# GEOGRAPHIC INFORMATION SYSTEMS (GIS) AND REMOTE SENSING IN THE MANAGEMENT OF SHALLOW TROPICAL LAKES

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**Abstract.** This paper reviews applications of remote sensing and geographic information systems (GIS) techniques to the assessment of tropical waters. These applications are discussed in the context of specific management objectives and sensors used. The need to monitor the spreading patterns of weeds in the tropical waters, land-use changes in the areas surrounding them, change detection, disappearance of wetlands, productivity and nutrient status, in order to establish trends and subsequently develop predictive models to facilitate effective management, is highlighted. GIS capability can be used to link ecological information with the management decisions of these waters. Remote sensing provides useful information in the form of satellite images and aerial photographs that can be integrated and analyzed in a GIS to provide useful spatial information and temporal changes over large geographic areas affecting the structure and function of tropical waters.

**Keywords:** *GIS, remote sensing, sustainable management*

## Introduction

Shallow tropical waters play a vital role in many people’s lives and contain remarkable communities of plants and animals. Shallow tropical waters are profoundly affected by their locality and by changes taking place on land, even at great distances from them. They are often faced with a number of threats as a result of socio-economic activities, taking place within them and their catchments. Rapid population growth in catchment zones has resulted in intensive use of land for farming, deforestation and growth of urban centers. Consequently, there is accelerated runoff leading to increased silt and nutrients discharge into the shallow tropical waters.

Currently most tropical lakes are being choked by water hyacinth (*Eichhornia crassipes*), which continues to cause severe hardship and immense economic difficulties to most countries. The pressure on tropical waters from the weed requires intensive research in order to come up with useful suggestions towards their management. It is at this level that availability of automated, real time data becomes imperative. Remote sensing has developed rapidly to address these needs. The advantage of remote sensing as documented by Richards [64] and Sabins [69] is its ability to capture and record land details instantaneously. Its spatial resolution and aerial coverage provide the researcher with a synoptic view of a land surface. Such data derived from remotely sensed images may be stored efficiently and analysed effectively in a GIS (Risser and Treworgy, [67]).

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This facilitates analysis of local, regional and inter-regional patterns. Because of its nature, processing of remote sensing data can also be part of the interpretation process [35, 64, 69, 80].

Before the launch of satellites, remote-sensing activities mainly revolved around the use of aerial photography. The introduction of digital satellite technology in the1970s has since stimulated a lot of application researches for the simple reason that digital data are collected uniformly in time and space, and over large areas. Twenty-seven years have gone since the establishment of this. The principal aim of this paper is to discuss the applications and, to some extent, limitations of remote sensing and GIS technologies in the overall monitoring and management of tropical waters. The paper starts with a brief discussion of what is meant by remote sensing, and GIS. Fundamental facts about these technologies are discussed. Regular management applications of these techniques are also highlighted. The degree, to which the problem of invasion of tropical waters by weeds such as the water hyacinth could be investigated using remote sensing and GIS capability, is also examined.

## Definitions and fundamental facts

Remote sensing is the acquisition of information about an object, area or event, on the basis of measurements taken at some distance from it. For the purpose of this discussion, the term is taken to describe the collection and analysis of data made by instruments carried in or above the earth’s atmosphere. Such data are obtained as a result of interactions of electromagnetic radiation with the earth’s surface, measured by airborne or spaceborne sensors. The term sensor here refers to a device that detects and measures a radiation as a physical parameter and converts it into a form that can be stored or transmitted to a receiving system. When electromagnetic radiation falls upon a surface some of the energy is absorbed. Some is transmitted through the surface, and some is reflected. Surfaces also naturally emit radiation, mostly in the form of heat (infrared radiation). It is reflected and emitted radiation that is recorded on either photographic film or a digital sensor. Since the intensity and wavelengths or this radiation are a function of the surface in question, each surface is described as possessing a characteristic “spectral signature”. If an instrument can identify and distinguish different spectral signatures, it is possible to map the extent of such surfaces using remote sensing.

The sensors commonly used in tropical areas include passive sensors that collect electromagnetic radiation (visible 0.38-0.75 µm) and infrared (0.76-1,000 µm) which is reflected and emitted from the earth. Since the sun is the source for such radiation data collection is restricted to daylight hours with clear skies. In contrast active sensors generate their own radiation (e.g. from radar and laser) and measure that which is reflected back to the sensor. Radar radiation (0.1-10cm) will penetrate cloud cover and is unaffected by nightfall. Most satellite are sun-synchronous which means that for any given point on the earth the satellite will pass overhead at the same time of day.

Satellite data can be obtained from international distributors such as the National Remote Sensing Centre (NRSC) in the United Kingdom or SPOT IMAGE in France. The potential buyer of remotely sensed data simply has to supply the relevant coordinates of an area of interest and request that the image catalog be searched. Airborne remote sensing is far more flexible. Given sufficiently good weather, the user can specify precisely when and where data are to be collected.

The following are terms commonly used in remote sensing:

1. Spatial resolution is a measure of the area on the ground covered by each sampling unit (pixel) and is dependent on altitude and sensor design. A whole image may be made up of millions of pixels, which partly accounts for the large data volume often encountered in remote sensing.

2. Swath width is the total width of the area on the earth's surface covered by the scanner. Together, spatial resolution and swath width determine the degree of detail that is revealed by the sensor and how large an area is covered.

3. Temporal resolution is the time interval between consecutive overpasses of a fixed point by a satellite. Generally, it is the maximum frequency at which imagery of any area covered by the satellite's orbit can be obtained.

4. Spectral resolution many sensors collect electromagnetic radiation in several distinct bands and are thus call "multispectral". Spectral resolution refers to the number and width of bands. For example, Landsat Thematic Mapper has seven bands, one of which (band1) records energy between 0.45 and 0.52um (blue light). A sensor with high spectral resolution has numerous bands of narrow range.

5. Radiometric resolution refers to the number of digital levels used to express the data collected by the sensor. The radiometric resolution of Landsat TM is such that the level of light intensity recorded for each pixel in each wave band can have a value between 0 (no reflectance) and 255 (100% reflectance), each value being referred to as a digital number (DN).

### *The Use of Different Sensors*

Before the individual management applications of remote sensing are discussed in further detail, it is useful to make some general comparisons between each of the sensors.

Landsat Multispectral Scanner. The most widely used sensor employed for coastal applications is Landsat Multispectral Scanner (MSS). This does not necessarily suggest, however, that MSS has been found to be the most desirable sensor. Landsat MSS has been available since 1972 and has supported much fundamental remote sensing work. Although the specifications of Landsat TM and SPOT sensors are superior to that of MSS for most applications, MSS retains the advantages of offering a long time series and data that are considerably less expensive than those from either Landsat TM or SPOT.

Landsat Thematic Mapper and SPOT XS. Both Landsat TM and SPOT XS offer good spatial and spectral resolution and have been applied to a wide variety of objectives.

SPOT Panchromatic and Airborne Multispectral Scanner. Surprisingly the digital sensors with the highest spatial resolution, SPOT Panchromatic (SPOT Pan) and Airborne MSS, have not been adopted widely for tropical area applications. To help explain this apparent anomaly, the problems of inadequate spectral resolution and the high cost of airborne data will be addressed briefly, although a full discussion of the major constraints to remote sensing appears at the end of this paper. SPOT Pan Data is limited to a single monochrome band spanning 0.55-0.75 µm. High spatial resolution (10 m) does not enable different habitats to be distinguished if their spectral signatures overlap in a single broad band and are therefore effectively inseparable.

MODIS, one of the most advanced remote sensing instruments built to date, is a moderate resolution multispectral imager designed to measure biological and physical processes globally. The ground swath and resolution provide images of every point on earth in a 48 hour cycle. MODIS collects information on surface temperature, concentration of chlorophyll, vegetative conditions – including leaf area index, cloud cover and cloud properties, and fire occurrence, size, and temperature. MODIS gathers data frequently, measures radiation in 36 spectral bands – the largest range ever, be "on" all the time, and have long-term calibration stability. In contrast to MODIS both Landsat 7 and ASTER are high resolution multi-spectral imagers. Data from these instruments generally resembles the high resolution data available from Landsats 4 and 5 France's SPOT, and India's IRS-1 satellite.

The sea-viewing Wide Field – of-view Sensor (Sea WiFS) instrument launched in August 1997 on the OrbView-2 platform is providing fast, repeated global coverage of marine phytoplankton, ocean surface currents, and global climate change, its primary application is commercial and sports fishing, fisheries management, and coastal zone management by state, county and regional planners and managers.

Tropical Rainfall Measuring (TRMM), launched in November 1997, obtains daily global estimates of tropical and subtropical rainfall. TRMM includes the first rain radar in the ESE constellation satellites. TRMM gathers data from the tropics and subtropics (33 degrees north latitude to 35 degrees south latitude).

Aerial photography. It seems that among the available remote sensing technologies producing high spatial resolution data, aerial photography has been superior to space-borne data, despite the higher spectral resolution of the latter. However, digital air-borne multispectral imagery such as the compact air-borne spectrographic imager (CASI) is at least as accurate as aerial photography for the same purpose and it is less expensive to acquire and therefore more cost-effective [57]. It is also important to proceed in the evaluation of new scientific applications of more common imaging techniques such as video and photography from low-flying aircrafts [27, 36].

In space-borne remote sensing, the IKONOS satellite, launched in September 1999, was the first one to challenge the very high spatial resolution data obtained from air-borne remote sensing technology. Compared to aerial photography, which may have a spatial resolution as low as 20 cm, and CASI (resolution: 1 m), IKONOS has a spatial resolution of 1 m for panchromatic imagery and 4 m for multi-spectral imagery, and its future successors are reported to generate images with a spatial resolution of approximately 50 cm [65]. The EROS satellite, launched in December 2000, has a spatial resolution of 1.8 m but no multi-spectral capability. However, its future successors are reported to generate multi-spectral imagery combined with a spatial resolution of 0.82 m [25]. In the mean time, the QUICKBIRD satellite, launched in October 2001, leads the quality list of optical remote sensing with panchromatic imagery of 70 cm spatial resolution, and multi-spectral imagery of 3 m spatial resolution. Yet, it is not unthinkable that too much spatial detail (particularly if combined with a high spectral resolution) may obscure image analysis, as single image objects such as tree crowns will be characterized by a large array of pixels featuring internal variation, for instance crown side (sun/shade), leaf age (fresh/senescent), water content, etc. Therefore, it is as important to explore the construction of both manual identification keys and programmed identification algorithms that integrate spectral data (cf. 'tonality' above), 'texture' and 'structure' analysis. With respect to the spectral resolution, future research should continue to assess the applications of remote sensing sensors. On one hand, this should be done specifically for the identification of a larger range of organisms; on the other hand, it should concentrate on a larger range of wavelengths. Vegetation is easier to study because of its immobility, and, specifically in remote sensing, because of its characteristic reflectance in the infrared wavelengths due to its photosynthetic pigments.

### *Geographic Information System (GIS)*

Geographic Information System (GIS) refers to a system used for storing, manipulating, and retrieving spatially referenced data. This definition also includes systems designed to capture spatial information and to process it. Data in a GIS are its database, usually composed of data planes derived from different data sources. The combination of data sets allows data interpretation [95]. A data plane is composed of one data type, for example, digitised elevation data. Digital data may either be in form of written text, maps, tables or photographs.

In order to manage tropical waters effectively it is inevitable that a large amount of data is handled. Those involved in the general management of these resources require rapid access to statistical data and thematic maps. Manual interpretation only allows integrating of relatively small amounts of field data, maps and aerial imagery. A GIS brings together spatially referenced statistics and remotely sensed imagery into one integrated system. GIS can also be useful in improving information extraction capabilities from remotely sensed data as outlined by Strahler [86]. The integration of remote-sensing into GIS has provided environmental studies with a genuine investigation power [68]. Nevertheless, it is only a potential source of data among others whose use finds its justification in the aim to be reached. At the spatial scales at which satellites observe the Earth, one cannot seriously envision to use satellite imagery to monitor the dynamics of small environments on short time-scale, e.g. every 5 years. To detect space changes in these areas, data-acquisition and-analysis scales must be greater than 1:5 000, with a measurement precision of 1 meter. Today, numerical orthophotographies or aerial remote-sensing (CASI) can punctually overcome the too low resolution of satellite sensors; so, one can use them to monitor tropical shallow lakes.

A GIS must be able to present information to users in a language and format that is not only accurate, but also graphic and comprehensible to all users. To facilitate urgent response from decision-makers in matters related to tropical water management, it is prudent to have a high ratio of maps and diagrams in written text. Such documents constitute a visual help essential for field staff, an aid for drawing up inventory as well as a mean of information and communication. In a short access time GIS allows one to store data from various origins, facilitates the design of maps meeting specific needs, e.g. scale, typology, and enables one to spare time in the production information through a possible automation of design. All these characteristics not only increase map production, but also improve their quality by a better adequacy with the objectives to be reached.

To secure such information, there are six prerequisite stages in a GIS to be followed as detailed by Tomlinson et al., [81] and Jackson [37]: Data acquisition, input and storage, processing, output and use.

## Management applications

The work of Graetz et al., [33] illustrates the existence of two-way flow of information between remote sensing and GIS, meaning that both can be used in monitoring physical and chemical variables important in the sustainable management of tropical waters. Given the extent of current threats facing tropical waters such as pollution, land-use changes in the areas surrounding them and the disappearance of wetlands, GIS is an essential tool for the process of assessing and monitoring the impact, as well as for manipulating and displaying information essential for their management. In most cases, much of the required data can be made available by remote sensing. Of particular importance is access to remotely sensed images in digital form, which can allow rapid integration of the results of remote sensing analysis into a GIS. The same technologies can also be used to study productivity and nutrient status of tropical waters in order to develop predictive models to facilitate effective management.

The following is a discussion on the main management applications of the said technologies.

### *Ecological information*

Remote sensing can be used to transit the gap between pure science and sustainable planning and management of any natural ecosystem [42]. GIS capability is used to link such ecological information with the management decisions for ecosystems. Remote sensing can provide useful information in the form of satellite images [40] and aerial photographs [59, 94] that can be integrated and analysed in a GIS environment. Pereira and Itami [60] have indicated that remote sensing data provide useful spatial information and temporal changes over large geographic areas. For instance, remote sensing and GIS have emerged to be important tools in the management and inventory of aquatic macrophyte distributions [1, 11, 13, 16, 17, 29, 38, 91, 92]. These technologies provide resource managers with an efficient method for monitoring plant distributions over large geographic areas. GIS analysis procedures permit managers to determine changes in macrophyte distributions over time and to identify critical environmental parameters influencing their growth. Models can be created that describe existing relationships among landscape components, predict future plant distributions and assist in making ecologically sound management decisions. Ecological models are generally defined as representations or abstractions of reality. They are used to represent interactions among ecosystem components in order to describe and ultimately understand systems as a whole. Such models can enhance the management of aquatic environments, because system behaviour can be quantified, analyzed and predicted [78, 84, 58]. An understanding of changes occurring over space as well as time is necessary for models to be useful for management purposes [67]. Such models can provide managers with information on both spatial and temporal responses of systems to proposed management scenarios [20, 74].

GIS can assist in modelling procedures by storing and organizing geocoded data at the landscape level [8]. They can also be utilized to create a specific type of spatial model known as a cartographic model [82]. Cartographic models are defined as the logical sequencing of map processes, conceptualized as an algebraic solution of equations which variables are replaced by data layers and fundamental operations can be combined to perform complex analyses [9, 10, 14, 83]. For example, a cartographic model might be created to determine sub-emergent and emergent macrophyte changes between two different dates in any given tropical shallow lake.

Therefore, the use of GIS and remote sensing techniques in the management of tropical waters facilitates the linking of ecological information with decision making in a quick and efficient manner. Since environmental degradation is an issue of concern to many governmental authorities, research institutes, commercial and private enterprises; objective, reliable and comparable information about the status of the environment is invaluable. Use of GIS and remote sensing technologies will facilitate information flow and thus, help to foster sustainable management of tropical waters without compromising the needs of future generations. Other authors [19, 39, 48, 51] have explained eloquently how remote sensing can be used as a tool for natural resource management.

### *Water plants*

There is increased recognition of GIS capability in integrating remote sensing data and database development to monitor natural resources. This is illustrated by an excellent example of a database constructed from aerial photographs, maps, and statistical information, and subsequent development of a lake management information system (LMIS) for monitoring aquatic macrophytes and water quality in the large inland reservoirs of South Carolina [91]. The construction of this database was aimed at understanding whether changes in water quality will cause an increase in an already extensive aquatic plant population of Upper Lake Marion, and promote the spread of undesirable macrophytes to other parts of the system. The database was used to determine changes over time and relate these to water quality, bathymetry and sedimentation.

Using this same approach, it is possible, for instance, to create an integrated database to address the issue of rapid spread of water hyacinth in Lake Victoria, Kenya. To achieve this, it is imperative that various data sets are structured. These should include information on bathymetry of the lakes, data on water quality, depth, aspect, suspended sediments, water temperature, wave action and a base map. Maps of vegetation representing changes over years, derived from aerial photographs or satellite imagery, are also part of this database. Jensen et al. [38] in most of their work have used Landsat Thematic Mapper to map aquatic vegetation.

Once these data sets are ready, the next step is to construct a database in order to answer the question of ecological relationships between water hyacinth, water quality and other environmental factors. The data sets should be compatible with each other for easy correlation, and this can be achieved through the use of software PMAP, available from spatial information systems. At this level, using GIS's analytical capability, it is possible to measure the actual aerial coverage of water hyacinth over a tropical water surface, and identify growth and spreading patterns by performing change detection analysis [91] using multi-date imagery. Such information is invaluable in assessing the success of control methods or in establishing environmental impacts of the weed. This ability to make change studies can be used as long as the ecology of the target species is known, and is understood to predict the future distribution of such weeds in invaded tropical waters. Several researchers [11, 13, 29, 38, 91] have documented the theory behind the use of these techniques for monitoring aquatic weeds.

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This process is, however, likely to face the problem of obtaining cloud-free image coverage in all seasons. High spectral resolution airborne multi-spectral scanner data are an option, notwithstanding their acute geometric distortions.

The following is a discussion of a case study by Welch and Remillard [90], demonstrating where remote sensing and GIS technologies have been used to good effect in guiding management of aquatic systems.

## GIS technologies for aquatic macrophyte studies

### *Database development and changes in the aquatic environment*

A case in point is the management of Lake Marion, South Carolina. The Lake experiences excessive growth of exotic aquatic macrophytes such as hydrilla (*Hydrilla verticillata*), native species such as Brazillian egeria (*Egeria densa*) and Water primose (*Uduigia uruguagensis).* These plants often cover extensive shallow water areas of the lake, block the passage of boats, and prohibit swimming and dock access along shorelines.

In order to control these weeds, the South Carolina Water Resources Commission (WRC) in conjunction with South Carolina Aquatic Plant Management Council and the South Carolina Department of Health and Environmental Control (DHEC), have applied herbicides to problem areas of the Lake. However, this effort has proved to be labor intensive and expensive. More cost-effective approaches such as the release of sterile triploid grass carp have been put in place.

It is important that ecological impacts of these practices are monitored, and the management potential of herbicides and grass carp on aquatic macrophytes be evaluated. It is against such a background that Lake Marion Project was formed with an aim of developing a database and GIS analyses approach to determine spatial and temporal changes in aquatic plant distributions related to herbicide applications. The GIS database for Lake Marion included macrophyte distributions for 1972-88, bathymetry, sedimentation and water chemistry. The aim of the database and GIS analyses was to assess changes in this ecosystem related to the management practices.

### *Methods*

To facilitate GIS analysis of the relatively large study area, Lake Marion was divided into 2- by 2.5-km map segments, tied to the Universal Transverse Mercator (UTM) Coordinate system. Color infra-red aerial photographs in film transparency format were interpreted under magnification with Bausch and Lamb Zoom 70 and SIS 95 instruments. Polygons representing the different types of aquatic vegetation were delineated on clear polyester overlays registered to the photographs. Based on the interpreted aerial photos, aquatic macrophyte distribution maps of Lake Marion were produced as 1:10,000 and 1:24,000 scale for 72 and 76. These analog maps (72-85) were converted to digital data compatible with ARC/INFO using the software package, CAPTURE.

The digitized areas were edited and topology developed to create ARC/INFO data layers. Attribute information for plant species and structural type (emergent and submergent) was input to the relational database, INFO. Herbicide application maps for 83, 84 and 85 were also digitized, converted to ARC/INFO format and entered into the Lake Marion database. The herbicide data layers permitted comparisons with vegetation change over time, for evaluation of herbicide effectiveness in aquatic plant management.

Another important component of L. Marion GIS's database was water quality. Information of levels of nitrogen, phosphorus and dissolved oxygen, sampled at the top and bottom of the water column, and of absolute light and percentage light at I meter depth, were included in the database because of their potential influence on aquatic plant growth. The ARC/INFO Triangulated Irregular Network (TIN) software was used to spatially interpolate water quality values by sampling stations. Information on environmental factors potentially influencing the growth of aquatic vegetation included water depth and sedimentation. Water depths at 1.2 m intervals were digitized and entered into the database.

### *Analysis*

Data sets for macrophyte distributions (72, 76, 83, 84, 85, 88) and herbicide applications (83, 84 and 85) within the Lake were analysed using PC ARC/INFO overlay procedures. To determine trends in aquatic plant growth, the vegetation coverages of different dates were coregistered and the ARC/INFO overlay command UNION used to produce maps depicting changes.

### *Results*

In this study, observation of changes indicated that herbicides act as a disturbance to normal wetland succession. In the absence of herbicide spraying, the normal sequence of aquatic plant succession was evident (i.e. open water areas being invaded by submergents which in turn succeeded to emergent dominance). These ecological finding was very useful to the managers of Lake Marion in the evaluation of herbicide for aquatic plant control. The study also demonstrated the effectiveness of herbicides in controlling nuisance macrophyte growth. However, it was found out that the spraying must be repeated annually to maintain clear open water areas in the reservoir. In the absence of herbicide applications in a single season, the study demonstrated that aquatic plants quickly reinvaded and proceeded in normal patterns of wetland succession.

### *Significance*

This way remote sensing and GIS database technologies have greatly assisted the managers and ecologists in Lake Marion in assessing ecological impacts of aquatic plant growth control on the lake. Further analyses include modeling macrophyte distributions to predict future plant growth and projecting vegetative responses to proposed management practices. The GIS procedures have assisted in constructing management plans that balance multipurpose uses of the reservoir with ecological stability of the aquatic environment.

### *Cost effectiveness*

This procedure was conducted on a suitably equipped IBM PC/AT and inexpensive GIS software designed to work with databases in raster format. It is an alternative to the costly minicomputer based GIS systems for inventorying tasks (*Table 1, 2*).

***Table 1.*** *Software and prices.*

| SOFTWARE | PRICE |
|---|---|
| Aoutodesk 1.0 world | $2,395 |
| AutoCAD Map 2.0 | $4,250 |
| Arcview Image | $2,500 |
| Arcview | $2,000 |
| ERDAS IMAGINE | $3,000 |
| Geoconcept | $2,000 |
| Geomedia Professional | £6,910 |
| Geomedia webmap | £6,915 |
| WinGIS Crypto HP | £6,900 |
| Datamap | £9,000 |
| Strumap | £9,000 |

*Source: GEOEUROPE, issue 7, July 1999*

***Table 2.*** *Peripherals and hardware.*

| PERIPHERAL AND HARDWARE | PRICE |
|---|---|
| Intergraph TDZ's | £2,500 |
| Intergraph TD PC's | £500 |

*Source: GEOEUROPE, issue 7, July 1999*

## *Conclusion*

This case study demonstrates an exciting prospect in the use of remote sensing and GIS capabilities to link theoretically oriented ecological studies with practical applications in resource planning and management. Scientists in all tropical countries need to assess the impact of management practices on the aquatic environment and can utilize the PC-based procedures developed by this case study.

## *Change detection*

Intuitively, remote sensing is ideally suited to the task of assessing changes in tropical waters (e.g. changes in water quality, aerial coverage and productivity changes) and in areas surrounding them. For instance, Landsat TM imagery is available for all tropical areas at intervals of 18 days. This means that changes in tropical water areas can be monitored twice monthly, or that historic changes can be assessed by reference to archived imagery. This ability to detect change is therefore crucial for an efficient management for it allows one to establish surveys, analyze the change-inducing factors and predict potential changes. However, use of remote sensing for change detection is faced by the following constraints:

a) The high costs of obtaining several sets of satellite imagery, for instance, a full scene of Landsat TM image which costs USD 4500.00.
b) The specified temporal resolution of the satellite data is rarely the same as the practical frequency at which useful data are collected, a case in point is 18 days for Landsat TM.

c) Most satellite data are not duly available for countries that are not actively involved in image acquisition, for example, the East African States. Bureaucracy, image cataloguing, ordering, pre-processing and delivery occasion these delays.

### *Field surveys*

Detailed field studies are vital in establishing databases on tropical waters. These data are in most cases missing and wherever they exist, they are outdated, scattered and incomplete. Remote sensing can play a critical role in the planning of such detailed field studies. For instance, as detailed by Link and Long [50] remotely sensed data has been used to plan detailed aerial surveys of aquatic plants.

GIS can be used to settle and implement field monitoring schemes, to detect and model ecological changes and simulate impacts taking place within the tropical lakes catchments. GIS technologies can be used to localize the sites to be inventoried prior to the field stage on combining specific data stored in the database to determine the ecological variables to be sampled. After the mission, the integration of the geographical coordinates of study plots permits one to better manage experimental sites. Within this framework, and thanks to the technological improvements of GPS, the localization as near as one meter of study plots is made possible, which reduces the risks of mistakes in the recording of spatial information. Within this operational context GIS can also help the piloting of experimentation plan through the search for the sites meeting the criteria required to set the operation or focus actions onto tropical shallow lakes either vulnerable or with a high heritage value.

One can also utilize GIS to elaborate a field-sampling or -operation scheme. For example, relief, nature of soils and vegetation often constitute the basic data used to define the place where study plots will be made to get a representation of the ecological diversity at a given site. This functionality is used above all by conservation institutions like the National Parks [12]. Another use of GIS technologies is the elaboration of intervention plan from a selection of sites meeting specific criteria.

### *Studies on suspended sedimentation and agricultural non-point pollution*

Understanding the eutrophication process has improved the ability to manage water as a multi-use resource. Understanding variability of indicators of eutrophication endpoints will improve the ability to monitor water bodies and detect significant changes due to management practices. Such restoration projects such as Medical Lake, Washington [73, 75], Lake Washington [26] and Shagawa Lake, Minnesota [46] have emphasized the benefits gained from a thorough understanding of the eutrophication process. There is a continuing need therefore to determine effective indicators which will aid in the monitoring of the eutrophication process in most of the tropical shallow lakes.

For the purpose of management, it is useful to identify the pathways of land-based runoff and regions of suspended sediments since, these directly affect aquatic environments. Dissolved organic compounds, thus nutrient runoff from agricultural farms needs to be monitored and mapped. In all these cases, remote sensing provides qualitative information. Ritchie et al., [66] determined that Landsat Multispectral Scanner data can be used to effectively estimate suspended sediments in aquatic systems. Lathrop and Lillesand, [47] found significant relationships between Thematic Mapper (TM) data and sechhi disk depth, chrolophyll-a concentrations, turbidity, and surface temperature in

Green Bay and Central Michigan. Lathrop and Lillesand, [47] also found significant correlations of SPOT-1 Multispectral data with the same water quality parameters, with the exception of temperature, not measured by the SPOT-1 system. Both Lillesand et al. [49], using Landsat Multispectral Scanner data, and Wezernak et al., [93], using low altitude mulispectral scanner data, determined that remotely sensed data could be used to effectively predict the trophic status of inland water bodies.

Agricultural non-point source pollution is currently one of the primary concerns in tropical water quality. Pollutants generated from agricultural activities are diffuse, stochastic and dynamic in nature [5]. In order to protect tropical waters from such pollution, there is need to:

i) Identify the critical areas generating this kind of pollution.
ii) Monitor spread patterns, determine the physical and chemical characteristics facilitating spread.
iii) Determine the best management practices, and
iv) Construct a comprehensive pollution control plan.

This will definitely require a lot of information, which in the long run will pose data quantity problems. However, studies by Vieux et al., [89] illustrate how different spatial data sets are combined with such hydrological non-point pollution source data to reduce time and effort required for data input and manipulation. Arnold et al., [3], Srinivassan and Engel ]71] and Mohite et al., [55], give an in-depth description of this approach. Review of this literature reveals that through the integration of simulation models and GIS databases, we should be able to use our tropical waters more efficiently and effectively for informed decision making.

### *Productivity measurement*

In studies of this type, remote sensing can only be used to map the extent of the habitat. In turn this can be related to other aspects like biomass or population size.

### *Limitations of remote sensing*

The use of remote sensing technology in the monitoring and management of tropical waters is likely to face some limitations as outlined below:

- Practical limitations, which are usually inherent in the technology itself, for instance, the limited ability of light to penetrate in water and atmospheric attenuation.
- User limitations referring to difficulties of assessing suitability of certain sensors. For example, remote sensing tends to provide geomorphological rather than ecological information on reef structure. This is due to limited spectral and spatial resolution of the sensors, and factors that confound image interpretation such as turbidity and variation in water depth. A more pronounced limitation in the tropics is cloud cover which significantly reduces the number of suitable images [7] to be available at all seasons. This situation has serious implications on change detection studies and efforts to relate field data to images.

### *Recommendations*

Tropical countries should be encouraged to establish computerized databases to address the need to integrate data of numerous and complex forms essential for better management of shallow tropical waters. There is need to carry out tropical water management oriented research using remote sensing and GIS technologies for informed decision making.

Currently, most researchers that intend to use satellite remote sensing technique in their works will find it unappealing because it does not provide enough information at a fine scale, for example, data on a single tree species in the catchment area (see the case study below). There is need to address this through further research in order to understand the correlation between image data and ecological systems. Once this is achieved, researchers will be able to make meaningful interpretations of remotely sensed data as soon as they are available.

On the other hand the use of GIS technology in ecological studies is a recent phenomenon, and therefore, lacks enough literature [21]. More studies at the ecosystem level should be carried out in an attempt to understand the complex interrelationships occurring over large geographic areas. This can be done through use of GIS to aid management decisions.

The following is a case study by Lo and Lee [52], to demonstrate where remote sensing and GIS technologies fail to capture the fine details ecologists are interested in.

## OKefenokee swamp vegetation mapping with landsat thematic mapper data

OKefenokee swamp covers about 167,00 ha in Ware, Charlton, and Clinch counties; Georgia and Baker County. Its climate is humid sub-tropical. The OKefenokee is a fresh water swamp.

In 1980, McCaffrey and Hamiltom mapped the vegetation communities in this fresh water swamp at a scale of 1:63,360 based on an interpretation of 1:30,000 scale color infra-red aerial photographs obtained in 1977, as well as field observations. McCaffrey and Hamilton developed a wetland vegetation classification scheme for the Okefenokee swamp based on a hierarchy of classes, sub-classes and dominance types. The mapping units defined from aerial photos closely correspond for classes, sub-classes or dominant types in this classification system.

In 1994, another research was done to produce a wetland vegetation map covering an area within the Okefenokee Swamp, using Landsat TM data and a digital approach, at a level of detail comparable to that of the map produced by McCaffrey and Hamilton from aerial photography and field observations. To equitably assess the ability of Landsat TM data and digital image processing to map the vegetation communities within the swamp, two small study areas were carefully selected to represent the full diversity and spatial complexity of the vegetation as a whole. An extensive survey of vegetation communities found in these study areas was done.

### *Method*

Color infrared aerial photos were interpreted and fieldwork done to produce a vegetation map of the area. This formed the basis on which the computer-assisted wetland vegetation mapping capability of TM data was evaluated using different sampling schemes and a GIS approach.

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### *Findings*

This research revealed that despite the high spatial resolution of the Landsat TM data, an accurate 21-class vegetation map of Okefenokee swamp could not be produced from computer-assisted digital image classification. The primary reason was the large number of vegetation classes, which tended to overlap in spectral signatures. This was particularly severe among heterogeneous classes, which exhibited very similar spectral response patterns. It should be noted that the accuracy of such vegetation map could be improved only by aggregating the original categories of the vegetation map into few, closely-related vegetation classes, however, with a considerable loss of detail on the ecological characteristics of the vegetation communities. Therefore, digital remote sensing data can only be fruitfully employed to produce generalized vegetation map of a diverse wetland environment.

### *Integration of past, present and future remote sensing studies*

The current challenge to remote sensing and GIS-based research on tropical shallow lakes is to combine data from the past and present in order to predict the future. On one hand, data from the past that were never ground-truthed require a calibration to current data, preferably (but not always possible), within the same remote sensing technology [23]. On the other hand it is likely that a long-term or integrative study will combine data from different sources. This requires a calibration between technology sensing technologies Discrepancies in post-launch calibrations of certain remote sensing devices may cause artefacts such as surface area change [30], and so may the shift from remote sensing one source to another [61, 62]. However, it is possible to integrate cartographic and multi-source remote sensing data into a homogeneous time series.

An important challenge to the sustainable management of ecosystems, whether or not tropical, is the use of GIS in the integration of data originating from ecology, geography, sociology, and other disciplines. For instance, biocomplexity, ethnobiology, demography, sociology and economics, research fields that are not directly associated with the use of remote sensing and GIS, can nonetheless often be integrated into such a spatial database [41]. A GIS-based combination of such fields to understand the biocomplexity of certain systems is not common. However, more applied possibilities such as GIS-based (disaster) management now becomes more and more widespread [2, 31, 70, 86]. At the level of organising new satellites for improved remote sensing, an emphasis should be put on international collaboration in order to reduce the cost of the space-borne missions [5].

### *Conclusion*

It is apparent that there is considerable progress in the use of remote sensing and GIS in studies related to shallow waters in general. Because of its multi-spectral capabilities, remote sensing seems to be the only method available in presenting a unique perspective for observation and measurement of bio-physical characteristics of large tropical areas, uniformly in space and time, and repeatedly. However, there is a need for more comprehensive approaches that deal with new remote sensing technologies and analysis in a GIS-environment, and that integrate findings collected over longer periods with the aim of prediction. It is also imperative to collect and integrate data from different disciplines. These are essential in the spirit of sustainable development and management, particularly in developing countries. Not only do these countries hold a large part of the world's biodiversity (particularly from tropical aquatic ecosystems), but also they are the most vulnerable to environmental degradation. Several authors [18, 22, 23, 24, 45, 79, 88] provided remote sensing studies relevant to the field of sustainable development in tropical developing countries. It should be emphasized that next to technological innovation and multidisciplinary integration there is also a need for fundamental understanding of the biocomplexity (including human factors) of tropical shallow lakes.

In spite of the advantages of remote sensing and GIS technologies in the management of tropical waters, there are several limitations that have to be overcome by most countries in order to realize maximum use of these technologies. For instance, many countries have no adequate materials, analytical equipment, computers (software and hardware) and imagery. The high cost of materials associated with these technologies is another problem (*Table 1 and 2*).

On the other hand, lack of suitably trained staff continues to be one of the most important factors hampering the development of remote sensing and GIS technologies in tropical countries. The situation is aggravated by many countries in the affected regions giving priority to other activities other than these technologies. Thus, a direct effect of conflicting priorities continues and will in future divert attention from these technologies.

In the long run, these technologies hold the key to the solution of many problems facing tropical waters, and are likely to become the accepted methods in the future. They are mainly limited today because of their high operating costs.

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