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Use of remote sensing and geographical information systems in developing lake management strategies

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Abstract

This work examines the holistic approach to lake management in terms of relevant in-lake and catchment area parameters. The basic concepts of remote sensing and GIS technologies and the possible use of both in lake studies are explored. The role of remote sensing as a potential data source and of GIS as an analytical tool in developing a management system based on this approach have been investigated through their application to management issues in the Norfolk Broads, England.

Introduction

Hutchinson (1957), some 40 years ago, indicated clearly that lakes are dynamic in nature and experience gradual changes over time. Since then, the slow gradual changes, in many lakes around the world, has been replaced by a more rapid change and swift degradation, mainly due to the additions of plant nutrients, organic matter or sediment. These additions usually produce increased algal and rooted plant biomass, increased turbidity and, typically, decreased lake volumes.

In the U.S.A., about 30% of all lakes and reservoirs assessed during 1988 were either eutrophic or hypereutrophic, whilst 23% were mesotrophic and 14% oligotrophic. The trophic status of 30% of the lakes was unknown (USEPA, 1990). Accelerated eutrophication is also widespread throughout Europe (Gulati et al., 1990), as well as other continents where scientific surveys have reported (e.g. South Africa, Australasia). Minimising the damage requires a clear understanding of the relationships between the loadings and the lake's response.

Elements in lake management strategies

The elements of lake management are well known and it is now widely realised that both control of catchment sources of nutrient (usually phosphorus) as well as in-lake management are necessary (Cooke et al., 1993; Phillips et al., 1999).

Lake management is a relatively new science. Thus, there is still much uncertainty in estimating the cost-effectiveness of some techniques. Remote sensing and Geographical Information Systems (GIS) can be used to provide a rapid or a large-scale understanding of lake change and in developing lake management strategies. The combination of remote sensing as an information source and GIS as an analytical tool enables managers to capture and update all the relevant information (e.g. water quality parameters), plan, simulate/implement, compare, visualise and evaluate the outcome resulting from simulating various management scenarios.

Basic concepts in remote sensing

The main objective of remote sensing, in terms of lake studies, is to record images of lakes and their catchment area by using electromagnetic radiation energy sensors mounted on satellites or aircraft (Figure 1).

The wavelengths that are of most interest to lake studies are the visible (0.4–0.7 μm), where in pure water the majority is transmitted, the near infra-red (0.7–2.0 μm), where the majority is absorbed and thermal infra-red (3–50 μm) (Curran, 1985) (Table 1).

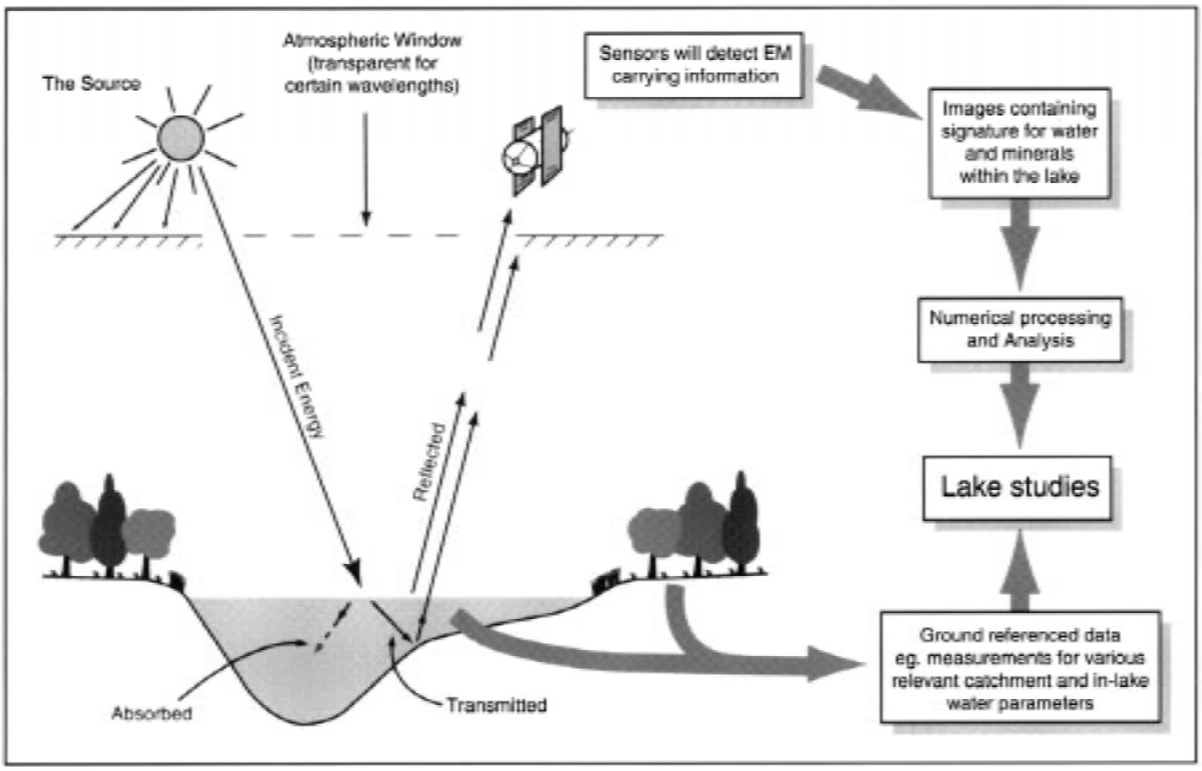

Figure 1. Schematic representation of the collection and use of remotely sensed data.

Table 1. The wavebands recorded by the Thematic Mapper sensor (after Curran, 1985)

Band number	Band name	Band width	Characteristics
TM1	Blue/green	0.45–0.52	Good water penetration, strong vegetation absorbance
TM2	Green	0.52–0.6	Strong vegetation reflectance
TM3	Red	0.63–0.69	Very strong vegetation absorbance
TM4	Near infrared	0.76–0.90	High land/water contrasts, very strong vegetation reflectance
TM5	Near middle infrared	1.55–1.75	Very moisture sensitive
TM6	Thermal infrared	10.4–12.5	Very sensitive to soil moisture and vegetation
TM7	Middle infrared	2.08–2.35	Good geological discrimination

The factors that affect the spatial variability in reflectance of a lake are usually determined by its physical configuration, water quality and climate. The three most important factors are: water depth, suspended materials (i.e. non-organic sediments, tannin and chlorophyll) and the surface roughness (Lillesand & Kiefer, 1994).

The interaction between electromagnetic energy, the water and the materials contained within it, results in various processes which depend on the wavelength and the atomic structure of water and its contents. The energy balance relationship is expressed thus:

$$E_{\mathrm{I}}(\lambda) = E_{\mathrm{R}}(\lambda) + E_{\mathrm{A}}(\lambda) + E_{\mathrm{T}}(\lambda),$$

where the incident energy (E_{I}) is a function of the reflected (E_{R}), absorbed (E_{A}) and transmitted (E_{T}). In this equation all the energy components are a function of wavelength, which has two important implications for lake studies. Firstly, the proportions of energy reflected, absorbed and transmitted will vary for different lakes, depending on their environmental and ecological conditions. Secondly, for a particular characteristic of a lake (i.e. water depth), the proportion of reflected, absorbed, and transmitted energy will vary at different wavelengths. Thus two features (i.e. shallow and deep water) may be indistinguishable in one spectral band and be very different in another spectral band. Thus each lake and its catchment may provide characteristic spectral signatures for analysis.

The use of remote sensing in lake management is based on the fact that the consequences of eutrophication and an increase in productivity will be associated with a change in the optical properties of the water mass. Increases in chlorophyll '*a*' are associated with a decrease in the relative amount of energy in the blue wavelength (0.45–0.52 μm) and increases in the green wavelength (0.52–0.60 μm) (Clarke et al., 1970). Increases in suspended solids are associated with an increase in the reflected energy, and the peak of reflectance will move towards the longer wavelengths (Lillesand & Kiefer, 1994). These changes are measurable by remote sensing techniques (Baban, 1996).

Most Earth observation from space is carried out by satellite-mounted instruments which have a number of sensors operating at different wavelengths. The popular instruments such as the Landsat Thematic Mapper (TM), System pour l'Observation de la Terre (SPOT), and the Advanced Very High Resolution Radiometer (AVHRR), have suites of sensors operating in most wavelengths relevant to lake studies (the visible and infrared regions). These should provide the staple diet of limnologists, hydrologists and ecologists, since their spectral coverage corresponds to regions of high energy output from the Sun and Earth, and suitable atmospheric windows, where the electromagnetic energy receives least distortions. More recently, Synthetic Aperture Radar (SAR) imaging devices have come to the fore, because even the visible and infrared atmospheric windows are shuttered when cloud is present. The microwave wavelengths of radar beamed down from satellite antennae readily penetrate cloud, to bounce off the lake surface and return to the spacecraft. These echoes are used to construct images containing information about morphology and composition.

The following concepts are important in selecting satellite imagery (Barrett & Curtis, 1992):

(1) Spatial resolution: this is the smallest feature size that can be studied in an image. This translates into a measure of the smallest ground objects that can be distinguished as a separate entity, usually as a single pixel on the imagery.

(2) Spectral resolution: the sensor capability to record spectral information at a particular range of wavelengths. Some sensors are broad-band and capable of recording energy across a range of wavelengths. Others are finely adjusted perhaps to the discrete reflectance frequency of a particular pollutant in a lake.

(3) Radiometric resolution. The amount of electromagnetic energy falling on a satellite sensor varies more or less continuously but the actual range of energies that can be recorded, and the precision of the measurement, depends on the operating range and radiometric resolution of the instrument.

(4) Temporal resolution. Satellites are placed in regular orbits so that they can regularly revisit a given location on the Earth. The time between visits depends on the angular field of view of the sensor, the latitude and longitude of the area of interest, and the characteristics of the spacecraft orbit.

Sensor design is largely concerned with reaching a compromise between these various kinds of resolution, since an increase in performance in one respect generally means a deterioration in another. The balance is met by optimising the sensor for the purposes for which it is expected to be used. The limnologist will need to consider the relative importance of spectral, radiometric, spatial and temporal requirements for a given objective, as well as the budget and economic viability, before deciding on which imagery to obtain.

Sensors produce a digital image containing the signatures of the water and its contents in the lake as well as the relevant attributes in the catchment area. This raw image needs to be adjusted and numerically processed through number of stages (e.g. correcting the image for any distortion and degradation, increasing the apparent distinction between the features to optimise visual interpretation, and to maximise the contrast between features of interest) producing an optimised image for use by a limnologist. Finally, the image needs to be calibrated with a number of measured parameters on the ground, the 'ground truth' samples.

Remote sensing and lake management

Remotely sensed data can never replace conventional hydrological observation networks in lakes, but they can provide essential information for developing lake management strategies. This is mainly due to:

(1) the provision of information that resembles reality as closely as possible (high resolution area-based synoptic data collected on a regular basis instead of conventional point measurements);

(2) the ability to deliver composite measurements (radiation/ reflectance), which integrates several relevant ecological characteristics of lakes;

(3) the ability to provide information concerning land categorisation and classification as well as some geomorphic elements required for lake management;

(4) the digital format of remotely sensed data makes it easy to retrieve and analyse large amounts of information at low cost in a short period of time.

Remote sensing has successfully extracted and provided relevant information on catchment characteristics, e.g. mapping the extent and the change in agricultural land over a particular period (Pattie, 1993) as well as providing the necessary in-lake water quality data for management including; chlorophyll 'a', total phosphorous, Secchi disk depth, suspended solids, salinity and temperature (Baban, 1993a, 1994; Smith & Addington, 1978).

Water circulation patterns can be detected through a study of the distribution of suspended sediments, which can act as natural tracers to indicate flow directions. Recent examples have used both reflective and thermal bands to map the spatial and temporal distribution of sediments and to deduce water circulation patterns in lakes from these maps (Baban, 1993a). Sediment distribution patterns deduced from Landsat imagery were also found to be positively correlated with sedimentation patterns in lakes by Smith et al. (1983).

Various mathematical algorithms have been used to estimate water depth in lakes using information from the 0.45–0.70 μm region. Such algorithms have been developed, tested and used to produce bathymetric charts for lakes (Baban, 1993b; Hathout, 1985). Therefore, remote sensing can also provide information about the shape of the lake basin. Shape has a major effect on lake productivity, types of organisms, water chemistry and upon the choices available to manage and restore it (Cooke et al., 1993). The thermal patterns in many lakes have been studied using remotely sensed information from the thermal infrared band (Baban, 1993c). Information relating temperature patterns to lake depth are essential.

Incorporation of Geographic Information Systems

In terms of lake studies, GIS can be defined as a powerful set of tools for capturing, storing, checking, manipulating, combining, analysing and, displaying data which are spatially referenced to lakes and to their catchment areas (Burrough, 1986; DeMers, 1997). Although different GIS software may vary in capabilities, most contain the following components (Martin, 1991):

(1) Data collection and input. Operations concerned with receiving data into the system, including manual digitizing, scanning, keyboard entry of attribute information, and online retrieval from other database systems.

(2) Data storage and retrieval mechanisms which organize the spatial data into a form that permits it to be quickly retrieved by the user for subsequent analysis, as well as allowing for rapid and accurate updates and corrections to be made to the spatial database.

(3) Data manipulation and analysis represents a group of techniques which converts data through user-defined aggregation rules, or produces estimates of parameters and constraints for various space-time optimization or simulation models.

(4) Data reporting, which cover a range of operations concerned with the display of all or part of the original database, as well as manipulated data, and the output from spatial models in tabular or map form.

Data acquisition represents an important part of a water resource based GIS project. It is labour-intensive and can account for up to 80% of the total cost of a GIS. Various data acquisition options for hydrologic oriented GIS are presented by Van Blargan & Ragan (1991) including, manual digitizing, commercial digitizing, satellite products, and automated scanning. Data storage in GIS is established by using either raster or vector data structures. A raster structure describes the geographical space in terms of a two-dimensional grid of rows and columns, whilst a vector system describes the space in terms of points, lines and areas. A raster-based GIS has advantages over a vector-based GIS in lake studies because virtually all types of relevant data, including remotely sensed data and scanned maps, are represented in raster form. However which format to use depends on two aspects of the specific application; first, the nature of the phenomenon the data represents and secondly, the processes that need to be performed on the data in order to realise all the necessary objectives.

Applications of GIS to lake management can be classified into two main areas, inventory studies and modelling.

Inventory studies

Inventory is the collection of base-line data and, its subsequent storage in a GIS for monitoring and management purposes. For example, prior to conducting an analysis of data, the process requires a number of lengthy and time consuming preparations, including collecting data on, lake topography, water quality, sources of pollution, climatic, etc. Followed by compilation, storage, retrieval and manipulation. GIS has evolved as a highly sophisticated database management system to put together and store the voluminous spatial data typically required in hydrologic modelling (Bhaskar et al., 1992; Vieux et al., 1988).

Modelling

The ability of a GIS to characterize and model the spatial variations in hydrological processes makes it an effective aid for managing the use of land within a drainage basin (Stuart & Stocks, 1993). Modelling capabilities of GIS can also be used to simulate various lake processes and to predict the outcome of development actions, natural hazards or environmental change within the contributing basin. Sharma & Anjaneyulu (1993), for example, have successfully integrated the use of GIS geo-referenced overlays with satellite imagery to study the degradation in water quality in Vembanad lake, India. The lake is endangered with two problems. First, it is becoming brackish due to an ingress of salt water from the Lakshadweep sea during high tide whenever the Tannir Mukkom barrage is opened for navigation. Secondly, it is becoming silted due to sediments contributed by streams from the south and east. The study used GIS to model the quality of water front movements during January, March and May.

GIS offers an effective spatial data handling tool that can enhance various hydrological lake models through interfacing. For example, the lake eutrophication model, PROTEC (Reynolds, 1999) models the growth rates of a number of algal types according to the nutrient levels and light climate within the lake. Input requirements to this model are extensive, requiring daily flow rates and nutrient concentrations of each major inflow to the lake. Wright (1994) has investigated the possibility of using a GIS system to estimate this set of inputs, with the aim of reducing field sampling efforts required to run the model.

The use of a model interactively within a GIS has a number of advantages such as; a short running time and an almost immediate turnaround of results. Smith et al. (1992) used GIS to calibrate and verify a continuous simulation model as well as an event-driven model. They found it beneficial in enhancing the modelling efforts due to increased accuracy, and minimization of human errors and time. Penning-Rowsell (1996) created and tested a spatially and temporally distributed deterministic model using a GIS. This model deals with phosphorus sources and loads from both non-point sources in the surrounding catchment and from sewage treatment works to streams flowing into lake Bassenthwaite and predicted the daily total phosphorous loads entering this lake.

A holistic approach to lake management

The large number of lakes suffering from eutrophication, often clustered in lake districts, makes conventional management difficult and yet favours the development of a holistic approach using remote sensing and GIS. Landsat imagery has been available for over 20 years in a relaible format, and is widely used. Smith & Blackwell (1980) developed an information system by integrating digital landsat data, digital terrain data, conventional maps and ground truth data for Lake Tahoe and its catchment. The system allowed them to cross correlate the remotely sensed information and topographic data with a variety of environmental data relating to such parameters as surface runoff, drainage basin area, and terrain configuration. Parameters were evaluated and compared for each drainage basin defined by the regional planning agency.

The holistic approach will allow managers to observe and model, for instance, the effects of a particular ecological scenario on a large number of small lakes or the full spatial extent of large lakes concurrently and over appropriate periods of time. This capability will facilitate experiment with various management scenarios through the GIS simulation facilities. It will also provide data for areas which have no ground measurements based on the interpolation of area-based information from a number of sampled lakes/locations, subject to their size and the spatial resolution of the imagery.

The Norfok Broads

The Norfolk Broads, a series of about 40 shallow lakes in eastern England (Phillips et al., 1999) (Figure 2) are taken as an example of these procedures.

The majority of the Broads are connected to a river by narrow dikes, while some are isolated. This feature, and the low flow rate of rivers, have been largely responsible for the rapid sedimentation in the Broads. As a result water depth ranges from 21 cm at Surlingham to 366 cm at Fritton Decoy (Mason & Bryant, 1975).

The water in the Broads is well mixed with little possibility of thermocline formation (Moss & Timms, 1982). Most of the Broads are no longer clear water and are without submerged plants, but frequently have a growth of unwanted and high concentrations of algae. The Broads in addition to low river flows suffers from depleted groundwater (water resources), the threat of increased saltwater incursion and flooding. The Broads Authority (1997) sets out an integrated management plan based on the central issues of water resources, water quality and flood protection. Clearly, the plan recognises that the quantity and quality of water in the Broads are influenced by water management in the Broads as well as landuse practices within their catchment areas. In recent years a number of the broads damaged by eutrophication have been restored using techniques for nutrient control, ecological engineering using fish manipulation, plant and fish re-establishment (Moss et al., 1996; Phillips et al., 1999).

The Landsat Thematic Mapper (TM) is a scanner carried on Landsat 4 & 5 satellites. It records 256 radiance levels in seven wavebands, operating in the range from blue to thermal infra-red (Table 1). The spatial resolution of all bands is 30 m apart from the thermal band which is 120 m. A Landsat TM imagery was used to estimate chlorophyll *a*, total phosphorus, suspended solids, salinity and temperature (Tables 2–4; Figures 3–6) in the Norfolk Broads using algorithms designed for water quality output from TM data (Baban, 1993, 1994, 1996). It was not possible to locate a control set of water quality data corresponding to the remotely sensed data as the National Rivers Authority did not then have a comprehensive sampling programme. Equivalent field data available for five Broads (Table 5) show general correspondence, although as data were not concurrently collected statistical comparison cannot be made.

Inputting the estimated data into the Carlson Trophic State Index (TSI) (Table 6) allows the Broads to be trophically ranked (Table 7, Figure 7).

The available Landsat TM images for the Norfolk Broads region (path 210, row 23) are listed in Table 8. As the availability of these images is hindered by cloud cover, calculating the amount and seasonal variation in susnshine hours is essential. The amount and seasonal variation in sunshine hours (a direct indication of cloud cover), taken from the Weather Log, Royal Meteorological Society, together with hours of daylight at latitude 50° N (Pearce & Smith, 1984), were used to calculate percentage possible sunshine (PS) for each month (Table 9). The outcome indicates that the lowest percentage of sunshine is during January (19.7%), while the highest is in May (44.6%). The Broads during the months from April to September when biological water quality information is most critical have a reasonable chance of obtaining regular and useful coverage.

A management information system could thus be built up based upon the concepts described above within a GIS framework (Figure 8) (Ragan & Fellows, 1980) and maintained up-to-date through an appropriate combination of satellite images and concurrent ‘ground truthing’.

The spatial, thematic and temporal characteristics of information provided by satellite imagery can provide the best spatial and temporal coverage of lakes and their catchment area. The management, visualisation, modelling and simulation capabilities of the GIS make a powerful and unique medium to take full advantages of the richness of digital remotely sensed information in terms of developing, testing and simulating and examining the consequences of implementing of any individual management strategy on lakes and their catchment areas.

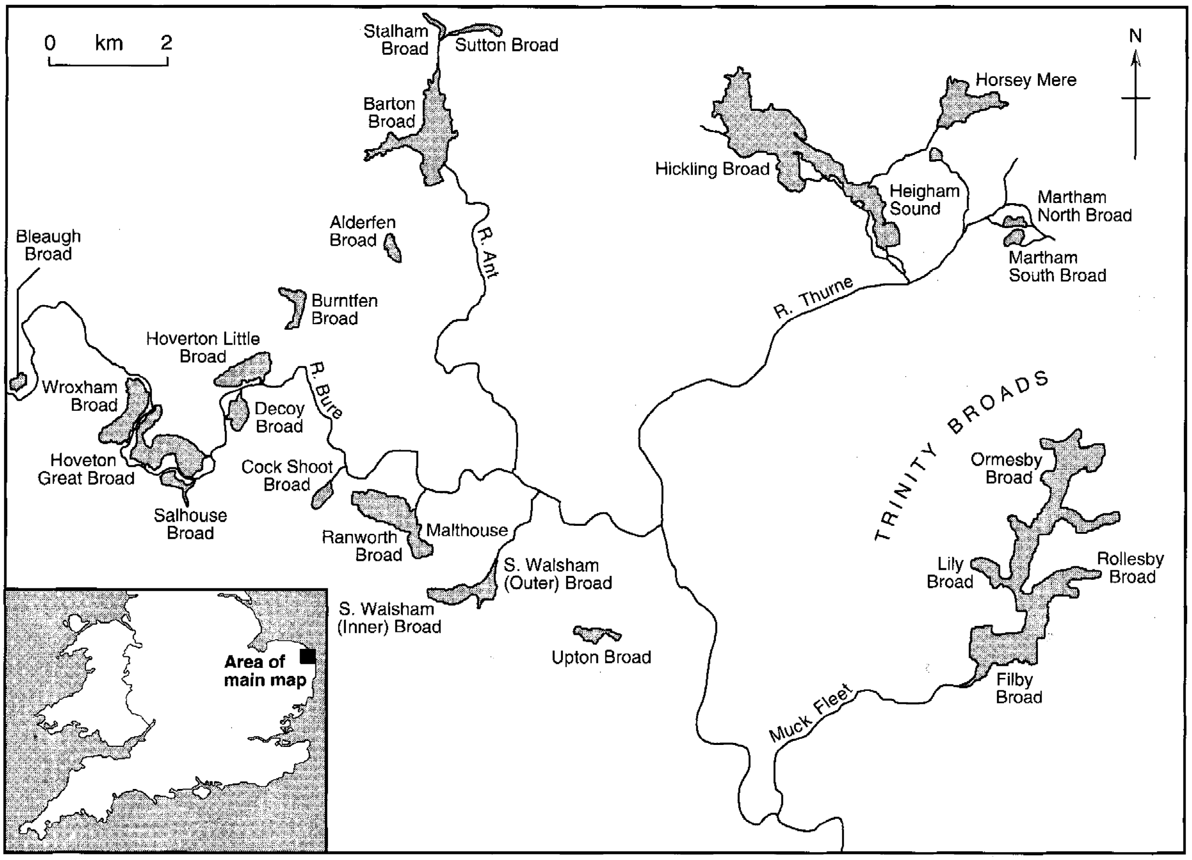

Figure 2. The Norfolk Broads.

Table 2. TM bands 1–4 and their combinations correlated with ground referenced data represented by the correlation coefficient (r) and the coefficient of determination (r^2). All these relationships are significant at the 99% confidence level apart from the ones which are marked by a (*) where they are only significant at the 95% level or less (after Baban, 1993a).

	Chlorophyll-*a* (μg/l)		Total phosphorus (μg/l)		Secchi depth (μg/l)		Suspended solids (μg/l)		Salinity (μg/l)	
Variables	r	r^2	r	r^2	r	r^2	r	R^2	r	r^2
1) TM3	0.85	0.72	0.75	0.56	0.76	0.58	0.77	0.59	0.75	0.56
2) TM2–TM3	−0.24	– *	−0.17	– *	0.44	0.19 *	−0.33	– *	0.07	– *
3) TM2/TM3	−0.52	– *	−0.17	– *	0.44	0.19 *	−0.55	– *	−0.10	– *
4) TM1/TM2	−0.73	0.53 *	−0.69	0.48 *	0.48	0.23 *	−0.33	– *	−0.38	– *
5) TM2	0.85	0.72	0.78	0.61	−0.58	0.34 *	0.67	0.45 *	0.51	– *
6) TM3/TM1	0.85	0.72	0.77	0.59	−0.8	0.64	0.64	0.41 *	0.76	0.58
7) (TM2+TM3)/2	0.85	0.72	0.77	0.59	−0.73	0.53 *	0.74	0.55	0.65	0.42 *
8) (TM2)^2	0.85	0.72	0.73	0.53 *	0.67	0.45 *	0.52	0.27 *		
9) (TM3)^2	0.85	0.72	0.73	0.53 *	−0.81	0.66	0.64	0.41 *	0.82	0.67
10) TM1	0.76	0.58	0.68	0.46 *	−0.83	0.69	0.88	0.77	0.66	0.43 *
11) (TM1+TM2)/2	0.83	0.69	0.75	0.56	0.82	0.67	0.84	0.71	0.62	0.38 *
12) (TM1+TM3)/2	0.81	0.66	0.72	0.52 *	−0.83	0.69	0.85	0.72	0.71	0.50 *
13) TM4	0.56	– *	0.43	– *	0.01	– *	0.63	0.40 *	0.51	0.26 *

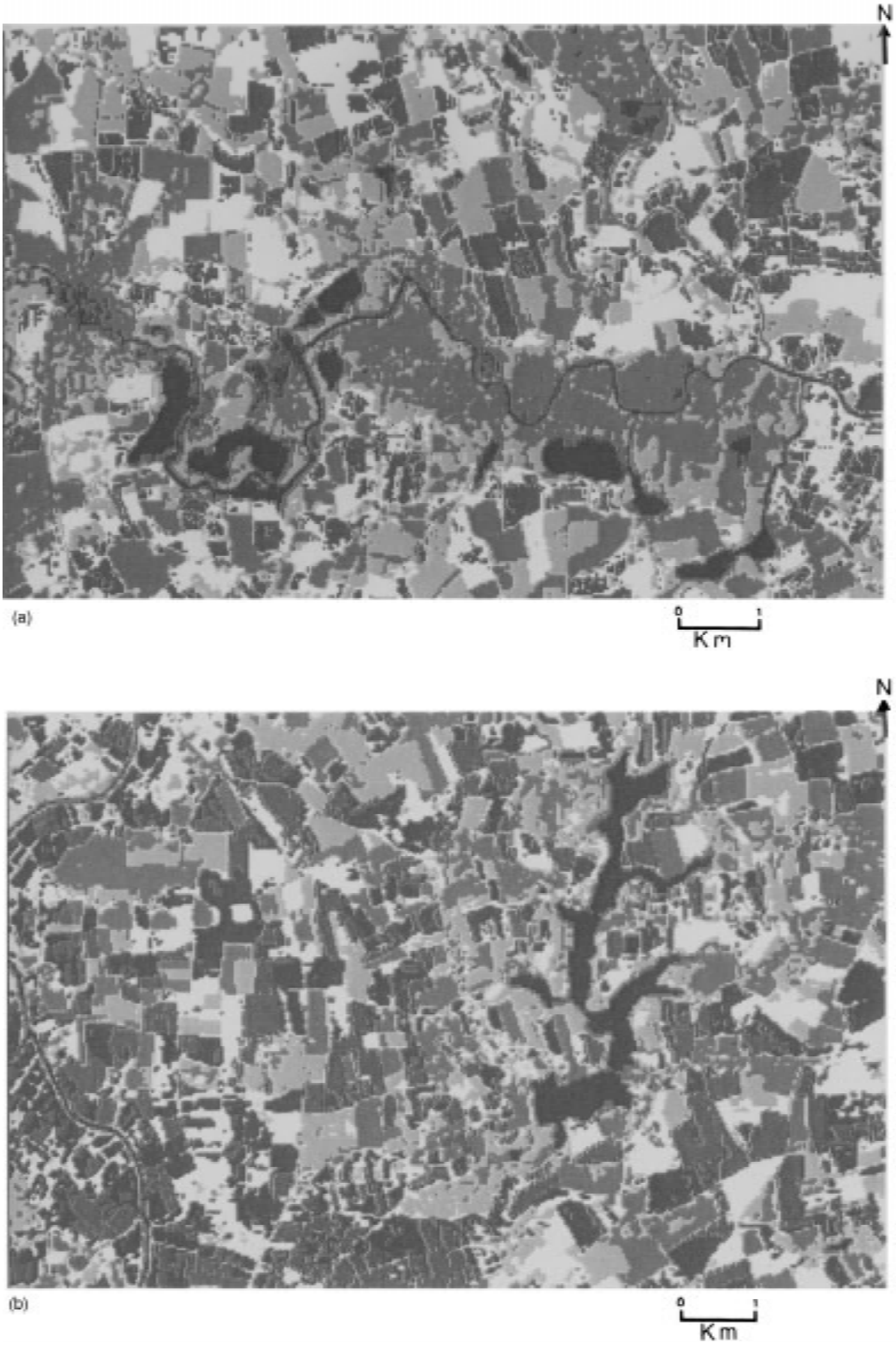

Figure 3. Satellite images of (a) the River Bure Broads and (b) the Trinity Broads.

Table 3. Predicted water quality parameters for the River Bure Broads and its surrounding Broads for June 1979 and June 1980 (after Baban, 1993a).

Broad	Pred. chlor-*a* (μg/l)	Pred. total P. (μg/l)	Pred. Secchi depth (m)	Pred. S. solids (μg/l)	Pred. salinty (μg/l)	Pred. temp. (°C)
Malthouse	117.4	271.3	0.4	38.7	94.0	17.55
Ranworth	129.4	296.1	0.6	25.5	89.7	17.90
Cockshoot	47.1	230.1	0.7	11.1	64.6	18.07
Decoy	40.3	179.9	0.6	17.7	64.6	17.20
Salhouse	40.2	190.7	0.6	19.2	68.9	17.65
Hoveton Gt.	37.5	166.1	0.6	23.2	72.2	16.85
Burntfen	69.4	212.5	0.6	26.3	75.5	16.53
Belaugh	61.5	173.5	0.5	31.0	79.3	15.1
Hoveton Lt.	96.3	215.1	0.5	31.6	87.4	17.2
S. Walsham (outer)	69.5	199.6	0.5	29.3	78.7	17.2
S. Walsham (inner)	51.1	165.5	0.5	32.1	75.5	17.55

Table 4. Predicted water quality parameters for the Trinity Broads, River Thurne and River Ant Broads for June 1979 and June 1980 (after Baban, 1993a).

Broad	Pred. chlor-*a* (μg/l)		Pred. total P (μg/l)		Pred. S. solid (μg/l)		Pred. Salinity (μg/l)		Pred. Secchi depth (m)		Pred. temp. (C°)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Ormesby	56.7	8.3	101.1	21.4	47.6	4.4	89.3	0.7	0.4	0.1	16.27	0.2
Rollesby	58.2	9.2	122.7	19.9	42.6	2.8	86.4	3.3	0.4	0.1	16.38	0.2
Filby	110.4	9.5	182.1	20.6	51.2	1.3	103.1	2.7	0.3	0.1	16.62	0.4
Lily	53.7	–	168.4	–	32.5	–	76.5	–	0.5	–	16.32	0.2
Hickling	222.8	29.6	375.4	17.1	45.7	10.9	124.8	15.1	0.4	–	16.32	0.2
Horsey Mere	210.4	13.1	470.8	18.7	56.7	5.5	136.5	6.1	0.2	0.1	16.15	–
Black Feet	83	–	249.2	–	21.6	–	74.4	–	0.6	–	14.75	–
Heigham Sound	135.2	–	261.7	–	38	–	99.5	–	0.5	0.1	16.15	–
Martham	37	–	13.7	–	34.1	–	75.5	–	0.5	–	16.15	–
Sutton	169.2	–	462.4	–	40.6	–	102.4	–	0.4	–	16.85	–
Barton	77.2	17.5	178.6	30	35.7	1.1	95.5	9.8	0.4	0.1	16.62	0.2
Crome’s	87.1	–	255.4	–	23.6	–	75.8	–	0.6	–	16.67	–

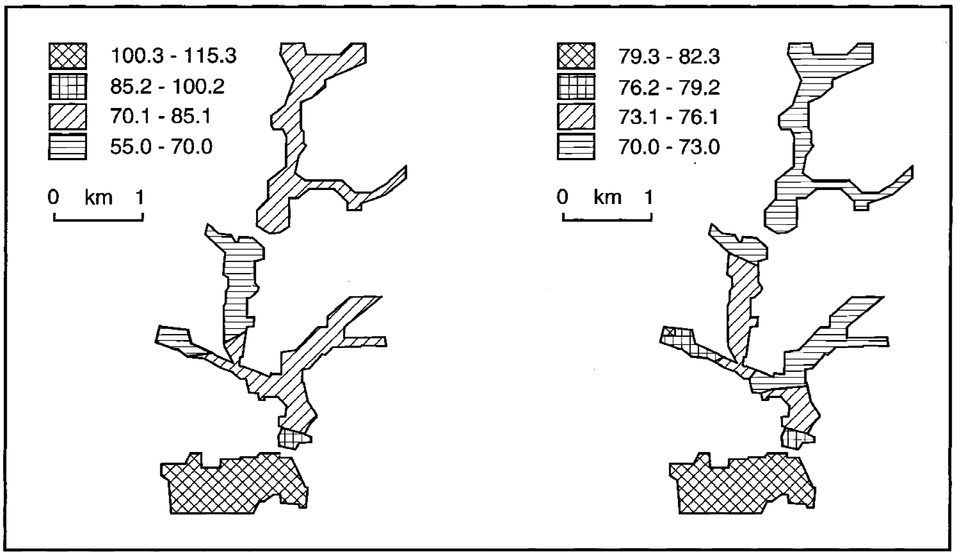

Figure 4. The distribution of estimated chlorophyll-*a* and total phosphorus (both in μg l^{-1}) in the Trinity Broads from June 1979 and 1980 images (after Baban, 1993a).

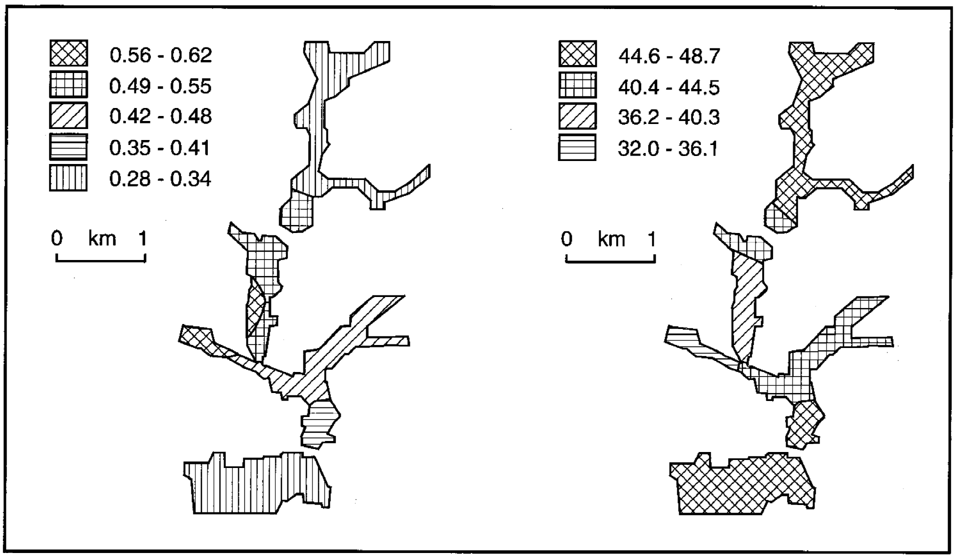

Figure 5. The distribution of estimated Secchi depth in m and suspended solids in mg l^{-1} in the Trinity Broads from June 1979 and June 1980 images (after Baban, 1993a).

Table 5. Ground truth data (mean value for June 1979 and June 1980) for water quality parameters in the Broads.

Broad	Concentration (μg/l)				Secchi depth (m)	Temp. (°C)
	Chlor-*a*	Total P.	S. solid	salinity		
Malthouse	165.5	390.5	34.45	116	0.365	17.33
Ranworth	122.5	281.5	24.95	89.5	–	–
Cockshoot	34.5	191	12	79.5	–	–
River Ant	190	332	61	114.5	0.26	–
Decoy	31.5	202	10.15	62.5		–
Salhouse	84.5	159.5	22.75	64.5	0.74	17.5
Hoveton Gt.	87	203.5	25.8	62.5	0.535	17.5
Burntfen	38.5	152	10.9	87	0.65	15.9
Belaugh	31.6	300.5	31.8	59.5	0.545	15.1
Hoveton Lt.	94.7	342	27.9	72	0.6	17.17
S. Walsham (outer)			36.55		0.415	17.5
S. Walsham (inner)			41.15		0.44	17.5

Table 6. Carlson trophic state index (TSI) values for the Trinity Broads, River Ant and River Thurne Broads, using different waterquality parameters from Table 4 (after Baban, 1996).

Broads	TSI		
	Chlor.-*a*	Total P.	Secchi depth
Ormesby	70.2	70.7	73.6
Rollesby	70.4	73.5	74.3
Filby	76.7	79.2	78.4
Lily	69.6	78.1	69.7
Hickling	83.6	89.7	74.3
Horsey Mere	83.0	92.9	80.6
Black Feet	73.9	83.8	66.9
Heigham Sound	78.7	84.5	70.3
Martham	66.0	74.6	70.9
Sutton	80.9	92.7	72.5
Barton	73.2	79.0	71.5
Crome’s	74.4	84.1	67.4

Table 7. Trophic categorisation of the Norfolk Broads based on the effect of nutrient loads (after Baban, 1996).

Group A:

There is nutrient loading but it is not the major influence for algal growth due to opposed influence of the replacement flushing rate (water residence time) and sediment coefficient is the loading of solids carried by water from the surrounding land into a water body and depends on two things: the size of the catchment in relation to the area of the lake and the rate of removal of the substance per unit area of catchment). The outcome wll be similar calculated TSI values for both Secchi disk depth and chlorophyll-*a* and much higher index values for total P. Typical examples for this group include Barton Broad (Table 6).

Group B:

Nutrient loading is the major influence for algal growth; this will result in variable TSI values for all parameters. The magnitude of the differences between these values is mostly proportional to the phosphorus activity. The following Broads represent good examples of this group: Hickling and Heigham Sound (Table 6).

Group C:

These is no loaded nutrient (or may be very little), the index value for all the parameters are similar. Typical examples include: Ormesby, Rollesby and Filby (Table 6).

Table 8. Availability of Landsat TM for the Norfolk Broads, 1984–1994 .

Date	Date
14.05.1984	25.04.1991
21.10.1984	07.07.1991
02.06.1985	21.07.1991
14.12.1986	30.07.1991
14.10.1987	05.08.1991
19.02.1988	31.08.1991
06.08.1988	22.01.1992
21.02.1988	29.01.1992
21.02.1989	14.02.1992
21.05.1989	20.05.1992
28.05.1989	22.01.1992
24.07.1989	21.04.1993
15.07.1989	07.05.1993
12.03.1990	07.05.1993
06.04.1990	23.05.1993
16.06.1990	08.06.1993
02.07.1990	10.07.1993
03.08.1990	27.08.1993
20.09.1990	19.02.1994

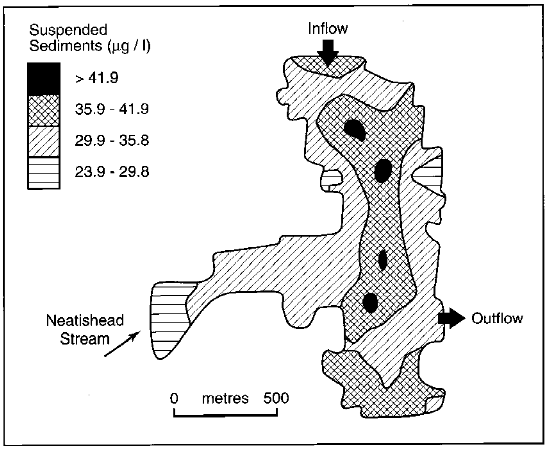

Figure 6. The estimated distribution of suspended solids in Barton Broad from June 1979 and June 1980 images (after Baban, 1994).

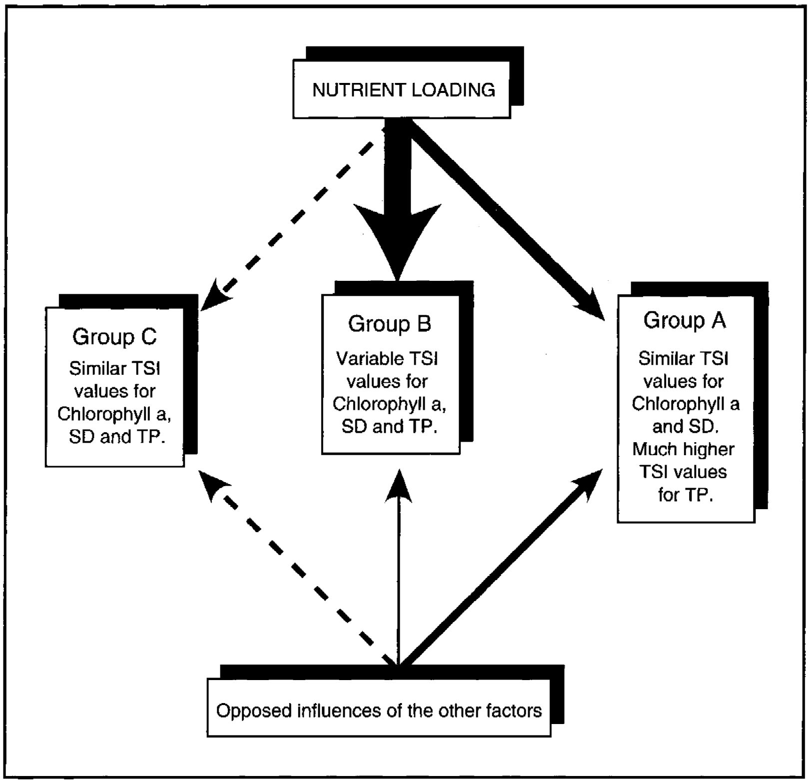

Figure 7. The alternative effects of nutrient loading on trophic state in the Broads (after Baban, 1996).

Table 9. Average sunshine, the length of day and percent possible sunshine in the Norfolk Broads area (calculated from data provided in the Weather Log, Royal Meteorological Society data and Pearce & Smith, 1984).

Month	Av. sunshine	Hours of daylight	Percent possible sunshine
January	50.82	8.30	19.75
February	66.67	10.07	22.83
March	119.01	11.48	33.44
April	170.37	13.44	42.45
May	210.48	15.22	44.61
June	216.05	16.21	44.42
July	202.20	15.38	42.41
August	182.24	14.33	41.02
September	150.45	12.42	40.38
October	114.03	10.47	35.13
November	60.21	9.06	22.15
December	50.00	8.05	20.04

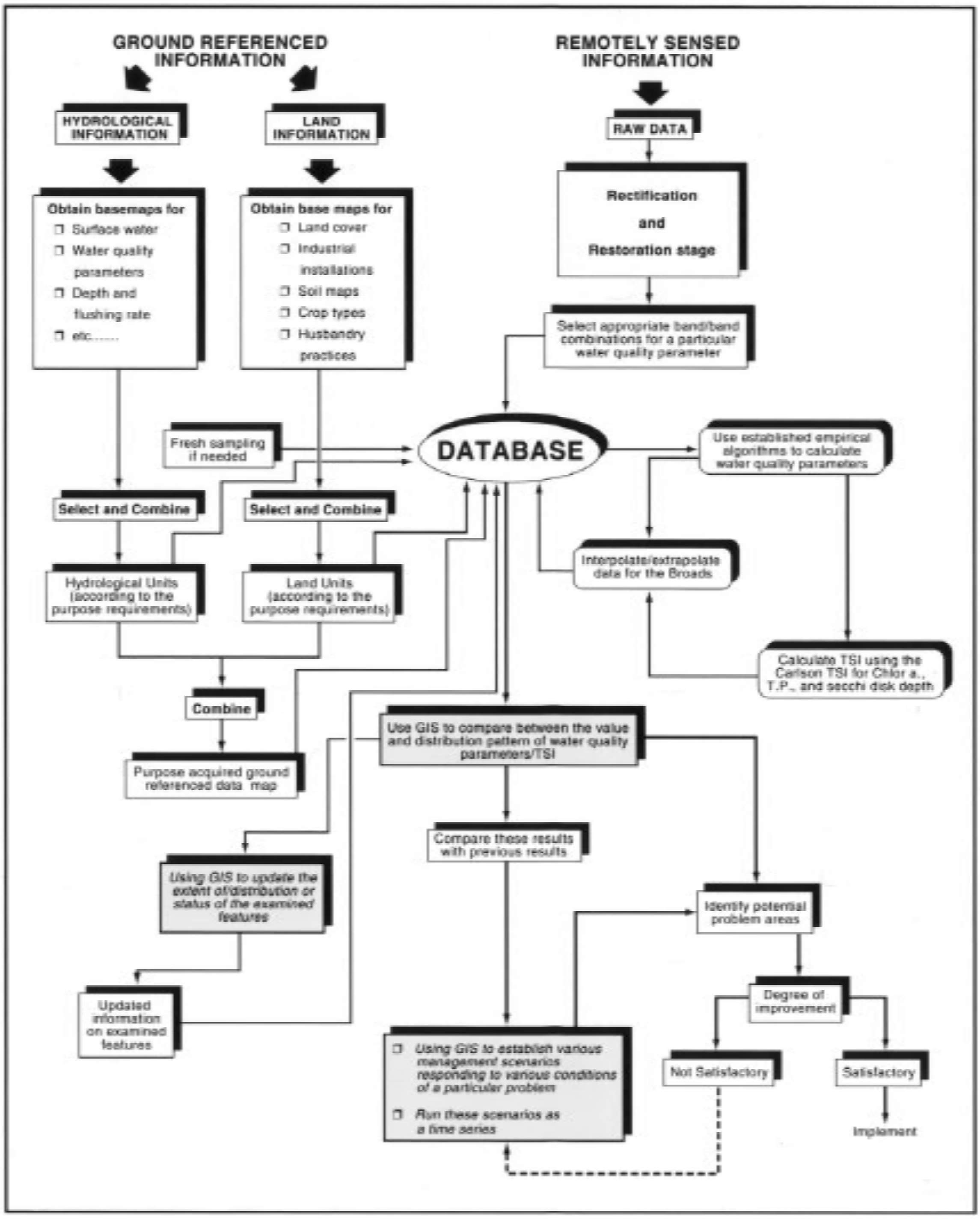

Figure 8. A proposed management system for the Norfolk Broads.

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