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# Remote Sensing Techniques to Assess Water Quality

Jerry C. Ritchie, Paul V. Zimba, and James H. Everitt

## Abstract

Remote sensing techniques can be used to monitor water quality parameters (i.e., suspended sediments (turbidity), chlorophyll, and temperature). Optical and thermal sensors on boats, aircraft, and satellites provide both spatial and temporal information needed to monitor changes in water quality parameters for developing management practices to improve water quality. Recent and planned launches of satellites with improved spectral and spatial resolution sensors should lead to greater use of remote sensing techniques to assess and monitor water quality parameters. Integration of remotely sensed data, GPS, and GIS technologies provides a valuable tool for monitoring and assessing waterways. Remotely sensed data can be used to create a permanent geographically located database to provide a baseline for future comparisons. The integrated use of remotely sensed data, GPS, and GIS will enable consultants and natural resource managers to develop management plans for a variety of natural resource management applications.

## Introduction

Water quality is a general descriptor of water properties in terms of physical, chemical, thermal, and/or biological characteristics. It is difficult to define a single water quality standard to meet all uses and user needs. For example, physical, chemical, and biological parameters of water that are suitable for human consumption are different from those parameters of water suitable for irrigating a crop. Water quality is affected by materials delivered to a water body from either point or nonpoint sources. Point sources can be traced to a single source, such as a pipe or a ditch. Nonpoint sources are diffuse and associated with the landscape and its response to water movement, land use and management, and/or other human and natural activities on the watershed. Agriculture, industrial, and urban areas are anthropogenic sources of point and nonpoint substances. Polluting substances that lead to deterioration of water quality affects most freshwater and estuarine ecosystems in the world (Dekker *et al.*, 1995). In the United States, off-site downstream deterioration of water quality has been estimated to cost billions of dollars per year (Pimentel *et al.*, 1995).

Monitoring and assessing the quality of surface waters are critical for managing and improving its quality. *In situ* measurements and collection of water samples for subsequent laboratory analyses are currently used to evaluate water quality. While such measurements are accurate for a

point in time and space, they do not give either the spatial or temporal view of water quality needed for accurate assessment or management of water bodies. The purpose of this paper is to review the use of remote sensing techniques for monitoring and assessing water quality.

## Basis for Using Remote Sensing

Substances in surface water can significantly change the backscattering characteristics of surface water (Jerlov, 1976; Kirk, 1983). Remote sensing techniques depend on the ability to measure these changes in the spectral signature backscattered from water and relate these measured changes by empirical or analytical models to a water quality parameter. The optimal wavelength used to measure a water quality parameter is dependent on the substance being measured, its concentration, and the sensor characteristics.

Major factors affecting water quality in water bodies across the landscape are suspended sediments (turbidity), algae (i.e., chlorophylls, carotenoids), chemicals (i.e., nutrients, pesticides, metals), dissolved organic matter (DOM), thermal releases, aquatic vascular plants, pathogens, and oils. Suspended sediments, algae, DOM, oils, aquatic vascular plants, and thermal releases change the energy spectra of reflected solar and/or emitting thermal radiation from surface waters which can be measured using remote sensing techniques. Most chemicals and pathogens do not directly affect or change the spectral or thermal properties of surface waters, so they can only be inferred indirectly from measurements of other water quality parameters affected by these chemicals. Remote sensing tools provide spatial and temporal views of surface water quality parameters that are not readily available from *in situ* measurements, thus making it possible to monitor the landscape effectively and efficiently, identifying and quantifying water quality parameters and problems.

Development of remote sensing techniques for monitoring water quality began in the early 1970s. These early techniques measured spectral and thermal differences in emitted energy from water surfaces. Generally, empirical relationships between spectral properties and water quality parameters were established. Ritchie *et al.* (1974) developed an empirical approach to estimate suspended sediments. The general forms of these empirical equations are

$$Y = A + BX \quad \text{or} \quad Y = AB^X \quad (1)$$

where  $Y$  is the remote sensing measurement (i.e., radiance, reflectance, energy) and  $X$  is the water quality parameter of interest (i.e., suspended sediment, chlorophyll).  $A$  and  $B$  are empirically derived factors. In empirical approaches

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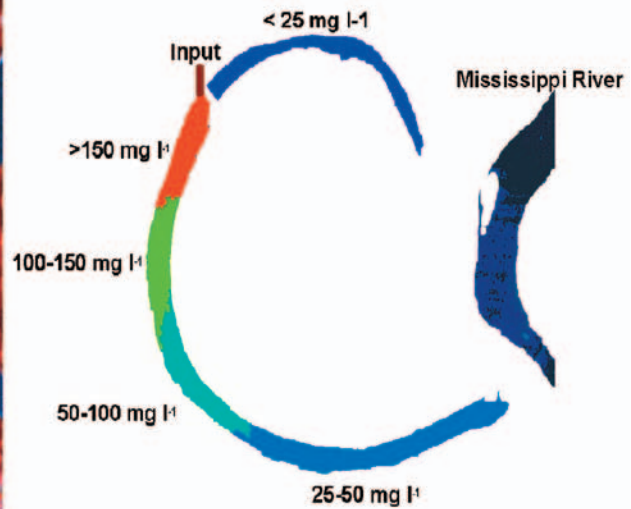


Plate 1. Landsat TM image of Lake Chicot, Arkansas (left) and a derived image (right) showing categories of suspended sediments mapped in Lake Chicot based on the radiance in the TM image.

statistical relationships are determined between measured spectral/thermal properties and measured water quality parameters. Often information about the spectral/optical characteristic of the water quality parameter is used to aid in the selection of best wavelength(s) or best model in this empirical approach. The empirical characteristics of these relationships limit their applications to the condition for which the data were collected. Such empirical models should only be used to estimate water quality parameters for water bodies with similar conditions.

Schiebe *et al.* (1992) used an analytical approach based on the optical properties of water and water quality parameters to develop a physically based model of the relationship between the spectral and physical characteristics of the surface water studied. This physically based reflectance model with statistically determined coefficients ( $B_i$  and  $S_i$ ) was successfully applied to estimating suspended sediment concentrations (Schiebe *et al.*, 1992; Harrington *et al.*, 1992). Their model has the form

$$R_i = B_i[1 - e^{(c/S_i)}] \quad (2)$$

where  $R_i$  is the reflectance (i.e., Landsat, SPOT digital data) in wave band  $i$ ,  $c$  is suspended sediment concentration,  $B_i$  represents the reflectance saturation level at high suspended sediment concentrations in wave band  $i$ , and  $S_i$  is the concentration parameter equal to the concentration when reflectance is 63 percent of saturation in wave band  $i$ .

This paper will be limited to the use of remote sensing technology to monitor suspended sediments, algae, aquatic vascular plants, and temperature. These are the key pollutants listed by the Environmental Protection Agency which estimated that approximately 40 percent of U.S. waters do not meet minimum water quality standards (USEPA, 1998). A discussion of *in situ* sensors for remote monitoring is also included because these are essential for measuring water quality parameters that cannot be measured with remote sensing techniques and for data to calibrate remote sensing models for determining water quality.

### Suspended Sediment

Suspended sediments are the most common pollutant both in weight and volume in surface waters of freshwater sys-

tems (Robinson, 1971; Lal, 1994). Suspended sediments increase the radiance emergent from surface waters (Figure 1) in the visible and near-infrared proportion of the electromagnetic spectrum (Ritchie *et al.*, 1976). *In situ*, controlled laboratory, aircraft, and satellite measurements have shown that surface water radiance is affected by sediment type, texture, and color (Novo *et al.*, 1989), sensor view, sun angles (Ritchie *et al.*, 1975), and water depth (Blanchard and Leamer, 1972). Spectral sensors on boat, aircraft, and satellite platforms have all been used to study suspended sediment patterns.

Significant relationships between suspended sediments and radiance or reflectance from spectral wave bands or combinations of wave bands on satellite and aircraft sensors have been shown. Ritchie *et al.* (1976), using *in situ* studies, concluded that wavelengths between 700 and 800 nm were most useful for determining suspended sediments in surface

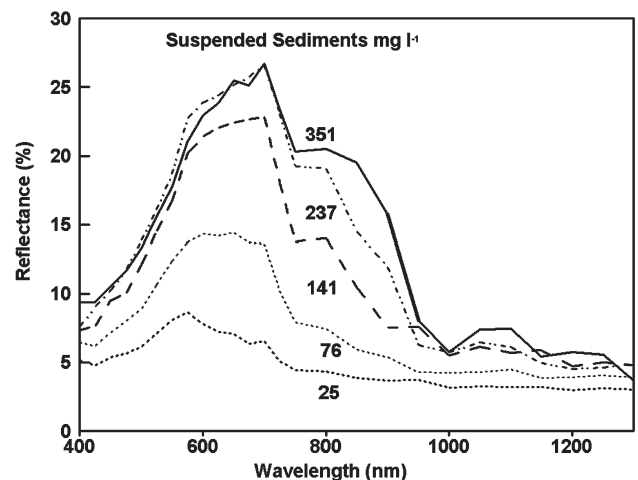


Figure 1. The relationship between reflectance and wavelength as affected by the concentration of suspended sediments (Ritchie *et al.*, 1976).

waters. Curran and Novo (1988), in a review of remote sensing of suspended sediments, found that the optimum wavelength was related to suspended sediment concentration. Many studies have developed empirical relationships (algorithms) between the concentration of suspended sediments and radiance or reflectance for a specific date and site. Few studies have taken the next step and used these algorithms to estimate suspended sediments for another time or place. Ritchie and Cooper (1988; 1991) showed that an algorithm developed for one year was applicable for several years. Once developed, an algorithm should be applicable until some watershed event changes the quality (size, color, mineralogy, etc.) of suspended sediments delivered to the lake.

A curvilinear relationship between suspended sediments and radiance or reflectance (Ritchie *et al.*, 1976; Ritchie *et al.*, 1990) has been found, because the amount of reflected radiance tends to saturate as suspended sediment concentrations increase. If the range of suspended sediments is between 0 and 50 mg l<sup>-1</sup>, reflectance from almost any wavelength will be linearly related to suspended sediment concentrations. As the range of suspended sediments increases from 50 mg l<sup>-1</sup> to 150 mg l<sup>-1</sup> or higher, curvilinear relationships are necessary. Schiebe *et al.* (1992) developed a physically based reflectance model (Equation 2) and used it to estimate suspended sediment concentrations in Lake Chicot, Arkansas. Most researchers have concluded that surface suspended sediments can be mapped and monitored in large water bodies using sensors available on current satellites. Plate 1 shows an example of mapping suspended sediment in Lake Chicot using Landsat Thematic Mapper Data. The mapping was done in categories related to a management plan proposed for the lake.

While most researchers and managers agree that suspended sediments can be mapped with remotely sensed

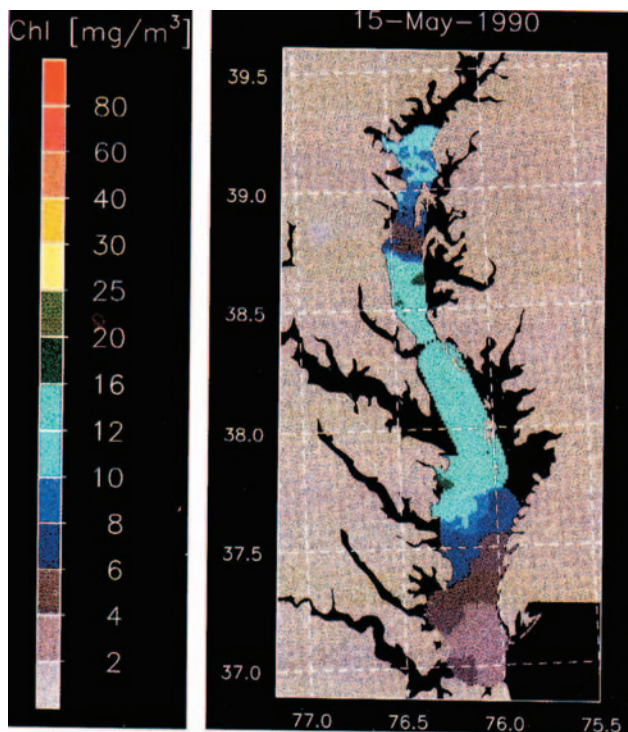


Plate 2. Distribution of Chlorophyll (Chl) in the Chesapeake Bay for 15 May 1990 determined from aircraft multispectral data (Harding *et al.*, 1995).

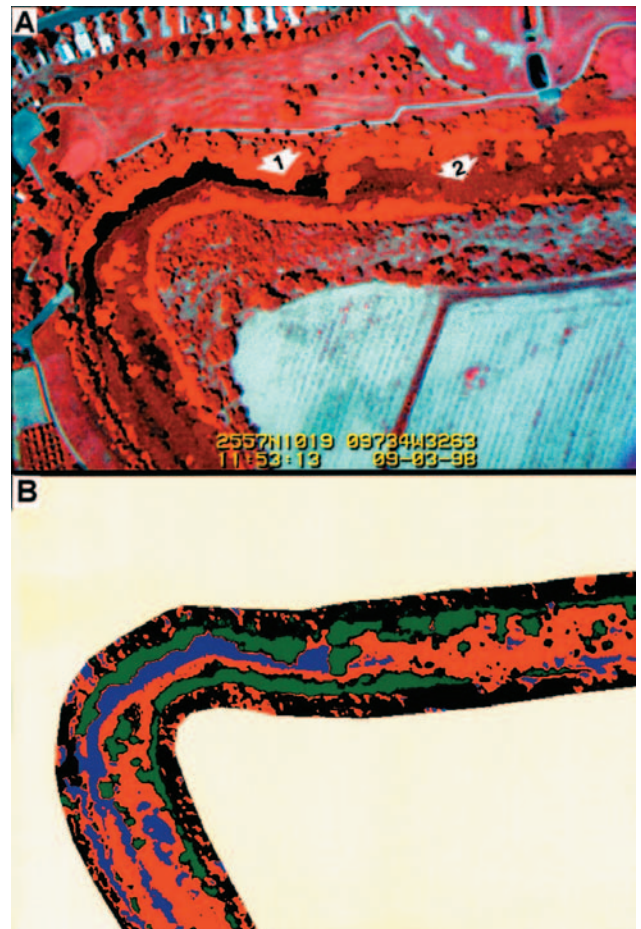


Plate 3. Color-infrared digital video image (A) of a portion of the Rio Grande River near Brownsville, Texas, infested with water hyacinth and hydrilla. Arrow 1 points to the conspicuous orange-red response of water hyacinth, whereas arrow 2 points to the reddish-brown tonal response of hydrilla. The image was obtained on 03 September 1998. The GPS data are shown at the bottom of the image. Unsupervised computer classification of the Rio Grande and its adjacent perimeter is shown in B. Color codes for the various land-use types are: red:hydrilla; green: water hyacinth; black: riparian vegetation; and blue:water.

data, the technique with the current spatial resolution of satellite data (Ritchie and Schiebe, 2000; Ritchie, 2000) does not allow the detail mapping of water bodies or measurements in or from streams needed for management decisions. As new satellites come on line with higher resolution spatial and spectral data, greater application of satellite data for monitoring and assessing suspended sediments will be possible.

### Algae/Chlorophyll

Monitoring the concentrations of chlorophyll (algal/phytoplankton) is necessary for managing eutrophication in lakes (Carlson 1977). Remote sensing has been used to measure chlorophyll concentrations spatially and temporally. As with suspended sediment measurements, most remote sensing studies of chlorophyll in water are based on empirical relationships between radiance/reflectance in narrow bands or band ratios and chlorophyll. Thus, field data

are collected to calibrate the statistical relationship or to validate models developed. Measurements made *in situ* (Schalles *et al.*, 1997) show spectra (Figure 2) with increasing reflectance with increased chlorophyll concentration across most wavelengths but areas of decreased reflectance in the spectral absorption region for chlorophyll (675 to 680 nm). A variety of algorithms and wavelengths have been used successfully to map chlorophyll concentrations of the oceans, estuaries, and fresh waters. For example, Harding *et al.* (1995) used the following algorithm (Equation 3) based on aircraft measurements to determine seasonal patterns of chlorophyll content in the Chesapeake Bay:

$$\text{Log}_{10} [\text{Chlorophyll}] = a + b (-\text{Log}_{10} G) \quad (3)$$

where *a* and *b* are empirical constant derive from *in situ* measurements and *G* is  $[(R_2)^2/(R_1 * R_3)]$ . *R*<sub>1</sub> is radiance at 460 nm, *R*<sub>2</sub> is radiance at 490 nm, and *R*<sub>3</sub> is radiance at 520 nm. Using this algorithm, Harding *et al.* (1995) mapped total chlorophyll content in the Chesapeake Bay (Plate 2).

While estimating chlorophyll using remote sensing techniques is possible, studies have also shown that the broad wavelength spectral data available on current satellites (i.e., Landsat, SPOT) do not permit discrimination of chlorophyll in waters with high suspended sediments (Dekker and Peters, 1993; Ritchie *et al.*, 1994) due to the dominance of the spectral signal from the suspended sediments. Research on the relationship between chlorophyll and the narrow band spectral details at the “red edge” of the visible spectrum (Gitelson *et al.*, 1994) has shown a linear relationship between chlorophyll and the difference between the emergent energy in the primarily chlorophyll scattering range (700 to 705 nm) and the primarily chlorophyll absorption range (675 to 680 nm). The relationship exists even in the presence of high suspended sediment concentrations that can dominate the remainder of the spectrum, as seen in Figure 3. These findings suggest new approaches for application of airborne and spaceborne sensors to exploit these phenomena to estimate chlorophyll in surface waters under all conditions as hyperspectral sensors are launched and data become available. Data from

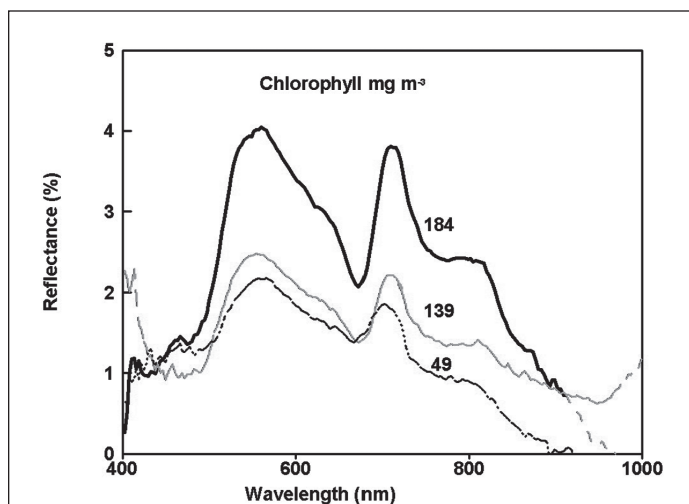


Figure 2. Relationship between reflectance and wavelength for different chlorophyll concentrations. Based on measurement made *in situ* with a high spectral resolution (1-nm) spectroradiometer at 1 meter over a large tank (Schalles *et al.*, 1997).

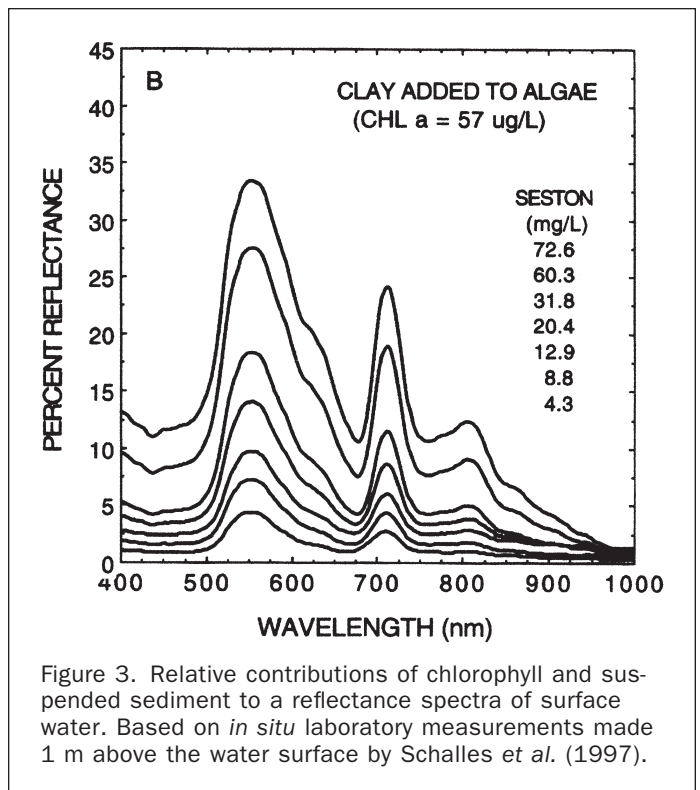


Figure 3. Relative contributions of chlorophyll and suspended sediment to a reflectance spectra of surface water. Based on *in situ* laboratory measurements made 1 m above the water surface by Schalles *et al.* (1997).

several recently launched satellites sensors (i.e., SeaWiFS, Modular Optical Scanner (MOS), Ocean Color and Temperature Scanner (OCTS), and Ikonos) are available and hold great promise for measuring biological productivity (chlorophyll) in aquatic systems. Such hyperspectral data may also make it possible to differentiate between algal groups. Laboratory and field studies with hyperspectral data have been used to separate green and blue-green algae (Dekker *et al.*, 1995). Richardson and Zimba (2002) were able to define aerial extent of cyanobacterial blooms, using carotenoid pigment markers, in addition to chlorophyll in Florida Bay. Useful wavelengths included a band near 500 nm that contained the absorbent peak for the carotenoid myxoxanthophyll. Airborne video cameras equipped with narrow-band filters have also been used to assess chlorophyll with success (Avard *et al.*, 2000). Fluorescence has also been used to identify algal and phytoplankton groups. Bazzani and Cecchi (1995) were able to identify phytoplankton species from fluorescence spectra using an excitation wavelength of 514 nm. Our ability to monitor chlorophyll will improve as hyperspectral and improved spatial data become readily available.

### Aquatic Vascular Plants

Aquatic macrophytes are important components of wetland communities, playing a crucial role in providing food and shelter for animals as well as regulating the chemistry of the open water (McLaughlan, 1974; Frodge *et al.*, 1990). These plants may be free-floating or rooted in bottom sediment and may be submersed or protrude from the water (Patterson and Davis, 1991). Uncontrolled growth of these plants can clog reservoirs, reducing water availability for human uses including recreational activities (Narumalani *et al.*, 1997).

The inaccessibility and often large expanses of wetlands make ground inventory and assessment difficult, time consuming, expensive, and often inaccurate (Scarpace

*et al.*, 1981). This has led to the use of remote sensing techniques (Carter, 1982; Tiner, 1997). Plant canopy light reflectance measurements have been used to differentiate among wetland plant species (Best *et al.*, 1981; Ullah *et al.*, 2000), and aerial photography has been used extensively to remotely distinguish plant species and communities in wetland environments (Seher and Tueller, 1973; Howland, 1980; Carter, 1982; Martyn, 1985). More recently, airborne videography has also proven useful for assessing wetlands (Mackey *et al.*, 1987; Sersland *et al.*, 1995).

Although remote sensing techniques have been used extensively for assessing wetlands, little information is available on their use for detecting noxious macrophytes (weeds) in waterways. Research efforts at the USDA-ARS Kika de la Garza Agricultural Research Laboratory, Weslaco, Texas, utilizing remote sensing, the Global Positioning System (GPS), and geographic information systems (GIS) for detecting and mapping noxious aquatic weeds has focused on three species: water hyacinth [*Eichhornia crassipes* (Mart.) Solms], hydrilla [*Hydrilla verticillata* (L. F.) Royle], and giant salvinia [*Salvinia molesta* D.S. Mitch.].

Water hyacinth and hydrilla are two aquatic weeds that often invade and clog waterways. Water hyacinth is a floating species that has been called the "world's worst weed" (Cook, 1990) and is found throughout the southeastern United States and California (Correll and Correll, 1972). Populations may double in size every 6 to 18 days and transpire 4 to 5 times that in areas with open water (Mitchell, 1976).

Hydrilla is a submersed species that is probably native to the warm regions of Asia (Cook and Luond, 1982) but now occurs in Europe, Asia, Africa, Australia, South America, and North America (Langeland, 1996). Hydrilla was first discovered in the United States in Florida in 1960 (Blackburn *et al.*, 1969) and has since spread throughout the eastern seaboard states as well as to California, Arizona, and Washington (Schmitz, 1990; Langeland, 1996). Because of its aggressive growth rate and ability to photosynthesize by C3 and C4-like metabolism (Bowes and Salvucci, 1989; Reiskind *et al.*, 1997), hydrilla has established itself in a wide range of aquatic habitats, replacing native aquatic vegetation and affecting fish populations (Barnett and Schneider, 1974; Colle and Shireman, 1980; Langeland, 1996). Hydrilla also interferes with movement of water for drainage and irrigation purposes and reduces boating access (Langeland, 1996).

Everitt *et al.* (1999) measured the light reflectance characteristics of hydrilla and water hyacinth and used airborne videography integrated with GPS and GIS for detecting and mapping these two aquatic weeds in Texas waterways. Field reflectance measurements made at several locations showed that water hyacinth generally had higher near-infrared (NIR: 0.76 to 0.90  $\mu\text{m}$ ) reflectance than associated plant species and water. Surfaced hydrilla had lower NIR reflectance than associated plant species and higher NIR reflectance than water. The low NIR reflectance of hydrilla was contributed to significantly by its open canopy and integration of water with the canopy which absorbed a large percentage of the NIR light (Myers *et al.*, 1983; Everitt *et al.*, 1989). Reflectance measurements made on hydrilla below the water surface had spectral characteristics similar to water.

Plate 3A shows a color-infrared (CIR) digital video image acquired along the Rio Grande River near Brownsville, Texas, on 03 September 1998. The image was obtained at an altitude of 460 m above ground level (AGL) and has a ground pixel resolution of 0.35 m. Arrow 1 points to the conspicuous bright orange-red image response of water hy-

acinth, whereas arrow 2 points to the reddish-brown image tone of surfaced hydrilla. The GPS data are displayed at the bottom of the video image and are useful for locating water hyacinth and hydrilla populations over remote and inaccessible areas.

Water hyacinth and surfaced hydrilla had color tonal responses similar to that shown in Plate 3A in additional CIR video imagery acquired at numerous other locations along the Rio Grande and could be readily separated from other vegetation at all sites. However, hydrilla submerged 2.5 to 7.5 cm below the water surface had a dark brown to nearly black image that could not easily be differentiated from water. Hydrilla submerged at depths below 7.5 cm could not be distinguished in the video imagery. The conspicuous orange-red image of water hyacinth was primarily attributed to its high NIR reflectance, whereas the reddish-brown or dark brown to nearly black image tones of hydrilla were attributed to its low NIR reflectance.

Plate 3B shows an unsupervised classification of the CIR video image of the Brownsville site (Plate 3A). Color codes and respective percent areas for the various land-use types are hydrilla (34.8 percent), water hyacinth (16.6 percent), riparian vegetation (36.6 percent), and water (12.0 percent). A qualitative comparison of the computer classification to the video image shows that the classification generally identified most of the hydrilla and water hyacinth. This technique can provide a means of quantifying hydrilla and water hyacinth infestations in waterways.

Plate 4A shows a regional GIS TIGER map of Starr, Hidalgo, Cameron, and Willacy Counties in the Lower Rio Grande Valley of south Texas. The Rio Grande forms the lower boundary of the map adjacent to Mexico. The map depicts the Rio Grande from its mouth in southeastern Cameron County to Falcon Dam in southwestern Starr County. The GPS latitude-longitude data provided on the aerial videographic imagery of the Rio Grande from June and August 1998 overflights have been integrated with the GIS to georeference infestations of hydrilla and water hyacinth in the river. Areas with green stars represent infestations of hydrilla; areas with red dots are water hyacinth infestations. The highest populations of aquatic weeds are located in Cameron County. The area was infested with both hydrilla and water hyacinth. Due to the small scale of the map, many of the symbols overlap. Each symbol represents a composite from three to eight video scenes. Water hyacinth was only found in Cameron County and extreme southeastern Hidalgo County. Isolated populations of hydrilla occur in central Hidalgo County, whereas numerous small infestations of hydrilla are found in Starr County. A more detailed GIS map of the portion of the Rio Grande infested with hydrilla and water hyacinth in Cameron County is shown in Plate 4B. This area corresponds to the enclosed box in the upper map. With this map one can associate general land-use characteristics (i.e., streets, roads) with the GPS locations where hydrilla and water hyacinth occur.

Giant salvinia is a floating fern native to Brazil that has spread to many other warm freshwaters of the world (Barrett, 1989). It develops dense mats that interfere with rice cultivation, clog fishing nets, and disrupt access to water for humans, livestock, and wildlife (Mitchell, 1976; Creigh, 1991). Additionally, giant salvinia will overgrow and displace native plants that provide food and habitat for wildlife and block out sunlight and decrease oxygen concentrations to the detriment of fish and other aquatic species (Holm *et al.*, 1977). In September 1998, a major occurrence of giant salvinia was found in Toledo Bend Reservoir in east Texas. It has since spread to a number of other public waterways and ponds in east and southeast Texas.

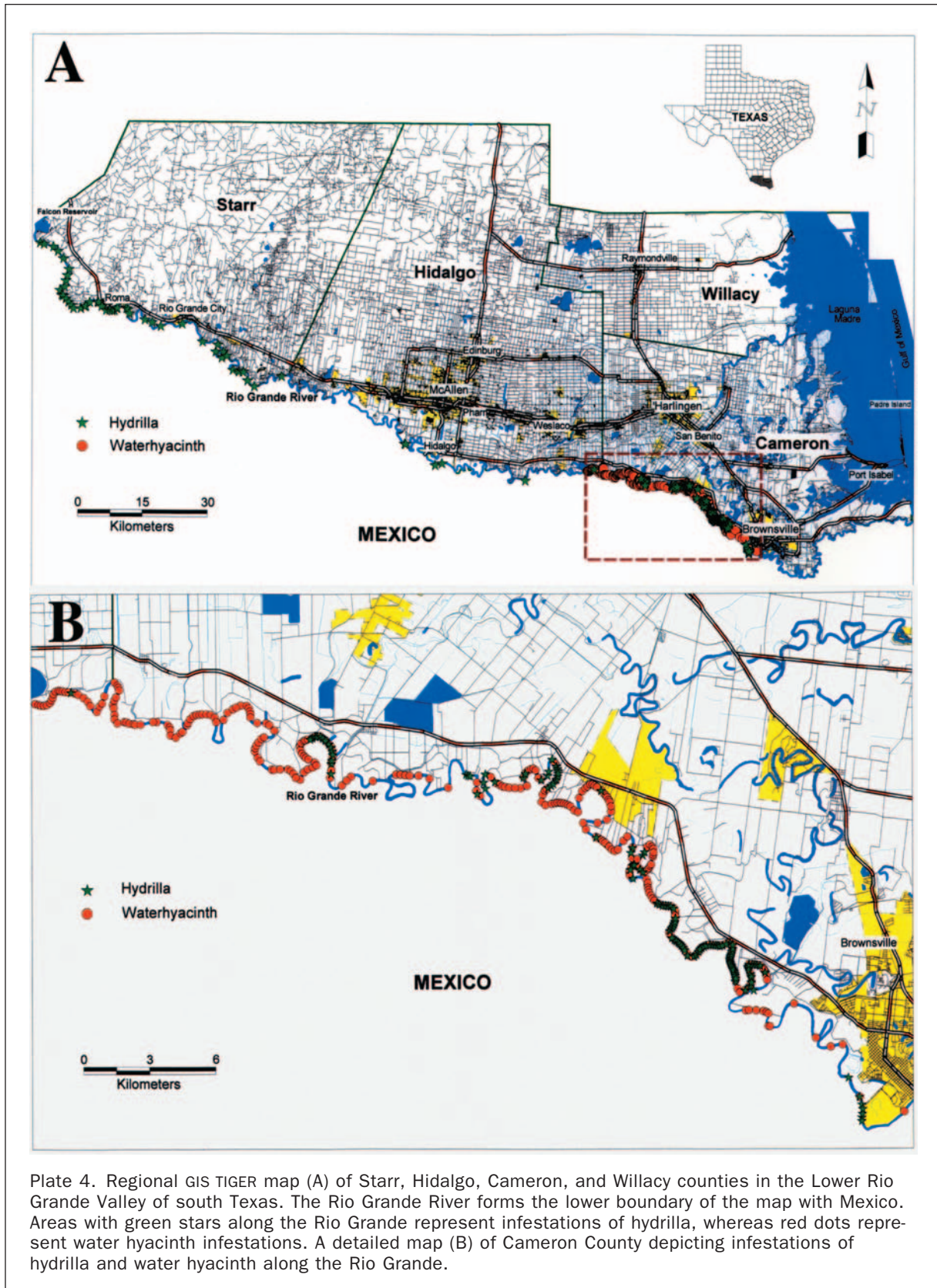


Plate 4. Regional GIS TIGER map (A) of Starr, Hidalgo, Cameron, and Willacy counties in the Lower Rio Grande Valley of south Texas. The Rio Grande River forms the lower boundary of the map with Mexico. Areas with green stars along the Rio Grande represent infestations of hydrilla, whereas red dots represent water hyacinth infestations. A detailed map (B) of Cameron County depicting infestations of hydrilla and water hyacinth along the Rio Grande.

Research efforts are underway to evaluate remote sensing techniques in distinguishing giant salvinia infestations in Texas waterways (Everitt *et al.*, 2001). Giant salvinia occurs in two growth classes. Plants with green foliage and

senesced plants with mixtures of green and brown foliage. Senesced giant salvinia occurs in areas where the plants have become extremely dense and available nutrients are probably limited. These two classes often occur together in

giant salvinia populations. Initial light reflectance studies showed that green giant salvinia could be best distinguished from associated plant species in the green (0.52 to 0.60  $\mu\text{m}$ ) wavelength, whereas senesced giant salvinia could be best separated at the NIR wavelength.

Plate 5 shows a CIR aerial photograph of a wetland area near Liberty, Texas. The print is part of a 23-cm photograph taken at a scale of 1:2,500 on 18 June 1999. Arrow 1 points to the pink image response of a large population of giant salvinia with green foliage. Additional smaller populations of giant salvinia (green foliage) occur in the center and upper-right portions of the photograph. Arrow 2 points to the olive-green image response of a large population of senesced giant salvinia with mixtures of green and brown foliage. The dark red image in the center of the photograph is water hyacinth. Giant salvinia had image tones similar to those shown in Plate 5 at three additional sites located near Liberty and Bridge City in June and July 1999 and could be easily distinguished from other plant species and ecological ground variables at all sites.

Aerial photography and airborne videography can be used for detecting noxious aquatic weeds. Ground reflectance measurements are useful for determining the spectral characteristics of aquatic weeds and aid in interpreting their image responses. Computer analysis of aerial images can be used to quantify weed infestations from associated vegetation and water. The integration of videography, GPS, and GIS technologies is valuable for detecting and mapping weeds in waterways. The video imagery can serve as a permanent geographically located image database to monitor future contractions or spread of aquatic weeds. The joint use of videography, GPS, and GIS technologies can enable consultants and natural resource managers to develop maps showing the distribution of weed infestations over large and inaccessible waterways. It is anticipated that the integration of these technologies can be used for a variety of other natural resource management applications.

## Temperature

Thermal pollution exists when biological activities are affected by changing the temperature of a water body by

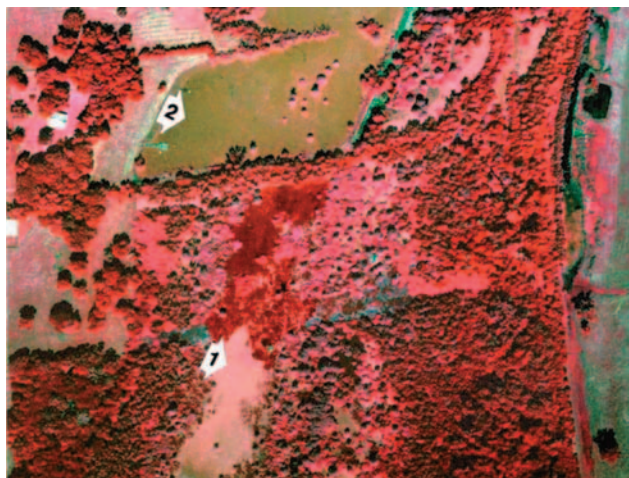


Plate 5. Aerial color-infrared positive photographic print of a wetland area near Liberty, Texas. The arrows on the print point to the following: arrow 1, giant salvinia (green foliage); arrow 2, senesced giant salvinia (mixed green and brown foliage).

anthropogenic activity. Remotely sensed data have been used to map thermal discharge into streams, lakes, and coastal waters from electrical power plants (Stefan and Schiebe, 1970; Gibbons *et al.*, 1989). Thermal plumes in river and coastal waters can be accurately estimated by remote sensing techniques. Mapping of absolute temperatures by remote sensing provides spatial and temporal patterns of thermal releases that is useful for managing thermal releases. Quantitative estimates of surface water temperatures also provide input for interpreting outputs from mathematical models of thermal plumes. Aircraft-mounted thermal sensors are especially useful in studies of thermal plumes because of the ability to control the timing of data collection.

Seasonal changes in the temperature of surface waters can be expected. Such seasonal changes of ocean surface temperatures have been routinely monitored using AVHRR and other satellite platforms, leading to new insights into the role which oceans play in regulating weather and climate (i.e., El Niño). Bolgrien *et al.* (1995) used AVHRR to monitor seasonal temperature in Lake Baikai (Figure 4).

Miller and Rango (1984) used Heat Capacity Mapping Mission (HCMM) data to map emitted thermal energy and to map algal concentration in the Great Salt Lake. They found a positive correlation during the day and a negative correlation at night between emitted energy and algal concentration. Ritchie *et al.* (1990) estimated surface temperatures of lakes along the Mississippi River using thermal data from Landsat TM. Thermal remote sensing is a useful tool for monitoring freshwater systems to detect thermal changes that can affect biological productivity. These techniques allow the development of management plans to reduce the effect of man-made thermal releases.

SPOT imagery has been used to delineate lake margins, a technique particularly useful in remote areas or in shallow-water systems having fluctuating margins (Zimba *et al.*, 1995). As part of an ecosystem analysis of Lake Okeechobee, Florida, the lake margin was mapped to delineate submersed vegetation during drought and flood stages (Table 1). This technique was critical for accurate delineation of the lake edge and will be useful in future shallow-water analyses. High suspended solids concentrations precluded use of remote sensing to assess submersed plant distributions in this system.

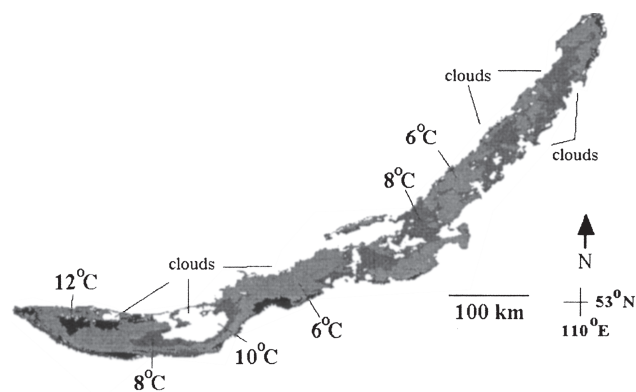


Figure 4. Surface temperatures of Lake Baikai derived from AVHRR band 4 data for 04 September 1991 (Bolgrien *et al.* (1995), reproduced with permission of the American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland).



TABLE 1. LAKE STAGE-LAKE AREA RELATIONSHIPS IN LAKE OKEECHOBEE, FLORIDA

	1989	1990	1991	1992
Lake Stage (m)	3.51	3.36	4.79	4.29
Open Water (ha)	136,918*	124,732	125,794	122,549
Submerged Vegetation (ha)	20,820	19,759	17,570	—

\*Includes periphyton (ca. 10,000 ha) within the littoral zone subtracted during subsequent years.

### In Situ Instruments

Several instruments are currently available for the detection of specific groups of algae. These instruments have generally combined some physiological aspect of these taxa to facilitate discrimination. Identification occurs while the instrument is moored underwater, with results transmitted remotely. One example of this instrumentation is the LWCC-liquid wave-length capillary cell (Kirkpatrick *et al.*, 2000). This system uses accessory pigment composition to identify algae containing these pigments. This tool has been used to assess red-tide forming dinoflagellates along the west coast of Florida.

*In situ* monitoring probes are currently available for detection of off-flavor metabolites produced by cyanobacteria and actinomycetes. These probes are based on antibody reactions and provide a means of rapidly assessing the presence of geosmin or 2-methylisoborneol. Off-flavor metabolites produced by aquatic organisms impact perceived potable water quality and harvesting of aquaculture products (Burligame, 1999; Zimba *et al.*, 1999). Current plans include the development of *in situ* sensors arrayed in networks to detect aquatic toxin producing algae. These sensors will contain molecular probes to identify the presence of toxin-producing algae. When detected, fluorescent probes will provide signal for identification.

### Conclusions

While we feel that current remote sensing technologies have many actual and potential applications for assessing water resources and for monitoring water quality, limitations in spectral and spatial resolution of current sensors on satellites currently restrict the wide application of satellite data for monitoring water quality. New satellites (SeaWiFS, EOS, MOS, Ikonos, etc.) and sensors (hyperspectral, high spatial resolution) already launched or planned to be launched over the next decade will provide the improved spectral and spatial resolutions needed to monitor water quality parameters in surface waters from space platforms. Research needs to focus on understanding the effects of water quality on optical and thermal properties of surface waters so that physically based models can be developed relating water quality parameters to optical/thermal measurements made by remote sensing techniques. Hyperspectral data from space platforms will allow us to discriminate between water quality parameters and to develop a better understanding of light/water/substance interactions. Such information should allow us to move away from empirical approaches now being used and develop algorithms that will allow us to use the full resolution electromagnetic spectrum to monitor water quality parameters.

The integration of remotely sensed data, GPS, and GIS technologies provides a valuable tool for monitoring and assessing waterways. Remotely sensed data provide a permanent geographically located image database as a baseline for future comparisons. The integrated use of remotely sensed data, GPS, and GIS will enable consultants and natural resource managers to develop management plans for a variety of natural resource management applications.

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