The National Centre for Environmental Data and Surveillance

The Investigation of Phytoplankton Dynamics in Coastal Waters Using Aerial Surveillance Case Study 3

ENVIRONMENT AGENCY

14 April 1997

EXECUTIVE SUMMARY

Understanding the dynamics of formation and development of algal blooms is important in the management of the coastal zone. Such dynamics are little understood as they present a significant challenge to conventional boat based point monitoring techniques.

This study aimed to exploit the synoptic overview provided by remote sensing and the ability to target airborne remote sensing to locate and study the dynamics of such blooms.

Despite considerable endeavour these proven techniques, in conjunction with a ground based information network, failed to locate a bloom that was in the correct stage for asessment of its dynamics. Given these efforts it is improbable that pre-programmed monitoring of the 5 kilometre coastal strip for algal bloom detection using airborne surveillance would yield better results in the future.

This study makes the following recommendations for improving the knowledge of algal bloom dynamics:

- Untargeted aerial remote surveillance of the coastal waters as a means of detecting algal blooms should not be continued because of its low probability of success. This low probability is a consequence of the low likelihood of finding a bloom, not a low probability that remote surveillance can detect a bloom.

- A strategy for locating algal blooms at an early stage is important and should be developed, based on a review of expert knowledge, of satellite detection of airborne surveillance and use of automatic instrumentation. Recently launched satellite systems with sensors suited to marine monitoring and subsequent availability of high temporal frequency of images covering large areas will allow targeted deployment of aerial platforms and placing of instrumentation packages. The National Centre has followed the developments in this satellite technology closely and has initiated research and development projects to investigate such a hierarchical system.

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1. BACKGROUND

1.1 Although background concentrations of chlorophyll-*a* are required for large scale estimates, the highest chlorophyll-*a* concentrations are found during phytoplankton bloom events. Such events can be devastating to aquaculture and shell fisheries as well as being a severe nuisance to tourism and as such an understanding of their dynamics is advantageous. Such knowledge will allow an assessment to be made of whether the region may be Sensitive under the provisions of the Urban Waste Water Treatment Directive (91/271/EEC) and will aid the Environment Agency in forming an opinion of the general state of pollution of the marine environment (Section 5, Environment Act, 1995).

1.2 The ability to identify and monitor algal blooms in the highly dynamic coastal zone is hindered by the speed of sampling offered by traditional sampling techniques. Remote sensing offers the potential for the retrieval of wide scale, synoptic estimates of chlorophyll-*a* concentration, as well as identification and tracking of specific bloom events.

2. PREVIOUS WORK

2.1 Marine algae are microscopic plants (called phytoplankton) that inhabit all the world's marine waters. Algae nutrients (nitrogen, phosphorus & silica) are at maximum concentrations in winter when plant growth is at a minimum. During spring, as sunlight and temperature increase, the abundance of phytoplankton increases rapidly into the summer and localised higher concentrations, or algal blooms, can form. The mechanism of formation is complex and at present it is not possible to predict where they will form. The purpose of this project is therefore to provide basic information to form a better understanding of algal bloom mechanisms.

2.2 Remote sensing systems record light returned to the sensor from the surface in question. Optical systems record light reflected or fluoresced from the surface. In the case of water surfaces the character of the light returned is altered by interactions within the water column, particularly absorption and scattering. The presence of chlorophyll-*a* within phytoplankton cells causes absorption of blue light and scattering of green light, and this spectral variation is one of the major effects of chlorophyll-*a* recorded by the sensor.

2.3 The use of remote sensing technology to provide information on the location of algal blooms and spatial estimates of chlorophyll-*a* concentration has been ongoing since the launch of the Coastal Zone Colour Scanner (CZCS) in 1979. This sensor had wavebands specifically designed for the detection of chlorophyll-*a*, with a dual algorithm developed allowing for changes in the chlorophyll-*a* concentration. The algorithms used depended on the ratio of the green channel (550 nm) to one of the blue channels (443 nm or 520 nm) (Gordon *et al.* 1980).

2.4 This type of algorithm relies on the absorption properties of chlorophyll-*a*. Thus an algorithm based on the ratio between these two wavelengths will be related to the chlorophyll-*a* concentration. Successful comparisons with *in-situ* data were carried out

(Gordon *et al.* 1980).

2.5 CZCS data proved unsuitable for working in the coastal zone, due to the low spatial resolution. Coastal phenomena are often at scales smaller than the 0.85 km square pixel size. Aerial systems combine a finer spatial resolution (dependent on altitude) with greater temporal flexibility. Algorithms of the form developed for CZCS were therefore applied to data from aircraft systems by a number of workers (for example Moore and Aiken, 1990, Matthews *et al.*, 1992). These were found to be applicable for the site at which the algorithms was developed, but were not portable between sites. This was due to two key factors: atmospheric interference and the presence of suspended sediment.

3. ENVIRONMENT AGENCY DEVELOPMENTS

3.1 The National Centre for Environmental Monitoring and Surveillance has previously used airborne platforms to characterise the controlled waters (out to 3 nautical miles) of England and Wales. This involved the collection of 189 flight lines around the coastline in nine different survey campaigns in the period between 1993 and 1995.

3.2 The survey has relied on the sensitivity of the Compact Airborne Spectograpic Imager (CASI) instrument to resolve small changes in the colour of water bodies that can then be linked to algal activity, suspended solids and other oceanic phenomena.

3.3 During these aerial surveys a number of coastal algal blooms have been periodically identified. The purpose of the surveys was not to search for such blooms, but it was likely that occasional blooms would be recorded by chance.

3.4 The identified blooms were in different stages of life cycle development. Figure 1 shows a true colour composite of a bloom off the coast of Pwllhelli, Wales. This bloom (chaetoceros) is characterised by a green colouration in the water, with a definite centre of activity. Analysis of the spectra (figure 2) shows that the "centre" of activity exhibits strong fluorescence, which is consistent with *in-vivo* fluorescence of chlorophyll-*a* in the red part of the spectrum (peak in channel 11). A small percentage of the visible light absorbed by chlorophyll is re-emitted as fluorescent energy after undergoing transition to a higher wavelength. This emission is manifested in the reflectance spectrum as a narrow peak at approximately 685 nm (Neville and Gower 1977).

3.5 Another bloom was identified off Exmouth in 1994 (figure 3). This bloom did not exhibit the same levels of fluorescence as the Pwllhelli bloom and was already in the stage of decomposition. Later images showed detritus on the water surface and near the shore which could cause a nuisance, especially if the bloom had become toxic (in this case it had not).

3.6 Further blooms have been sensed on freshwater lakes, especially Lake Coniston (figure 4) and Lake Bala. These images showed features that were similar to the coastal blooms, though the blooms were constrained by the topography and local wind effects.

3.7 In addition to the identification of blooms in the aerial imagery, laboratory water samples recorded some regions with consistently high nutrient concentrations, which may result in high chlorophyll-*a* concentrations. For examples, the Mumbles, on the south coast of Wales, recorded elevated nutrient concentrations at all seasons but did not result in high chlorophyll-*a* concentrations at the time of the baseline surveys. Figures 5 to 7 show the average chlorophyll levels for 1993 to 1995 shown as the Spring, Summer and Autumn surveys. These data have been discussed elsewhere (National Rivers Authority, 1996), especially with regard to the spatial distribution of chlorophyll-*a*.

3.8 Given this previous experience, this case study sought to study the development of phytoplankton blooms in coastal waters, specifically to map its spatial extent and temporal variability. This may be attained using CASI data calibrated for chlorophyll-*a*, to identify the full extent of the bloom, with subsequent integration into a Geographical Information System (GIS). In addition, changes in the balance of species within the bloom could to be studied.

3.9 Recent work carried out by the Agency's National Centre for Environmental Data and Surveillance (Marine Case Study 1, Calibration of CASI imagery for high concentrations of chlorophyll-*a* in turbid waters) has shown that imagery calibrated with laboratory samples can predict chlorophyll-*a* with a random error of 3.1mg/l and a systematic error of 2.4 mg/l. If concentrations of chlorophyll-*a* in excess of 10 mg/l are assumed as an indicator of eutrophism, then remote surveillance should be capable of detecting it.

4. SURVEY STRATEGY

4.1 The success of this study hinges on finding a marine algal bloom that is in the early stages of development. This can then be intensively surveyed to provide an insight into the dynamics of the bloom. The initial phase of the project includes the creation of an information network on the location of algal blooms and proactively surveying areas of known algal activity for signs of developing blooms.

4.2 Previous baseline survey data was mined for areas where chlorophyll values were frequently high. Regional opinion was also sought on areas where algae were likely to be encountered. Two areas were catered for in the original proposal. The north Norfolk coast and the Cumbrian coast. North Wales was considered as an area where algae were prevalent, but local opinion in the North West region swayed the area to the Cumbrian coast.

4.3 Figure 8 shows the main sections of this information network. Environment Agency Coastal Survey Vessels and external vessels (such as the Port Erin Laboratory vessel) notified the National Centre if they encountered elevated levels of chlorophyll-*a*. Regional biologists were asked to inform the Centre of any blooms or anticipated blooms. In addition, the routine beach monitoring reports were supplied to the Centre. These vary from region to region, with the most detail being supplied by Welsh Region.

4.4 It is well known that maximum algal activity in the coastal zone is in the Spring season,

especially May, when the maximum nutrient supply is available to trigger blooms and the weather warms the waters. It was imperative to start the project as soon as possible to maximise the chances of finding the beginning of a suitable bloom in the Spring season. Further blooms do occur in the Summer and Autumn seasons, but these are often likely to be a continuation of high populations from the spring season. Such blooms may have different dynamics as a result, which whilst being important may not yield information that may lead to understanding the initial "trigger" factors of the bloom.

5. SURVEY RESULTS

5.1 The project did not receive final authorisation until 7th June. Algal bloom development usually commences in late April or early May. It was decided that despite the late start, past data had shown the study areas have a high likelihood of algal blooms throughout the year, with an Autumn resurgence of algae being common. It was considered worthwhile to endeavour to find such blooms as there was a good chance that algal blooms in the early stage of formation, suitable for this project.

5.2 A series of investigational flights were programmed using the information network and in areas of known high algal activity. A total of 19 surveys were carried out between 30 May and 17 September during which all reports of algal bloom sightings, and ground based indications of possible eutrophic conditions were investigated. During this time no firm indications of blooms were detected by remote surveillance. but all peripheral indications of possible eutrophic conditions were investigated by ground staff. Despite this high intensity of scrutiny no algal blooms could be located during this entire period. The individual surveys are detailed in Appendix 1 (figs 9 to 36)

5.3 Welsh region produce the most comprehensive beach algal monitoring service in the Agency. Table 1 and Figure 30 provide a summary of the north and south Wales reports through 1995 and 1996. Comparing 1995 and 1996 shows that 1996 had 79% of the reported blooms of 1995. In addition the spread of blooms in the season is worth examining. As stated previously (section 4.4), the majority of blooms occur in May. In 1996, 26% of the blooms that were seen on the beach occurred after the project had received final permission (June 7th).

6. DISCUSSION OF RESULTS.

6.1 The present state of knowledge on the formation of algal blooms is very limited, and is unable to predict whether blooms will form inshore, offshore or beyond the three mile limit. Selection of target areas for investigation in this exercise was made using the best local experience of past prediction based on events.

6.2 Despite the best efforts of ground and surveillance activities, no blooms at an early stage could be found for intensive study in this exercise. Subsequent coastal baseline surveying and Welsh Region's beach algal monitoring programmes confirmed the relatively low incidence of marine chlorophyll concentrations at the selected sampling areas.

6.3 The coastal baseline survey data (fig.37) for the selected sampling areas show chlorophyll-*a* concentrations to be less than 10 mg/l. This confirms the remote surveillance findings of no algal blooms as correct and supports its applicability for this use. Conclusive proof, however, would require surveillance to correctly identify a positive bloom, and this could not be tested in this exercise.

6.4 Work in progress in other parts of the Agency (Environment Agency (1997)), corroborates the findings of this study.

6.5 Although this exercise was not successful in locating an algal bloom for further study, the following useful points can be made.

(I) Scheduling

Welsh Region's beach algal monitoring data (Table 1 and fig.30) show that most algal blooms occur in May and only one quarter of them occurred during the surveillance time frame of this case study (June - September).

(ii) Prediction

Historical information and local knowledge are clearly not able to accurately predict the likelihood of algal blooms. On-going work at the TAPS National Centre (not yet reported) may assist in predicting bloom events, or at least in defining boundaries. This work is likely to conclude that large algal blooms are very difficult to predict and usually start well offshore. Accumulations of algae found on beaches are often local aggregations produced by tidal hydrodynamics, not connected with bloom conditions close to the shore.

(iii) Spatial Coverage

In the absence of any definitive guidance it has to be assumed that algal blooms that impact on beaches can form anywhere in the 20,000km^2 controlled coastal waters or even in the open sea. The 5km wide swaths of remote surveillance surveys, therefore, do not have a high likelihood of locating blooms. Space-borne imaging may provide a better option, provided it has suitable spectral channels and temporal frequency for identifying build ups of chlorophyll.

(iv) Temporal Coverage

If a bloom was identified for further study that was out to sea, the cost of intensive boat based sampling could be prohibitive. The use of an automatic marine monitor such as Proteus (particularly since it can monitor through a range of depths of water column) could provide reference data relatively cheaply and efficiently.

7. CONCLUSIONS

7.1 Using the present state of predictive knowledge of algal bloom location a suitable bloom could not be identified, and this study was thus not able to quantify the spatial and temporal characteristics of algal blooms, their speciation and nutrient inputs.

7.2 As far as can be determined, the reason why no bloom could be identified was that there

were no blooms in the areas studied at the times the areas were mentioned rather than a failure to detect blooms by aerial remote surveillance. The project was delayed until after the recognised start of bloom development. Aerial remote surveillance successfully identified a lack of algal blooms, but could not be conclusively tested on quantitative measurement of an actual bloom. It has, however, been conclusively shown elsewhere that aerial and satellite based remote sensing systems can be used to observe blooms.

7.3 It seems improbable that a repeat pre-programmed monitoring of areas of the coastal strip using aerial remote sensing for the identification of blooms in the early stages of development would achieve better results in the future. It would be more useful to review the state of expert knowledge, and assess the potential of satellite imagery to expand the area covered and automatic instrumentation to provide reference data once a bloom was located. It has been clearly shown (Environment Agency 1997) that the remote sensing techniques employed in this study are capable to assessing chlorophyll values with systematic errors of 3.04 to 3.11 µg/l, and therefore capable of assessing the extent and dynamics of blooms.

8. RECOMMENDATIONS

8.1 Untargeted aerial remote surveillance of the coastal waters as a means of detecting algal blooms should not be continued because of its low probability of success. This low probability is a consequence of the low likelihood of finding a bloom, not a low probability that remote surveillance can detect a bloom.

8.2 A strategy for locating algal blooms at an early stage is important and should be developed, based on a review of expert knowledge, of satellite detection of airborne surveillance and use of automatic instrumentation. Recent launches of CZCS like sensors and subsequent availability of high temporal frequency of images covering large areas will allow targeted deployment of aerial platforms and placing of instrumentation packages. The National Centre has followed the developments in this satellite technology closely and has initiated research and development projects to investigate such a hierarchical system.

9.0 REFERENCES

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Table 1: Welsh Region: beach algal monitoring reports 1996.

1996 North Wales

Date w/e	Number of blooms	phaeocyst	chaetocer	asterionella	noctiluca
10-May-96	8	8	0	0	0
17-May-96	17	17	0	0	0
24-May-96	11	11	0	0	0
31-May-96	10	10	0	0	0
07-Jun-96	7	7	0	0	0
14-Jun-96	5	5	0	0	0
21-Jun-96	0	0	0	0	0
28-Jun-96	0	0	0	0	0
06-Jul-96	0	0	0	0	0
12-Jul-96	0	0	0	0	0
19-Jul-96	2	0	0	0	2
26-Jul-96	0	0	0	0	0
02-Aug-96	0	0	0	0	0
09-Aug-96	1	0	0	1	0

1996 South Wales

Date w/e	Number of blooms	phaeo	chaet	asteronella	noctiluca
03-May-96	3	3	0	1	0
10-May-96	3	1	0	2	0
17-May-96	9	8	1	1	0
24-May-96	7	5	2	0	0
31-May-96	6	6	0	0	0
07-Jun-96	10	8	2	0	0
14-Jun-96	6	8	0	0	0
21-Jun-96	6	6	0	0	0
28-Jun-96	4	0	4	0	0
06-Jul-96	0	0	0	0	0
12-Jul-96	1	0	1	0	0
19-Jul-96	0	0	0	0	0
26-Jul-96	0	0	0	0	0
02-Aug-96	1	0	1	0	0
09-Aug-96	0	0	0	0	0
16-Aug-96	0	0	0	0	0
23-Aug-96	5	0	5	0	0
30-Aug-96	0	0	0	0	0
06-Sep-96	1	0	1	0	0
13-Sep-96	1	0	1	0	0
20-Sep-96	0	0	0	0	0

1995 South Wales

Date w/e	Number of blooms	phaeo	chaet	asteronella	noctiluca
05-May-95	9	8	0	1	0
12-May-95	15	15	0	0	0
19-May-95	26	26	0	0	0
26-May-95	21	21	0	0	0
02-Jun-95	8	8	0	0	0
09-Jun-95	9	9	0	0	0
16-Jun-95	1	0	0	1	0
23-Jun-95	1	1	0	0	0
30-Jun-95	0	0	0	0	0
07-Jul-95	0	0	0	0	0
14-Jul-95	4	0	4	0	0
21-Jul-95	3	0	3	0	0
28-Jul-95	5	0	5	0	0
04-Aug-95	1	0	1	0	0
11-Aug-95	0	0	0	0	0
18-Aug-95	1	0	1	0	0
25-Aug-95	5	0	5	0	0
01-Sep-95	0	0	0	0	0
08-Sep-95	1	0	1	0	0
15-Sep-95	3	0	3	0	0

1995 North Wales

Date w/e	Number of blooms	phaeo	chaet	asteronella	noctiluca
14-Apr-96	0	0	0	0	0
21-Apr-96	1	1	0	0	0
28-Apr-96	2	2	0	0	0
06-May-95	3	3	0	0	0
13-May-95	6	6	0	0	0
20-May-95	5	5	0	0	0
27-May-95	10	10	0	0	0
03-Jun-95	9	9	0	0	0
10-Jun-95	6	6	0	0	0
17-Jun-95	2	2	0	0	0
24-Jun-95	3	3	0	0	0
01-Jul-95	3	3	0	0	0
08-Jul-95	0	0	0	0	0
15-Jul-95	0	0	0	0	0
22-Jul-95	2	0	2	0	0
29-Jul-95	0	0	0	0	0
05-Aug-95	0	0	0	0	0
12-Aug-95	0	0	0	0	0
19-Aug-95	0	0	0	0	0
26-Aug-95	0	0	0	0	0
02-Sep-95	0	0	0	0	0
09-Sep-95	0	0	0	0	0
16-Sep-95	0	0	0	0	0

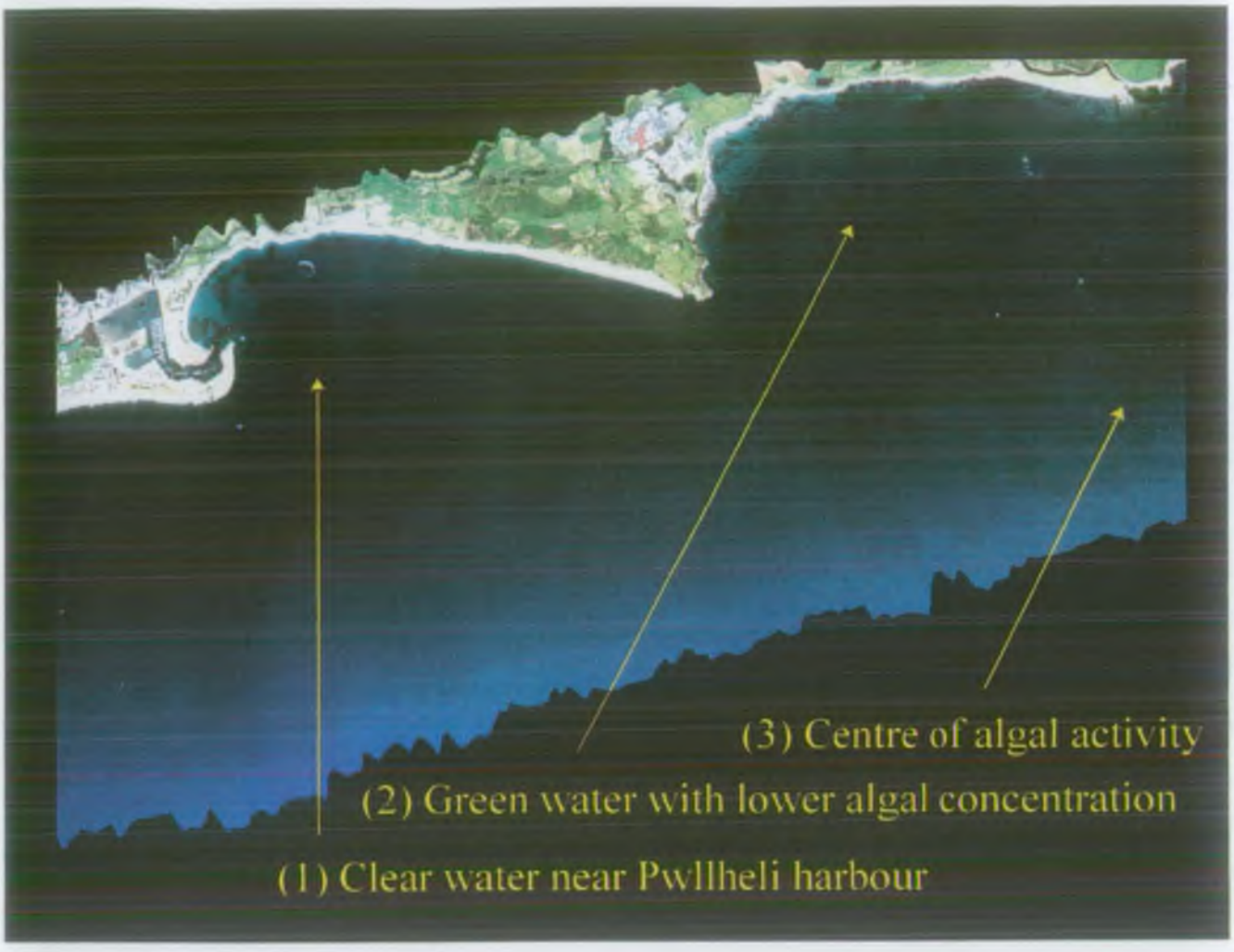


Figure 1
CASI image of Pwllheli area showing confirmed algal bloom
27th July 1995

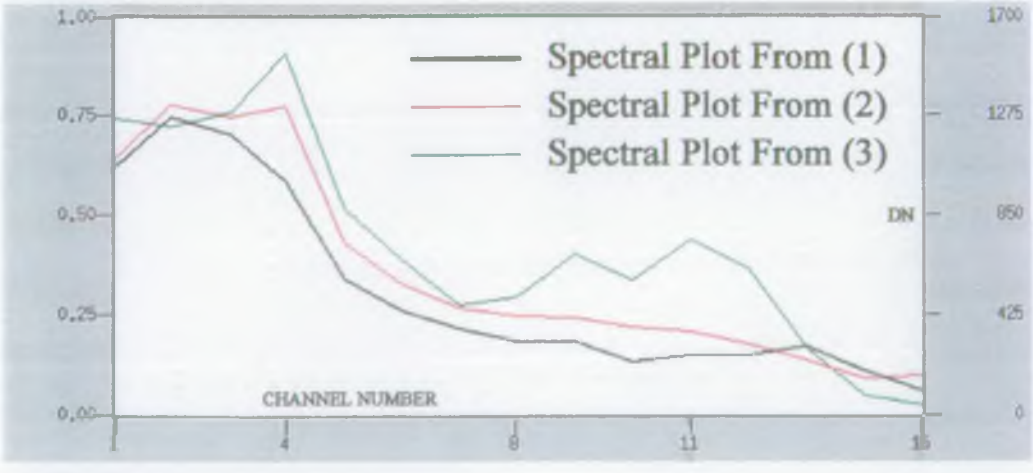


Figure 2
Spectra derived from image shown in figure 1 (see key)

Figure 3

Exmouth, 28th May 1994, 10:27GMT
Bloom clearly visible directly off Exmouth (3Km)

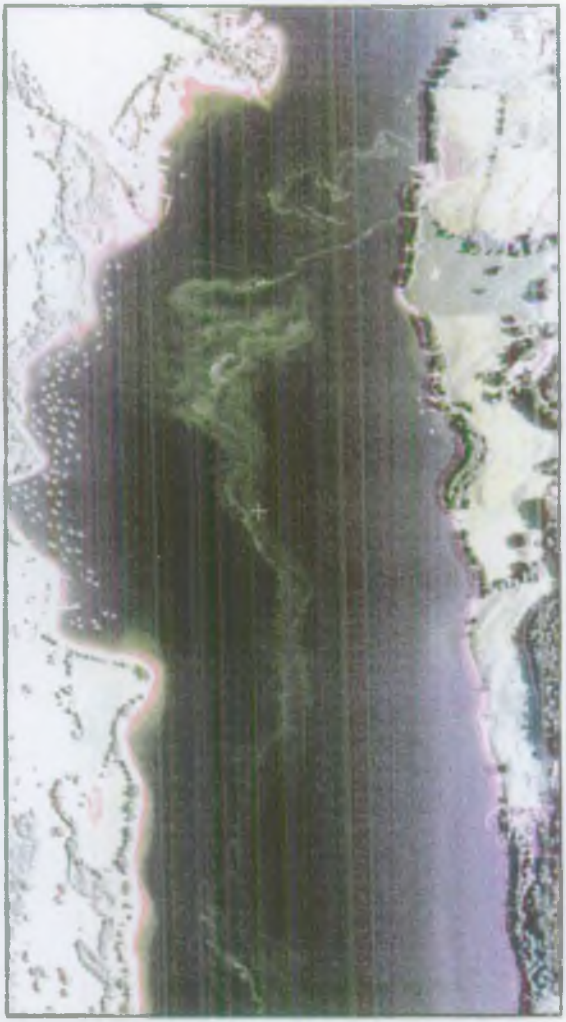
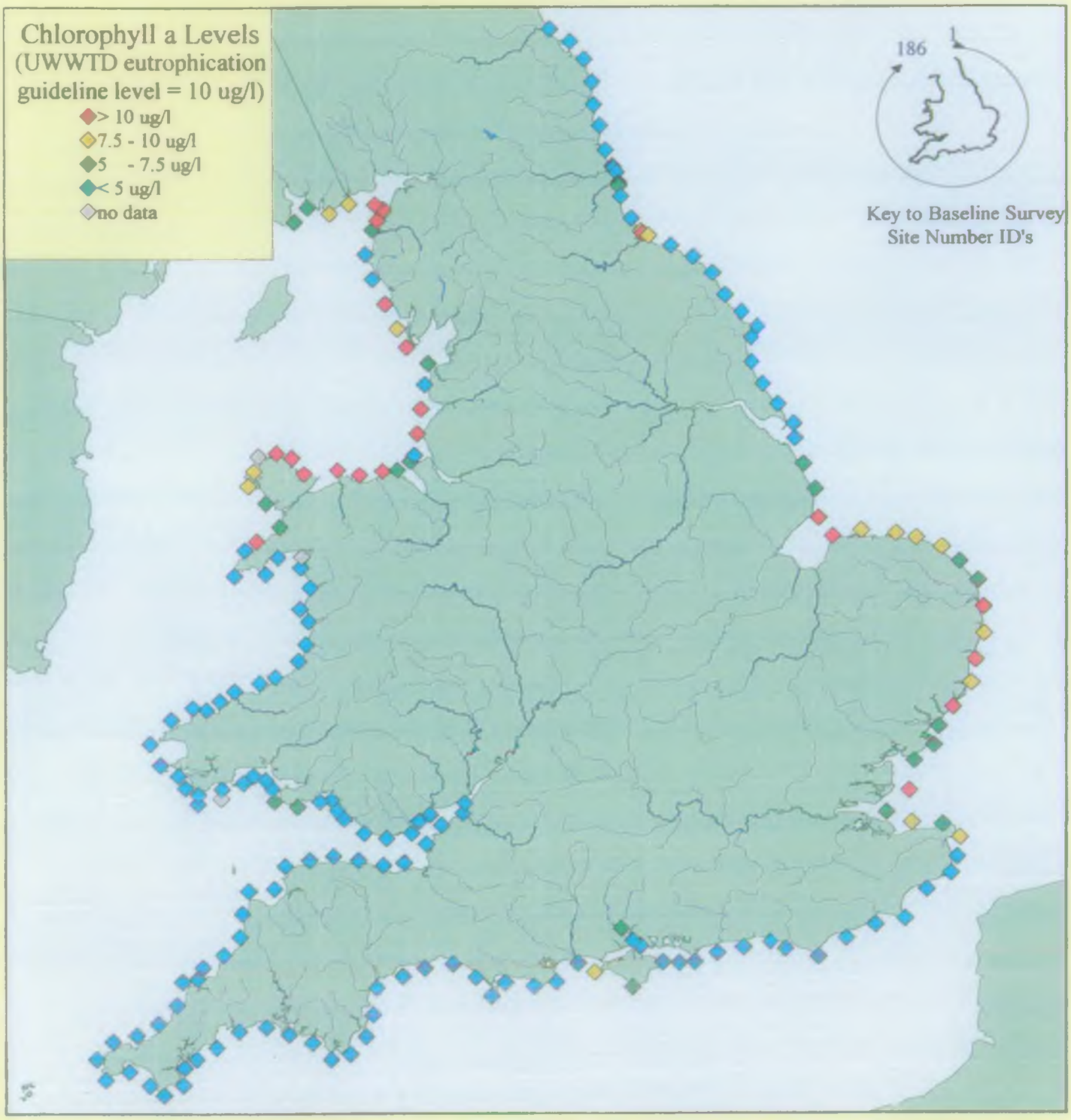


Figure 4

Coniston Water, 22nd June 1995
Bloom clearly visible in the centre of the lake.

Figure 5

Chlorophyll a Levels, National Baseline Survey, Spring Average 1993 to 1995.



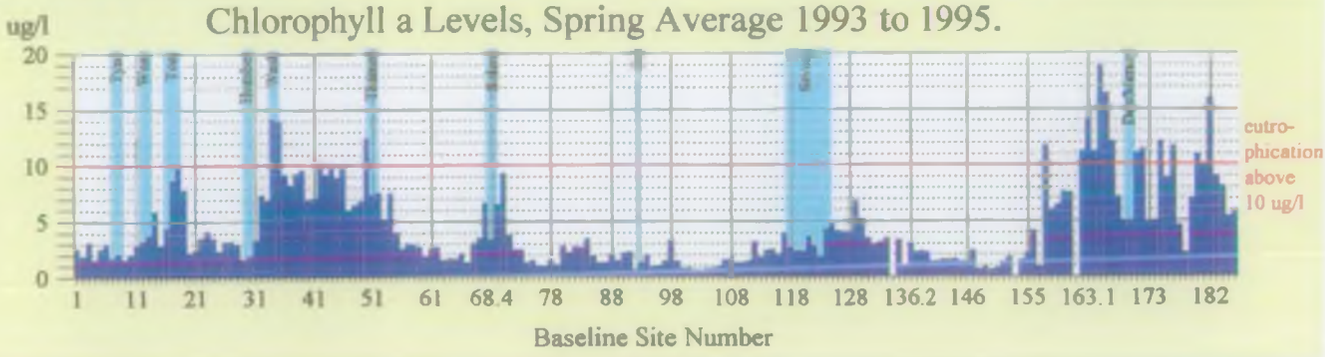
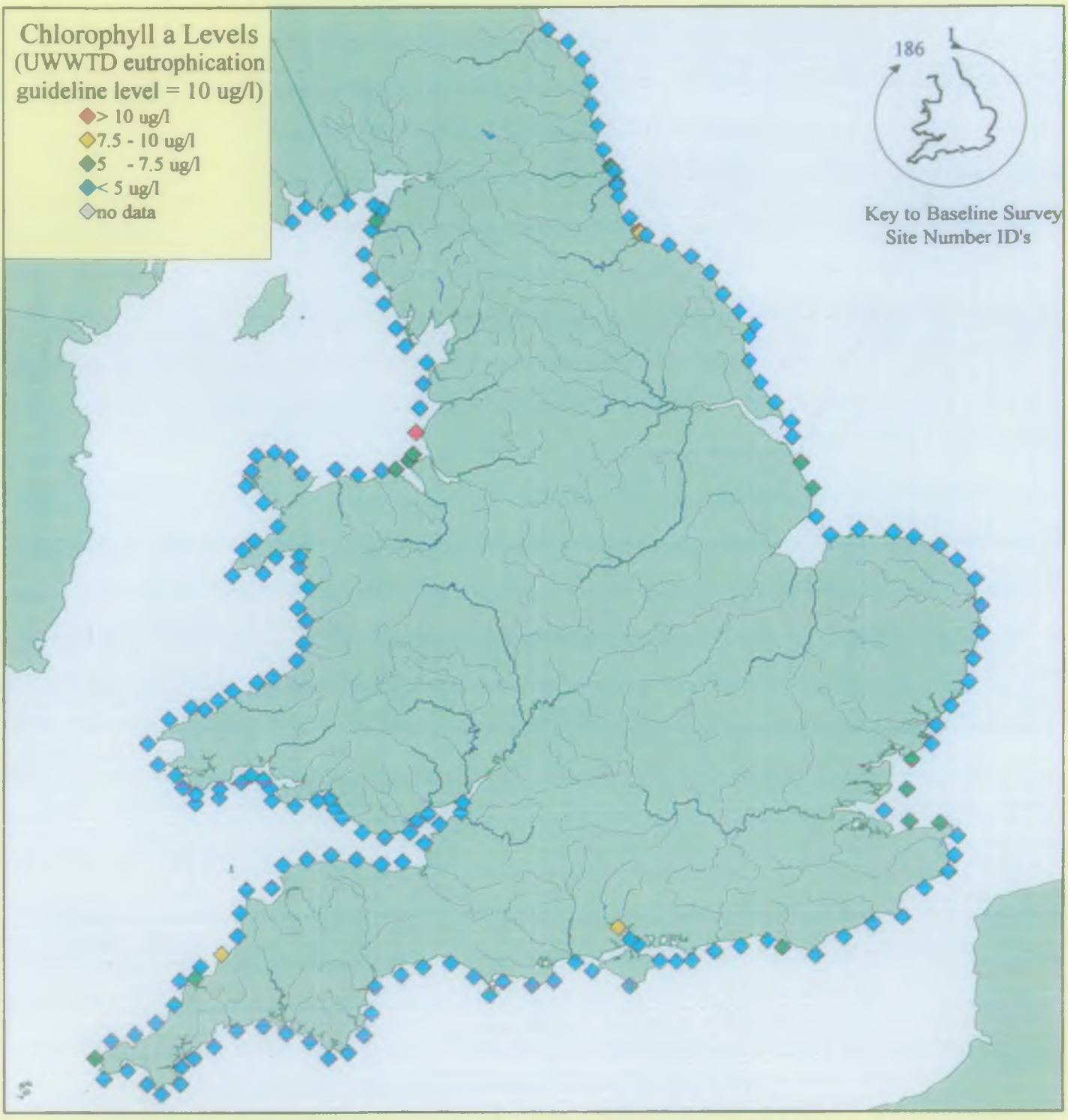


Figure 6

Chlorophyll a Levels, National Baseline Survey, Summer Average 1993 to 1995.



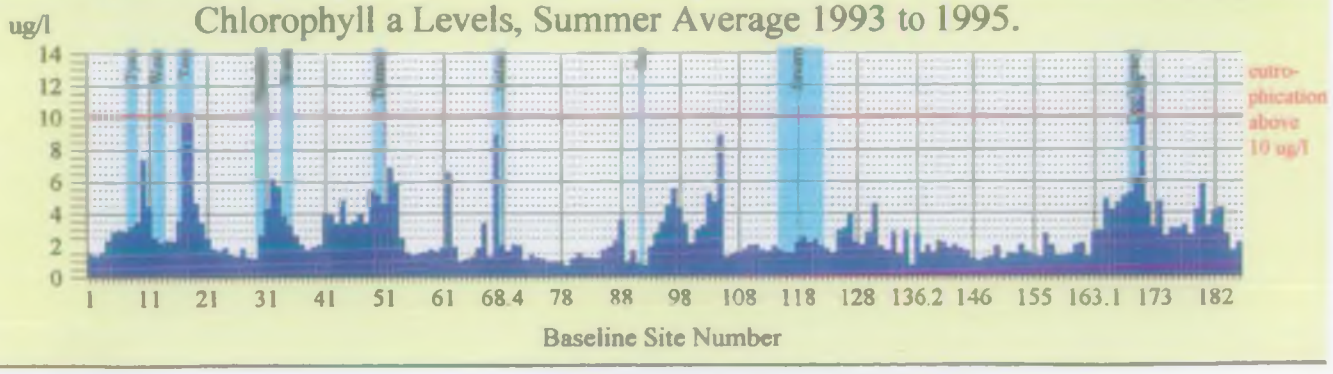
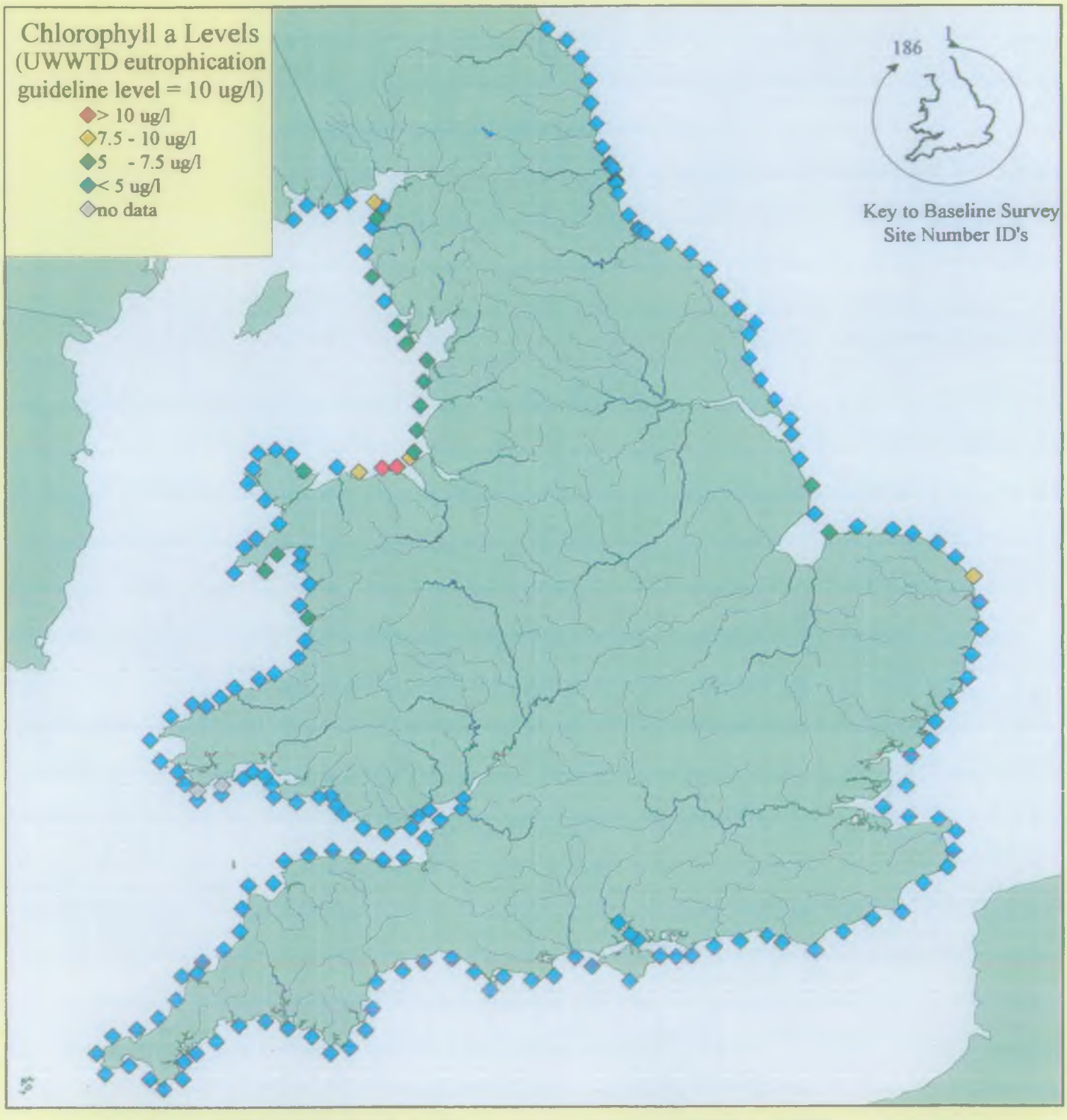
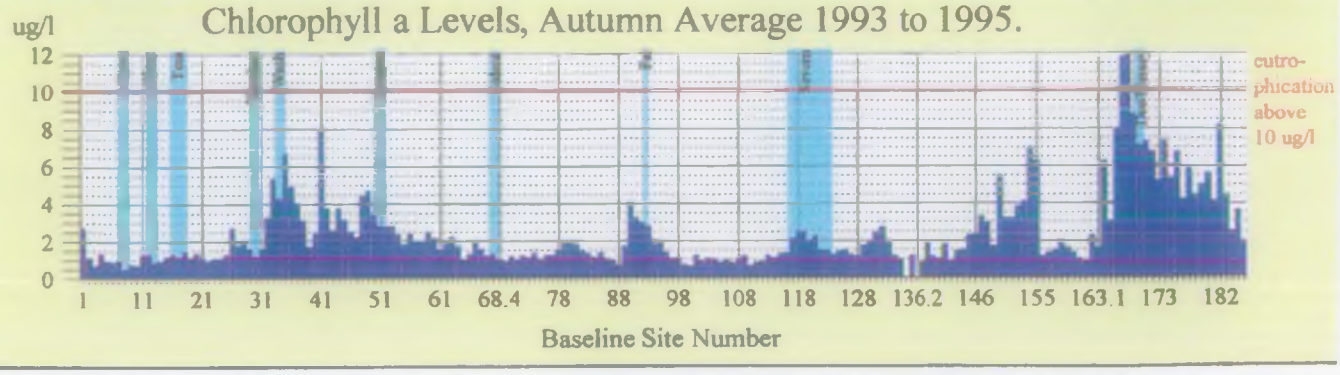


Figure 7

Chlorophyll a Levels, National Baseline Survey, Autumn Average 1993 to 1995.





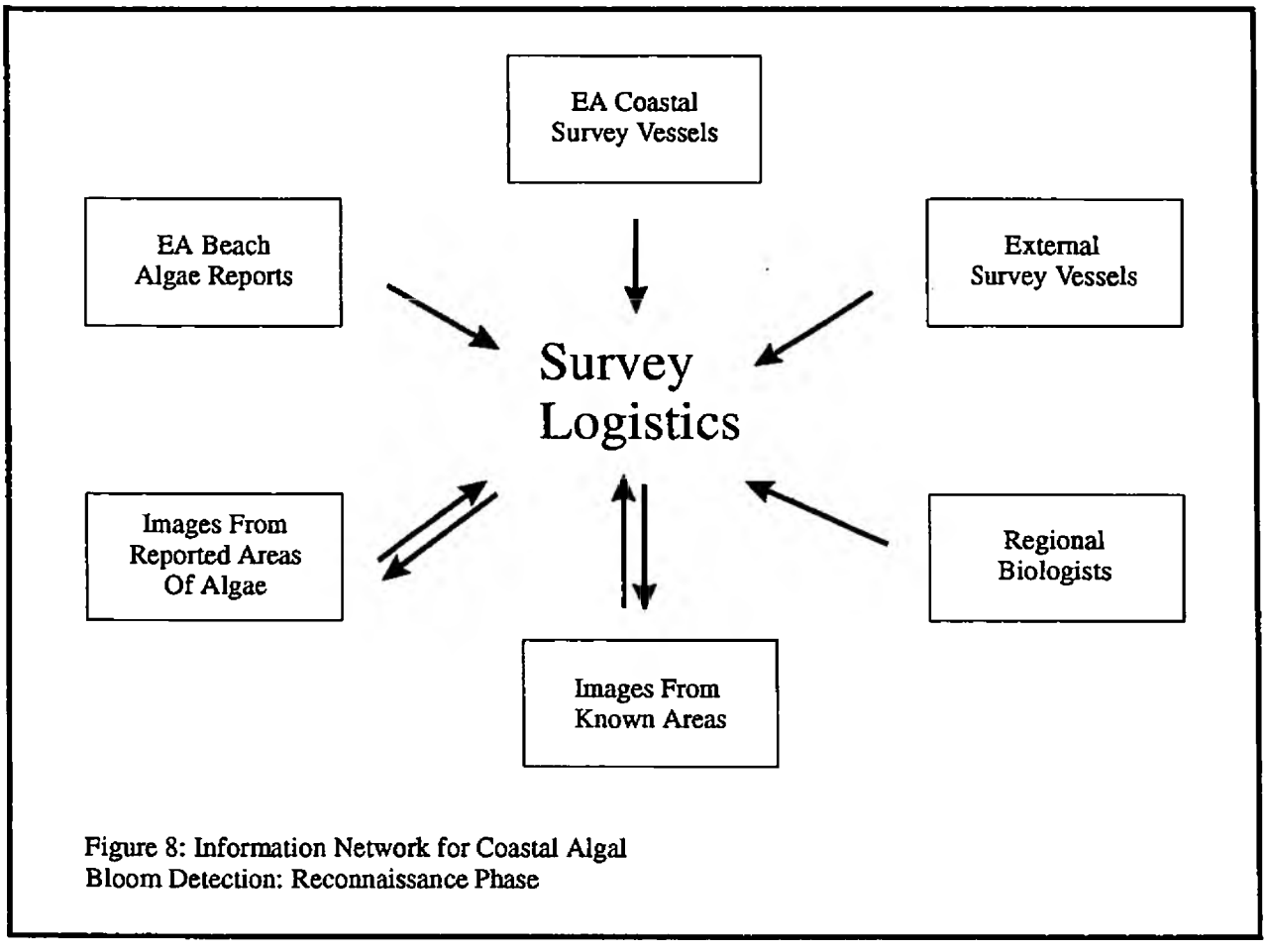


Figure 8: Information Network for Coastal Algal Bloom Detection: Reconnaissance Phase

Figure 9

Mission Number: 1
Date: 30/05/96
Target Area: North Norfolk / Wash

Image A:
Image 1863: Noth East Norfolk

Image B:
Image 1875: The Wash: Hunstanton area

B

A

Figure 10

Mission Number: 2
Date: 5/7/96
Target Area: Upper Severn
Archive Number 1890

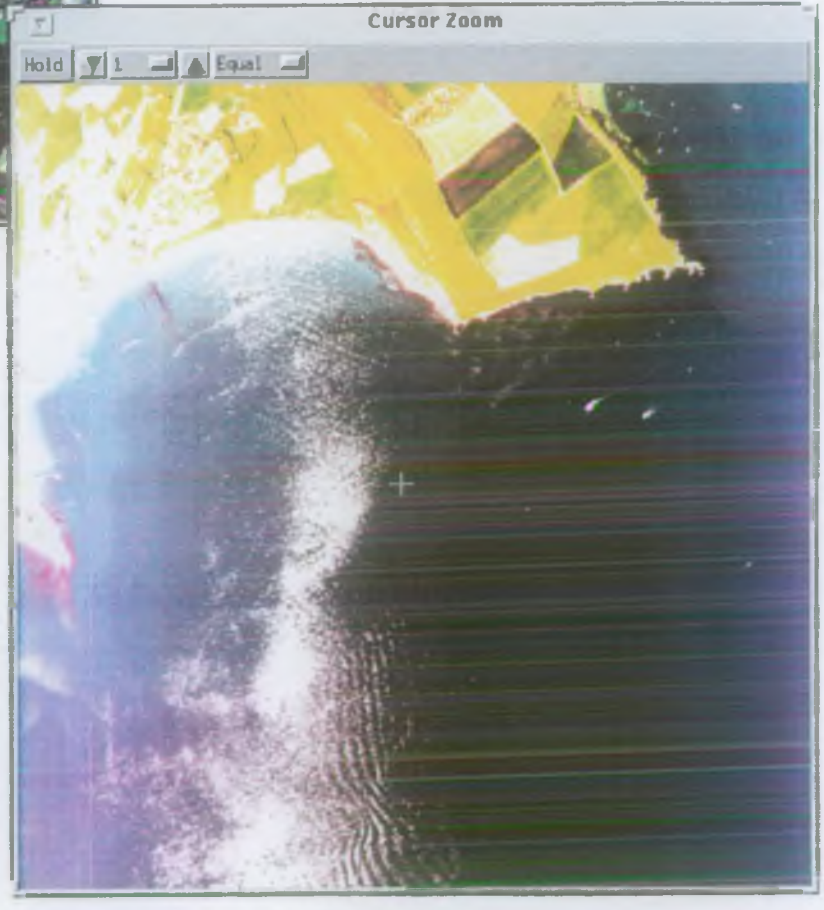


Figure 11

Mission Number: 3
Date: 6/7/96
Target Area: South Coast
Image number 1901: Studland point

Figure 12

Mission Number: 5
Date: 24/6/96
Target Area: North Devon
Archive Number 2037: Porlock bay

A

B

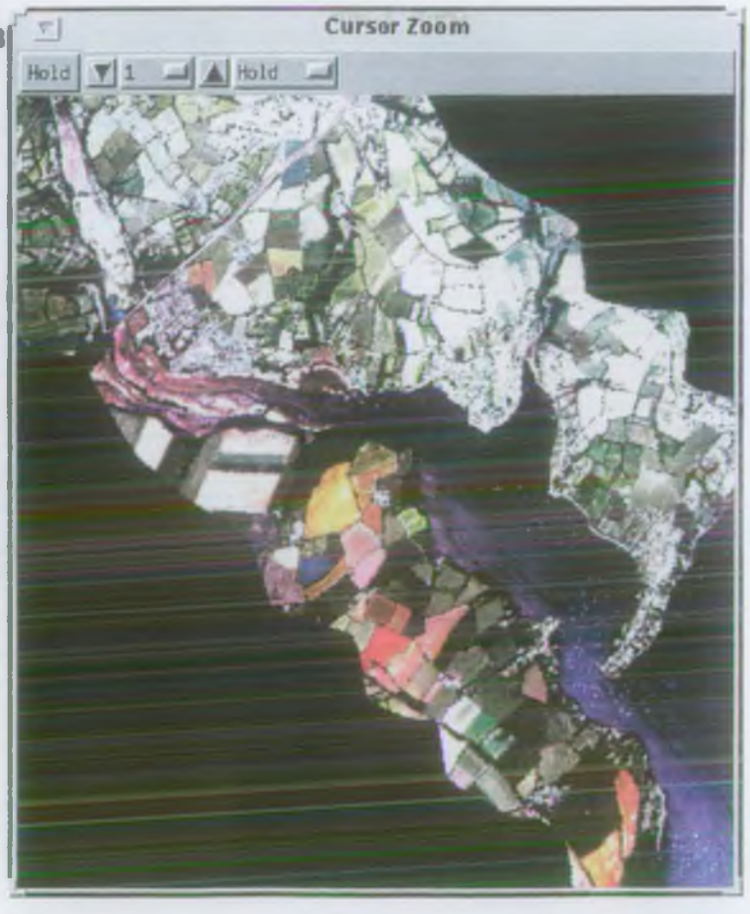


Figure 13

Mission Number: 6
Date: 10/7/96
Target Area: Fal

Image A:
Low tide image (no. 2068)

Image B
Close up of A

A

B

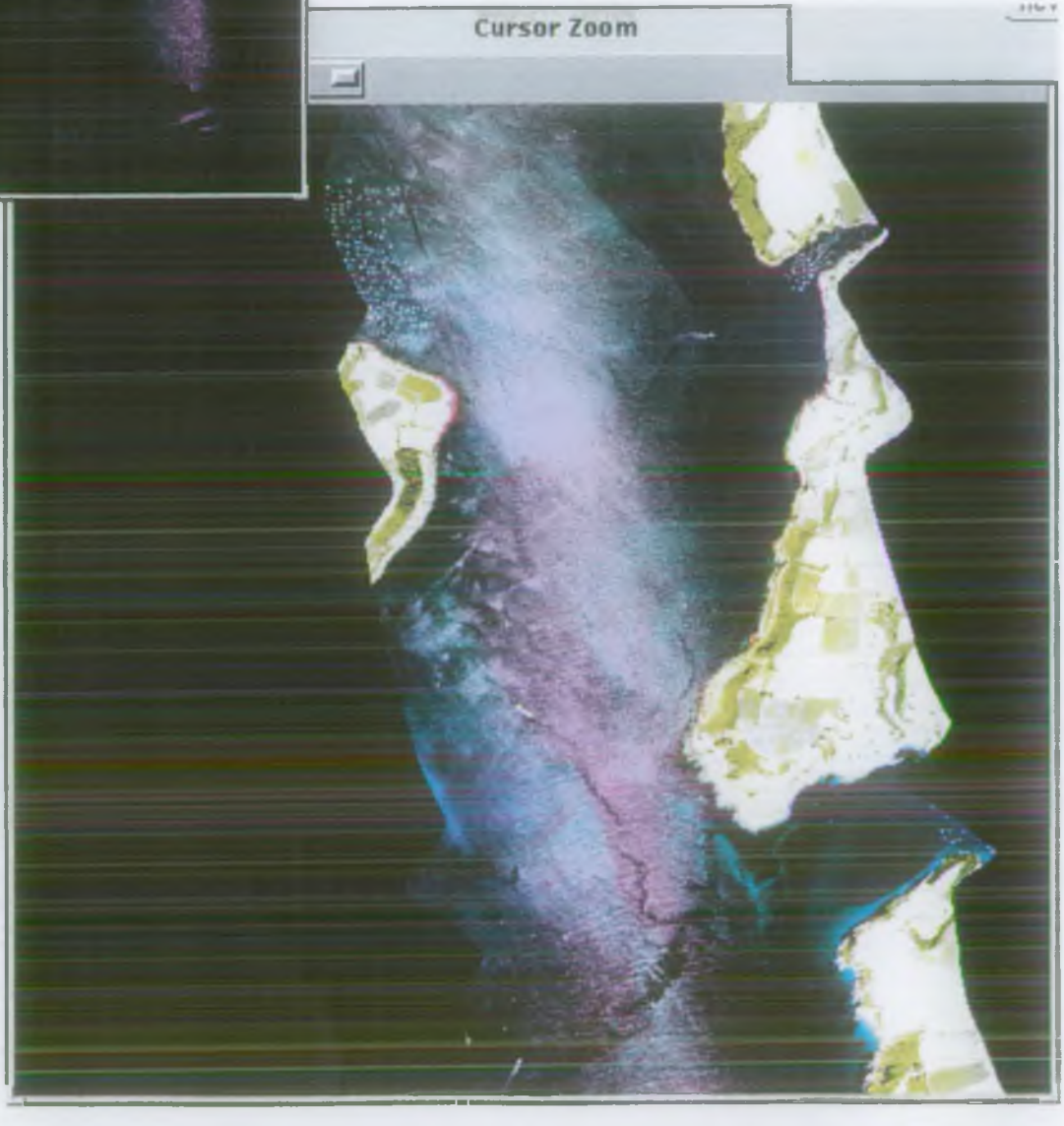


Figure 14

Mission Number: 6
Date: 11/7/96
Target Area: Fal

Image A:
High tide image (no. 2078)

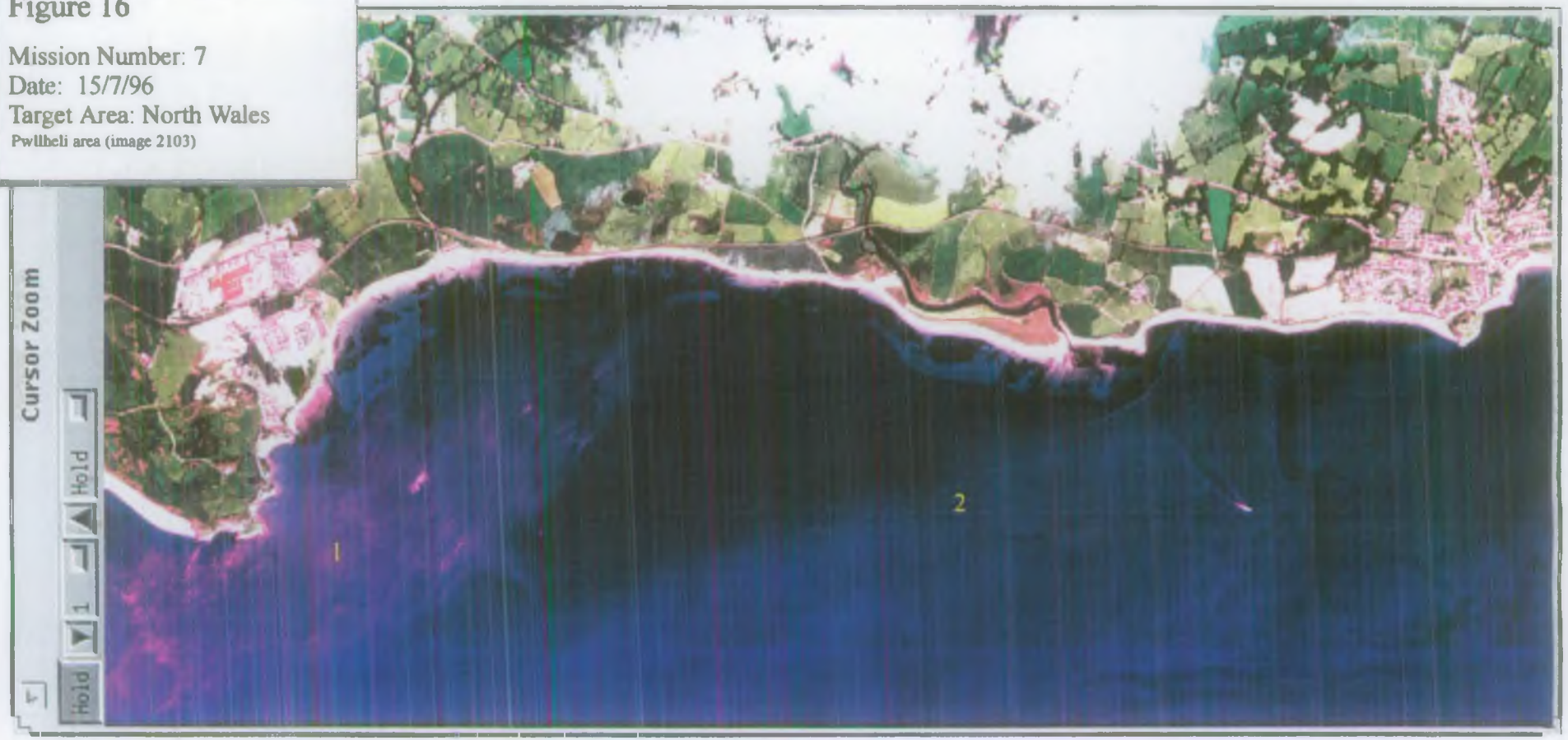
Image B
Zoom of image A

Figure 15

Chlorophyll a Levels
Fal Estuary 12/07/96

Figure 16

Mission Number: 7
Date: 15/7/96
Target Area: North Wales
Pwllheli area (image 2103)



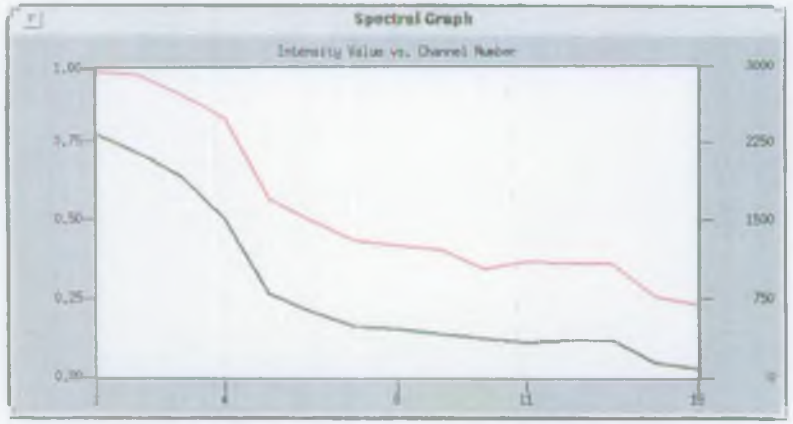


Figure 17

Spectral plots (brightness vs channel number) for two areas on image 2103 (fig 16)

Spectra from area 1
Spectra from area 2

Figure 18

Mission Number: 8
Date: 16/7/96
Target Area: Holdeness Coast
Image 2139, Spurn Head

Figure 19

Mission Number: 9
Date: 16/7/96
Target Area: Cumbrian Coastline

Image 2146

Figure 20

Mission Number: 10
Date: 19/7/96
Target Area:
North Norfolk Coastline

Image 2203: Scolt Head Island

A

B

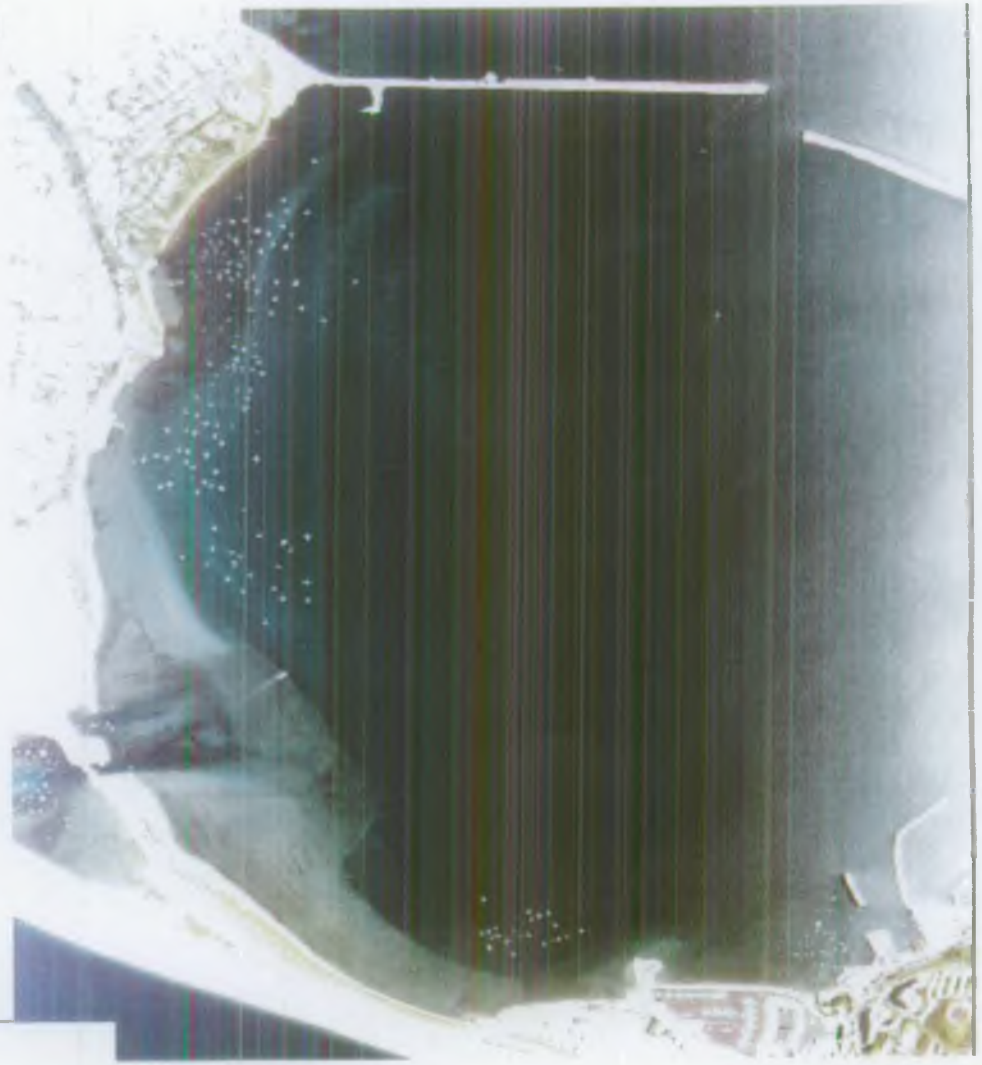


Figure 21

Mission Number: 11

Date: 3/8/96

Target Area: Weymouth

Image A:

Overview image (no 2304)

Image B

Detail of Harbour

A

B

Figure 22

Mission Number: 12
Date: 11/8/96
Target Area: North Norfolk Coast

Image A:
Image 2335: Offshore line - North East Norfolk

Image B:
Zoom in of image A

A

B

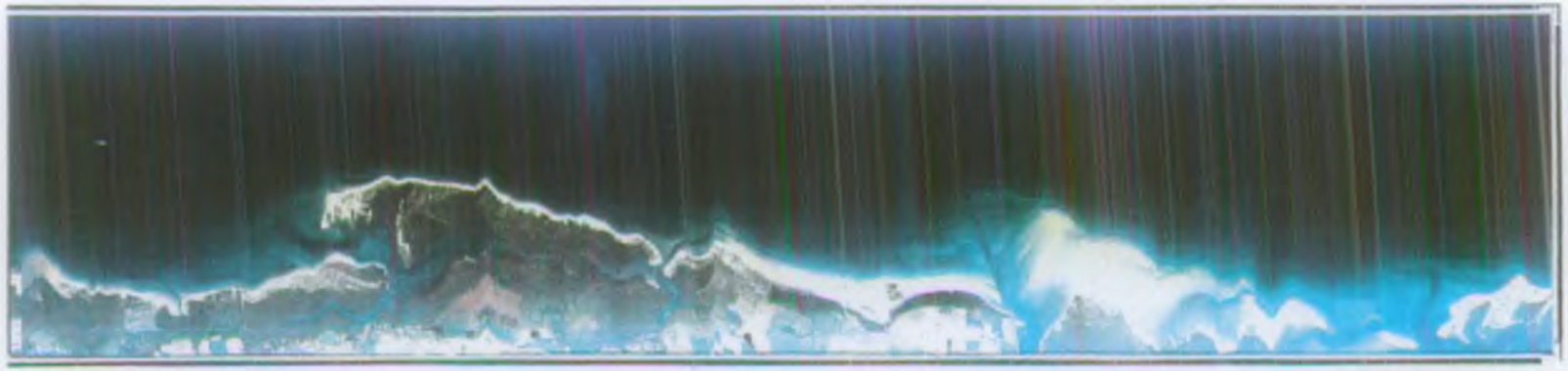
Figure 23

Mission Number: 13
Date: 13/08/97
Target Area: North Wales

Image A:
Red Wharf bay, Anglesey. Image 2343

Image B:
Zoom in of image A

A



B

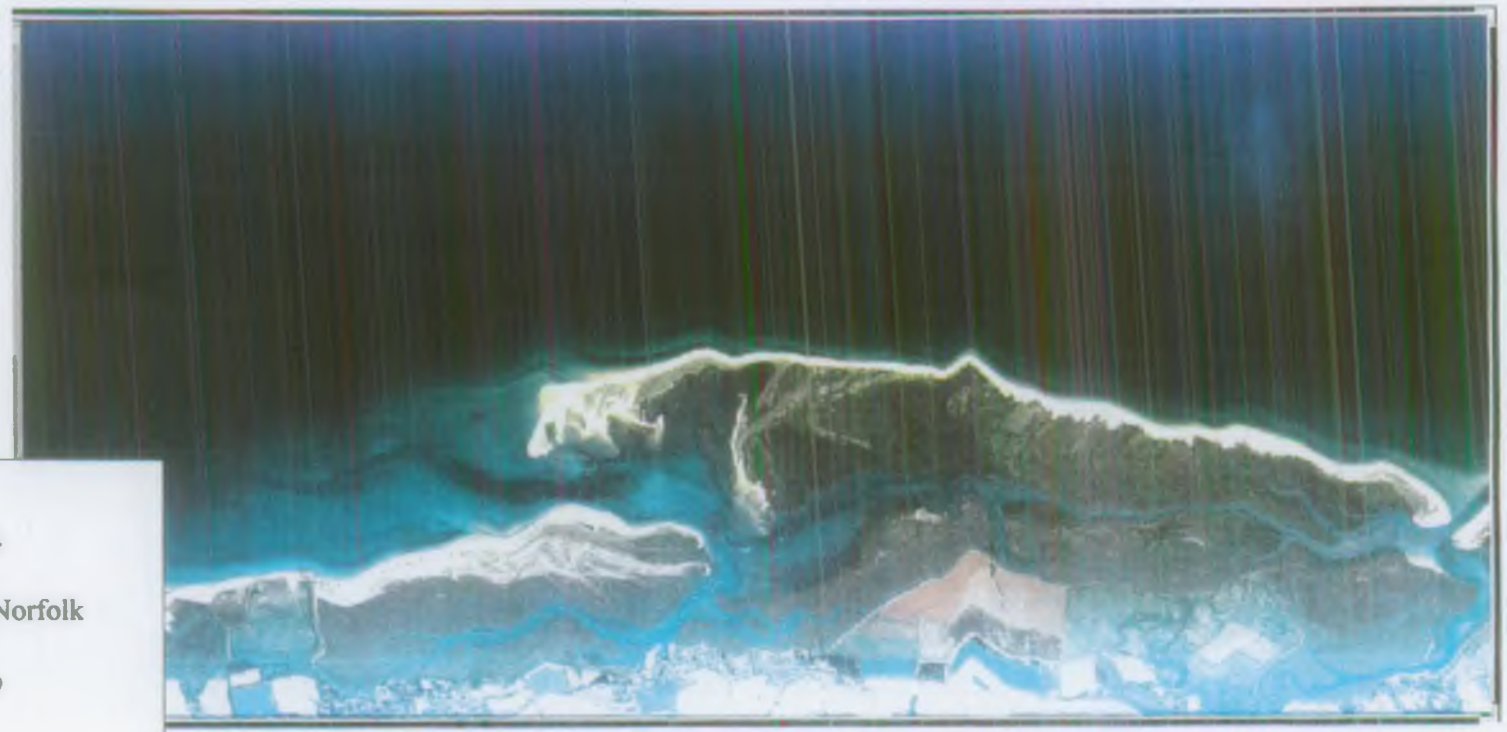


Figure 24

Mission Number: 14
Date: 19/8/96
Target Area: North Norfolk

Scolt Head Island: Image 2349

Close up of image A

B.

Figure 25

Mission Number: 15
Date: 4/9/96
Target Area: N.Wales

Image A:
Little Ormes head: (image 2398)

Image B:
Zoom in of A: Sediment off Lt. Ormes head

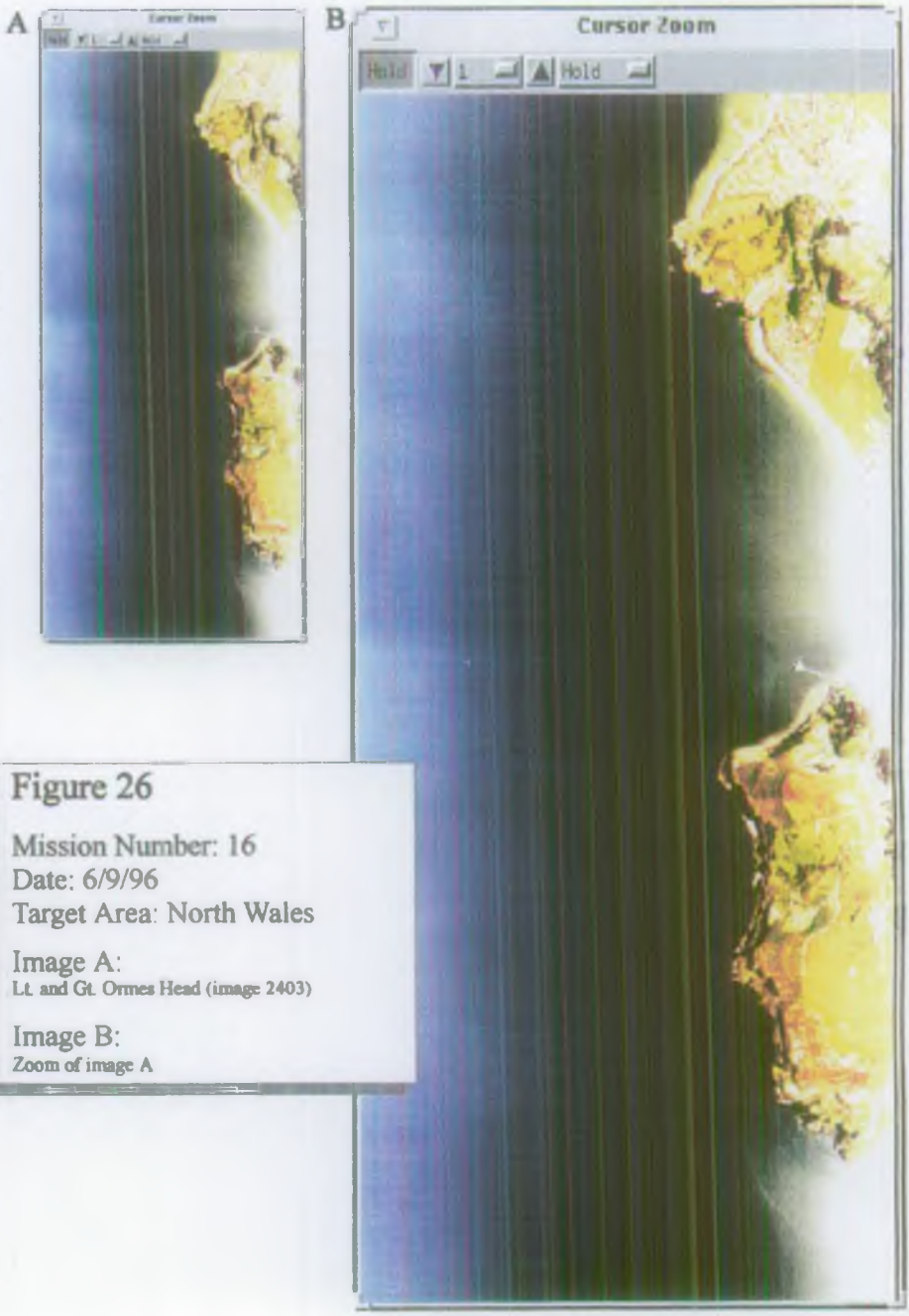


Figure 26

Mission Number: 16
Date: 6/9/96
Target Area: North Wales

Image A:
Lt. and Gt. Ormes Head (image 2403)

Image B:
Zoom of image A

Figure 27

Mission Number: 17
Date: 12/09/96
Target Area: North Devon

Image A:
Image 2426: Offshore line from Porlock bay

Figure 28

Mission Number: 18
Date: 13/9/96
Target Area: Cumbrain Coast

Image A:
Overview of image 2448

Image B:
St. Bees Head area

A

B

A

B

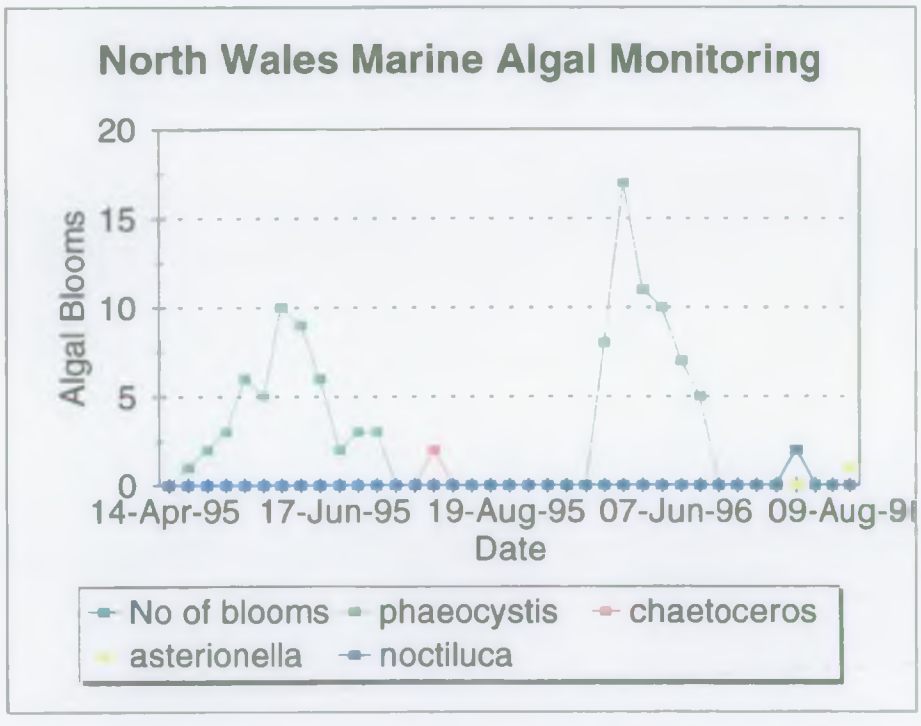
Figure 29

Mission Number: 19
Date: 17/9/96
Target Area: Cumbrian Coast

Image A:
Overview of river Esk area (image 2555)

Image B:
Close up of A (lower segment of image)

Fig. 30 North & South Wales Marine Algal Monitoring 1966



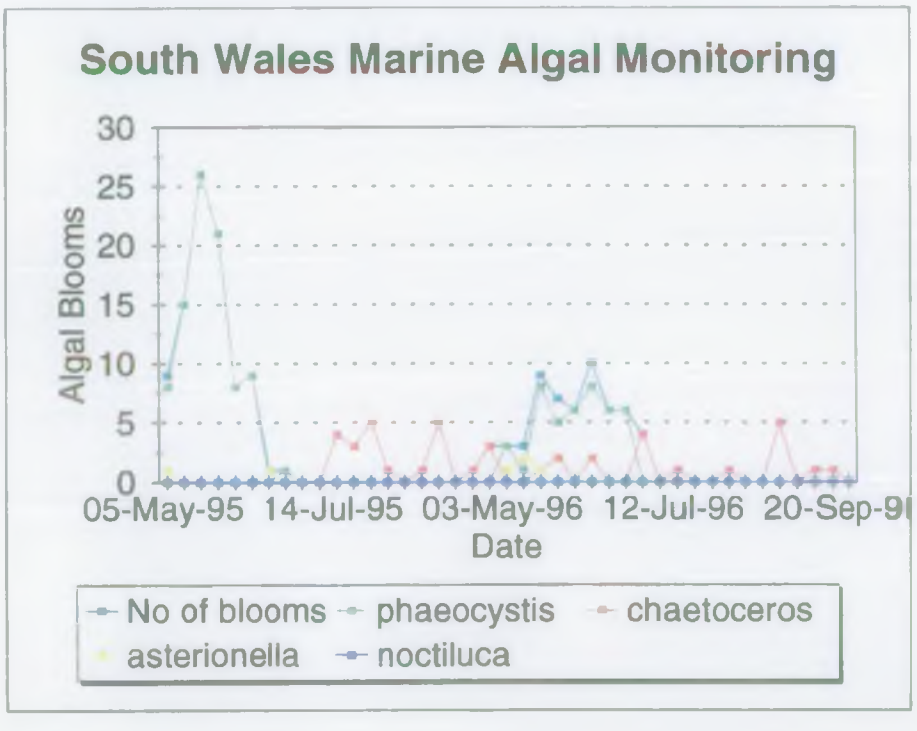
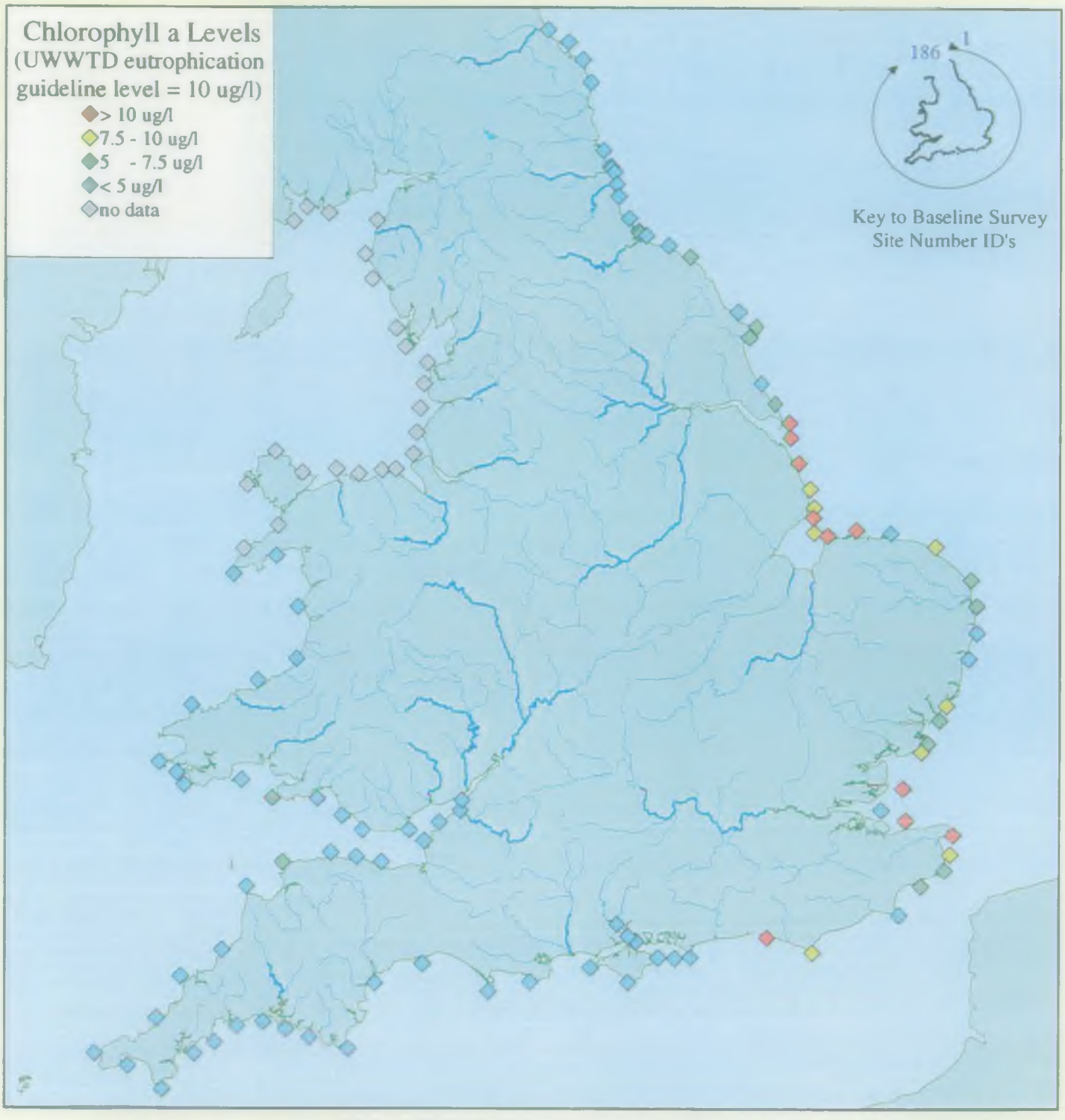


Figure 31

Chlorophyll a Levels, National Baseline Survey, Spring 1996.



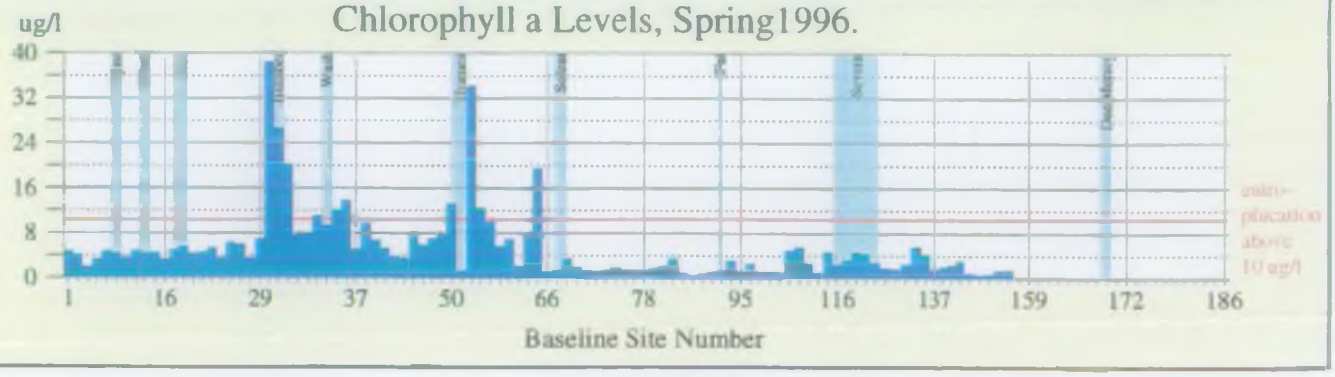
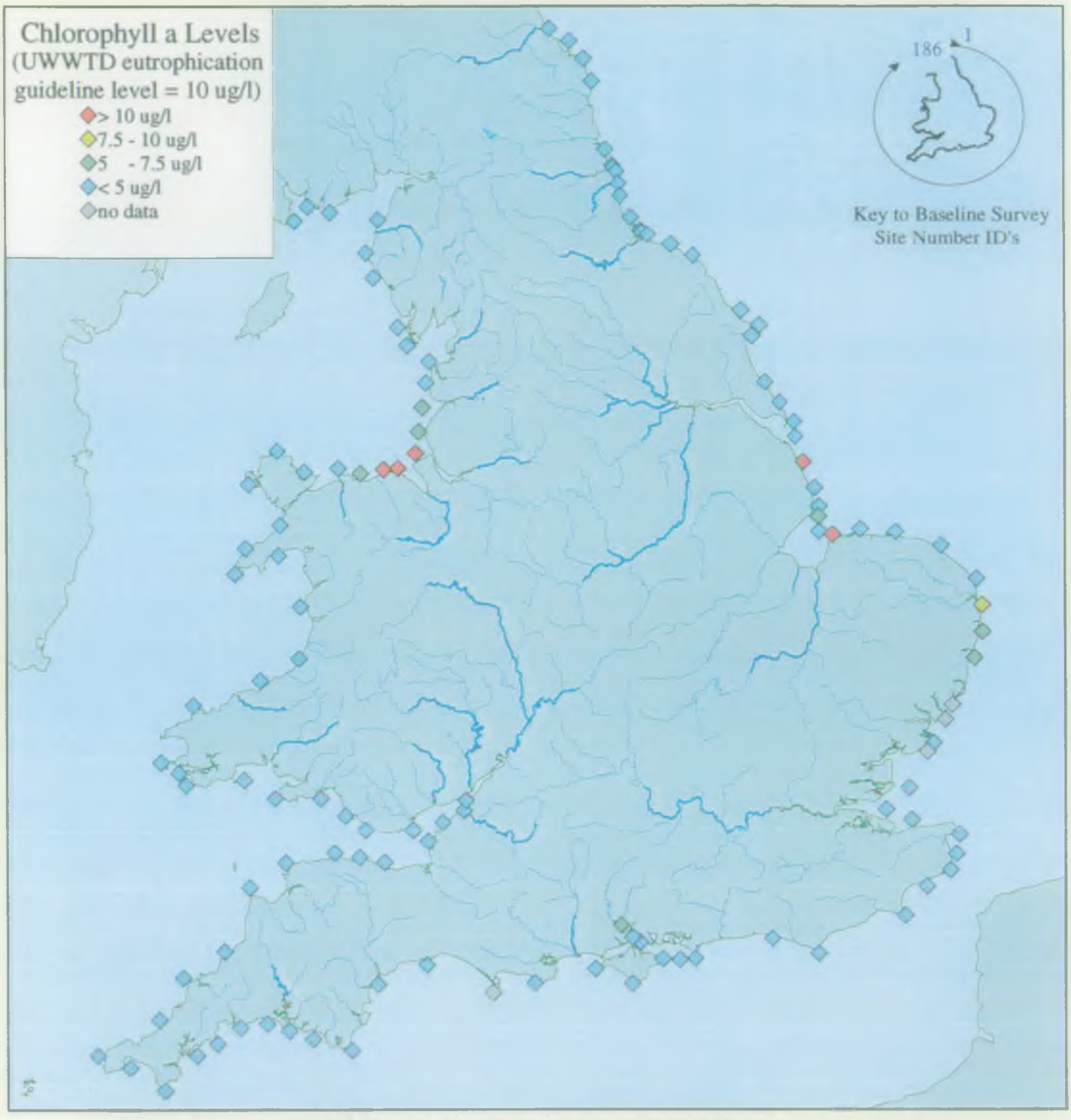


Figure 32

Chlorophyll a Levels, National Baseline Survey, Summer 1996.



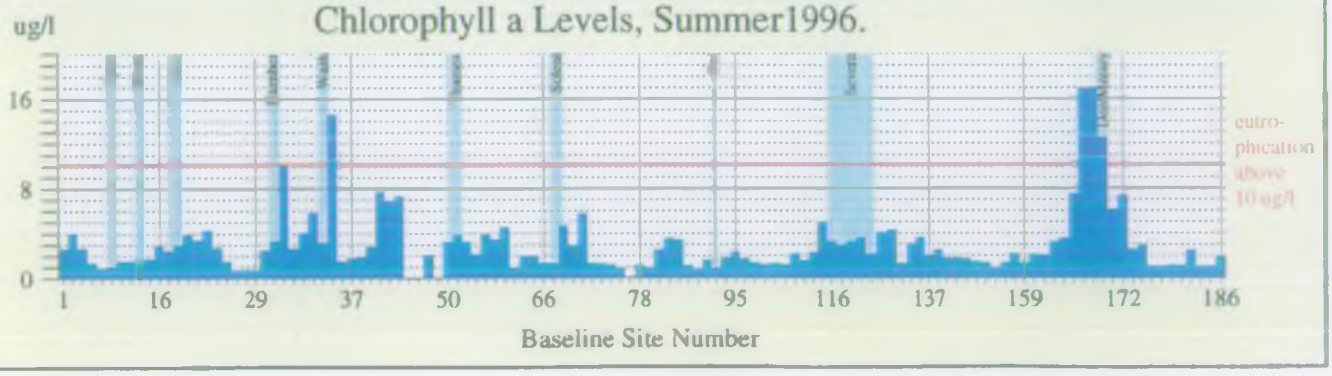
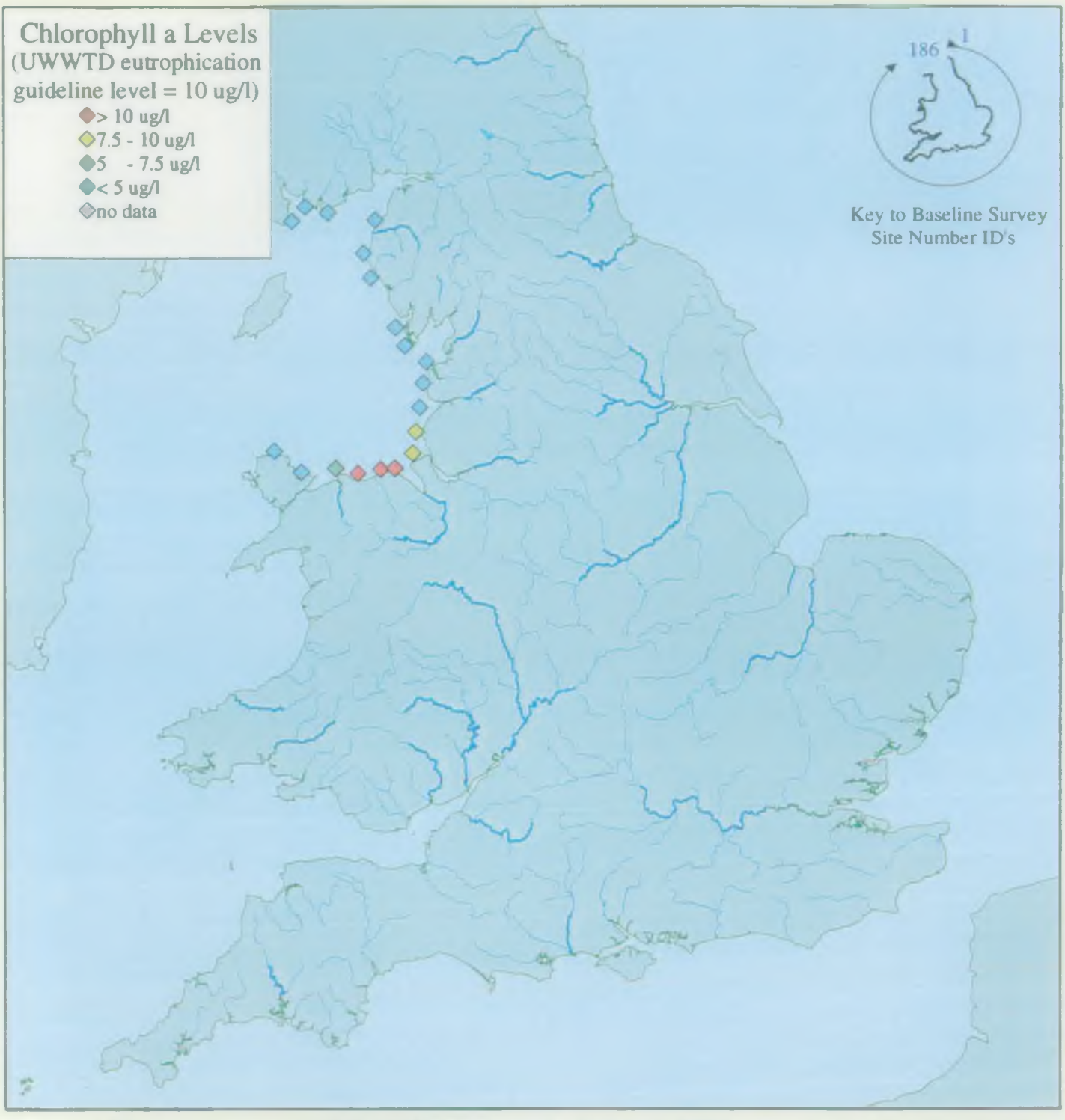
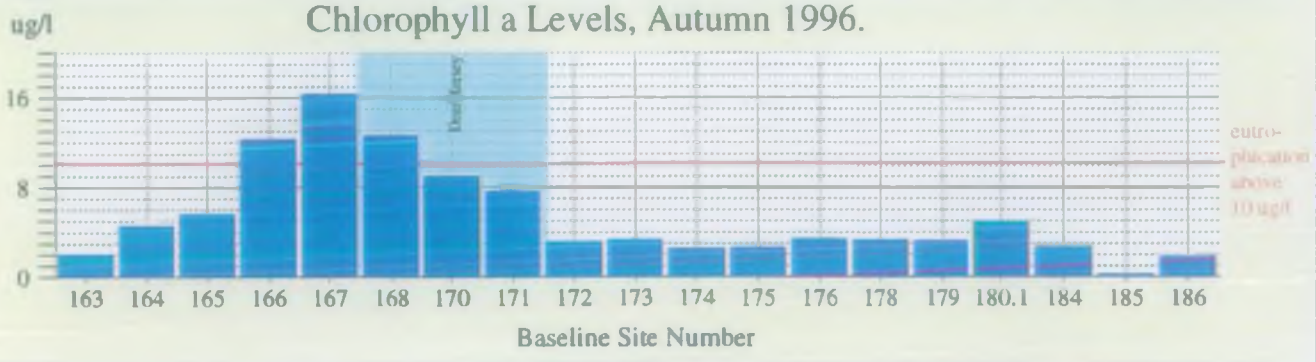


Figure 33

Chlorophyll a Levels, Northwest Baseline Survey, Autumn 1996.





APPENDIX 1: DETAILS OF INVESTIGATIONAL FLIGHTS

Mission 1 30 May 1996 North Norfolk Coast and the Wash.
Approximately fifty miles of coast line were flown in four lines parallel to the coast between Kings Lynn and Cromer. The weather was hazy, but good quality data were produced. The coastal lines showed no evidence of local blooms. Figure 9a shows a CASI image for the north east Norfolk with little or no variation apparent in the water. Figure 9b shows a part of the Wash data, near Hunstanton. The Wash data showed a large amount of structure due to sediment, mud banks and bottom reflections. No discernable aggregations of algae were found.

Mission 2 5 June 1996 North Devon / Somerset Coast/ Bristol Channel
Approximately sixty miles of coast line were flown in four lines, three parallel to the coast between Bridgwater Bay and Ilfracombe and one perpendicular to the coast 15 km out to sea. Because of poor conditions and the orientation of the coastline data suffered from cloud shadow and glint, with two images out of the 13 gathered passing the first quality control steps. Normally, this orientation of coastline would not be surveyed at this time of day to avoid sunglint. Patches of cloud shadow make interpretation difficult as patches of darker water cannot safely be attributed to variations within the water as they could be due to variations in illumination caused by clouds. Figure 10 shows a part of the Severn estuary with cloud shadow and glint.

Mission 3 6 June 1996 Poole to Southampton Coast
Approximately sixty miles of coast line were flown in six lines parallel to the coast between Poole Bay and Selsey Bill. Six images were collected, with only one passing the quality control steps. The image shown in figure 11 is of the Studland Point area. Sediment plumes can be seen around the head. There is sun glint in the centre of the image. Rocks and bathymetry can be seen as red and light blue features close to the shore. No features that would be consistent with algal blooms were seen.

Mission 4 13 June 1996 North Norfolk Coast and the Wash
Approximately fifty miles of coast line were flown in three lines parallel to the coast between Kings Lynn and Cromer. The imagery showed some haze. There were no discernable features in the water that could be attributed with algal blooms.

Mission 5 24 June 1996 North Devon / Somerset Coast
Approximately sixty miles of coast line were flown in four lines, three parallel to the coast between Bridgwater Bay and Ilfracombe and one perpendicular to the coast 15 km out to sea. 8 images were generated, with 3 of top quality. Figure 12 shows the offshore line from the North Somerset coast. Even though there was cloud on the image sediment patterns could be seen. No aggregations of material with spectral characteristics consistent with chlorophyll were seen.

Mission 6 10 - 12 July 1996 Fal Estuary *Alexandrium tamerense event*
A report was received from Agency biologists in the Bodmin office that there were high levels of the red algae *Alexandrium tamerense* in the Fal estuary and nearby Carrick Roads. The samples that were analysed suggested that there were still relatively low at about of 450 algal cells per ml and this was likely to increase to the bloom levels of 1000 per ml during the next few days or weeks. If a bloom did occur it would not have been strictly suitable for this case study as it was an estuarine bloom that would have been constrained by the topography and estuarine water chemistry, rather than an open sea bloom that would have different factors contibuting to its

development. After a further day it was reported that the algae, although not at bloom levels was releasing the paralytic shellfish poison that occasionally accompanies such events, and it was decided that this incident was worth examining.

Although the weather was less than perfect the plane was dispatched and arrived on scene on the 10 July to begin a survey at various states of the tide. Carrick Roads and the tributaries of the Fal and Truro Rivers were imaged to try and detect any high algal concentrations. A boat, equipped with continuous towed instruments was deployed to investigate any potential target sites identified for the air. The boat crew were protected from any possible toxic effects with dry suits, goggles and respirators. The algae appeared to cover the entire area of Carrick Roads, with a homogenous layer. Figure 13 shows an overview of the eastern part of the estuary and a close up of the outer areas. The generally purple tinge to the water column was investigated, and shown to cover the whole estuary. Image 14 shows a high tide situation, where the channel and bathymetry (lighter blue) can be seen.

Live algal samples were collected for examination on the RV Vigilance but no counts in excess of 1000 per ml were recorded. It was reported that there were other algae present including *Gyrodinium sp.*, *Polykrikos*, and *Chaetoceros.*

The weather did not improve and at one tidal state the plane had to fly at 500 feet to gather imagery under the clouds. This makes processing and interpretation of the 250 metre swath difficult. The plane remained in the area for three days and flew eight surveys before it was withdrawn due to poor weather and the seeming lack of the onset of true bloom conditions. The algae did not produce an aggregation that was consistent with a bloom.

Laboratory samples were also taken at several sample sites around the estuary and the results indicated some elevation in nutrient and chlorophyll levels but nothing suggesting bloom conditions. Figure 15 shows the results of the laboratory sampling, with chlorophyll values consistently below 10µg/l, a level which can be used to indicate bloom conditions in sea water.

Mission 7 15 June 1996 Coast of Wales

The south and west coastline of Wales was flown at 10000 feet between Chepstow and Pwllheli. This was flown to assess if the bathing beach reports indicating bloom levels were showing any algal activity in the coastal zone. 23 images were collected, with 18 of good quality. No direct evidence of bloom structures was found. Figure 16 shows the Pwllheli area (also see figure 1 from 1995). The variations in the blue can be accounted for by bathymetry and rocks. The redder tinge to the left of the image may be due to elevated chlorophyll levels. Investigation of the spectra showed this area to have an elevated spectra throughout the spectrum in comparison to the water to the right of the image (see figure 17), though some variation is seen in the red part of the spectrum. This does not tie up with the spectrum of the confirmed bloom structure shown in figure 1. The confirmed bloom showed much more variation in the green and red wavelengths than this image.

Mission 8 16 July 1996 Holderness Coast

Approximately thirty miles of coast line were flown in two lines, one parallel to the coast between Bridlington and Spurn Point and one perpendicular to the coast 15 km out to sea from Spurn Point. 4 images were taken, of which 3 were of good quality. Figure 18 shows a line taken out to sea across Spurn Point. As with all the images from this mission, all structures seen in the sea

were consistent with sediment patterns rather than algal activity.

Mission 9 16 July 1996 Cumbrian Coast
Approximately one hundred and twenty miles of imagery were flown in four lines, three parallel to the coast between Morecombe Bay and St. Bees Head, and one perpendicular to the coast fifteen miles out to sea. The three parallel lines were flown adjacent to each other to cover a band approximately eight miles wide. The lines were flown at 10000 feet. All the imagery was gathered twice to improve the chance of gathering data coincident with the boats and counteract the effects of the weather. Of the nine images gathered 4 were of good quality. Figure 19 shows an offshore line. The features in the water are rocks. No variations that can be assigned algae were identified.

Mission 10 19 July 1996 North Norfolk Coast and the Wash
Approximately fifty miles of coast line were flown in four lines parallel to the coast between Kings Lynn and Cromer. Four images resulted, all with cloud or cloud shadows making interpretation difficult. No algal patterns were seen. Figure 20 shows an offshore line in the Scolt Head Island area. No features can be seen in the water column.

Mission 11 3 August 1996 Weymouth Harbour
The plane was dispatched to examine the report of an algal bloom in Weymouth Harbour and Bay. 4 lines were programmed and were flown twice. The first three images were of good quality, the remaining 4 being subject to partial cloud cover and shadow. Previous algal blooms in Weymouth were of the "red tide" type as was this report (Jamieson 1994). Previous blooms were restricted to the inner harbour area and manifested themselves as "occasional red slicks". Careful examination of the imagery revealed no such features. Figure 21 shows the harbour. Carefule examination of the imagery and spectra revealed no trace of the algae.
Expand!

Mission 12 11 August 1996 North Norfolk Coast and the Wash
Approximately fifty miles of coast line were flown in four lines parallel to the coast between Kings Lynn and Cromer. Seven images were recorded, all of good quality. Careful examination showed some patches in the imagery that may be concentrations of algae. Figure 22 shows an offshore line that has blue patches offshore, outside the influence of the beach slope. It was decided to return to the area as soon as weather allowed (mission 14)

Mission 13 13 August 1996 North Wales Coast
This mission followed a report from the Coastal Guardian that there appeared to be some elevated fluorescence values at a position north west of the Little Orme near Colwyn Bay. The plane was deployed to try and home in on the position of the suspected bloom. 5 images were generated, all of poor quality (due to low cloud). The plane flew the coast from Angelsey to the mouth of the Mersey. Although some features were seen in the water column they were faint and inconclusive. Figure 23 shows some features in the water column in Red Wharf Bay, Anglesey. It was decided to return to this area as soon as weather permitted (mission 15).

Mission 14 19 August 1996 North Norfolk Coast and the Wash
In response to mission 12 eight days earlier a second visit was organized. Approximately fifty miles of coast line were flown in four lines parallel to the coast between Kings Lynn and Cromer. Ten images were sensed, of which seven were of good quality. Figure 24 shows the Scolt Head Island Area, which showed the only possible algal feature (lighter area to top right of zoomed

view). Investigation of spectra showed that this feature to have a consistently raised spectra from the surrounding water. This is consistent with atmospheric interference rather than algal activity. In addition, this area did not show the patchiness of those seen on mission 12 (figure 22).

Mission 15 4 September 1996 North Wales
A return visit to the coast from Angelsey to the mouth of the Mersey produced 11 images of very good quality. Because of low cloud the mission was flown at between 2,000 and 4,000 feet, producing images with a narrow swath width that did not cover the area of reported high algal concentrations that lead to mission 13. Some inshore variations were identified, including a large area of suspended solids off Little Ormes head (Figure 25). It was decided to re-fly at a higher altitude as soon as possible so that suspected areas could be assessed.

Mission 16 6 September 1996 North Wales
This mission was a repeat of mission 15 at 10,000 feet. 5 images of good quality were recorded. Figure 26 shows the Little and Great Ormes Head area. No features were seen in the water column.

Mission 17 12 September 1996 North Devon / Somerset Coast
Approximately sixty miles of coast line were flown in four lines, three parallel to the coast between Bridgwater Bay and Ilfracombe and one perpendicular to the coast 15 km out to sea. The lines were flown at 10000 feet. 7 images were recorded, with three classed as good quality. Figure 27 shows the offshore line. This image showed an increase in suspended solids out to sea, hence the whitening of the image. No small scale features consistent with high algal concentrations were seen in these images.

Mission 18 13 September 1996 Cumbrian Coast
Approximately thirty miles of imagery were flown in two lines, one parallel to the coast between Morecombe Bay and St. Bees Head, and one perpendicular to the coast fifteen miles out to sea. 2 images were recorded at 10000 feet, both of good quality. Large scale sediment patterns consistent with those seen in previous years were identified (Figure 28, overview image). In shore inspection shows features which are most likely consistent with the tidal streams moving sediment from the shore (figure 28, zoomed view). However, it was decided to re-fly as soon as weather permitted.

Mission 19 17 September 1996 Cumbrian Coast
After quality controlling the previous data gathered a week earlier and finding interesting features on it, a return mission was arranged in the same area between Morecombe Bay and St. Bees Head and one perpendicular to the coast fifteen miles out to sea. Unfortunately, all four images collected were hazy, and no features other than suspended solids could be seen in the water column (Figure 29)