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REMOTE SENSING APPLICATION TO SEDIMENTATION STUDIES

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Monitoring of sediment load in water bodies is an integrated part of any water resources management programme. After the advent of satellite age, remote sensing technique with its unique synoptic and repetitive coverages could admirably supplement the conventional ground based data collection endeavour.

Remote sensing techniques to study sediments and turbid water are essentially based on conmplex energy water interaction physics. More the physics is understood, better is the result of remote sensing methods subjected to available spatial, spectral, radiometric and temporal resolutions which are being improved with each satellite mission.

Investigators by and large are able to found out a positive correlation between suspended solids and reflectance values recorded by sensors in the satellite in visible and near infrared wavelength of the spectrum. Water surface is excellent reflector in microwave band of the spectrum which results in a uniform black tone image and as such microwave band is unsuitable for deciphering any information of water quality. Also identification of potential erosive land use zones helps in estimating sedimentation. Besides providing valuable information about the turbid water, remote sensing methods offer effective assistance in properly designing and minimising the numbers of ground sampling points. Besides factors of spatial, spectral, radiometric and temporal resolutions, atmospheric correction is one of the main difficulty in using remote sensing methods for sedimentation studies.

Presently the status of sedimentation studies by remote sensing is experimental and to be used as supplemental data base.

Though the remote signal from turbid water is more reflective than clear water, but the signal represent only the near surface conditions. Also the problems of calibration of the signal with respect to sediment size and concentration are often formidable.

Improved satellite missions like French satellite 'SPOT' and Indian Remote Sensing Satellite (to be launched) take care of these difficulties to the extent technology permits. All such future satellites will exhibit some improvement over the present satellites in terms of orbit and sensors in order to meet operational data requirement. It is expected that the status will improve appreciably in near future and the remotely sensed water quality data will serve as a good data base for both surveillance and modelling of water quality.

1.0 INTRODUCTION

Sediments create problems in navigable rivers, inlets, channels and harbours. Sediments restrict water movemeent, occupy space and restrict the usefulness of water body. Sediments may also adversely affect the chemical quality of water, aquatic organism and recreational potential of a water body. Regular monitoring of status of sedimentation in water is of paramount importance to hydrologists for the proper development and use of water resources. Quality of water may often seriously affect the use of otherwise available abundunt water. This is more so when the availability of water is scarce and planner has to allocate water amongst users of conflicting interests. Sediment is one of the major physical impurities present in any natural water. The most important sources of sediments are sheet erosion, gully erosion, and stream channel erosion. Sheet erosion of the land surfaces usually accounts the major portion of sediment load. The steeper the slope and less consolidated the rock formation, greater is the erosion. The Himalayas are example of such erosion. As most of our extra-peninsular rivers originate from the Himalayas, the problems of sedimentation in these rivers and reservoirs built across them are quite common. Even the rivers in the peninsular area of our country suffer from this ailment with a lesser degree. Landslides, slumps,avalanches, soil creeps, wastes dumped in the streams or left in position favourable to erosion also add to the sediment load. Estimation of sediment load in a river at regular interval is sine-qua-non mainly due to two major reasons:- (i) to know the changes in river regime including the deltaic area to monitor coastal areas and (ii) reservoir operations and to increase the life of reservoirs.

The physical features that appear to be significant are (1) size of the drainage area, (2) watershed slope, (3) degree of channelization and (4) hydrologic characteristics including precipitation and runoff pattern (peak and total amount of precipation and runoff). However the science of sedimentalogy has not progressed to the state where relative influences of each of the physical and hydrological factors have been evaluated to the degree of accuracy desired. (Gottschalk, 1964)

Well established measurement and estimation techniques are available for sediment load evaluation in rivers and reservoirs. Remote sensing methods available with present state of art could very well supplement the efforts in monitoring the sedimentation status of water bodies in the pursuit of timely, accurate, easily reproducible and relatively inexpensive data to utilise for implementing best management practices for water quality. At present, suspended sediment concentreations are determined gravimetrically. This technique has limited usefulness as it involves point measurement and takes lot of time, effort and money. Synoptic, repetitive and multispectral view of satellite remote sensing is very advantageous to monitor suspended sediments in water bodies. Concentration of suspended sediments is an important parameter in reservoir sedimentation, erosion in catchment area and in pisiculture. Sedimentation in reservoirs is a difficult problem for which an economical solution has not yet been found except by providing a 'dead storage' to accomodate the deposits during the life of a dam. As such estimation of rational sediment yield in the upstream catchment and to monitor the same properly to maintain the designed life span of the reservoirs are very important. Because of the synoptic view available in satellite imagery, both sedimentation status and the cause of it (like deforestation in upstream catchment) are often admirably discernable to take appropriate ameliorative methods to prevent soil erosion. It will be worthwhile to mention the estimated and observed sedimentation rate in some of the major reservoirs in the country to highlight the gravity of the problem.

Table 1: Assumed (at the time of project formulation) and subsequent observed rate of sedimentation of some of the major reservoirs in India (Source: Ministry of Water Resources, 1986)

Sl. No.	Name of reservoir	Year of reservoir filling	Annual rate of silting: Assumed/ha.m/100 sq.km./year	Annual rate of silting: Observed/ha.m./100 sq.km.year (year of reservoir survey)
1.	Bhakra	1958	4.29	5.93 (1973)
2.	Panchet (DVC)	1956	6.67	10.00 (1974)
3.	Mainthon (DVC)	1955	9.05	12.38 (1979)
4.	Mayurakshi	1955	3.75	16.48 (1969)
5.	Tungabhadra	1953	4.29	6.03 (1981)
6.	Matatila	1956	1.33	3.82 (1974)
7.	Nizamsagar	1938	2.78	6.37 (1967)
8.	Shivajisagar (Koyna)	1961	6.67	15.24 (1971)
9.	Hirakund	1957	2.52	6.82 (1982)
10.	Gandhisagar	1960	3.61	9.64 (1975)
11.	Lower Bhawani	1953	-	3.56 (1977)
12.	Girna	1965	0.56	8.03 (1979)

NOTES: (1) The sedimentation rate shown in last Col. is apparent rate as no correction for silt density has been applied. Moreover no account is taken of the possible consolidation of deposit in the reservoir with the passage of time.

(2) The observed sedimentation rate is based on the period from the year of impounding to the year of the last survey for which results are avilable.

Remote sensing data is basically based on energy-matter interaction. The interaction is relatively simple in the case of non water targets. But, in contrast to land targets where only the surface reflectance characteristics are important, the signal from water bodies is composed of many components and hence remote sensing for mapping or monitoring water quality is somewhat more complex. The primary indicative signal useful in water quality is the volume reflectance or backscattered energy caused by the materials added to water. Besides, there may be signal (noise) caused by the reflection of the sunlight and skylight from the water surface and light that passes through water and gets reflected by the bottom. Water parameters that affect the energy levels, detected by a camera or scanner are colour ana turbidity. Differences in water colour and turbidity affect signals in the visible and infrared wavelengths. An increase in water colour decreases the energy flux reaching a sensor, because more sun's energy is absorbed in water. An increase in turbidity increases the energy flux reaching a sensor because more solar energy is reflected by the particles that produce turbidity. An increased signal also occurs in clear and shallow water where some solar energy is reflected from bottom.

If energy that reaches a water surface is represented by I_o,

$$I_o = I_{SR} + I_a + I_B \qquad \text{... (1)}$$

Where,

I_{SR} = Solar flux specularly reflected at the water surface,

I_A = Flux absorbed by the water,

I_B = Flux backscattered to the water surface.

I_B is available for remote detection. Absorption and backscatter produce distinct spectral signatures. The solar energy that is not specularly reflected, is reflected downward at the water surface and begins to be affected by absorption and scattering. Energy absorbed slowly warms up the water. Most near infrared light is absorbed within 0.2 m of the surface, and most red light is lost within the upper 2 m. The light remaining at any wave length and any depth can be calculated from the equation.

$$I = I_s/e^{kx} \qquad \ldots (2)$$

where

I_s = Flux entering the water surface,

x = Depth,

k = coefficient of extinction

In natural water, most of the solar energy is scattered and eventually absorbed. About 2 percent of light flux is back scattered in a clear infinitely deep water. The part of the back scattered energy that returns to the water surface is the signal for remote sensing (Figure 1).

In a pool of clear and deep water, 50 percent of the signal for blue light (0.4 - 0.5 μm) comes from depth of less than about 15 m, but for red light (0.6 - 0.7 μm) most of the signal comes from a depth of 1 m. The downwelling light as it penetrates the water is attenuated by the water itself (Figure 2) (Moore, 1978).

At wave lengths greater than 1 μm the water apparently acts as a black body absorber and the reflected solar energy is very low and insensitive to any suspended contaminants.

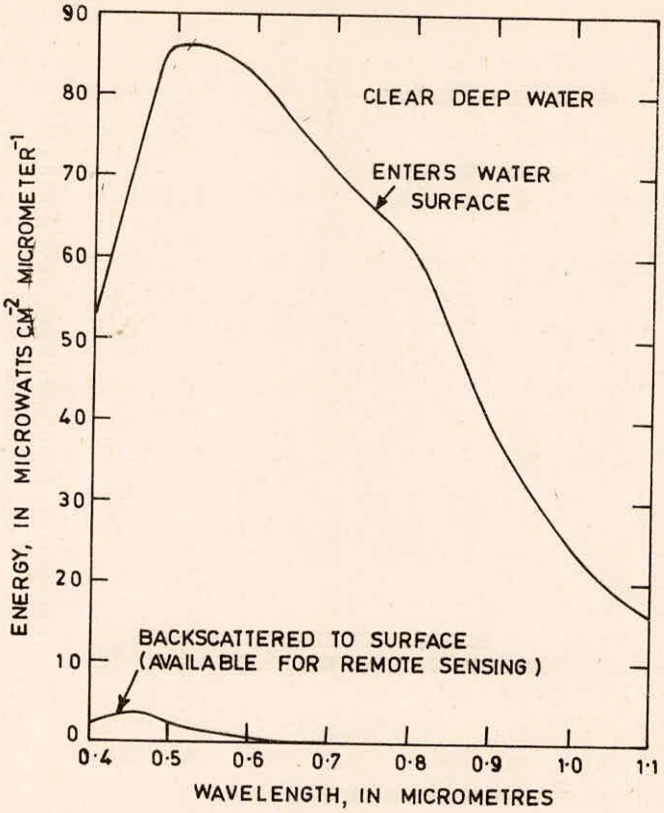

FIG.1 Energy water interaction in clear infinitely deep water

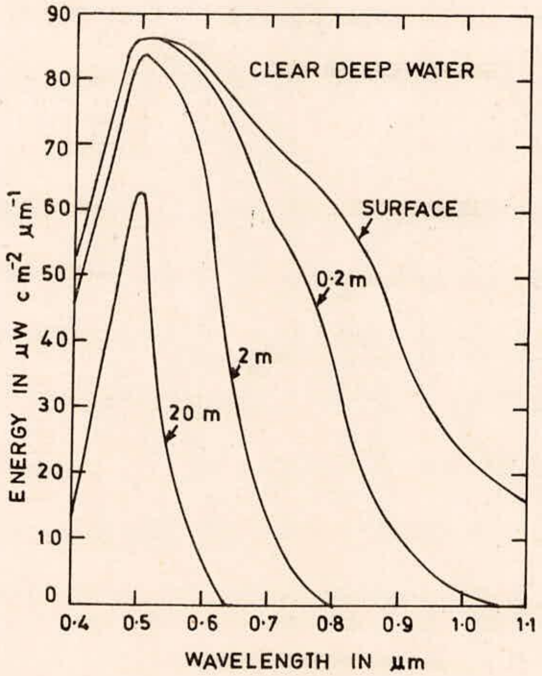

FIG.2 Attenuation of downwelling light by clear deep water

Dissolved constituents that do not add colour to water have no effect on the absorption and scattering of light as measured by MSS. So, the clear sea water and distilled water have same spectral signatures. To be detectable by remote sensing, it is necessary that the pollutants should affect the colour, turbidity, temperature or microwave emissivity of water. The average path length for light in a coloured water is the same as in clear water. There has been little use of remote sensing to measure water colour as inland waters are generally turbid and it is not possible to separate the effects of colour and turbidity in remote sensing signatures.

Suspended particles in water tend to increase the total scatter and backscatter and consequently change the spectral distribution of light and reduce average path lengtr in which suspended silt backscatter light depends on silt concentration (Figure 3) (Moore, 1978).

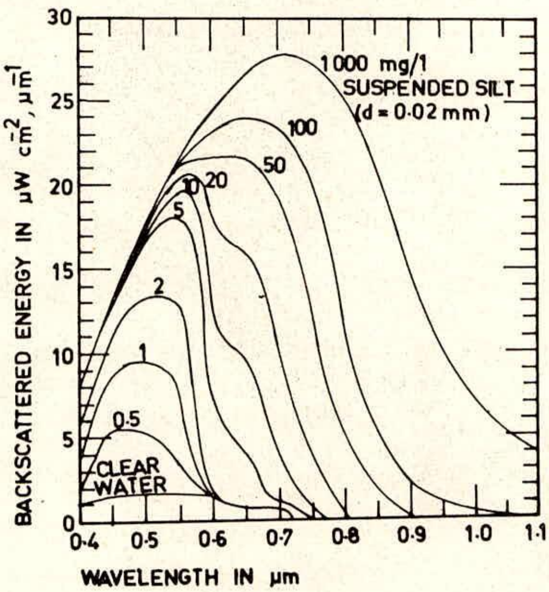

FIG.3 Back scattered radiance from suspended silt

The most important results so far obtained indicate:

1. a turbid water is more reflective than clear water at all visible and near infrared wave length.
2. the remote signal from a turbid water represents only near surface conditions.
3. the measured signal at any wavelength is dependent on particle size and concentration.

In case, there is frequent changes in the source and grain size distribution of suspended sediments in the river, it is unlikely that remote monitoring of suspended load will be possible in such situation (Moore, 1980). In fine, using the principle of water energy interaction, it is found that remote sensing can be used to obtain either qualitative and quantitative estimates of water turbidity. This will supplement the ground measurement endeavour greatly. Landsat images in particular have confirmed that these could be used to great advantage to the determination of suspended solids, colour variations. In many cases, these could be related to specific pollutants or sources. Remote measurement of water quality will appeal greatly to resource managers because it provides a synoptic view that is unmatched by surface data collection. Also satellite observation is an economical way to repetitively monitor large areas of water bodies compared to more conventional surveillance techniques and aerial sensing. But as with all techniques, however, remote sensing has also limitations and it should be used as a supplement data base.

2.0 REVIEW

Sediment pollution is often clearly depicted on aerial photographs. Observations about sediment concentrations using qualitative photographic radiometry coupled with the laboratory analysis of selective water supply is possible in case of suspended sediments. Because the spectral pattern of the suspended materials is distinct from that of the natural water, these two can be readily distinguished on the photographs.

Most suspended materials and some dissolved materials generally cause a change in emitted light intensity from a water body or a change in its colour due to their presence. Using simple photographic techniques differences in water colour or brightness can frequently be recognised either as variations in image density in the case of black and white film or more usefully, as changes in colour, hue, saturation, and brightness with colour film. The use of colour film helps in identification of organic, inorganic or chemical causes of colour change. If the colour of a suspended sediment is detectable, it may be possible to determine whether it derives from a particular source of erosion (Currey, 1977).

Clear water absorbs little energy having wavelengths less than 0.6 m. However, as the turbidity of water changes transmittance and consequently reflectance changes dramtically. Water containing large qualities of suspended sediment resulting from soil erosion usually have much higher visible reflectance than clear water in the same geographic area, Table - 2 shows the attenuation/wavelength relationship as found in typical surface waters (Jerlov, 1951).

Table 2 - Typical transmission characteristics of large water bodies

Types of ocean water	Wavelength of maximum (transmission (m)	percent transmission per m.
Clearest Ocean	0.470	98.1
Average Ocean	0.475	89.0
Clearest Coastal	0.50	88.6
Average Coastal	0.55	72.4
Average inshore	0.60	60.8

The broad band photographs film can relate image or colour density with the integrated measured concentration of suspended or dissolved solids in a body of water. If a simple relation can be shown to exist between these two variables then contouring of the water's concentration over a given depth may be possible. A drastic reduction in the number of water samples required can thus be expected when compared to conventional water quality mapping methods which solely rely on point water sampling. Aircraft data have been used to reveal features caused by dynamic turbidity such as the Niagara river plume in Lake Ontario (Falconer, 1973 and Harris, 1973). Lillesand et al. (1975) made a similar exercise by using false colour infrared film to monitor the waste outfall plume from a paper mill into the Lower Falls River, Wisconsin. The results showed that for typical non-thermal discharges, photo image density measurements can be used quantitatively to predict water quality throughout the mixing zone if (1) a systematic relationship is determined between water sample reflectance and some measure of water quality like suspended solids, turbidity etc. (2) the relationship between film exposure and scene reflectance is accounted for, and (3) the relationship between film density and film exposure is adequately approximated. In case these three criteria are satisfied, the measured image densities can be used to find out film exposure levels which could be used to find scene reflectance levels. Scene reflectance levels then can be used to predict water quality parameter values. Aircraft, however, can cover only relatively small areas of the waterbody at one time and repetitive flights for temporal data are cost prohibitive.

Blanchard and Leamer, (1973) made spectral reflectance measurements of water from various sources containing suspended sediments and found that peak sediment reflectance occured at 0.57 m.

Moore (1980) suggested that remote sensing techniques can be used gainfully to obtain either qualitative or quantitative estimates of water turbidity. The relative turbidity appear on Landsat images can be summarised and is given in Table - 3.

Table 3 Qualitative estimate of relative turbidity of water from landsat images

Relative Turbidity	Tone of image Bands				Hue of colour composite
	4	5	6	7	
None	Dark	Dark	Black	Black	Black
Slight	Medium	Dark	Black	Black	Dark blue
Moderate	Light	Medium	Dark	Black	Medium blue
Heavy	Light	Light	Medium	Dark	Light blue
Very Heavy	Light	Light	Light	Medium	White

Quantitative remote sensing of water turbidity is possible under some conditions but a thorough understanding of the effects of all variables as given in Table 4 is necessary to interpret the remote signal. It is important to understand that remote sensing results are optical measure of water turbidity and colour.

Table -4 Variables that can affect remote sensing of physical water quality characteristics

Variables	Explanation
Time of year	The earth receives 7 percent more energy from the sun on 1 January than on 1 July because of an oval orbit
Sun-elevation angle	More solar energy is specularly reflected from water surfaces at low sun-elevation angles than at high angles. Also, the path length of solar energy through the atmosphere is longer at low sun elevation angles and more solar energy is absorbed and scattered.
Aerosol and molecular content of atmosphere	These constituents determine the amount of solar energy absorbved and scattered by the satellite, is backscattered before reaching the water surface.
Water vapour content of the atmosphere	Water vapour affects energy absorption at near infrared and thermal infrared wavelengths.
Specular reflection of skylight from water surface	Specularly reflected skylight is receivea by a satellite. The intensity and wave-length distribution of this energy depends on atmosphere scattering, which produces skylight.
Roughness of water surface	A rough surface may produce more or less specular reflection than a smooth surface. At high sun-elevation angles, the area of sun glint may be within the satellite fields of view.

Film, foam, debris, or floating plants on water surface	These features may not be resolved on a satellite image, but they contribute to the spectral characteristics of the measured signal.
Water colour	Dissolved, coloured materials increase absorption of solar energy in water.
Water turbidity	The concentration, size, shape, and refractive index of suspended particles determine turbidity and increase the amount of energy backscattered in water bodies.
Reflectance and absorptance characteristics of suspended particles	Particles may be inorganic sediments, phytoplankton, zooplankton, or a combination. When present in high concentrations, particles affect the spectral distribution of backscattered energy.
Multiple reflections and scattering of solar energy in water	The spectral results of these processes are difficult to predict, but may not be important.
Depth of water and reflectance of bottom sediments	Water clarity determines the importance of bottom reflectance. Solar energy may not reach bottom in a turbid water.
Submerged or emergent vegetation	Vegetation may change bottom reflectance obscure water surface, or contribute to the spectral characteristics of the measured signal.

Suspended particles may occur in sizes that range from colloids to sands. As such definition of high concentration depends on grain size. Johnson (1975) demonstrated that colloids (< 1 μm) and clay (1 to 4 μm) have respectively poor and good correlation with reflectance. A fine grained material contains more particles and produces more scatter than an equal weight of coarse grained material. A high concentration of fine sand is more than 200 mg/1, but a high concentration of clay and colloids is 2 mg/1. It is likely that a few large particles of dark material which scatter back considerably less energy than a large number of exceedingly fine white particles with the same total weight (Scherz and Van Domelen, 1975). Particles more than 10 times the size of a wavelength of light scatter all wavelengths equally.

It is suggested by Moore (1980) that the nature of remotely sensed signal from a turbid water can be best studied by modelling as few field situation provide a wide range in water turbidity. A crude model could be made by representing the suspended particles as a homogeneous monolayer and by using expressions like equation (2) to represent the absorption and backscatter of energy by water. Such a model does not account for the results of multiple reflections from the particles or the effects of variations in shape, absorptance or refractive index. Also, assumptions must be made about the amount of light entering the water surface, particle size, and the reflectance of the particles. Nevertheless, using assumptions that are believed reasonable, model results provide some insight into the nature of data obtained by remotre sensing instruments. (Fig. 4 and 5). Consideration of exponential nature of the graph in Fig. 4 should be based on two factors: (i) sensivity of a particular band to changes in turbidity (slope) and total available energy. Most recent studies have found that MSS band 5 digital values correlate best with turbidity measurements in inland lakes and reservoirs. Studies show the feasibility of correlating satellite data with concurrent measurements of water turbidity.

Thoreson et al. (1975) used multiple regression technique to determine correlation between various field measurements and film densities on landsat images, aerial photographs and ground photographs. Water turbidity could be calculated directly from the backscatter flux measured at a satellite provided problems introduced by changing sun

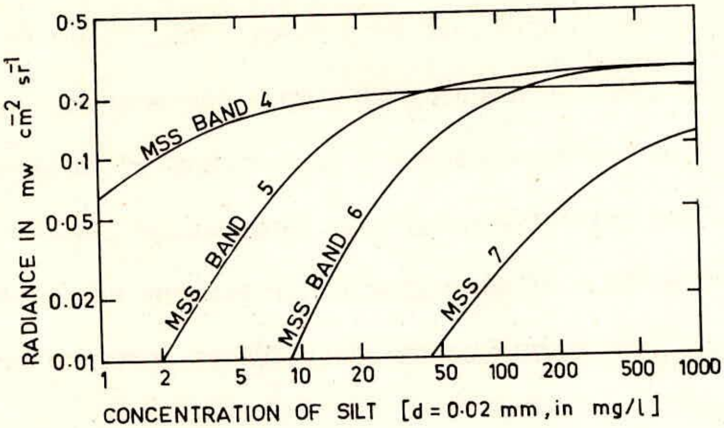

FIG.4 Nature of signal from MSS bands of Landsat from water with suspended silt

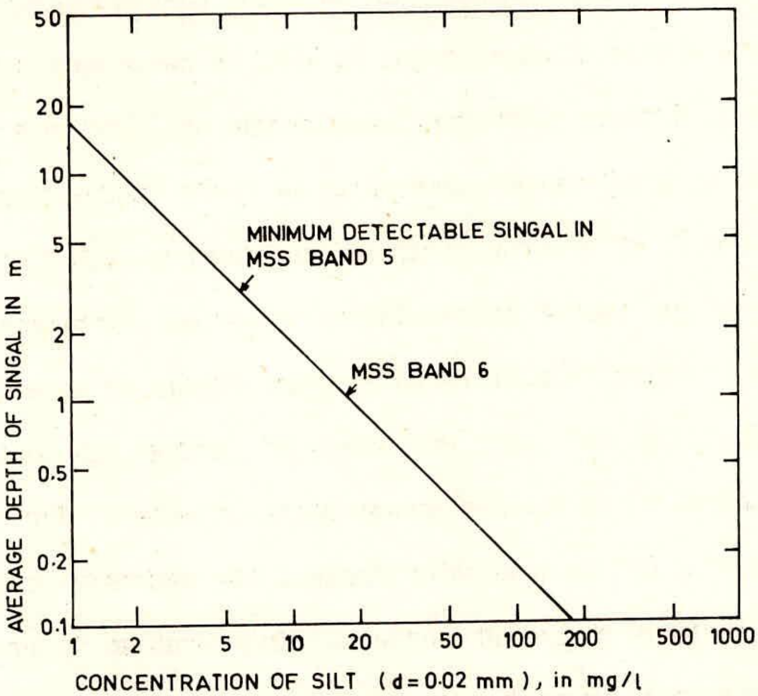

FIG.5 Average depth of signal in varying concentration of silt (concentration of silt that produces a detectable signal in MSS bands 5 and 6 are shown in arrow)

angle and atmospheric condition could be solved. Thus there is an important need to confirm the adequacy of simple corrections, such as dark-object-subtraction and band ratios. Corrections of these types have been developed and patented by Calspan Corporation (Walker et al., 1977). It may be noted that if atmospheric corrections can be devised, all landsat data will have significance and value as a record of water turbidity and colour.

As stated earlier, the principal advantage of remote sensing especially in satellite data for the water quality survey is the synoptic, large region overview and high observational density capability in multispectral mode. The reflectance of tonal changes observed in remote sensing data are a result of scattered and reflected light interacting with particulate matter in the water.

In order to gain some measure of effluent concentrations at different depths within a water body, it will be necessary to use multispectral data. Because different wavelengths of light are absorbed by water bodies to varying degrees depending on their state, certain wavelengths are capable of greater depth of penetration into the water than others (Fig. 6) and therefore resulting radiation corresponding to each wave band will result from different column depths of water. Various invesitgators studied the different MSS bands of landsat for sediment deciphering. MSS band 4 has maximum penetration in water. But using this band, it is difficult to determine whether the sediments are suspended in near surface or in sub surface. This problem is aggravated by contribution from scattering by atmospheric haze in this band (Klemas et.al , 1973 a and b). Best correlation was found by Sausen (1980) between Seechi disc and MSS band 4 during rainy season.

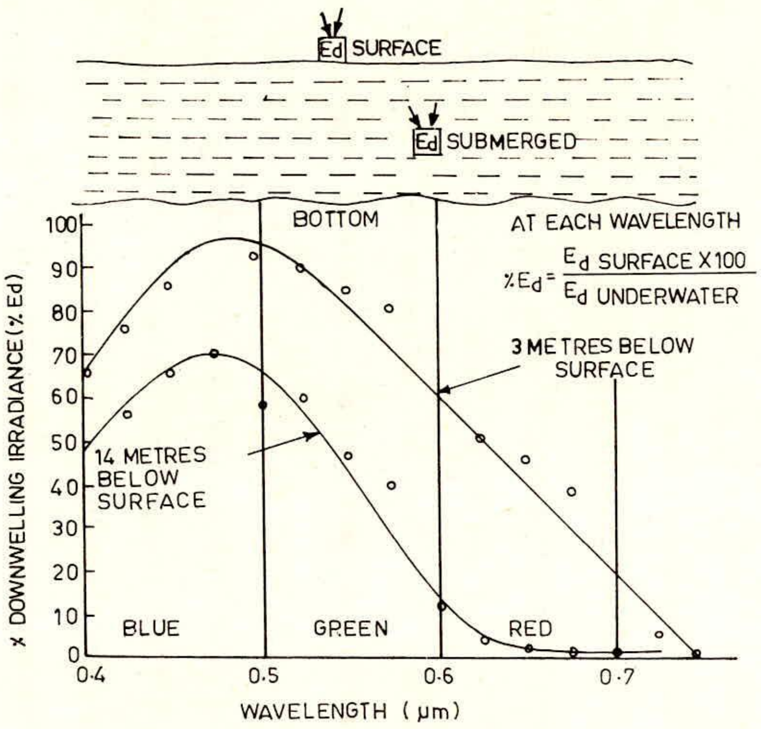

FIG.6 Downwelling radiance in clear water

Many previous investigators have suggested that MSS 5 (0.6-0.7μm) gives the best contrast in delineating suspended sediment concentration and their transport in upper 1 m of water column (Klemas et al., 1973 a and b; Sakata et al., 1975; Bowker et al., 1975; Bartolucci et al., 1977 Sausen, 1980; and Barker, 1975). This band is comparatively less affected by atmospheric effects. Its response to suspended load is similar to MSS band 4 (Yarger et al., 1975).

When MSS band 4 data are interpreted in combination with band 5 data, it is possible to determine which sediments are near-surface as band 5 detects only surface, and near surface suspended particles (Carlson, 1974; Stellar and Birie, 1975), the pentration of 'red' radiation being less than that of 'yellow-green' radiation.

MSS band 6 considered to be single most important band for predicting water quality parameters (Rogers et al ., 1975). This band is suitable for the detection of highly turbid areas of water. But because of its limited penetration capacity, it does not show clear pattern of suspended sediments. (Klemas et al., 1973 a).

When MSS band 7 shows high radiance, it indicates surface film of suspended sediments (Klemas et al., 1973 b). Band 7 radiance can be correlated to very high suspended load of sediments. (Yarger et al., 1975 and Sausen, 1980).

Coker et al. (1973) looked at the response of landsat RBV imagery to turbidity plume caused by dredging in Tampa Bay, Florida. The three spectral band used where green (RBV 1), red (RBV 2) and near infrared (RBV 3). The near infrared radiation was almost totally absorbed by the surface water so that only particulate matter at the very surface caused a reflection of the radiation, which appeared as a small, light toned area on the image. The light area on the red band was much larger than in the infrared, whereas the area of the plume recorded in the green band was subsequently larger than the red. Also is each band the centre of the area was observed to be lighter than the outer edges which gradually faded to dark tones. These confirmed that turbidity concentration of light coloured sediment was highest in the centre of the plume and that the outer areas either contained less particulate matter in suspension or else the particles were at a greater settling depth. Through a definite measure of sediment concentration with depth was not possible, considerable information on the three dimensional dynamics of the plume was obtained and its outward spread coupled with its increase in depth could be readily inferred . Fig. 7 highlights the results obtained using this technique.

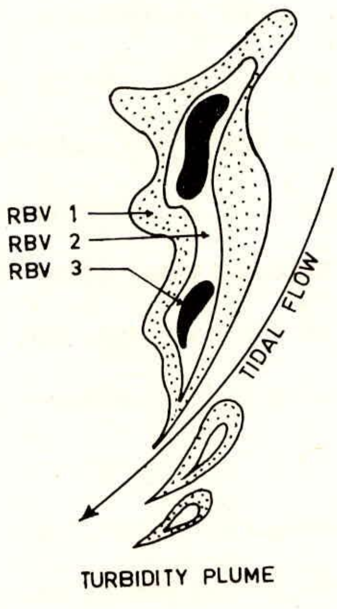

FIG.7 Extent of turbidity plume as recorded on bands 1, 2 and 3 of Landsat 1 RBV.

If however point water samples were also taken within the three dimensions of the sediment plume, a complete water quality and turbidity model could be reconstructed (Wertz et al., 1976).

In order to obtain truly three dimensional remotely sensed information on water quality variations using multispectral techniques, complex spectroradiometric calculations are necessary which are generally best applied by computer processing methods. The Grumman Aerospace report (1973) describes how sub surface turbidity profiles were achieved using a 'digital photometric mapper' which is basically a very stable single channel vidicon which may be operated through narrow band pass filters. The analog output from this instrument and from a non scanning photometer operating along the centre line of the scanned field was converted to a digital form and was stored directly on to computer compatible tape (CCT). Using this equipment configuration, it was possible to construct a model of water depth which accounted for the effects of water attenuation of different wavelength. Along with the effects of bottom reflectance, water reflectance, sky reflectance, polarization etc. on a given water body. By taking measurements in different spectral bands such as the green and red, different measured signal attenuation could be used to calculate water depth. It was observed that an increase in turbidity may often result in a decrease in reflectance in the blue part of the spectrum, but in an increase in the red part due to different forms of light scattering. In order to evaluate the degree of particulate contamination, a measurable effect in either direction must be present. Successful estimations of water turbidity at given depths were carried out by measuring the resulting reduction of polarization of light in the red region, but different modelling approaches were found necessary for different physical situations. Although the polarimetric approach was found to be the best single method, it was concluded that a combination of polarimetric, multispectral and laser techniques coupled with in-situ water sampling and measurements of incoming solar radiation would be the best combination. Computer compatible sensor outputs would be necessary for the complex calculations involved.

The practical utility of remote sensing is to serve as a means of extrapolating point measurements of water quality parameters over large areas. For example, turbidity status due to sediment variations in the near surface layers (< 1 m) of water bodies can be easily observed in landsat imagery in bands 4 (0.5 - 0.6 μm) and 5 (0.6 - 0.7 μm) (Scherz et al., 1974). When combined with point measurements or used as guide to select the points of ground measurement, remote sensing is a powerful tool. Persistent anomalous regions of turbidity such as associated with industrial plant effuent can often can be detected.

Scherz et al. (1974) mapped changes in turbidity in the south western part of lake superior using different shapes of brightness on satellite imagery. It was pointed out that had the planners examined low attitude aerial photographs (available as early as 1939) or satellite imagery, the water supply intake for the city of Duluth would have been constructed in a different area. Because of this omission, the intake was installed in an area of excessive turbidity and over 50% of the time yielded a water too turbid for drinking purpose.

Some encouraging empirical relationships between radiometric reflectance measurements and sediment load in near surface layers are observed. But, these relationships are dependent on local environmental conditions. They change because of the variations in -

i. the type and concentrations of the constituents of material in the water,

ii. the reflectance geomtry

iii. the atmospheric composition

This approach has been successfully applied for monitoring and estimating the extent of surface sediment load in small stream and large water bodies, including inlets and rivers (Rosgen, 1975 and Yarger et al., 1975).

Blue and green wavelengths in the visible range tend to get the maximum penetration in clear and turbid waters. In clear water, the maximum penetration occurs in 0.45μm. This tends to shift towards longer wavelengths in turbid water. The penetration of light in clear waters vary from 4 to 15 m and no more than 20 m. In moderately turbid waters average penetration depths are reduced to 1 to 2 m. This ability of landsat data depends on clear sky and uniform atmospheric transmission. Success will be greatest in combining reliable, conventional depth information with the landsat data where in landsat information are employed for interpolating between the conventional information. The main application would come in updating navigation charts in coastal area and near island. From landsat MSS imagery, it has been possible in shallow coastal waters to map, within useful accuracies, sediment types and sand bars (Anderson et al., 1973).

Shoreline erosion along the edges of Albemarle sound, North Carolina was significant for a number of years and it appeared that certain stretches of the shoreline is more susceptible for erosion than other reaches. In order to investigate the possibility and to assess the possible use of landsat imagery for predicting the more vulnerable stretches of storeline, Welby (1980) used a time series of landsat images from August, 1972 to June 1977. Several circulation patterns recorded by distribution of suspended sediments were recognised. Details on the images suggested that eastern one third of the northern shore has been more susceptible to erosion. Although all the 14 images used did not made an ideal statistical sample, but the patterns found on the images are representative of the images studied contain one general pattern. Aerial photography and skylab photograph support the interpretation made from the landsat-1 imagery and observations by other investigators lend further support. Thus it appears that use of landsat imagery in a retrospective fashion can provide clues for improved shoreline management and can be effectively applied.

Historical landsat derived MSS data of Apalachicola Bay Florida were used by Hill (1978) to demonstrate that water colour and turbidity distributions could be nicely discriminated. These patterns were shown by Graham et al. (1978) to coincide with characteristic pattern determined from long term field data base.

Salomonson (1973) studied the Tuttle Creek reservoir in Kansas and worked out the relationship between suspended load in the reservoir and average MSS CCT digital level of landsat-1 data. These are illustrated in Figures 8 and 9.

Schiebe and Ritchie (1975) studied the behaviour of suspended sediments in North Mississippi reservoirs. They observed that for concentrations of suspended sediments greater than 15 ppm, the dominant wavelength lay in the range 0.57 - 0.58 μm for the six north Mississippi reservoirs studied. Within this range, the concentration of suspended

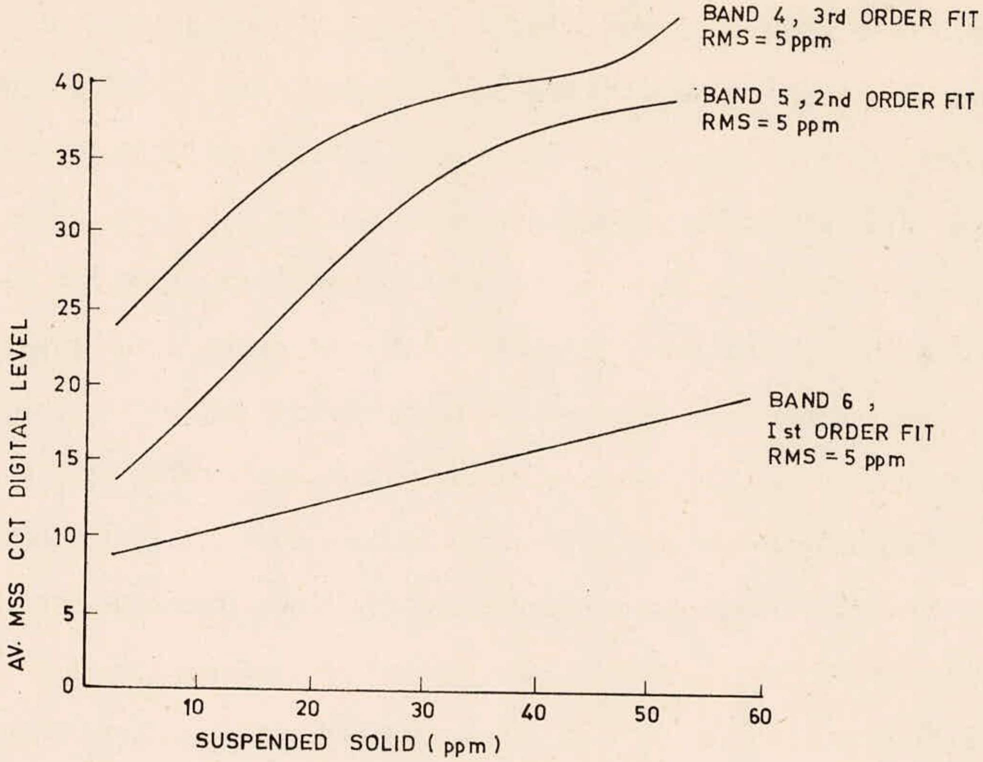

FIG. 8 Relationship between suspended solid and average MSS digital value for Tuttle creek reservoir in Kansas.

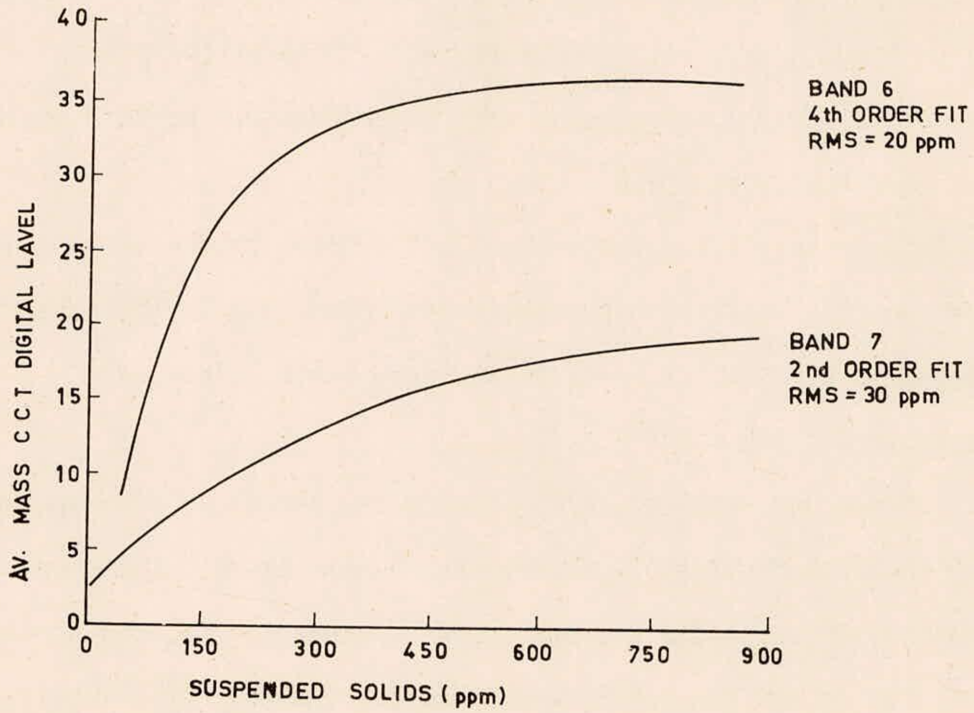

FIG.9 Relationship between suspended solid and average MSS digital value for Tuttle creek reservoir in Kansas.

sediment appears to be independent of dominant wavelength. This is to say that no noticeable trends exist with dominant wavelength after the concentration exceeds 15 ppm. The colour purity follows an exponential relationship with the concentration of suspended sediment when the dominant wavelength measurement indicates the presence of suspended sediment. The useful range of this relationship appears to be from 15 to 100 ppm.

Sediment deposition in freshwater lakes is a major world problem, yet there is no simple method to determine deposition rates for recent sediments. Deposited sediments affect many properties of freshwater lakes. They can absorb or release phosphorus, nitrogen, carbon and heavy metals and affect the chemical properties of a water body (Ritchie and McHenry, 1976).

Examination of the satellite scene permits a determination of the distribution of suspended sediment during a major runoff event in River Detroit draining in Lake Erie. Close similarity between turbidity patterns and mercury concentrations was observed. This indicates that satellite data could be used to predict the paths that sediment will take in a large lake or reservoirs as well as the major areas of deposition. Lake sampling programmes, if based on satellite imagery, would allow a greater refinement of grount truth data collection than would otherwise be possible (Siegel and Gillespie, 1980).

Chagarlamudi et al. (1979) used landsat multispectral scanner bands 4, 5 and 6 in a simple transformation and achieved 93 percent correlation between estimates obtained from landsat data and actual measurement of Seechi disk depths for 43 stations of multidate data. Sorensen (1979) reported measuring suspended solid concentrations in the range of 0 to 30 mg/1 with an accuracy of 30 percent in log suspended solid concentration.

A system for automated multidate landsat CCT MSS measurement of suspended sediment concentration (S) has been implemented and verified on nine sets (108 points) of data from the Bay of Fundy, Canada (Munday et al.,1979). The system employs "chromaticity analysis" to provide automatic pixel by pixel adjustment of atmospheric variations, permitting reference cdalibration data from one or several dates to be spatially and temporally extrapolated to other regions and to other dates. Correlation between a landsat "chromaticity coefficient" and $\log_e S$ was $r = 0.965$, which produced a mean standard error of prediction of 30 percent of S. For verification, each data set was used in turn as test data against the remainder as a calibration set; the average absolute error was 44 percent of S over the range $1 < S < 1000$ mg/1. Effects of sediment type and size were negligible. The effect of solar angle was also negligible. The system can be used to measure turbidity. In a study related to the Fundy Tidal Power Project, S contour maps were used to initialize and calibrate a numerical model, and were also interpreted in order to define sediment transport paths and hydrodynamic flow. Results indicate that no significant sedimentation is expected from the proposed Fundy tidal barrage during its design life time.

While it is not practical to try to establish an exact cause and effect relationship in any given area, water quality control can be initiated if potential polluting sources are located and identified. Once the existing nonpoint sources are found, the implementation of a comprehensive area wide and **statewide** planning programme for nonpoint agricultural source control can be established. Through the use of satellite data, which can give accurate land-cover/land-use information, coupled with a geographic computer information system, nonpoint pollution assessment can be undertaken at a regional scale and be cost effective. Information organized on a computer basis utilizing landsat data can be used to refine soil delivery ratio equations, e.g., the Universal Soil Loss Equation, the result in reasonable predictions of agricultural load generation and the potential transport of nonpoint source pollution based on watershed parameters (such as soil, slope, vegetation cover acreage involved, spatial proximities). The University Soil Loss Equation is:

$$A = RKLSCP \qquad \ldots (3)$$

where:

A = average annual soil loss per unit area,

R = rainfall factor,

K = soil erodibility factor,

L = slope length factor,

S = slope steepness factor,

C = cropping management factor, and

P = erosion control practice factor

Cambell (1979) derived land cover mapping from satellite data by using computer system and used compuer mapping techniques for a rapid and accurate analysis of agricultural conditions which cause potential erosion and results in water quality problems. To identify the nonpoint pollution potential (NPP) of the eight county study area in Indiana state a generalised index based upon the interaction of following conditions was created;

NPP = f (soil characteristics x agricultural land use intensity x proximity to water)

A geo corrected reformatted landsat digital tape of September, 1972 was analysed for land cover inventory. A comparison of the two watersheds by total acreages by four criteria analysis is given in Table 5. The severe erosion potential watershed in Boone county has a total of 49,166 acreas as compared to 52,824 acres in the Morgan County Watershed. Even though Morgan County Watershed has more acreage, its water pollution potential is less drastic as defined by the model used.

Table 5 : Watershed Model

	Soil Erodibility (Acres)	Agricultural combined use (Acres)	Search from surface water (1500 meters or less) (Acres)	Index of Agricultural use soil erodibility (1500 meters or less to surface water) (Acres)
		BOONE COUNTY		
Watershed 482,483 severe erodibility	49,166	32,674	36,890	27,875
		MORGAN COUNTY		
Watershed 561,562 slight erodibility	52,824	24,269	32,302	26,660

A knowledge of land cover con'.ributes to the C factor in the Universal Soil Loss equation Repeated coverage of the same area allows interpretations of cropping seauences. Using Univesal Soil Loss equation the estimate of a'erage so'l loss subsequently available as sediments are estimated in Madison and Wapellow county in Iowa (Fenton, 1982).

Similar studies were carried out for potential soil erosion mapping with landsat imagery in New Brunswick area in Canada (Stephens and Cihlar, 1982). Relationship between C values of individual farms and ratioed landsat-2, multispectral scanner radiance values has been determined for 14 farms in study area. Ratioed multispectral scanner data considered was the mean (x) and standard error (Se) of the ratio of Band 7 to Band 5. A multiple linear regression has been determined for the relationship between ratioed radiance values (x, se) and the C values. The regression (r = 0.88) is described by the equation

$$C = 0.057 + 0.024 \left[\bar{x} \frac{\text{Band 7}}{\text{Band 5}} \right] - 0.003 \left[Se \frac{\text{Band 7}}{\text{Band 5}} \right] \quad \ldots (4)$$

Ripple and Miller (1982) reported the use of Universal Soil Loss Equation by extracting C values from the land cover map derived from satellite data for the Lake Herman Watershed in South Dakota for delineating priority watershed areas. Similar approach was followed by All India Soil and Land Use Survey Organisation for delineating wateshed with "sediment yield index" methodology (Bali, 1984).

Sedimentation in lake Chicot was studied by landsat MSS data (LeCroy, 1982). Lake Chicot is a large oxbow lake in Arkansas on the lower Mississippi river flood plain formed six centuries ago. Total suspended solids in the lake ranged from 168 to 508 mg/1. Schiebe et al. (1983) made comparison with ground data collected and the thematic mapper data of landsat-4 of September 23, 1982. A preliminary analyses of limited data indicate that thematic mapper data is useful for monitoring suspended sediment. TM band 3 appears to be most useful with band 1, 2 and 4 which also contain useful information relative to suspended sediments.

Gupta and Bodechtel (1982) while conducting geotechnical investigations of Bhakra dam reservoir, demarcated two areas of potential soil erosion zones from landsat imagery. These zones are later on confirmed to be susceptible to soil erosion from the available field data.

The distribution of sedimentation levels within a reservoir depends on (Smith et al., 1980).

i. the volume of flood water,

ii water level in the reservoir at the onset of flood period, and

iii. the distribution of the flood water in the reservoir at the end of the flood period.

All these parameters are susceptible to be inferred from pre and post monsoon landsat data. Satellite imagery of pre-monsoon season for peninsular India will be useful to provide clues to the sediment deposited. The regular exposure of more and more fringe land out of the water during dry season every year indicative of heavy siltation from the adjoining hills. If the area of a reservoir at the same water level at two different dates are varying, it means that there have been heavy siltation in the reservoir. This can be monitored effectively using landsat data (Choudhary et al., 1980).

A preliminary study on Ukai reservoir sedimentation by Space Applications Centre showed appreciable changes in the water level in the reservoirs between pre and post monsoon period. Such change indicates irregular pattern of deposition. It was reported that during March and November, 1975, the areal extent of water spread in the reservoir increased by 224 sq.km. This area gets exposed during pre-monsoon season and pattern of sediments deposited could be known. Ground sampling provide further useful information on sedimentation rate and types. It was observed that sediment concentration is high in post monsoon season and low during pre-monsoon period (Nayak, 1983).

Semi-quantitative maps of different concentration levels in Gulf of Khambhat were made using density slicing technique. The seasonal variations in suspended sediments were studied. Sedimnents which were brought in suspension by strong monsoon currents started settling after the sediments. (Nayak and Sahai, 1983).

Muralikrishna (1983) analysed a landsat scene around Gulf of Cambay. The seene 160-046 is selected because 4 rivers carrying terregeneous substances join the sea around the Gulf. The landsat MSS band 4/band 5 values are evaluated. This ratio has been taken as basis and the corresponding sediment levels are evaluated by making use of the sea truth information. Here main source of error is the nonlinear variation of spectral radiance value with landsat CCT digital count in each band as the digital counts in the each band correspond to different spectral reflectance levels. This error due to non linearity has been neglected by the investigator. The scene was analysed in an interactive computer and a six level delineation represented by various colour shades was carried out. The concentration of suspended matter in the surface water ranged from 0.5 to 3.5 mg/l. Moderate concentration 1.5-2.0mg/l is extending upto a distance of about 25-30 km from coast. This has been somewhat usually high rate of dispersal and is rarely found in tropical ocean water. The study reported here amply demonstrated the usefulness of remotely sensed data for monitoring suspended matter distribution.

Dubey and Bhatia (1985) attempted the multivariate analysis after evaluating geological, morphological, pedological, and botanical parameters from Remote Sensing data. Study has been carried out for evaluating erosion rate using remote sensing data for proposed Tehri reservoir. In the first stage of the study, the geomorphology and vegetation have been mapped from satellite imagery, FCC and from aerial photographs. In the second stage the descriptive classifications are compiled and possible estimated sediment production was evaluated. High and low sediment production area have been identified.

Shimoda et al. (1986) correlated various water quality parameters measured at ground with the machine processed landsat data characteristics for Lake Balaton in Hungary. This lake is the largest water source in Hungary. System correlated landsat MSS image covering the study area acquired on 2nd July, 1981 was used. Ground truth measurements on the lake were done simultaneously with the data acquisition of MSS data. Fourteen items of water qualities were measured at thirty points. Items that are relevant for sediments are:

1. Transparency (TR)
2. Suspended Solid Concentrations (SS)
3. Water Temperature (TM)
4. Light energy on the Water Surface (LE)
5. Light energy reflected from the water surface (RF)
6. Light energy penetration (PE)

Image analyses were made using TIAS-2000 (Tokai Image Analysis System). Multiregression analyses were made between the ground truth data and four kinds of image signatures, i.e. original MSS values, mean values of 3 x 3 pixel window, normalized values within 4 bands and ratios of band 4 and band 5. Normalized values were calculated according to the following equation:

$$N_j = \frac{M_j}{\sum_i M_i} \times K \quad \cdots (5)$$

$i = 1, 2, 3, 4$

$j = 1, 2, 3, 4$

Here, M_i is the mean value of 3 x 3 pixel window of band i, N_j is the normalized value, K is a constant, and suffix i corresponds to band 4, band 5, band 6 and band 7.

Table 6: Correlation coefficients between the ground truth data and four kinds of image signatures

Item	Original value	Mean value (3 x 3 pix)	Normalized value	Ratio (B4/B5)
TR	0.752	0.860	0.827	0.301
SS	0.572	0.538	0.424	0.193
TM	0.547	0.553	0.655	0.681
LE	0.773	0.786	0.699	0.251
RE	0.705	0.706	0.681	0.277
PE	0.845	0.773	0.736	0.589

As a result of this study for water quality monitoring using landsat MSS data, following conclusions were obtained.

1. The strongest correlation was observed between MSS data and transparency among those fourteen items of ground truth.
2. No correlation was observed for suspended solid concentrations.
3. Mean values of 3 x 3 pixels window can be considered to be most desirable signature.
4. Although there are some reports about water quality monitoring using band to band ratios e.g. band 4/band 5, no special effect was recognised in this study.

3.0 REMARKS

Regular information about the quality of water over space and time alongwith the quantity are essential for water resources development and management amongst conflicting demands. Suspended sediments which are almost ubiquitous, are an important environmental parameter for monitoring sedimentation in reservoirs and water quality in rivers, lakes and estuaries.

Three aspects are important in sediment monitoring: identification of sediment source, point and non-point nature of sediments, sediment influx, and dispersal in the aquatic environment. These data are essential for setting standards of water quality and enforcing regulations on effluent discharge into fresh waters.

Remote sensing techniques specially after the satellite era can gainfully supplement the ground based data collection regarding sediments. The large area synoptic view, repetitive and multispectral coverages of satellite data suit the water quality data monitoring endeavour. The study of the sediments and turbid water involves complex interaction of light and water and thus the physics involved in it should be properly understood for conventional and as well as remote sensing methods.

Many investigators have found out positive correlation between suspended solids and reflectance in the visible and near infrared wavelength and satellite data have demonstrated potential in identifying and estimating qualitatively as well as to some extent quantitatively. But, there are still some problems associated with the study of sediments in its proper perspective.

The first problem in estimating the suspended sediments from satellite data is the variation in absorption and scattering characteristics of solar energy at different times and effects of sun elevation angle. A combination of dark object subtraction method (Aheren et al.,1971) and band ratioing (Yargar and McCauley, 1975) has been tried which provide satisfactory results as regards to the atmospheric corrections. However, further work still to be done.

The second problem that needs to be addressed is that the remote signal of a turbid water may be a mix of dissolved matter, bottom reflectance, phytoplankton and suspended sediments. In order to monitor the suspended sediments the relative contribution of each of them need to be quantified.

The third problem is the spatial resolution of currently available satellite data. It is hoped that improved resolution of the French satellite 'SPOT' and other future missions will offer solutions to this problem.

After the atmospheric corrections are made, the back-scatter from the turbid water can be quantified. The real problem that remains is to develop models by which the concentrations and distribution of sediments can be correlated with actual sedimentation rates. An AGRISTARS research activity on the development of 'sediment only' algorithms for total suspended solid values upto 1000 ppm has shown promise (Whitelock et al., 1981). A parallel laboratory and field experiment programme is believed to be faster approach for development of such remote sensing data analysis algorithms.

Though remote sensing methods help to reduce the number of sampling points and ground truth data, still the ground truth data requirements are more difficult in remote water quality survey than in land survey because of dynamic nature of water quality and complex water energy interaction giving rise to noise signal measured by remote sensor (Thiruvengadachari et al., 1983) . Development of suitable and effective ground truth strategies is essential for successful execution of remote water quality surveys. Simaltaneous boat level spectral measurements, if needed, should be identified.

There is need to evaluate presently used ground truth equipment. There is need to modify or develope new ground truth infrastructure to suit Indian condition. Depth samplers, under water camera systems etc. are some of the instruments needed to be developed. Sensor package for various in-situ measurements for water quality parameters need to be developed. Commercially available spectral instruments need modifications and technology transfer group of Deptt. of Space is taking appropriate actions in this regard. A good amount of works in this regard have been done by NRSA scientists also (Deekshatulu et al., 1981).

As suggested by Singh et al., (1983), for the use of remote sensing for reservoir sedimentation, the bench mark studies for establishing suitability of remote sensing to reservoir sedimentation and soil conservation studies could be initiated on pilot projects like D.V.C. Hirakud, Machkund etc. for which extensive studies with use of conventional data have been carried out. Soil survey that are being carried out by All India Soil and Land Use Survey in the selected sub-watersheds may be used in this connection.

It may be pointed out that during the year 1985-86, detail soil surveys of an area of 4.46 lakh ha were conducted (Annual Report, 1985-86). They include the catchments of Ajay (Bihar and West Bengal), Bhawani Sagar

(Kerala and Tamil Nadu), Chambal (MP), Dantiwada (Gujarat and Rajasthan), DVC (Bihar), Kangsabati (West Bengal), Matatilla (MP), Nagarjuna Sagar (AP, Karnataka & Maharashtra), Nizamsagar (Maharashtra), Pochampad (Maharashtra), Rupnarayan (West Bengal), Sahibi (Haryana), Sone (Bihar), Tawa (MP), Tista (West Bengal), Tungabhadra (Karnataka), Ukai (Maharashtra), Upper Ganga (U.P.) and Upper Yamuna (H.P.). The total coverage under these survey so far made is 45.64 lakh ha. These soil survey reports could serve as indirect ground truth for sedimentation studies.

Besides soil colour, dendritic drainage pattern, appearance of sand, gravel and bare rock in landsat imagery are indicative of land erosion and area of sediment production.

Though the indications for use of remote sensing techniques for sediment studies are encouraging, but very few investigators claim to have an operational water quality measurement technique. The truly efficient techniques that are satellite based and multi date are even fewer because they tax the technology to its limits. Deptt. of Space has categorised the water quality monitoring endeavour by remote sensing methods as Experimental Application Project.

Several new earth resource satellites areanticipated for launch in near future. French satellite SPOT has been launched recently. Virtually all of them will exhibit some improvement over present satellite in terms of orbit and sensor characteristics. These technical developments can be categorised into four basic dimensions: spatial, spectral, radiometric, and temporal. The significance of these four areas for water quality applications include:

1. Spatial Resolution: Smaller, instantaneous field of view or pixel size including reduced under estimation of suspended sediment concentration in non homogeneous water.

2. Spectral Resolution: Narrower, better positioned bands including better discrimination of and among water phenomena, improved quantification accuracy of water quality parameters and improved opportunity for atmospheric corrections.

3. Radiometric Resolution: Lowered system noise including better measurement of small concentrations of sediments, improved discrimination of and among water phenomena and more accurate quantification of water quality parameters.

4. Temporal Resolution: More frequent coverage-including better coverage of dynamic phenomena, greater probability of cloud free imaging, and finer temporal descriptioin of events.

Indian Remote Sensing Satellite (IRS) will be launched soon and will meet some of these required improvements. The details of sensors, spectral bands, resolution etc. of most recent satellites and IRS is given in Table 7.

Observational requirements for monitoring sediments using remote sensing has been described by the Task Force on Water Resources Constituted by Planning Commission and is given in Table 8.

With these improvements and using the technological advancement in the physics of water energy interaction, the satellite remote sensing is emerging as a creditable and affordable tool for monitoring important water quality parameters and it is hopefully expected that this tool will be part and parcel of monitoring the quality of global water resources by the turn of the century.

Table 7 : Satellite Platforms, Sensors and Characteristics of Spectral bands

Satellite	Landsat-4/5		SPOT		IRS			
Sensor	MSS	TM	Camera-1	Camera-2	LISS-1	LISS-2		
Spectral bands (Micrometer)	-	-	-	-	-		Blue	Shallow water studies, bathymetry
	-	0.45-0.52	-	-	0.45-0.51			
	0.5-0.6	0.52-0.60	0.50 to	0.5-0.59	0.515-0.585		Yellow green	Shallow water studies, chlorophyll
	0.6-0.7	0.63-0.69	0.90	0.61-0.69	0.61-0.69		Red	Suspended sediments, chlorophyll
	0.7-0.8	0.76-0.9	-	0.80-0.91	0.76-0.9		Near infrared	Land-water boundary delineation
	0.8-1.1	-	-	-	-			
	-	10.4-12.5	-	-	-		Thermal infrared	Temperature
Resolution (in m)	80	30 & 120+	10	20	36.5-73.0			
Repeatability (days)	16		26		22			
Grey-level	64	256			128			

MSS = Multispectral scanner TM = Thermatic Mapper LISS = Linear Imaging Self-Scanning System,

\+ = Resolution of the thermal band.

TABLE 8 : Observational requirements for hydrology

Parameter and its definition	Requirement				Available from satellites	
	Scale	Resolution	Frequency	Accuracy	Expected 1980s	Remarks
WATER QUALITY						
Turbidity: Condition of a liquid due to fine visible material in suspension which impedes the pssage of light through the liquid	A B C	30m 100m 300m	(Daily) (Daily)[1] (Daily)	(+0.5 FTU)* (+0.5 FTU)* (+0.5 FTU)*	Not possible Not possible Possible over limited areas only	Some information about turbidity can be derived from multi-spectral imaging as those obtained experimentally from "LANDSAT" and "METEOR" and expected from the coastal zone colour scanner to be flown on Nimbus-G.
Suspended sediment:sediment which remains in suspension in flowing water for a long time without setting on the streambed	A B C	30m 100m 300m	(Daily) (Daily) (Daily)	(+10 ppm) (+10 ppm) (+10 ppm)	Not possible Not possible Possible over limited areas only	Same as Turbidity above
Colour:deviation from the aspect of pure transparent water	A C C	30m 100m 300m	(Daily) (Daily) (Daily)	(+10mg Pt/1)** (+10mg Pt/1)** (+10mg Pt/1)**	Not possible	Same as Turbidity above

*Range of measurements is 0.0025-5.0FTU:(FTU=(FORMAZIN TURVIDITY UNIT) = 400 JTU (JACKSONTURBIDITY UNIT), i.e. accuracy listed in the Table corresponds to 20% of the range.

1 Six hours for pollution monitoring for rivers and small lakes.

** Range of measurements is 1-50mg Pt/1: (mg Pt/1 = mg of Platinum per litre), i.e. accuracy listed in the Table corresponds to 20% of the range.

A- less than 100 km^2
B- between 100 and 1000 km^2
C- more than 1000 km^2

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