Remote sensing of tropical blackwater rivers: a method for environmental water quality analysis

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Abstract

The paper demonstrates the application of remote sensing techniques to the collection of data on water quality in tropical regions characterized by peatswamp hydrology. The Landsat Thematic Mapper sensor's 0.40–0.52 μm waveband is successfully utilized for identifying and delineating organic plumes at the estuaries of rivers, streams and small drainage channels in a selected study area of the Singapore region. The results are related to the present industrial and tourist development scenario in the Singapore-Johor-Riau growth triangle, and to water quality standards defined within the region.

The quality of water in tropical regions is poorly documented and this lack of information restricts environmentally viable resource development. Where baseline water analysis is carried out, it is often attached to feasibility studies and the data are rarely available subsequently. Development projects may proceed with insufficient data due to the cost of data collection. Many southeast Asian countries do not yet stipulate formal environmental impact assessment, although the assessment and monitoring of water quality on a regional basis is increasingly important due to inter-government initiatives such as that instigated within the Singapore-Johor-Riau growth triangle (Plate 1). This involves the setting up of a trade-free zone to stimulate industrial and tourist development in areas of Malaysia and Indonesia immediately adjacent to Singapore. Multispectral remote sensing offers the potential for assessing both coastal water quality and that in adjacent catchments through the identification of river plumes containing substances which distinguish them visually from non-plume water. On this basis, river plumes whose constituents can be identified and quantified can act as tracers for a variety of coastal processes as well as indicators of water quality in a catchment.

Aims

The aims of the study were to examine the spectral separability of blackwater rivers from other types of water and thus to evaluate remote sensing techniques for assessing water quality on a regional basis. A secondary aim was to utilize the visual characteristics of river plumes as indicators of ecological processes in coastal regions.

Remote sensing and water quality assessment

Remote sensing of water quality in coastal regions is particularly valid in much of southeast Asia due to the highly organic nature of runoff, giving rise to a distinctive
Plate 1. Southern half of a Landsat Thematic Mapper image of 24 May 1989 showing the study area. The islands to the south of Singapore belong to the Riau Archipelago of Indonesia.
marine environment dominated by brackish water of low salinity. Organic water is common in rivers draining inland peat bogs and is visible in estuaries due to its brown colouration. Generally assumed to be imparted by phenolic substances including tannin dyes, the colouration is also attributed to a lack of clay particles in the soil which would otherwise provide adsorption sites for the dark humic material (Sioli 1975; St John 1982). Thus the water is low in suspended sediment as well as inorganic ions and is extremely pure (Sioli 1975). Dark-coloured plumes containing varying concentrations of dissolved organic substances—often referred to as gelbstoff or yellow substance (Kalle 1961)—extend seawards or spread out along the coast according to local tides and currents and are readily identified on multispectral satellite imagery.

Observation of the dispersal of fresh water in the adjacent saline environment may help to identify a range of potential secondary impacts on the coastal ecosystem associated with human-induced alteration of the natural runoff regime.

The sharp contrast in parameters such as temperature, salinity, pH and organic matter content between river and seawater may have implications for resource management and economic development decisions within a region. For example, Carter (1959) attributed interruptions in the mangrove succession on the southwest coastline of Peninsular Malaysia to lowering of salinity where dark tongues of river water with high organic load (observed on air photos) persist adjacent to the coast. The importance of the mangrove environment for the productivity of local fisheries is well known (Ooi 1990). It is notable in this context that salinity is said to be inversely related to yellow substance since yellow substance breaks down by flocculation in water of high salinity (Hojerslev 1980; Mantoura and Woodward 1983). Moreover, land runoff is the only significant source of yellow substance in the sea (Hojerslev 1980).

Thus relative salinity concentration can be derived from observation of the characteristics of yellow-substance-dominated coastal plumes. Observation of yellow-substance concentration can also supplement conventional methods of determining the mixing between different coastal water types, which use temperature and salinity.

Water quality in inland lakes and reservoirs can also be evaluated by examining the spectral characteristics of the plumes draining the catchment or of the waterbodies themselves. This may indicate potential positive or negative impacts due to ecological change. Berg (1961), in studying the distribution of the water hyacinth, Eichornia crassipes, introduced into the Congo river system around 1950, found the plant only in tributaries in the northeast of the catchment in neutral waters above pH 5.2. Since pH values below this level inhibit its growth, areas of potential infestation could be predicted to exclude all locations with acid brown water containing high levels of dissolved organic matter (yellow substance). These areas included all tributaries in the northwest portion of the Congo river system, where lowland peat swamp forests predominate.

The study area

The study area includes the coastal and riverine environments of Singapore and its immediate neighbours—southern Johore, Malaysia, and the Riau Archipelago of Indonesia. The latter is a group of over 2000 islands, the largest of which are Batam and Bintan (Plate 1). The natural resource endowment of the study area is well suited to the issues addressed in this study for the following reasons:
1. Fifty-seven per cent of the world’s tropical organic soils are located in southeast Asia. Over 85 per cent of these occur in Indonesia and 12 per cent in Malaysia.

2. A large proportion of the rivers in this region are blackwater rivers. They drain ombrogenous peat bog, usually found inland of coastal mangroves, tend to be low in nutrients and acid in reaction (Johnson 1967; Whitten 1984). However, few data are available on water quality in the region. Johnson (1967) recognizes four different types of blackwaters in the Singapore–Malaysia region, all having low pH but differing widely in ion concentration.

3. The most noticeable characteristic of the water is its dark brown colour which, together with large amounts of inorganic sediment, extends several kilometres offshore from river estuaries and drainage channels. The plume water is readily differentiated spectrally on air photos or satellite imagery due to high absorption in the short wavelength region and appears black in reflected light.

4. These coastal plumes are not recent phenomena and can be observed on air photos taken in 1952. The plumes have sharp boundaries with non-riverine water even though the near-coastal water is highly turbid within 3 km of the coast. Their shape and size depend on stream size and flow rate as well as on the dominant current direction and tidal state. However, their spatial extent appears large compared with the size of their catchments.

Furthermore, the study area is of interest due to its potential for development.

1. Peat bog soils are not agriculturally fertile and their coastlines are not rich fishing grounds since phenolic substances and/or the low-nutrient content of the water (Andriesse 1988) inhibit organic growth. Due to their undeveloped status and low population density, therefore, these areas are under increasing pressure for non-resource-based industries.

2. Batam and Bintan islands are presently undergoing investigation for light industrial, water resource and tourist development in an international growth triangle linking the three countries—Singapore, Malaysia and Indonesia. Estuarine barrages are proposed for catchments corresponding to over half the land areas of Batam and Bintan islands, accompanied by long-distance trans-national water transport.

Methodology

Baseline environmental conditions for the development scenario described above can be provided by the Landsat Thematic Mapper image of the Singapore region shown in Plate 1. Existing patterns of coastal discharge can be clearly seen on full-resolution images and indicate the type and direction of freshwater runoff.

A 25-km stretch of coastline in Pontian district, Johor, was chosen for more detailed study (Fig. 1). Here, numerous dark-toned river plumes are evident at the mouths of rivers, streams and small channels and extend up to 4 km offshore (Plate 2). The majority of these watercourses are short, having their source only 1–2 km inland, in peat swamp. A few larger watercourses originate on granite at a higher elevation and drain peat swamp only in the lower reaches.

The image was acquired at approximately high tide on 24 May 1989, during the inter-monsoon period when winds and currents were low. In spite of shallow bathymetry, the highly turbid nature of the near-coastal water due to erosion of the mangrove-dominated coastline makes the sea-bed contribution to water volume reflectance negligible in depths greater than 30 cm (corresponding to the critical Secchi disk depth).
Evaluation of the imagery was limited to bands 1, 2, 3 and 6—the visible and thermal infrared bands—due to the negligible spectral response of water in the reflective infrared wavelength regions corresponding to bands 4, 5 and 7 of the sensor (Table 1). Image processing techniques were chosen in order to quantify and enhance the difference between the main types of water quality found in the detailed study area, namely river plume water containing differing concentrations of yellow substance and non-plume seawater. Four main types of coastal water were recognized:

1. plumes draining peat bog only;
2. plumes draining granite, sandstone and peat bog;
3. coastal non-plume water less than 3 km offshore;
4. non-plume water more than 3 km offshore.
Plate 2. Thematic Mapper image of 24 May 1989: 0.45–0.52 μm waveband (blue) showing plumes (P1-P3) corresponding to streams 1, 2 and 3 on Fig. 1, and location of sampling sites (S1–S3) streams 1 to 3, (NP) non-plume water less than 3 km offshore and (SW) non-plume water more than 3 km offshore.

Figure 2 represents the idealized spectral reflectance curves for different water qualities. This indicates a distinct difference in intensity due to high absorptance in the blue wavelength region between water containing high concentrations of yellow substance and other types of water, suggesting that single band processing of TM1 may effectively distinguish areas where land runoff contains high concentrations of yellow substance. Additionally, as the concentration of yellow substance declines, a distinct colour change occurs due to increased reflectance in the blue wavelength region, between 0.4 and 0.5 μm.

Table 1. Landsat Thematic Mapper wavebands and resolution

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (μm)</th>
<th>Spectral region</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45–0.52</td>
<td>Blue</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>0.52–0.60</td>
<td>Green</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>0.63–0.69</td>
<td>Red</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>0.76–0.90</td>
<td>Near infrared</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>1.55–1.75</td>
<td>Near infrared</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>10.50–12.50</td>
<td>Thermal infrared</td>
<td>120</td>
</tr>
<tr>
<td>7</td>
<td>2.08–2.35</td>
<td>Far infrared</td>
<td>30</td>
</tr>
</tbody>
</table>
Thus both single and multi-band processing techniques were investigated, in an attempt to distinguish both high and low concentrations of yellow substance from other water types. These included a density slice of TM1 and TM3. The class limits for the different types of water quality derived from the detailed study area on the Johor coastline were then applied to other areas of the image. These included inland water bodies and the river estuaries of Batam and Bintan islands, Indonesia, many of which are currently being investigated for water supply to Singapore and Riau for both domestic and industrial purposes.

Limited water sampling was carried out—of pH, salinity, conductivity, temperature and Secchi depth—in both fresh waterbodies and seawater corresponding to the sites shown on Plate 2, as well as three stream sites in Batam island.

Due to the long-lived nature (and thus relative time stability) of the blackwater plumes in the area, field data collected at the same time of year, but not synchronous with image acquisition, were considered relevant as an estimate and general indicator of water quality. Direct tests for yellow substance were not carried out, but a linear, inverse relationship between yellow substance and salinity is assumed, as noted above. Water samples initially tested for suspended sediment

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Figure 2. Idealized spectral reflectance curves (after Robinson 1983)
for calibration purposes were discarded as being unreliable due to the small sample volume. The chlorophyll concentration of blackwater rivers is considered negligible due to the oligotrophic nature of the water (Andriesse 1988), thus removing a third potential contributor to water volume reflectance.

Results

Spectral characteristics of plumes

Detailed study area: Johor coastline. Figure 2 shows that the standard reflectance curve for water containing high levels of yellow substance is the reverse of pure seawater. The former exhibits low reflectance relative to pure seawater in TM1 (the 0.45–0.52 μm region), similarity in TM2 (the 0.52–0.60 μm region), and high reflectance relative to seawater in TM3 (the 0.63–0.69 μm region). Statistics derived from training samples in plumes 1 and 2 (P1 and P2) indicate their distinguishing characteristics to be low reflectance in low wavelengths typical of yellow-substance-dominated water. Pixels in non-plume water 5 km offshore (SW) are similar to the spectrum for pure seawater (Fig. 2). This is confirmed by visual inspection of TM1 alone (Plate 2), in which plumes 1 and 2 are distinctly darker than surrounding non-plume water (NP) and much darker than non-plume water 5 km offshore (SW). In the absence of field data for image calibration, limited data from the three streams (Table 2), including salinity, pH and conductivity, suggest that plume 3 contains lower concentrations of yellow substance. Its source on granite and sandstone bedrock beyond the peat bog formation (Fig. 1) would explain and confirm this.

The above-noted colour change for increasing concentration of yellow substance, as reflectance in the blue and green wavelength regions decreases, is readily apparent on a colour composite image as the relatively higher red component of plumes 1 and 2 imparts a reddish hue, whereas plume 3 with lower concentration of yellow substance and a higher green component appears green or yellow. Using TM1 alone, plumes 1 and 2, with low blue reflectance, and plume 3 with somewhat higher blue reflectance, are separable visually and statistically. However, based on spectral characteristics of TM1 alone, plume 3, with lower yellow-substance concentration, is not completely separable from non-plume water. A good separation of all four recognized water types can be obtained using both TM1 and TM3 (Fig. 3b). This combination enhances the colour differences between the blue and red wavelength regions for water containing differing concentrations of yellow

<table>
<thead>
<tr>
<th></th>
<th>Plume 1 stream</th>
<th>Plume 2 stream</th>
<th>Plume 3 stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>29.0</td>
<td>29.6</td>
<td>29.0</td>
</tr>
<tr>
<td>Salinity (%)</td>
<td>0.22</td>
<td>0.02</td>
<td>0.64</td>
</tr>
<tr>
<td>Conductivity (μS)</td>
<td>445</td>
<td>550</td>
<td>285</td>
</tr>
<tr>
<td>pH</td>
<td>5.7a</td>
<td>5.5a</td>
<td>6.4a</td>
</tr>
<tr>
<td>Iron (mg l⁻¹)</td>
<td>2.5a</td>
<td>1.0a</td>
<td>0.5a</td>
</tr>
</tbody>
</table>

* Indicates non-compliance with environmental standards (Table 5) for some (or all) classes of use
Figure 3. Coincident spectral plots based on training signatures in the four water types, showing (a-c) superiority of TM1 for differentiating plumes 1 and 2, with high concentration of yellow substance, from other water types, and of TM3 for differentiating clear seawater, and (d) a 1°C higher mean temperature for plumes 1 and 2 than for other water types.

Thus, a Maximum Likelihood Classification using both TM1 and TM3 produced a very clear differentiation of plume from non-plume water, as well as of the differing concentrations of yellow substance within the plumes (Fig. 4). This classification allocates each image pixel to the most likely class according to the probability distribution of training pixels in the two bands.

Other areas. When the signature statistics for P1 and P2 were applied to the coastline of Bintan Bay, Indonesia, it was found that a density slice (isolating a discrete range of pixel values within a single waveband) of TM1 alone (Plate 3) gave as good a representation of yellow-substance-dominated streams and their dispersal in the bay as a classified image using TM1 and TM3. This is because no significant difference was observed in the concentration of yellow substance between the plumes in this region and high concentrations existed along the centre of each estuary. Thus intensity differences in TM1 were adequate for differentiating plume from non-plume water. Yellow-substance-dominated plumes exhibit low TM1 reflectance whereas both clear and sediment-dominated shallow
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Figure 4. Maximum Likelihood Classified image of TM1 and TM3 showing three concentrations of yellow substance

Water near the coast show high reflectance (Fig. 2). Thus, despite shallow bathymetry and turbid coastal water, organic plumes are readily identified on all major streams entering Bintan Bay using TM1 alone.

On neighbouring Batam Island, where rapid industrial development is taking place in previously low-populated terrain dominated by peat swamp, a density slice of TM1 revealed high yellow-substance concentrations in seven out of some ten main estuaries, the largest of which is to be barraged for water supply. Additionally, inland water bodies containing yellow-substance-dominated water derived from peat swamp catchments were successfully differentiated from other water bodies.

Band ratio

The ratio \( \frac{TM1 - TM3}{TM1 + TM3} \)
Plate 3. Central Bintan Island, Indonesia. The six main rivers entering Bintan Bay show distinct organic plumes (numbered 1–6) along the centre of each estuary and dispersing in the bay. Land is masked except for cloud shadows. Plumes correspond to a density slice of TM1 (DN = 66–77) effectively emphasizes features with a large reflectance difference between TM1 and TM3, the blue and red wavelength regions. Thus clear seawater would be expected to have distinctly higher ratio values than other water types, due to its high reflectance in TM1 and its near zero reflectance in TM3 (Fig. 2). A ratio of TM1 to TM3 effectively enhanced the existing colour differences and gave clear separation between the four water types in the Johor study area. Density slicing of the rescaled pixel values (Table 3) gave a clear differentiation of water quality.

<table>
<thead>
<tr>
<th>Table 3. Rescaled ratio values for training areas, TM1 and TM3</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Plumes 1 and 2</td>
</tr>
<tr>
<td>Plume 3</td>
</tr>
<tr>
<td>Non-plume (NP)</td>
</tr>
<tr>
<td>Clear seawater (SW)</td>
</tr>
</tbody>
</table>

Note: DN (digital number) represents image pixel values on an 8-bit scale (0–255). Three standard deviations from the mean pixel value of each class of water type represent 99.7 per cent of training pixels falling between DN Min and DN Max.
similar to that achieved using a Maximum Likelihood Classification of TM1 and TM3.

**Temperature**

The temperature of blackwater is known to be potentially higher than of clear water bodies due to greater heat absorption (Whitten 1984). Both field and image data showed this to be true in the study area (Table 4 and Fig. 3d). Black Body Temperatures obtained from the Thematic Mapper's thermal band using a quadratic conversion (Malaret et al. 1985) show the yellow-substance-dominated plumes (P1 and P2) to be between 1 and 2°C warmer than those lower in yellow substance (plume 3) and non-plume water. [Conversion of satellite radiance values to Black Body Temperature in °C is not essential unless multi-temporal or multi-sensor comparisons are required. Conversion was carried out for the present study since these comparisons will be made as other satellite data become available. The quadratic conversion of Malaret et al. (1985) was used to convert satellite radiance to Black Body Equivalent Temperature and an emissivity value of 1.0 was assumed. Values obtained are approximately 10°C lower than actual sea surface temperature due mainly to atmospheric absorption. The Landsat TM thermal band digital values are correct to a noise equivalent temperature difference of 0.5°C (Gibbons and Wukelic 1989)].

**Salinity**

Salinity values within plumes 1, 2 and 3 (Table 4) fall well below the limit at which, according to Hojerslev (1980) and Mantoura and Woodward (1983), dissolved organic carbon in coastal water will flocculate and disperse.

**Discussion**

**Environmental standards for water quality**

Not all southeast Asian countries enforce environmental impact assessment for development projects and existing water quality guidelines may be intended to deal specifically with the regulation of the most common industrial pollutants and processing effluents, rather than to provide a wholesome water supply defined across a broad range of parameters.

One exception to this rule is the Republic of the Philippines, which has comprehensive legislation on water quality (comparable with that of many developed countries) defined according to five levels of use. Table 5 indicates the standards specified by the Philippines Natural Environment Protection Council for transparency (Secchi disk depth), pH and iron content for the five uses.

Applying the Philippines standards to the data in Table 2 suggests that river water in the study area does not comply with these standards in terms of acidity, for water use classes A and D, or in terms of iron content for classes A and C. Analysis of the pH and iron content of water from three blackwater streams on Batam Island gave similar levels of non-compliance. Additionally, seawater within the plumes and in non-plume water near to the coast does not meet the minimum standard of transparency for recreation and fish culture (Table 4).
Table 4. Mean image and ground data for seawater

<table>
<thead>
<tr>
<th></th>
<th>Plume 1</th>
<th>Plume 2</th>
<th>Plume 3</th>
<th>Coastal non-plume</th>
<th>Clear sea water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water type&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Location on Plate 2</td>
<td>P1</td>
<td>P2</td>
<td>P3</td>
<td>NP</td>
<td>SW</td>
</tr>
<tr>
<td><strong>Image data</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TM1 radiance</td>
<td>4.19</td>
<td>4.22</td>
<td>4.67</td>
<td>4.91</td>
<td>4.94</td>
</tr>
<tr>
<td>TM2 radiance</td>
<td>3.77</td>
<td>3.62</td>
<td>4.81</td>
<td>4.47</td>
<td>4.05</td>
</tr>
<tr>
<td>TM3 radiance</td>
<td>3.53</td>
<td>3.34</td>
<td>4.30</td>
<td>3.06</td>
<td>2.20</td>
</tr>
<tr>
<td>Black body temp. (TM6)</td>
<td>21.00</td>
<td>21.60</td>
<td>19.60</td>
<td>20.00</td>
<td>20.00</td>
</tr>
<tr>
<td><strong>Ground data</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. (°C)</td>
<td>31.0</td>
<td>31.0</td>
<td>29.0</td>
<td>29.8</td>
<td>29.0</td>
</tr>
<tr>
<td>Salinity (%)</td>
<td>17</td>
<td>16</td>
<td>20</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>pH</td>
<td>7.6</td>
<td>7.3</td>
<td>7.5</td>
<td>7.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Conductivity (μS)</td>
<td>39500</td>
<td>28500</td>
<td>40500</td>
<td>41000</td>
<td>44000</td>
</tr>
<tr>
<td>Secchi depth (cm)</td>
<td>30&lt;sup&gt;b&lt;/sup&gt;</td>
<td>30&lt;sup&gt;b&lt;/sup&gt;</td>
<td>76&lt;sup&gt;b&lt;/sup&gt;</td>
<td>55&lt;sup&gt;b&lt;/sup&gt;</td>
<td>120&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Water types:
1. Plumes 1 and 2 draining peat bog only
2. Plume 3 draining granite, sandstone and peat bog
3. Coastal non-plume water located 3 km offshore (NP on Plate 2)
4. Clear seawater located 5 km offshore (SW on Plate 2)

Coastal hydrology

The classified image (Fig. 4) indicates that the boundaries of the plumes at the surface are sharp and clear for several kilometres offshore, suggesting discrete water masses with distinctive physical and chemical properties not conducive to mixing. Although the dispersal of land-derived yellow substance in the marine environment is poorly indicated (Mantoura and Woodward 1983), the delayed mixing between yellow-substance-dominated water and seawater below a critical level of salinity suggests a direct relationship between plume size and yellow-substance concentration. The critical salinity level may be lower in warmer,
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tropical seas since Mantoura and Woodward observed that in a summer situation in the UK, dissolved organic carbon dispersed at concentrations lower than the critical 35 per thousand salinity level recognized by Hojerslev (1980) (i.e. DOC = 0 at S = 35 per thousand). The present study observed mixing at well below this level; in fact the salinity of seawater in the Singapore region rarely exceeds 32 per thousand.

The large size of plumes observed in the study area may be explained in terms of their persistence and slow mixing rate with seawater at low salinity (Table 4). Additionally, the higher water temperature combined with very low salinity of the plumes appears to create a less dense water mass resulting in a buoyant plume which is further heated by direct solar radiation on the sea surface. Further studies using multi-temporal data are required to confirm this.

Three levels of concentration of yellow substance can be identified on the classified image (Fig. 4). These correspond to high concentration at the centre of plumes 1 and 2, lower concentration at the edges of plumes 1 and 2 and the edge of plume 3, and the lowest concentration for the larger part of plume 3. The unexpectedly high concentration at the outer edge of plume 3 indicates the trapping of riverine water at the saline-freshwater boundary as saline infilling takes place below the surface. This process is enhanced by gravitational circulation in the direction of plume movement (to the right in the northern hemisphere). The differences in temperature, salinity and other chemical characteristics between riverine and coastal water have implications for resource management and economic development in the region.

The overall effect of river discharge on the adjacent ocean in tropical regions is generally to decrease fertility in two ways, thus differing from temperate zone rivers (Ryther et al. 1967): first, by increasing the stability of an already well-developed thermal stratification, thereby reducing the resupply of nutrients from below, and secondly by their lower inherent nutrient levels.

Yellow-substance-dominated plumes further reduce the pH and salinity of seawater, thus hindering mangrove regeneration (Carter 1959). This, as well as the higher temperature of the darker-coloured water, creates an unfavourable environment for marine organisms, which tolerate only a narrow range of these three parameters. Local fisherman avoid the nearshore dark-coloured water, habitually fishing beyond it.

Planning implications

Medium-term environmental planning in this rapidly developing region, as in southeast Asia generally where peat swamp forests are common, may be influenced by riverine and marine waters not meeting minimum environmental standards in terms of pH, heavy metal content, transparency and turbidity due to what may be termed natural factors. Published data on water quality of blackwater streams (Johnson 1967, 1968), as well as limited data collected in the present study (Tables 2 and 4), indicate that stream water may not meet the standards of pH and iron content for most categories of water use. Additionally, such water is usually of low quality as drinking water, being deficient in most nutrients, particularly iodine (Andriesse 1988).

One obvious implication is the incompatibility between dams and estuarine barrages utilizing such rivers for industrial or domestic water supply, and for fisheries or watersports inside the resulting impoundment. On the other hand, increased salinity throughout the coastlines affected by the presently observed river
plumes but outside the immediate estuarine area would be expected to favour mangrove regeneration and productivity of coastal fisheries.

Seawater quality within and adjacent to the coastal plumes falls below the minimum standards of transparency for purposes of primary contact recreation and for fish culture (Table 4). This is due to the combined effect of the dark colour of the water, from land drainage, and tidal resuspension of the blue/grey mud comprising the sea bed on this eroding, mangrove-dominated coastline.

European Community directives on water quality recognize situations in which, due to 'natural phenomena', water may undergo natural enrichment from the soil, which may have public health significance (Kay and Stoner 1988). Where these conditions occur, a member state may itself decide upon appropriate measures, though the ultimate implications for acid-susceptible waters may depend on land use in the catchment and the potential for further acidification.

Conclusion
The superior spectral characteristics of the 0.45–0.52 μm waveband of the Landsat Thematic Mapper offers the potential for identifying yellow-substance-dominated waterbodies and quantifying the concentration of yellow substance in river plumes entering a saline environment due to the delayed mixing of the distinct water types. This depends on the observed image attenuation in the blue wavelength region with decreasing salinity (increasing yellow substance).

A density-sliced ratio of TM1 and TM3 or a two-band classification was able to distinguish all four main water types on the Johor coastline, though TM1 alone proved adequate for differentiating plumes with high concentration of yellow substance from non-plume water both here and in Bintan Island, Indonesia, in spite of high coastal turbidity in both areas. In fact the high reflectance from suspended sediment in coastal waters contrasts strongly with the low reflectance from river plumes, thus improving their identification.

Thus the high absorptance characteristic of yellow substance in the blue wavelength region appears to be adequate for clear identification of organic plumes containing high concentrations of yellow substance, but plumes with lower concentration cannot be adequately distinguished from surrounding water without the addition of TM3.

Further empirical investigation of these relationships in tropical oceans is required, including quantification of the associated sediment contribution to water volume reflectance using field sample calibrations. These are constrained by low image availability in the humid tropics due to cloud cover. However, the technique described here can successfully provide a regional overview of the distribution of acid-susceptible catchments and individual waterbodies down to a size of 30 m. Even with bi-annual image availability, a baseline survey and periodic updating would be possible. Despite the comparatively small amount of existing data on water quality in southeast Asian countries, Landsat Thematic Mapper offers the potential for creating and periodically updating such a database, which is urgently needed in view of the accelerated pace of development and water use.

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