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Airborne Remote Sensing of Coastal Waters

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AIRBORNE REMOTE SENSING OF COASTAL WATERS

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EXECUTIVE SUMMARY

In considering the problems of monitoring the coastal environment, the National Rivers Authority of the UK commissioned a pilot study along the south coast of England utilizing airborne remote sensing of both the seas colour and temperature in July 1991. The study tested the feasibility of operating such campaigns for routine monitoring as well as the value, in absolute physical and biogeochemical terms, of the data obtained. This final report provides an overview of the air and supporting sea campaigns and the results of the analyses carried out on both data sets, those for the airborne campaign by the Southampton group and for the sea campaign by the NRA. In spite of relatively poor weather and a narrow time frame for the field campaign the results are encouraging and demonstrate the potential for the technique on both a larger spatial scale and over a longer time frame. Maps of chlorophyll and of water turbidity are produced from the airborne data which when compared to the seatruth data, given uncertainties in the general techniques of gathering in-situ measurements of chlorophyll and suspended sediment, are considered to be good.

In addition to specific quantitative information on water quality, the data are also capable of providing information on dynamics and mixing processes in the coastal zone. This is particularly useful in studies involving mixing zones and in water body movements.

KEY WORDS

Airborne remote sensing, Chlorophyll, Imaging spectrometry, Suspended particulate matter, Water quality assessment.

1. INTRODUCTION

1.1 Background

As part of a recent government re-organisation of the water industry the National Rivers Authority (NRA) was established with, among other remits, the responsibility for monitoring the state of the health of the coastal zone around the UK. This task extends to three miles off the coast, and includes monitoring anthropogenic impacts on the environment as well as natural phenomena where these affect mans use of the sea. Monitoring such an extensive area is carried out by ship programmes, but whilst a ship measurement can be precise for any particular water quality parameter and offer fine depth and temporal resolution, it is often difficult to view such measurements related to the general background of water quality for a particular section of coastline.

Satellite remote sensing of the sea surface can offer such an overview but suffers in two areas: sensors and platforms are either optimised for spatial or temporal resolution. Systems such as the Coastal Zone Colour Scanner (CZCS) or the Advanced Very High Resolution Radiometer (AVHRR) provide coverage over large areas of the globe daily, but have a spatial resolution of the order of 1km, providing very little benefit in the 3-mile coastal zone. The Landsat (TM) and SPOT series of platforms do provide sensors of much better resolution (TM providing 30m resolution) but as a result the area covered in a single overpass is less, leading to fewer than two repeat overpasses per month. Detail on the limited value of the data from such sensors aside, it does mean that co-ordinating a programme of sea measurements to co-incide with such data becomes impossible. Typical cloud conditions for North West Europe leaves only 3-4 clear visible or infra-red images for a particular site per year which are not always equally distributed throughout the year.

The only real option for gathering data co-incident with ship measurements to provide a synoptic overview, and for the timely monitoring of specific incidents, is to mount sensors on an aircraft. The spatial resolution for such systems is dependant on the altitude of the platform and is typically between 1m and 10m. The temporal resolution is completely controllable. Although cloud does effect results to varying degrees it is often possible to fly beneath a relatively high cloud base, which reduces weather dependency.

It was with such an operation in mind that the NRA approached The University of Southampton's Department of Oceanography (SUDO) with a view to a pilot programme of a single set of flights between the Severn Estuary and the Medway, covering the south coast of England. The Department has over the years gained considerable experience of Ocean remote sensing from both satellites and aircraft and the programme was very timely given recent developments in sensor technology and SUDO's involvement in such developments. The programme began in July 1991 with a brief data gathering exercise using both the NRA vessel Vigilance and aircraft. The exercise was purposefully short (10 days) to test the feasibility of operational programmes in the future. There then followed a period of data processing, with the detailed analysis being carried out at Southampton. The programme was completed in April 1992, with this final scientific report and the supply by SUDO of an imaging system allowing easy access to the airborne data set. The report contains examples of the data from the analysis, with the full data set being contained on the imaging system.

The purpose of the programme was principally to:

- Test the feasibility of operating such campaigns for routine monitoring of the coastline.
- Identify the value, in physical and biogeochemical terms of such data.

1.2 Sensor Technology

There are a number of ways of remotely sensing the sea surface. All make use of electromagnetic radiation, either emitted by the water (passive) or emitted by the sensor to be reflected by the water back to the sensor (active). In the current programme it is passive sensor technology that is of direct relevance. The ocean emits both infra-red radiation which is directly proportional to the sea surface temperature, and visible light (colour) which is sunlight reflected by both the water and materials dissolved and suspended within it. Colour is the only parameter that includes information from the integrated surface layers (from 1m to 80m depending on water clarity), the others are absolutely surface values (surface mm.).

The colour of the sea contains information on suspended sediments (types and concentrations), productivity (chlorophyll concentrations), plankton types, dissolved humic substances (Gelbstof) and many dissolved and suspended organic and inorganic pollutants. The problem has always been to interpret such data and to obtain enough detail on the intensity (radiometric resolution) and specific "colour" (spectral resolution).

The instrument that has been widely used for many years is the Daedelus Airborne Thematic Mapper (ATM). It was designed to provide data similar to the spaceborne TM and has 12 channels of information. The ATM is a multi-user instrument with the majority of applications being terrestrial. These include geology of remote areas, crop studies, urban development etc., where a substantial amount of information is contained in the near infra-red part of the E.M. spectrum (800-2000 nm). There is no emission from the sea in this region of the spectrum as water rapidly absorbs such wavelengths. Consequently there are only 6 channels of relevance to the marine scientist (1-5) in the visible, with channel 1 being the blue end of the spectrum and channel 5 the red (usually used for land discrimination). These channels are fairly broadband and so the spectral resolution of the system is poor, ie: there is insufficient information to fully determine the colour of the sea, though as will be demonstrated much information can still be extracted. The traditional use of the system in terrestrial applications has given a requirement to cover a wide range of intensities, from the brightest white concrete building to the darkest tarmac road. The sea reflects light over a fairly restricted intensity range and so a further disadvantage of the ATM is its limited radiometric resolution, or ability to distinguish subtly varying brightness levels.

For all of its drawbacks, the ATM does have two very major advantages, and it is these that justify its use in this pilot programme. Firstly it has two thermal infra-red bands (11 and 12) which provide valuable information on the SST. Secondly it is a tried, tested and reasonably understood technology and provides a good sensor for testing the feasibility of future campaigns with any sensor.

The second sensor used in the campaign was one of the new generation of colour sensors, or imaging spectral radiometers that have recently been developed. Rather than just five broadband channels covering the visible, instruments such as the Itres Research, Compact Airborne Spectral Imager (CASI) contain 288 channels of 1.5 nm bandwidth. The data is 12-bit rather than 8-bit (ATM) and consequently the radiometric resolution is several orders of magnitude better; this is further enhanced by the ability to change the radiometric range of the system to suit varying conditions. The systems use Charge Couple Device (CCD) array technology. One dimension of the array views the scene below, removing the need for complex scanning mirrors, whilst the light is passed through a diffraction grating, splitting it up into its spectrum which is then projected across the second dimension (figure 1). Thus one dimension of the 2-D CCD array contains spatial and the other spectral information.

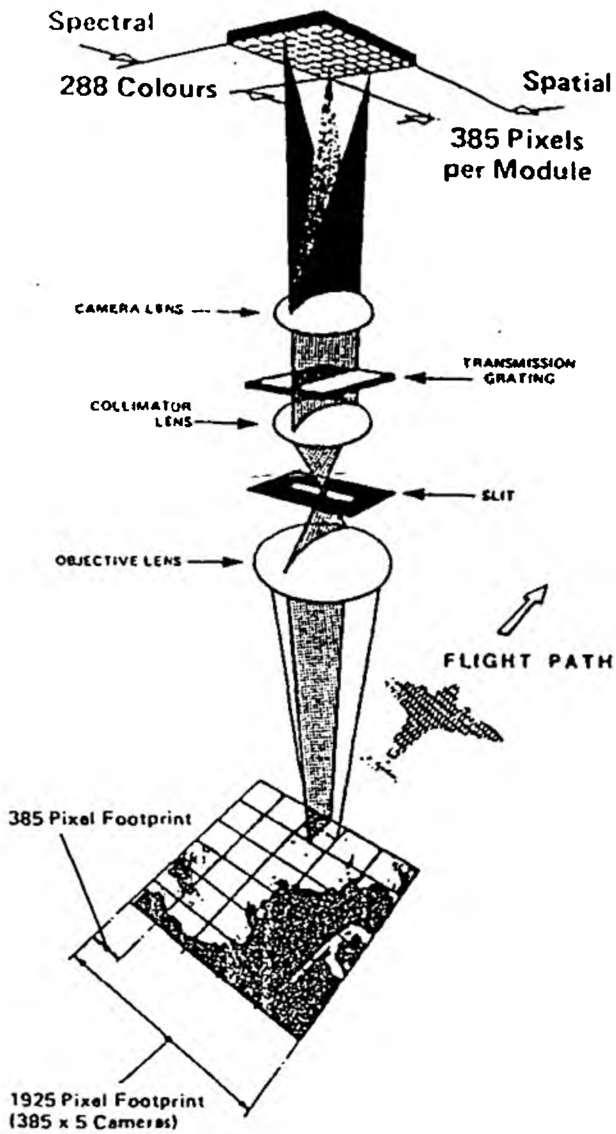


Figure 1.1 Configuration of a CCD imaging spectrometer.

There are two fundamental problems:

- The speed of data flow is so great that most systems provide an option for either a spatial or spectral mode. In spatial mode all of the spatial array is stored but only a selection of the spectral data. This may be 8 or 12 user selected channels and can include an integration of a number of the original channels to provide broader band information if required. In spectral mode the full spectral information is recorded but only a number of the spatial pixels (typically 40 across the field of view). Again these can be specific spatial points, or pixels, or an integration of several. In the case of the CASI, in spectral mode a "scene recovery channel" is included, which contains one band/channel at full spatial resolution in order to orientate the spectral data. With recent improvements in data recording technology it is now possible, on the most recent CASI systems, to operate in a Hyperspectral Mode. In this mode all of the spatial and spectral data can be stored for short bursts; this has more application in the research environment at the present time.

- The use of a CCD array as opposed to a single (or 10) sensors scanning the field of view can cause problems if the array is not correctly calibrated, leading to stipes in the data. This was a particular problem in one of the first spectral imager systems, the Moniteq FLI.

There is one other disadvantage of the CASI when compared to the ATM: the CASI has no thermal band at this point in time.

The potential value of this new form of sensor meant that it was essential to fly a CASI (or similar) as part of the programme, but the lack of thermal information meant that the ATM was still used as the prime instrument.

2. The Campaign

The measurement campaign can be considered in two co-ordinated parts: the ship measurements carried out by the NRA principally aboard the Vigilance and the airborne measurements carried out by Global Earth Sciences (ATM) and the Natural Environmental Research Council (CASI).

The Vigilance was fitted out with underway sampling for surface (1-2m) temperature, salinity, dissolved oxygen, pH, depth, transmission (optical density), fluorescence and depth. This was logged at 1min intervals throughout the transect from The Severn to the Medway. Details of the equipment used are given in table 2.1, with the baseline survey track shown in figure 2.1. In addition, at 15km intervals full water sampling stations were carried out with T/S profiles, dissolved oxygen, suspended sediment measurements and chlorophyll analysis to (i) calibrate the underway instrumentation, (ii) investigate depth variability and (iii) calibrate the remotely sensed images. These are detailed in table 2.2. Additional chemical parameters covered by the survey are included in Appendix B.

Table 2.1 Details of equipment used in campaign

Vessel	**R.V. Vigilance**	**Aircraft**	**Queen Air**
Navigation	Primary Decca Mk 53 GPS Secondary Decca Mainchain	Navigation	GPS: Trimble NAV TRAC Decca: Philips AP4
Computer	Qubit TRAC 5	Scanner	Daedalus 1268 ATM
Sounder	Simrad EA300 200Khz	Camera	RC8
WQ Flow System	pHOX DPM100 -DO, Temp pH, Salinity & Turbidity	Incident Radiation	Four channel cosine collector (Wernand,NIOZ)
Fluores.	Chelsea Inst. Aquatraka III		
Transmis.	Sea Tech 25cm pathlength	**Aircraft**	**Navajo Chieftan**
CTD	WS Ocean Systems SAL 1	Navigation	Decca
DO profile	YSI model 33	Imager	Itres Res. CASI

The vessel left Royal Portbury Dock on the Sunday 30th June and carried out the programme finally arriving at Medway on the 10th July. The underway data was logged on a Qubit Trac V system (figure 2.2) and the samples returned to NRA's Welsh Region Laboratories at Llanelli for subsequent analysis. This data has been made available to SUDO in a computer compatible format to compare with and, where possible calibrate, the ATM and CASI data. In total there were 72 stations worth of data with over 1100 kilometres of underway data, providing a very comprehensive data set. These figures do not include the return trip from the Medway to the Solent, timed to satisfy Southern region requirements and those of the NERC/CASI flights.

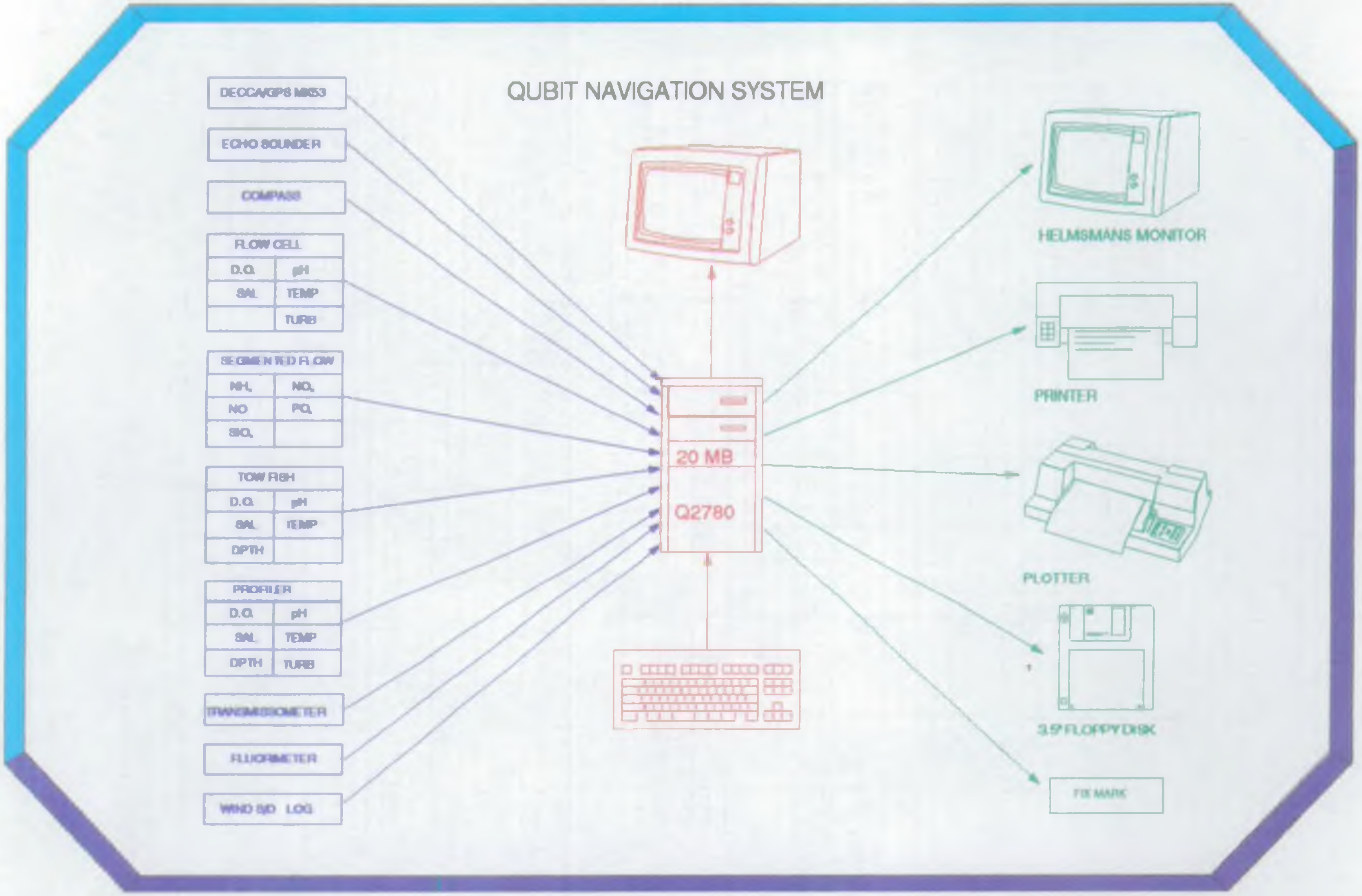

COASTAL BASELINE SURVEY
COASTAL AREA COVERED BY R&D PROJECT
R.V. VIGILANCE

	SITE NUMBER	SUSPENDED SOLIDS	DISSOLVED METALS	TOTAL METALS	METAL BLANK	TOTAL MERCURY	CHLOROPHYLL 'a'	NUTRIENTS
ANVIL POINT	BASE 69	•	•	•		•	•	•
ST ALDHELMS	BASE 68	•	•			•	•	•
WEYMOUTH BAY	BASE 67	•	•			•	•	•
PORTLAND BILL	BASE 66	•	•			•	•	•
CHESIL	BASE 65	•	•			•	•	•
BRIDPORT	BASE 64	•	•			•	•	•
SEATON	BASE 63	•	•	•	•	•	•	•
SIDMOUTH	BASE 62	•	•			•	•	•
EXMOUTH	BASE 61	•	•			•	•	•
TORBAY	BASE 60	•	•	•	•	•	•	•
DARTMOUTH	BASE 59	•	•			•	•	•
START POINT	BASE 58	•	•			•	•	•
SALCOMBE	BASE 57	•	•			•	•	•
BIGBURY BAY	BASE 56	•	•			•	•	•
PLYMOUTH	BASE 55	•	•	•		•	•	•
EAST LOOE	BASE 54	•	•			•	•	•
FOWEY	BASE 53	•	•			•	•	•
DODMAN POINT	BASE 52	•	•			•	•	•
ST ANTONY HEAD	BASE 51	•	•			•	•	•
FALMOUTH	BASE 50	•	•	•	•	•	•	•
BLACK HEAD	BASE 49	•	•			•	•	•
LIZARD	BASE 48	•	•			•	•	•
MULLION	BASE 47	•	•			•	•	•
PENZANCE	BASE 46	•	•			•	•	•
RUNNEL STONE	BASE 45	•	•			•	•	•
CAPE CORNWALL	BASE 44	•	•	•	•	•	•	•
THE CARRACKS	BASE 43	•	•			•	•	•
GODREVY ISLAND	BASE 42	•	•			•	•	•
ST AGNES	BASE 41	•	•			•	•	•
NEWQUAY	BASE 40	•	•			•	•	•
TREVOSE	BASE 39	•	•			•	•	•
PADSTOW	BASE 38	•	•	•	•	•	•	•
PORT ISAAC	BASE 37	•	•			•	•	•
BOSCASTLE	BASE 36	•	•			•	•	•
BUDE	BASE 35	•	•			•	•	•
MOREWENSTOW	BASE 34	•	•			•	•	•
HARTLAND	BASE 33	•	•			•	•	•
BIDEFORD	BASE 32	•	•	•		•	•	•
BULL POINT	BASE 31	•	•			•	•	•
COMBE MARTIN	BASE 30	•	•			•	•	•
FORELAND	BASE 29	•	•			•	•	•
PORLOCK	BASE 28	•	•			•	•	•
MINEHEAD	BASE 27	•	•			•	•	•
BRIDGWATER BAR	BASE 26	•	•	•	•	•	•	•
WESTON-S-MARE	BASE 25	•	•			•	•	•
CLEVEDON	BASE 24	•	•			•	•	•
AVONMOUTH	BASE 23	•	•			•	•	•
No 1 BEACON	BASE 22	•	•	•		•	•	•

	SITE NUMBER	SUSPENDED SOLIDS	DISSOLVED METALS	TOTAL METALS	METAL BLANK	TOTAL MERCURY	CHLOROPHYLL 'a'	NUTRIENTS
DOCKHEAD	BASE 0A	•	•	•		•	•	•
CALSHOT	BASE 0B	•	•	•	•	•	•	•
EAST BRAMBLES BUOY	BASE 0C	•	•	•		•	•	•
HENGISTBURY HEAD	BASE 01	•	•			•	•	•
THE NEEDLES	BASE 02	•	•			•	•	•
ST CATHERINES PT	BASE 03	•	•	•		•	•	•
WEST PRINCESSA BUOY	BASE 04	•	•			•	•	•
NAB TOWER	BASE 05	•	•			•	•	•
SELSEY BILL	BASE 06	•	•	•	•	•	•	•
MIDDLETON ON SEA	BASE 07	•	•			•	•	•
WORTHING	BASE 08	•	•			•	•	•
BRIGHTON	BASE 09	•	•			•	•	•
NEWHAVEN	BASE 10	•	•			•	•	•
BEACHY HEAD	BASE 11	•	•	•	•	•	•	•
BEXHILL	BASE 12	•	•			•	•	•
RYE BAY	BASE 13	•	•			•	•	•
DUNGENESS	BASE 14	•	•	•		•	•	•
SANDGATE BAY	BASE 15	•	•			•	•	•
SOUTH FORELAND	BASE 16	•	•			•	•	•
GOODWIN FORK BUOY	BASE 17	•	•			•	•	•
EAST BRAKE BUOY	BASE 18	•	•	•	•	•	•	•
EAST MARGATE BUOY	BASE 19	•	•			•	•	•
SHIVERING SAND BUOY	BASE 20	•	•			•	•	•
MEDWAY BUOY	BASE 21	•	•	•		•	•	•

SAL_TEMP & OXYGEN READ @ .1_.5 1.0 2.0 & 5.0 Mtrs
D/METALS BLANKS & NUTRIENTS BY INLINE FILTERS
CHLOROPHYLLS BY 1 Ltr FILTER CHAMBER & PAD

Table 2.2 Results from baseline survey


QUBIT NAVIGATION SYSTEM
DECCA/GPS MK53
ECHO SOUNDER
COMPASS
FLOW CELL
D.O.
pH
SAL
TEMP
TURB
SEGMENTED FLOW
NO
SIO
TOW FISH
D.O.
pH
SAL
TEMP
DPTH
PROFILER
D.O.
pH
SAL
TEMP
DPTH
TURB
TRANSMISSOMETER
FLUORIMETER
WIND S/D LOG
20 MB
Q2780
HELMSMANS MONITOR
PRINTER
PLOTTER
3.5" FLOPPY DISK
FIX MARK

In addition to the main ship campaign Rhodamine-B dye was introduced to the Sharkham Point outfall and the mouth of the river Axe at Seaton to coincide with the aircraft overpasses to test the validity of dye tracking for path and dispersal studies using airborne sensors.

The ATM airborne measurements were timed to coincide where possible with the ship measurements. The coast was divided into 70 straight line sections, which when flown would cover the full coastline out to the 3-mile region of interest. In addition 12 sites of particular interest where identified, which were to receive repeat overpasses or special timings (to coincide for example with the dye release). The flight sections are shown in figure 4, with table 4(a) highlighting the special areas. The ATM campaign began on 1st July and continued until 8th July with a two day break in the middle for logistical reasons. The instrument was operated by Global Earth Sciences and flown aboard a Queen Air twin engined light aircraft. The aircraft also flew a Wild survey camera with colour film and was fitted with an upward looking 4 band irradiance sensor, developed by M. Wernand of NIOZ in the Netherlands, to correct for any changes in the incoming light intensities. Navigation was logged using Decca and GPS.

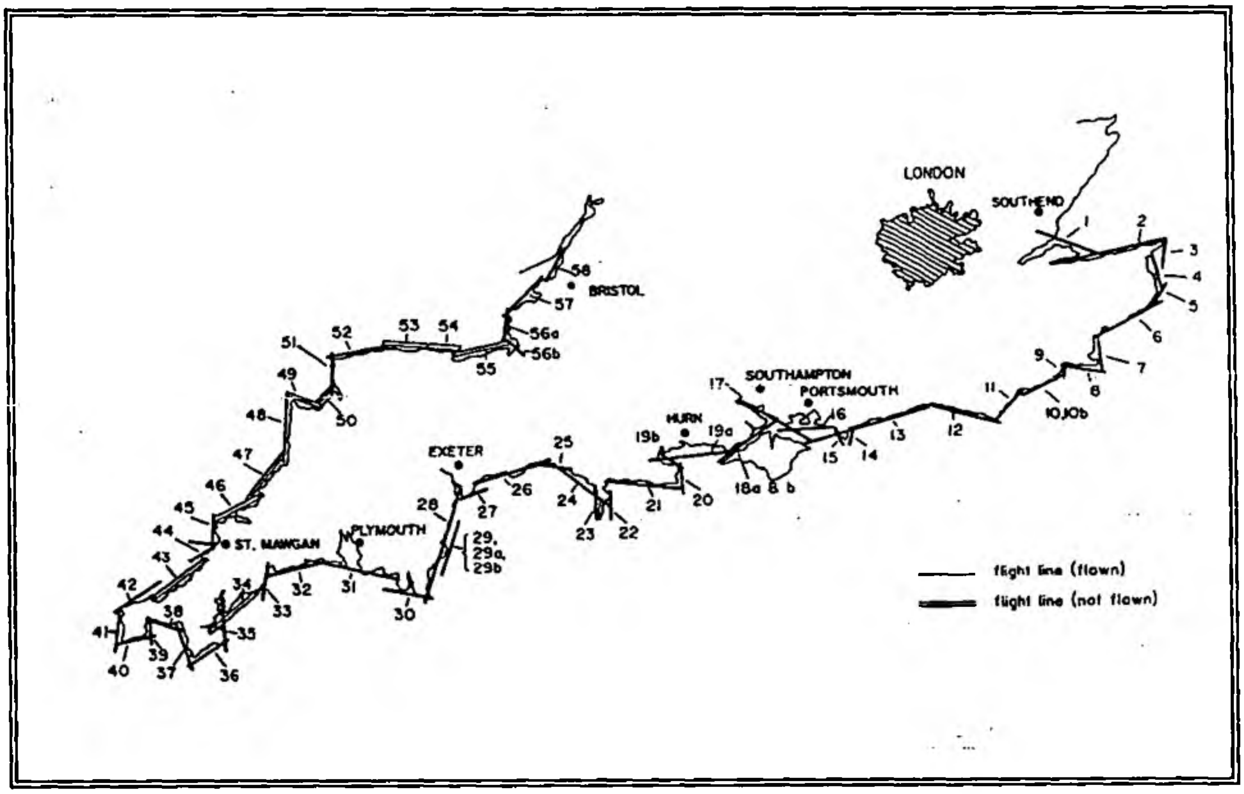


Figure 2.3 Flight line sections

In total 61 of the proposed 70 flight lines were achieved in this short period, corresponding to a 90% coverage of the coastline.

The CASI campaign, due to instrument availability, could not begin until late July, and was given a narrow 2 day window! To achieve optimum success a total of 8 potentially interesting sites were selected from Fowey in Cornwall to Mudeford in East Dorset, in the hope that the weather would be sufficiently clear at one site in the period. In the event all 8 sites were

Table 2.3 Areas of special interest and CASI sites

Southern	Swale Estuary	**CASI SITES**
	Stour Estuary	
	Shoreham	
	Pegwell Bay	
South West	Newquay	Fowey, Cornwall
	Torbay	Plymouth, Cornwall
	Sharkham Point	Exmouth, Devon
	Teignmouth	Teignmouth
Wessex	Poole	Poole and Mudeford
	Bridgewater Bay	Brixham
	Portland Long Sea Outfall	Swanage
	Christchurch Harbour	Salcombe

flown on the 17th July in both spectral and spatial modes, listed in table 2.3, using the NERC Navaho Chieftain twin engined light aircraft. Again a Wild survey camera, fitted with colour film, was flown in conjunction with the CASI though due to a technical fault only two pictures were actually taken (Poole Harbour and Mudeford).

In total the ATM campaign produced 85 data tapes and 649 photo images, which have been delivered to SUDO for processing. The data tapes have been loaded onto the PC based image processor and backed up onto Exabyte cartridges and the data has received the initial processing for radiometric corrections.

All the data has been studied initially and the overall quality is good. Initial data were made available to SUDO after the first two days of the campaign and were processed within twelve hours to check the data quality. A sinusoidal interference pattern was noted on the images which was brought to the attention of Global. No clear reason for the effect was found (it appeared sporadically on subsequent data sets) but the overall quality of the data should not be effected. Subsequent enquiries revealed that the effect had been apparent on this particular sensor for over a year and eventually the problem was traced to a faulty capacitor. There were some problems with sun glint and cloud shadow on a number of images, a restriction of timing and having to work longer days and in less than perfect conditions than would normally be the case in a research application. However, again the data is still of a good and operationally usable quality.

The CASI campaign produced 5 data tapes which were delivered to SUDO at the beginning of September 1991. There were some delays in decoding the data for processing due to an unusual format used by the German contractor in this case, and in certain areas both the calibration files for the sensor and the angle of view for the "spectral mode" were incorrectly set up by ECO-Scan. This resulted in larger proportions of land to sea than would have been preferred and in difficulties in obtaining absolute radiance values in some instances. In addition a slight amount of image striping can be observed in some of the data as a result of the miscalibrations from ECO-Scan. However, the overall quality of the data is high, as demonstrated by the results.

3. RESULTS OF AIRBORNE SURVEYS

3.1 An Overview of the General Results

With such a large data set (probably the most comprehensive airborne data set of the marine environment to date) it is difficult to distil the complete results in a readable sized document. Instead an overview of the results are presented herein, with some specific examples, with the sites of special interest being covered in section 3.5. The full data set is available on the image system supplied to NRA as part of the Southampton University contract. The details of the ship data are given in Appendix A.

3.2 The ATM Data

3.2.1 Chlorophyll and SPM from the ATM

The ATM data consists of 12 channels of information, of which channels 1-5 and 11 are the only ones which contain information of direct importance to the marine environment (visible colour and thermal infra-red). The instrument was calibrated by Global Earth Sciences before the campaign and this data was applied to the raw ATM data to provide a true radiance measurement for these relevant channels. Figures 3.1 and 3.2 show the data from the ATM for Poole Bay between Studland and Swanage (flight line 20 in figure 2.3). Figure 3.1 (inset) represents the colour data, presented as a false colour composite, whereby radiance corrected channels 5,3 and 2 are displayed on the red, green and blue guns of a colour monitor. It represents a near "as the eye would see" image, but has the added bonus that it can be manipulated and enhanced and reproducible data can be extracted from it. It corresponds to patterns of suspended sediment, chlorophyll and other water quality parameters. Figure 3.2 (inset) represents the thermal data, with dark corresponding to cold water, bright to hot. Note that the data have not been geometrically re-orientated so north is to the bottom of the image.

Figures 3.1 and 3.2 (main) show a more detailed image of Studland Bay, superimposed with the track of the Vigilance in the case of 3.2. Where possible synoptic seatruth measurements were to be taken, but often weather limitations made this difficult. In this case the vessel actually made the measurements 37 hours earlier (same tidal state). Figure 3.3 shows the corrected and calibrated radiance values from the ATM along the ships track, the red line corresponding to channel 5, green to 3 and blue to 2. Figure 3.4 shows the ships chlorophyll data set along the track, whilst figure 3.5 gives the transmissometer data (corresponding to a combination of plankton and inorganic sediment effects). Increased chlorophyll levels cause an increase in the absorption of blue light for photosynthesis, and thus a relative increase in green reflected light. This is clearly seen where the chlorophyll increases dramatically after station 140; the green reflectance increases with respect to that in the blue part of the spectrum. However the same event occurs on the ATM data between pixels 120 and 280 (equivalent of stations 134 to 137) without a corresponding increase in chlorophyll. A study of the transmission data shows a marked drop in transmission. Given that there was no peak in chlorophyll at these points, it is implied that the cause was an increased suspended sediment load. A study of the ATM red channel in figure 3.4 shows how one can determine between the two; there is an increase in red reflectance between 134 and 137 but not after 140 (sediment tends to reflect strongly at all wavelengths whereas chlorophyll has little effect

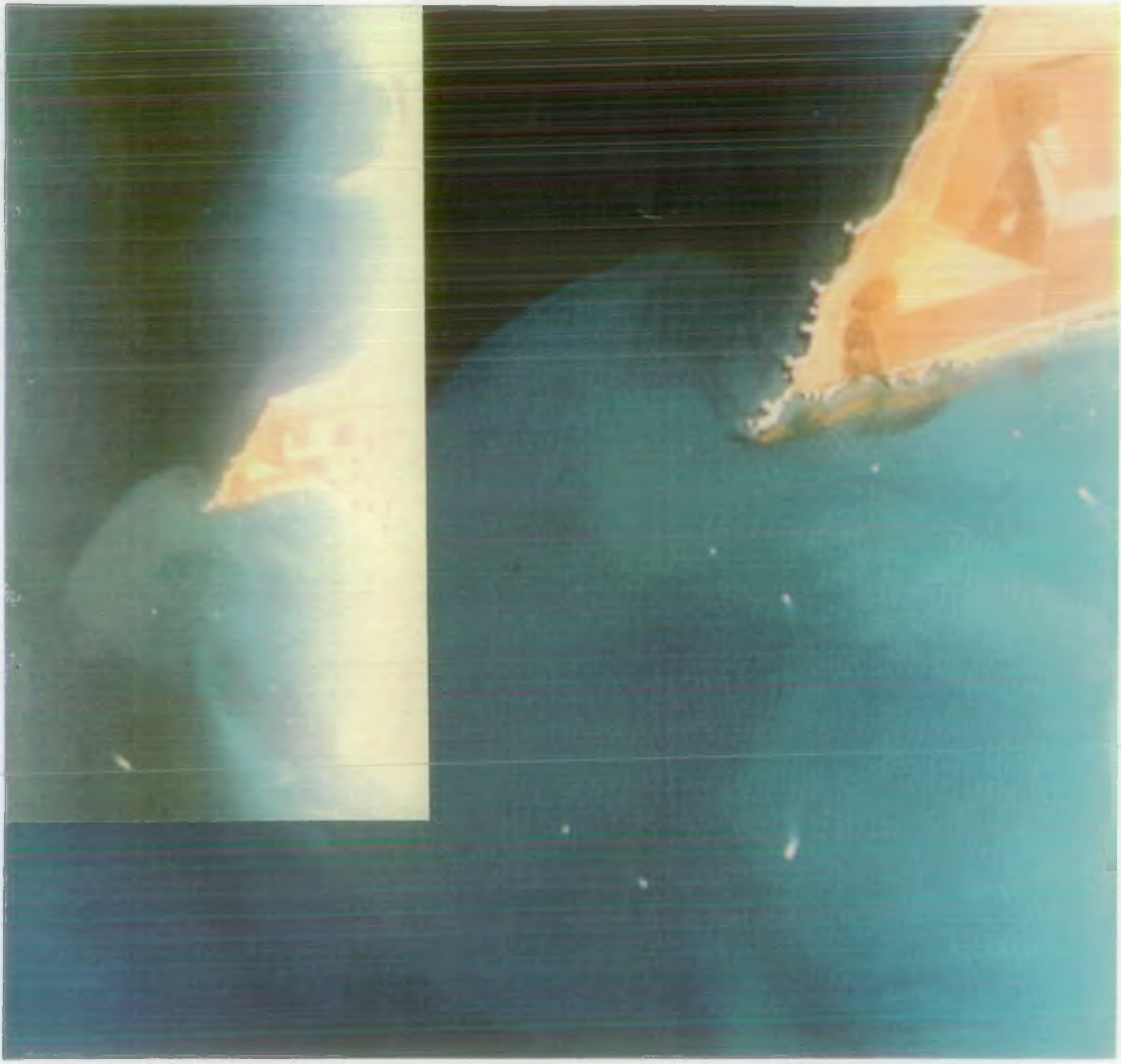


Figure 3.1 Colour composite ATM image of Studland Bay with overview inset

Figure 3.2 Thermal image of Studland Bay with overview inset

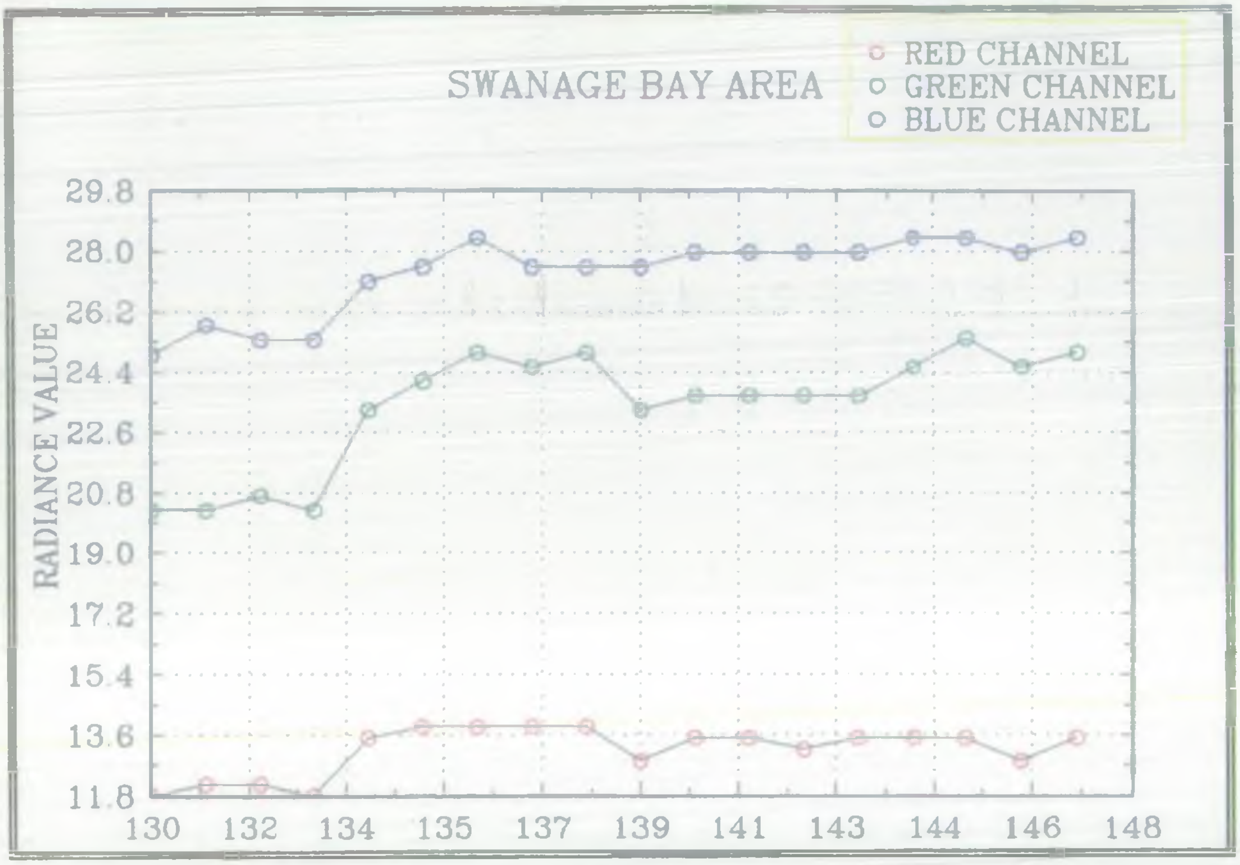


Figure 3.3 Radiance values from the ATM along the ships track

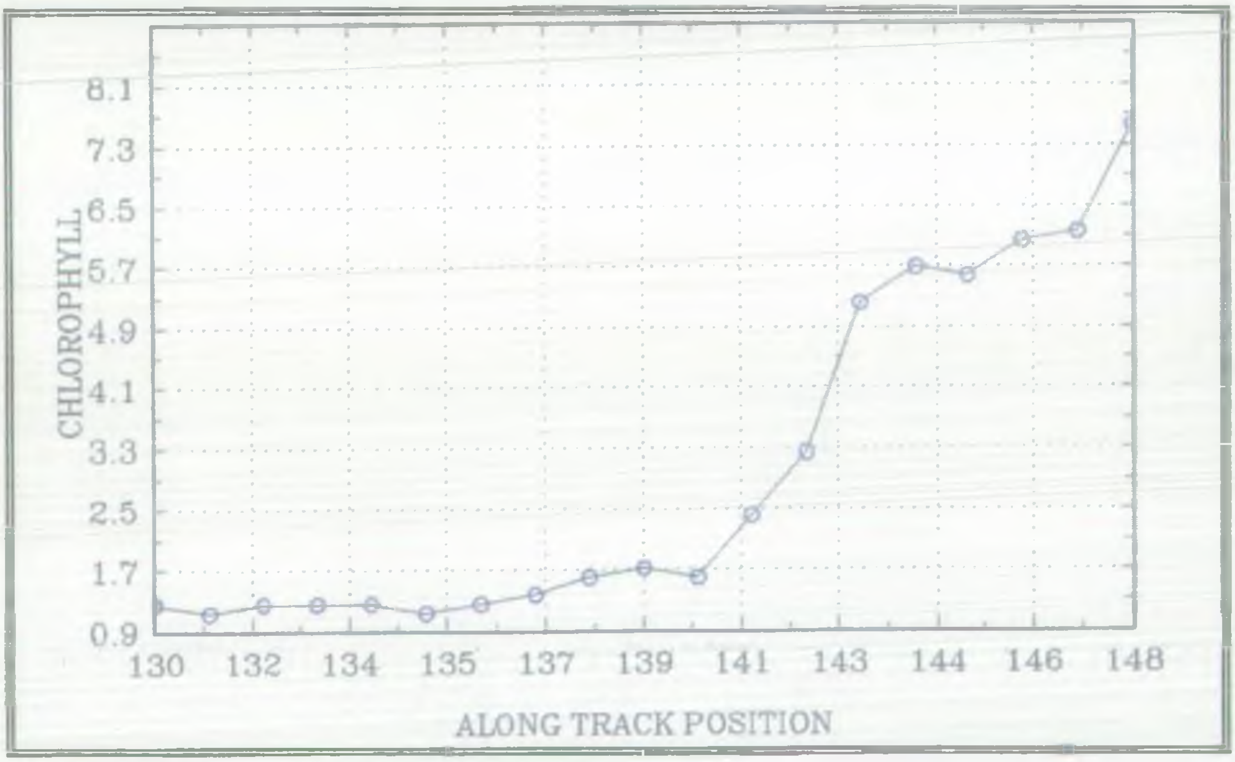


Figure 3.4 Along track ships chlorophyll

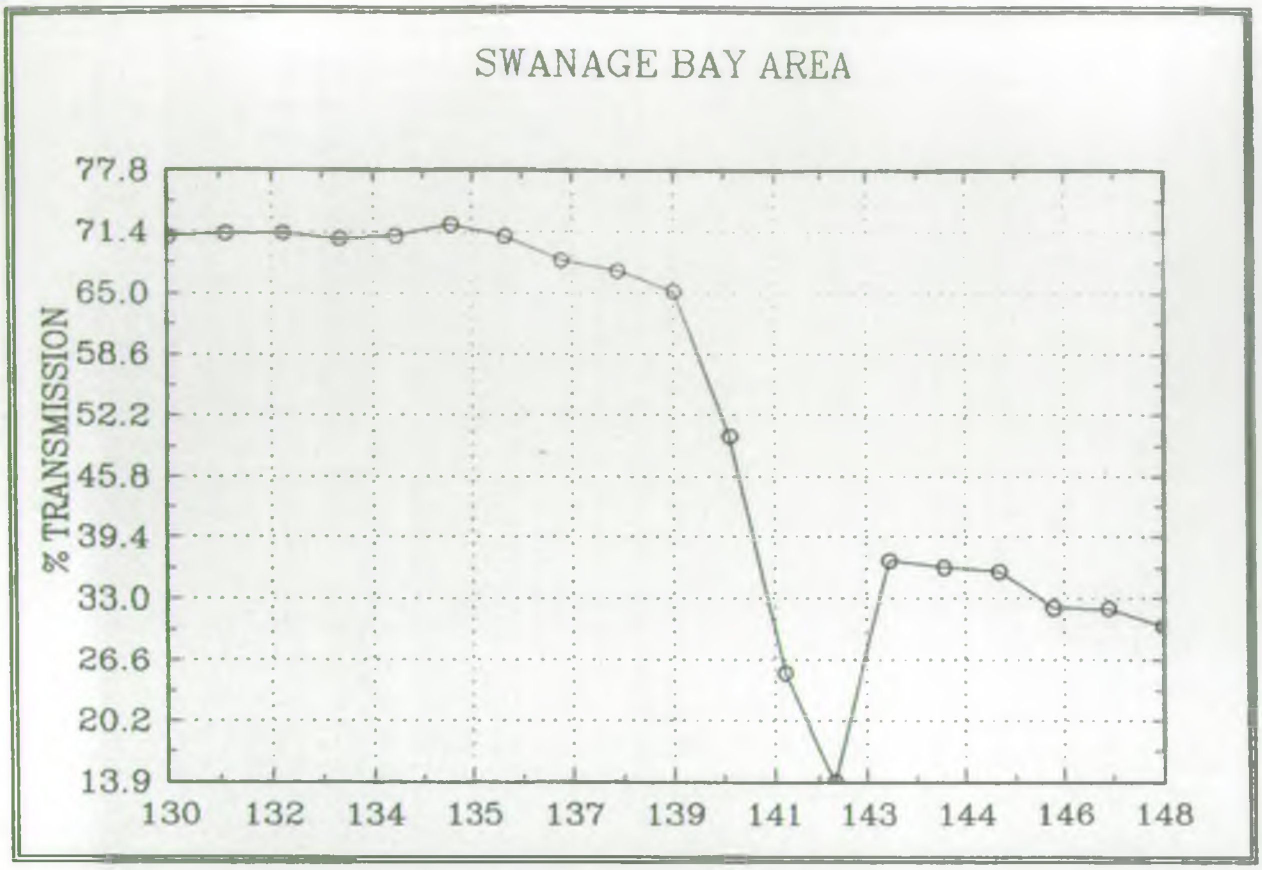


Figure 3.5 Along track transmissometer data

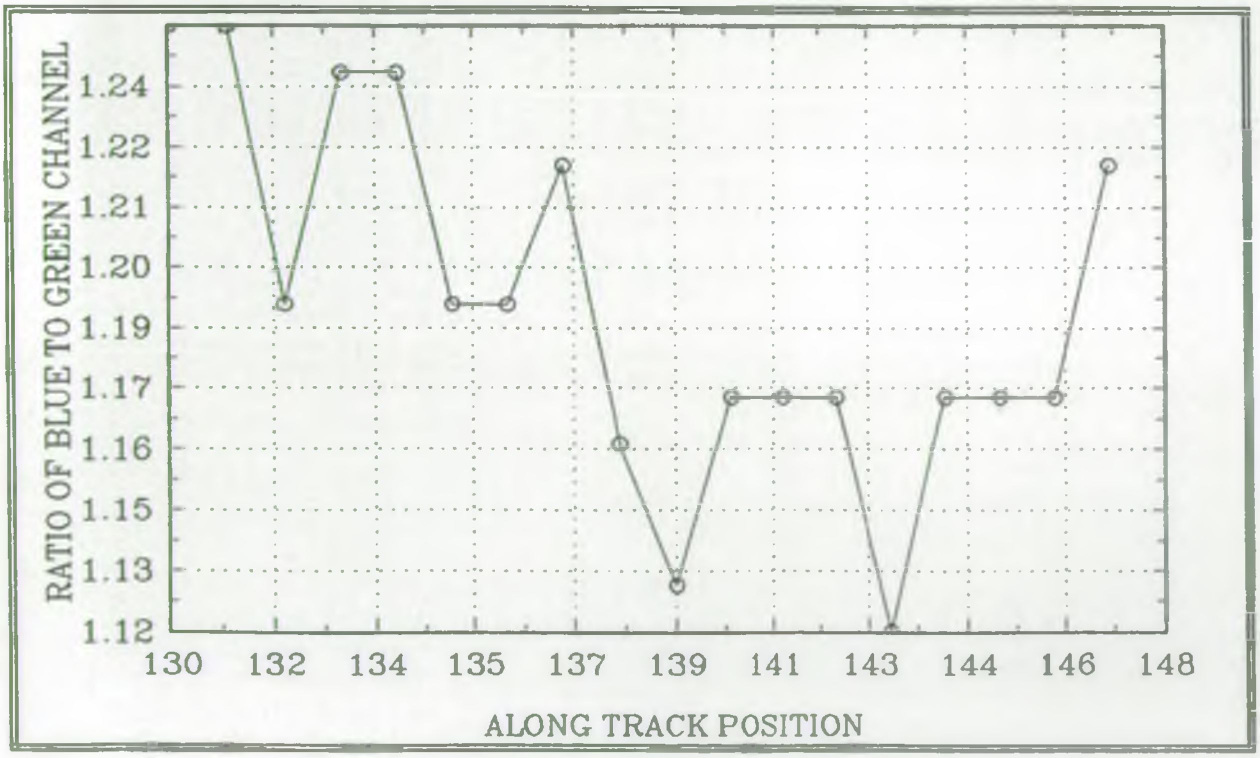


Figure 3.6 Ratio of green to blue channels from the aircraft data

at the broad red end). Figure 3.6 shows a value of the blue/green ratios from the ATM data to simplify the interpretation as to when green radiance is increased with respect to blue.

Thus it can be seen that for this particular subset of data, given seatruth data, one can produce a simple algorithm to calculate chlorophyll and transmission. In this case we have:

$$log\ chlorophyll = -1.957 - 7.294 \log (R_b / R_g) - 7.205 \log (R_r / R_g)$$

$$log\ \%transmission = 4.124 + 5.143 \log (R_b / R_g) + 1.978 \log (R_r / R_g)$$

where R. are the radiance values of the red, green or blue channels. Figure 3.7 gives the correlation between in-situ chlorophyll and that calculated from the ATM data and figure 3.8 the same for transmission. As can be seen, for chlorophyll there is good agreement but for transmission (and ultimately SPM) the agreement is not as good. This is fundamentally a function of the limited spectral information available from the ATM compared to the CASI. The spectral signature of chlorophyll is fairly consistent for all areas, whereas that for SPM will vary dramatically over relatively small spatial scales. This equation can be applied to the ATM data to produce a map of chlorophyll and transmission as illustrated in figures 3.9 and 3.10 respectively. The pictures show, as indicated by the ships data, that there is a productive water mass emerging from the Poole Bay (probably Poole Harbour) region, to the bottom left of the figure. Whilst the colour image indicates some form of plume, it requires the detailed objective analysis to show that this plume is principally composed of chlorophyll/organic material with very little suspended sediment. The transmission figure shows high levels along the coastline, progressively reducing offshore, with little corresponding bio-activity. This is to be expected given the nature of the chalk cliffs in the area and the high levels of coastal erosion. The apparent gradation to the left edge of the image is due to sunglint. This effect cannot be removed as it represents a saturation of the instrument. The importance of the supporting ship data in producing these maps cannot be over emphasized. However, it is obvious that the ship measurements are not capable of producing such detailed 2-D maps of surface water quality parameters. The remotely sensed data shows the complexity of variability of the marine environment around a single line of seatruth measurements. If the extent of an outfall or river plume is to be studied in the tidal environment, or a measure of the integrated sediment/chlorophyll load is required, aircraft data calibrated by ship measurements are the only feasible tools.

A comparison made between ships temperature data and that from the aircraft showed that the values for the ATM data were typically 1°C cooler than those for the ship and that there was considerably more spatial variation. The surface skin layer of the ocean is, for varying reasons (Robinson 1986), of the order of 0.5°C cooler than the bulk temperature of the surface layers, explaining some of the difference. The region itself is stratified and while the ATM measures the upper layer, the ship is actually measuring at 1-2m depth, below any shallow thermocline. Whilst this contradicts the absolute difference between the two it does explain some of the short scale variability. As vessels pass through the area they mix the warmer surface layers with the cooler deep water and these tracks can be clearly seen on the image as dark, or cool, streaks. Another reason for the difference in variability is that the ship measurement system uses a pumped system putting water into a small reservoir which is then measured every minute. The reservoir and time sampling period both act as effective low pass filters, smoothing out many small scale heterogenities in the data.

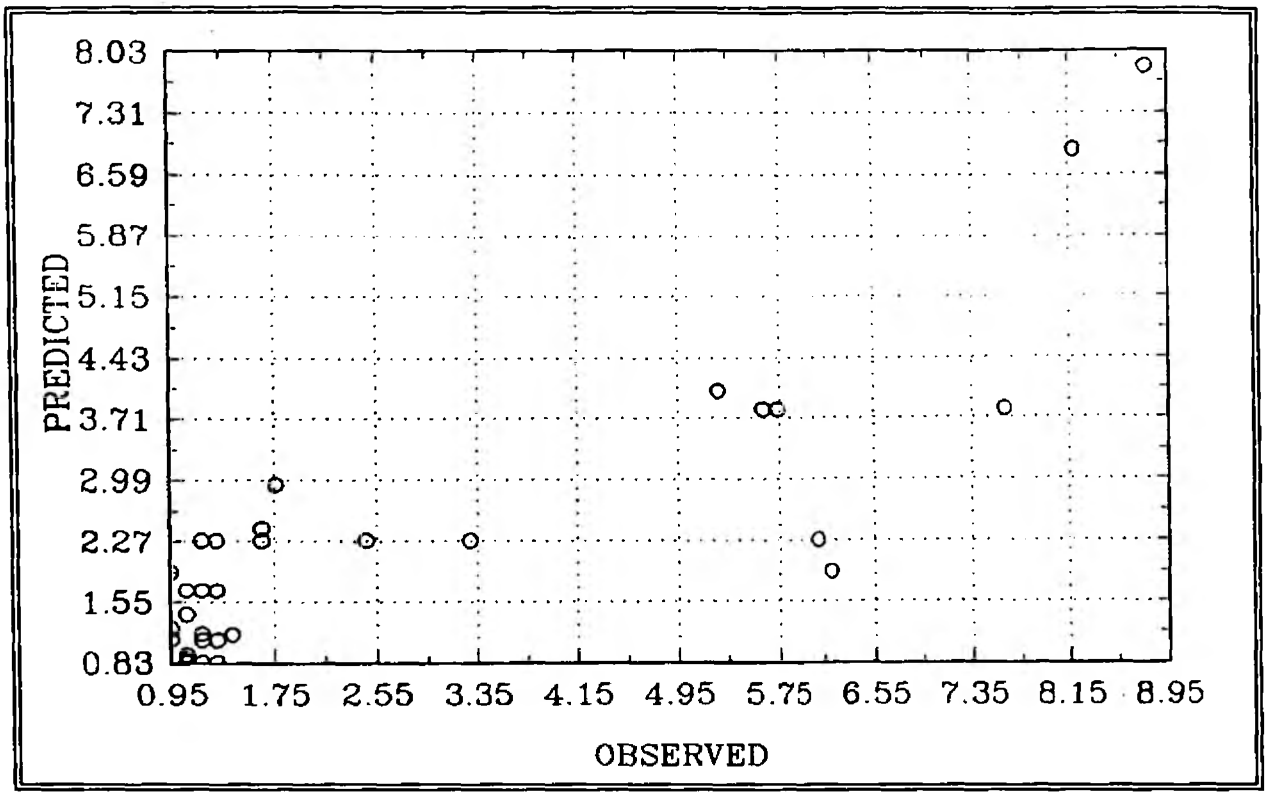


Figure 3.7 Comparison between calculated and measured chlorophyll (μg/l) for Swanage

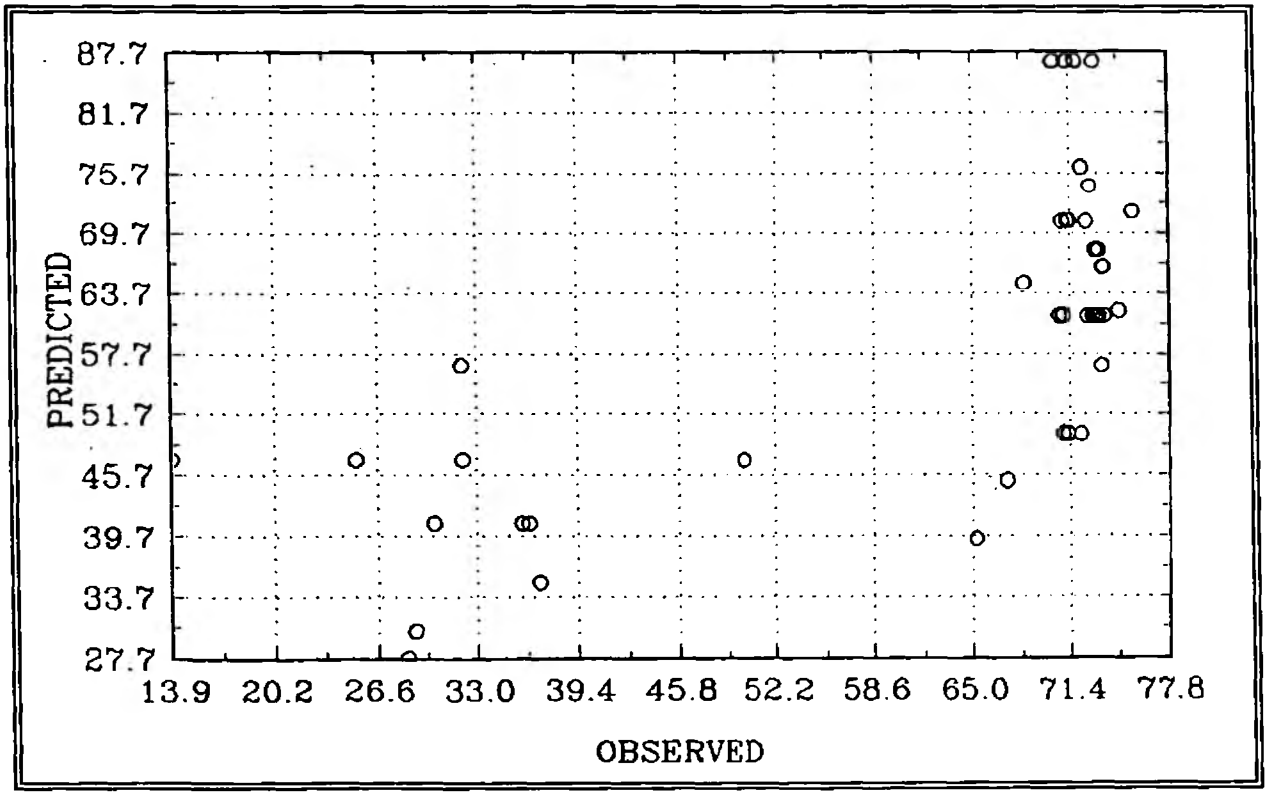


Figure 3.8 Comparison between calculated and measured % transmission for Swanage

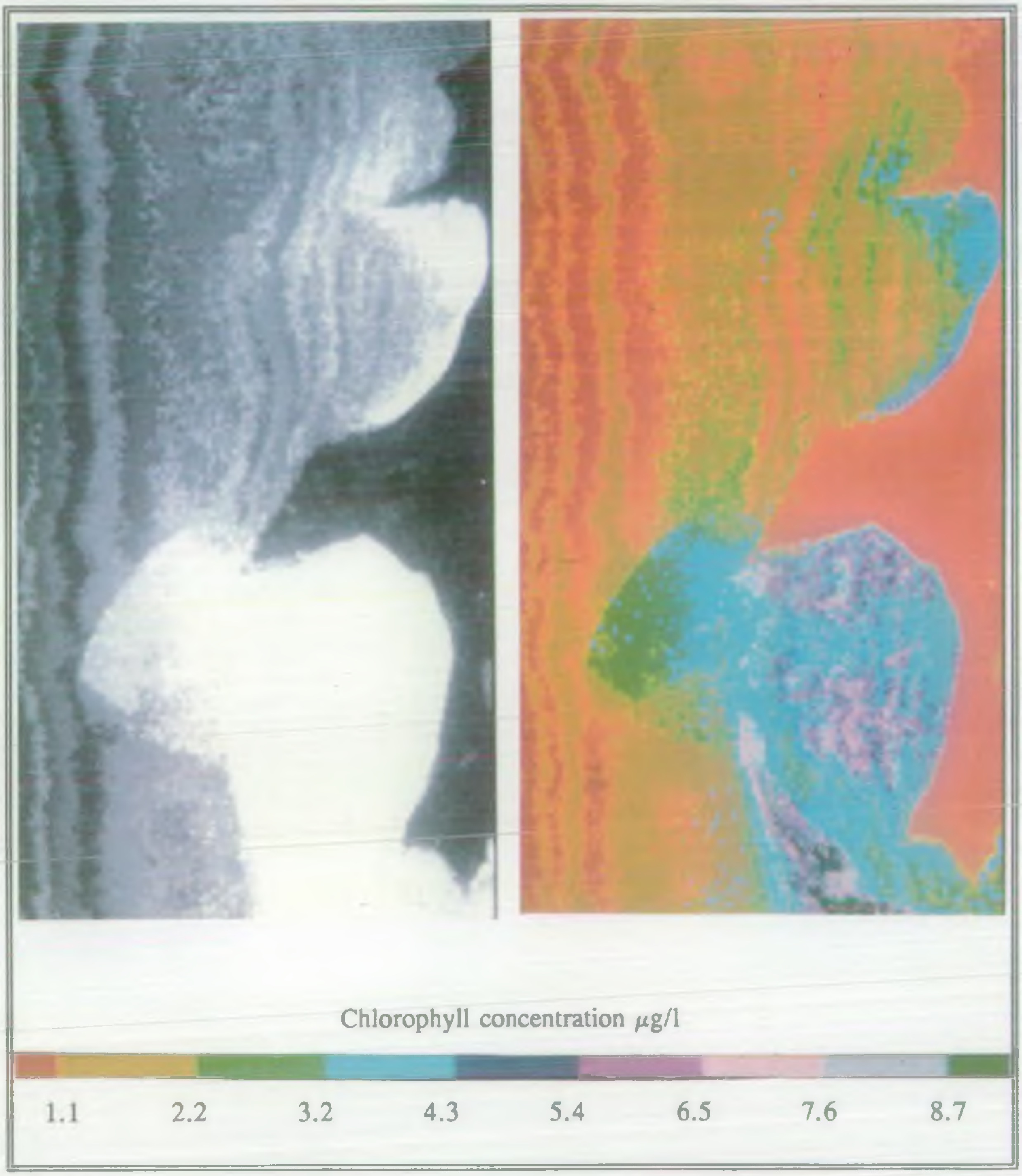


Figure 3.9 Chlorophyll concentrations calculated from the ATM data in the Swanage Bay area. The two maps are the same, but with the right hand one coloured to make data extraction easier. Black on the colour map corresponds to concentrations in excess of 9.8 μg/l. The banding effect to the left of the maps is due to sunglint.

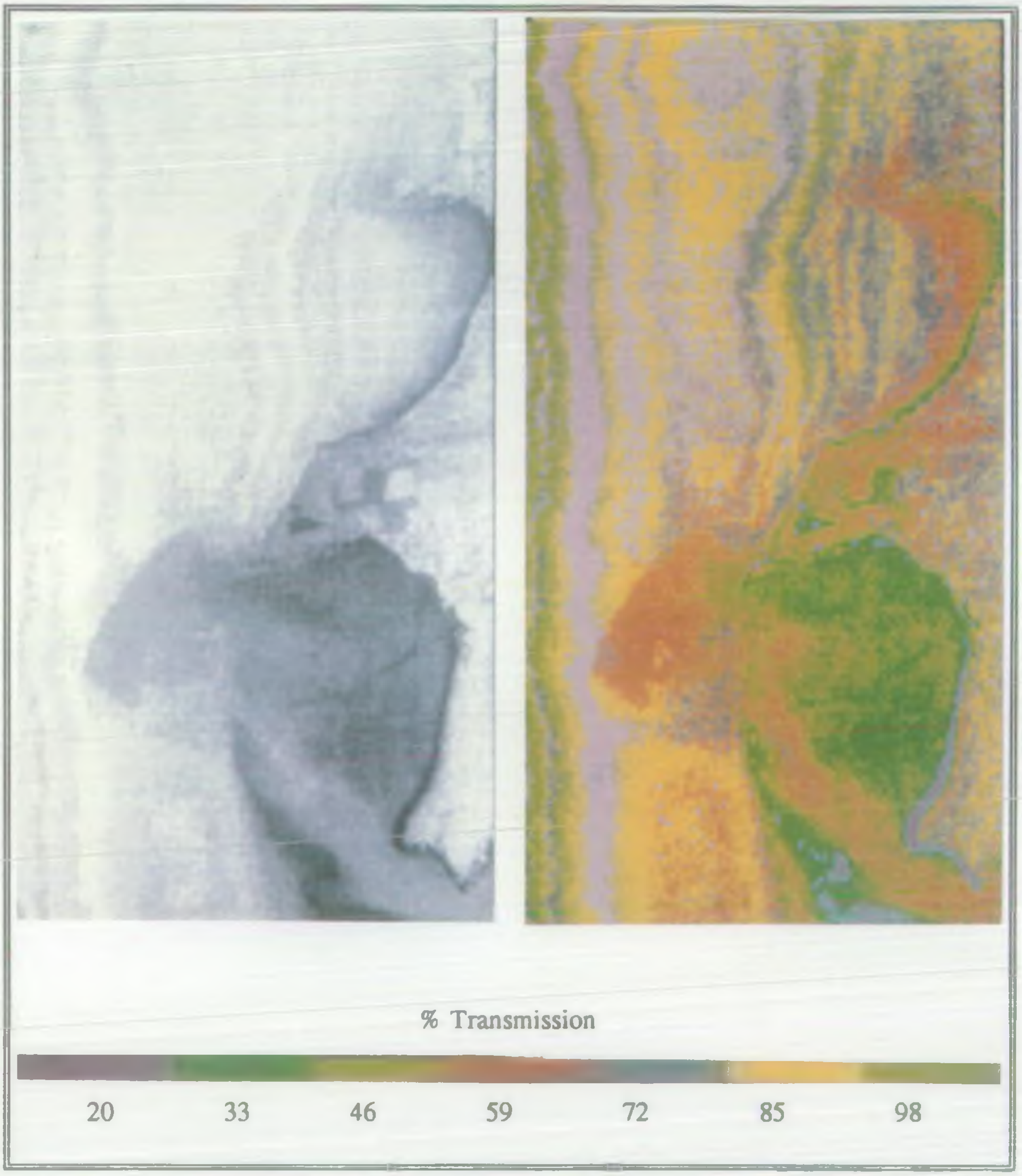


Figure 3.10 % Transmission calculated from the ATM data in the Swanage Bay area. Note the banding effect due to sunglint as seen in figure 3.9. In this case light pink implies a transmission in excess of 100%! This is error caused by sunglint.

The algorithms used to determine chlorophyll and transmissometry in the Swanage Bay area are in general specific to the particular area. They relate to the particular combinations of sediments suspended in the water in this region which have to be accounted for when calculating both the sediment and chlorophyll concentrations. If the same algorithms are used in other areas the correlations will not always be as good. Figures 3.11 and 3.12 show the ships transmissometry and chlorophyll data for Pegwell/Sandwich Bay in Kent, with figure 3.13 illustrating the radiance values for the red, green and blue channels for the ATM. As in the Swanage Bay case, as the ship moves from low to high chlorophyll levels so we see a reversal in the blue to green ratios of the signals. In this area there is not such a high variability in SPM and so there are fewer anomalous reversals. If one estimates chlorophyll from the original algorithm, then the correlation on a specific point to point basis would not be as good as for Swanage, and although the general pattern would give a fair representation, the value range would not compare well with the ship data. If however a specific algorithm is applied, of the form of:

$$\log chlorophyll = 0.382 + 1.379 \log (R_b / R_g) - 0.381 \log (R_r / R_g)$$

$$\log \%transmission = 4.290 - 1.225 \log (R_b / R_g) + 1.367 \log (R_r / R_g)$$

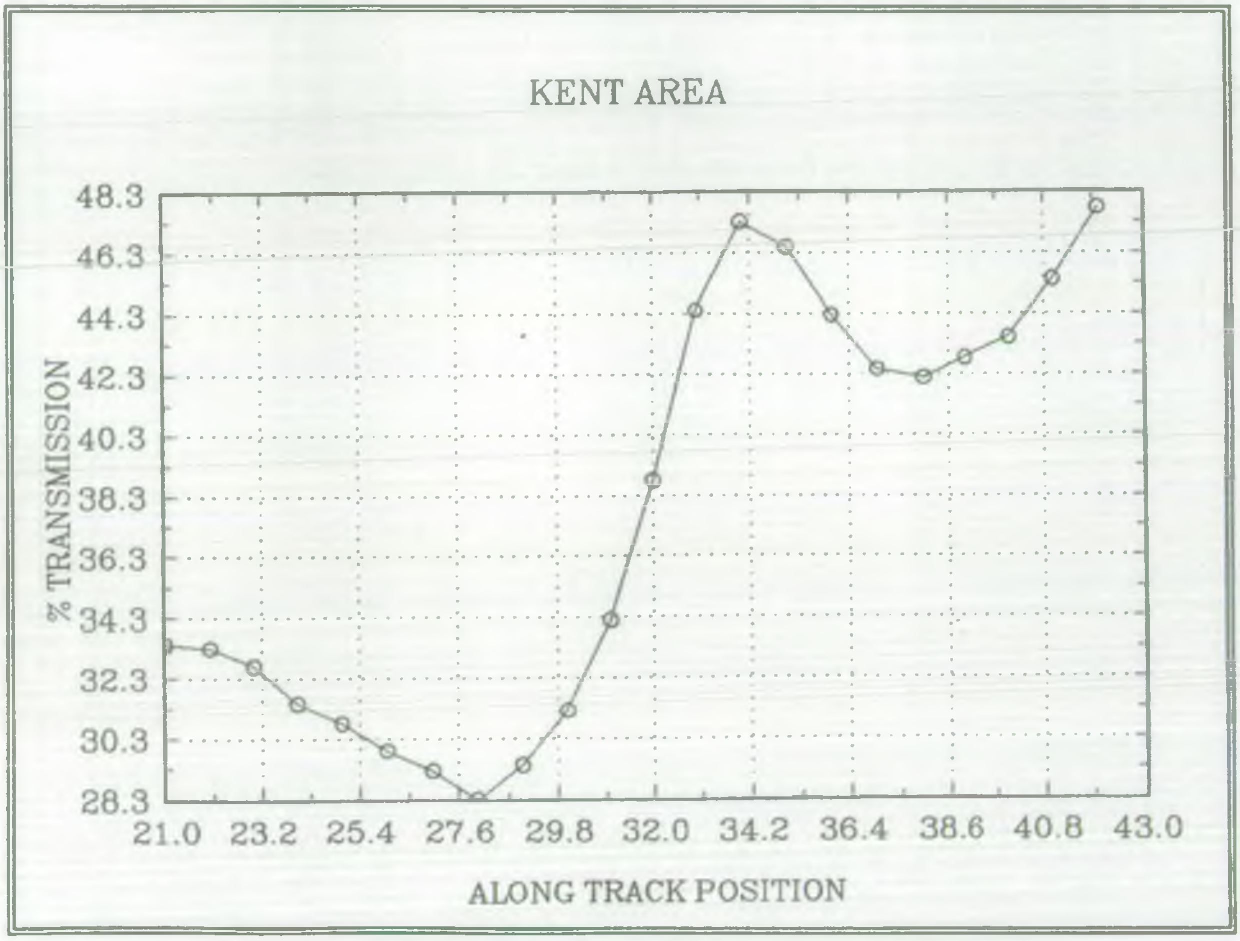


Figure 3.11 Along track transmissometer data

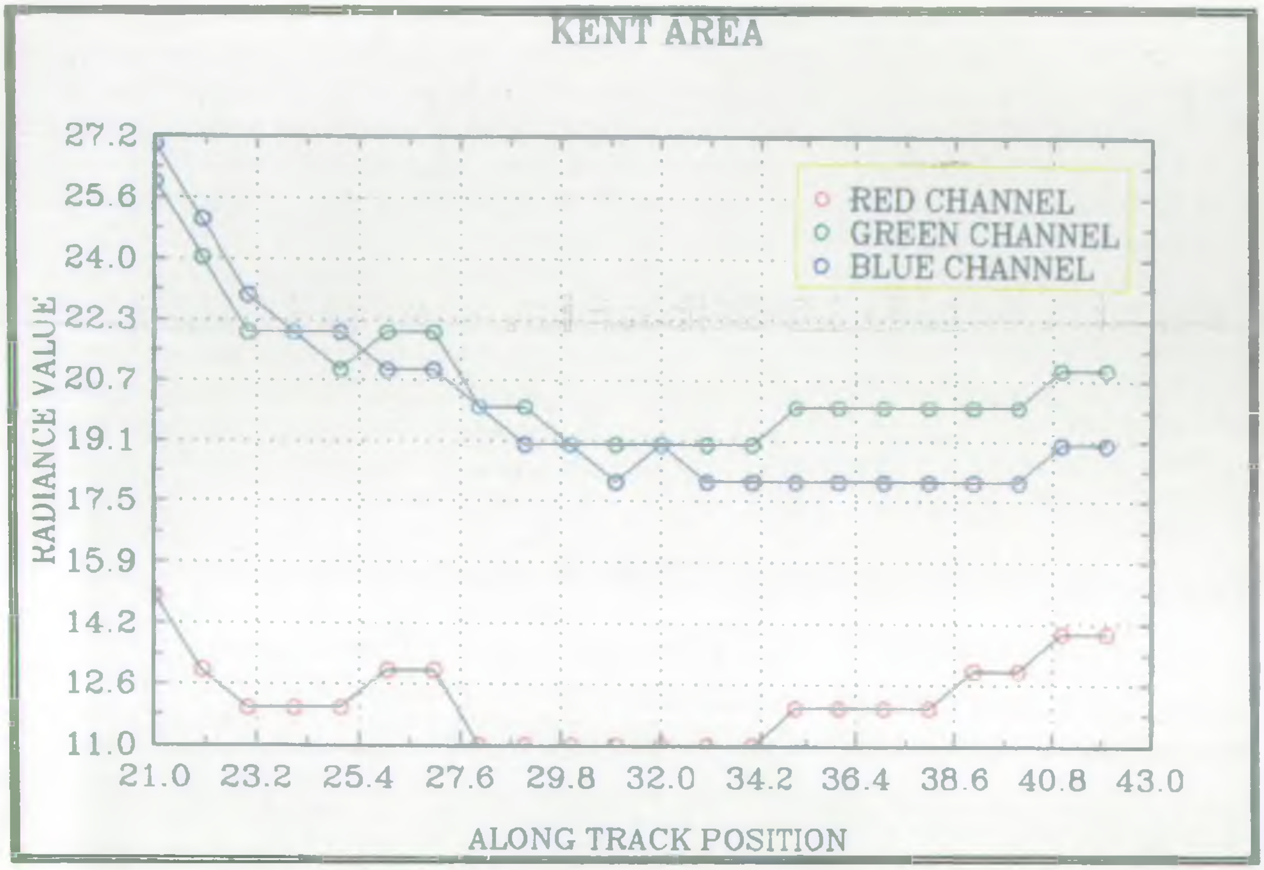


Figure 3.13 Radiance values from the ATM along the ships track

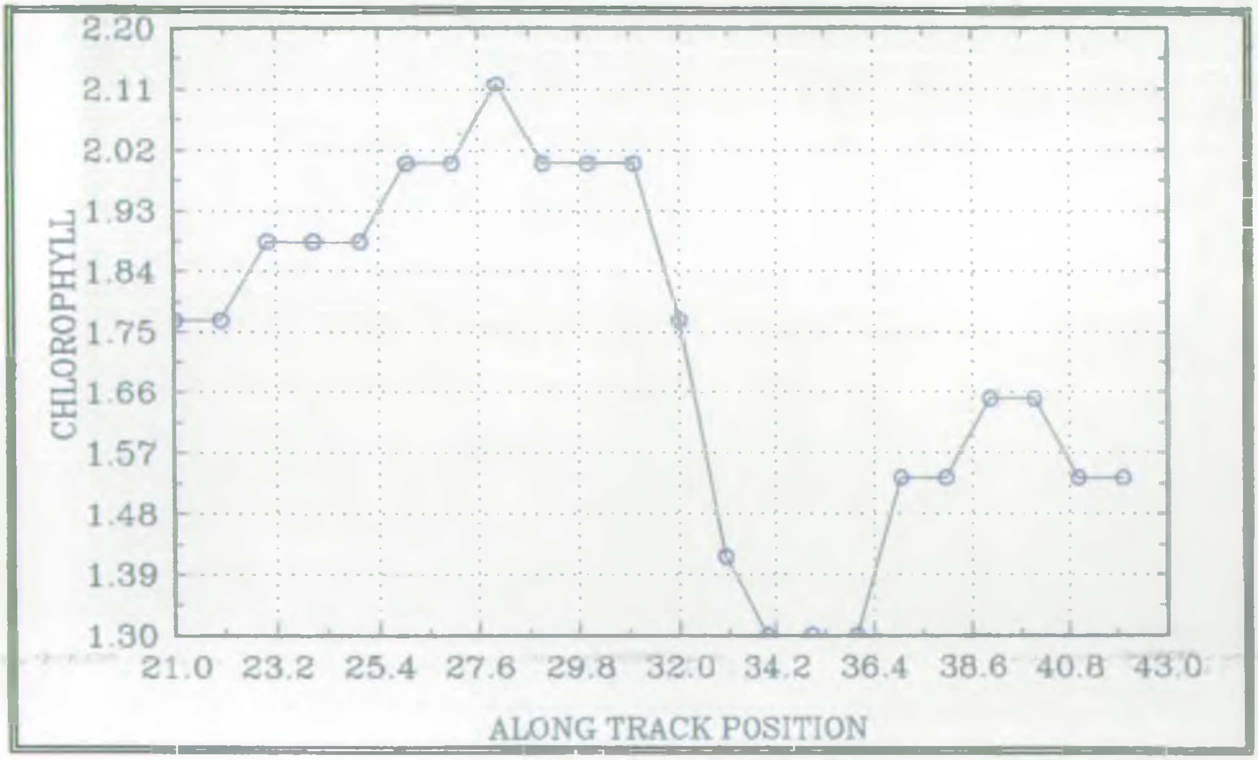


Figure 3.12 Along track ships chlorophyll

then not only does the correlation between sea-truth and image data improve, but also the range of values compares well between the two data sets. Figure 3.14 illustrates the pattern of chlorophyll and transmission based on the localised algorithm. A relatively poor correlation (adjusted R^2 for chlorophyll of 0.27, for transmission 0.49) probably results from the fact that in this case the data taken by the ship was 6 days after that collected by the aircraft and also at a different tidal state.

Figure 3.14 Chlorophyll (left) and %transmission (right) calculated from the ATM data. Black to white corresponds to 1.6 to 2.0 μg/l chlorophyll and 28 to 52% transmission.

Figure 3.15 A colour composite image of Deal and Pegwell Bay (inset) and Ramsgate Harbour (main).

However the basic water quality constituents will be similar and so the aircraft data is a good representation of the water quality at that particular time: it is interesting to note that a comparison of the two sets of ship data, the second taken when the ship returned on the same track a week later, also gave a poor comparison. The water column is a dynamically active media and will always undergo spatial and temporal changes. Note how the colour composite image, figure 3.15, gives a good indication of the presence of certain water quality "features" but not what they are. The analyzed results provide the required information: in this case for example, the high reflectivity from water emerging from Ramsgate Harbour (bottom of image) is as a result of low transmissivity but with no chlorophyll signature, indicating a high SPM content, whilst that near Deal (top of image) corresponds to a plankton bloom, or at least raised chlorophyll levels.

The overall levels of sediment and chlorophyll at both of the sites studied thus far were similar but with differing mineralogical constituents, requiring a different algorithm. By contrast figures 3.16 and 3.17 show the ships chlorophyll and transmissometry for the southern section of Lands End in Cornwall. Here the region has very low chlorophyll levels (an order of magnitude less than at Swanage) with apparently very low sediment levels as well (50-70% transmission). Figure 3.18 illustrates the Red, green and blue channels of the ATM, with slight blue/green trends at higher chlorophyll levels but better net radiance variability with transmission. Note that radiance levels are in places lower than usual. In this instance a local algorithm was applied and gave values of chlorophyll close to zero.

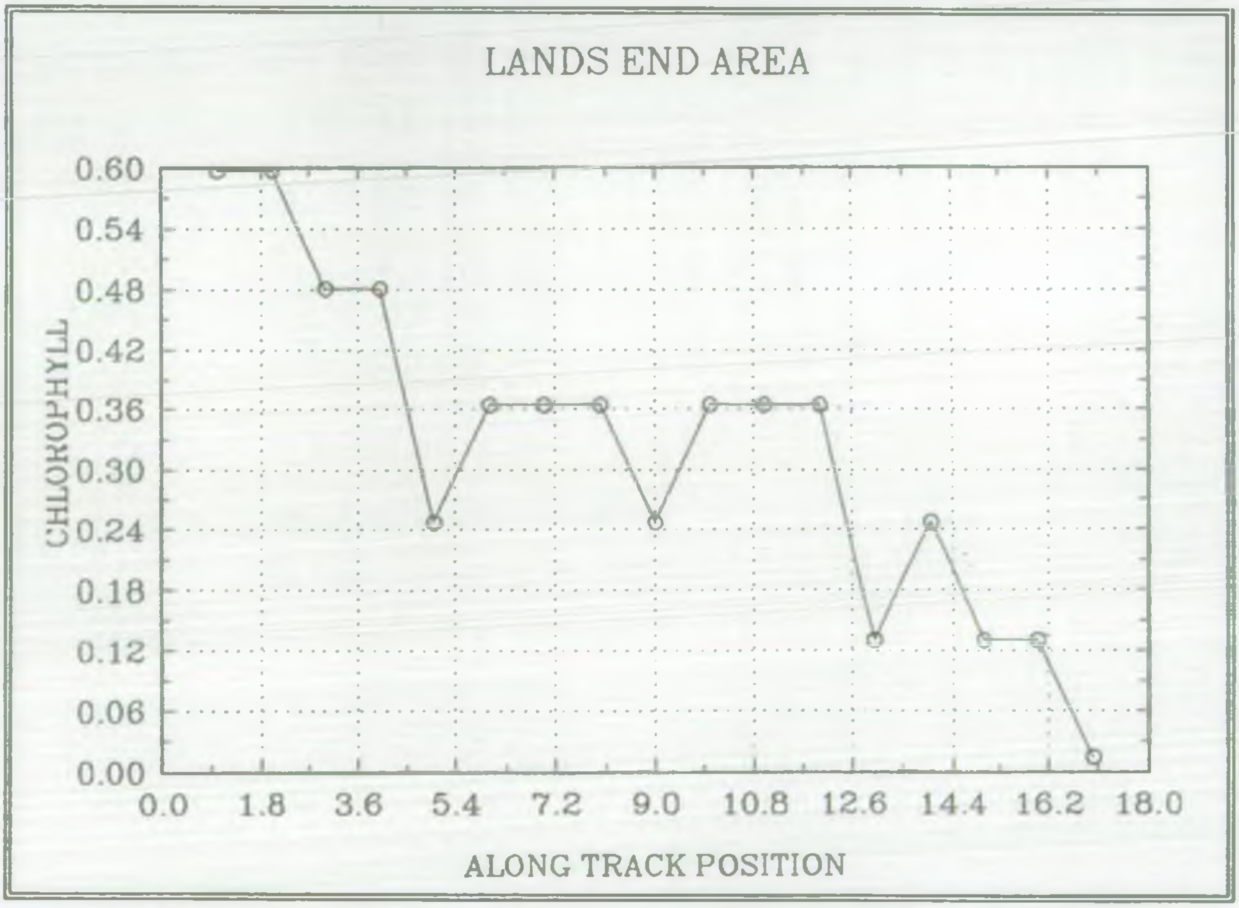


Figure 3.16 Along track values of chlorophyll measured by the ship

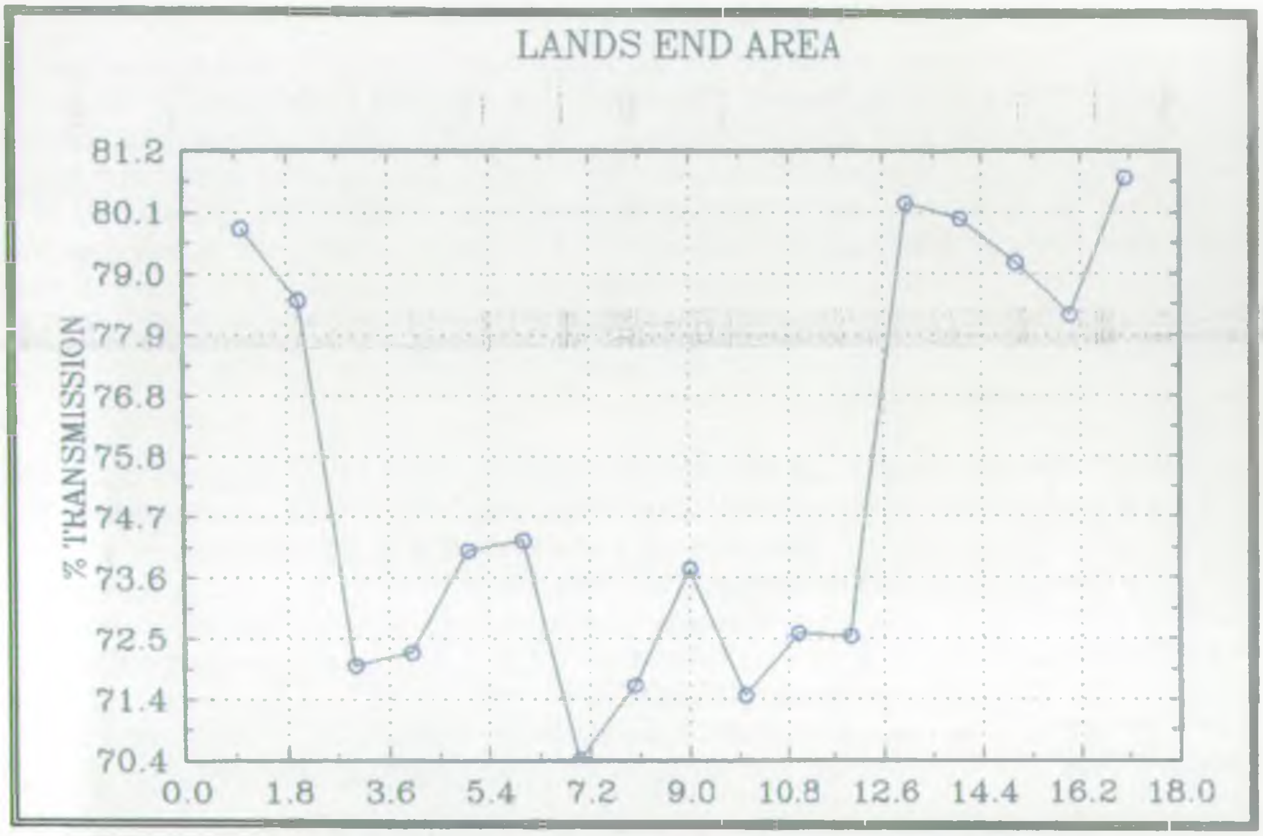


Figure 3.17 Along track values of transmission measured by the ship

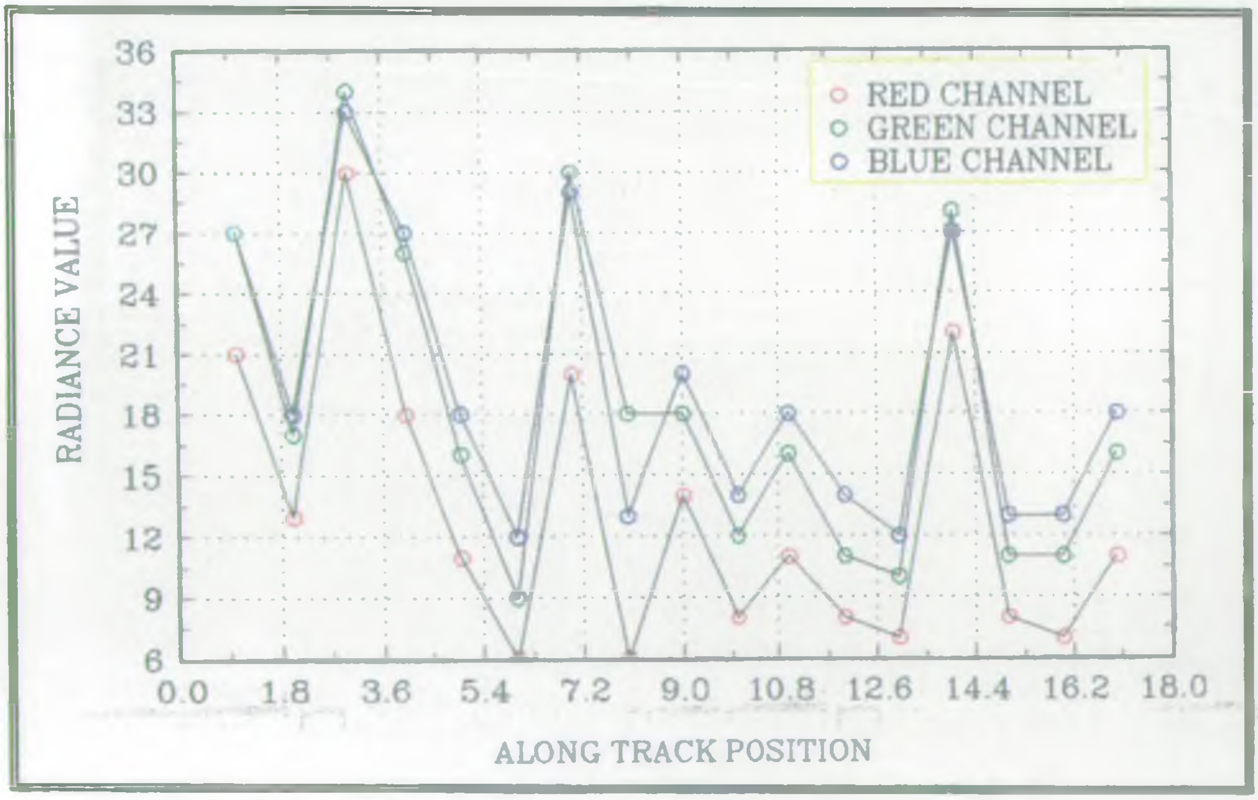


Figure 3.18 Radiance values of ATM along the ships track

In this instance, because of the high values of transmission, with very little variability measured along the ships track, the local algorithm for transmission gave a poor correlation coefficient. This is likely to be due to the small range of values available to produce a regression line.

The entire data set has been processed in a similar fashion. A general algorithm, covering the whole coastline, has also been established, of the form:

$$log\ chlorophyll = -2.068 + 0.262\ log\ (R_b\ /\ R_g) - 4.319\ log\ (R_r\ /\ R_g)$$

$$log\ \%transmission = 4.430 + 1.07\ log\ (R_b\ /\ R_g) + 1.11\ log\ (R_r\ /\ R_g)$$

which provides approximate values of chlorophyll and transmissometry (or SPM). Site and season specific algorithms (the algorithms described would only apply for the period of the study) are required for more precise measures of water quality parameters, but do require a data base of sea-truth information for their formulation. Unusually, in the case of Lands End however, the global algorithm predicts the transmission more acurately and is illustrated in figure 3.19. Note the high levels of SPM in Porth Curno which would not have been detected by the vessel.

Figures 3.20 and 3.21 illustrate both chlorophyll and transmission maps for Kent and Swanage and show quite clearly the similarities, spatially, with the site specific calculations but also the differences in absolute values and on some of the more complex areas.

The examples thus far have concentrated on specific measurements of chlorophyll and SPM, and although this has to be one of the main goals of the exercise, it is not the only information available from the data.

Figure 3.19 Transmission calculated for Lands End using the global algorithm. Black to white corresponds to 8% to 50% in Porth Curno, with white offshore up to 80%.

Figure 3.20 Maps of chlorophyll (left) and % transmission (right) for Kent calculated from the ATM data using the global algorithm.

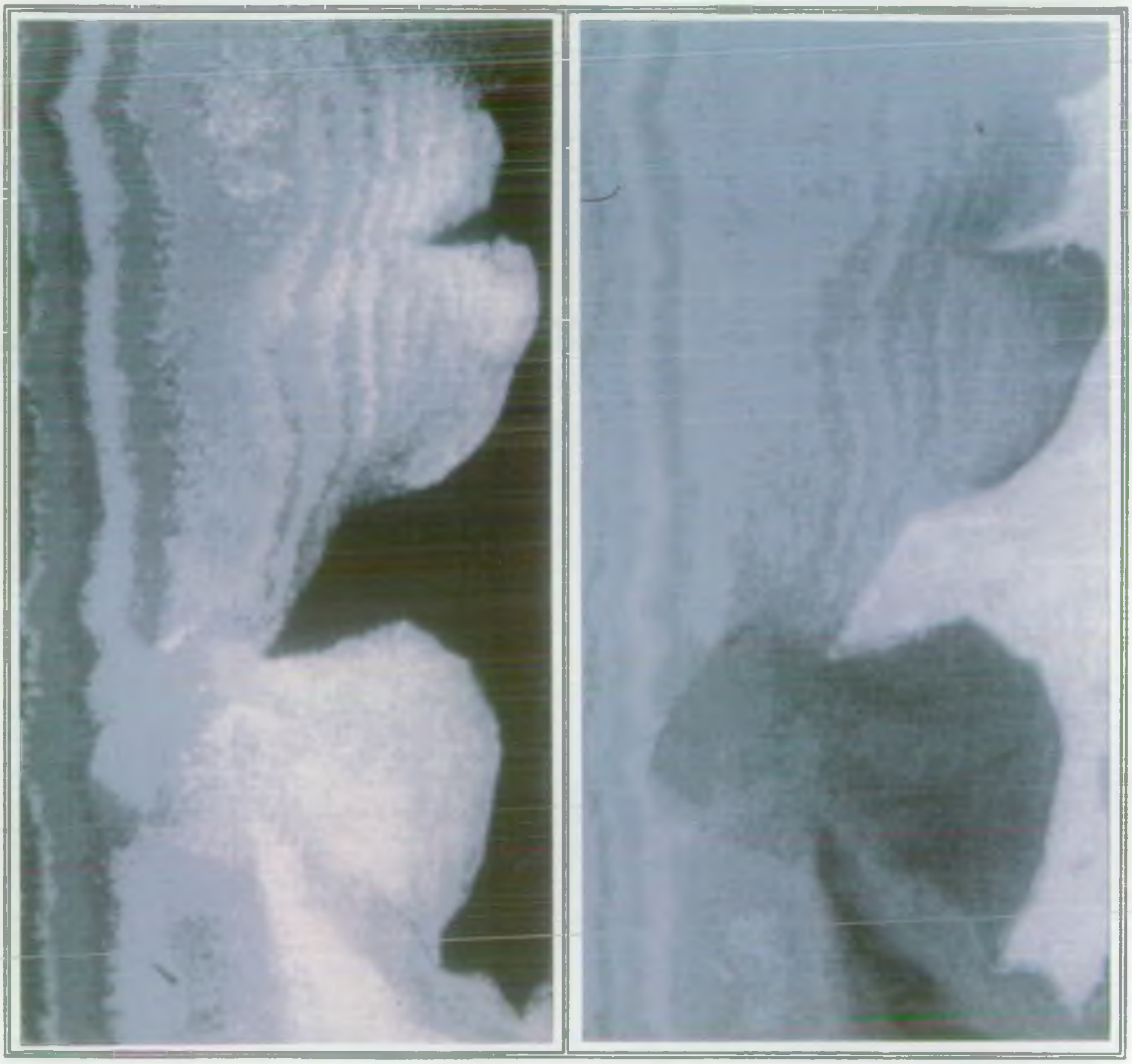


Figure 3.21 Maps of chlorophyll (left) and % transmission (right) for Swanage Bay calculated from ATM data using the global algorithm.

3.2.2 ATM Data - Wider Applications in the Marine Environment

Whilst absolute measurements of water quality parameters must be one of the main objectives of gathering airborne ocean colour data, there is still a great deal of value in the more subjective information available. The science of ocean colour has often in the past been criticised as being a "pretty picture" science; lots of interesting patterns but no objective numerical data. As has been seen this is now an unjustified criticism, but the patterns are just as capable of providing both the research and operational scientist with valuable data. Measurements from a vessel represent a very precise but often blinkered view of the marine environment - they provide no true synoptic spatial perspective. The airborne data fills this shortfall. This can be in terms of monitoring a known feature, of identifying new ones, and, as will be seen, of identifying and tackling "incidents".

One of the specific sites of interest was the outfall at Sharkham Point, near Brixham. It was intended to add a quantity of Rhodamine-B dye to the outfall at the time the aircraft flew over the site. It was also intended to make a multiple overpass after the dye had been deployed. However, due to a number of operational difficulties the dye was actually released 4 hours earlier than the first and only flight. Figure 3.22 illustrates the colour composite image of the area. The dye does not show up red on the image but as a yellow/green patch. It is also difficult to distinguish some of the effects of sunglint and cloud shadow (the data was gathered on a fairly cloudy day). As can be seen, the dye has been transported to the west on the outgoing tide (image right) and is now returning on the incoming tide. The outfall itself can just be seen on the image. Ironically the airborne photo taken in the area (figure 3.23) actually gives a clearer picture of the dye patch which relies heavily on the human eye for detection (the photographic technique of data representation being more similar to that of the eye). This allows the user to make better use of the digital data contained in the imagery, as the photo does not provide the detailed numerical data for final analysis. Whilst in principal it should be possible to detect concentrations of the dye (and thus not only path but also dispersion), the sensitivity of the ATM is not sufficient to do this; the CASI is.

It is not necessary in some outfalls to directly tag the "water", whether they be sewer, river or storm drain inputs. Figure 3.24 illustrates a colour composite image from Pevensey Bay. The outfall in the Bay is very clearly delineated by its own particulate load. The pipe coming into the sea can be seen, as can the path of the outfall. It is also possible to obtain a rough estimate of the rate of dispersion just by a visual inspection of the image. Given that the material in the outfall was not characteristic of the region, and that the vessels track did not pass through the outfall, it would be difficult to provide a very precise measure of the type and concentrations of the outfalls constituents in the region. However, it is important to point out that in this case the vessel did not see the outfall at all - the vessels track was beyond the immediate zone of influence of the outfall. Thus, the air data has in this case provided more information than the ship. Operationally the data could be used to direct the vessel sampling regime in order to optimize it.

The use of airborne remote sensing in monitoring incidents, both in a responsive mode and on an opportune basis, was also demonstrated during the NRA campaign. The pilot spotted a small oil slick off the Torbay coast with a moored tanker nearby. An overflight was carried out and figure 3.25 shows an ATM colour composite image of the scene. With such data, given the relevant tidal stream data it would be possible to trace the oil to the moored tanker. The ATM is sufficient to do this. However, should legal mitigation be required then more scientific evidence would be needed. This could be obtained with the spectral imagery provided by the CASI. The utilization of airborne spectral imagers and line scanners to fingerprint oil which could then be compared with the ships manifest has been demonstrated recently by Reuter (1989) in Oldenburg University.

Other examples of spatial information and insights to certain processes are highlighted in the brief descriptions on the sites of specific interest not already covered.

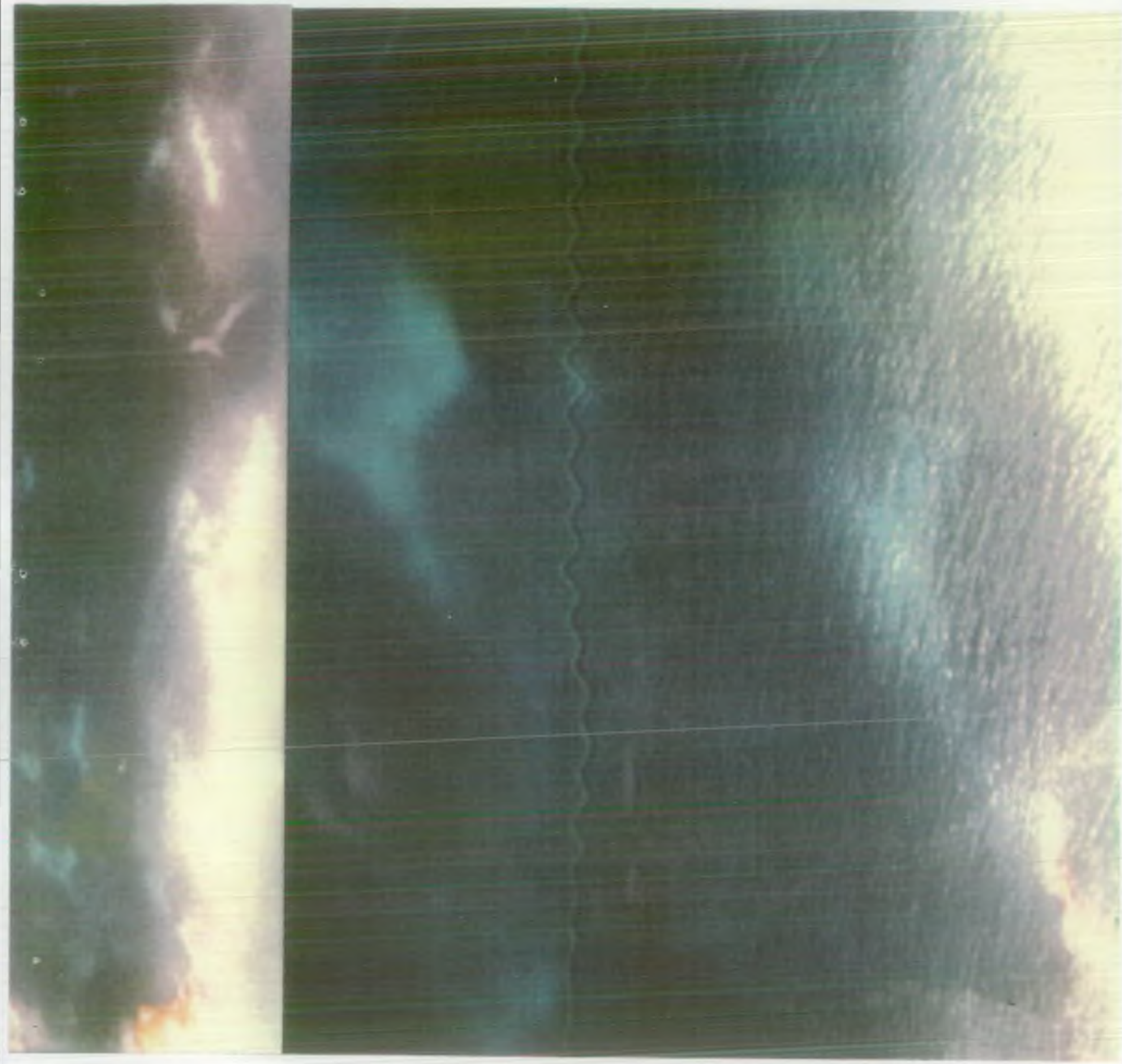


Figure 3.22 Colour composite image showing area of dye release off Sharkham Point. Note the sinusoidal interference pattern discussed in chapter 2 across the image. Note also the strong glint to the right (west) of the image.

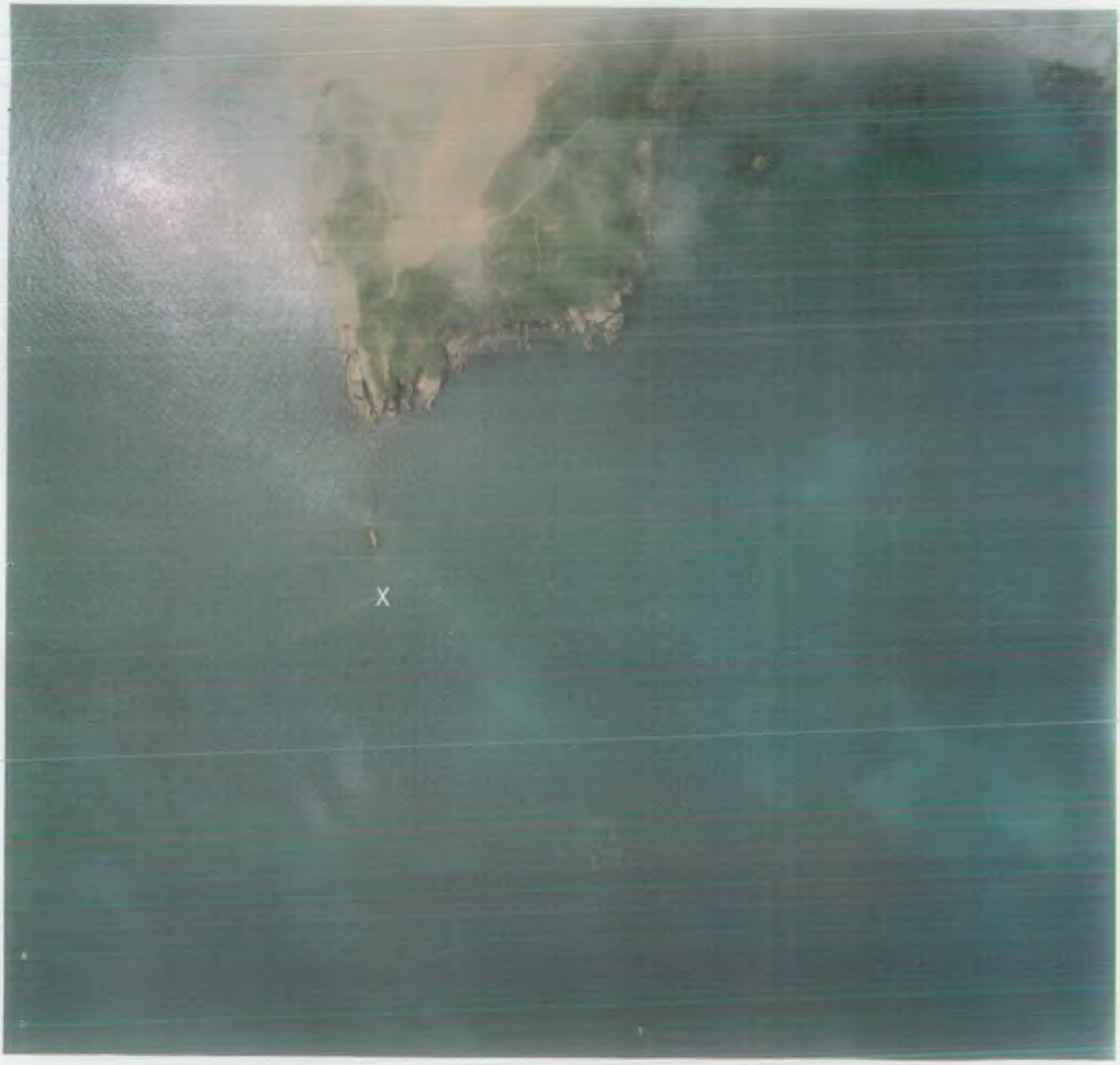


Figure 3.23 Air photograph corresponding to figure 3.22, showing the dye release off Sharkham Point. Note the outfall to the south of the image marked X.

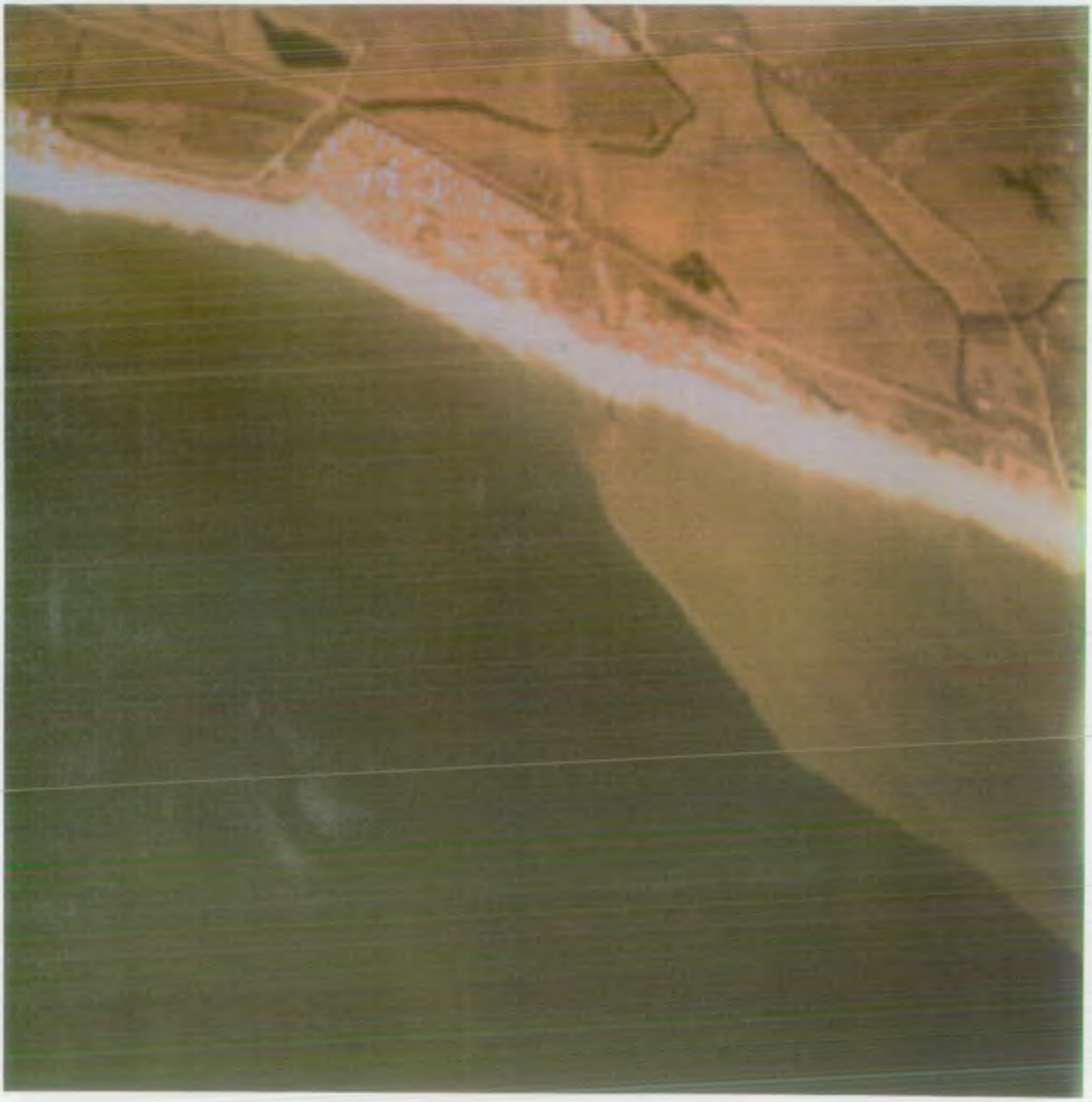


Figure 3.24 Colour composite image of Pevensey Bay illustrating very clearly the track of the outfall waste.

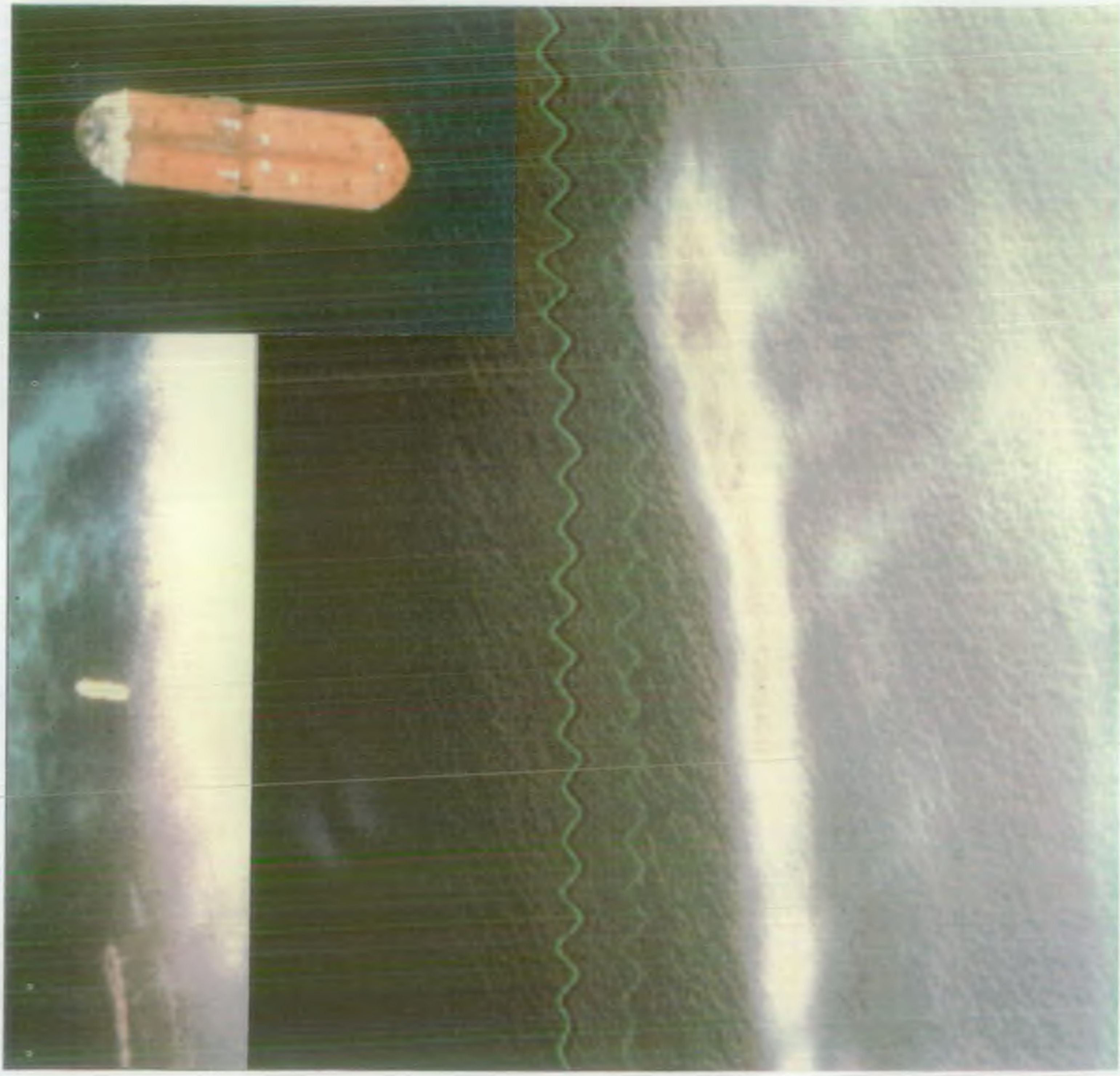


Figure 3.25 Colour composite ATM image of oil spill off Sharkham Point. The inset shows the overview with the ship and the slick, the main view shows detail of the slick.

3.3 CASI Data - Operational reality.

The ATM has provided a valuable data set for chlorophyll and total SPM (via transmission), but for both of these properties site specific algorithms with quasi-synoptic sea-truth data are required. Whilst it may be the intention to make use of operational airborne remote sensing in conjunction with ships campaigns, it would be advantageous to be able to detect chlorophyll and total SPM irrespective of what data, if any, were available on the ground. The CASI is capable of doing just this now, although in order to detect any of the more subtle water quality parameters, such as sediment type, it will still be necessary to use sea data in order to classify an area (see later).

For the ATM chlorophyll is determined by considering the blue/green ratio of the sea's radiance. Other influences on this ratio, such as sediment, have to be accounted for by further information such as that in the red end of the visible spectrum. Chlorophyll has a second effect on colour, that of natural fluorescence. Blue light energy is absorbed from the sun by the phytoplankton in order to photosynthesize. Some of this energy is re-emitted at a longer wavelength in the far red part of the visible spectrum and over a very narrow bandwidth, between 682 and 688 nm. It effectively produces a narrow peak, or spike, in the spectrum and is referred to as the Fluorescent Line Height (FLH). The intensity of the FLH is directly dependant on the concentration of chlorophyll, and if measured can thus be used to measure chlorophyll concentration.

There is one main advantage of using the FLH, it is not necessary to correct for background sediment concentrations. Sediments tend to have a broad band effect on the spectrum, in a similar way to chlorophyll in the blue-green part of the spectrum, but in contrast to the FLH. Thus the FLH is seen as a peak above the background sediment level, regardless of that level. The aim therefore is to detect the height of the peak with respect to the "shoulders" either side. Figure 3.26 illustrates this peak. The main disadvantage in the past of using FLH

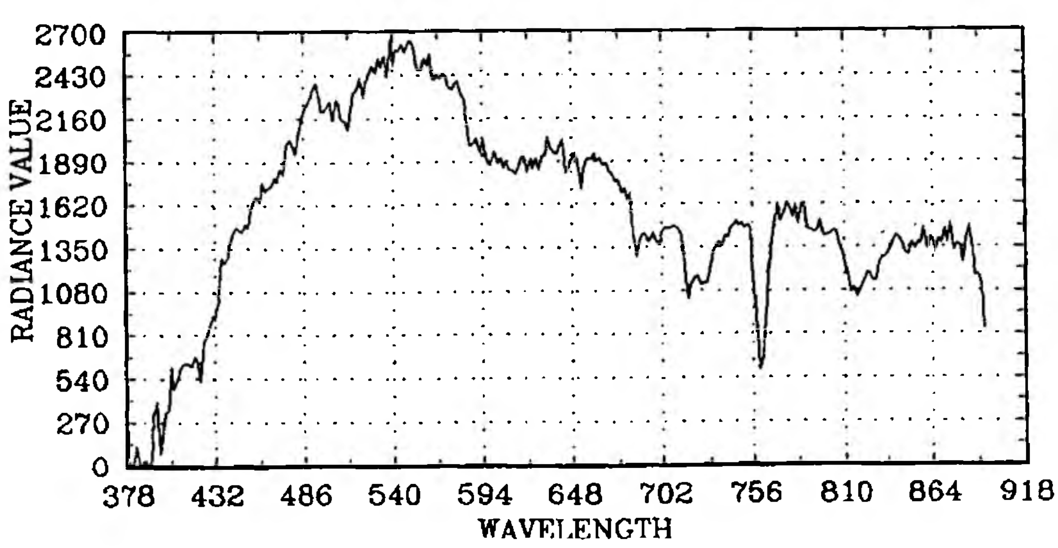


Figure 3.26 CASI spectrum illustrating the fluorescence peak of chlorophyll at 685nm.

has been the lack of a sensor with sufficient spectral resolution to detect the peak; the nearest that the ATM comes for example, is channel 5. The broadband characteristics of channel 5 integrates the peak into the background and thus gives no chlorophyll information. However, with the CASI there is sufficient resolution and it is relatively straight forward to obtain a precise measure of chlorophyll.

During the NRA CASI campaign the unit was flown in both spatial and spectral modes. The spatial mode band set was chosen in order to measure, amongst other factors, the FLH with integrated narrow (6nm) channels centred on 666.05nm (ch.5), 682.05nm (ch.6) and 712.35nm (ch.7). Channels 5 and 7 give the background radiance levels whilst channel 6 gives the fluorescence peak. A simple algorithm, originally developed by Gower and Borstad (1990) can be used to determine chlorophyll in all situations of the form:

$$FLH = (R_6 - R_7) - \left(\frac{\lambda_6 - \lambda_7}{(\lambda_5 - \lambda_7) * (R_5 - R_7)} \right)$$

where Rn is the radiance value in channel n, and λ_n is the central wavelength of channel n. This equation was applied to the CASI spatial data set for Swanage Bay and the result is shown in figure 3.27. For cross reference the RGB equivalent image, using the CASI, is given in figure 3.28.

Two things are immediately evident. First the CASI RGB image provides more dynamic spatial data than the ATM (figure 3.1), which itself was still good. This is due to the fact that the CASI measures radiances to 12-bits in comparison to the ATM's 8-bits. Second the chlorophyll measurements compare well with the ATM estimates, which in turn compared well with the seatruth data. However the equation has not depended on any external data. A direct comparison with the Vigilance data would be of limited value in this case, given that the CASI data were collected 13 days after the ships data. However the range of values, from 1.065 μg/l to the south (top of the image) to 11.1 μg/l to the north (bottom) in the Poole Bay plume compares well with the total range seen by the vessel. The algorithm used here applies just as well to the other CASI data, see for example data for Christchurch Bay, section 3.5.

In this example from Swanage Bay only part of the power of the CASI system has been used. The spatial data represents an integration of the spatial information to a higher accuracy and resolution than any other airborne system. But besides the colour data shown in figure 3.28 are 208 channels of information on the visible spectrum. An example of this data was shown in figure 3.26. These spectra theoretically contain a wealth of information on water quality but do require further and more detailed analysis.

The CASI data was late in arriving at Southampton and there have been a number of other delays in its processing. So far the use of CASI to provide the same information as the ATM and to meet the basic operational requirements of the NRA have been demonstrated. A more complete analysis of the NRA CASI data is still underway and a more complete picture will be available when the image processing system containing the analyzed campaign data is delivered to NRA. What follows is still at a research level and studies the potentials of the full data set.

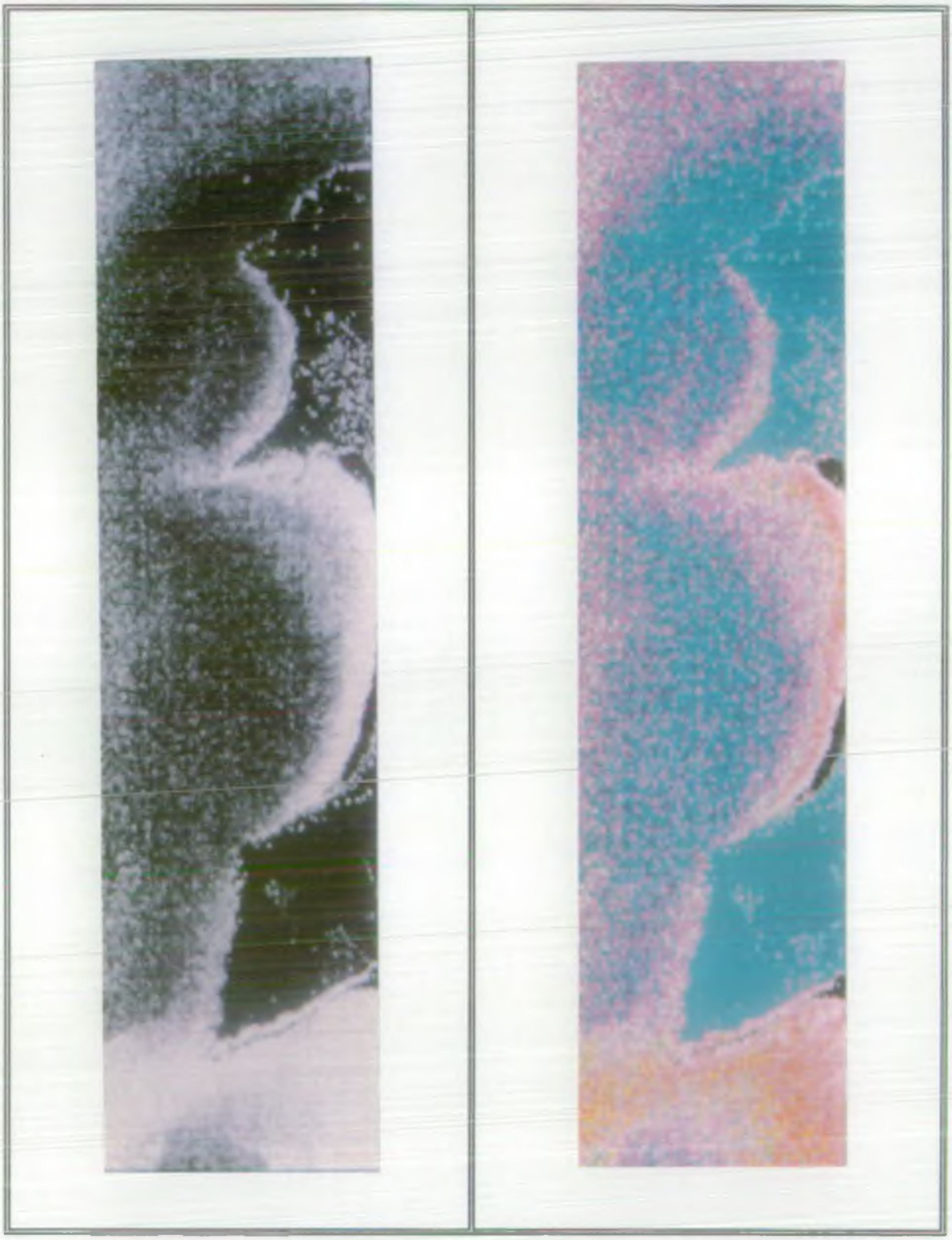


Figure 3.27 Chlorophyll calculated from the CASI data for Swanage Bay using the FLH technique. The right hand image is a colour density sliced image of the left hand grey scale making interpretation easier.

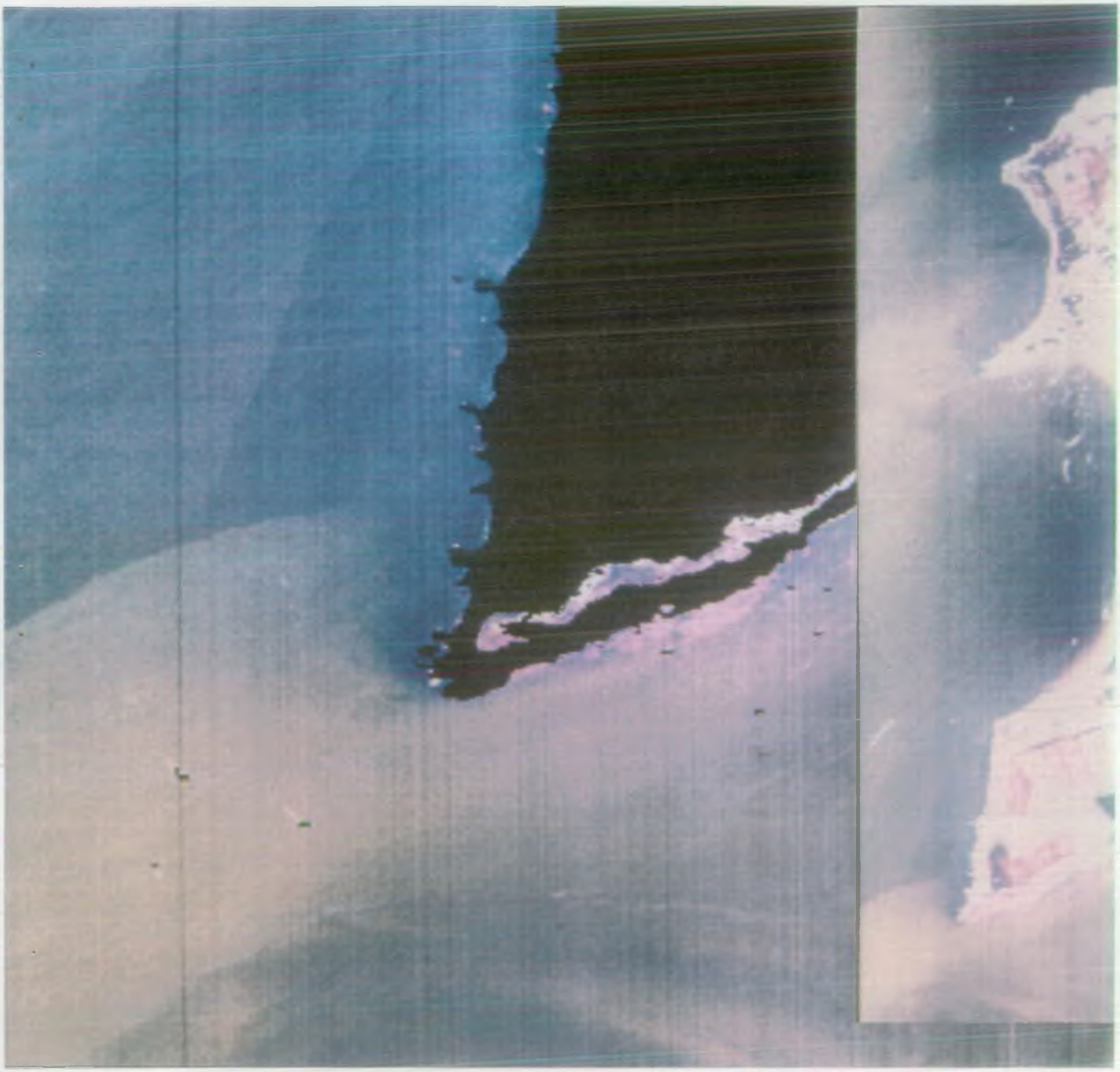


Figure 3.28 Colour composite CASI image of Swanage Bay.

3.4 CASI - the operational future.

The analysis of remotely sensed optical data that is spectrally detailed is still in its infancy, but progress is good. One of the limitations to date has been (a) the operational urgency for answers from the research and (b) a sufficiently large data set to work on. The NRA programme has provided both over the past few months.

The main problem to overcome is in defining what the spectra actually mean and what characteristic spectra are produced by the multivariate water quality constituents. Studies over land have been more straightforward. Libraries of typical spectra, for different soil mineralogies, for grasslands, forestry, crop types and health etc. have been established in terrestrial applications for some years now. However in the sea the situation is complicated by the translucency of the water. Land targets offered a solid body of radiating material, whereas water targets present a combination of signals from different levels in the water column. This not only leads to complications as to where the signal is actually coming from, but also the way in which different spectral signals from different reflectors/emitters combine. It cannot be assumed that given a typical characteristic spectra for both clay and chalk suspensions that the spectra would combine linearly when both materials are in the water together. Because of multiple scattering of light photons in the water one needs to consider photons scattered by clay only, by chalk only, by water, by chalk and clay, by chalk and water etc. Very much a non linear problem.

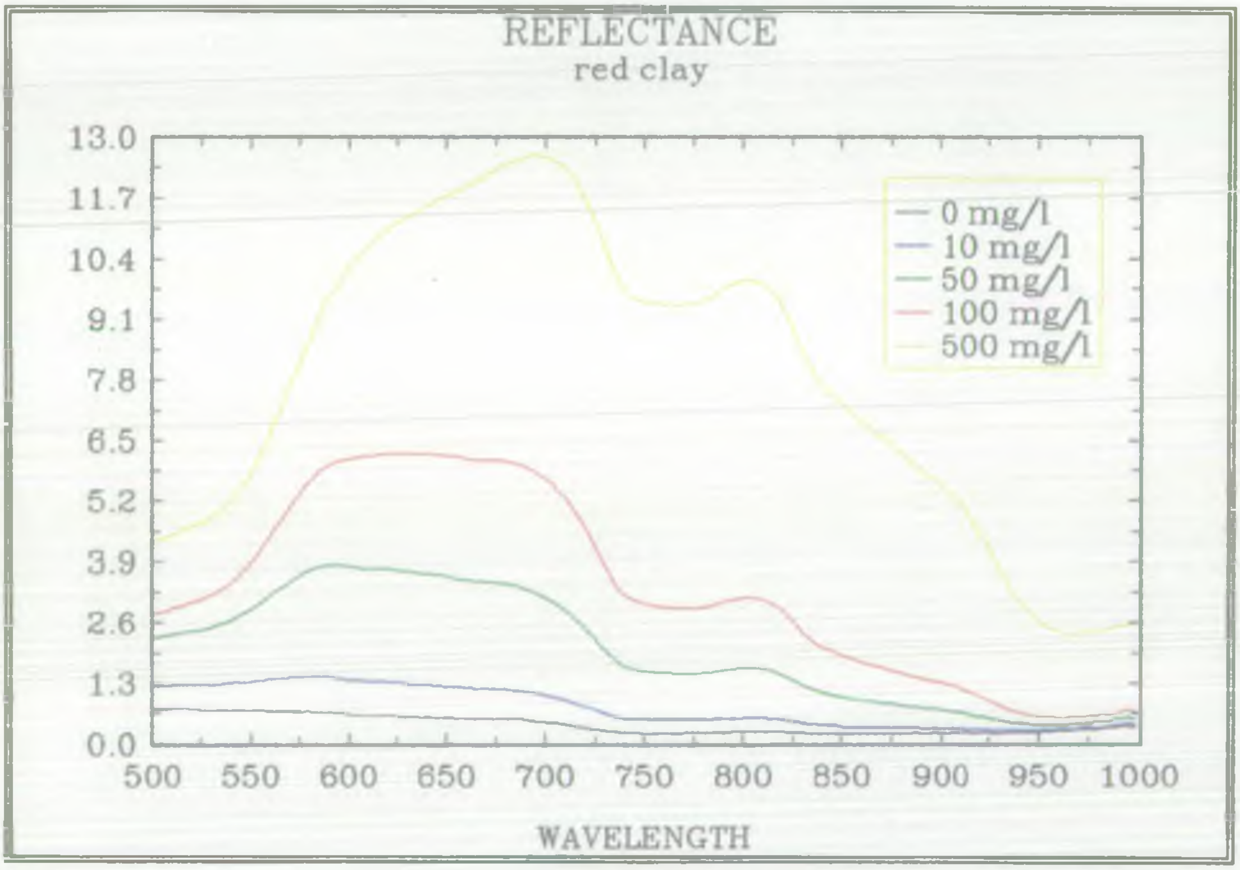


Figure 3.29 Laboratory experiment studying the effects of concentration and particle depth on spectra.

Two programs of research have begun at Southampton to investigate these problems over the past year. The first is part funded by the NRA and consists of a series of laboratory experiments to analyze spectra. The second is carried out in conjunction with SD-Scicon and utilizes neural network technology to *characterize* spectral shapes for rapid identification of specific water types. Possible applications could include identify the characteristics of an outfall quality and measure the concentration of the pollutant over the surrounding area.

Results from both of these programs will be disseminated in the near future, but one interesting result to date is of relevance to the "but what depth is the signal coming from" question. Figure 3.29 illustrates an experiment run studying the effects of varying red clay concentrations in seawater. As one might expect the clay has a peak of reflectance in the red end of the visible spectrum, above 600nm, with increasing concentrations giving increased overall reflectance. A simple relationship between the integrated peak between 600nm and 700nm will provide a very accurate measure of concentration in this single population experiment. However, note how with increasing concentration there is also a shift of the peak to the red end of the spectrum. As higher concentrations are attained so the photons pass through less water before they are reflected back from the air/water interface. Pure seawater attenuates red light but passes blue light. Thus, as the photons are passing through less water so less red light is absorbed. This shift in the spectrum, whilst still maintaining the peak and overall shape provides an insight as to the problem of where the signal originates.

3.5 Results from selected sites of special interest

In this final results section the areas of special interest that have not already been covered in earlier sections are briefly discussed. The applications of the data and the relative importance of additional thermal data, of spectral detail and of good radiometric detail, are also expanded upon.

One of the sites of interest to the South West regional NRA was an outfall at Newquay. Figure 3.30 shows a section of both the colour composite and thermal image of the area with the outfall at the marked point *A*. The signature of the outfall itself is barely distinguishable and certainly nothing like as pronounced as that in Pevensey Bay (section 3.3.2). However it is just possible to see a sweep of lighter coloured water coming away from the outfall, around the headland and to the right hand side of the image. This is considerably clearer on the original computer screen and begins to highlight one problem that can occur in extreme cases - that the mechanisms for producing photographic hardcopy from the image processor are never quite as good as the image processor itself. However, what can be seen more clearly is a still brighter and warmer (dark is cold on the thermal data) patch of water to the right of the peninsular and separating the outfall water mass from the shore, which is just off the top of the picture shown. The implication here is that at this particular state of the tide, and under the wind conditions prevailing at the time, although the outfall water mass did maintain its identity around the headland it did not impinge on the beaches beyond the headland itself.

Figures 3.31 and 3.32 show ATM and CASI colour composites of the Exe estuary respectively. The ATM image shows a number of features quite clearly, in particular the shallow bank off Exmouth (*A*). The CASI image was taken at the same tidal state but notice the improved detail. Both images show the main navigation channels through the bank but

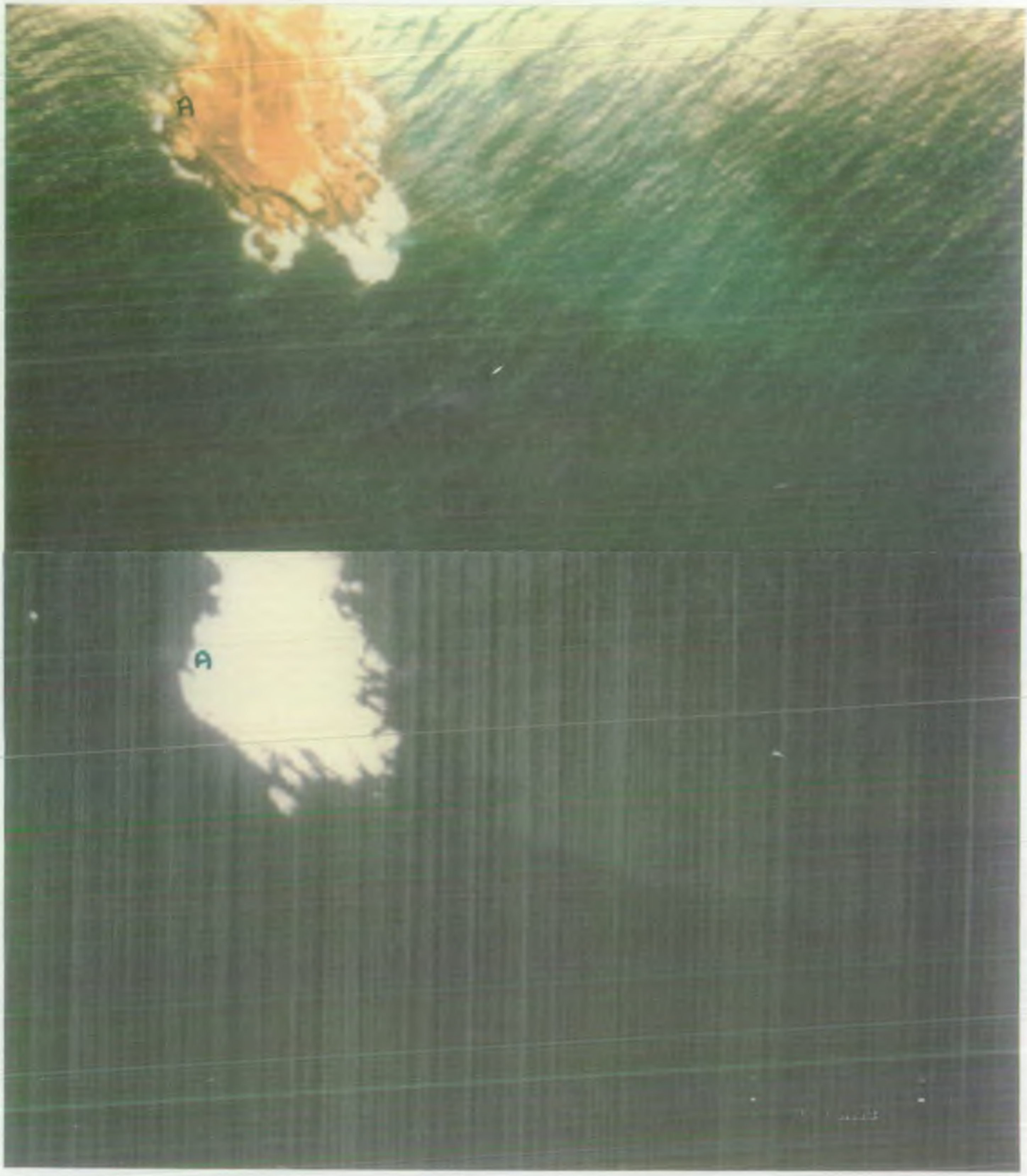


Figure 3.30 ATM colour composite (top) and thermal (bottom) images of Newquay. The patterns of the outfall are just distinguishable.

Figure 3.31 ATM colour composite of the mouth of the river Exe. North is to the top of the image. Features marked are described in the text.

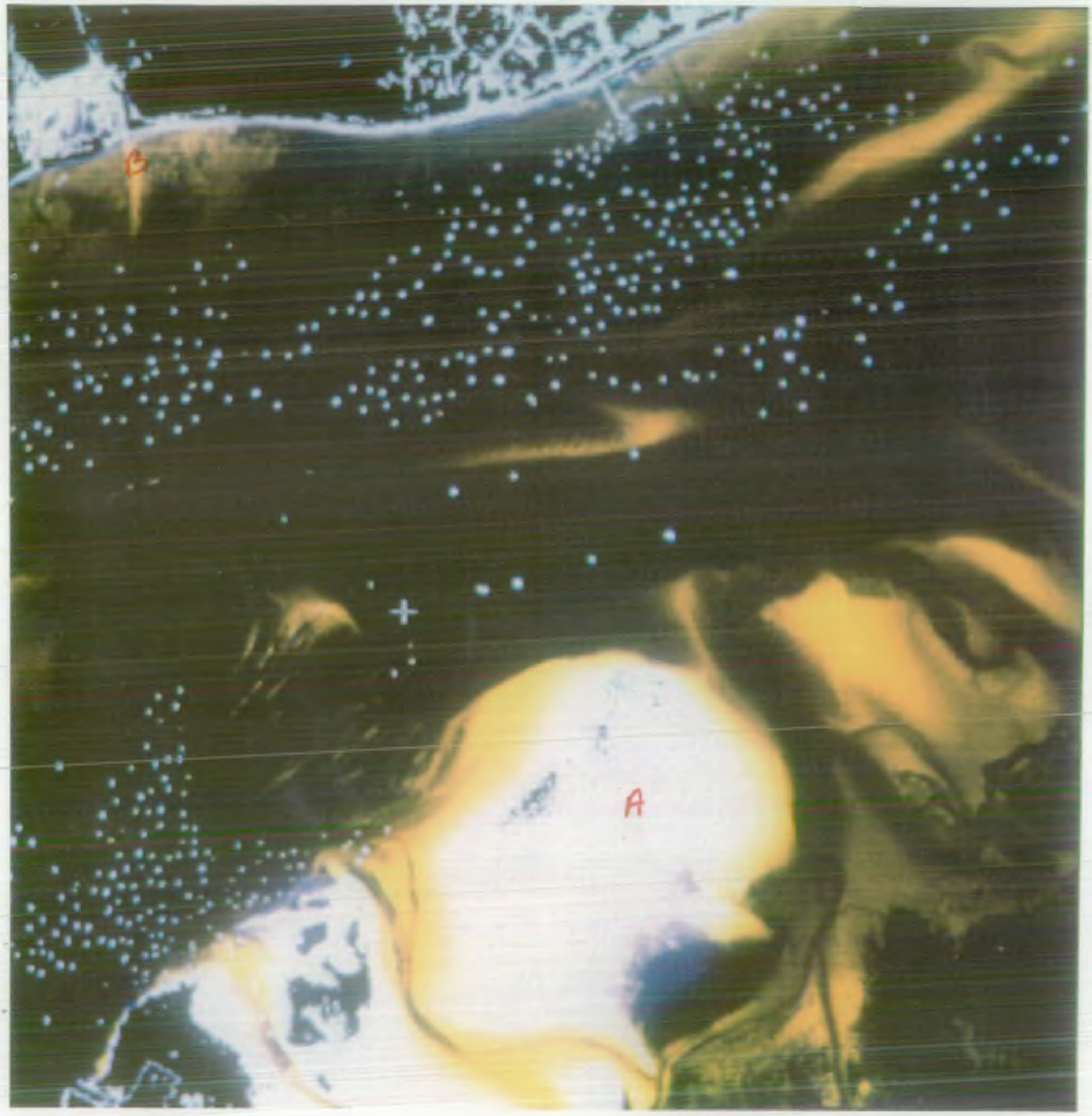


Figure 3.32 CASI colour composite of the mouth of the Exe. The orientation of the image is the same as for figure 3.31, with the same features marked.

the CASI shows substantially more detail of the submerged banks to the north east of the main bank. At present one has to use local knowledge to confirm that these features are submerged banks and not water column sediments, however the studies outlined in section 3.4 will soon allow such discrimination to be carried out autonomously and without detailed priori knowledge. However, as it stands, over a period of time, the images allow the operational scientist to both chart the current positions of navigable channels through transient banks such as these and to study the dynamics of sand bank movements. In addition on these images there is a small input of water from a creek to the north (*B*). This is barely noticed on the ATM image but is quite clear on the CASI, and in this case there is enough information within the spectral data to at least provide a first estimate of what the prime input is. This part of the study is still underway and will be included in the final computer analysis provided to the NRA.

The use of colour data to map certain topographic features can also be seen in Poole Harbour (figure 3.33). Here the ridge extending away from Shell Bay (*A*) can clearly be seen as can the small sandbanks at the mouth of the Harbour entrance. However in addition a strong region of turbulence and turbidity can be seen in the central-right part of the image, to the seaward side of the mouth, over banks of about 5m depth. In the central part of the image the deep channels between Studland (bottom) and Brownsea Island (top-left) can be seen. In spite of the high degree of bottom reflection in this area, by studying the ratios of the various ATM channels and applying the local algorithm developed for the area (3.3) the general levels of chlorophyll have been determined and are seen to be the likely source of the raised chlorophyll levels seen in Swanage Bay (figure 3.9). The high reflectivity structure at the top of the image is cloud.

The data gathered for Christchurch Harbour included both ATM (figure 3.34) and CASI (figure 3.35). As with the Exe study, bathometric features such as the main submerged sandbank, just inside the harbour entrance and the partially submerged banks just outside are clearly seen on both, but more so on the CASI image. Here however the thermal data proves to be essential in understanding the mixing zone of the output from Christchurch Harbour. The theory for the area is that the flow out of the harbour is channelled along the coast to the east by the submerged banks on the approaches to the narrows. This is important not only on any potential impact on the densely populated tourist beaches along this coast but also on coastal erosion which has given cause for concern for some years in this area. The ATM colour data does give some indication that some water may in fact pass over the shallows, through gaps in the bank, and hence directly south of the mouth or narrows. The CASI data shows this more clearly with increased reflectances along the coast of Hengistbury Head (left of narrows). It is not immediately clear from the CASI data however as to whether the increased reflectance is the mixing of water from Christchurch to the west or local resuspension of particulate matter.

The thermal data makes the situation clear. The warmer harbour water exits the narrows to mix with the cooler seawater. The water divides evenly along the coast to the east and through the banks to the south. Only the outer most bank is exposed and the lee of the bank can be seen clearly in the data. This billowing plume to the south merges again with the eastward coastal plume beyond the lee of the exposed bank and also spreads, in a diluted mass westwards to culminate in a small headland eddy, seen clearly on both the ATM thermal as well as the CASI, at the southern point (the bottom of the images). Thus although

Figure 3.33 ATM colour composite of the entrance to Poole Harbour. North is to the top of the image.

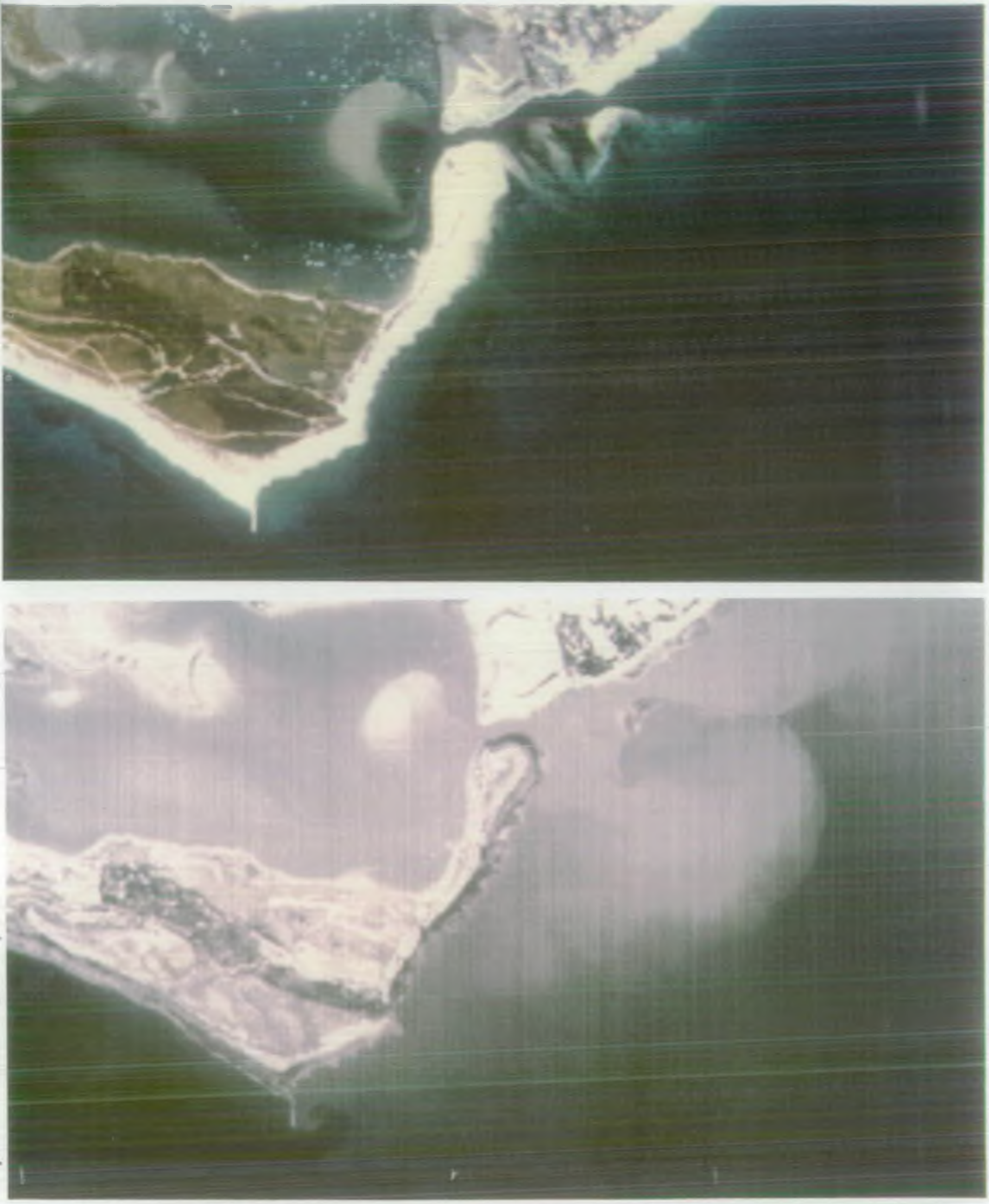


Figure 3.34 ATM colour composite (top) and thermal (bottom) images of Christchurch Harbour. Features marked are discussed in the text.

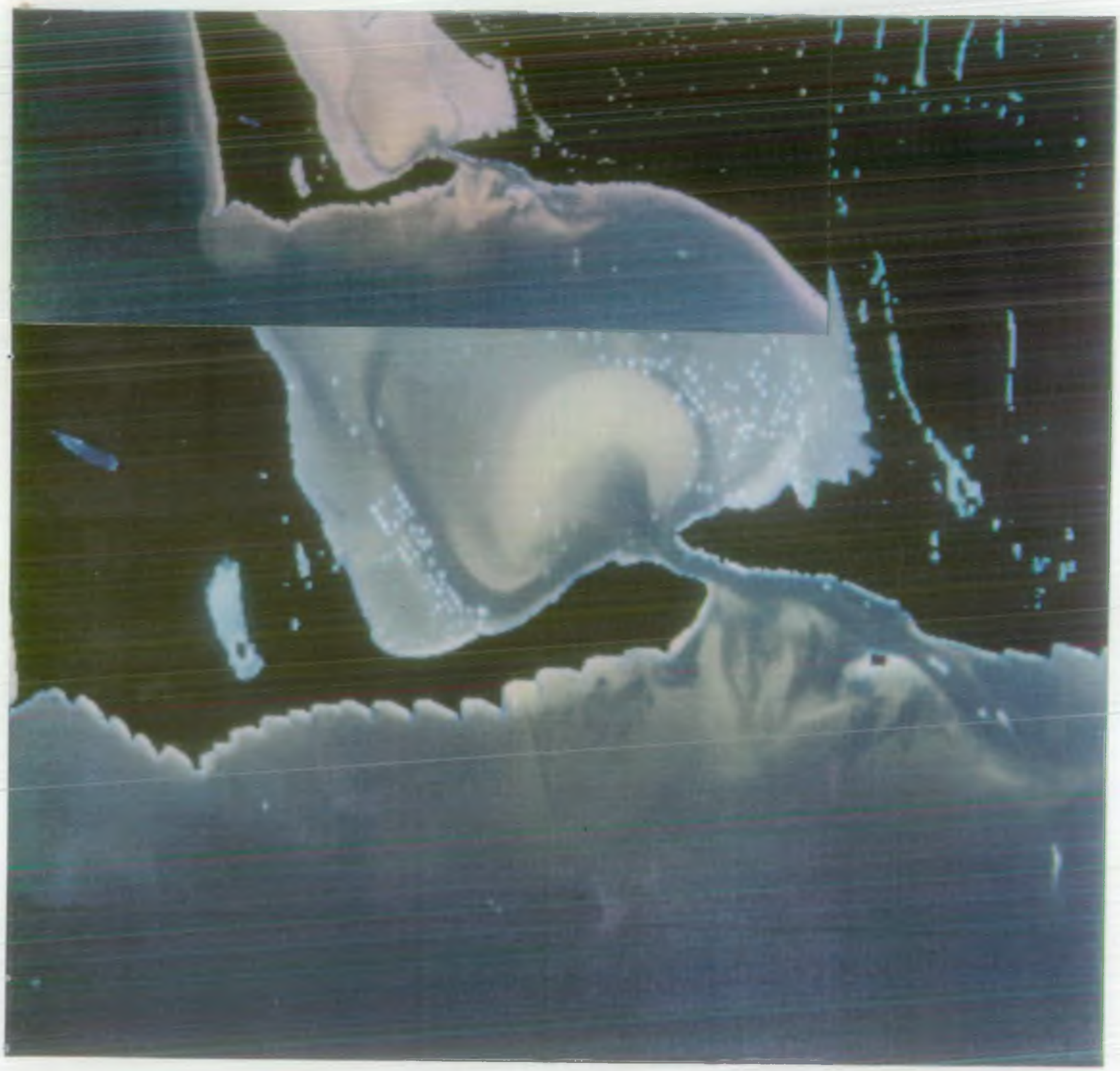


Figure 3.35 CASI colour composite image of Christchurch Harbour, with overview inset. The orientation and features marked correspond to those of figure 3.34.

some of the additional material seen in the CASI data along Hengistbury Head may be resuspended material, a certain amount will also have originated recently from the harbour - recently otherwise the thermal signature would have gone. It would be interesting to monitor the region over a long period to see whether the changes in the banks due to tidal erosion/deposition and storm events change the path and mixing characteristics of the harbours output. It may also help to decide whether artificial removal (or build up) of the banks may assist in solving the local coastal erosion problems.

The study of Southampton Water highlighted another mixing question; does shipping traffic have an impact on estuarine mixing? Figure 3.36 shows the ATM colour composite image of a small section of the Solent and Southampton Water at the point where the river Hamble joins Southampton Water. Fawley oil refinery is seen to the north-west (top) of the image. The Hamble Spit is very clear as are the mud flats and creeks along the Fawley shore. The tide is on the flood and so no specific input from the Hamble would be seen. However the resuspension and transport of material northwards from the Hamble Spit is clearly seen. The most interesting feature though is the variability over the mid-channel of Southampton Water. The same spatial structure can be seen in the thermal data and is due to the shipping traffic passing up and down this busy water way. Although the size of a vessel compared to the total size of the waterway is small, the fact that the vessel disturbances are so persistent and extensive (a study of the full flight line from the northern section of Southampton Docks to the Isle of Wight has enabled the tracks to be traced to specific ships in a number of cases) means that there must be a significant contribution to mixing from shipping in this area. In fact some mixing can even be seen to be taking place in the tidal wake of the vessels moored on the Fawley jetty.

The Fawley mud flats and marshes are also seen clearly on this image and a number of studies of the health of intertidal zones and marshlands using airborne remote sensed data have been carried out to some success (see for example past NERC airborne workshop proceedings). However, such studies are beyond the scope of the present work.

The final image highlighted for a brief study was that for the Parrett estuary. The ATM thermal data for the estuary is shown in figure 3.37. It illustrates clearly the rich spatial information on eddy structure that remote sensing can provide the scientist. In this case, although there was structure on the colour data, the clouds seen as black to the left hand side of the image, cast a large shadow over the meander in the estuary masking some of the detail. Although thermal signals are as effected by cloud obscuring the view in the same way as the visible signals, there are not problems of shadows. In addition, in this case a large proportion of the image was lost due to sunglint; again the thermal data is not influences by sunglint in quite the same way.

Figure 3.36 ATM colour composite of Southampton Water. The river Hamble can be seen to the left of the image with the Fawley oil refinery to the top (north) left.

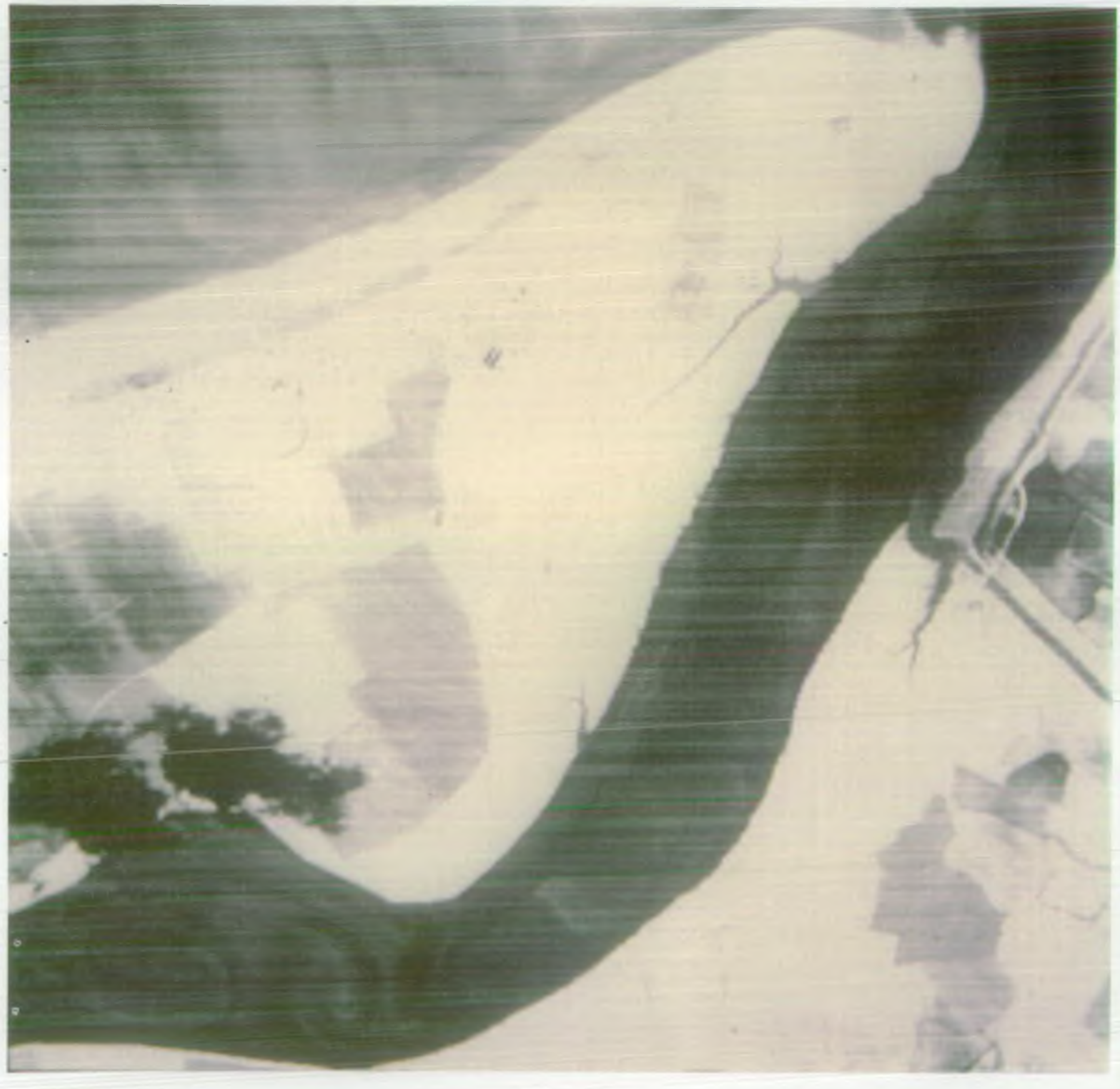


Figure 3.37 ATM thermal image of the river Parrett, flowing into Burnham-on-sea. North is to the top right of the image.

4 CONCLUSIONS

The purpose of the project has been fulfilled. As a pilot study to investigate the operational feasibility of using remotely sensed data from an aircraft to provide water quality information the case has been proven. The south coast of Britain was successfully covered in a period of eight days during a period of average cloud cover for the UK. To fly the full extent of the coast of England and Wales in a season would be relatively straightforward. There would be odd stretches of coastline that may not be flown every single season each year and some lines may be flown at less than perfect conditions, but over a period of years a spatial and temporally detailed archive of coastal water quality would be built up. This data set would not only enable the average scenario to be established, but also enable studies to be made of long term changes and to highlight short term changes and potential problems for operational control.

The system also has a role beyond routine monitoring on a quarterly basis. Many features (natural and anthropogenic) would benefit from more detailed studies, hourly over a tidal cycle or monthly say. In such cases a permanent system could fly such sites in addition to the routine work. Finally there is a role for such a unit in risk assessment and in incident management; in the Cornish Weale Jane incident correctly predicted by NRA, the mixing of contaminated water into the estuary and eventually into the sea could have been monitored very successfully using an imaging spectrometer.

Having demonstrated the feasibility, the applicability of the technique was then studied. Using even a simple Daedelus ATM scanner, given reasonable quasi-synoptic ground data from a vessel, it is possible to determine both chlorophyll and SPM to a satisfactory accuracy. It has to be said that the exact precision is still uncertain, but that this uncertainty is more due to the limits of accuracy of traditional ground truth measurements than the aircraft sensors.

Even more useful is the data from the CASI imaging spectrometer. Not only does the system provide more accurate radiometric information (12 bits), more detailed spectral information (essential if the FLH technique of chlorophyll determination is to be used as opposed to the green/blue ratios) but it is also cheaper than the ATM. It has a further operational advantage; there are no complex moving parts, such as scan mirrors, and makes use of the most recent tried and tested technology leading to a more reliable and compact instrument that requires less power in the aircraft to operate.

With the CASI it is possible to obtain data on chlorophyll and some SPM information without the necessity of supporting ship data. Thus, even if the vessel cannot operate due to sea conditions in winter say, the aircraft can still collect valuable data to maintain a full years coverage of the coastline. However, to gain full benefit from the system sea data will be important.

The one drawback of the CASI is the lack of a thermal channel. As has been shown thermal data is both a useful complement to, and in some cases offers a new perspective over the CASI. Similarly there are features and parameters for which the colour data is essential. Work is being carried out between Itres in Canada (CASI) and HGH in France to add a thermal capability to the CASI.

The usefulness of direct photography should also not be forgotten (for example in the Sharkham Point dye release experiment) as it also offers a different perspective which is often easier to analyze rapidly, even if specific water quality parameters cannot be obtained from photos.

A recommended system would therefore comprise a CASI imaging spectrometer with a thermal scanner and some means of obtaining colour photos. Such a system can achieve a number of operational tasks now. Other tasks are still the subject of ongoing research whilst some are not obtainable.

The system *will not* replace ships or predictive models. It *will* however complement them, providing an improved spatial perspective over ship data and act as an input of real data to models. It *will* provide data at times and in conditions when the ship may not be able to operate (windy sunny days are more common than most people realise) or when models are not operable. It *will not* provide data in patchy cloud or poor visibility conditions.

The system *will not* give information about depth variability (although data from Swanage did provide an insight to the depth variability of temperature), this is only possible by ships vertical profiling. It *will not* provide measurements of salinity or dissolved materials directly, unless they have a specific colour signature, as in the case of dissolved humic substances or Gelbstof. It *will* provide measurements of chlorophyll and SPM, independently of detailed ship measurements (note in this case transmission was actually used for the ATM calculations). It *will* provide detailed spatial patterns of mixing and flow, allowing ship data and model output to be put into a real spatial perspective. It *will* provide detailed maps of sea surface temperature and, where ships pass through an area, near surface variability.

The system *will soon* be capable of providing more detailed water quality information on items like sediment mineralogy, plankton population age/health and sewerage outfall constituents. It is hoped that initial applications on sediment typing and plankton dynamics will be operational during 1993. It *will eventually* provide a means of typing oil from spills, though whether any system will ever be able to do so 100% reliably in order that legal proceedings may be taken out against the culprit remains to be seen.

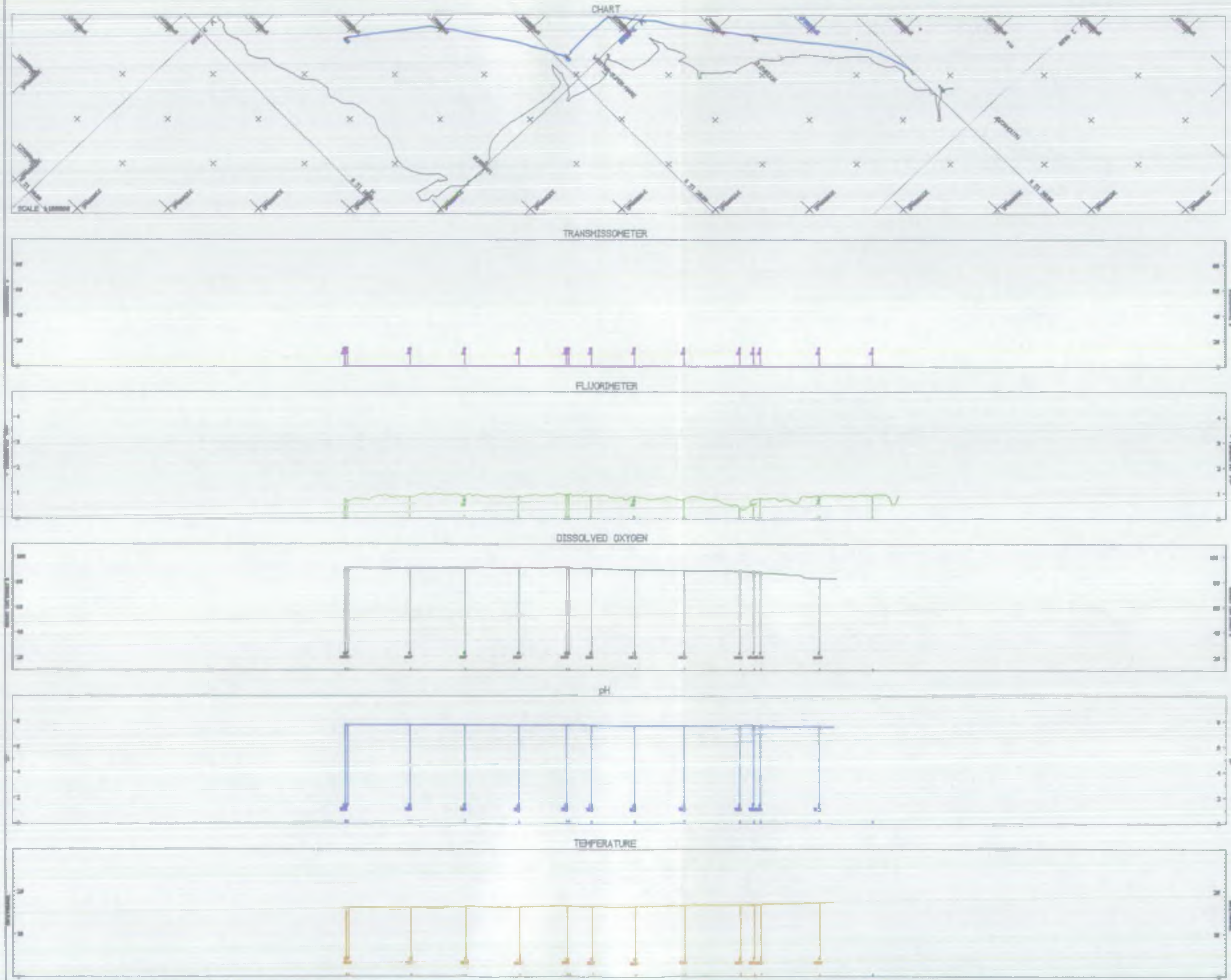
The system demonstrated during this project does not provide the panacea for coastal monitoring, far from it. But, it does provide the coastal scientist with eyes to view the coastal zone.

ACKNOWLEDGEMENTS

The authors of the report would like to thank the crew of the Vigilence, in particular Peter and Malcombe, for collection of the sea data. The aircraft data were from Global Earth Sciences Limited and we would like to thank them for the rapid turn around of data and for the perseverance of the air crew, G. Osborne, R. Cooper and R. Bouchet. Additional CASI data were made possible with thanks to NERC and in particular S. White and J. Cook. We would particularly like to thank R. Palmer for his assistance on computer programme development.

Finally we would like to thank NRA Wessex region and the faith of D. Palmer who provided us the opportunity to demonstrate the operational reality of airborne remote sensing.

APPENDIX A - DATA FROM THE VESSEL CAMPAIGN



NRA

CHEMICAL ANALYSIS
OF
SEA WATER SAMPLES
SOUTH COAST OF ENGLAND

NATIONAL RIVERS AUTHORITY

RESEARCH VESSEL VIGILANCE

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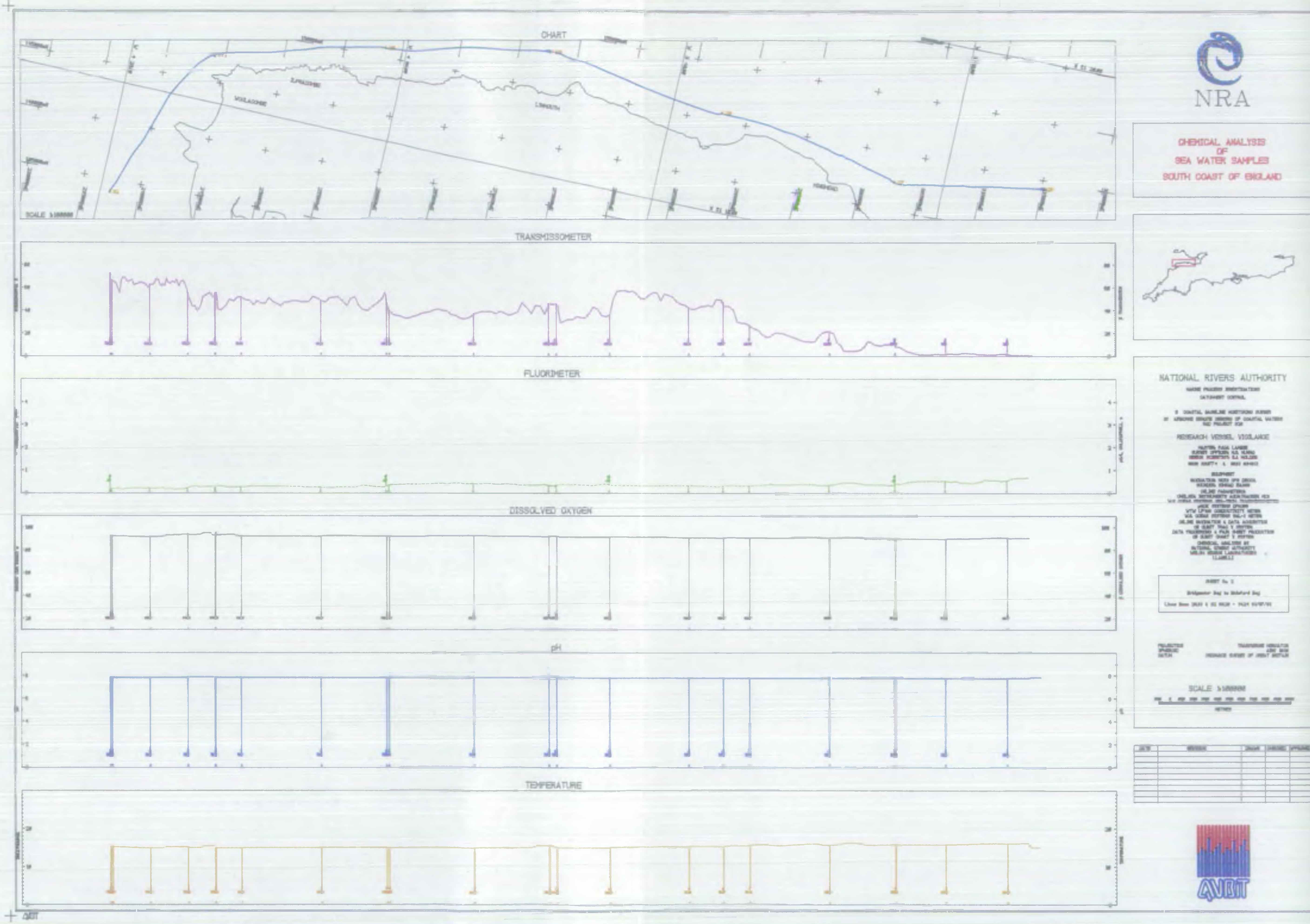
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FLUORIMETER
DISSOLVED OXYGEN
pH
TEMPERATURE
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CHEMICAL ANALYSIS
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SOUTH COAST OF ENGLAND
NATIONAL RIVERS AUTHORITY
RESEARCH VESSEL VIGILANCE
SCALE
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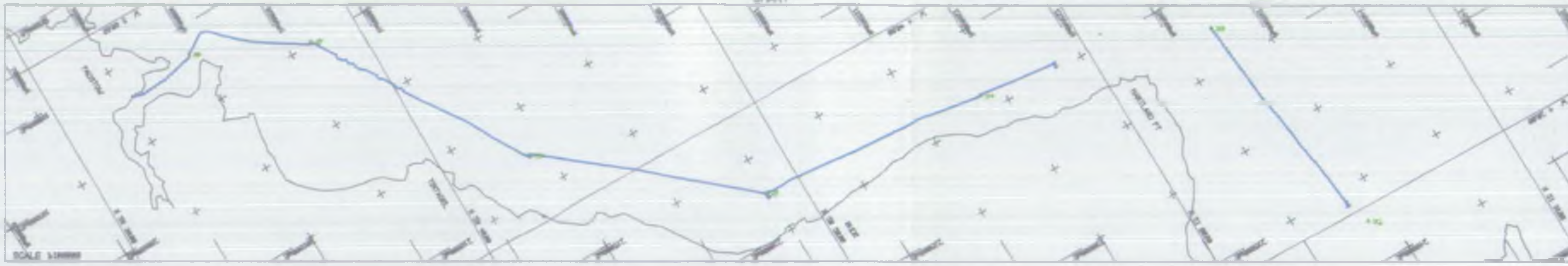
CHART



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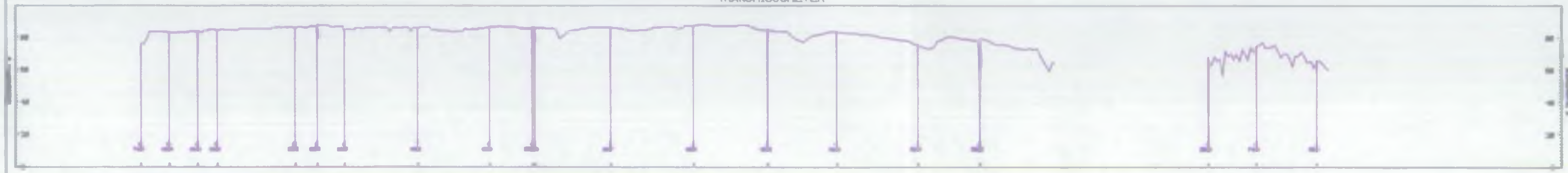

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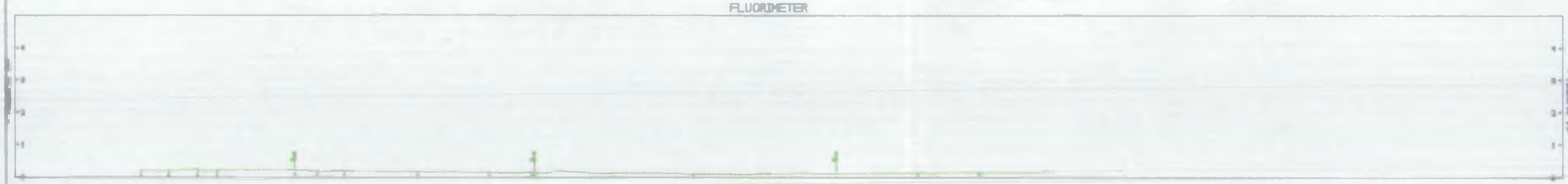

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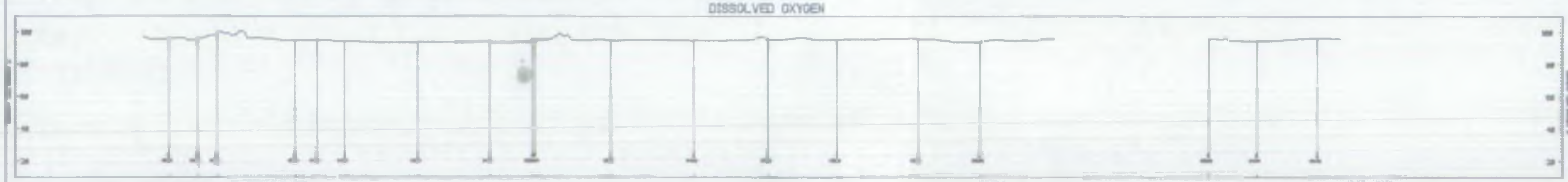

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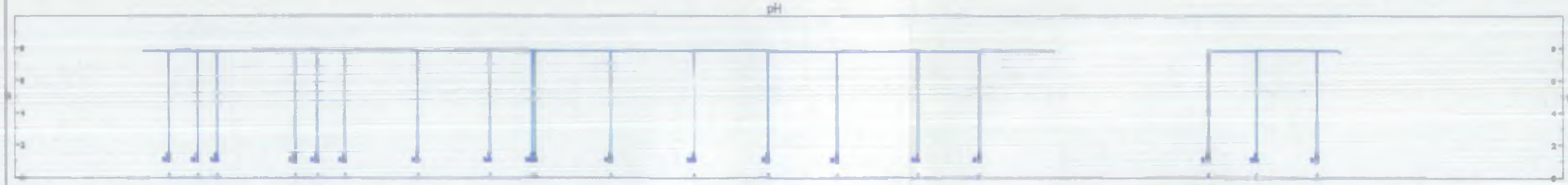

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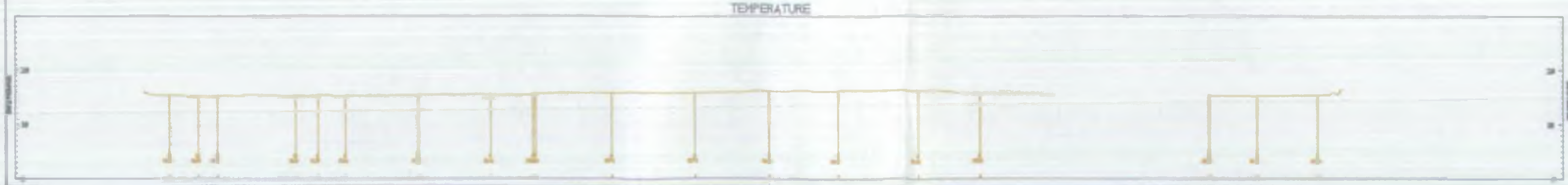

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CHEMICAL ANALYSIS
OF
SEA WATER SAMPLES
SOUTH COAST OF ENGLAND

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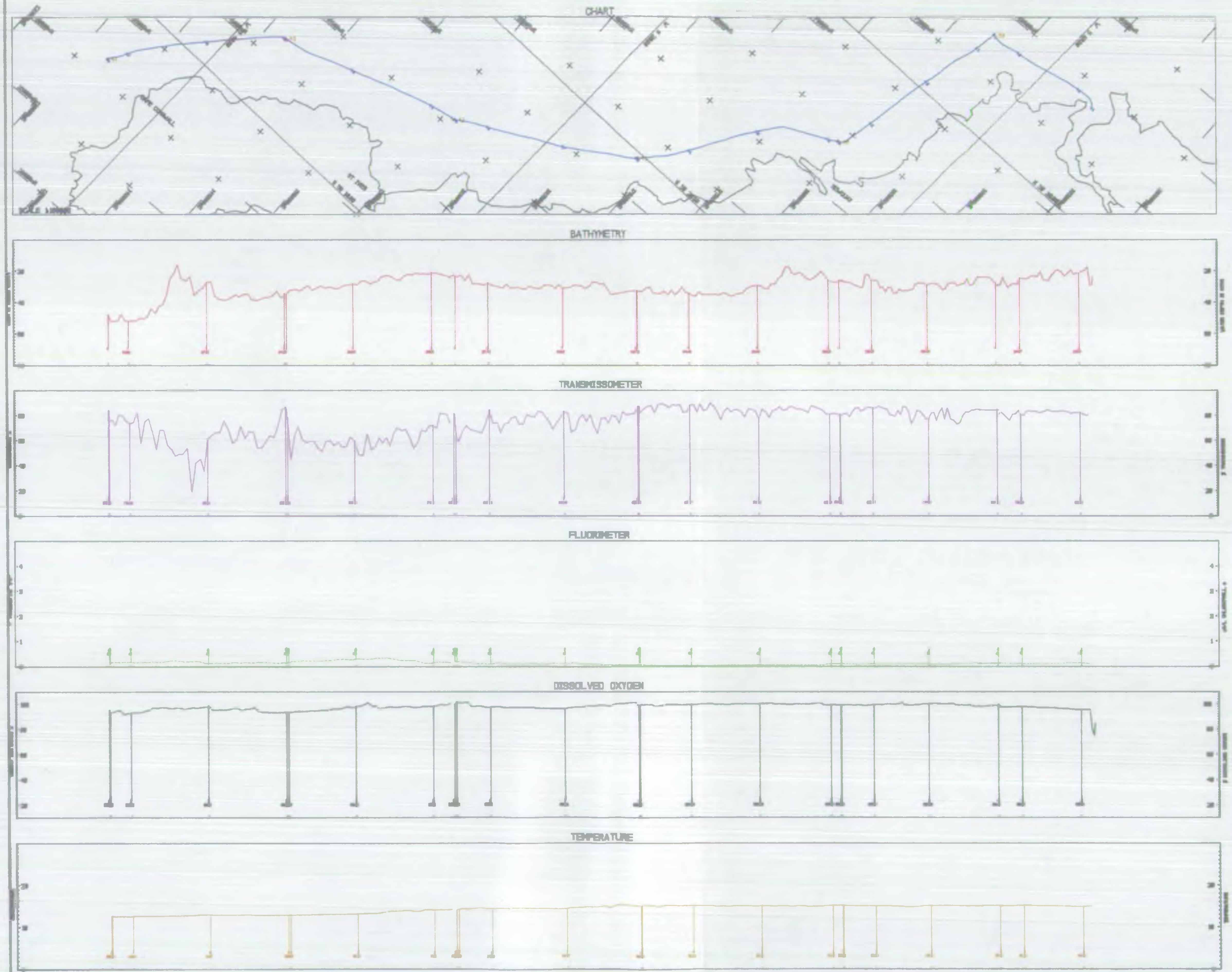

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CHEMICAL ANALYSIS
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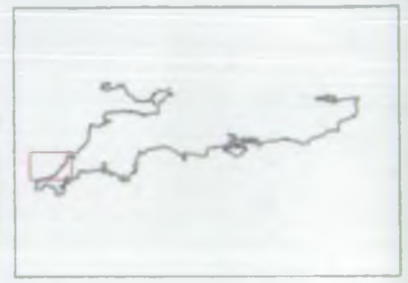

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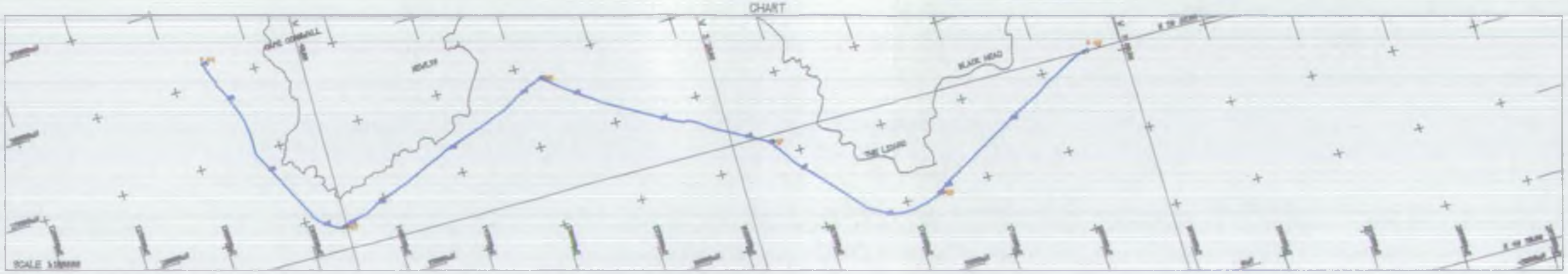

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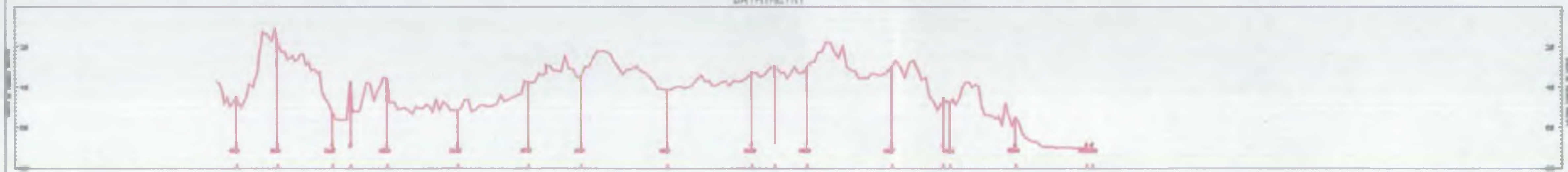

TRANSMISSOMETER

FLUORIMETER

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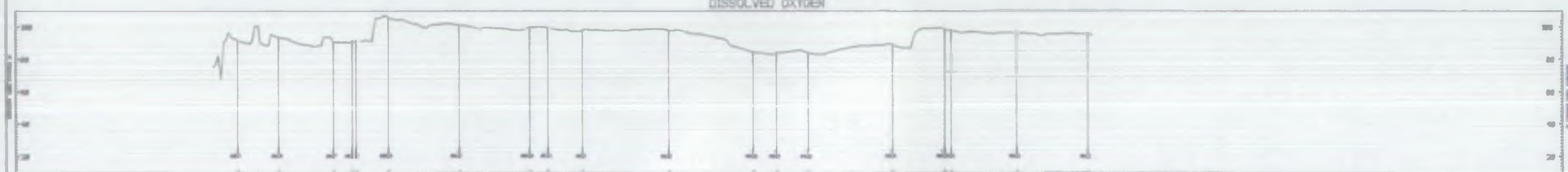

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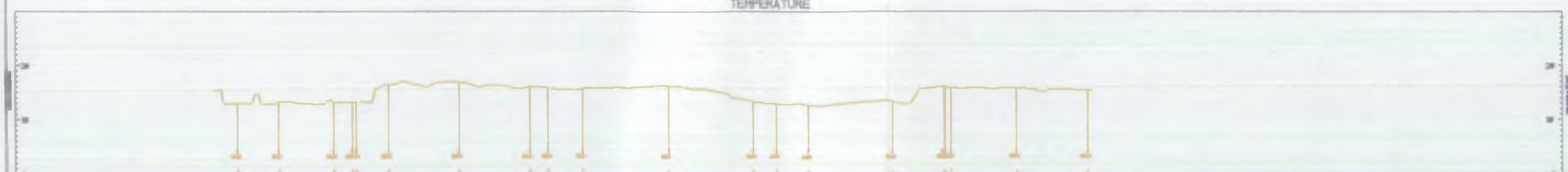

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CHEMICAL ANALYSIS
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SEA WATER SAMPLES
SOUTH COAST OF ENGLAND

NATIONAL RIVERS AUTHORITY

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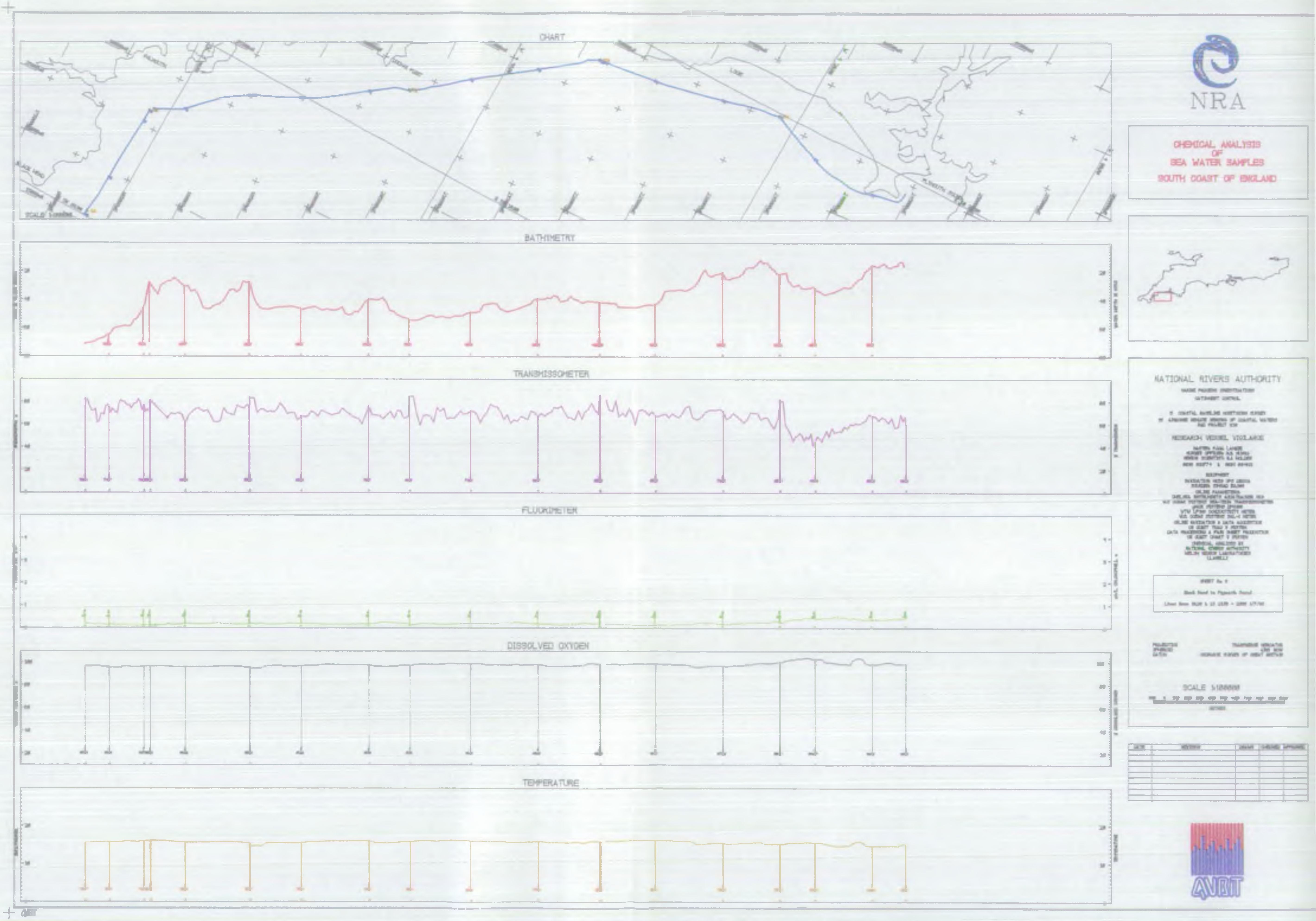

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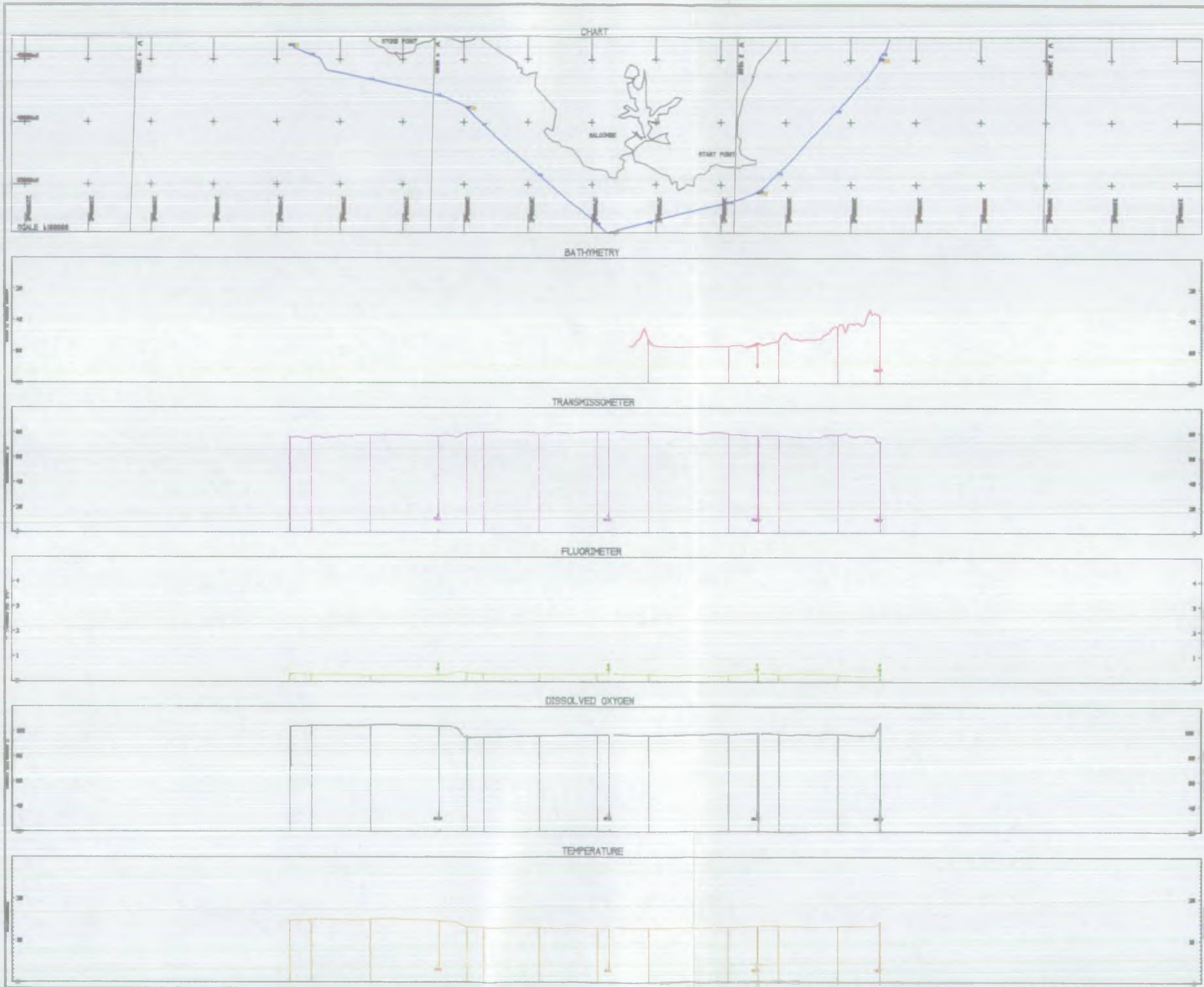

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CHEMICAL ANALYSIS
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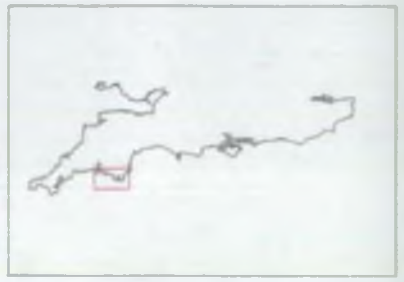

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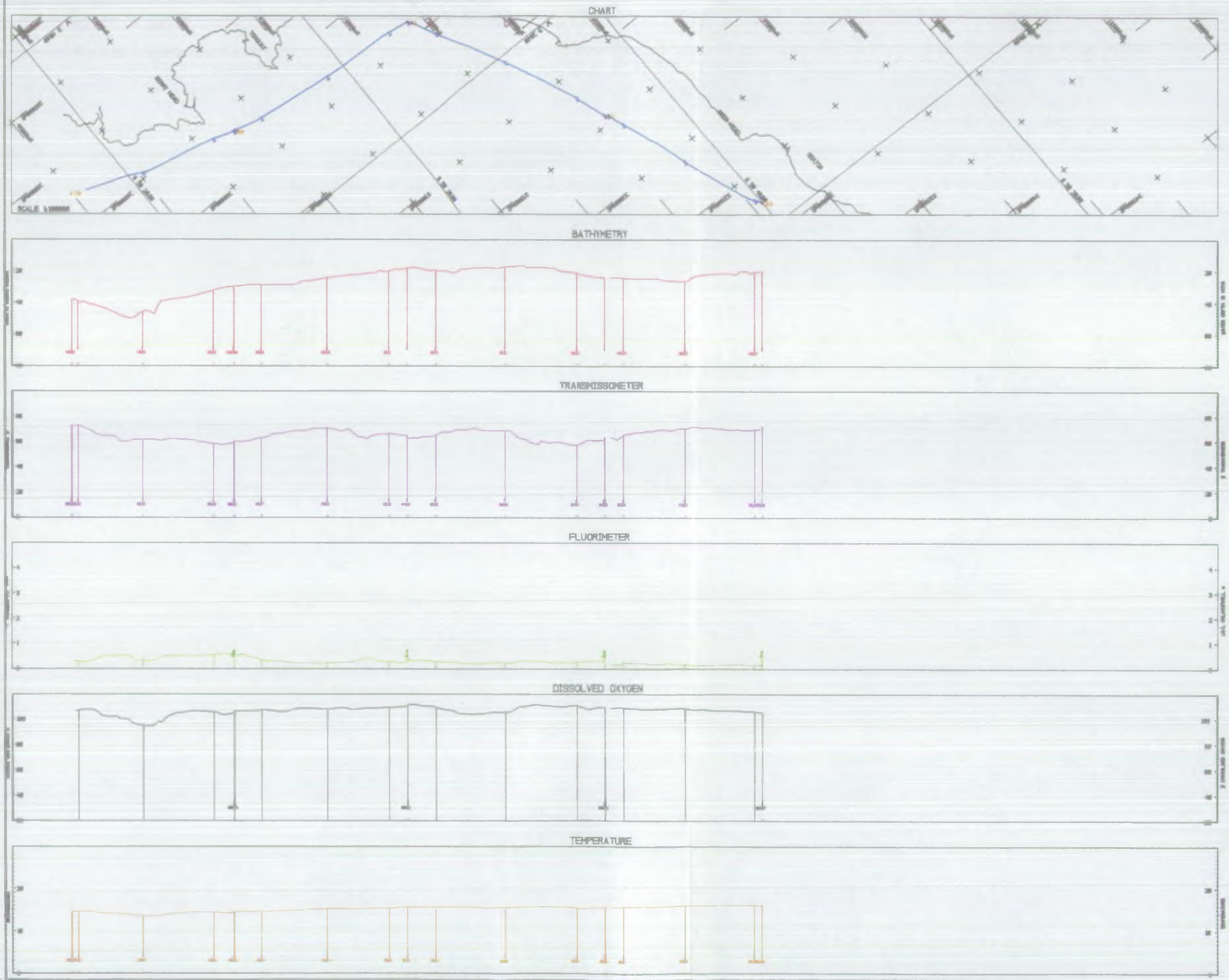

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SEA WATER SAMPLES
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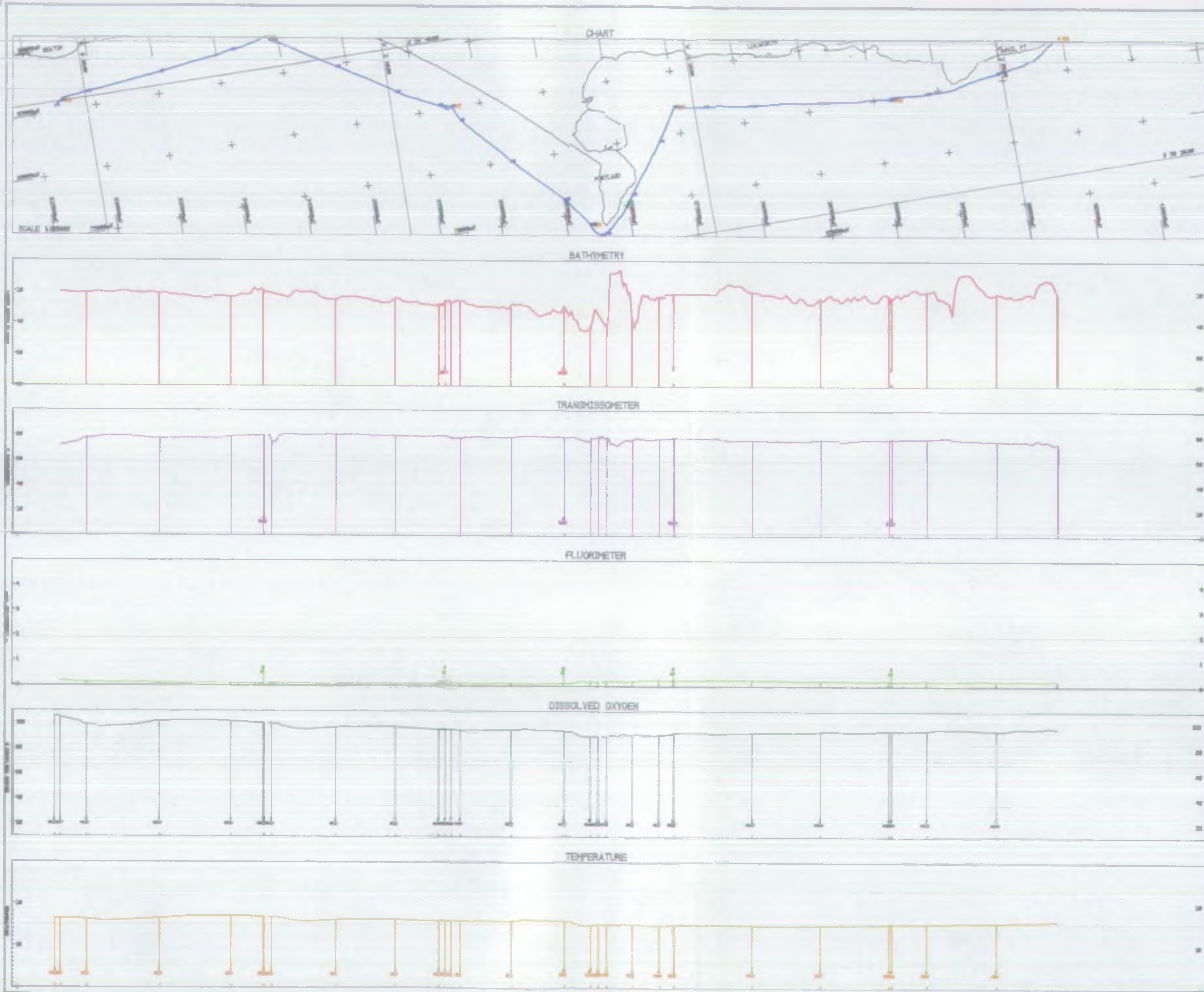

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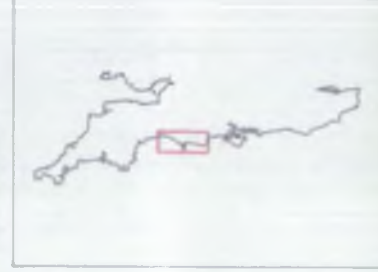

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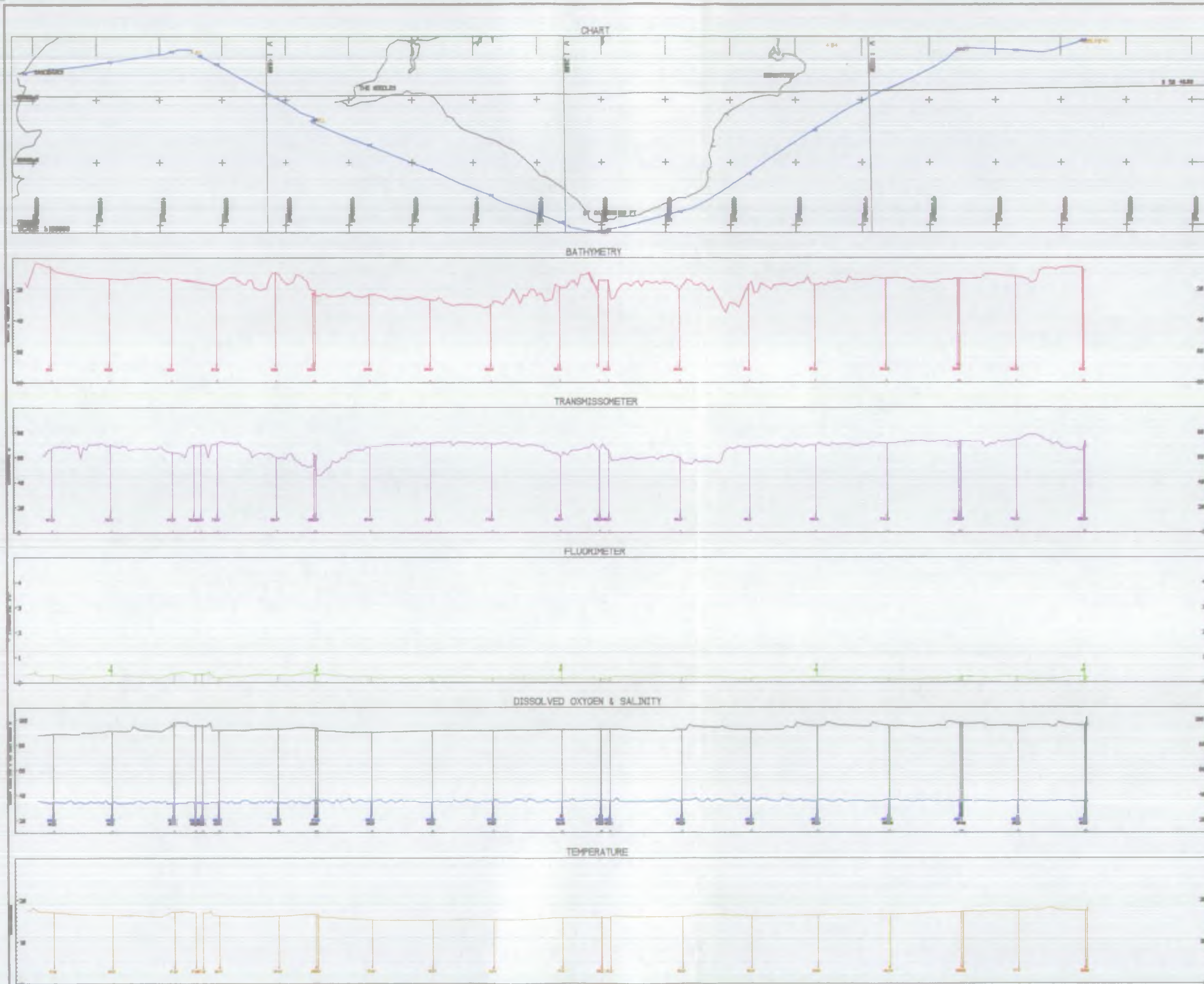

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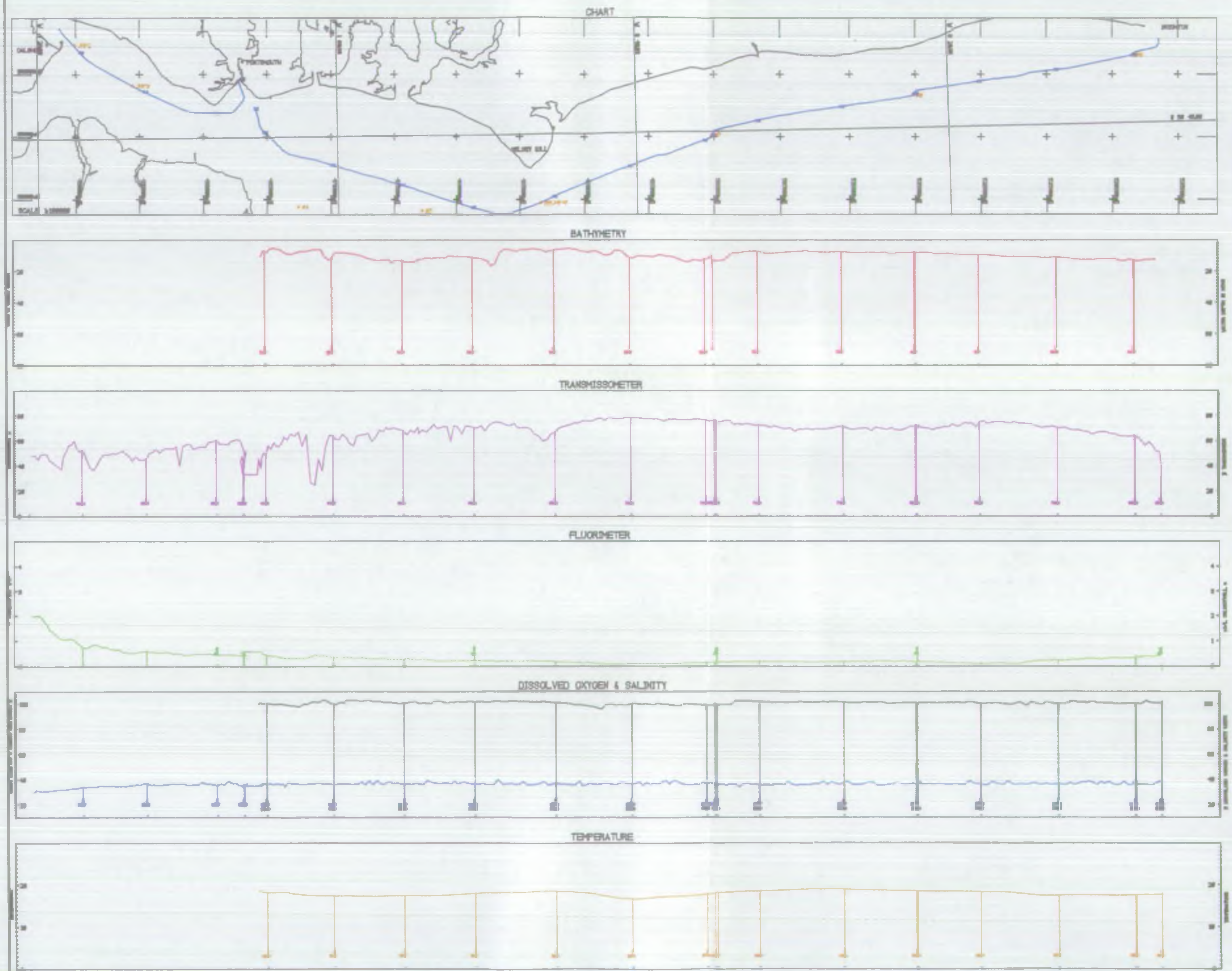

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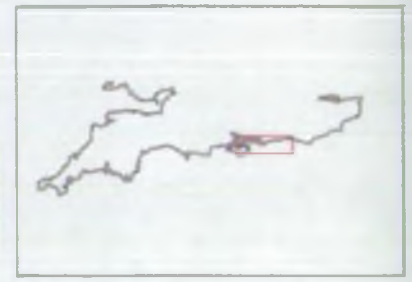

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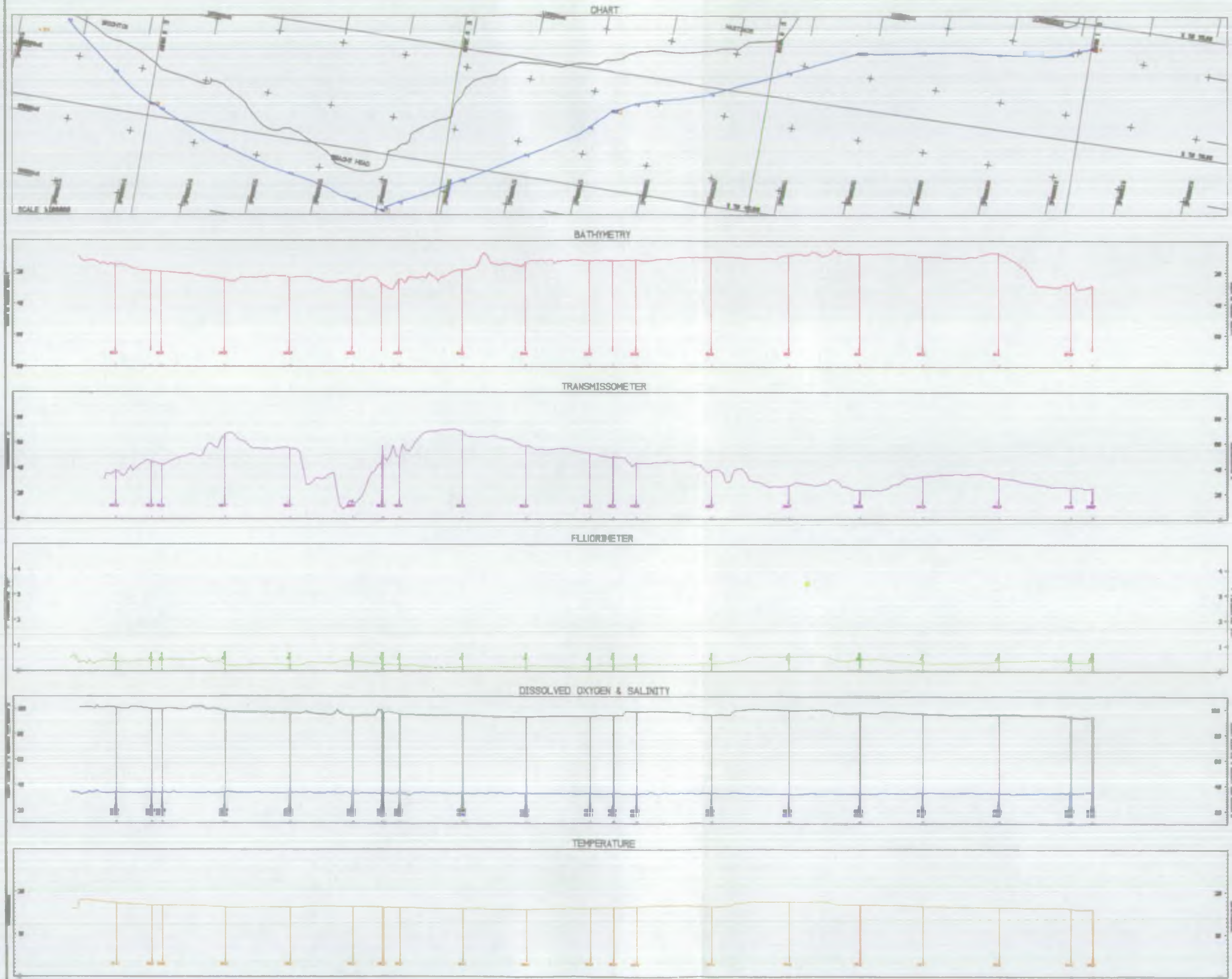

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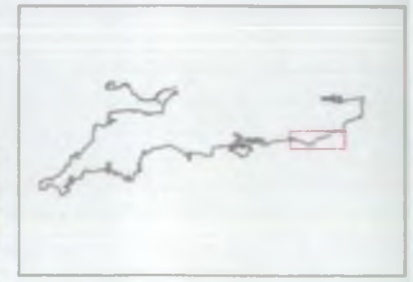

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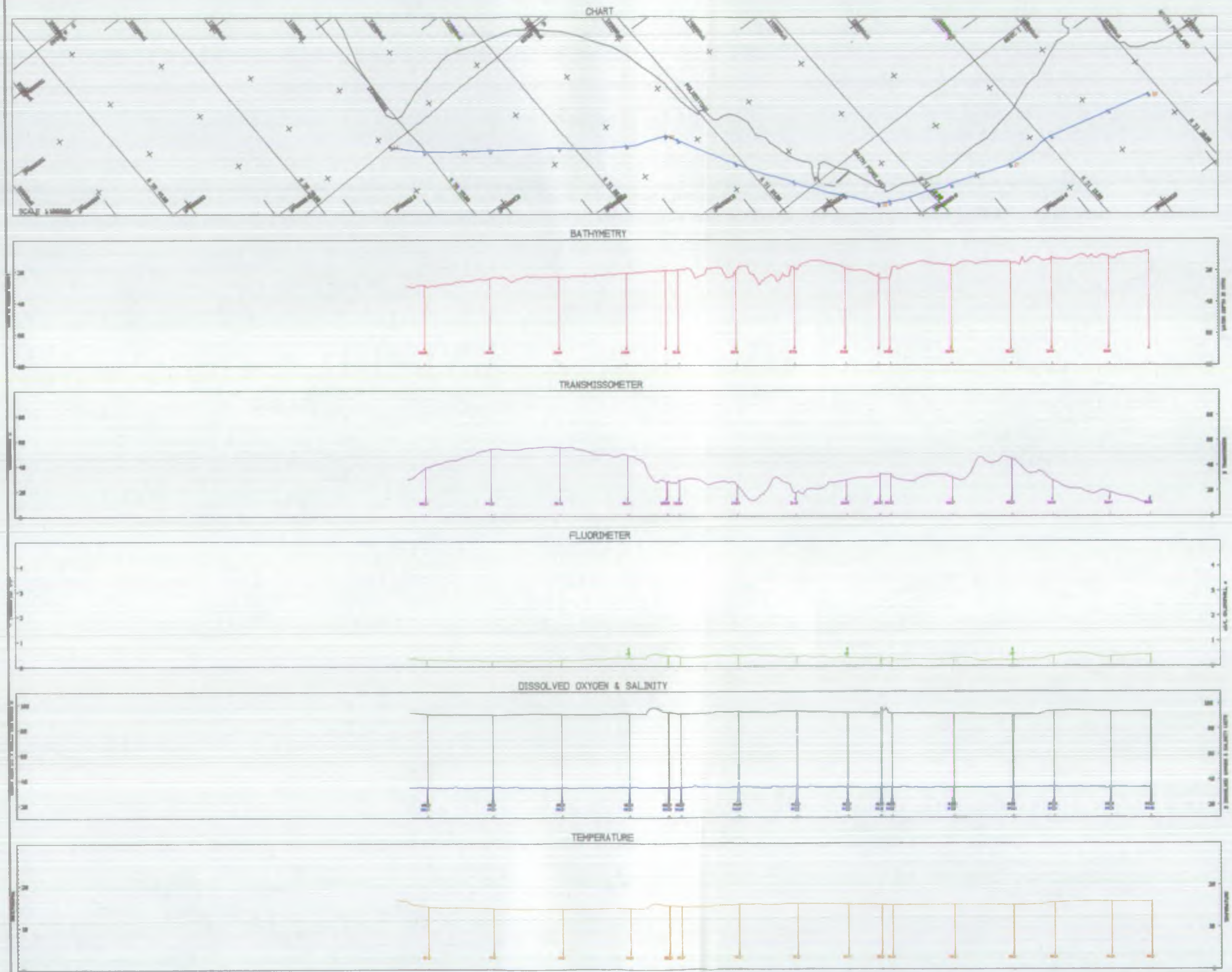

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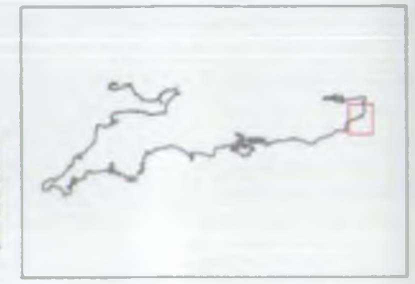

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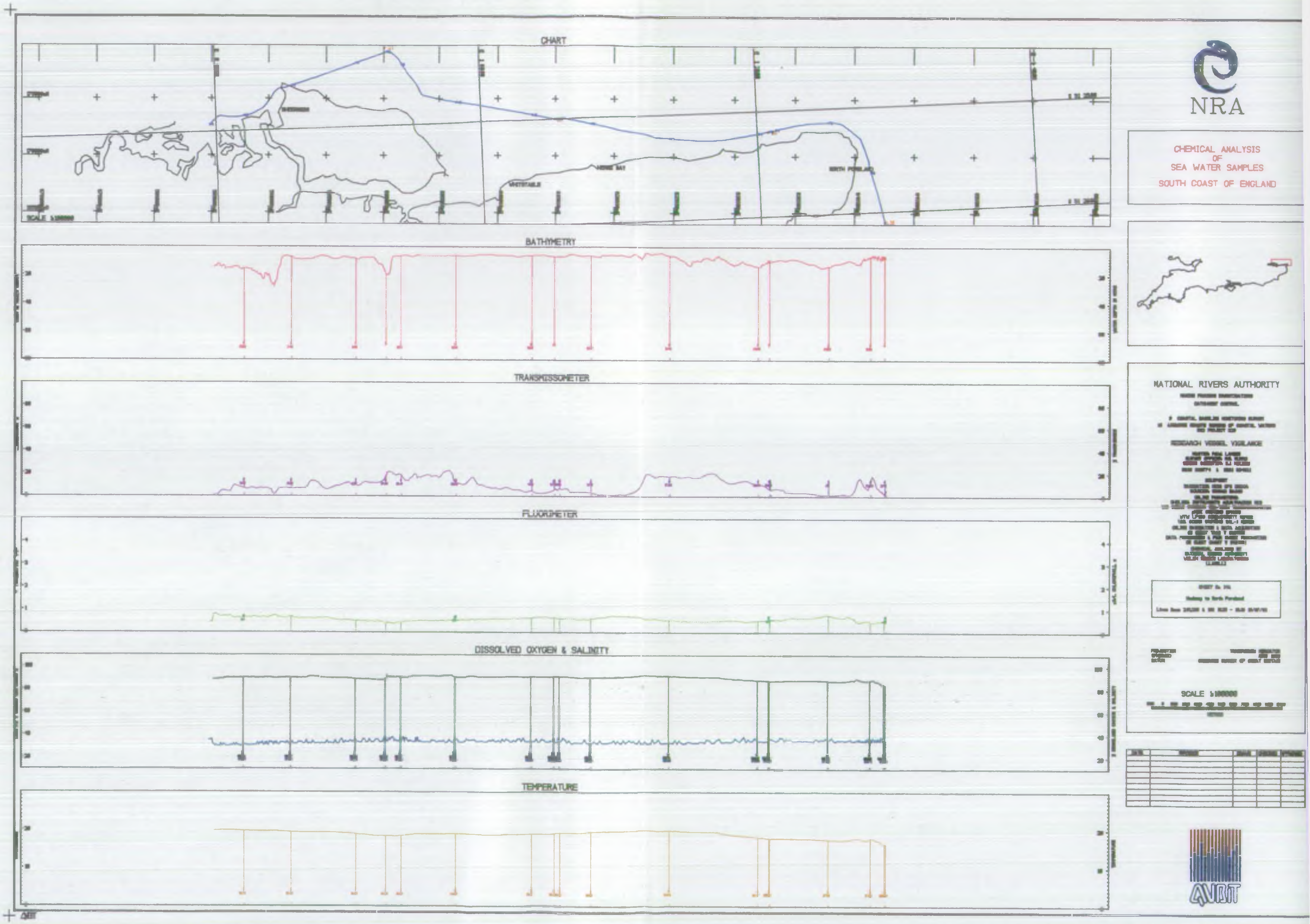

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FLUORIMETER
DISSOLVED OXYGEN & SALINITY
TEMPERATURE
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OF
SEA WATER SAMPLES
SOUTH COAST OF ENGLAND
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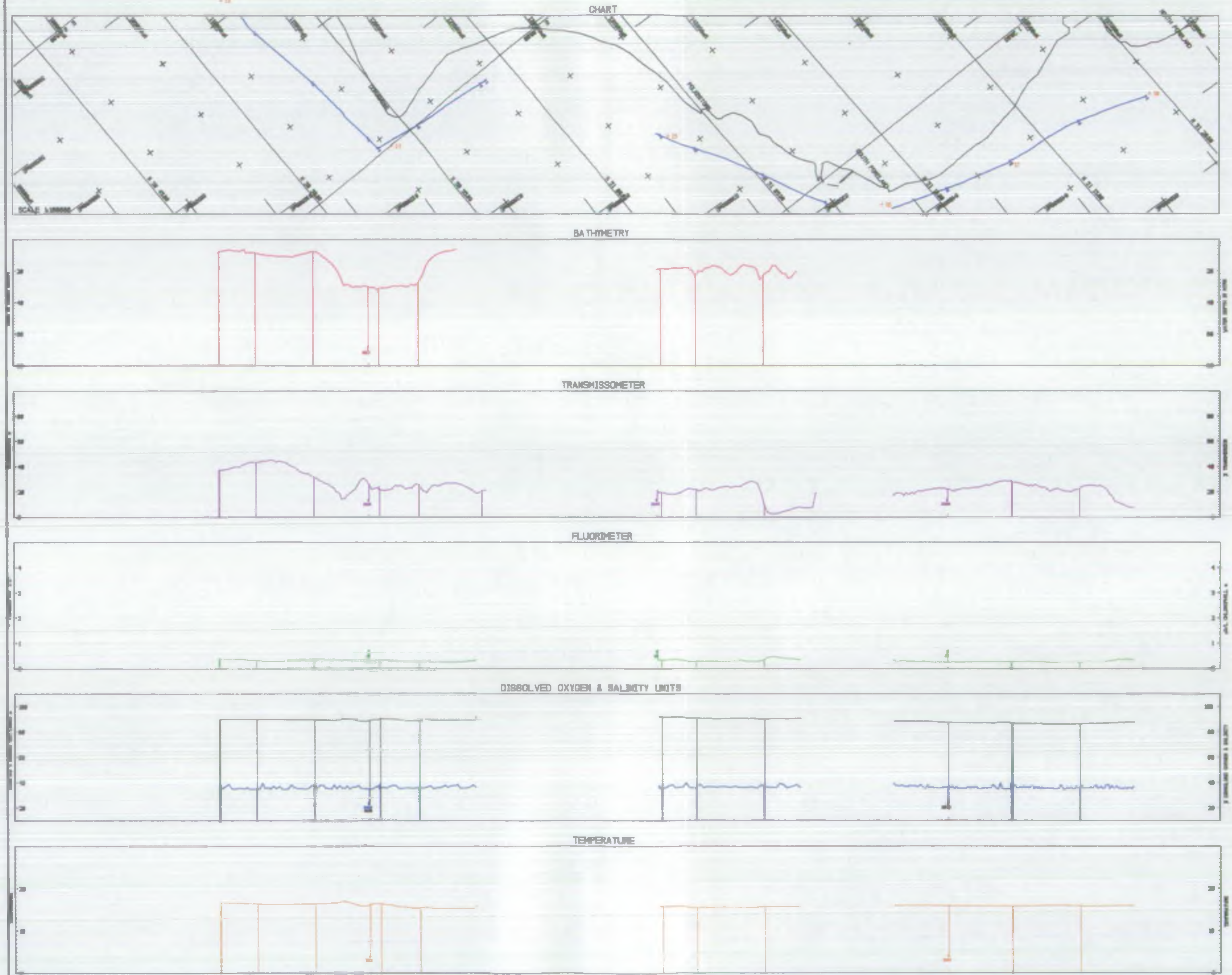

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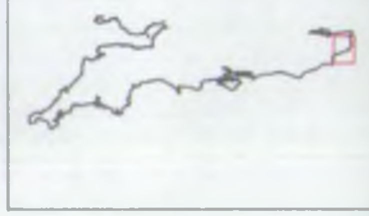
CHEMICAL ANALYSIS
OF
SEA WATER SAMPLES

SOUTH COAST OF ENGLAND



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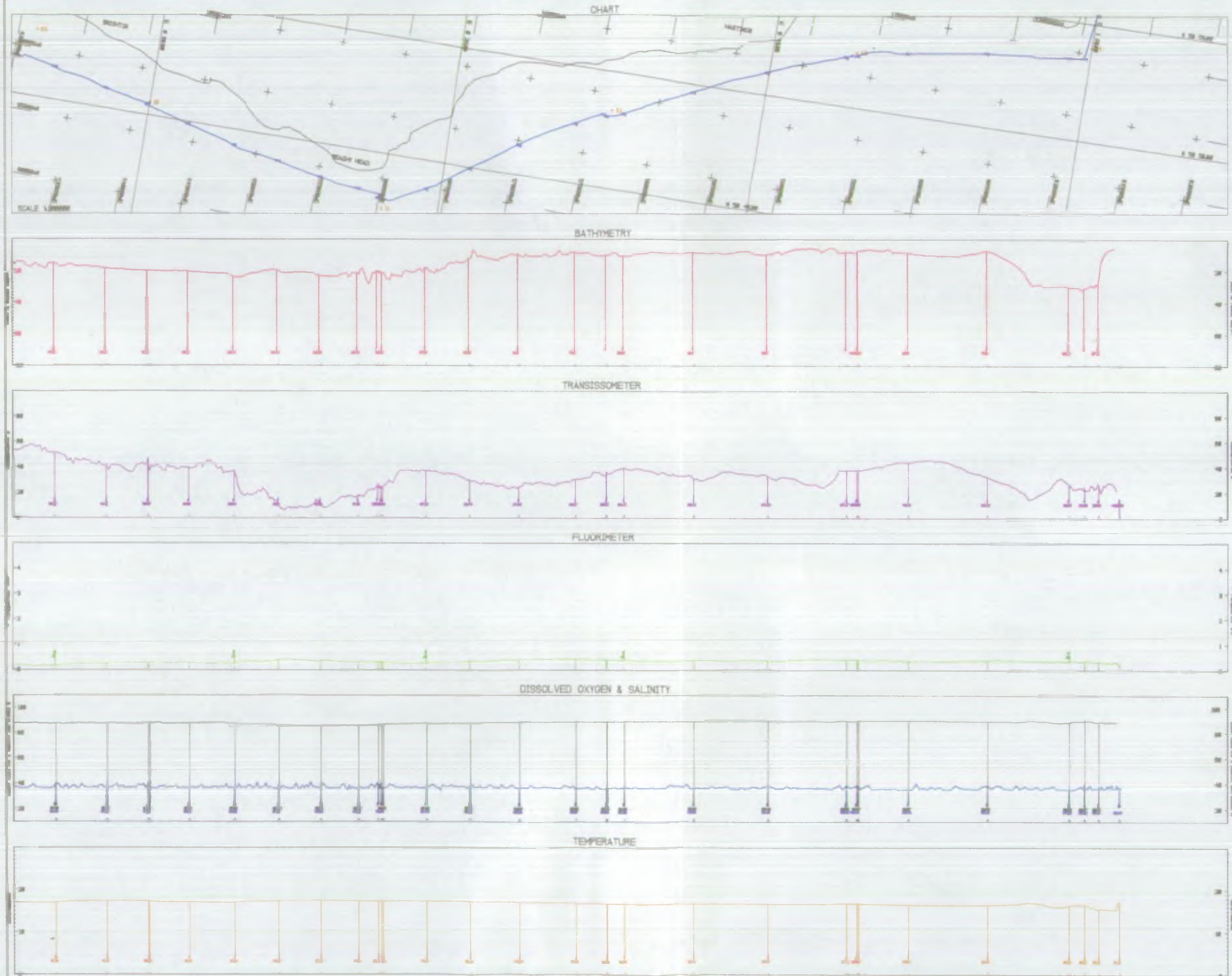

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CHEMICAL ANALYSIS
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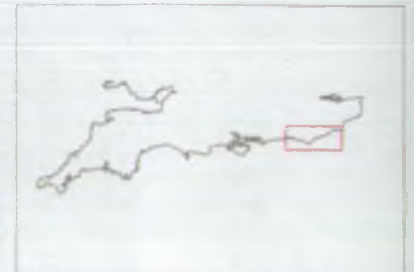
SOUTH COAST OF ENGLAND



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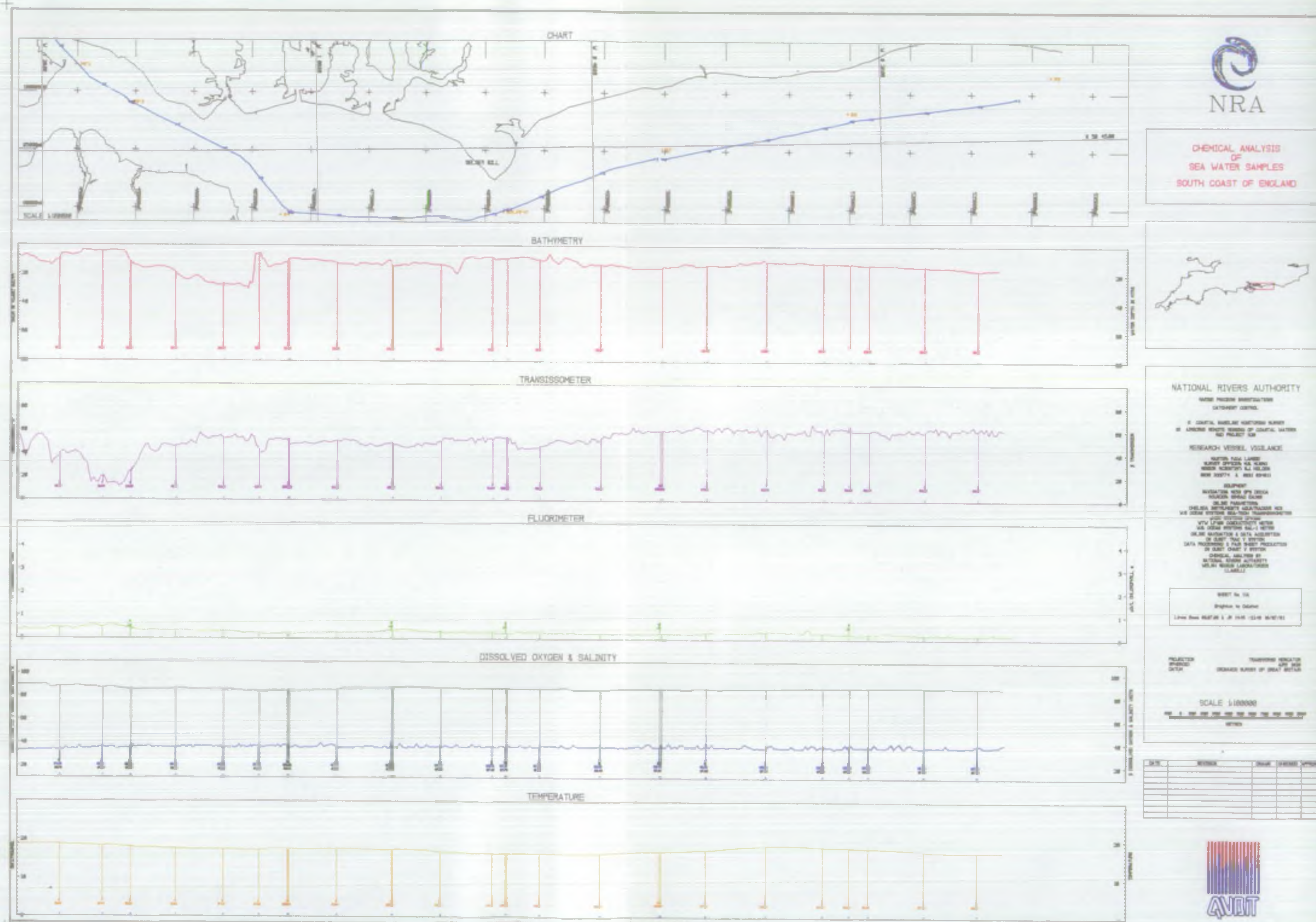
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SELSEY BILL
BATHYMETRY
TRANSISSOMETER
FLUORIMETER
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TEMPERATURE
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CHEMICAL ANALYSIS
OF
SEA WATER SAMPLES
SOUTH COAST OF ENGLAND
NATIONAL RIVERS AUTHORITY
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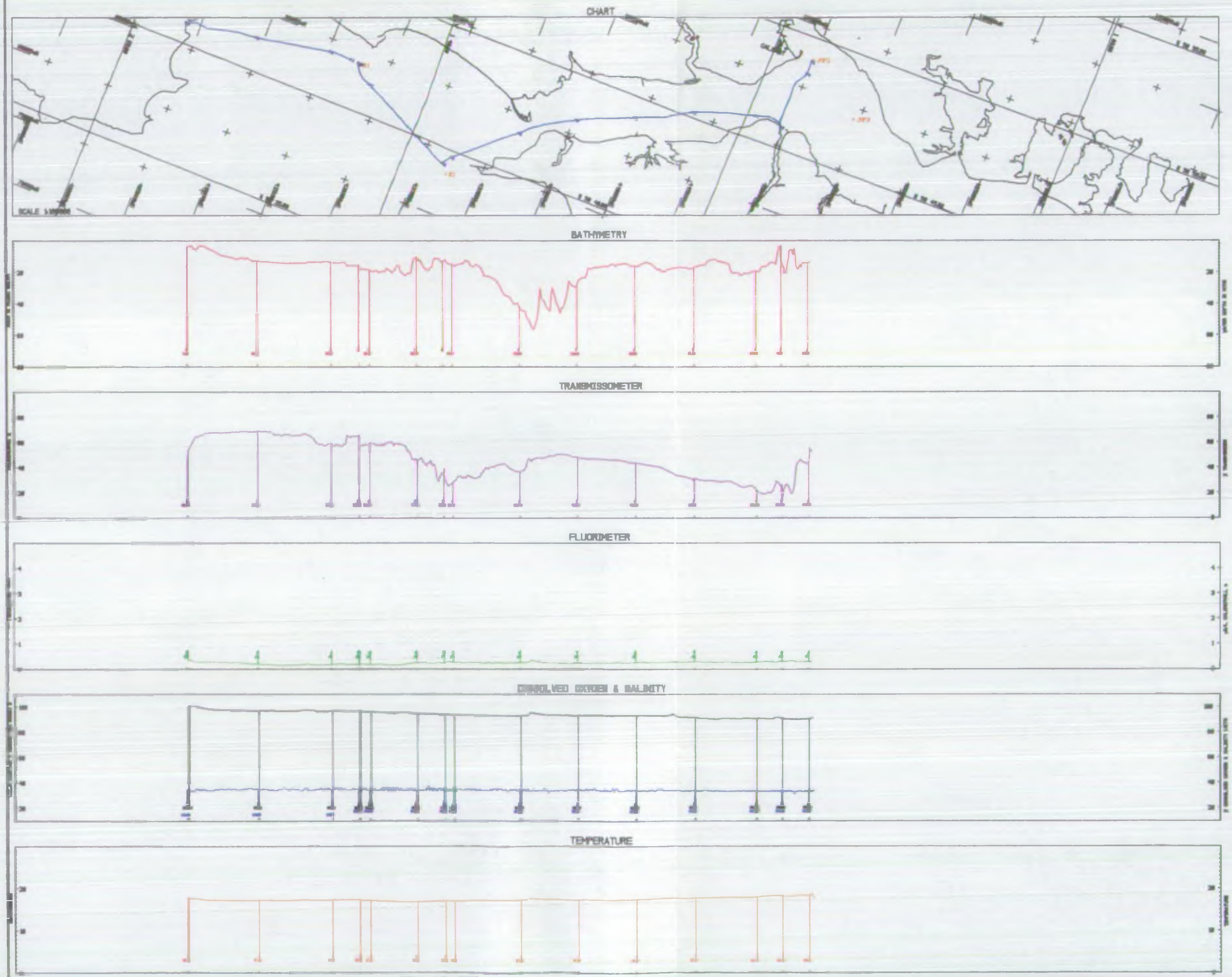
DATE
REVISION
DRAWN
CHECKED
APPROVED
AVRT



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CHEMICAL ANALYSIS
OF
SEA WATER SAMPLES

SOUTH COAST OF ENGLAND

NATIONAL RIVERS AUTHORITY

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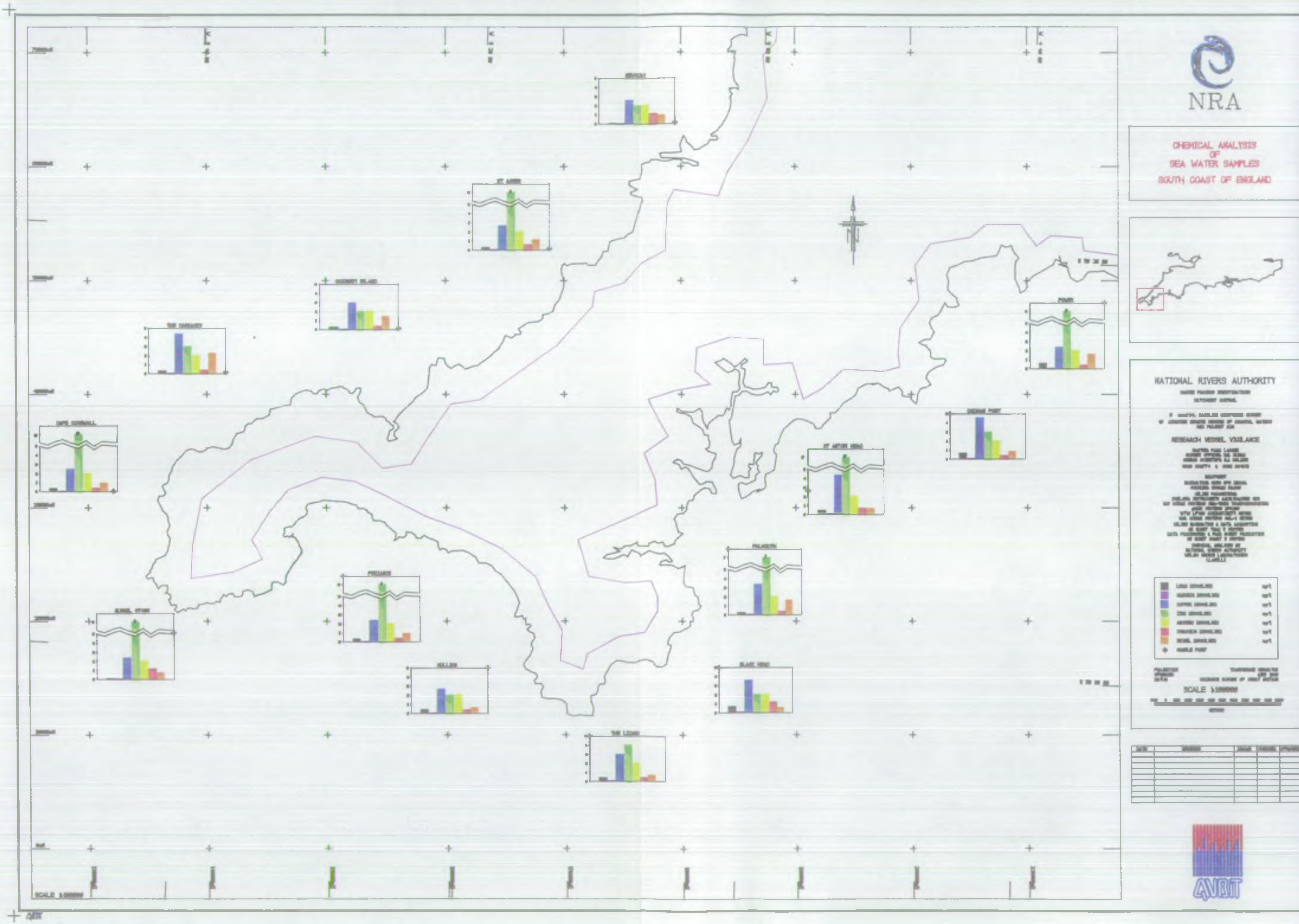

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OF
SEA WATER SAMPLES
SOUTH COAST OF ENGLAND
NATIONAL RIVERS AUTHORITY
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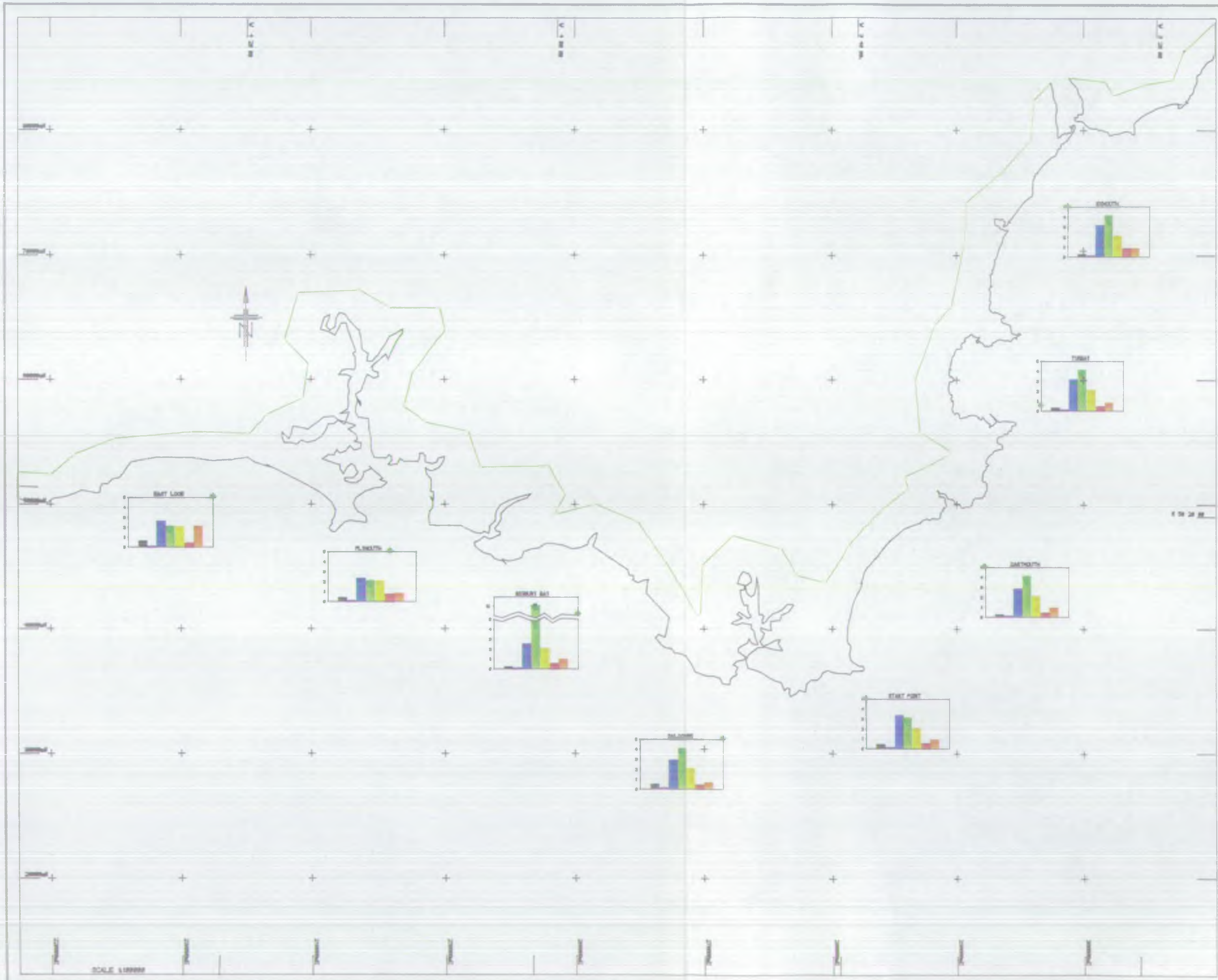

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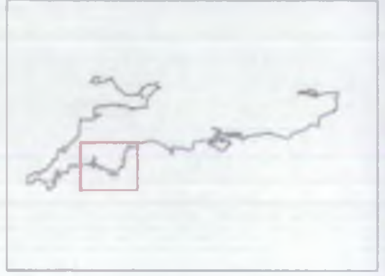
CHEMICAL ANALYSIS OF SEA WATER SAMPLES
SOUTH COAST OF ENGLAND



NATIONAL RIVERS AUTHORITY

RESEARCH VESSEL VIGILANCE

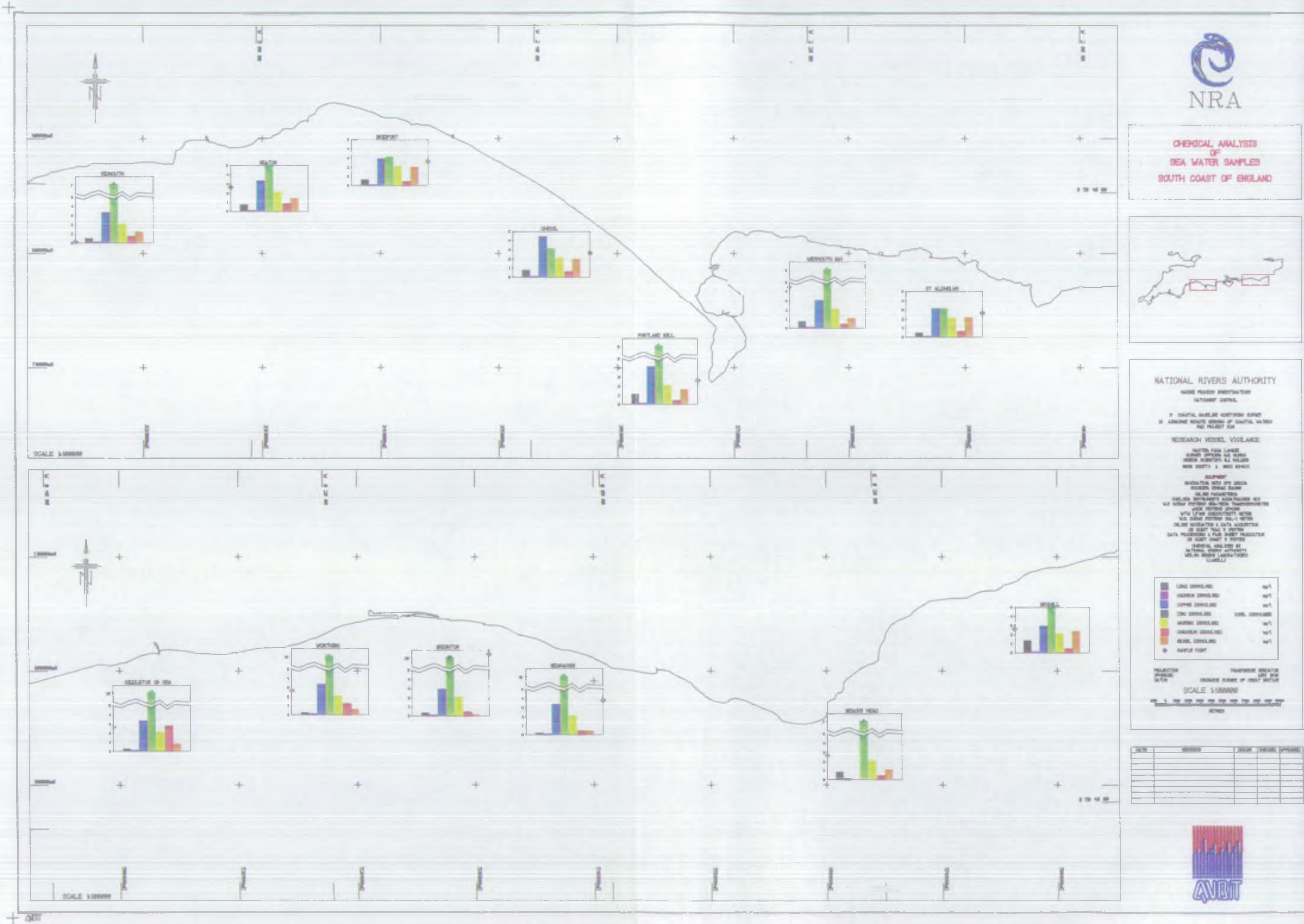
	LEAD (DISSOLVED)
	CADMIUM (DISSOLVED)
	COPPER (DISSOLVED)
	ZINC (DISSOLVED)
	ARSENIC (DISSOLVED)
	CHROMIUM (DISSOLVED)
	NICKEL (DISSOLVED)
+	SAMPLE POINT

PROJECTION TRANSVERSE MERCATOR

DATUM ORDNANCE SURVEY OF GREAT BRITAIN

SCALE 1:100000

DATE	REVISION	DRAWN	CHECKED	APPROVED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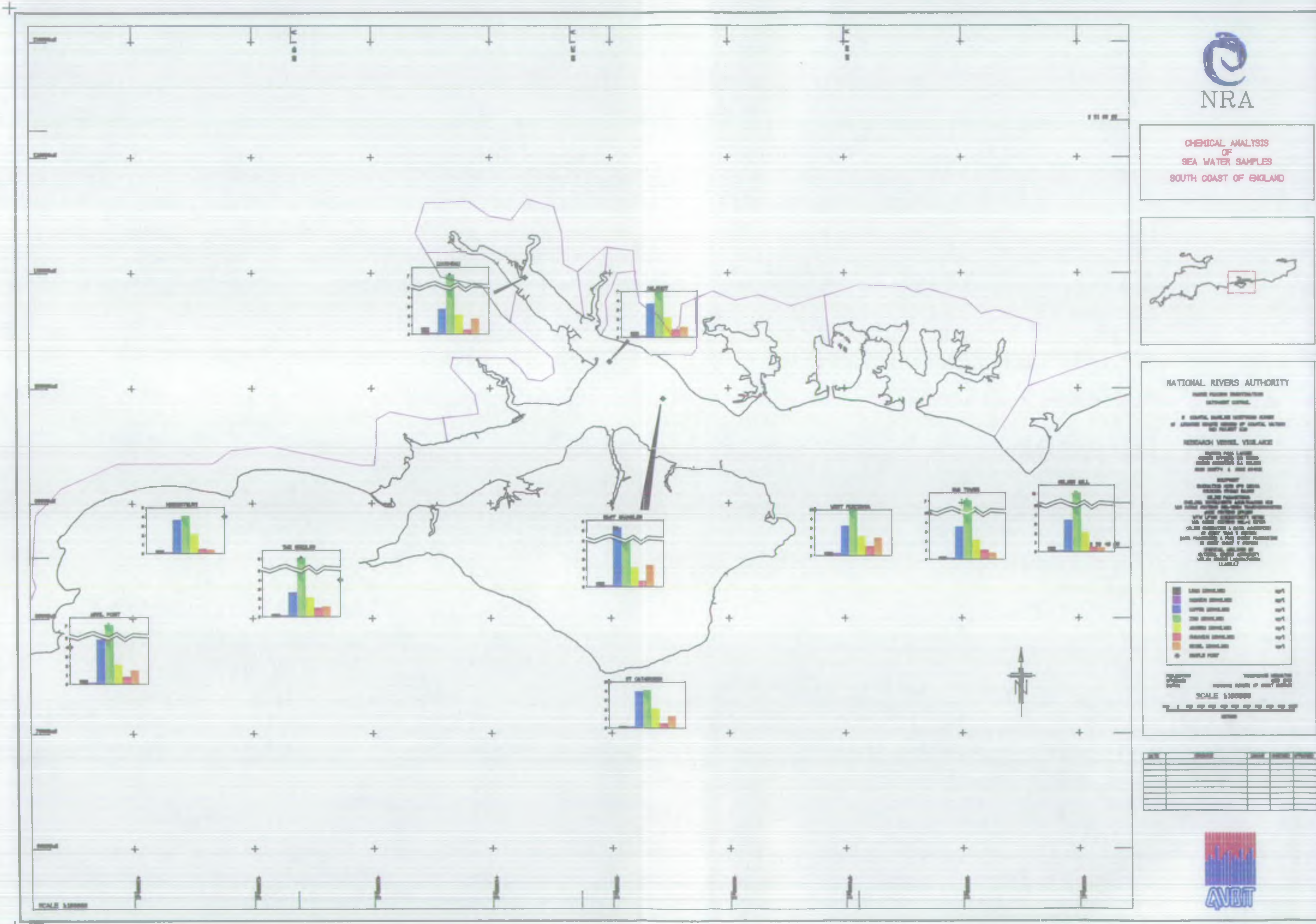
CHEMICAL ANALYSIS
OF
SEA WATER SAMPLES
SOUTH COAST OF ENGLAND
NATIONAL RIVERS AUTHORITY
RESEARCH VESSEL VIGILANCE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SEA WATER SAMPLES
SOUTH COAST OF ENGLAND
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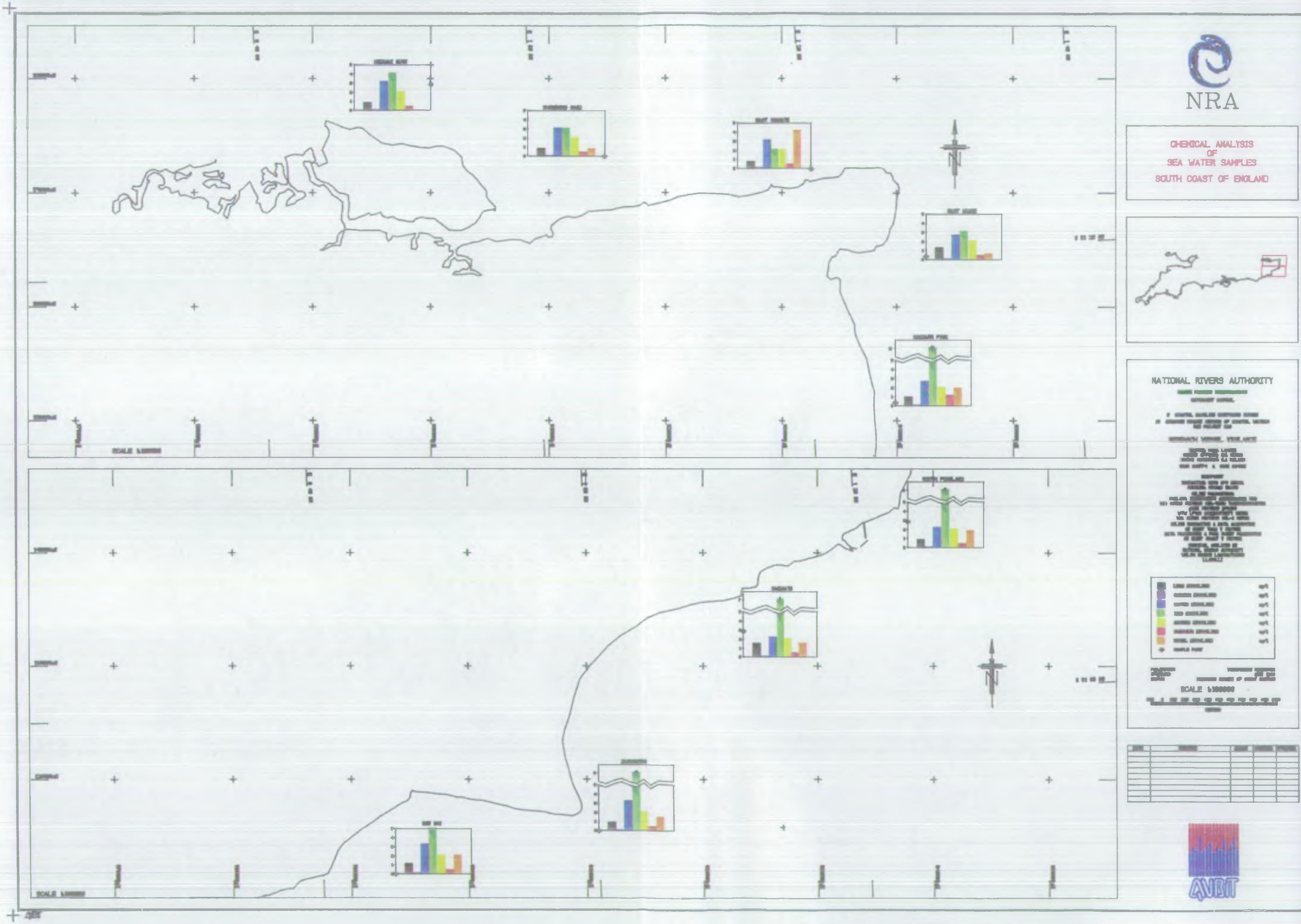

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CHEMICAL ANALYSIS
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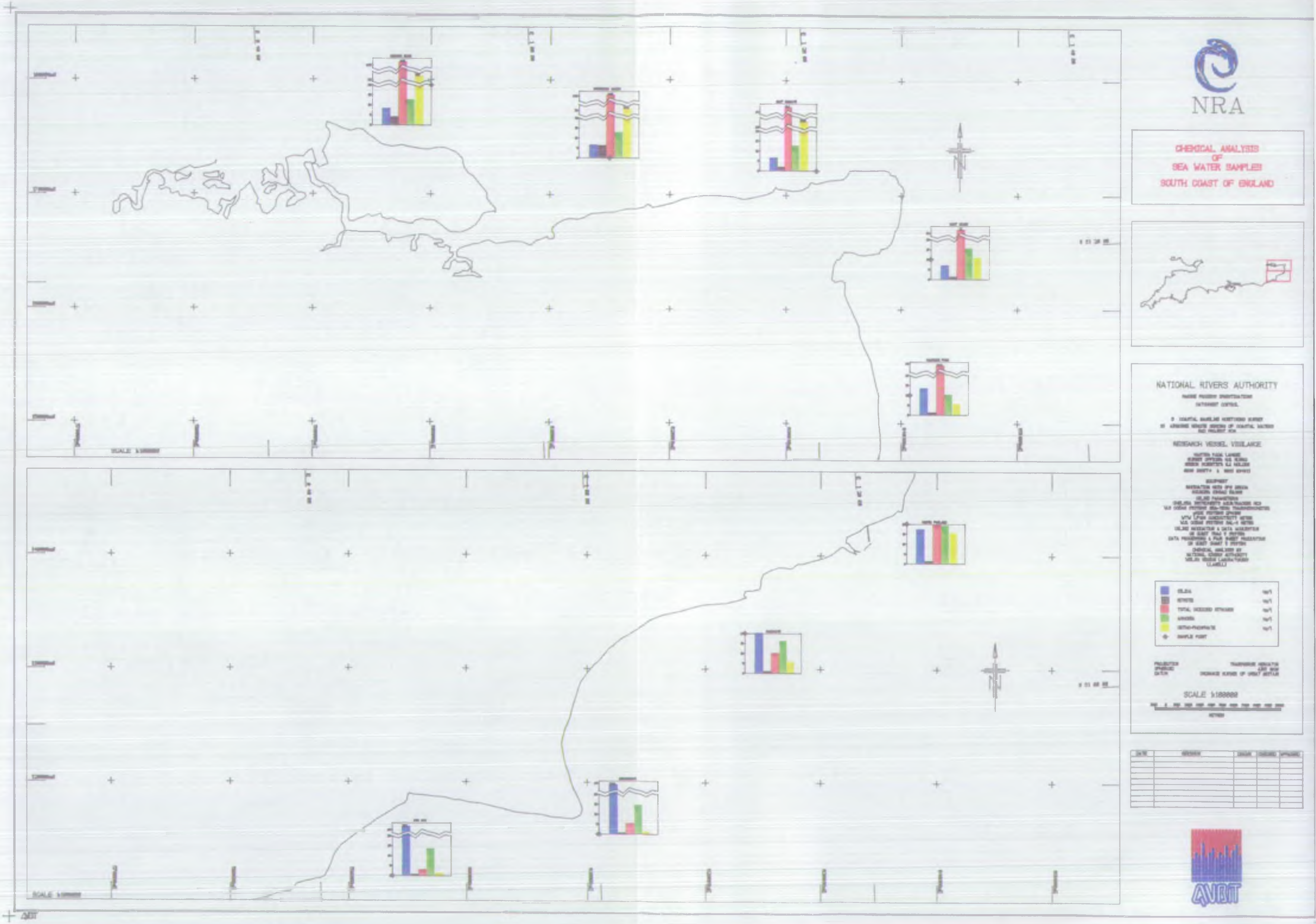
SEA WATER SAMPLES
SOUTH COAST OF ENGLAND
NATIONAL RIVERS AUTHORITY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OF
SEA WATER SAMPLES
SOUTH COAST OF ENGLAND
NATIONAL RIVERS AUTHORITY
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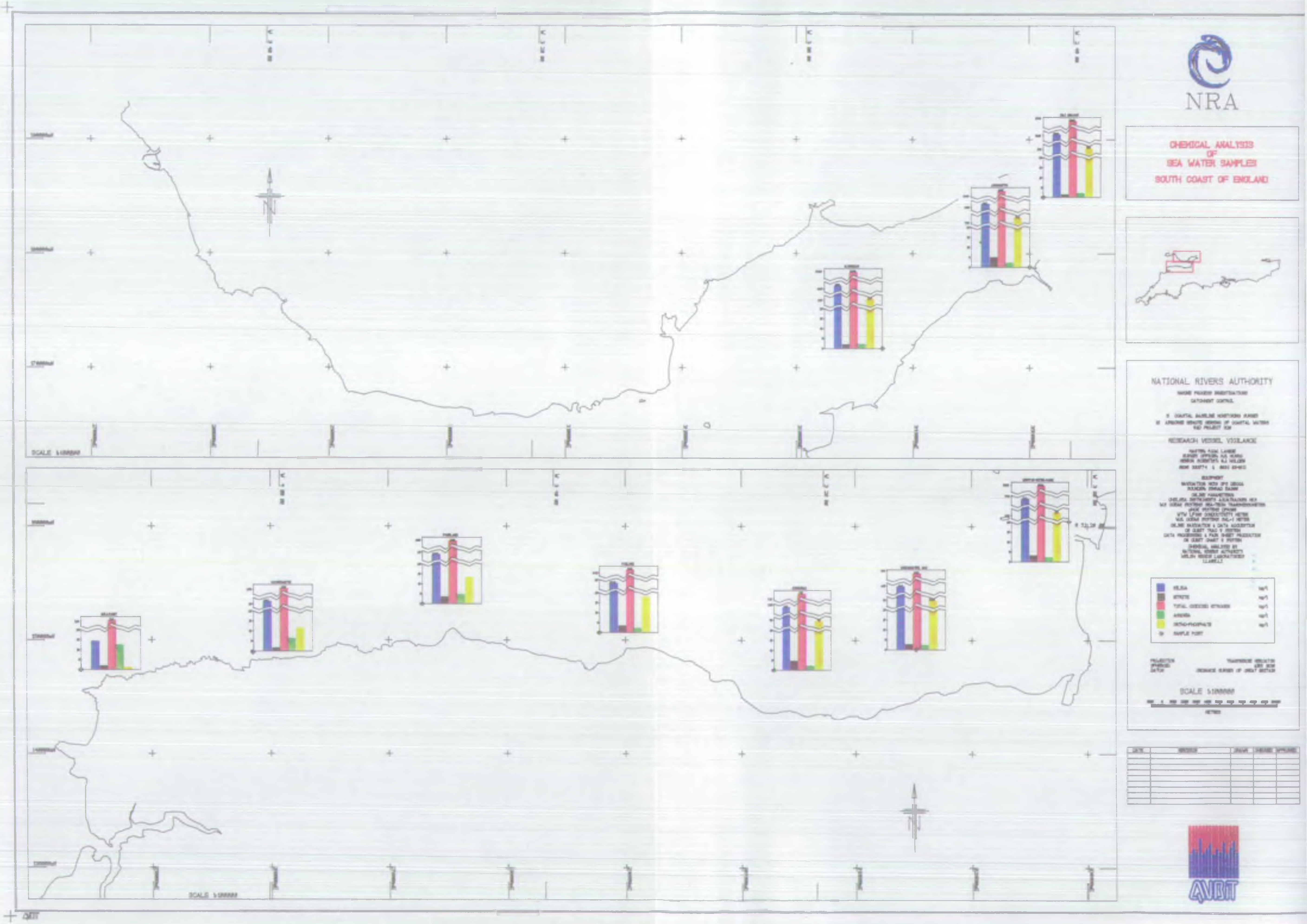
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NATIONAL RIVERS AUTHORITY
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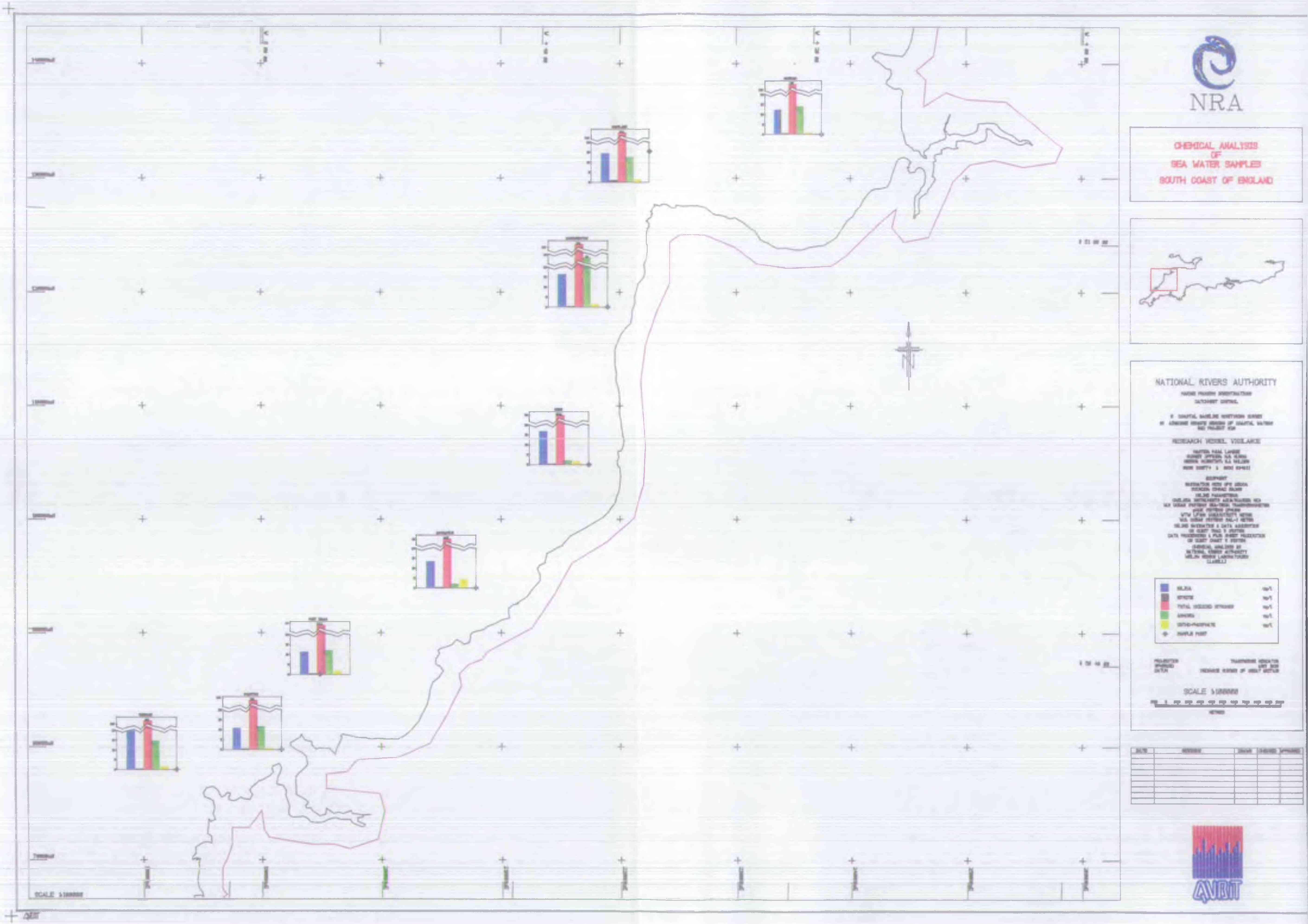

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SOUTH COAST OF ENGLAND
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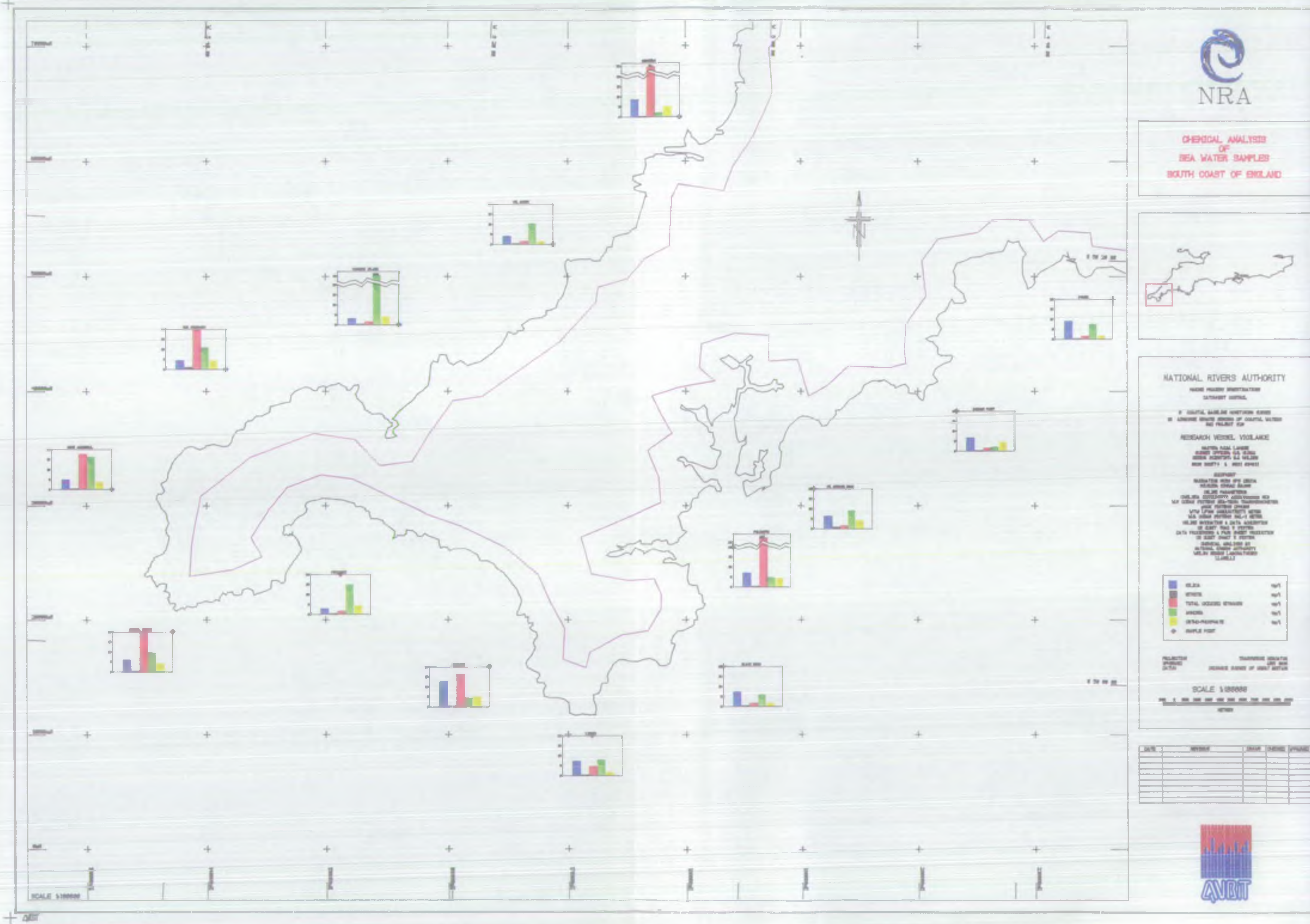
RESEARCH VESSEL VIGILANCE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SOUTH COAST OF ENGLAND
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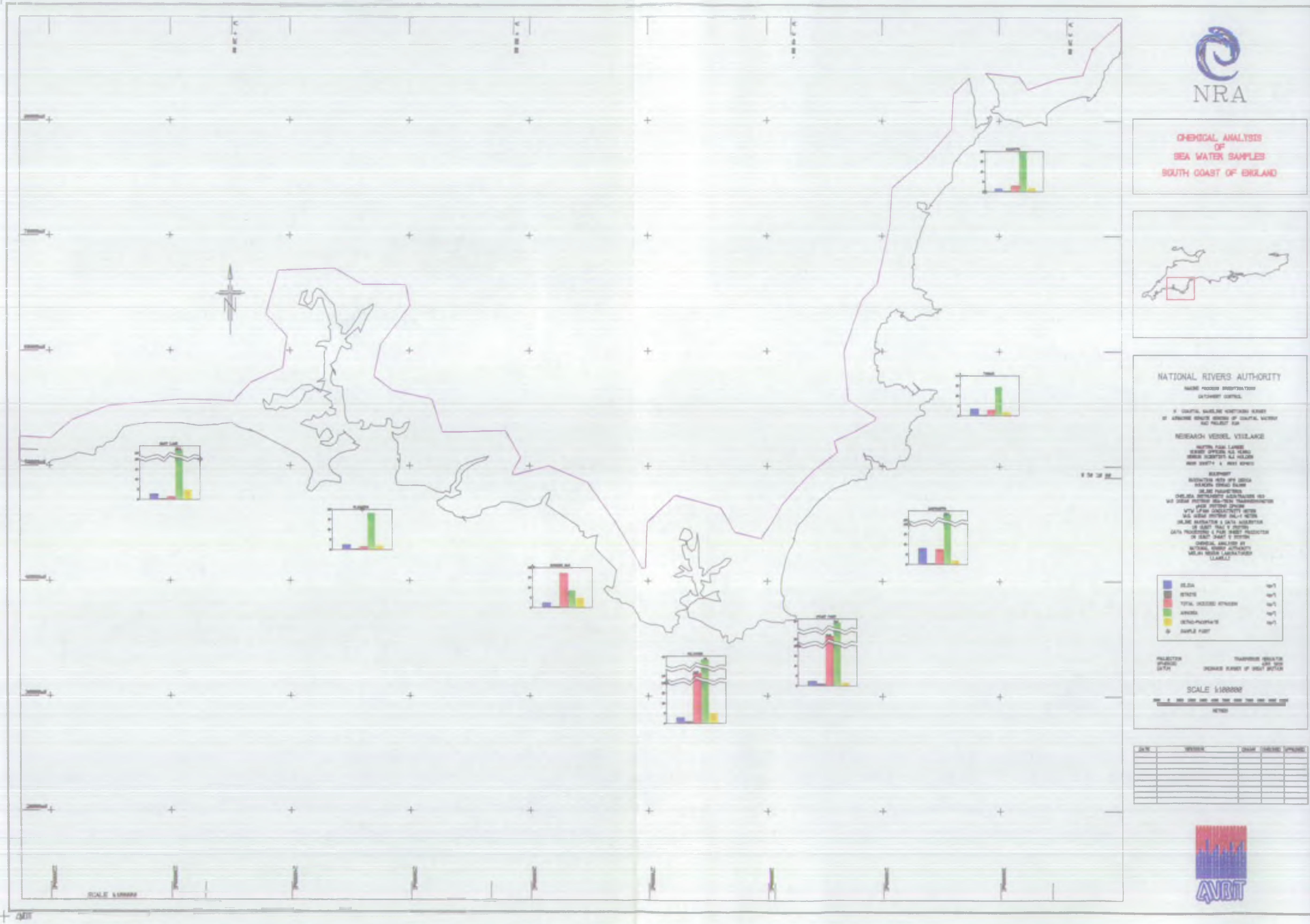
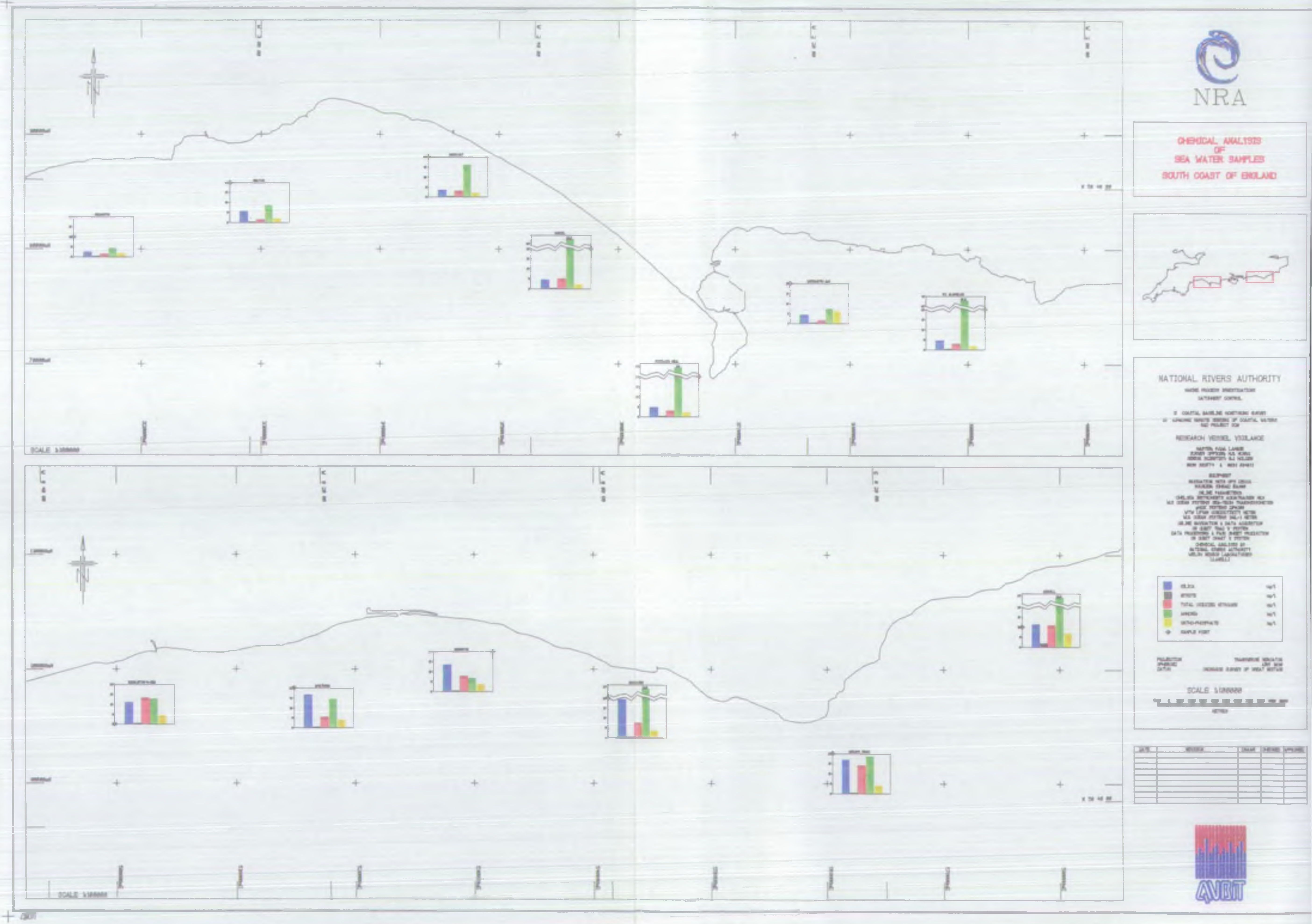


NRA
CHEMICAL ANALYSIS
OF
SEA WATER SAMPLES
SOUTH COAST OF ENGLAND
NATIONAL RIVERS AUTHORITY
CATCHMENT CONTROL
RESEARCH VESSEL VIGILANCE
SILICA
NITRATE
TOTAL OXIDISED NITROGEN
AMMONIA
ORTHO-PHOSPHATE
SAMPLE POINT
SCALE 1:100000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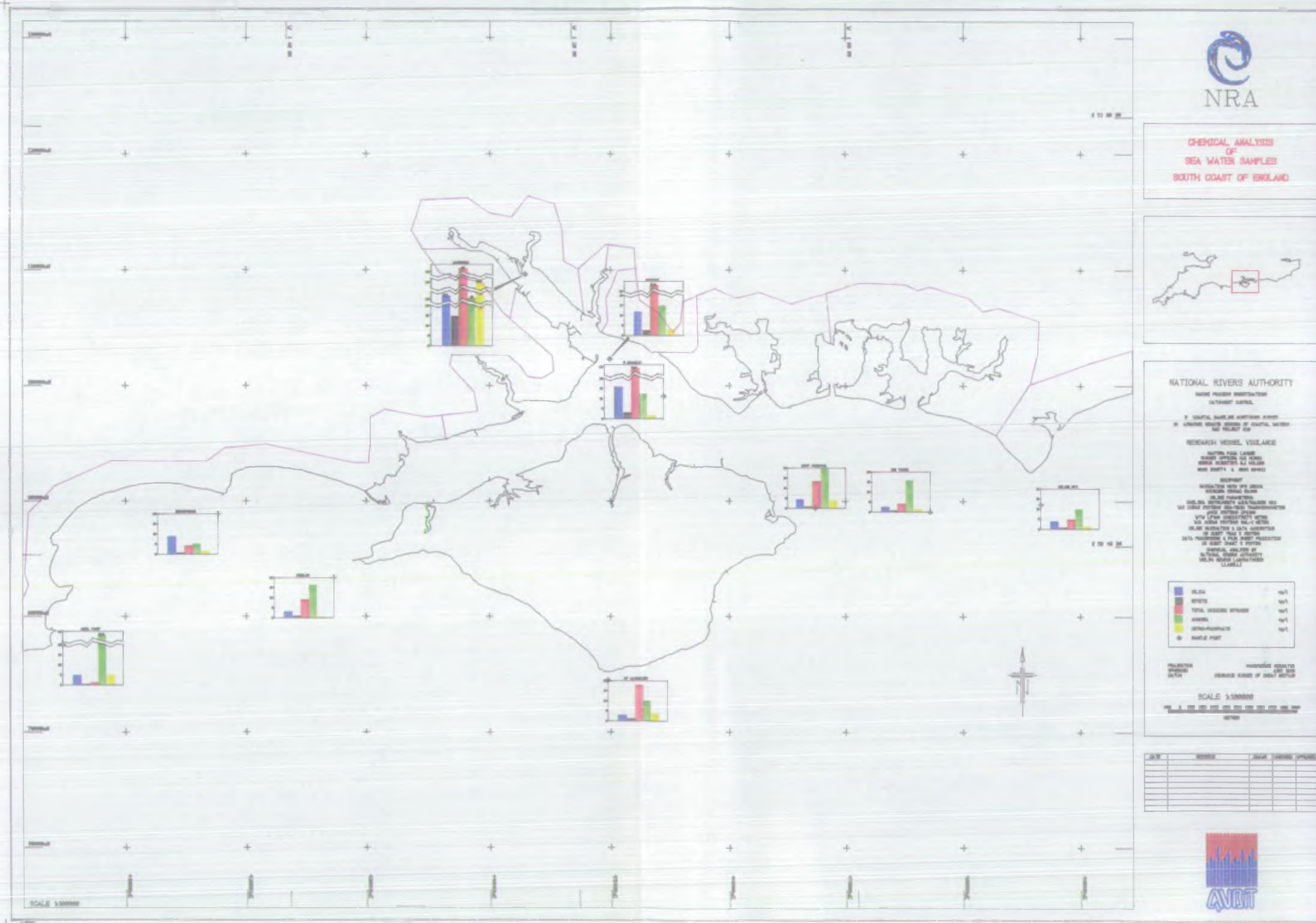
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