Effects of Suspended Particle Size and Concentration on Reflectance Measurements

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ABSTRACT: Laboratory based studies related to reflectance response of suspensions carrying five different soil types and particle sizes of varying concentrations indicate dependence of reflectance measurements on soil type characteristics, particle size, and concentration. Reflectance for any soil type and size increases with suspended sediment concentration and turbidity but decreases with increase in the modified secci depth of the suspension. Reflectance also increases with a decrease in particle sizes for any soil type. Models have been evolved for the prediction of suspended sediment concentration, turbidity, and modified secci depths from measured reflectance values for a given soil type and size, and also with due involvement of particle size in the predictive models. The predicted and observed values of suspended sediment concentration, turbidity, and modified secci depth, by the various evolved models, show good agreement.

INTRODUCTION

NUMEROUS STUDIES have shown that remote sensing techniques can be used as a means to collect water quality data. Clarity of a water body expressed in terms of suspended sediment concentrations, turbidity level, or secci depth can be predicted using remote sensing technique (Ritchie *et al.*, 1976; Holyer, 1978; Muralikrishna, 1979; Johnson and Harriss, 1980; Khorram, 1981; Whitlock *et al.*, 1982; Bhargava, 1983a; Nayak, 1983; Mckim *et al.*, 1984; Khorram and Cheshire, 1985; Lodwick and Harington, 1985; Amos and Toplins, 1985; Ritchie and Schiebe, 1986; Ritchie *et al.*, 1987; Ritchie and Cooper, 1988, Colley *et al.*, 1988; Curran and Novo, 1988, Novo *et al.*, 1989a, Novo *et al.*, 1989b; Bhargava and Mariam, 1990).

Suspended sediment load carried by streams varies considerably both in quality and quantity as it comes from a variety of sources. The major portion of the sediment load carried by streams comes from the erosion of material in the drainage basin; a certain amount also originates as a result of weathering of rocks from the beds and banks of streams. The amount of sediment load carried depends on the size of materials, discharge, slope, channel configurations, and catchment characteristics.

Quality conditions in the Ganga River (whose basin accounts for as much as about 20 percent of India's land surface) are strongly affected by waste discharges from thousands of industries and municipalities and are influenced by a host of natural variations. The Ganga receives domestic and industrial wastewaters from about 100 large or small cities and towns during its 2525-km journey. The quality of the river Ganges has a profound effect on almost 33 percent of India's population who depend on it for a potable water supply, irrigation, industry, recreation, and religious activities. These needs call for a technique that can be used to get rapid and reliable data for a better quality interpretation and management of water resources. Remote sensing as a technique has the potential to meet these needs.

The incident energy on the water surface is reflected, absorbed, and/or transmitted. In clear water the transmitted energy is greater and in turn the reflected energy will be reduced. Due to the presence of suspended sediment, the transmitted energy will be greatly reduced and, depending on the suspended sediment properties to absorb the energy, the reflectance energy will vary. In remote sensing, the reflected energy is measured, carrying some information of the object from which it is reflected. Reflectance is not only a function of the sediment concentration level but is also a function of the properties of the sediments present. (Novo *et al.*, 1989a; Bhargava and Mariam, 1990), environmental influences (Curran and Novo, 1988), and viewing geometry (Novo *et al.*, 1989b). The models developed by previous investigators did not fully account for spatio-temporal variations in the type, size, and concentrations of sediments in different seasons or geographic locations. Because of this, all previously developed predictive models are applicable only to the study area for which they were developed. "Extrapolating the models to predict water quality parameters outside the immediate study area must be done with caution" (Lathrop and Lillesand 1986). "Factors which contribute to their failure may be the difference in physical, chemical, and biological conditions. Flow conditions and atmospheric conditions may also contribute to these failures" (Khorram and Cheshire, 1985; Wallace, 1973; Lindell, 1981; Khorram, 1981). If we cannot extrapolate the models to predict water quality parameters outside the immediate study area due to environmental changes, we cannot for the same reason always use only one model based on one time observation in a given study area. Environmental properties change from place to place and time to time. This shows the need of a study to isolate and quantify some of the major interfering properties and their inclusion in the model.

While dealing with sediment problems, properties of individual particles as well as bulk properties of sediments must be considered, and of all the properties (size, shape, mineral composition, surface texture, etc.) of sedimentary particles, sediment size is one of the important and commonly used properties.

The variations of water quality parameters in different proportions will greatly affect the prediction. For example, reflectance is expected to increase with suspended sediments concentration. An increase in the algal concentration would decrease reflectance in the blue wavelengths but increases reflectance in the green wavelengths. Thus, when algal concentration is high, we may underestimate the suspended sediment concentration in the blue wavelengths region but overestimate it in the green wavelengths region. Organic matter has a tendency to decrease reflectance. Iron oxide selectively reflects red light (600 to 700 nm) and absorbs green light (500 to 600 nm) (Curran, 1985). These and many other similar interfering and integrated effects need detailed investigations.

Out of the many possible interfering parameters (organic matter, mineral composition, etc.), an attempt has been made herein to study in the laboratory only the effect of particle size variation on the spectral response measurement of different suspended solids concentration, turbidity level, and modified secci depth in the water through a comprehensive discussion of the results.

PHOTOGRAMMETRIC ENGINEERING & REMOTE SENSING,
Vol. 57, No. 5, May 1991, pp. 519–529.

0099-1112/91/5705–519$03.00/0

EXPERIMENTAL METHODOLOGY

In this study, five different types of soils have been used to evaluate the effect of particle size variation on reflectance measurement. The five soil types included (1) A local alluvial soil of the gangetic plain (Roorkee soil); (2) Black cotton soil (montmorillonite clay); (3) Bentonite, which occurs in partially weathered volcanic deposits and in the more arid regions of the world; (4) Grey soil (known in India as "Dhauri clay"); and (5) Kaolin, (soils of humid - temperate and humid tropical regions). Table 1 summarizes some of the physical and chemical properties of the various soil types used in the study. These could be of help to compare these studies with other similar studies. The dry soil samples were sieved with the help of an automatic shaker; geometric mean diameter (as an expression of the size) of the soil particles used for these studies is given in Table 2.

Dry soil samples were taken for determination of the soil color using the Munsell Book of color. While using the color charts, an approximate comparison was obtained by holding the soil sample close to the matching chips. The soil color names and the corresponding hue, value, and chroma are indicated in Table 1. The Munsell notation is written in the order hue, value, and chroma (for example, the notation for a color of hue 5Y, value 6, chroma 2, is indicated as 5Y 6/2, a light olive grey) (Munsell Soil Color Charts, 1975).

The pH of the soil samples was measured as per IS: 2720 (Part XXVI) - 1973, by the electrometric method using a pH meter. Volatile matter in the soil was determined by igniting a known quantity of the sample at 600°C in the muffle furnace.

Different suspended solids concentrations were obtained by adding weighed amounts of soils into a 0.5 m by 0.5 m by 0.75 m high tank. The tank was painted black in all its inside to minimize the bottom and side reflectance. The samples used in this experiment were kept in suspension by continuous agitation with a stirrer, during the experimentation period, except for the moment when the observational reading for reflectance was taken so that a calm and even water surface was ensured at the time of taking the reflectance reading.

A 1000 W tungsten halogen lamp emitting most of the visible radiation at a wavelength of around 600 nm (light yellow color) was used to illuminate the tank uniformly from a height of about 1 m from the water surface. Using an SRR-02 Spectroradiometer of 10° field of view (manufactured by Indian Space Research Organization (ISRO), Bangalore, India), measurements of reflectance were taken from a height of 1.0 m from the water surface. For these studies, both the sensor look angle [90° nadir (i.e. vertical instrumental axis) and 45° with the light direction from the source] and the incident angle of the light source (45° to the surface of the water body) were kept constant. Figure 1 depicts the experimental set up. Reflectance was measured at wavelengths ranging from 500 to 1000 nm at a 50 nm interval. A plate coated with barium sulfate was used for calibration of the radiometer. The largely varied suspended solid concentration of the test suspension ranged from 20 mg/l to 1280 mg/l (20, 40, 80, 160, 240, 320, 480, 640, and 1280 mg/l). The concentrations were prepared through accurately weighed soils and measured water volumes. Therefore, no samples were collected for concentration determinations. For turbidity measurements, a sample volume of about 100 ml was collected only once, which volume did not create any change in the water volume in the tank. Turbidity level was measured using a Hach turbidimeter in nephelometric Turbidity units (NTU). Turbidity levels ranged between 18 and 255 NTU.

To measure a modified secci depth (Bhargava, 1983b), a locally prepared metal disc of 10 cm in diameter colored red and white in alternate quadrants was used. The red and white colors provided better visibility changes in turbid waters (unlike the

TABLE 1. PHYSICAL AND CHEMICAL PROPERTIES OF THE SOIL

Soil Type	Specific Gravity	pH	Organic Matter	C.O.D. (mg/l) of the suspension (1 gm/L) Unfiltered sample	Filtered sample	Color
Roorkee	2.61361	8.35	6.3267	0	0	5YR 5/B Yellowish Red
B.C. Soil	2.71475	8.17	5.3890	15	12	10YR 5/1 Grey
Bentonite	2.31594	8.84	13.5330	12	0	10YR 7/4 Very Pale Brown
Grey Soil	2.64623	8.62	4.6620	34	26	5Y 6/2 Light Olive Grey
Kaoline	2.56442	9.27	3.8940	0	0	7.5YR 8/0 (NB/) White

TABLE 2. GEOMETRIC MEAN DIAMETER OF THE SOILS USED IN THE STUDY

Soil Type	Geometric mean sizes (mm) of the used soils				
Roorkee	0.1253	0.0962	0.0704	0.0460	0.0320
B.C. Soil	0.0962	0.0817	0.0704	0.0460	0.0320
Bentonite	0.1253	0.0962	0.0817	0.0460	0.0320
Grey Soil	–	0.0962	0.0817	0.0460	0.0320
Kaoline	0.0962	0.0817	0.0704	0.0460	0.0320

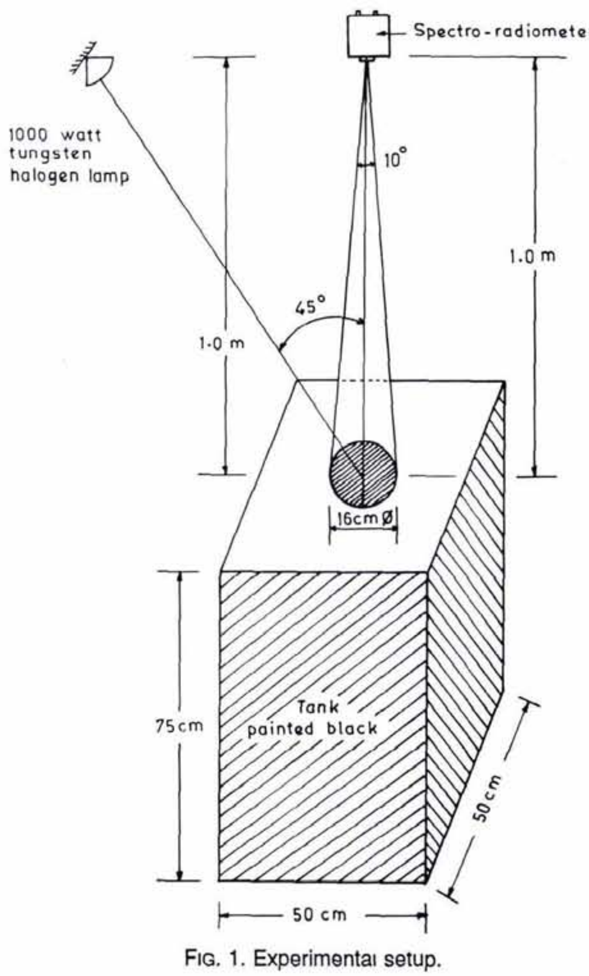

FIG. 1. Experimental setup.

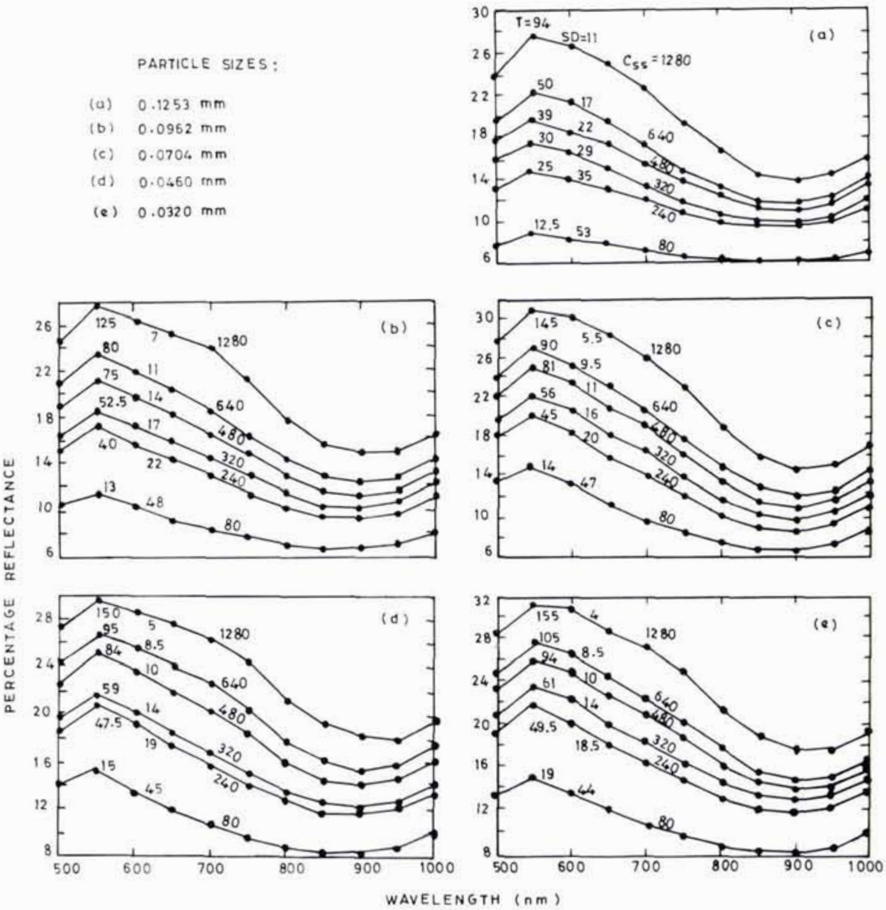

FIG. 2. The variation of percent reflectance with wavelength for different turbidity levels (NTU) and modified secci depths (cm) caused by different particle sizes of Roorkee soil.

standard secci disk using the black and white colors). The modified secci disc was lowered and the depth from water surface at which it just became invisible was recorded. This depth is reported as a measure of clarity of the water body. In general, the modified secci depth ranged from 4 cm to 55 cm.

RESULTS AND DISCUSSIONS

The reflectance from water is expected to increase with suspended sediment concentration and turbidity level (or with decrease in secci depth). It is not only the suspended sediment concentration, turbidity level, or secci depth that influence the reflectance but also some properties of the sediments present in suspension (Novo *et al.*, 1989; Bhargava and Mariam, 1990) and some environmental influences (Curran and Novo, 1988). Out of the many possible interfering parameters, the effect of particle size variation on the reflectance measured from a sediment laden water has extensively been studied.

Figures 2 to 6 depict the relationships of percentage reflectance with wavelength (500 to 1000 nm range) based on the observed data with regard to the various soil types for different suspended sediment concentration, turbidity levels, and modified secci depth of the various particle sizes. These graphs indicate that, at any wavelength and particle size, reflectance increases with an increase in suspended sediment concentration. This is represented by the functional relationship: $R = f(C_{ss})$. To predict suspended sediment concentration, turbidity level or modified secci depth from reflectance measurements, the above stated functional relationships have been modeled for the observed data and are presented in Equation 1: i.e.,

$$C_{ss} = a_1 R^{a_2} \quad \text{(1a)}$$

$$T = a_3 R^{a_4} \quad \text{(1b)}$$

$$SD = a_5 R^{a_6} \quad \text{(1c)}$$

In Equation (1), C_{ss} represents the suspended sediments concentration (mg/l), T the turbidity level (NTU), SD (cm) the modified secci depth, and R the reflectance. The linearized forms of Equations 1a, 1b, and 1c were regressed and the function coefficients a_1 and a_2 (suspended sediment concentration), a_3 and a_4 (turbidity level), and a_5 and a_6 (modified secci depth) were determined through a linear regression of the data. For all the soil types, the values of the function coefficients along with their coefficients of correlation and standard error of estimate are shown in Table 3. Figure 7 depicts one such sample plot of Equation 1a at a wavelength of 700 nm with regard to the suspended sediment concentration and the percentage reflectance.

Sediments of different properties and particle sizes are encountered at the different reaches of a river or in different seasons in a reservoir. The plot of percentage reflectance versus wavelength for the different soil types having the same suspended sediments concentration and sediment sizes is shown in Figure 8. It was reported by the authors (Bhargava and Mariam, 1990) that the different curves are obtained for the different soil types of the same concentration and particle sizes because

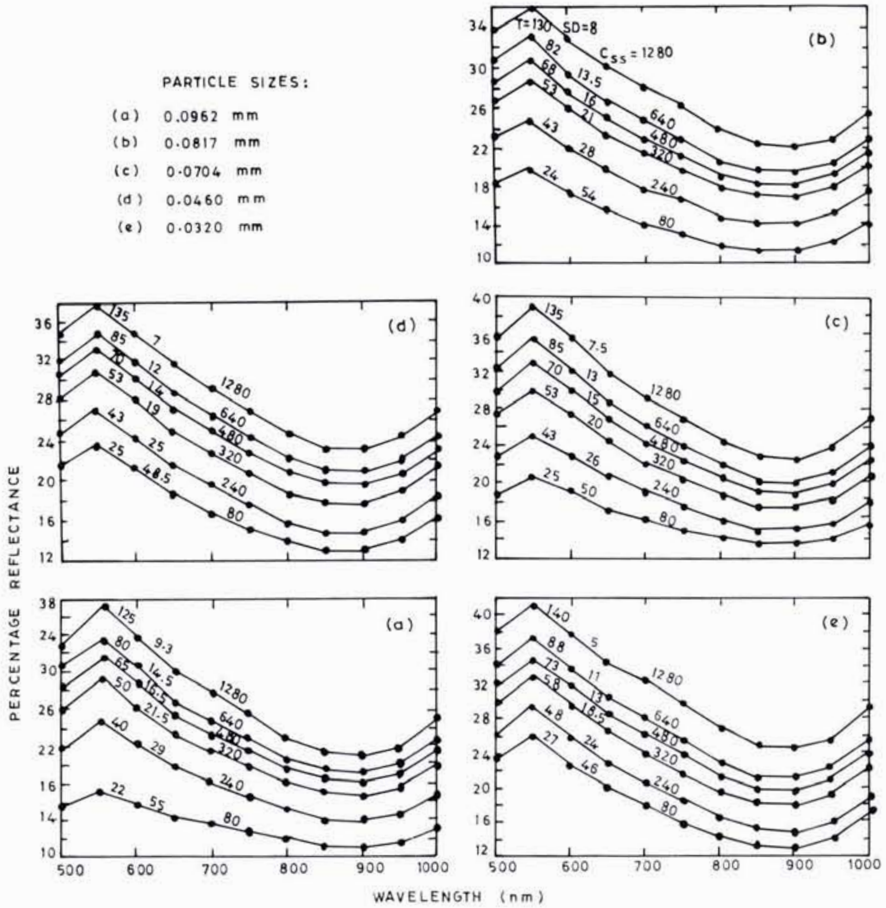

FIG. 3. The variation of percent reflectance with wavelength for different turbidity levels (NTU) and modified secci depths (cm) caused by different particle sizes of Black cotton soil.

TABLE 3. FUNCTION COEFFICIENTS FOR EQUATIONS 1A TO 1C AND 2 ALONG WITH THEIR COEFFICIENT OF CORRELATION (R) AND STANDARD ERROR OF ESTIMATE (E) AT 700 NM FOR VARIOUS SOIL TYPES

Soil Type	R	a_1	a_2	E	R	a_3	a_4	E
Roorkee	0.9983	0.01	3.5661	0.0605	0.9954	0.0773	2.3048	0.0736
B.C. Soil	0.9991	1.8×10^{-5}	5.2595	0.0498	0.9894	0.0141	2.6338	0.0885
Bentonite	0.9982	4.134×10^{-4}	4.2881	0.0662	0.9930	0.2496	1.9479	0.0813
Grey Soil	0.9995	2.266×10^{-8}	7.5917	0.0404	0.9885	7.2960×10^{-4}	3.6690	0.0948
Kaoline	0.9996	4.7277×10^{-8}	7.1984	0.0352	0.9901	1.2302×10^{-4}	4.1627	0.1013
	R	a_5	a_6	E	R	a_7	a_8	E
	0.9902	2.578×10^{4}	−2.5920	0.1212	0.9122	22.3826	0.1757	0.8626
	0.9844	9.341×10^{5}	−3.4459	0.1405	0.9536	25.7218	0.1972	0.6173
	0.9926	1.211×10^{4}	−2.2414	0.0957	0.9730	26.5443	0.3016	0.7982
	0.9942	2.214×10^{7}	−4.6253	0.0846	0.9222	23.6431	0.2015	0.9951
	0.9943	1.082×10^{7}	−4.2706	0.0789	0.9256	31.3975	0.1936	0.7850

of the differences between the properties and characteristics of the various soil types.

Figure 9 shows the plots and variation trends of the percentage reflectance versus wavelength with regard to the different particle sizes for the five soil types of the same suspended sediment concentrations (320 mg/l) based on data collected in the 500 to 1000 nm wavelength range. It was observed from Figure 9 that the effect of particle size on reflectance measurement is almost equally appreciable in the entire 500 to 1000-nm range. As also seen from Figure 9, an increase in particle size results in a decrease in reflectance for all soil types. This is due to a larger scattering surface area when the particle size is reduced. Thus, reflectance is also a function of particle size. The relationship of particle size variation and reflectance for the given sediment concentration and soil type is expressed by an equation of the type shown in Equation 2, i.e.,

$$R = a_7 + a_8 \frac{1}{D} \qquad (2)$$

In Equation 2, D represents the geometric mean diameter (mm). The function coefficients a_1 and a_8 were computed through linear regression of the data shown in Figures 2 to 6 at 700 nm wavelength and 1280 mg/l suspended sediment concentration. Table 3 contains these evaluated values of the function coefficients a_7 and a_8 along with their coefficients of correlation and

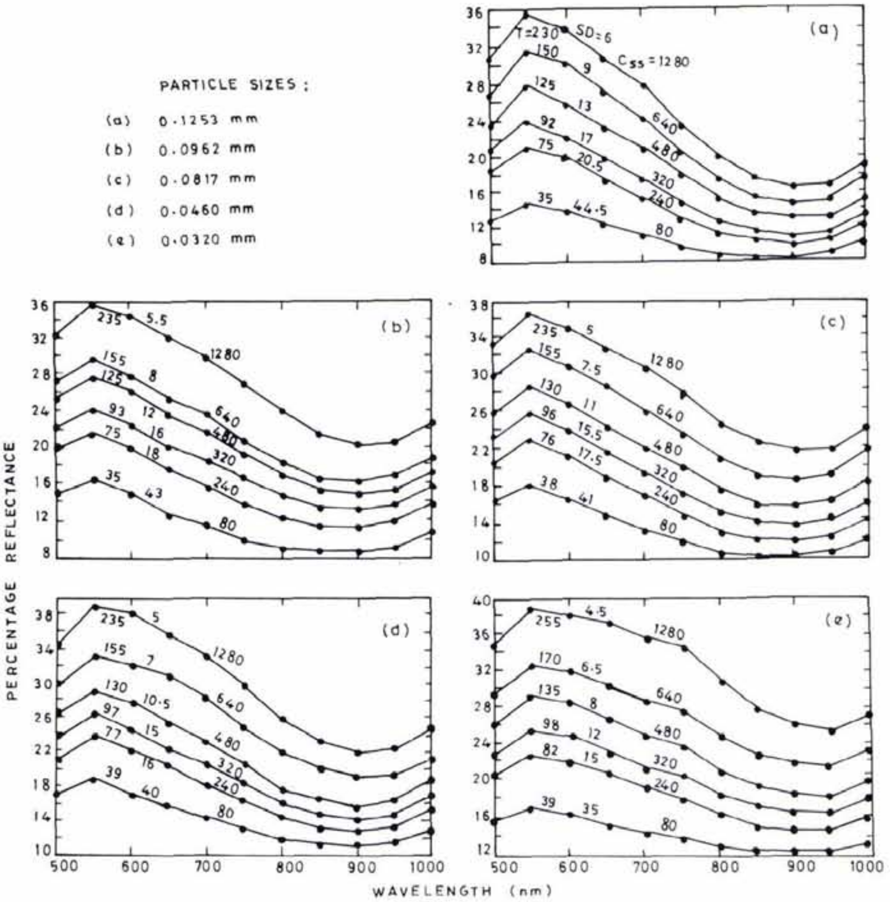

FIG. 4. The variation of percent reflectance with wavelength for different turbidity levels (NTU) and modified secci depths (cm) caused by different particle sizes of Bentonite soil.

standard error of estimate for all soil types. Figure 10 depicts the relationship (Equation 2) of reflectance with different particle sizes of the same suspended sediment concentration (1280 mg/l) of the various soil types. The above noted dependence of the reflectance on particle size shows the need to account for the effect of particle size variation while developing a model to predict suspended sediment concentration, turbidity level, or modified secci depth.

The spectral response relationship with concentration and particle sizes was observed in the wavelength range of 500 to 1000 nm. The wavelength range of 700 to 900 nm is an ideal range for prediction of suspended sediments concentration as this wavelength range was more pronounced for reflectance.

The predictive models for suspended sediment concentration, turbidity level, or modified secci depth therefore are correlated in the 700 to 900 nm range at the 50-nm interval.

The interdependence of sediment concentration, turbidity, or modified secci depth on particle size and reflectance as a functional relationship are modeled in a more generalized form in Equations 3a, 3b, and 3c, respectively, to predict the suspended sediment concentration, turbidity level and the modified secci depth: i.e.,

$$C_{ss} = (a_9 + a_{10} D + a_{11} R)^3 \quad (3a)$$

$$\ln T = a_{12} + a_{13} D + a_{14} R^3 \quad (3b)$$

$$\ln SD = a_{15} + a_{16} D + a_{17} R^3 \quad (3c)$$

The function coefficients a_9 to a_{11} (Equation 3a), a_{12} to a_{14} (Equation 3b), and a_{15} to a_{17} (Euation 3c) were determined through multiple linear regression, and their corresponding values along with their coefficients of correlation and standard error of estimate are shown in Table 4. Figures 11 (a-e), 12 (a-e), and 13 (a-e), respectively, show the plots of the predicted versus observed values with regard to the models shown in Equations 3a, 3b, and 3c for all particle sizes corresponding to the various soil types at the 700-nm wavelength.

A good agreement of the observed and the predicted values, as manifested by the plots shown in Figures 11 to 13, indicate the robustness of the models shown in Equations 3a to 3c.

To use Equation 3, the function coefficient values must be available at all the wavelengths, and this restricts the flexibility in working conditions. To avoid this limitation of the knowledge of model coefficients at all the different wavelengths, wavelength value in nm was also incorporated in the model. Equation 4, therefore, relates spectral reflectance (R) with sediment concentration (C_{ss}) (reflectance increases with concentration), sediment size (D) (reflectance decreases with the increase in particle diameter), and the corresponding wavelength (W) [reflectance from water surface decreases with an increase in wavelength (from visible to infrared): i.e., $R = f(C_{ss}, D, W)$] for Roorkee soil. Function coefficients of Equation 4 were determined through the multiple linear regression of the data: i.e.,

$$C = -0.1297\, e^{0.0036w} + 0.302 \times W^{0.6516} \times D + 1.1542 \times 10^{-7} \times W^{2.3083} \times R. \quad (4)$$

In Equation 4 C, W, D, and R represent the concentration in mg/l. wavelength in nm, geometric mean diameter of the par-

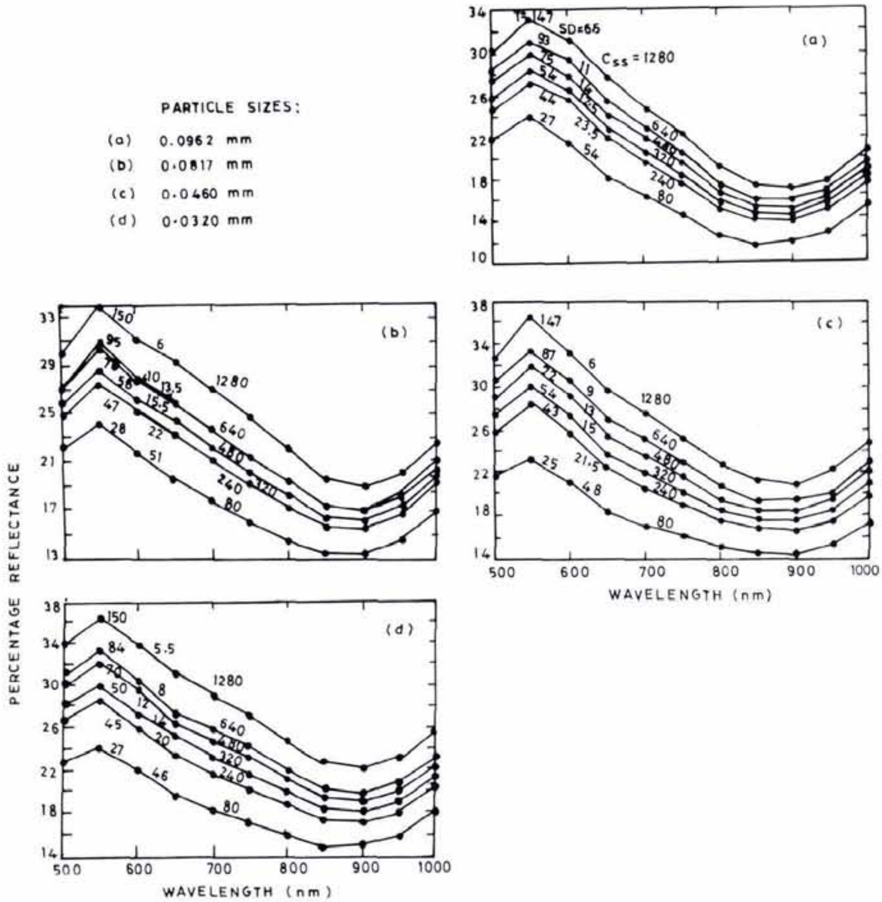

FIG. 5. The variation of percent reflectance with wavelength for different turbidity levels (NTU) and modified secci depths (cm) caused by different particle sizes of Grey soil.

TABLE 4. FUNCTION COEFFICIENTS FOR EQUATIONS 3A TO 3C ALONG WITH THEIR COEFFICIENTS OF CORRELATION (R) AND STANDARD ERROR OF ESTIMATE (E) AT DIFFERENT WAVELENGTH FOR VARIOUS SOIL TYPES

Soil Type	Wave-Length (nm)	R	a_9	a_{10}	a_{11}	E	R	a_{12}	a_{13}	a_{14}	E	R	a_{15}	a_{16}	a_{17}	E
Roorkee	700	0.9929	−1.6784	21.4025	0.4309	0.3028	0.9624	1.6606	0.4667	0.1314	0.2024	0.9782	5.0055	−0.0458	−0.1286	0.1501
	750	0.9912	−1.8668	22.7909	0.4862	0.3379	0.9540	1.6410	0.9412	0.1458	0.2234	0.9743	5.0389	−0.5485	−0.1434	0.1624
	800	0.9876	−2.3006	23.5501	0.5839	0.3996	0.9463	1.5269	1.1422	0.1740	0.2408	0.9664	5.1504	−0.7442	−0.1711	0.1856
	850	0.9829	−2.8293	24.4555	0.6850	0.4702	0.9332	1.3631	1.4062	0.2044	0.2677	0.9539	5.3139	−1.0101	−0.2012	0.2167
	900	0.9777	−3.3619	25.3366	0.7489	0.5360	0.9268	1.1618	1.6506	0.2269	0.2797	0.9439	5.4954	−1.2088	−0.2222	0.2402
B.C. Soil	700	0.9859	−4.1519	23.3941	0.4429	0.4264	0.9861	1.2266	4.1420	0.1137	0.0916	0.9857	6.0459	−2.8582	−0.1302	0.1076
	750	0.9866	−3.8942	20.0998	0.4803	0.4161	0.9854	1.2982	3.2602	0.1232	0.0941	0.9863	5.9687	−1.8572	−0.1412	0.1050
	800	0.9846	−3.7298	17.9551	0.5279	0.4465	0.9810	1.3557	2.9336	0.1339	0.1071	0.9835	5.9077	−1.4911	−0.1538	0.1152
	850	0.9832	−3.8387	16.9013	0.5702	0.4656	0.9802	1.3341	2.6733	0.1444	0.1092	0.9835	5.9350	−1.1962	−0.1659	0.1152
	900	0.9825	−3.9566	16.6797	0.5846	0.4747	0.9790	1.2914	2.7697	0.1482	0.1125	0.9820	5.9830	−1.3053	−0.1702	0.1203
Bentonite	700	0.9868	−1.5525	16.1841	0.3557	0.4136	0.9716	2.4220	3.4326	0.0912	0.1428	0.9730	4.9364	−1.9667	−0.1034	0.1596
	750	0.9801	−1.9530	22.3332	0.3901	0.5059	0.9626	2.3377	5.1027	0.0989	0.1635	0.9654	5.0355	−3.8691	−0.1123	0.1802
	800	0.9745	−2.4243	25.2985	0.4550	0.5727	0.9559	2.2498	5.8172	0.1140	0.1773	0.9602	5.1392	−4.6913	−0.1296	0.1931
	850	0.9712	−2.9890	28.0734	0.5201	0.6075	0.9483	2.1046	6.5332	0.1304	0.1915	0.9537	5.3072	−5.5141	−0.1484	0.2078
	900	0.9705	−3.5156	29.5769	0.5653	0.6149	0.9441	1.9645	6.9113	0.1421	0.1990	0.9501	5.4685	−5.9498	−0.1618	0.2155
Grey Soil	700	0.9768	−8.6285	18.4055	0.6586	0.5509	0.9843	−0.0333	6.4902	0.1672	0.1005	0.9825	7.5855	−4.2893	−0.2040	0.1302
	750	0.9757	−9.6771	27.5150	0.7406	0.5642	0.9817	−0.2398	8.6775	0.1857	0.1083	0.9795	7.8353	−6.9514	−0.2264	0.1406
	800	0.9602	−11.0103	42.5390	0.8423	0.7184	0.9651	−0.5738	12.6130	0.2109	0.1489	0.9605	8.2271	−11.7133	−0.2564	0.1944
	850	0.9717	−12.9745	52.2107	0.9921	0.6079	0.9756	−1.1046	15.2129	0.2497	0.1248	0.9747	8.8970	−14.9439	−0.3048	0.1563
	900	0.9696	−14.2349	55.0164	1.0658	0.6301	0.9734	−1.5196	16.2646	0.2725	0.1303	0.9723	9.4026	−16.2246	−0.3327	0.1633
Kaoline	700	0.9617	−0.4494	10.6498	0.3232	0.6990	0.9722	2.2064	4.0198	0.0806	0.1448	0.9464	4.3145	2.6577	−0.0739	0.1932
	750	0.9592	−0.8264	12.3799	0.3815	0.7213	0.9702	2.1097	4.5888	0.0949	0.1499	0.9469	4.4078	2.1278	−0.0871	0.1923
	800	0.9538	−1.6710	16.5976	0.4730	0.7654	0.9666	1.8774	5.9825	0.1177	0.1587	0.9440	4.6223	0.8452	−0.1081	0.1973
	850	0.9509	−2.5997	20.9116	0.5641	0.7896	0.9637	1.6285	7.3614	0.1399	0.1685	0.9440	4.8574	−0.4387	−0.1290	0.1974
	900	0.9522	−3.0651	20.6126	0.6069	0.7791	0.9619	1.4947	7.2635	0.1519	0.1691	0.9446	5.9870	−0.3634	−0.1404	0.1963

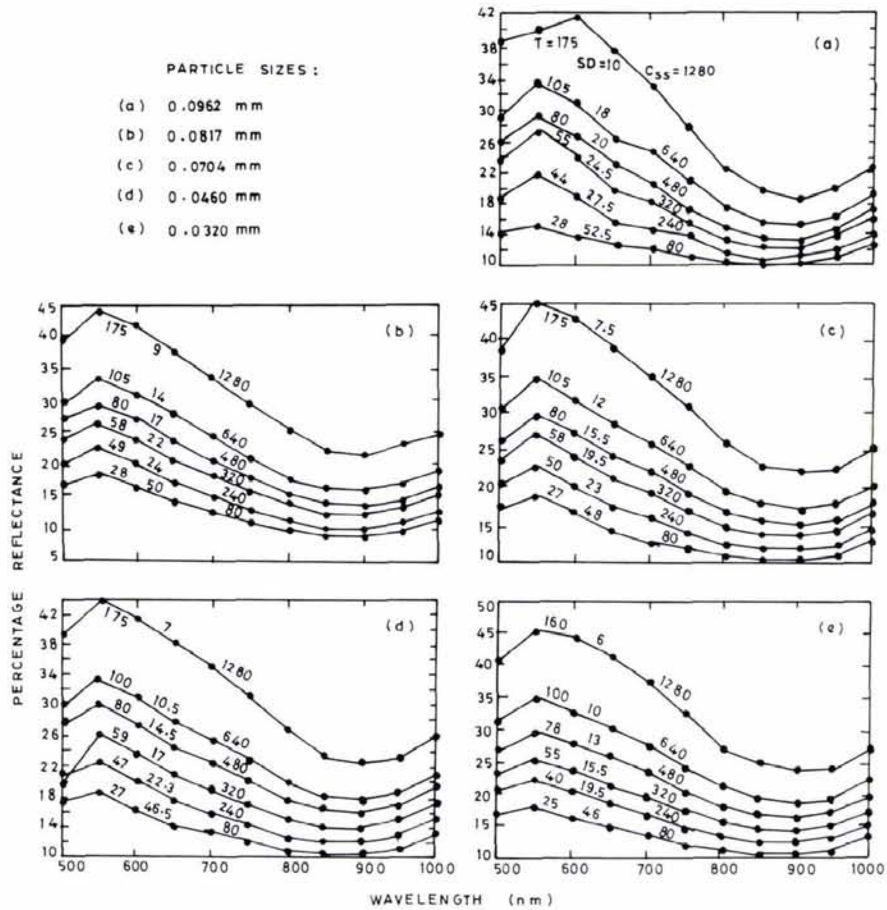

FIG. 6. The variation of percent reflectance with wavelength for different turbidity levels (NTU) and modified secci depths (cm) caused by different particle sizes of Kaoline soil.

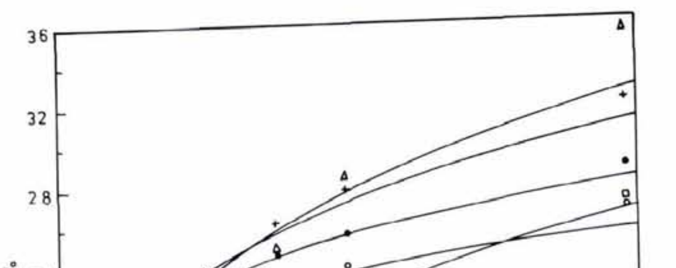

FIG. 7. Relationship between percent reflectance and suspended sediment concentration at 700 nm for different soil types.

ticles in mm, and percentage reflectance, respectively. This form of generalized model can be developed for other soil types also. Figures 14 and 15 depict the observed and predicted value of sediment concentration using Equation 4. As it is shown, there exists good correlation between the observed and the predicted values.

CONCLUSIONS

Based on a laboratory conducted study of reflectance responses of suspensions of five different soil types and particle sizes, present in different concentration in the suspension, the following inferences are drawn:

- The percentage reflectance increases with suspended sediment concentration for all particle sizes, all soil types, and at all wavelengths in the 500 to 1000 nm range. A model for the prediction of suspended sediment concentration from measured reflectance values has been developed for all soil types and particle sizes.
- Soil type characteristics and particle size play a dominant role in affecting the reflectance characteristics of a suspension. Reflectance increases with a decrease in particle size.
- The percentage reflectance increases with turbidity for all particle sizes, all soil types, and at all wavelengths in the 500 to 1000 nm range. The rate of this increase of the percentage reflectance is dependent on the soil type as well as the particle size present in the suspension. A model for the turbidity level prediction has been developed for predicting a suspension's turbidity from the measured percentage reflectance value of a suspension of known soil type and particle size.
- The percentage reflectance increases with a decrease in the modified secci depth for all particle sizes, all soil types, and at all

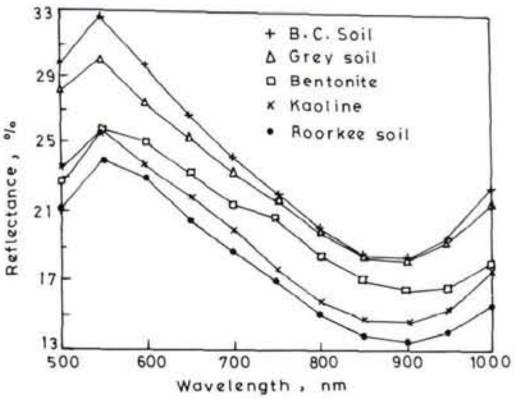

FIG. 8. The variation of percent reflectance with wavelength for different soil types of the same suspended sediment concentration and size.

wavelengths in the 500 to 1000 nm range. A model for the prediction of the modified secci depths from the measured reflectance values has been developed for all soil types and particle sizes.

- Models for predicting the suspended sediment concentration, turbidity, and modified secci depth incorporating reflectance and particle size have been evolved, and the model coefficients at one wavelength were determined. A more generalized model for predicting suspended sediment concentration at any wavelength and particle size and from observed reflectance has been developed for one soil type.

To develop more generalized models for predicting suspended sediment concentrations, turbidity level, or secci depth, the interference effects of some of environmental parameters and sediment properties needs evaluation. In this paper an attempt has been made to address only one such parameter, sediment size. More similar studies are needed to express and quantify the effects of the many other possible interfering parameters. The evaluation of the overall integrated effect of all such parameters simulating field conditions is a greater and much more difficult task. Use of radiometers compatible to the sensors carried by existing satellites (like Landsat MSS, TM, SPOT, etc.) will be more desirable.

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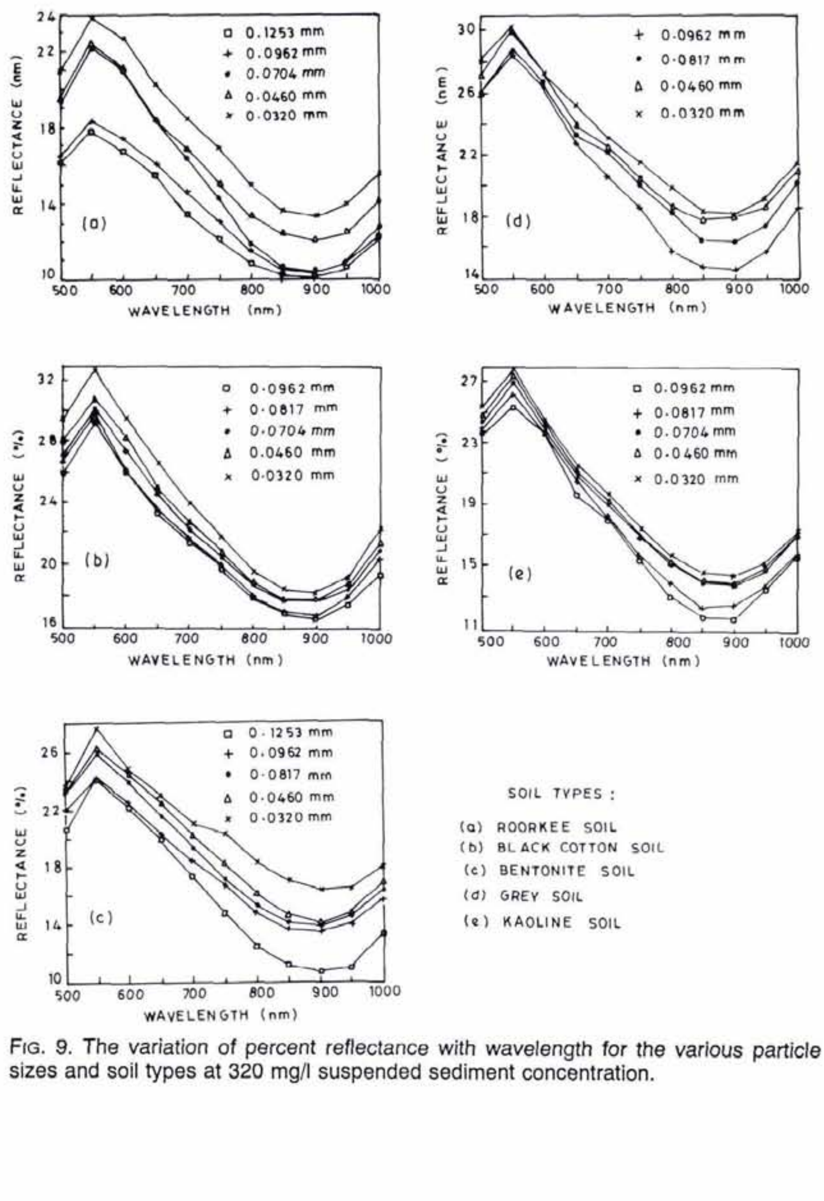

FIG. 9. The variation of percent reflectance with wavelength for the various particle sizes and soil types at 320 mg/l suspended sediment concentration.

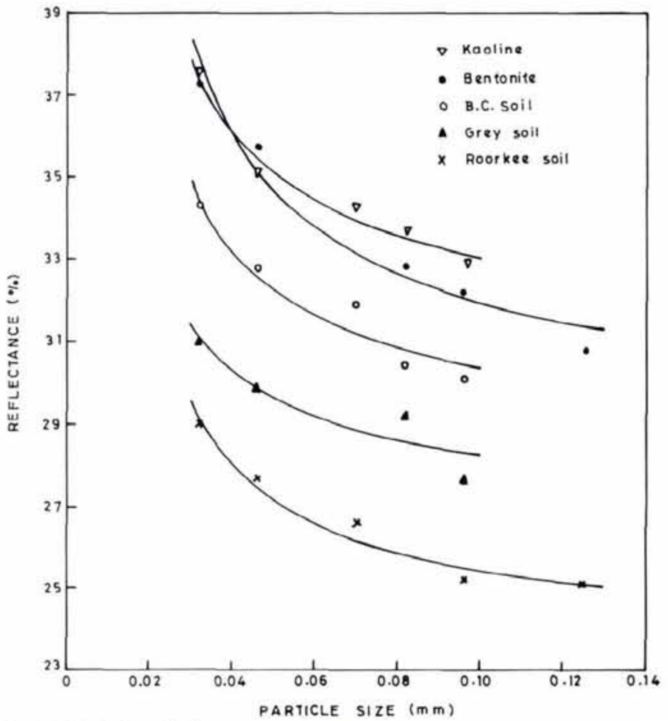

FIG. 10. Relationship between percent reflectance and particle size at 700 nm for different types of soils.

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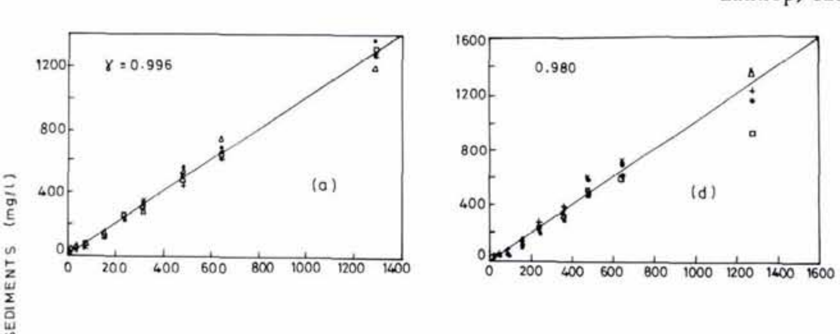

FIG. 11. Comparison of predicted and observed values of suspended sediments using Equation 3 for different types of soils.

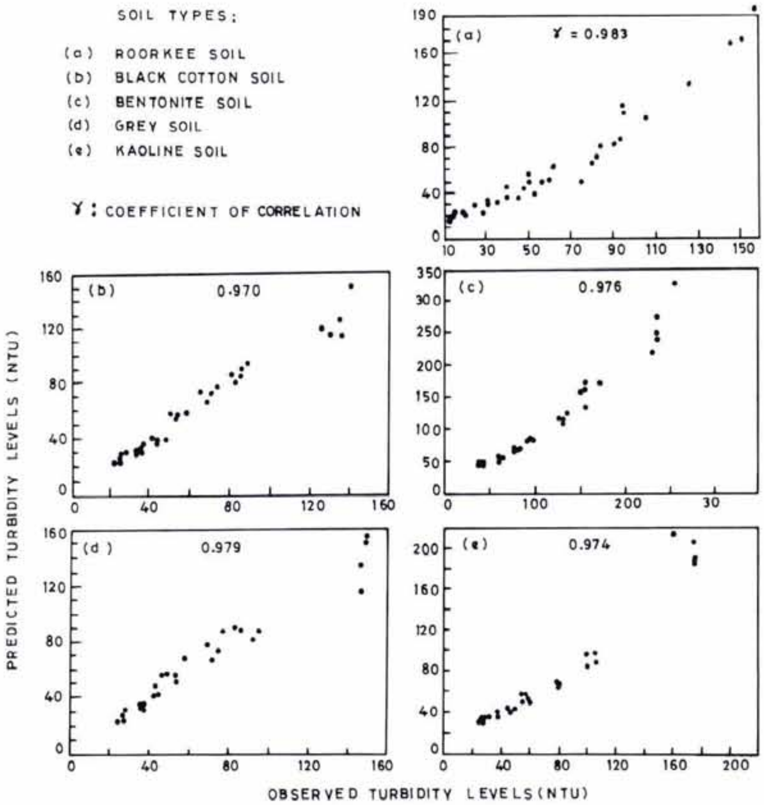

FIG. 12. Comparison of predicted (Equation 4) and observed values of turbidity levels (NTU) for different soil types.

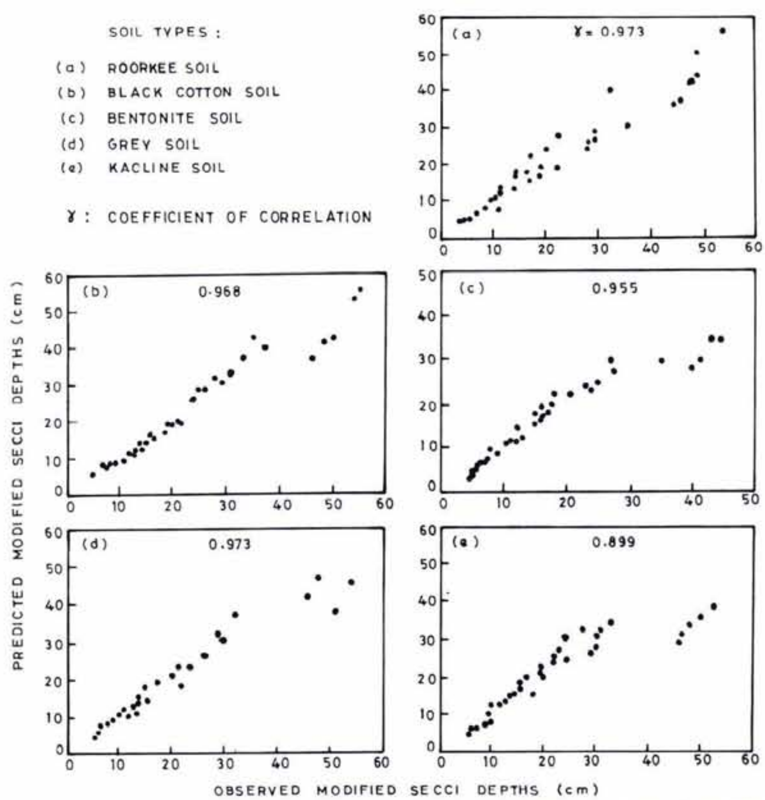

FIG. 13. Comparison of predicted (Equation 5) and observed values of modified secci depths (cm) for different soil types.

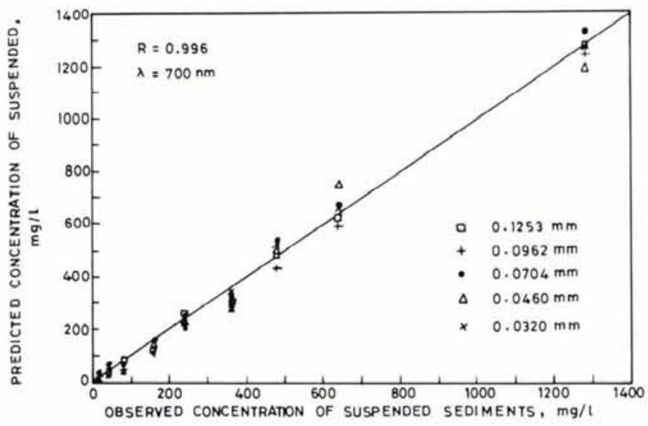

FIG. 14. Comparison of predicted and observed values of suspended sediment concentration of Roorkee soil using Equation 4 for different particle sizes at a wavelength of 700 nm.

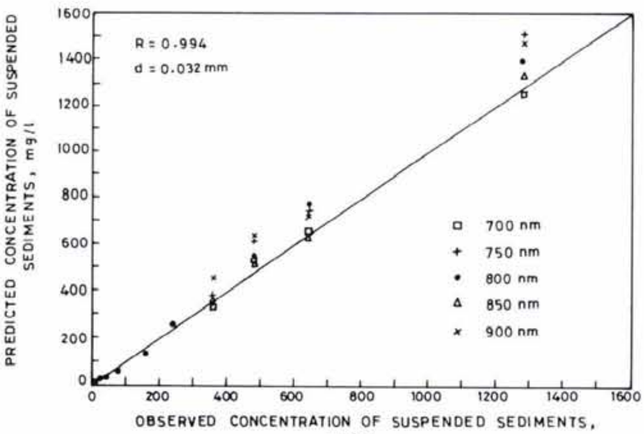

FIG. 15. Comparison of predicted and observed values of suspended sediment concentration of Roorkee soil using Equation 4 for wavelengths of 700, 750, 800, 850, and 900 nm.

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(Received 11 April 1990; revised and accepted 1 August 1990)