REMOTE SENSING TECHNIQUES FOR DETERMINING WATER QUALITY: APPLICATIONS TO TMDLs

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ABSTRACT

Remote sensing techniques can be use to assess several water quality parameters (i.e., suspended sediments (turbidity), chlorophyll, temperature) that are key factors in defining TMDLs. These optical and thermal sensors on boats, aircraft, and satellites provide both spatial and temporal information needed to understand changes in water quality parameters necessary for developing better management practices to improve water quality. With recent and planned launches of satellites with improved spectral and spatial resolution sensors, greater application of remote sensing techniques to assess and monitor water quality parameters will be possible. These remote sensing techniques should improve our abilities to assess the landscape and thus better define TMDLs and then provide monitoring data to follow clean-up efforts.

INTRODUCTION

More than 20,000 waterbodies across America have been identified as polluted including more than 300,000 miles of river and shoreline and 5 million acres of lakes. It is estimated that approximately 40% of US waters do not meet minimum water quality standards (U.S. Environmental Protection Agency 1998). The Clean Water Act (P.L. 92-500) and its subsequent reauthorizations provide legislative authority for restoring polluted waters with the stated goal of making US waters fishable and swimable again. While the Clean Water Act is credited with significant improvements in water quality, water pollution remains a problem.

The Clean Water Act requires the establishment of total maximum daily loads (TMDLs) for polluted waters by States, Territories, and authorized Tribes. Following the establishment of TMDLs the States, Territories, and authorized Tribes must identify lists of polluted waterbodies impaired by pollutants, develop plans to clean-up for polluted waters, and monitor the effectiveness of the clean-up plan.

The purpose of this paper is to show the potential of remote sensing technologies for identifying and assessing the quality of surface waters for TMDLs and for monitoring the effectiveness of the clean-up programs.

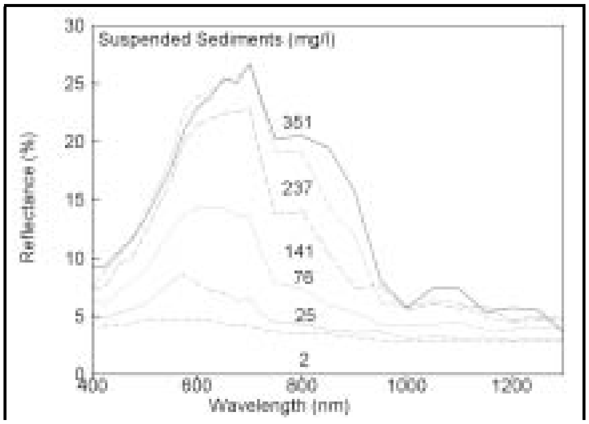
BACKGROUND

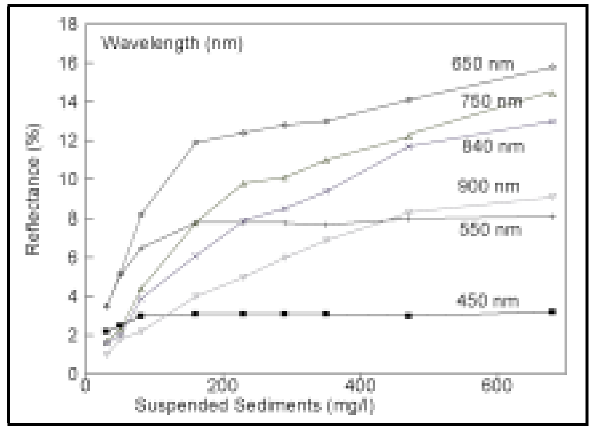
TMDLs are attempts to define water quality in general terms of the physical, chemical, thermal, and/or biological properties of water. We usually define substances affecting water quality as coming from either point or nonpoint sources. Point sources are associated with substances that can be traced to a single source, such as a pipe or a ditch. Nonpoint substances are more diffuse and associated with the landscape and its response to water movement and land use. Human and natural activities contribute nonpoint substances to runoff water thus affecting its quality. A TMDL is the calculated amount of a potential pollutant (sum of watershed point sources, nonpoint sources, and a margin of error) which will not impair the ecological integrity of a water body. Each state s list of impaired water bodies (303d list) is derived from a combination of direct biological measurements and/or indirect water quality measurements.

Monitoring and assessing the quality of waters in streams, reservoirs, lakes, and estuaries are critical for establishing TMDLs to improve water quality. Current techniques for measuring water quality involve *in situ* measurements and/or the collection of water samples for subsequent laboratory analyses. While these technologies provide accurate measurements for a point in time and space, they are expensive, and do not provide either the spatial or temporal view of water quality needed for monitoring, assessing, or managing water quality for an individual water body or for multiple water bodies across the landscape. Remote sensing of indicators of water quality offers the potential of relatively inexpensive, frequent, and synoptic measurements using sensors aboard aircraft and/or spacecraft.

Major pollutants requiring TMDL correction plans are suspended sediments (turbidity), pathogens, nutrients, metals, dissolved organic matter (DOM), pesticides, chlorophylls (algae, plants), temperature, and oils. Remote sensing applications to determine water quality are limited to measuring those substances or conditions that influence and change optical and/or thermal characteristics of the surface water properties. Suspended sediments, chlorophylls, DOM, temperature, and oil are water quality indicators that can change the spectral and thermal properties of surface waters and are most readily measured by remote sensing techniques. Substances (i.e., nutrients, metals) that do not change the optical and/or thermal characteristics of surface waters can only be inferred by measuring surrogate properties (i.e., chlorophylls) which may have responded to an input of chemicals.

The strength of remote sensing techniques lies in their ability to provide both spatial and temporal views of surface water quality parameters that is typically not possible from *in situ* measurements. Remote sensing makes it possible to monitor the landscape effectively and efficiently, identifying water bodies with significant water quality problems. These water quality parameters, often, can be quantified using remote sensing techniques allowing management plans to be formulated to reduce movement of substances from watersheds to water bodies thus reducing the effects of the pollutant on water quality. Remote sensing also has a potential role in selection of sub-ecoregion reference sites and in defining historical conditions. Examples of applications of remote sensing for measuring suspended sediments, chlorophylls, and temperature will be given.



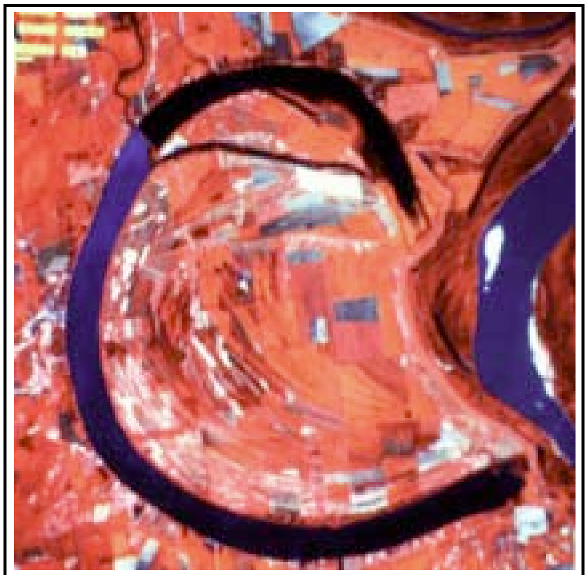
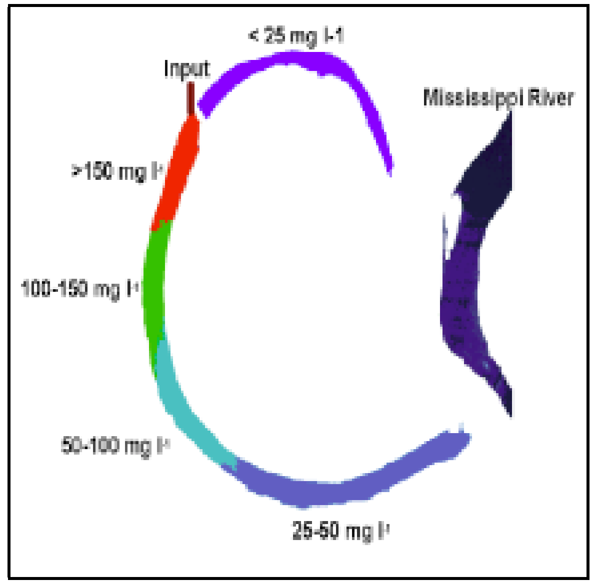


SUSPENDED SEDIMENTS

Suspended sediments are the most common pollutant both in terms of weight and volume in surface waters of freshwater systems. Suspended sediments may serve as a surrogate contaminant in agricultural watersheds since phosphorus, insecticides, and metals adhere to fine sediment particles.
Suspended sediments increase the radiance emergent from surface waters (Fig. 1) in the visible and near infrared proportion of the electromagnetic spectrum (Ritchie and Schiebe 2000). Airborne platforms using photography, line scanners, multispectral scanners, and video have all been used to study suspended sediment patterns. Since the late 1970's remote sensing studies of suspended sediments have been made using data from satellite platforms.

Most research that had a large range (i.e., 0-200+ mg/l) of suspended sediment concentration has found a curvilinear relationship between suspended sediments and radiance or reflectance (Ritchie et al. 1976, 1990; Curran and Novo 1988) because the amount of reflected radiance tends to saturate as suspended sediment concentrations increase. The point of saturation is wavelength dependent (Figure 2) with the shorter wavelength saturating at low concentrations. If the range of suspended sediments is between 0 and 50 mg/l, reflectance from almost any wavelength will be significantly related to suspended sediment concentrations. As the range of suspended sediments increases to 200 mg/l or higher, curvilinear relationships have to be developed with reflectance in the longer wavelength.

Significant relationships have been shown between suspended sediments and radiance or reflectance from spectral wave bands or combinations of wave bands on satellite and aircraft sensors. 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 waters. However, Curran and Novo (1988) in a review of remote sensing of suspended sediments found that many wavelengths have been used and found that the optimum wavelength was related to suspended sediment concentration. Many studies have developed algorithms for the relationship between the concentration of suspended sediments and radiance or reflectance. A few studies have taken the next step and used these algorithms to estimate suspended sediments for another time or place (Ritchie and Cooper 1988,

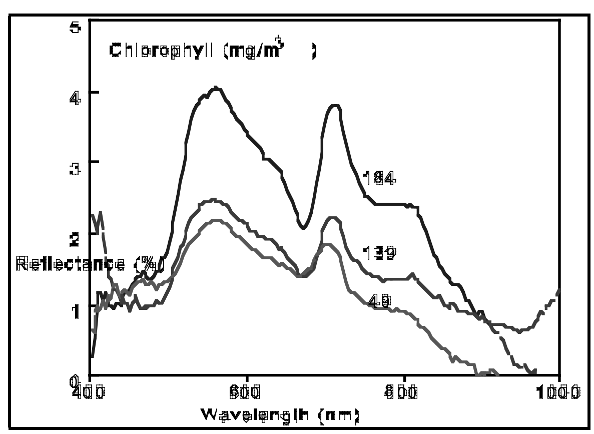
 

1991). Once developed, an algorithm should be applicable until some watershed event changes the quality (size, color, mineralogy, etc.) of suspended sediments delivered to the lake.

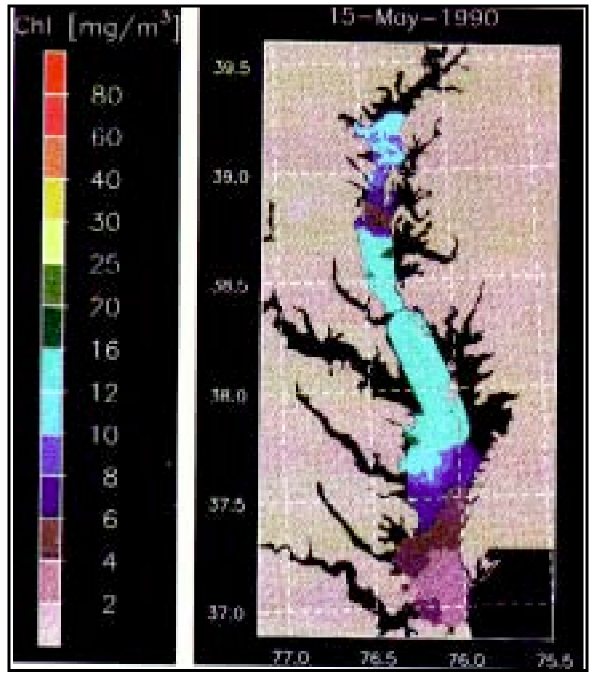
Landsat Thematic Mapper (TM) data was used to map the suspended sediment concentration in increments related to the management of suspended sediments in Lake Chicot, Arkansas. Figures 3 and 4 show examples of the type of mapping done for suspended sediments. Such a concept could be used to assess water bodies across the landscape for their compliance to proposed TMDL s. Using developed algorithms suspended sediments could be mapped in any increments needed to determine water bodies with suspended sediment problems.

CHLOROPHYLL

Lakes and other water bodies depend mainly on their watersheds for nutrients and other substances to sustain biological activities. While these nutrients and substances are required for a healthy aquatic environment, an excess of these inputs leads to nutrient enrichment and eutrophication of the lake. Eutrophication of a water body is usually quantified in terms of the concentration of the chlorophyll contained in the algal/plankton. While aging of water bodies is a normal process, detailed information on eutrophication (chlorophyll content) in a lake will allow better management plans to be developed to control the source in nutrient input from the watershed.



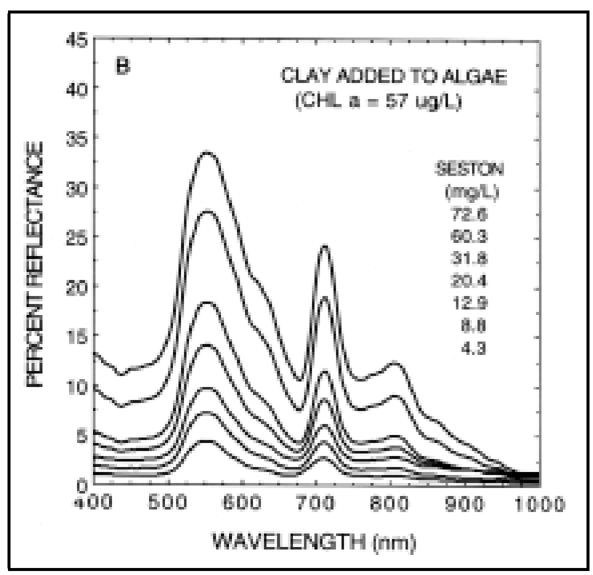
Monitoring the concentration of the chlorophyll (algal/phytoplankton) is needed to manage eutrophication in lakes (USEPA 2000). Remote sensing can be used to measure chlorophyll concentrations and patterns in water bodies. As with suspended sediment measurements, remote sensing of chlorophyll in water is based on developing relationships between radiance/reflectance in narrow bands or band ratios and chlorophyll. Figure 5 shows the relationship between reflectance and chlorophyll from *in situ* measurements made under control conditions.



Estimates of chlorophyll content have been made *in situ* and from aircraft and satellite platforms. These studies have used a variety of algorithms and wavelengths to successfully map chlorophyll concentrations of the oceans, estuaries, and fresh waters. For example, Harding et al. (1995) used the following algorithm based on aircraft measurements to determine seasonal chlorophyll-a content in the Chesapeake Bay.

$$\mathbf{Log_{10}\,[Chlorophyll] = a + b\,(-Log_{10}G)}$$

Where a and b are empirical constants derived from *in situ* measurements and G is $[(R_2)^2/(R_1{*}R_3)]$. R_1 is radiance at 460 nm, R_2 is radiance at 490 nm, and R_3 is radiance at 520 nm. Using this algorithm Harding et al. (1995) mapped total chlorophyll content in the Chesapeake Bay (Figure 6).



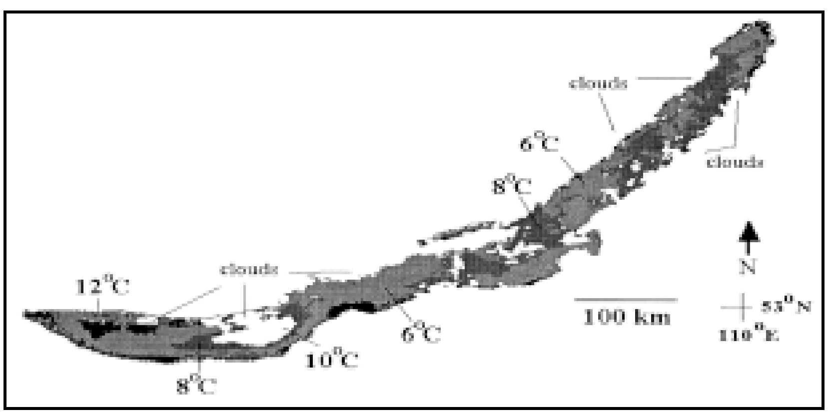
While measuring chlorophyll by remote sensing technique is possible, studies have also shown that the broad wavelength spectral data available on current satellites do not permit discrimination between chlorophyll and suspended sediments when suspended sediment concentrations are high due to the dominance of the spectral signal from suspended sediment (Ritchie et al. 1994). Recent research has concentrated on the relationship between chlorophyll-a and the narrow band spectral details at the red edge of the visible spectrum (Gitelson et al. 1994). Data has shown a linear relationship between chlorophyll-a and the difference between the emergent energy in the primarily algal scattering range (700-705 nm) and the primarily chlorophyll-a absorption range (675-680 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 7. These new efforts suggest new approaches for application of airborne and spaceborne sensors to exploit these phenomena to estimate chlorophyll in surface waters under all conditions as new hyperspectral sensors are launched and data become available.

Hyperspectral and fluorescence data may also make it possible to differentiate between phytoplankton groups. Laboratory and field studies using hyperspectral data have been used to develop algorithms to estimate green and blue-green algae (Dekker et al. 1995). Bazzani, M. and G. Cecchi (1995) identified unique spectral properties for 10 algae species using fluorescence spectrometry. Hyperspectral data now available from several satellite platforms should allow better discrimination between pigments thus allowing the identification of broad algal groups.

TEMPERATURE

The most common sources of thermal pollution are cooling water releases from electrical power plants. Thermal discharge into streams, lakes and coastal waters from electrical power plants has been mapped with remotely sensed data (Gibbons et al. 1989). Mapping thermal enrichment in streams, lakes, reservoirs, and coastal waters (Figure 8) has been useful in managing thermal releases from electrical power plants and understanding aquatic ecosystems. Management of power plant releases can be designed to reduce the impact of thermal releases based on thermal patterns determined for different flow regimes from remotely sensed data. Improved 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 that is critical for studying thermal releases.

Other anthropogenic activity can also lead to changes in surface water temperature. One effect of



suspended sediments in water is to backscatter significant quantities of solar energy that would otherwise be absorbed in a clear lake. This process, in effect, reflects solar energy and results in turbid impoundments being cooler than its clear water neighbor (Schiebe et al. 1976). Landsat TM data was used to estimate surface temperatures of an oxbow lake along the Mississippi River (Ritchie et al. 1990). Thermal remote sensing is a useful tool for monitoring freshwater systems to detect thermal changes that can affect biological productivity.

CONCLUSIONS

While we feel that current remote sensing technologies have many actual and potential applications for assessing water resources and for monitoring the progress of clean-up efforts, limitations in spectral and spatial resolution of current sensors on satellites currently restrict the wide use of satellite data for monitoring water quality. New satellites (SEAWIFS, EOS, MOS, OrbView, 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. 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.

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