed species. Conversely however, some long-beaked species such as Brent geese (*Branta bernicla*) and Wigeon (*Anas penelope*) can benefit from algal growth. In particular, anoxic conditions occur under mats of green algae. The resulting anoxia and associated hydrogen sulphide production by sulphate reducing bacteria effects sediment structure and in turn the flora and fauna the sediment can support. Weed cover can also smother eelgrass species resulting in the death of eelgrass leaves and beds. Algae also have effects on the recreational activities; in particular local harbour authorities receive complaints about brown micro-algal scums which may be associated with eutrophication. In many harbour areas, algae attract swarms of flies and become entangled with litter leading to complaints from the public.

Description of the study areas

Langstone, Chichester Pagham and Portsmouth harbours all lie along the southern English coast in the counties of Sussex and Hampshire (Fig. 1). Chichester, Langstone and Portsmouth harbours form part of a biological continuum with connecting corridors at their landward ends. Pagham Harbour is a smaller separate harbour situated to the east of Chichester Harbour. Langstone Harbour is a fully saline inlet with a total area of 1900 ha of which 1500 ha is in the intertidal zone. Langstone Harbour has been designated a Site of Special Scientific Interest (SSSI) since 1958, it is also a Ramsar Site and a Special Protection Area (SPA). At low tide large areas of mud flats are exposed.

Chichester Harbour is a large estuarine basin of extensive mud flats and salt marsh. It is 3695 ha in total area. Chichester Harbour is also an SSSI, SPA and Ramsar Site. Portsmouth Harbour like Langstone and Chichester, has large areas of mud flats and tidal creeks. Portsmouth is a busy commercial and naval harbour, as well as being popular for recreational activities. Portmouth Harbour is designated as an SSSI, SPA and a Ramsar Site. Pagham the smallest of the harbours is a tidal inlet which was formerly reclaimed for agriculture. Pagham Harbour has a large intertidal area which is under threat from sea level rise. Pagham is an SSSI, SPA, Ramsar Site and a Local Nature Reserve. Pagham as with Portsmouth has being monitored to identify if it qualifies as eutrophic under the Nitrates Directive.

Project methodology

Photogrammetric mapping techniques were seen as the most suitable method of data capture due to the size and inaccessibility of the harbours. These data are captured digitally, which gives greater flexibility in map production and database enquiries (Fig. 2). Metric aerial photography of the harbours was taken by University of Cambridge in July and August of 1998, 1999 and 2000 using Kodak 2443 (CIR) diapositive film. Typical coverages were 26 diapositives (transparent positives) for Portsmouth, eight for Pagham, 27 for Langstone and 43 for Chichester Harbours. Each of these diapositives is 230 mm × 230 mm, at a scale of ca. 1:10 000. The individual photographs were overlapped by 60% so that a stereo image of the surface could be viewed. Stereo viewing properties enable the interpreter to use texture and the three-dimensional appearance of vegetation, in addition to the spectral properties, this greatly assists in its correct identification.

The photographs were viewed in a Leica DSR 14 analytical photogrammetric plotter which can provide data in digital form via photogrammetric mapping software. Using the analytical plotter, it is possible to plot digital outlines of the vegetated areas into the software as the operator interprets them directly from the photographs. During the mapping process a map of known scale is created showing polygons (areas) of particular vegetation types. Each of these polygons is then coded with attribute data, (i.e. vegetation class and percentage cover).

For this research, the GIS software PC ARC/INFO was used for the data processing stage of the project. This resulted in digital maps covering Langstone and Portsmouth, Chichester and Pagham Harbours and computer database tables, which contained the polygon attributes of vegetation type, together with percentage cover. In addition, the databases also hold information about the polygons derived directly from the digital map including each polygon's area in m^2 and perimeter measurement in m. Therefore, for each mapped area the vegetation type, the percentage cover, the area covered and the perimeter distance are known. Calculation of the total area covered by one particular type can be easily achieved. Any combination of vegetation cover types or percentages can be calculated from this database. Also, it is possible to calculate the ratio of perimeter to area covered giving a potential index of area shape allowing distributions of long thin areas to be compared with more compact ones. Essentially, the main advantage of the digital map is its extreme flexibility which allows a much more detailed investigation of the data to be made than could be achieved with a traditional paper map.

The main primary data for this study was 1:10 000 scale colour infrared aerial photography. To maximize compatibility the same scale and type of photography was used for all harbours. The photographs were taken with a Zeiss LMK metric aerial camera with forward motion compensation by the Committee for Aerial Photography, University of Cambridge on July 1998, August 1999 and July 2000. The interpretation of the vegetation cover from the photographs was made by a single researcher who has considerable experience of working in intertidal areas. This interpretation has been supported by field observations made in the late summer of 1999 by field operatives. Differential Global Positioning System (DGPS) ground control was produced for Portsmouth, Langstone and Pagham Harbours. These were static control points with a positional accuracy of ± 10 mm captured with a Leica GPS system.

Interpretation of the vegetation type from the aerial photographs

Colour infrared film is normally the film of first choice for vegetation analysis due to its ability to record subtle changes in vegetation in the near infrared part of the spectrum (Drury 1998). In the visible part of the spectrum the peak reflectance from healthy vegetation and will normally be in the green wavelengths (ca. 0.5 μm). The reflectance will usually be ca. 12-15% of available light. In the near infrared (0.7 - 0.9 μm), the reflectance from healthy vegetation will typically be ca. 40% of available light. Reflectance in these wavelengths is mainly due to the scattering of light that takes place within the mesophyll of plants. The combination of cell walls, air spaces and water makes an ideal diffusing medium (Gibson & Power 2000). Any physiological changes that take place in the plants due to stress will have a pronounced affect on the ability of the plant to diffuse near infrared radiation. Equally, small variations in the structures of different plants will have significant effects on their near infrared reflectances. These small changes in reflectance, due to intra and inter species variations will therefore be more easily detected with CIR photography than with conventional colour or monochrome photography.

Remote sensing vegetation interpretation by human interpreters is a subjective process which is dependent upon the image quality and the skill and experience of the observer. The interpreter can use the spectral properties of the surface, its texture, pattern, size, shape and location as aids, but the final decision on its classification will depend on what the 'trained eye' feels it to be. That may lead to some inconsistencies in the interpretation from image to image and from day to day. These inconsistencies will normally be very small, well within the acceptable error margins of studies such as this.

Before the mapping project began, tests were performed using Budd's (1985) vegetation mapping technique as a base. Field visits were also made to identify the species required by the mapping project in Langstone and Portsmouth Harbours. This gave an indication of texture and height but not of colour. Test areas were then selected and the researchers classifications were compared against ground truth data. As a final check 'blind' tests were carried out involving areas of Langstone Harbour previously mapped by the EA.

Vegetation classification index

The cover of vegetation was split into the following categories of identified species:

Enteromorpha (green alga)
Enteromorpha/ Ulva (*green alga*)
Degenerate *Spartina* bank
Fucus (brown alga)
Fucus/Enteromorpha
Bare substrate – e.g. mud, gravel or sand
Spartina
Moribund *Spartina* with *Enteromorpha/Ulva*
Moribund *Spartina* with *Fucus*
Spartina and upper salt-marsh plants
Ulva
Upper salt-marsh plants
Zostera
Zostera/Enteromorpha

As the density of a number of the species was crucial to the EA eutrophication assessment, polygons of *Enteromorpha and Ulva* were assigned a code relating to an estimated percentage cover for that area. The same procedure was followed for *Zostera* and *Fucus*. The cover values identified were divided into four intervals:

1 = < 25% cover
2 = 25 -50 % cover
3 = 50 - 75% cover
4 = 75 - 100% cover

The remaining polygons representing the other categories listed in the table above were all showing a pure stand of the species.

A further classification of mixed species into relative percentage covers was also carried out. For example, the two vegetation types *Enteromorpha* and *Ulva* where mixed, were subdivided into separate coverages. This process proved to be problematic as some of the grouped species are masked by others and therefore an incorrect assessment of the value could be made. However, despite the problems an estimate of the cover and thickness of each species was given. To support this analysis ground truth maps were sampled by researchers in small hovercraft and were used to help in the classification.

Table 1 describes the main species types and characteristics relevant to this study.

Table 1. The main types of intertidal vegetation mapped and some of their chatacteristics.

***Enteromorpha* (Green alga)**

Enteromorpha is the key macro-algal species present in both harbours. It forms vast mats which lie on the mud surface. These mats can be very fine coverings of several cms deep. The two extremes can be easily identified whilst those between cause more of a problem. This problem is further enhanced by the water retention characteristics of the species and the presence of thin layers of water covering the algae, reducing the reflectance. Infrared reflectance is high, and the range of colours on the film vary from a dull blue/grey when saturated to deep red when present in thick healthy mats. Where found in free floating mats, *Enteromorpha* may be deposited on other vegetation types. This mat may form a crust of dead material on the upper surface, having characteristics similar to gravel.

***Ulva* (Green alga)**

Ulva tends to grow in sheltered areas. The smooth texture acts as an efficient reflective surface, pure areas of *Ulva* will be seen as a bright pink image. Its flat sheet-like structure implies that it is vulnerable to desiccation so is often associated with 'wet' areas and found predominantly in and around channels. It grows on the channel banks, a variation in look angle results in a darkening of the image. *Ulva* is frequently associated with *Enteromorpha*.

Fucoid algae

The brown fucoid algae all have identical spectral characteristics, we are dealing with *Fucus*, *Ascophyllum* or *Pelvetia*. The resulting colour on CIR film is a distinctive orange. *Fucus* is almost always attached to a hard substrate, often stones, rocks or gravel.

***Spartina* (Smooth cordgrass)**

Spartina is almost always associated with other species, thus the image is complicated to discern on CIR film. The substrate plays an important part in the reflected radiation exposed on the film. It is usually present on mud, therefore the spectral characteristics of mud must be taken into account. A small clump of *Spartina* is best picked out when looking at the polygon created; often circular or in the form of an ellipse. On a larger scale, *Spartina* beds are easy to pick out because of their massive structure and small channels within the large bed. A pure stand of *Spartina* may appear as a dark red/brown image; where surface water is present a darkening of the image to blue-grey/khaki may be observed.

***Zostera* (Eelgrass)**

Texture is the most important factor for identifying *Zostera* on aerial photographs. This is fortunate as the characteristic colour is almost identical to *Enteromorpha*. *Zostera* appears slightly more red with a smooth shimmering texture from the leaves on the photographs at certain angles of sun. This will aid interpretation since it does not occur with any other species.

Upper salt marsh species

The upper saltmarsh area is a very complex habitat with any number of species growing together in one zone. Therefore a pure sector of one species is very difficult to identify. This problem and the lack of definition in these particular aerial images (due to the need for optimal conditions when photographed) means that species such as *Agropyron*, *Salicornia* and *Halimione* have all been placed in this one category. The colour will vary depending on the species present. Generally, it is slightly lighter than *Spartina*, giving a reddish tan colour. Often there will be specks of other colours mixed in and sometimes it forms a relatively bright, slightly pink colour. To provide uniform results the sun must be high in the sky, reducing the amount of shade.

Results and implications of the mapping project

The detailed results of the mapping project will be discussed in relation to Portsmouth and Pagham harbours. The final product of the mapping project was a series of maps of each of the harbours for the dates examined. There were also a series of separate species maps with varying densities described previously. Examples of the maps are given in Figs. 3, 4 and 5. These maps show the distribution of the species across the harbours. In particular, they show phenomena including *Spartina* dieback areas which are classified as 'degenerate *Spartina*'. The distribution of weed across the harbours is also shown. It can be seen from a comparison of the Pagham and Portsmouth weed maps (Figs. 4 and 5) that Portsmouth has large areas of thick *Enteromorpha*. Much of this denser weed is situated to the north of the harbour or along the channels where sheltered conditions allow its accumulation. In Pagham Harbour (Fig. 4) the thick weed areas are much smaller although again the weed tends to dominate the more sheltered areas of the harbour. However, on their own these maps merely give a visual impression of the species distributions. Using the digital maps, it is possible to calculate the intertidal area of each species. This data can then be combined with field sampling to make biomass calculations for the algae. It is also possible to work out the total of the intertidal area which is covered by weed. This weed coverage is a vital statistic which can then be combined with other data to assess the eutrophic state of the area.

The EA sets a limit that a maximum of 25% of the intertidal area may be covered by thicker weed before the harbour is identified as eutrophic or at risk of eutrophication and classified as a Sensitive Water area under the UWWT Directive. The thicker weeds coverage does not generally include the thinner weed (< 25%). In Portsmouth Harbour, which was mapped for three consecutive years (1998, 1999, 2000), green weed coverage varied between 53-62 % (Fig. 5). The thicker weed coverages (> 25%) ranged from 38.1% to 43.7%. This exceeded the EA limit of 25% on each year. The combination of the aerial survey and field survey was then used to calculate the biomass and standing crop in the harbour. Ca. 100 macro-algal samples were collected at a variety of locations. The standing algal crop for Portsmouth Harbour for 1999 was 2441 tonnes and for 2000 2566 tonnes. The results of this evidence and water sampling data resulted in Portsmouth Harbour being identified as a Sensitive Water under the UWWT Directive based on indirect qualifying discharges into the area. As a result the nearest sewage works at Eastney and Peelcommon now receive tertiary nitrogen and phosphorus removal to control eutrophication in the harbour.

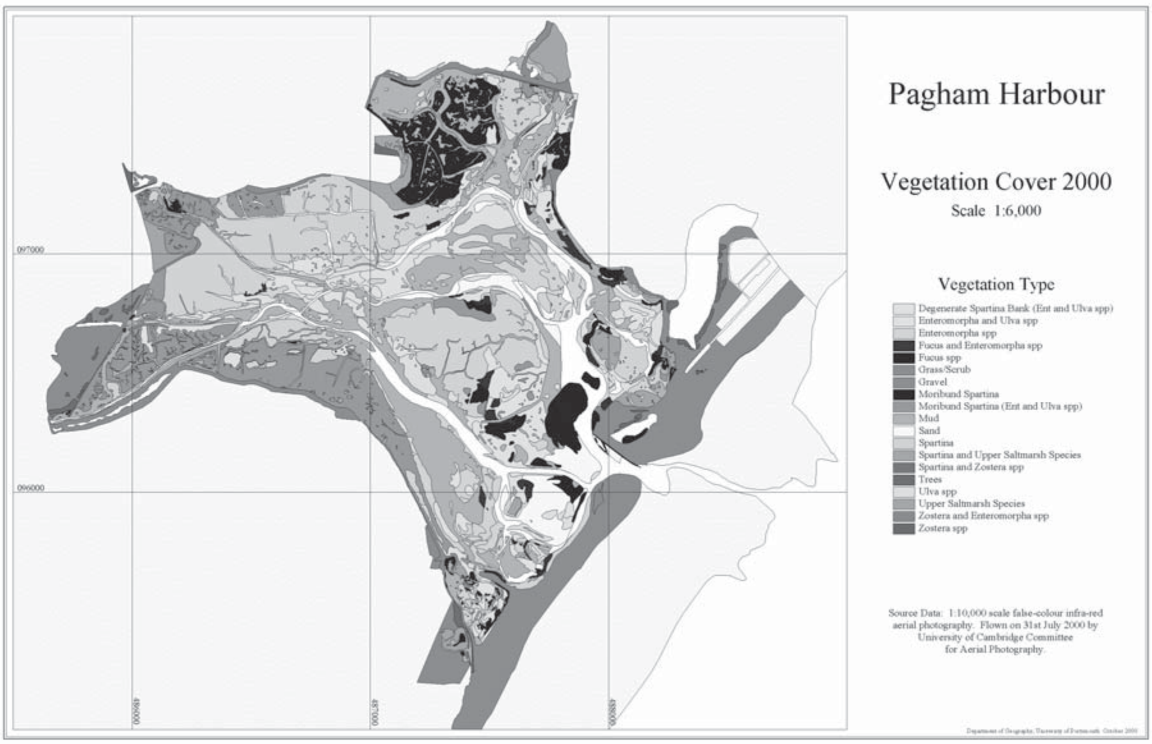

Fig. 3. Pagham Harbour mixed vegetation cover in 2000.

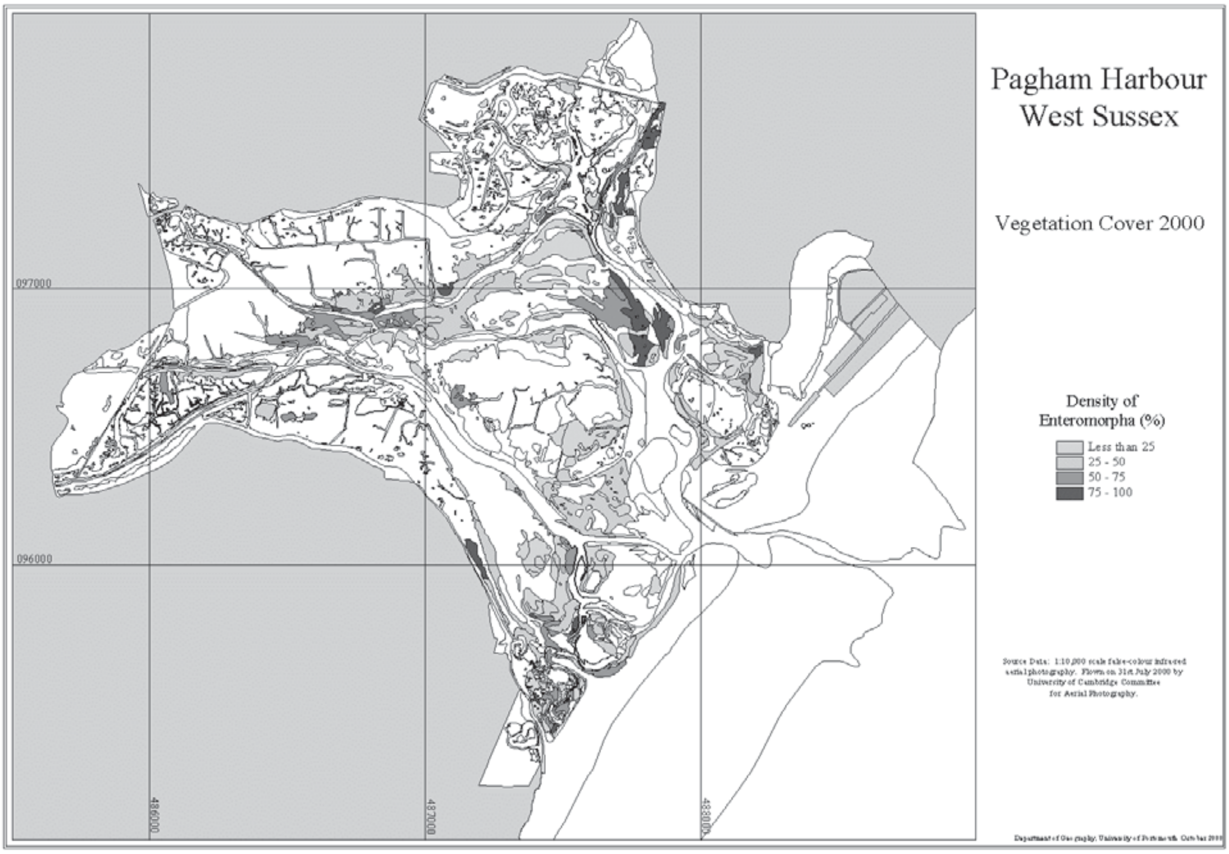

Fig. 4. *Enteromorpha* cover for Pagham Harbour, 2000.

Pagham Harbour in Sussex, has a lower macro-algae coverage than Portsmouth Harbour ranging between 25.3% cover in 2000 to 34.7% in 1999 (Fig. 4). However, if the thicker weed (> 25%) is examined the range is between 17.2% in 1999 to 15% in 2000 as a percentage of the intertidal area. Both of these figures are below the EA threshold of 25%. The standing crop for the two years is 491 tonnes in 1999 and 446 tonnes in 2000. Although the EA threshold was not breached, the large areas of thin weed (< 25%) suggest that action is required. Therefore, the EA recommended that Pagham Harbour be classified as a Sensitive Water under the UWWT Directive. As with Portsmouth Harbour the adjacent sewage works at Siddlesham will now receive tertiary nitrogen and phosphorus removal to control eutrophication.

Comparison of weed cover with previous studies

The weed cover for the various harbours gives an insight into the problem of weed in estuarine areas. In order to examine longer-term change the only harbour where significant repeated surveys of weed have taken place is Langstone Harbour, east of Portsmouth. The intertidal weed cover of Langstone Harbour has been mapped in previous studies for Southern Water using a technique outlined by Budd (1985). Later surveys were ordered by the Environment Agency as part of their monitoring programme of weed growth in the harbour. This data allows a longer-term comparison to be made of the weed growth for a particular area. In the longer-term, repeat surveys of Chichester, Pagham and Portsmouth will allow similar comparisons at these sites. Green macro-algae growth there has been recorded as a problem over a number of years (Anon 1976; Anon 1996). The earlier maps were compiled for Southern Water in the 1980s by Budd (1985); the 1990s maps were produced by the University of Portsmouth for the Environment Agency. The *Enteromorpha* data for Langstone shows that large fluctuations take place in algal growth between years. For example, in 1980 2 797 238 m^2 of the intertidal zone were covered with *Enteromorpha*. This peaked in 1994 at 4 221 040 m^2 in 1994 before falling to 2 344 663 m^2 in 1996 (Fig. 6).

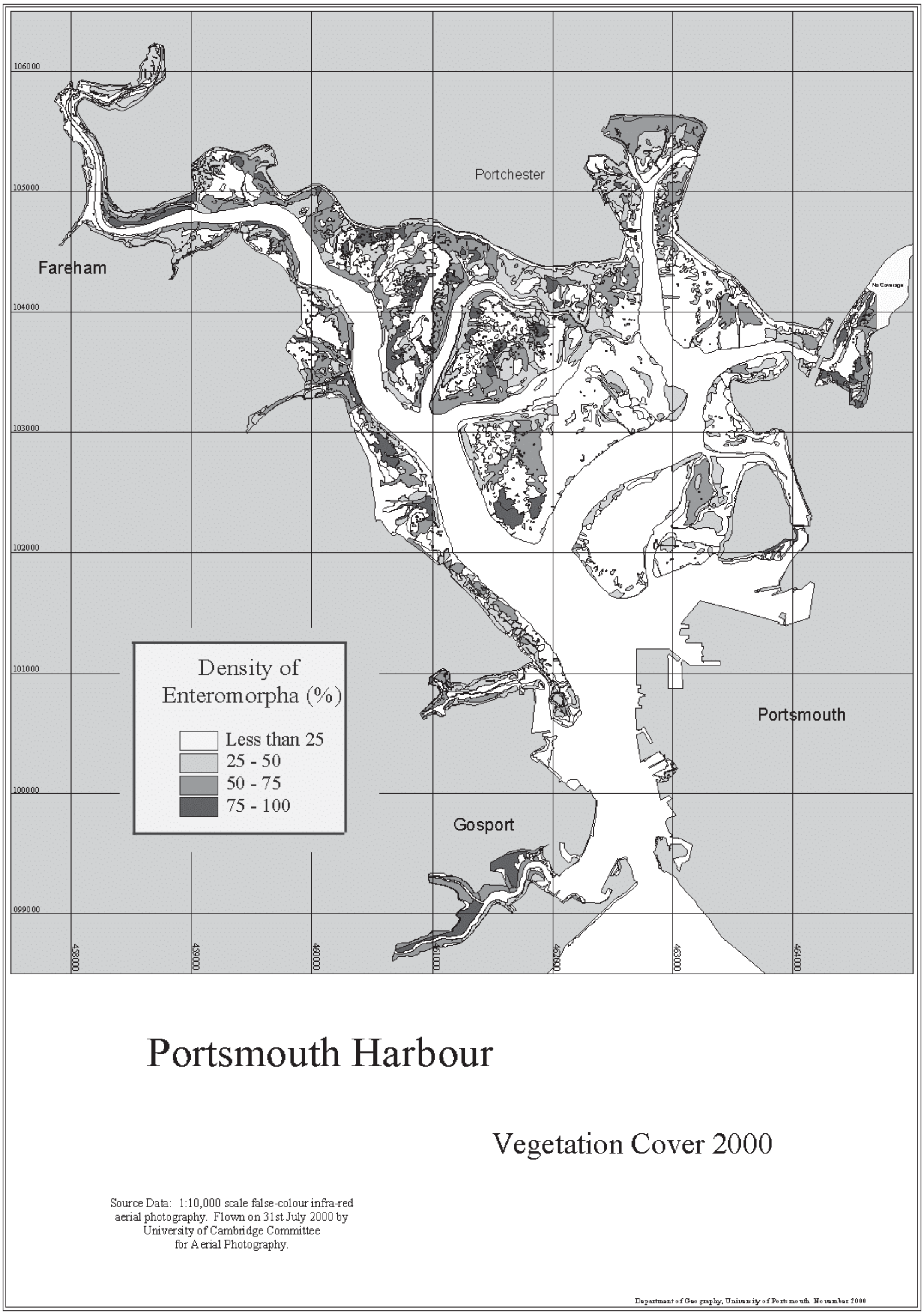

Fig. 5. *Enteromorpha* cover for Portsmouth Harbour in 2000.

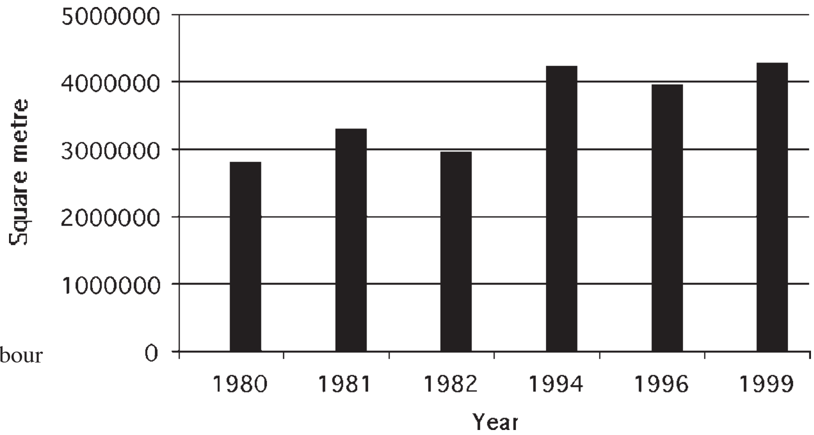

Fig. 6. *Enteromorpha* cover for Langstone harbour from 1980 to 1999.

These fluctuations demonstrate that although sewage into Langstone Harbour has been treated, other factors including climate and the influx of nutrients from the Solent are crucial factors in the control of weed growth. The University of Portsmouth undertook the latest survey of Langstone in 1999. The green weed coverage in Langstone is widespread with particularly heavy concentrations in the north of the harbour. The polygon coverage for the 1999 data shows that the weed cover is 4 277 461 m^2, which is near the peak recorded in 1994 (Fig. 6). Overall, it can be seen from the graph that *Enteromorpha* levels are generally on the increase within Langstone Harbour. Again, conclusions cannot be drawn on one mapping sample but the data for all years suggest strong fluctuations in weed cover which remains a persistent problem in spite of the treatment of sewage at qualifying plants.

The data for Langstone demonstrates the importance of taking more than one vegetation sample from an area. It can be seen that the weed within Langstone is still a problem many years after treatment of sewage began. These types of repeated surveys are necessary to place recent results in context and to show if present strategies are successful in controlling eutrophication.

Discussion

The method described above offers a cost-effective technique with which to monitor intertidal vegetation and in particular green algae coverage. The interpretation showed consistency with the Environment Agency ground truth data as mapped by the hovercraft teams and with data obtained by the University of Portsmouth. However, it should be understood that in a subjective process variations and misclassification will always occur. This research has also clearly shown that the accurate mapping of the intertidal vegetation using infrared film is reliant upon the experience of the interpreter and requires some time for training and analytical skills to develop. Whilst many of the species are easily identified, others require careful examination as the changes are often subtle. It is also important to note that variations within photography occur with changes in film quality, weather and lighting conditions and processing methods. Whilst this may not be a problem for most species, it will cause problems for species such as *Zostera* where the highest quality imagery is required for successful identification. Vegetation mapping requires photographs taken at the peak of the growing season, in good weather, at a low spring tide. In reality, getting a perfect combination of all of these factors is not always possible.

This research has shown how photogrammetry of the intertidal zone of the harbours can be used to assess the water quality of a particular area. This research is part of an ongoing programme which has now expanded to include the Medway estuary in Kent and the Thames Mud flats. Photogrammetry offers a proven non-contact monitoring technique which can record high levels of detail over large spatial areas The data recorded by this research can then be applied by the Environment Agency in its commitment to improve water quality and in turn protect coastal habitats from eutrophication.

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