Spectral Reflectance Relationships to Turbidity Generated by Different Clay Materials

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ABSTRACT: The spectral response of turbid waters caused by different clay materials (bentonite clay, black cotton soil, kaoline, and grey soil) was studied using a spectro-radiometer in the 450 to 1000 nm wavelength. Illumination was provided by a 1000 W lamp. The analysis shows a linear relationship between turbidity and percentage reflectance for bentonite clay and black cotton soil, whereas curvilinear variation was observed for kaoline and grey soil. The organic content of all the clay materials was determined and, in the 550 to 750 nm wavelength, grey soil which has the lowest organic content shows the highest reflectance whereas black cotton soil with the highest organic content shows lowest reflectance.

INTRODUCTION

IN THE LAST FEW DECADES man's understanding of the environment and his awareness of the dangers of environmental pollution have increased enormously. Chemical, bacterial, organic, and thermal pollution have been given a lot of attention. The sources of pollution in any water body are natural as well as man made. The natural sources of pollution include the infiltration of ground water carrying impurities from the subsoil strata, rain water carrying atmospheric impurities, surface runoff carrying impurities from the exposed soil (including erosion), and vegetative materials (Bhargava, 1987b). Man made sources of pollution include domestic [generating sewage, sullage (spent water from bathrooms, kitchen, sinks, etc.)]; controlled and uncontrolled municipal wastes, industrial (generating wastes containing the different kinds of pollutants originating from various industries); agricultural (generating fertilizers, insecticides, pesticides, herbicides, etc.); and farms (drainage, erosion, landwash, etc.). In most situations, it is the man made sources which generally govern the type and extent of pollution (Bhargava, 1987a).

Sediments which fill streams, channels, harbors, lakes, and reservoirs are major problems around the world (Chagarlamudi *et al.*, 1983; Amos and Toplins, 1985; Myers, 1983; Ritchie *et al.*, 1987; Merry *et al.*, 1988; Ritchie and Cooper, 1988). Studies have been done to determine the influence of high sediment concentrations on aquatic animals and plants. High concentrations of sediments in suspension cause erosion of hydroelectric power and pumping equipment; affect fish and shell fish population by blanketing fish nests, spawning grounds, and food supplies; reduce light penetration (Bhargava, 1983b); and increase the cost of water treatment. Because of these effects many countries have regulations (Bhargava, 1985a, 1985b) controlling land use from the point of view of an adverse increase of sediment load in streams. The effects of soil erosion include loss in the productivity of lands, undesirable deposition of eroded material, increase in the frequency of floods, and depletion of ground water flow. Resource managers require rapid and accurate methods of acquiring and interpreting data for the development and management of our natural resources.

Many studies have shown that suspended materials can be detected using remote sensing techniques (Ritchie *et al.*, 1976; Muralikrishna, 1979; Johnson and Harriss, 1980; Khorram, 1981; Bhargava, 1983a; Nayak, 1983; McKim *et al.*, 1984; Khorram and Cheshire, 1985; Lodwick and Harrington, 1985; Amos and Toplins, 1985; Ritchie and Schiebe, 1986; Ritchie *et al.*, 1987; Ritchie and Cooper, 1988). However, most of these studies have not considered the spectral characteristics of different suspended sediment materials.

Suspended materials carried in water vary considerably both in quantity and quality at different points of the water body, at different times of the year, and under different flow conditions. Hence, models developed so far are not applicable for all seasons and different geographic areas as they do not take into account the variation in types of suspended materials present. An attempt was made herein to study in the laboratory the spectral response of different suspended materials in water, and the results are discussed in this paper.

EXPERIMENTAL METHODOLOGY

In this study four different turbidity causing materials were used, including (1) bentonite clay, which occurs in partially weathered volcanic deposits and in the more arid regions of the world; (2) kaoline, which is found in soils of humid-temperate and humid tropical regions where heavier rainfall occurs; (3) grey soil, which is a light greenish grey colored clay locally known in India as "Dhauri clay" and designated herein as grey soil; and (4) black cotton soil, whose internationally accepted name is montmorillonite clay. These materials are composed of diverse granular mineral particles, humus or organic matter, and various inorganic chemical compounds. Some of the laboratory analyzed physical and chemical properties of the various clays used in this study are presented in Table 1. X-ray analysis of the clays was, however, not carried out in the present studies.

The pure clay samples used in the experimentation were prepared through sieving of the locally available soil samples. The clay samples below the 35 μm size were selected, all of which, when added (without any dispersing agent) in the water contained in a tank, remained in suspension during the experi-

TABLE 1. PHYSICAL AND CHEMICAL PROPERTIES OF THE SOILS

Soil Name	Visually observed color	Volatile matter representing organic content, %	pH	Specific gravity	Chemical Oxygen Demand of the suspension (1 gm of clay in a liter of distilled water), mg/l: Unfiltered sample	Chemical Oxygen Demand of the suspension (1 gm of clay in a liter of distilled water), mg/l: Filtered sample
Black Cotton Soil	Light Black	21.85	7.96	2.53	440	17.6
Bentonite	Brown	18.41	8.54	2.051	105.6	52.8
Kaoline	White	13.87	8.94	2.62	0	0
Grey Soil	Light Green	7.15	8.01	2.662	96.8	17.6

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mentation period for which time the suspension was continuously agitated and appropriately stirred by a stirrer. This not only ensured the particles remaining in suspension at uniform turbidity levels, but the individual particle sizes were maintained and there were no aggregates formed in the suspension.

The inside (all sides and the botton) of the 0.5 m by 0.5 m by 0.75 m high tank was big enough and was painted black in order to avoid any reflectance from any side or bottom of the tank. A 1000 W tungston filament lamp glowing at a temperature of around 4,500°K and emitting most of the visible radiation at a wavelength of around 600 nm (light yellow color) was used to illuminate the tank uniformly. Using an SRR-02 spectro-radiometer (manufactured by ISRO, Bangalore, India), the reflectance was measured from a height of 1.5 m above the water surface. The reflectance was measured at wavelengths ranging from 450 nm to 1000 nm at a 50-nm interval. A plate coated with barium sulfate was used for calibration of the radiomenter. The turbidity levels that were used in this study, ranged from 10 NTU to 950 NTU. Relationships between the suspended solids concentration (expressed as mg/1) of the clay suspensions and the Nephelometrically measured turbidity (expressed as NTU, the Nephelometric Turbidity Units) were established for the different kinds of clays that were used in this study. Figure 1 depicts the relationship between the turbidity of the samples and the suspended solids concentration of the clay suspensions for each type of clay. The figure also shows the corresponding equations for the lines fitted through the observed data, together with the respective correlation coefficient values.

Water samples from the tank were collected and tested (within about eight hours) for turbidity in the laboratory using the Nephelometry method. For the same soil samples, an experiment was conducted to see if there was any change in the Nephelometry measurements with time, and the results showed no variations in the readings within about 12 hrs.

RESULTS AND DISCUSSIONS

The spectral response of the suspended materials was measured in terms of percentage reflectance. Figure 2 shows the variation in the reflectance value with respect to the various wavelengths with all the materials having a turbidity value of about 100 NTU. Initially, they exhibit a rather sharp decrease of reflectance with increasing wavelengths from 500 nm to 800 nm, and a moderate increase of reflectance for wavelengths from 800 to 1000 nm. Between about 450 and 500 nm wavelength range, a very steep decrease in reflectance is observed with increasing wavelengths. To differentiate the various types of soil materials present in a suspension, it would be more rational to choose a wavelength range in which the reflectance values of the different soil materials with respect to each other are significantly different, and at the same time, the variation of the reflectance values for each soil material with respect to the wavelengths is small. Otherwise, if the reflectance value versus wavelength variation is very sharp, then the observed values of reflectance will be subject to more errors when the wavelength (at which the observations of reflectance are to be made) unnoticeably shifts due to any reason (including, human error) during observations supposed to have been made at one particular choosen wavelength. Between 800 and 900 nm significant variations in the reflectance values are observed with respect to the different materials.

The above pattern of responses cannot be generalized for all the types of material present in the suspension. For example, in the case of lakes in particular, where most of the material present in suspension also consists of algae (whose spectral responses are different from that of the clay materials) and the effect of clay in such resuspended lakes may not dominate in

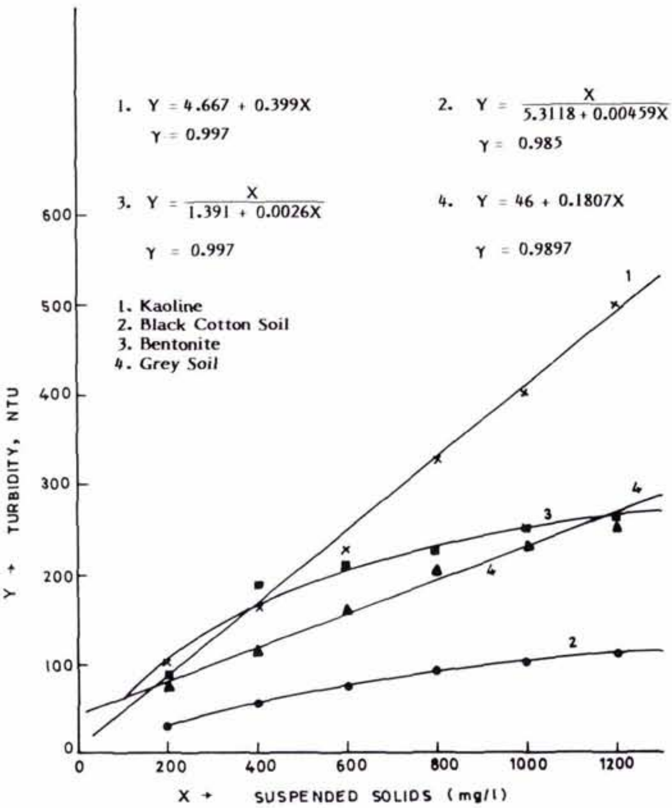

FIG. 1. Relationship between the nephelometry measurements and suspended solids concentration.

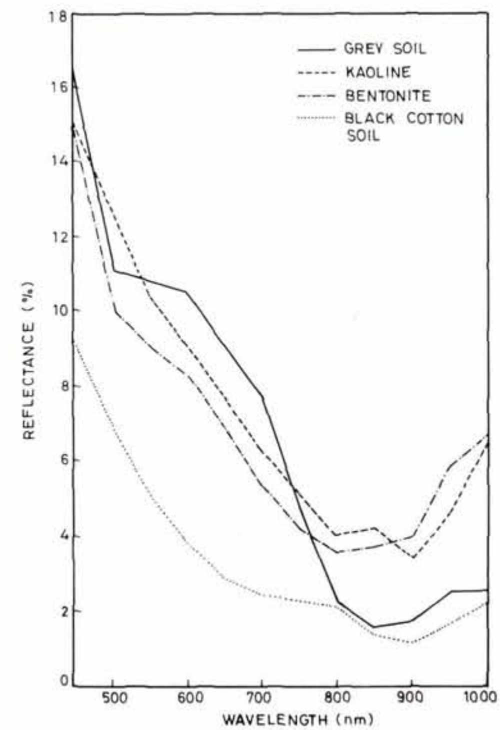

FIG. 2. Spectro-radiometric reflectance measurements of turbidity caused by grey soil, kaoline, bentonite clay, and black cotton soil over wavelengths ranging from 450 to 1000 nm.

the total spectral responses, and, thus, the reflectance response at the different wavelengths as reported by Whitlock *et al.* (1981) may not follow the pattern shown by pure clay suspensions.

At the same wavelength and with nearly the same turbidity level of the various materials, the variation observed in the reflectance values is significantly contributed by the sample's nature which depends on the properties of the different clay materials. For example, from the data shown in Figure 2 pertaining to a turbidity value of 100 NTU, it is seen, on qualitative comparison with the physical and chemical properties of the various soils (Table 1), that the soils' organic matter (manifested by the parameter volatile matter which alters the solids surface features) bears a rough correlation with the reflectance values of the various soils in the 550 to 750 nm wavelength range (higher reflectance at lower content of the volatile matter, and vice-versa, showing that the volatile matter contributes little to the reflectance in the stated wavelength range); the soils' pH bears an approximate relationship with the reflectance values of the various soils in the wavelength range of 800 to 900 nm (higher reflectance at higher pH); and the soils' specific gravity bears a rough relationship with the reflectance values of the various soils (except the black cotton soils) in the 850 to 1000 nm wavelength region (higher reflectance for lower specific gravity and vice-versa because the denser particles provide lesser volume (or surface area) and, thus, lower reflectance value). Black cotton soil exhibits the lowest reflectance value for all the wavelength ranges that were used in this study. In the blue-green and near infrared (IR) region of the spectrum, kaoline shows the highest reflectance value whereas in the red region, grey soil has highest reflectance value.

Figure 2 can be divided into three phases or wavelength groups. These phases are approximated as a straight line, and regression analysis was carried out to find the best fit lines of each phase. The evaluated slopes of these lines are shown in Table 2. In the visible region, all the different clay materials exhibit negative slopes whereas in the reflected infrared region of the spectrum they exhibit positive slopes. The steepest slope is observed in the visible region for the turbid water caused by the grey soil and in the infrared region for that caused by the bentonite clay.

Generally, soil reflectance exhibits a gentle increase with increasing wavelength (Colwell, 1983) whereas water absorbs nearly all the incident energy in the near IR region of the spectrum (Lillesand and Kiefer, 1979). In the 500 to 800 nm band, the reflectance response of clear water has almost the same pattern as is manifested in the turbid water used in this study. But in the near IR region, the response of clear water is different from turbid water. The increase in the reflectance values that are observed in the near IR region are contributed directly by the turbidity causing matter that is present in the water. This region can thus be used to get information about the turbidity level and, as already discussed, some property (such as the organic content, specific gravity, etc.) of the turbidity causing material present in the water body. Although, the reflectance variation between the different materials is maximum in the visible region and gradually reduces in the near IR region of the spectrum, it would be better to choose the visible range. But in situations where the wavelength (at which the observations are intended to be made) fluctuates during observations, due to any reason (including human errors) whatsoever, then, as discussed before, it would be more desirable to take observations of the reflectance values in the near IR region where the reflectance versus wavelength variation for the intended soil is not sharp, when compared to the observations in the visible range. Thus, if different turbidity causing materials exist in suspension, it would be more appropriate to take the reflectance responses in the visible region if the wavelength (at which observations are intended to be made) does not fluctuate during observations, and in the near IR region if the wavelength (at which observations are intended to be made) deviates during the course of observations due to any expected reason (including human errors).

Table 1 shows the average percentage of organic content present in the various soil types used in this study. However, a clay with different organic content was not used in this study. As discussed before, the reflectance values for the wavelengths between 550 and 750 nm also vary in the same order as shown in Table 1, and the black cotton soil with highest organic content shows the lowest reflectance value whereas grey soil with lowest organic content shows the highest reflectance value. Thus, the organic content of the soil present in the water body can be predicted, and this property of the soil may help to identify the soil type present in the various zones of water stream.

Figure 3 depicts the spectral response of different turbidity levels of black cotton soil for wavelengths from 450 to 1000 nm. Distinct differences in reflectance values corresponding to the different turbidity values is observed for black cotton soil in the 700 to 900 nm wavelength range. The merging of the reflectance response in the 600 to 800 nm wavelength region for the 90 and 120 NTU turbidities may be due to some observational errors. This range can therefore be used to monitor a wide variation in turbidity levels and it is also similar to band 3 of the Landsat MSS. This near IR band was best for monitoring the reflectance changes due to the different natures of the turbidity causing materials. For all materials in common, the wavelength range 700 to 900 nm, therefore, gives a significant relationship over a wide range of turbidity levels also. All the aforesaid discussion points out that the near IR range is ideal for monitoring the type of turbidity causing clay material as well as the turbidity magnitude.

Figure 4 shows measurements of reflectance as a function of turbidity for the various materials, at a wavelength of 750 nm (which manifests a maximum variation in reflectance for the various materials). Such plots when prepared at other wavelengths between 700 and 900 nm also manifest a similar trend. Linear regression was used to quantify the relationship between reflectance and turbidity. In these figures we also see how the observed values are distributed around the best fitted curve(s) or line(s). Grey soil and kaoline gave the highest coefficient of correlation and low standard error when they were fitted to the curvilinear values whereas black cotton soil and bentonite clay were best fit to a straight line equation. Table 3 shows correlation coefficients (γ) and and corresponding standard error of estimate for the linear regression between reflectance and turbidity for the various materials, and the regression models based on the available data points are presented in Equations 1 to 4.

$$Y_{GS} = \frac{X_{GS}}{12.47 + 0.115X_{GS}} \quad (1)$$

$$Y_K = \frac{X_K}{13.022 + 0.065X_K} \quad (2)$$

$$Y_{BC} = 0.04X_{BC} + 0.813 \quad (3)$$

$$Y_{BCS} = 0.031X_{BCS} - 0.49 \quad (4)$$

where Y_{GS}, Y_K, Y_{BC}, and Y_{BCS} are reflectance from grey soil, kaoline, bentonite clay, and black cotton soil, respectively, and

TABLE 2. VARIOUS PHASES OF THE VARIATION BETWEEN WAVELENGTH AND REFLECTANCE

Material	Wavelength range(nm):		Phase I 450-500	Phase II 500-800	Phase III 800-1000
Black Cotton Soil	Slope	=	−0.0363	−0.0084	+0.0111
Bentonite Clay	Slope	=	−0.100	−0.0232	+0.0170
Grey Soil	Slope	=	−0.1050	−0.0307	+0.0077
Kaoline	Slope	=	−0.0648	−0.0265	+0.0108

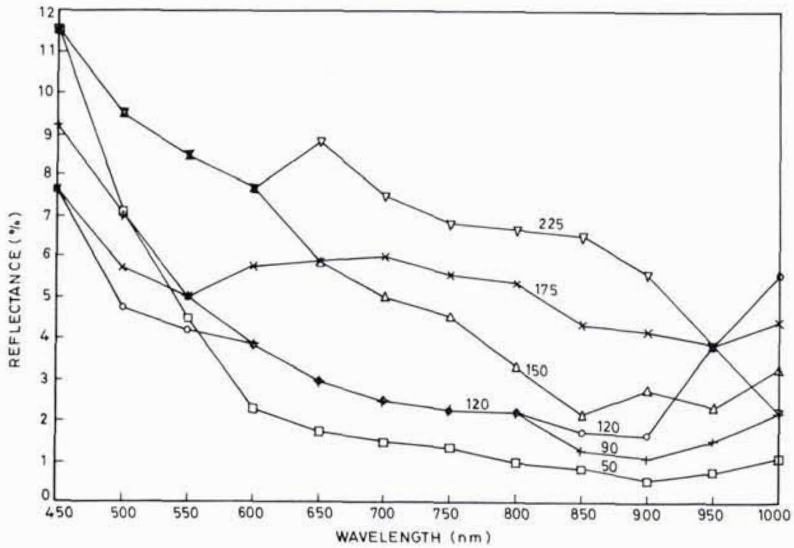

FIG. 3. Spectro-radiometric reflectance measurements of different turbidity levels caused by black cotton soil over wavelengths ranging from 450 to 1000 nm.

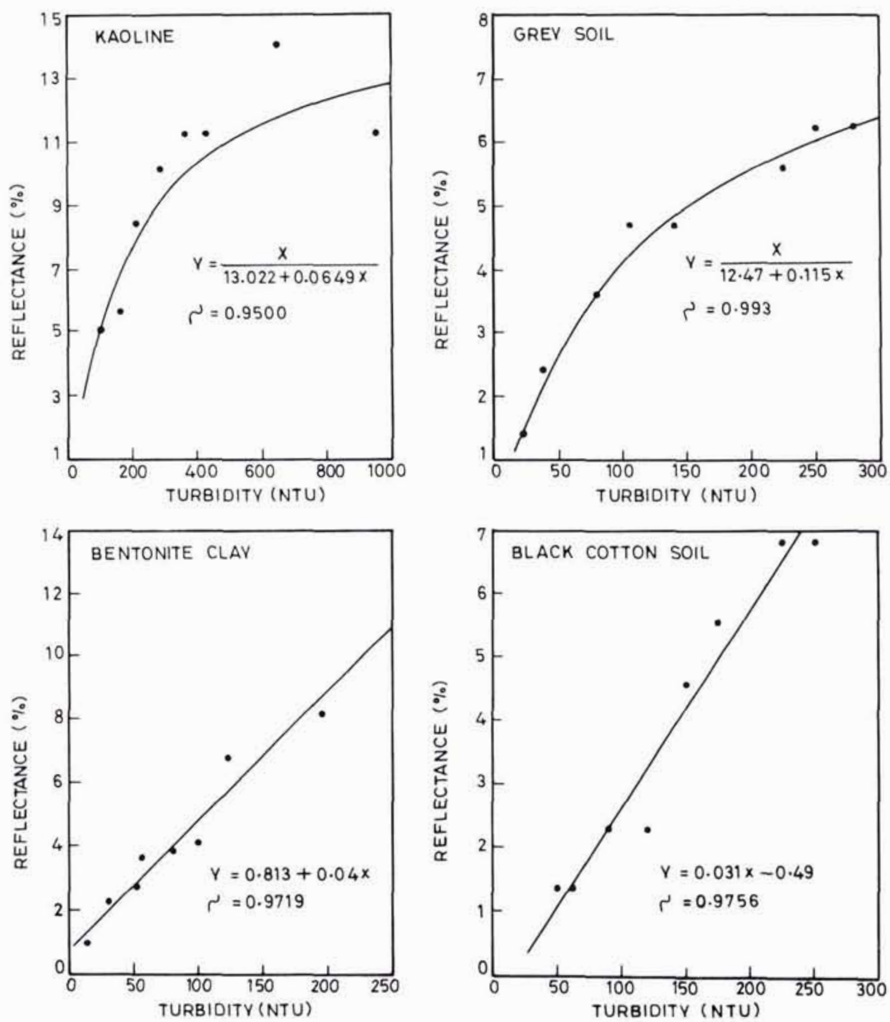

FIG. 4. Regression of reflectance on turbidity cause by grey soil, kaoline, bentonite clay, and black cotton soil at a wavelength of 750 nm.

TABLE 3. CORRELATION COEFFICIENT (γ) AND STANDARD ERROR FOR THE LINEAR REGRESSION BETWEEN REFLECTANCE AND TURBIDITY AT A WAVELENGTH OF 750 NM.

Turbidity causing material	Coefficient of correlation	Standard error of estimate
Black Cotton Soil	0.97	0.43
Bentonite Clay	0.97	0.53
Kaoline	0.95	5.30
Grey Soil	0.99	1.27

X_{GS}, X_K, X_{BC} and X_{BCS} are turbidity values for grey soil, kaoline, bentonite clay, and black cotton soil, respectively.

Soil reflectance depends upon the chemical and physical properties of the components, organic matter content, iron oxide content, texture, and surface roughness (Colwell, 1983). The regression models that are developed have different natures mainly because of these factors. For example, the nature of the plot for bentonite clay and black cotton soil are the same because bentonite is one of the well known ultra-fine clays, mainly composed of the montmorillonite group of clay which is commonly known as black cotton soil (Jumikin, 1967), and both these soils have high percentages of organic content compared to the kaoline and the grey soil.

CONCLUSIONS

The following conclusions are inferred from the presented study:

- A significant relationship exists between a wide range of suspended material concentration and reflectance.
- High coefficient of correlation and low standard error were observed in the 700 to 900 nm region (but shown at 750 nm only in Figure 4) for all materials that were used in this study.
- Distinct differences in reflectance values corresponding to the different turbidity values were observed in the 700 to 900 nm wavelength range. This region can be used to get information about a wide range of turbidity levels and some properties (such as the organic content, specific gravity, etc.) of turbidity causing material present in the water body.
- In some regions a sharp decrease of reflectance with increasing wavelength is observed, but in other regions the reflectance value is nearly constant with respect to the variation in the wavelength. Selection of the wavelength range would be more rational when it is taken in the wavelength regions where the spectral response is nearly constant with respect to the variation in the wavelength.
- Reflectance exhibits an increase with increasing suspended solids. But due to the variation in spectral characteristics of these materials, the increase is linear for bentonite clay and black cotton soil whereas curvilinear variation was observed for kaoline and grey soil.
- In the wavelength range to 550 to 750 nm, materials with higher organic content showed lower reflectance than those materials with lower organic content.
- To develop a model which can be used in different geographic areas and various seasons and flow conditions, properties of the suspended materials present in the water body should be considered.

This technique can be used to get rapid, reliable, and repetitive data for a better quality interpretation and management of our water resources.

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