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Remote Sensing of Suspended Sediments in Surface Waters

Quantitative estimates of suspended sediments in the surface water of six northern Mississippi reservoirs were made using reflected solar radiation.

INTRODUCTION

SUSPENDED SEDIMENTS are a major problem in streams, lakes, and estuaries (Robinson, 1971) and carry adsorbed chemicals (Romkens *et al.*, 1973). They affect aquatic ecosystems (Ritchie, 1972) and the recreational potential (Bondurant and Livesey, 1965) of many water bodies. Present techniques for measuring suspended sediments involve measuring turbidity by optically (National Oceanographic Instrument Center, 1974) or gravimetrically determining suspended sediment concentrations. These measurements have limited usefulness, since they represent point samples and do not give a synoptic view of the waterbody. Recent studies, using measurements from LANDSAT (ERTS) (Kritakos *et al.*, 1974; Yarger *et al.*, 1974; Carlson and McCulloch, 1974; Williamson, 1974; Klemas *et al.*, 1973, 1974; Johnson, 1975; Clark *et al.*, 1974) and aircraft measurements (Pionke and Blanchard, 1975) of reflected light from waterbodies, have shown the potential for the use of such remote platforms to give qualitative, as well as quantitative, synoptic views of suspended sediment in the surface waters of waterbodies. The purpose of our studies is to determine the optimum wavelength for quantitatively determining suspended sediment concentrations of surface water from a remote platform.

ABSTRACT: *Reflected and incident solar radiation 20 to 50 cm above the water surface were measured on six northern Mississippi reservoirs between August 1973 and December 1974. Linear regression analyses showed the best fit for the relationship between reflected solar radiation, or reflectance, and suspended sediment concentration of surface water was between 700 and 800 nm. Further analyses, using sun angle grouping, showed that sun angle had a definite effect on these relationships. These studies showed that quantitative estimates of suspended sediment concentration of surface water could be made using reflected solar radiation.*

METHODS AND MATERIALS

Six reservoirs in northern Mississippi were chosen for study (Figure 1). These reservoirs were all located within 70 kilometres of Oxford, Mississippi and ranged in size from 3 to 4300 hectares. Located on the Coastal Plain Province, the geologic material is composed of Upper Cretaceous, Paleocene, and Eocene sediments. Loess covers the watersheds in depths ranging from 0 to 3 metres. The geologic formations dip to the west. The formations from east to west are Selma, Ripley, Prairie Bluff, Clayton, Porters Creek, Fearn Springs, Ackerman, Meridian, Tallahatla, and Koscius-

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 42, No. 12, December 1976, pp. 1539-1545.

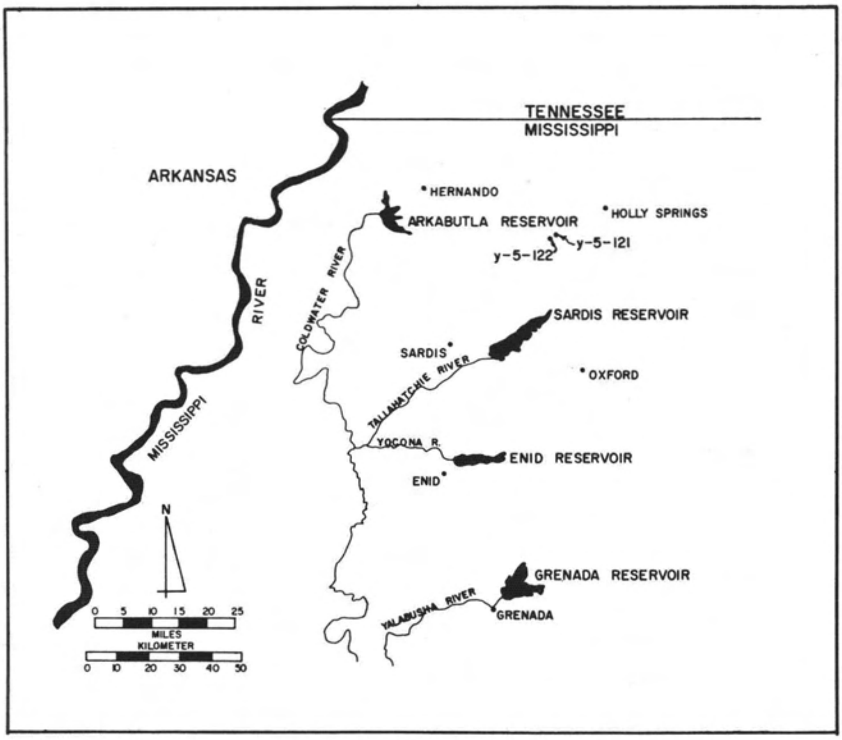

FIG. 1. Location map of six study reservoirs in northern Mississippi.

ko. The soils of the six watersheds are predominantly of the Memphis, Grenada, and Loring series. These three soil series are similar in color and many properties.

Reflected and incident solar radiation were measured on the six northern Mississippi reservoirs between August 1973 and December 1974, using a portable ISCO (Instrument Specialties Company) Model SR Spectroradiometer[1] equipped with a 2.95 m fiber optic conduit and a Teflon diffusing screen. The diffusing screen produces an angular response to radiation in accordance with Lambert's cosine law. The light pipe and diffusing screen were mounted on a 2 metre aluminum rod. The rod was mounted on the side of the boat so that the diffusing screen was 1.5 metre from the edge of the boat. The spectroradiometer was calibrated with an ISCO Model SRC Spectroradiometer calibrator. Solar radiation was measured in microwatts per square centimeter per nanometer (μ watts cm^{-2} nm^{-1}). Reflected solar radiation data were measured 20-50 cm above the water surface, over water whose total depth was at least five times the Secchi extinction depth. Secchi depth ranged from 8 to 160 cm. Incident solar radiation was measured at 180° from the water surface. Reflected and incident solar radiation measurements were made at 25-nm intervals from 400 to 750 nm, and at 50-nm intervals from 750 to 1550 nm on cloud free days. All measurements were made within 2 hours of solar noon. Sun angle (defined as the deviation from zenith) was calculated for each set of data.

The concentration of total solids in the surface waters, expressed in milligrams per litre (mg/1), was determined from two surface water samples (0-2 cm) collected at each site where radiation reading was made. Samples were collected by dipping the collecting vessel into the surface water. A 100-ml aliquot from each sample was evaporated to dryness and the total solids weighed. Dissolved solids were determined by filtering a 100-ml aliquot through a 0.45 micrometre filter, evaporating to dryness and weighing. Dissolved solids ranged from 20 to 50 mg/l and exhibited no seasonal pattern or difference between lakes during the 16 month study.

Data equivalent to that of LANDSAT for incident and reflected solar radiation between 500 to 600 nm, 600 to 700 nm, 700 to 800 nm, and 800 to 1100 nm were calculated by integrating the area under the reflected solar radiation spectra. Statistical studies showed that a linear regression best fit the relationship between the concentration of total solids in surface water, and both reflected solar radiation and reflectance (ratio of reflected solar radiation to incident solar radiation). Therefore, a linear least squares routine was used to determine statistical parameters.

Results and Discussion

Solar radiation reflected from water surfaces varied with the amount of suspended sediment and wavelength (Figure 2). In general, reflected solar radiation between 450 to 900 nanometres (nm) increased as the concentration of suspended sediment increased. The region of maximum reflected solar radiation shifted from about 550 nm at low sediment concentration to above 600 nm at higher sediment concentrations. Between 700 and 800 nm, the change in reflected solar radiation with change in suspended sediment exhibited a more regular pattern than that seen between 400 and 700 nm. Reflectance measurements (the ratio of reflected solar radiation to incident solar radiation to incident solar radiation) exhibited patterns (Ritchie *et al.*, 1974; Kalko, 1972) like those of reflected solar radiation. Suspended sediment in the surface water show seasonal differences due to climatic factor and reservoir management (Figure 3).

The data (Figure 2) indicated that a change in the concentration of suspended sediment caused a change in the amount of radiation reflected from the water surface. Linear, least-squares regression analyses were used to evaluate these changes at different wavelengths. The fit (Figure 4) of the calculated linear regression equation improved from 400 to 800 nm for reflected solar radiation and from 400 to 725 nm for reflec-

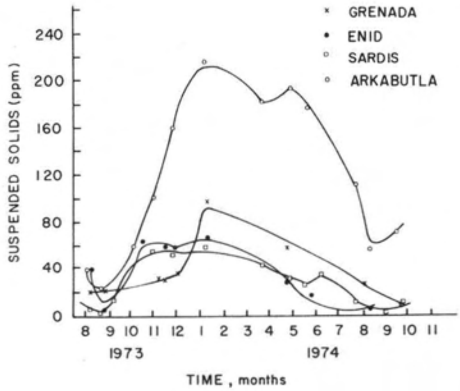

Fig. 3. Seasonal distribution of suspended sediment in the surface water of some north Mississippi reservoirs.

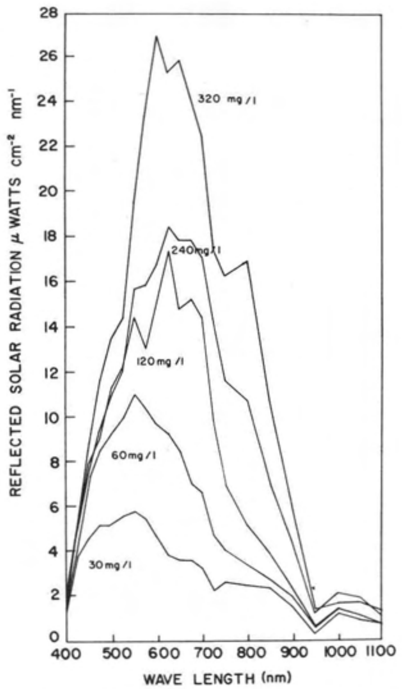

Fig. 2. The relationship of reflected solar radiation with wavelength for different concentrations of suspended sediments in the surface water.

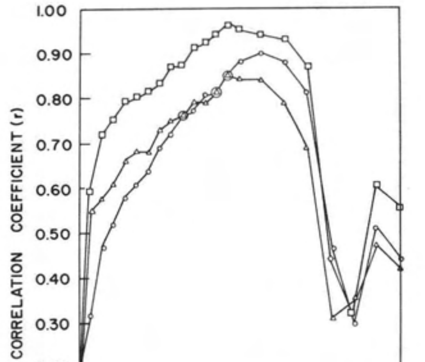

Fig. 4. The relationship between the correlation coefficients (r) for the linear regression of concentration of suspended sediment in the surface water and reflected solar radiation and reflectance with wavelength.

tance. Although the change in the amount of radiation reflected from the water surface was greater between 600 and 700 nm, the best region of the spectra for predicting suspended sediment from linear equations, using reflected solar radiation or reflectance, would be between 700 and 800 nm. Representative plots of the data (Figures 5 and 6) show the scatter and also the few data points collected above 200 mg/l suspended solids. For these six lakes in northern Mississippi, suspended solids concentration above 200 mg/l were unusual. Before the shape of the curve for higher concentrations of suspended sediment can be defined accurately, more data are needed when the suspended sediment concentration is above 200 mg/1. An earlier study had shown very little difference in reflectance between these six reservoirs (Ritchie *et al.*, 1974).

Reflected solar radiation measurements from the different spectral regions were combined to provide data equivalent to LANDSAT bands 4, 5, 6, and 7. Linear regression analyses showed the best fit (Table 1) was between 700 and 800 nm for both reflected solar radiation and reflectance. A greater total amount of reflected solar radiation was measured between 600 and 700 nm, but there was also more variation which caused a poorer fit.

The Fresnel formula shows that the reflectivity of a water surface changes as the sun angle changes, so that at sun angles less than 40° the reflectivity is less than 2.5 percent, while greater than 40° the reflectivity increases rapidly to reach 100 percent at 90° (List, 1971). Our data were divided into two groups, those with sun angle less than 40° and those with sun angle greater than 40°, and a linear regression analysis was made of each group. The correlation coefficients for the relationship between reflected solar radiation and surface suspended sediment concentration by wavelength were between 5 to 15 percent greater for the group with sun angle less than 40° than those greater than 40°. This group, with sun angles less than 40°, had correlation coefficients of from 2 to 5 percent greater than the correlation coefficients for all samples.

The correlation coefficients for the different sun angle groups improved more for the relationship between reflectance and surface suspended sediment. The group with sun angles less than 40° had correlation coef-

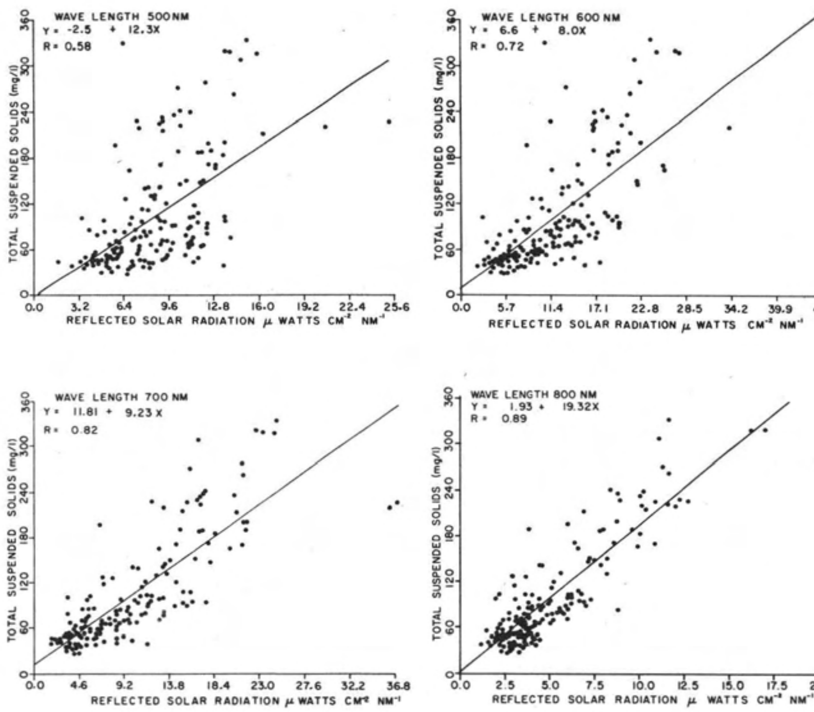

FIG. 5. Relationship between reflected solar radiation and concentration of suspended sediment in the surface water at 500, 600, 700, and 800 nm.

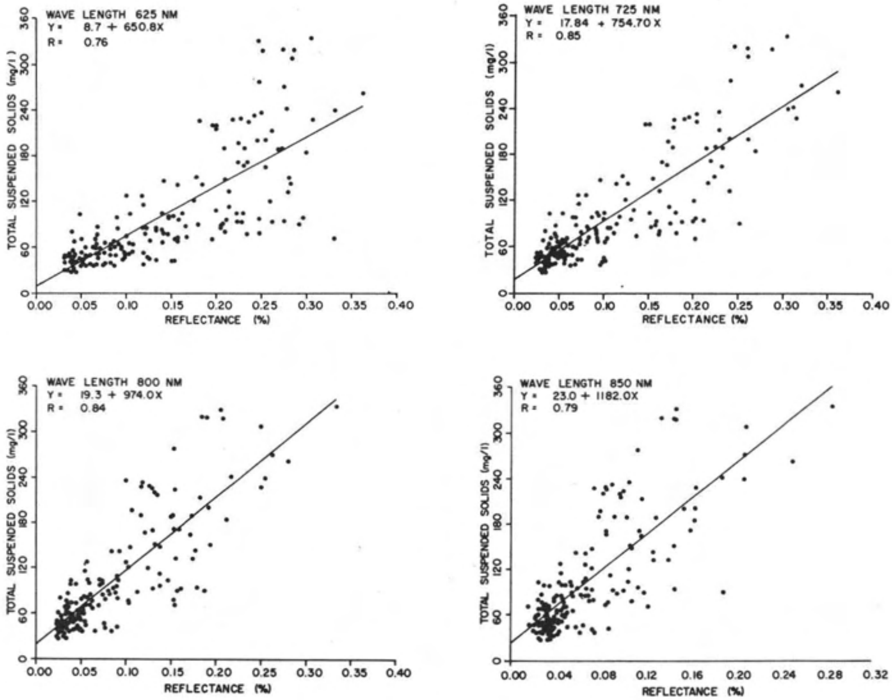

FIG. 6. Relationship between reflectance and concentration suspended sediment in the surface water at 625, 725, 800, and 850 nm.

ficients that were 5 to 20 percent greater than either the group with sun angles greater than 40° or all the samples (Figure 4). Correlation coefficients as high as 0.96 were calculated (Figure 7) with sun angles less than 40°. Similar improvements were also found for LANDSAT equivalent data for both reflected solar radiation and reflectance by dividing the data into two sun angle groups (Table 1).

Knowing that sun angle has an influence on the calculated relationship between reflected solar radiation and suspended sediment in the surface water, Fresnel reflectivity formula was used to calculate the amount of reflected solar radiation due to the reflectivity of the water surface. Since the total energy radiation away from the water surface is the sum of the Fresnel reflectivity and the emergent energy backscattered by the particles in the water, the calculated Fresnel reflectivity was subtracted from the total measured reflected solar radiation to obtain the emergent energy from the water produced by the backscattering from the suspended particles. The statistical parameters of the relationship between this calculated backscattered radiation and the concentration of suspended sediment in the surface water were calculated. This calculated backscatter radia-

TABLE 1. CORRELATION COEFFICIENTS FOR THE LINEAR REGRESSION ANALYSES FOR LANDSAT EQUIVALENT DATA.

		Reflected Solar Radiation			Reflectance		
		Sun Angle			Sun Angle		
LANDSAT Band	Wavelength nm	10–70°	<40°	>40°	10–70°	<40°	>40°
		Correlation Coefficient (r)					
4	500–600	0.51	0.73	0.60	0.72	0.83	0.65
5	600–700	0.66	0.84	0.73	0.78	0.91	0.72
6	700–800	0.88	0.92	0.84	0.84	0.96	0.83
7	800–1100	0.84	0.87	0.78	0.72	0.90	0.72

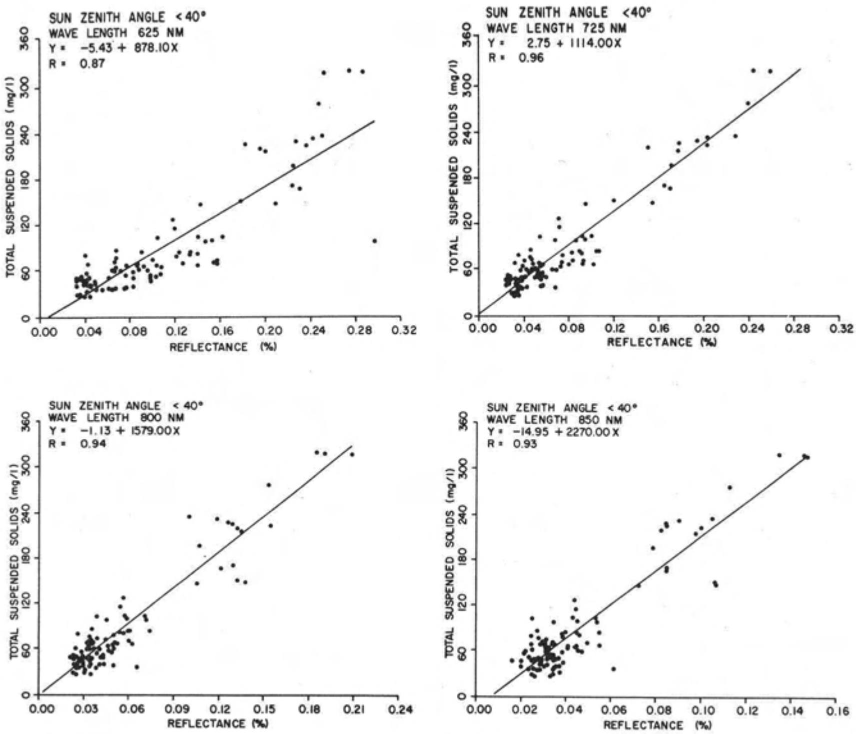

FIG. 7. Relationship between reflectance and concentration of suspended sediment in the surface water for samples with sun angles less than 40° at 625, 725, 800, and 850 nm.

tion had correlation coefficients that were 2 to 10 percent greater than those for total reflected solar radiation (Table 2). A small improvement was also found in the correlation coefficients for reflectance.

These data show that there is a quantitative relationship between reflected solar radiation and suspended sediment concentration of surface water. The best spectral region for using this quantitative relationship

TABLE 2. COMPARISON OF CORRELATION COEFFICIENTS CALCULATED FOR THE RELATIONSHIPS BETWEEN TOTAL REFLECTED SOLAR RADIATION AND SUSPENDED SEDIMENT IN THE SURFACE WATER AND THE RELATIONSHIP BETWEEN CALCULATED REFLECTED SOLAR RADIATION DUE TO BACKSCATTERING AND SUSPENDED SEDIMENT.

Wavelength nm	Reflected Solar Radiation Total*	Reflected Solar Radiation Minus Reflectivity**	Reflectance Total*	Reflectance Minus Reflectivity**
		Correlation Coefficient (r)		
650	0.77	0.81	0.79	0.80
675	0.80	0.84	0.79	0.80
700	0.81	0.84	0.81	0.82
725	0.85	0.88	0.85	0.86
750	0.87	0.90	0.84	0.85
800	0.90	0.92	0.84	0.85
850	0.88	0.90	0.79	0.81
500−600	0.66	0.72	0.72	0.73
600−700	0.78	0.82	0.78	0.80
700−800	0.88	0.91	0.84	0.86
800−1100	0.84	0.88	0.72	0.75

* Total measured reflected solar radiation.
** Calculated reflected solar radiation due only to backscattering from suspended sediment in the surface waters.

would be between 700 and 800 nm. Sun angle has a definite effect on these quantitative relationships and must be considered when one attempts to estimate suspended sediment in surface water with reflected solar radiation and/or reflectance. Our data indicate that it should be possible to quantitatively determine suspended sediments in surface waters from remote platforms.

ACKNOWLEDGMENTS

This paper is a contribution of the Sedimentation Laboratory, USDA-ARS, Alabama-North Mississippi Area, Southern Region, in cooperation with the University of Mississippi and the Mississippi Agricultural and Forestry Experiment Station. Jonathan May, Kathleen Roush, and Willie Bender helped with the field and laboratory analyses. Robert Wilson helped with the computer analyses of the data, and Donna Bethany helped prepare the manuscript.

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