Estuarine, Coastal and Shelf Science (1997) **44,** 589–598

Environmental Monitoring of Estuaries; Estimating and Mapping Various Environmental Indicators in Breydon Water Estuary, U.K., Using Landsat TM Imagery

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Received 17 July 1995 and accepted in revised form 27 March 1996

The spatial and temporal distribution of suspended solids, turbidity, temperature, salinity, chlorophyll *a* and total phosphorus were estimated and mapped with various degrees of success in Breydon Water Estuary using satellite (Landsat Thematic Mapper) imagery. All the indicators exhibit a similar spatial pattern within the estuary. High values are found at both the saltwater and freshwater ends of the estuary, and low values are found in the mixing zone. The pattern is thought to be due to the influence of suspended solids and turbidity on the optical characteristics of water in this environment. The distribution of suspended solids and turbidity are influenced by the flood–ebb intervals, the sedimentation processes and the internal topography of the estuary. All of the predicted values are consistent with those reported in the literature.

Keywords: environmental monitoring; estuaries; remote sensing; Breydon Water

Introduction

Estuaries are one of the most complex of all environments, thus attempting to provide a definition has been a difficult task. Cameron and Pritchard (1963) defined an estuary as a semi-enclosed coastal body of water which has free connection with the open sea and, within which, seawater is measurably diluted with freshwater derived from land drainage. Fairbridge (1980) defined it as an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise, normally being divided into three sections: the lower estuary, maintaining free connection with the sea; the middle estuary, a saltwater and freshwater mixing zone; and the upper estuary, dominated by freshwater but exposed to tidal movements. Dionne (1963) had earlier proposed a similar threshold classification of the St. Lawrence Estuary in Canada.

Estuarine environments are amongst the most productive and sensitive ecosystems. Their importance in terms of carbon fixation, fisheries habitat, nutrient assimilation, water storage and sediment stabilization has been recognized for a long time (Odum, 1983). However, only a small amount of information is available on their spatial and temporal variability. This might be due to the fact that estuaries are dynamic systems which undergo numerous daily changes. Knowledge and understanding of their spatial and temporal heterogeneity is frequently based on interpolations between a number of sampling stations. In reality, the large size of estuaries and their spatial and temporal variability limits the effectiveness of sampling stations and interpolation techniques, and, consequently, the perceived picture deviates considerably from reality.

The physiology of organisms within estuarine habitats depends on suspended solids, turbidity, temperature, salinity, chlorophyll *a* and total phosphorus concentrations. Therefore, there is a need for information concerning these environmental indicators, in particular for information on their spatial and temporal variability within the estuary. It is also necessary to study the influence of pollution on these indicators, and the impacts of the induced variations on different species in the estuarine environment. These issues are of a particular importance to Britain, as it has a greater number of estuarine habitats than any other country in Europe. Therefore, it has a particular international responsibility for their conservation (Zisman, 1992).

Landsat Thematic Mapper (TM) imagery has proven to be effective in mapping temporal and spatial variations in environmental indicators within large

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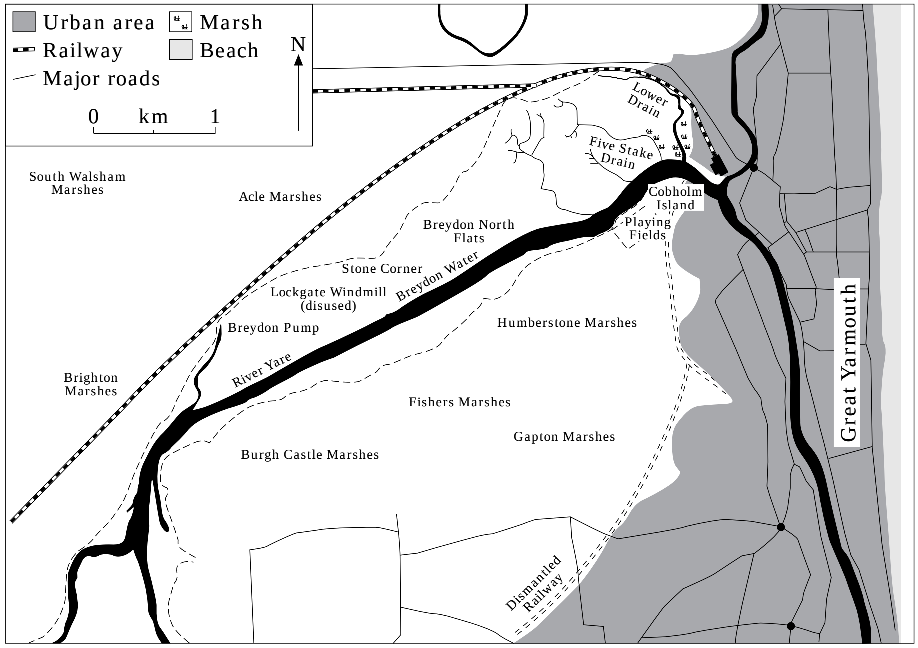

FIGURE 1. Outline map of Breydon Water Estuary.

water bodies. Several studies have demonstrated, with various degrees of success, the predictive capacity of satellite imagery in mapping surface distributions of suspended solids, turbidity, salinity (Klemas *et al.*, 1975; Khorram & Cheshire, 1983; Khorram, 1985) and chlorophyll *a* (Khorram & Cheshire, 1983; Cheshire *et al.*, 1985) in turbid waters. This success is mainly due to three facts. Firstly, spatially, the sampling frame is area based. Secondly, the data are collected from the whole estuary at a single incident in time with the added benefit of providing repetitive coverage (subject only to cloud cover). Thirdly, it is thematically consistent, since the same instrumentation is used to extract the relevant information from all areas throughout the estuary (Baban, 1993).

The study area

Breydon Water is a large body of tidal water located in Norfolk, East Anglia, England. It stretches eastward from the Rivers Yare and Waveney confluence towards the recently built Breydon lifting bridge (Figure 1). Rivers Yare and Waveney drain into the North Sea via Breydon Water. Breydon Water, as described by Sabri (1977), is relatively shallow, very turbid and well mixed, with a mean tidal range of *c.*1·5 m and little semi-diurnal inequality. The area of Breydon Water at high water is about 7 km^2 with an average width of 1–1·2 km. At low tide, the water is confined to a distinct channel *c.* 10–12 m in width running along the entire length of the estuary. The residence time of tidal waters in this estuary and the estuaries of Rivers Yare and Waveney is very short, and probably no more than 1–2 days. Indeed, most is flushed every tide (Sabri, 1977).

Supplementary ground observations on the tidal cycle

It was necessary to undertake some ground observations in order to collect some basic information concerning the local environment, the topographical and morphological characteristics of Breydon Water, and the extent and optical quality of water during flood and ebb tides. Field observations were made on 28 September 1989. Researchers have indicated that in Breydon Water, the water repeats the same pattern within each flood–tide cycle (Sabri, 1977), therefore, despite the difference in time between the Landsat TM image and the field observation, the latter should represent a reasonable picture of the estuary during the Landsat overpass (Baban, 1993).

The observation began at high tide, starting at the most easterly point continuing along the Northern Bank, and down to the confluence of Rivers Waveney and Yare (Figure 1). On retracing the route, all the previous observation points were re-visited while the tide was receding. This meant that the estuary was observed during flood as well as ebb tides.

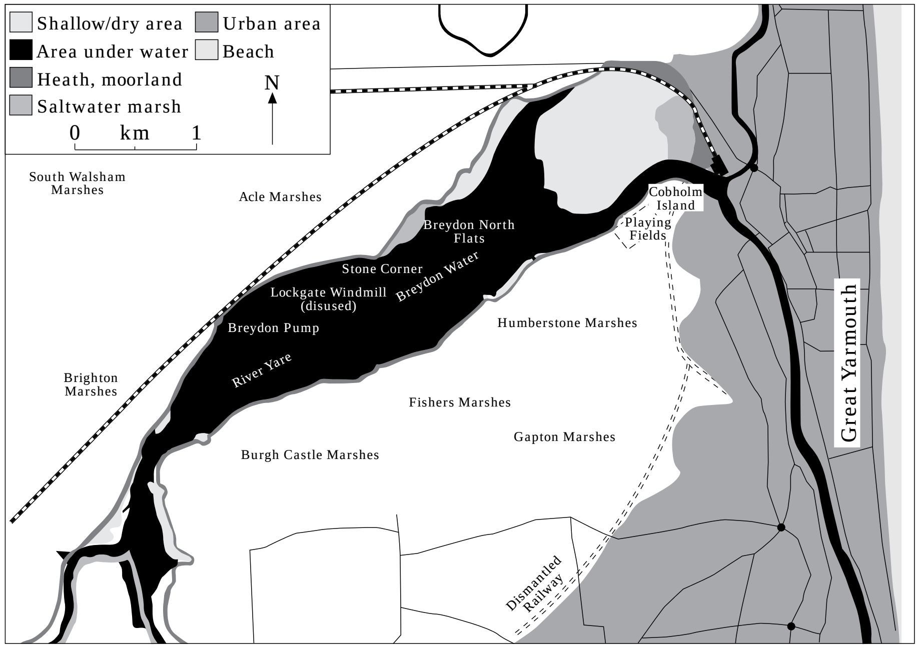

FIGURE 2. Ground-referenced map, compiled from field observations, aerial photographs and available maps.

The following observations arose from this process:

(1) The area between Stone Water and the Lockgate Windmill (Figure 1) was still underwater during the ebb, despite the exposure of mud flats at most places.

(2) In the mouth, mud flats with large channels were observed.

(3) At low tide, the northern bank of the mouth consisted of small islands. Further toward the centre of the estuary, mudflat exposure was very clear and it appeared to be the highest area in the estuary.

When aerial photographs taken 2 h after high tide were examined to supplement and complement the field observation data, all the above observations were confirmed.

Figure 2 shows the compiled ground referenced map from field observations as well as the available maps and aerial photographs for Breydon Water.

Remotely sensed data

A satellite Landsat TM image of Breydon Water acquired shortly after high water by Landsat 5 on 2 June 1985 was accessible for use in this study. This image consisted of seven bands; five of which were relevant to this research project. These are TM1, TM2, TM3, TM4 and TM6, operating in the wavelength ranges of blue (0·45–0·52 μm), green (0·52–0·60 μm), red (0·63–0·69 μm), near-infra-red reflected radiation (0·76–0·90 μm) and emitted thermal infra-red radiation (10·4–12·5 μm), respectively, with the ground resolution of 30 m for TM1, TM2, TM3 and TM4, and 120 m for TM6.

The darkest pixel approach was employed to perform atmospheric corrections on the image. The equations used in this work, to estimate suspended solids, temperature, salinity and chlorophyll *a*, were derived during a different study using ground-referenced values and reflected values in the form of digital numbers (DN) from the same image (Baban, 1993). All predicted environmental indicators in Breydon Water Estuary are within the prediction range of the equations. When Landsat imagery is used in studies of this nature, there are usually errors associated with the estimation of parameters. The significance of these errors depends on the application of the data. This paper is mainly concerned with a synoptic account of variations in the indicators and their relative magnitudes, and therefore these errors will not have a significant effect on the objectives of this work (Baban, 1994, 1995).

Detecting and mapping environmental indicators in Breydon Water Estuary

Suspended solids

In Breydon Water, 57 samples were taken from the TM image, each 3×3 in extent using the band

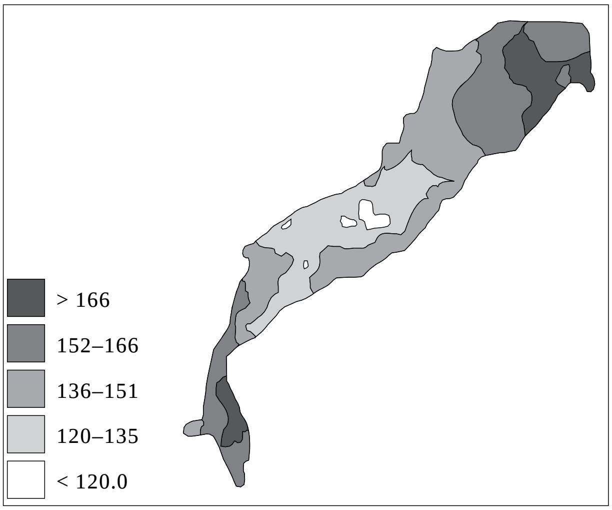

FIGURE 3. The spatial distribution of estimated suspended solids ($\mu g\ l^{-1}$) in Breydon Water Estuary.

TM1, averaged and converted to suspended-solids concentration, using the equation:

$$\text{Suspended solids } (\mu g\ l^{-1}) = -427 + 7{\cdot}01 \times \text{TM1 (DN)} \quad (1)$$
$$n=11,\ r=0{\cdot}88,\ \text{rms}=0{\cdot}88$$

The resultant values were mapped (Figure 3). This figure suggests that the suspended-solids distribution can be divided into three zones: the lower estuary zone with high concentrations (in excess of 150 $\mu g\ l^{-1}$); the middle estuary zone, characterized by lower concentrations (less than 136 $\mu g\ l^{-1}$); and the upper estuary zone with high suspended-solid concentrations (in excess of 150 $\mu g\ l^{-1}$). This distribution pattern agrees with the findings of other investigations. Generally speaking, the two extremities of the estuary have higher suspended-solids concentrations than the middle part (Sabri, 1977).

In the lower estuary zone, Burgh mud flats were characterized by a very high suspended-solids concentration (in excess of 166 $\mu g\ l^{-1}$). These values are probably biased by the influence of the bottom reflectance, as the water is very shallow in this area. Nevertheless, field evidence shows that this zone has a high suspended-solids concentration. Hassan (1988), for example, observed this and suggested a local source for the suspended material. The middle estuary zone has the lowest concentrations, as only the fine suspended solids reach this region, which might contribute to its relatively lower reflectance (Cheshire *et al.*, 1985), as well as being a mixing area for the freshwater and seawater. The upper part of the estuary is associated with high concentrations. Some of these values are also believed to be biased because of the bottom reflection. The existence of high concentrations in this zone is due to tidally-induced re-suspended bottom sediments, and also to suspended particles transported upstream by the coastal water (Hassan, 1988). Sabri (1977) demonstrated that up to 5 cm of the intertidal mud is deposited and re-suspended by tidal movement in the estuary. The size of the suspended material plays an important role in the reflection and transmission of the light from the water (Cheshire *et al.*, 1985). Sabri (1977) suggested that the suspended materials are quickly dumped at both ends of Breydon Water when currents slacken. Consequently, the coarser sediment is deposited at both ends of the estuary while the central part will receive the finer sediments. This might be the case even when the estuary is underwater as a result of the re-suspension effect, and this will also account for the higher reflectance at both ends and the lower reflectance in the middle part of Breydon Water (Figure 3).

Turbidity

No algorithm was available to relate turbidity measurements on the ground to reflected values on the imagery. Turbidity levels and distribution were estimated by using image processing techniques on the Landsat TM imagery.The spectral ranges of TM2 and TM3 are often used for detecting turbidity (Siegal & Gillespie, 1980; Baban, 1994, 1995). Using the spectral information in the bands TM1, TM2, TM3 and TM4, and employing the contrast stretching technique, four levels of turbidity were recognized in the estuary. The pattern existed in TM1–TM4, but has its sharpest definition in TM3 followed by TM4. Usually TM4 is insensitive and marks all water as black unless there is a significant sediment concentration on or within a few millimetres of the surface (Robinova, 1978). This could be the case with Breydon Water as TM4 displayed the pattern clearly.

Depending on the pattern of the suspended-solids distribution (Figure 3), the output image from the contrast stretching and density slicing techniques, and field observations, an automatic classification (Parallelepiped) was performed; representative samples (training areas) for the four zones were taken. These groups are located at the mouth, the area between the mouth and Stone Corner, the area between Stone Corner and Breydon Pump, and the rest of the estuary (Figure 2). The classification was carried out by using TM3 and TM4 (Figure 4). The output represents four well-defined zones of turbidity (Figure 5). These zones are located at the mouth (highest turbidity), the area between Stone Corner

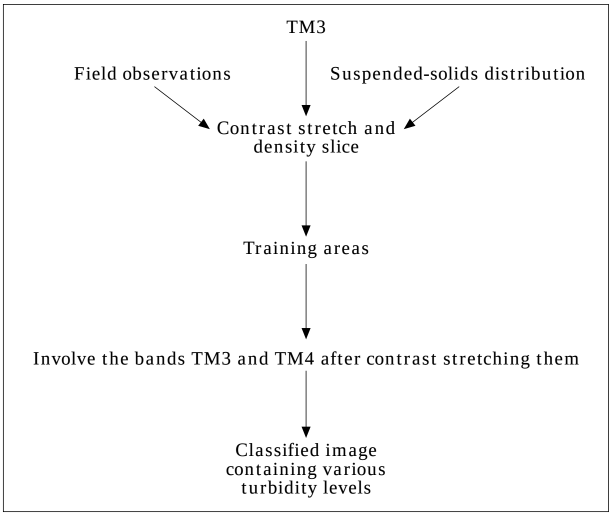

FIGURE 4. Various stages of the classification process.

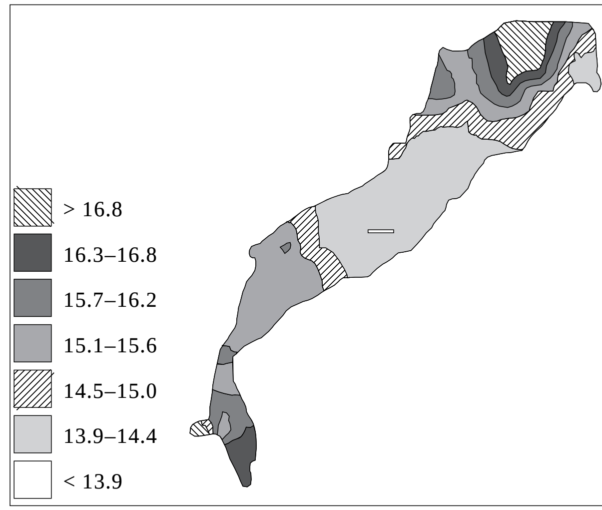

FIGURE 6. The spatial distribution of estimated temperature in Breydon Water Estuary (°C).

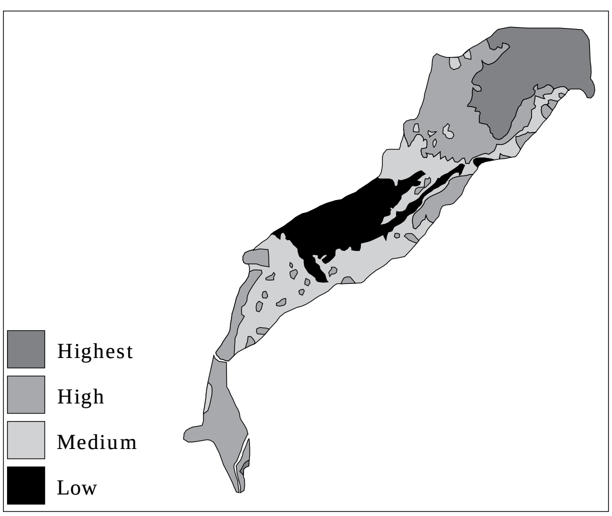

FIGURE 5. Turbidity levels in Breydon Water; the outcome of classification involving the bands TM3 and TM4.

and Breydon Pump (lowest turbidity) and two intermediate zones within the estuary.

An examination of Figure 5 indicates that levels of turbidity are heavily influenced by the topography of Breydon Water. For example, the area between Stone Corner and Breydon Pump, as well as the channel, have the lowest turbidity which, according to the ground-referenced map (Figure 2), is the deepest part in the estuary. Figure 5 in association with the ground-referenced map (Figure 2), provides a reasonable topographic map for Breydon Water. This is significant as this information did not exist before, despite its importance in defining habitats in the estuary.

Temperature

Temperature patterns will reflect variations resulting from the mixing of freshwater and saltwater (Barrett & Curtis, 1992).

Forty-eight samples were taken within Breydon Water; these samples were calibrated against TM6 to provide an estimate of temperature (°C) by applying the equation:

$$\text{Temperature (C°)} = -23{\cdot}4 + -0{\cdot}35 \times \text{TM6 (DN)} \quad (2)$$
$$(n=8,\ r=0{\cdot}91,\ \text{rms}=0{\cdot}32)$$

Resultant temperatures were mapped (Figure 6). The temperature ranged from 13·3 to 17 °C with both extremes of the estuary having the highest values. Sabri (1977) reported a uniform temperature throughout the estuary with a temperature range of 18–20 °C, while Hassan (1988) indicated that there were slight variations (1–2 °C) between sampling points with the temperature range of 16–17 °C. Broad similarity could be detected between reported temperatures in the literature and the estimated temperature using Equation (2).

Salinity (chloride concentration)

Salinity is defined as the total dissolved material in seawater when all carbonate is converted to oxide, all bromine and iodine are replaced by chlorine, and all organic matter is oxidized. Salinity is measured in parts per thousand (Lo, 1986). Salinity has no effect on water spectral characteristics, as has been proved by laboratory studies (Scherz *et al.*, 1969). Nevertheless, salinity has been successfully predicted from the

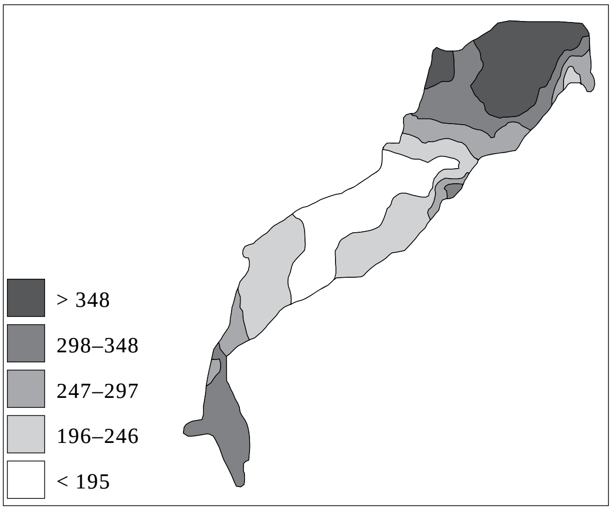

FIGURE 7. The spatial distribution of estimated salinity in Breydon Water Estuary.

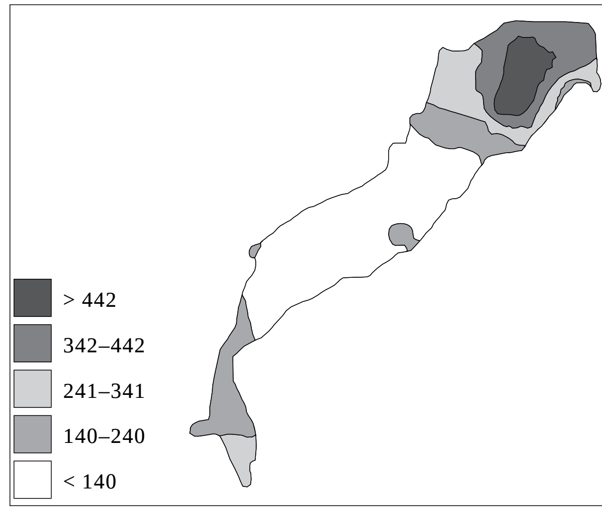

FIGURE 8. The spatial distribution of estimated chlorophyll *a* ($\mu g\ l^{-1}$) in Breydon Water Estuary.

spectral data (Khorram, 1982; Baban, 1993). It is clear that a correlated parameter highly associated with salinity affects the optical properties of the water. For example, suspended solids has been identified as a possible surrogate for salinity (Cheshire *et al.*, 1985). This might well be the case in Breydon Water, where Hassan (1988) has reported a good correlation between suspended matter and salinity.

In Breydon Water, 45 3×3 averaged samples were extracted in TM3 and converted to salinity using the equation:

$$\text{Salinity} = -102 + 9{\cdot}8 \times \text{TM3} \qquad (3)$$
$$(n = 9,\ r = 0{\cdot}75,\ \text{rms} = 7{\cdot}06)$$

Resultant salinity values are mapped (Figure 7).

Both extremes of the estuary are saline with a range of 298–396. In the central part of the estuary, the salinity ranges from 246 to less than 195. The salinity distribution pattern is similar to that of suspended solids and turbidity (Figures 3 and 4), apart from the confluence area (the fresh end), where it shows high rather than low salinity. This might be biased due to the influence of the locally generated suspended materials or the bottom reflectance influence.

Chlorophyll a

Quantifying chlorophyll *a* concentrations in estuaries has met with variable results. The inconsistency is partly due to two factors. First, chlorophyll *a* and inorganic sediment are not separable and, secondly, suspended sediments, which dominate the total reflectance in this environment, behave as a broad band back scatter (Klemas *et al.*, 1980).

Thirty-six 3×3 samples were taken from TM1, TM2 and TM3, and averaged values were converted to chlorophyll *a* concentrations by employing the equation:

$$\text{Chlorophyll } a\ (\mu g\ l^{-1}) = -770 + 4768 \times (\text{TM3/TM1}) - 24{\cdot}6 \times (\text{TM2} + \text{TM3})/2 \qquad (4)$$
$$(n = 12,\ r = 0{\cdot}74)$$

The results are presented graphically in Figure 8, in which the apparent concentrations of chlorophyll *a* ranged between 40 and 640 $\mu g\ l^{-1}$. Obviously, these values are biased, particularly those that are greater than 342 $\mu g\ l^{-1}$, where the bottom reflectance effect is an additional factor.

Chlorophyll has two absorption peaks, one in the blue region (440 nm), the other in the red (665 nm) region of the electromagnetic spectrum. In an estuarine environment, other substances such as iron oxide, dissolved organic pigments and some algal pigments (e.g. carotenoids) also absorb blue and green light, which results in masking the response in this wavelength significant to chlorophyll *a*. Phytoplankton, in which chlorophyll *a* is found, have other pigments with varying predominance which combine with the factors in producing the water's spectral reflectance (Cheshire *et al.*, 1985; Stumpf & Tayler, 1988).

In Equation (4), TM1–TM3 were used in the relationship; therefore, the target is the chlorophyll absorption peak in the blue light region, which is influenced by several factors mentioned above, as well as the suspended-solids concentration which will suppress it in such environments (Witzing & Whitehurst, 1981). This could explain the resultant bias in chlorophyll *a* values.

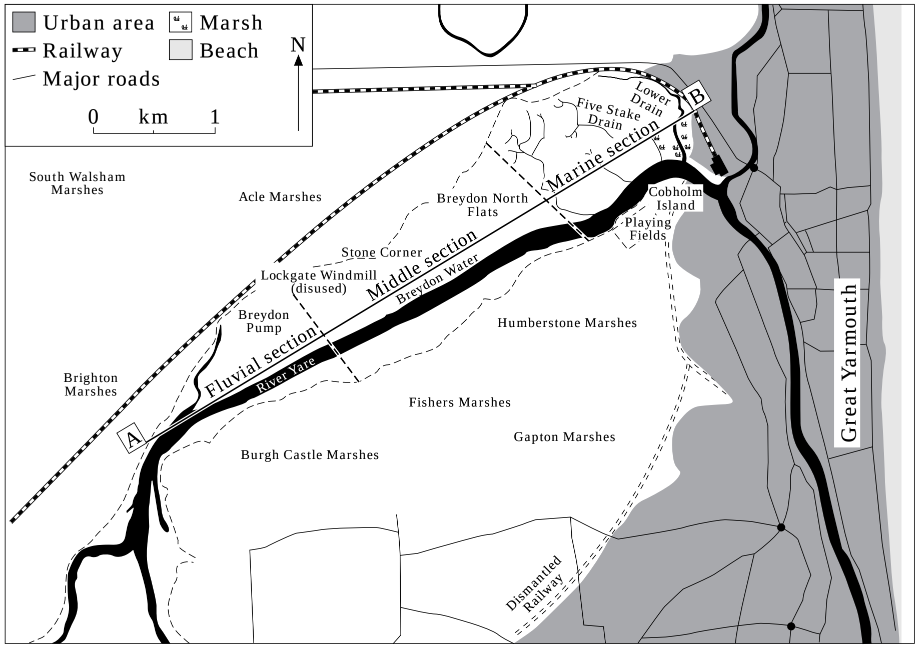

FIGURE 9. The cross-section AB and the extension of marine, middle and fluvial sections within Breydon Water.

The red region could be preferable to the blue region for this reason. Stumpf and Tayler (1988) concluded that a ratio of red to near-infra-red (NIR) reflectance will possibly indicate the presence of chlorophyll *a* in estuaries. A ratio of RED/NIR (TM3/TM4) was adopted to locate the relative concentrations of chlorophyll *a* in Breydon Water. The resulting image showed a uniform concentration throughout the estuary which indicated the failure of this procedure in recognizing chlorophyll *a*. This failure could have been caused by the biological, chemical and physical nature of the water in Breydon Water.

Total phosphorus

Breydon Water is completely flushed within one tidal cycle. Therefore, it does not serve as a ‘ nutrient trap ’ in terms of physical water-movement patterns. Biological utilization, and especially adsorption onto suspended sediment, are the main removers of phosphate from the water (Sabri, 1977). Thirty-three 3×3 samples were extracted, averaged and converted to total phosphorus concentration by using the equation:

$$\text{Total P } (\mu\text{g l}^{-1}) = -11\,050 - 465 \times (\text{TM2- TM3}) + 1237 \times (\text{TM3/TM1}) + 7913 \times (\text{TM2/TM3}) \quad (5)$$
$$(n=12,\ r=0{\cdot}68)$$

Resultant values ranged from 308 to 2992 μg l^{-1}. These are extremely high when compared with the range (160–800) μg l^{-1} reported by Hassan (1988) and cannot be correct. One of the contributors to this biased result could be the fact that Breydon Water has very high silt and clay contents in suspension, and total phosphorus is bound to these particles resulting in a very high concentration of phosphorus (Witzing & Whitehurst, 1981) because of the back scatter of the suspended sediments.

Further analysis

The distributions of suspended solids, turbidity, temperature and salinity appear to have a similar pattern (Figures 3 and 5–7), which is distinguished by high values at the mouth of Breydon Water, low values in the middle, and high values at the confluence of Rivers Yare and Waveney. In order to support this observation, a cross-section AB is taken through Breydon Water starting above the confluence and ending at the NW corner of the mouth, consisting of 18 sample locations (Figure 9). For comparison purposes, the values of each parameter were scaled as high, medium and low, and assigned numerical values ranging from 3 to 1; the results are plotted in Figure 10. This figure demonstrates the existence of a similar pattern for all the indicators in Breydon Water, which is mainly due to the effect of suspended solids. This pattern has been imposed on Breydon Water by flood-ebb and

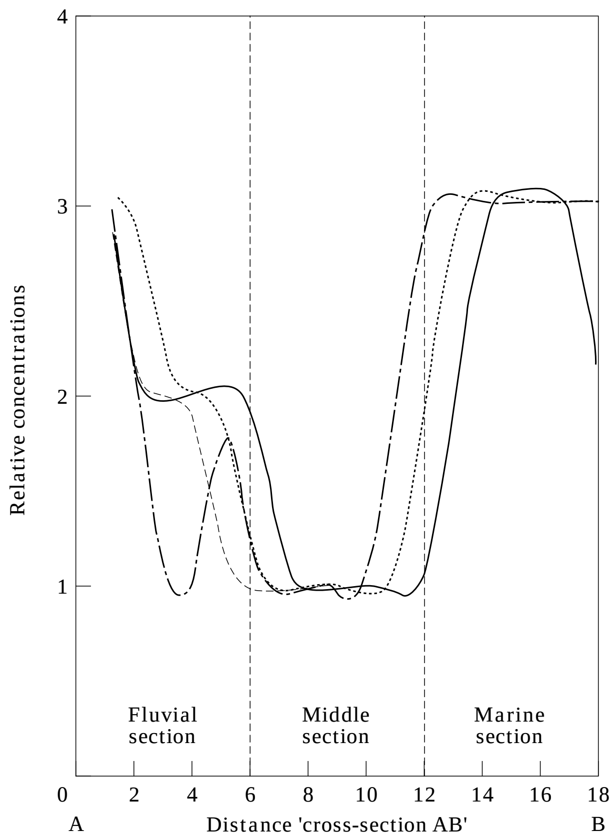

FIGURE 10. Correlations among various and environmental indicators in Breydon Water Estuary along cross-section AB. ——, temperature; – – –, salinity; · · · ·, tubidity; —·—, suspended solids.

sedimentation processes. The two extremities receive the heaviest loads, which consist of relatively coarser sediments, leaving the finer material to settle in the middle (Sabri, 1977), and consequently produce the pattern which is detectable by remote sensing techniques through the influence of the sediments on the reflectance in this environment.

This finding indicates that Breydon Water follows Fairbridge's (1980) definition of an estuary in which he divides the estuary into three sections: marine or lower section; middle section; and fluvial or upper section. The borders between these sections, however, will vary according to the season (Figure 9).

Discussion and conclusions

Results from this study indicate that the spectral sensitivity, resolution and synoptic view of Landsat TM sensors are capable of detecting, estimating and mapping the spatial distribution of suspended solids, turbidity, temperature and salinity in estuarine environments (Figures 3 and 5–7). All results are consistent with previous knowledge (Sabri, 1977; Hassan, 1988), and follow the expected distribution in Breydon Water Estuary.

A cross-section taken through Breydon Water (Figure 9) has revealed that suspended solids, turbidity, salinity and temperature have a similar pattern. Furthermore, the estuary can be divided into three sections (Figure 10): the marine section is characterized by high values; the middle section is characterized by low values; and the fluvial section is characterized by high values. Therefore, Breydon Water follows Fairbridge's (1980) definition of an estuary.

The distribution pattern of all the environmental indicators seems to be influenced by the spatial distribution of both suspended solids and turbidity (Figures 3 and 5). In turn, the spatial distribution of these two indicators is controlled by flood–ebb intervals, the sedimentation process and the internal topography of Breydon Water Estuary.

The predicted chlorophyll *a* values are not reliable (Figure 8). One reason might be that in estuaries, other substances, such as iron oxide, dissolved organic pigment and some algal pigments, absorb the light in the blue and green region, as does chlorophyll *a*, and thus mask its response. The presence of these substances will produce lower values, while suspended solids, which dominate the reflectance, will tend to produce higher values. More radiometric sensitivity is required if passive techniques are to be used in mapping chlorophyll *a* concentrations in estuaries. One solution is to increase the quantization levels, and another is to decrease the dynamic range of the sensors and to match them more closely with the reflectance ranges expected in estuarine environments.

Calculated values for total phosphorus are extremely high, which could be a function of its sorption to the clay particles, but it is more probable that suspended-sediment back scatter dominates the radiance and so gives false values.

A basic knowledge of the estuary's topography was deduced from the turbidity map in conjunction with the ground-referenced map (Figure 2). This information did not exist before, yet it could be significant as water depth is an important factor in defining habitats in estuarine environments (see below).

The clear appearance of the channel on the Landsat image means that it is currently at least 30 m wide, which is almost three times the width reported by Sabri (1977). One explanation might be that when the flow in the channel takes place at first, it is strong enough to erode the banks at the top, resulting in a wider channel.

The spectral region of TM3 was particularly sensitive for mapping turbidity in Breydon Water (Figure

5). This might be due to the existence of suspended matter at the penetration range of TM3, and their concentration range and grain size distribution throughout Breydon Water Estuary. The distribution of turbidity levels is heavily influenced by Breydon Water topography.

Current ground-based techniques for measuring environmental indicators are limited, time consuming and do not give a synoptic view. This work demonstrates the possibility of mapping and studying the spatial distribution of key environmental indicators involving the entire estuary, rather than the interpolation of a number of point samples. Some ground point samples will always be necessary to either check the reliability of remotely sensed data or to calibrate them in terms of the variables being examined.

Britain holds greater estuarine habitat than any other European country. Therefore, it has a particular international responsibility for their conservation. The estimated concentrations and the spatial distribution of mapped environmental indicators in this study in conjunction with the deduced topographical map of Breydon water (see above), can be used in this context:

(1) To establish a better understanding of the physical and biological aspects of Breydon Water dynamics. Due to the mixing of the two water types in the estuary, the environmental indicators often vary rapidly, both spatially and temporally. The organisms in this environment must be capable of surviving these fluctuations. Any attempt to study these fluctuations will require an instantaneous and synoptic coverage at various tidal conditions. Landsat imagery is an ideal medium to provide information of this nature, subject only to cloud cover.

(2) To study the habitats of estuarine organisms, as their physiology is mainly dependent upon the following environmental indicators:

(i) Temperature (Figure 6) is important because the rate of most biological and chemical reactions increase with temperature. Temperature itself can be a pollutant if the water is heated above its normal level by the hot discharge of a processing plant.

(ii) Salinity (Figure 7) has a great impact on the growth and distribution of phytoplankton, as well as the abundance and migration of shrimp and fish population.

(iii) Suspended solids and turbidity (Figures 3 and 5) are important for two reasons: firstly, the concentration of suspended solids and the level of turbidity indicates the quantity of sunlight that can penetrate the water; and secondly, they indicate the amount of undissolved material that is transported in suspension by the water and may eventually settle out in the estuary.

(iv) Water depth (Figure 2) has an influence on i–iii above.

(3) To monitor pollution effects, chlorophyll *a* is a good indicator for biological activity. High concentrations of it may be due to such sources as sewage treatment plants and industrial wastes, and low concentrations of it may be due to toxic substances from industrial sources.

(4) To monitor and examine slowly progressing changes which might endanger elements of food chains (algae, invertebrates and fish) in estuarine' ecosystems. Remote sensing can provide reliable information on the spatial distribution of these species through deductive modelling by mapping and monitoring the fluctuations in the quality and the extent of their habitats (variations in the environmental indicators, water depth, etc.) within the estuary (see 2 above).

(5) To evaluate and monitor the potential impacts of man-made activities on estuary ecosystems and habitats over time, through time-sequence series. These impacts could be generated through the alterations of water salinities and salinity gradients, introducing pollution in the shape of sewage and solid wastes, increasing suspended solids due to urbanization and discharging thermal pollution. An effective evaluation of man-made activities will require an integrated approach with bird, habitat and recreation data.

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