APPLICATION OF REMOTELY SENSED DATA FOR QUANTIFICATION OF SUSPENDED SEDIMENT IN TURBID RIVER WATER

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ABSTRACT

Remote sensing is proved to be a useful tool to provide an instantaneous and synoptic view of suspended sediments in rivers & estuaries. Erosion of the land surface yields sediments which are transported downstream by rivers. Turbidity is not a uniform parameter, either spatially or temporally. The objective of the research study is to quantify suspended sediments in turbid sediment-dominated waters from high spatial resolution remotely sensed data. In this study, near real time satellite data from Landsat TM coupled with in situ measurements is used to establish relationship between the remote sensing reflectance (Rrs) signal and suspended sediment concentration (SSC). Reflectance spectra of different concentration of suspended sediments were measured 1m above the water surface in the laboratory using hyperspectral Field SpecPro FR Spectroradiometer in the electromagnetic spectrum region of 400 nm to 900 nm. Regression model was developed to quantify the suspended sediment concentration. Results show that a strong correlation exists between the suspended sediment concentration and red & infrared domain. Variations of quantity and characteristics of suspended sediment affect the reflectance signal and limit the accuracy of suspended sediment measurement. However, remotely sensed data makes it possible to efficiently monitor the seasonal distribution and concentration of suspended sediment in the water bodies.

Key words: Suspended sediment monitoring, remotely sensed data, NIR, Landsat TM , SPOT

1- INTRODUCTION

Water resources & environmental management is essential for sustaining quality of life on earth. Most of the problems in water resources sector are common in arid & semi-arid regions of the world. These are generally: scarcity of water, inadequate storage and sedimentation in water bodies. Soil erosion is a widespread problem causing the deterioration of both land & water resources. High concentrations of suspended sediment in water are a critical element in the economic feasibility of a project and could shorten the useful life of many reservoirs & dams. It is estimated that approximately 1,100 km^3 of sediments have been accumulated in the world's reservoirs, taking up almost one fifth of the global reservoir storage capacity [1]. The sedimentation has engineering consequences because it leads to a reduction of the storage capacity of the reservoir and, hence, of its efficiency. Most of the sediment which is eroded from the land surface is in the form of fine particles which are transported in water courses as a suspended load. These fine sediments account for the turbidity often observed in rivers and their natural fall velocity in water is so low that the natural turbulence maintains them in suspension. A small proportion of the sediment, perhaps around 10%, is coarser material which is transported as bed load. These sediments roll along the bed of the river or saltate (hop) close to the bed [2].

Soil provides ecological capacity by delivering a range of functions including food and fiber production, biodiversity, environmental services, landscape and heritage, raw materials and physical platforms for the built environment. Erosion of the land surface yields sediments which are transported downstream by rivers. Globally the erosion rate has been estimated by many authors ranging between 0.06 mm/year and 0.16 mm/year [2]. Sediment discharge assessment in the river basin provides a useful perspective on the intensity of erosion in upstream watershed. For estimation of the sediment yield one of the methods is the analysis of suspended sediment concentration and their relations to discharge at the outlet of catchment. Suspended sediment concentration measurement posses the advantage of providing a spatially integrated assessment of erosion rates in the upstream area. Monitoring of suspended sediment is a difficult task because of many influencing factors. Suspended sediment monitoring stations are generally fairly sparse. Thus any extensive spatial resolution cannot be obtained. Some ad-hoc spatial monitoring campaigns do take place, however their expense and logistical difficulty prohibits extensive use. New sources of data must be explored to complement traditional data collection techniques. Current technological advances and scientific/engineering knowledge can analyze various scenarios with a fair degree of accuracy. Remotely sensed data is widely touted by practitioners as providing solutions to the data problem. Data from remote sensing can easily indicate a spatial pattern of a parameter, which is not possible though traditional measurement campaign.

Remote sensing makes it possible to monitor the water bodies effectively & efficiently and, identifying areas with significant water quality problems. Remote sensing (hyperspectral, satellite and airborne platforms) is a tool that addresses problems of a regional or global nature. Several studies have been conducted to address the impact of suspended sediments on the spectral profile of surface waters. Most of these studies focus on the relationships between spectral reflectance and suspended sediment concentrations in surface waters. Few studies actually address how different sediment types and size affect spectral reflectance [3] [4 [5]. Variations of sediment type (grain size and refractive index) and changing illumination conditions affect the reflectance signal of coastal waters and limit the accuracy of sediment-concentration estimations from remote-sensing measurements [6]. It is believed that the main differences between the two types of waters are located in the 400 – 700 nm spectral range [7], where the turbid water has significantly larger reflectance than the clear water. This formed the basis for the detection of turbid water and SSC estimation algorithms. In this paper spectroradiometer data and spatial information available from satellite is comprehensively analyzed and regression model was developed to estimate suspended sediment concentration (SSC) from Landsat TM and SPOT data.

2- STUDY AREA

Sediments, which fill lakes, reservoirs, and dams, are one of the most important environmental problems throughout the world. The rivers of Pakistan carry much sediment either as bed load or in suspension. Sedimentation in the three major reservoirs – Tarbela, Mangla, and Chashma in Pakistan is going to deplete their storage capacities by over 25 % by the end of the year 2010 [8]. Much of the land in Pakistan is highly erodible because of sparse vegetal cover, steep slopes, and non-resistant soils and rocks. The Indus River is one of the largest sediment producing rivers in the world. The main source of sediment is from the glacial landscape and erosion from steep sided barren slopes. Melting glaciers and falling rocks leave behind large quantity of sediments each year.

Table 1 : Sediment data of World Rivers

River	Catchment Area (km^2)	Annual Runoff (km^3)	Annual Sediment load (million tons)	Average Sediment Concentration (kg/m^2)
Yellow	687,869	42.6	1,600	37.5
Ganges	955,000	371	1,451	3.91
Bramaputra	666,000	384	726	1.89
Yangtze	1,700,000	933.6	490	0.52
Indus	969,000	175	470	2.68
Amazon	5,770,000	5,710	363	0.06

Source : [9]

The Indus rises in Tibet, in the snow-clad Kailas range of the Himalayas, is about 5,500 m above mean sea level. The river slope from the headwaters to Attock is approximately 1/ 300; from Attock to Mithankot it is 1/4,000; and from Mithankot to the sea it averages 1/7,000. The total length of the Indus is about 29,00 km. The Indus River alone provides 65% of total river flows, while the contribution of River Jhelum is 17 %.

The Tarbela Dam is the largest earth and rockfill dam of the world across the river Indus. The 169,650 km^2 catchment area of river Indus above Tarbela consists of two distinct hydrological regions. Over 90 % lies between Karokoram and Himalayan mountain ranges and about 10 % lying immediately upstream of the dam. This 10% part of the basin is subject to monsoon rainfall (July to September) casing sharp floods of short duration. The length of Tarbela dam reservoir is 97 km with an area of 260 km^2.

Table 2 : Flow and sediment loads of the Indus catchment to Tarbela

	Upper Catchment (Non-monsoon area) %	**Lower Catchment (Monsoon area) %**
Catchment Area	94	6
Annual flows	92	8
Annual sediment loads	96	4

Source : [10]

The river flow regime of the Indus is consistent from year to year. The sediment load varies with discharge, seasonal differences and conditions of the watershed and river morphology. The river basin and catchment areas have significant effect on the grain size distribution of the suspended sediments. About 94% of the catchment area of the Indus river is located in semi-arid to hyper-arid environment. A very large portion of the total sediment load is carried by the river during the summer time. The predicted rate of sediment inflow was 0.294 BCM (Billion Cubic Meter) per year meaning that the dam would silt up to 90% capacity in 50 years and thereafter continue to provide only about 1.2 BCM of live storage.

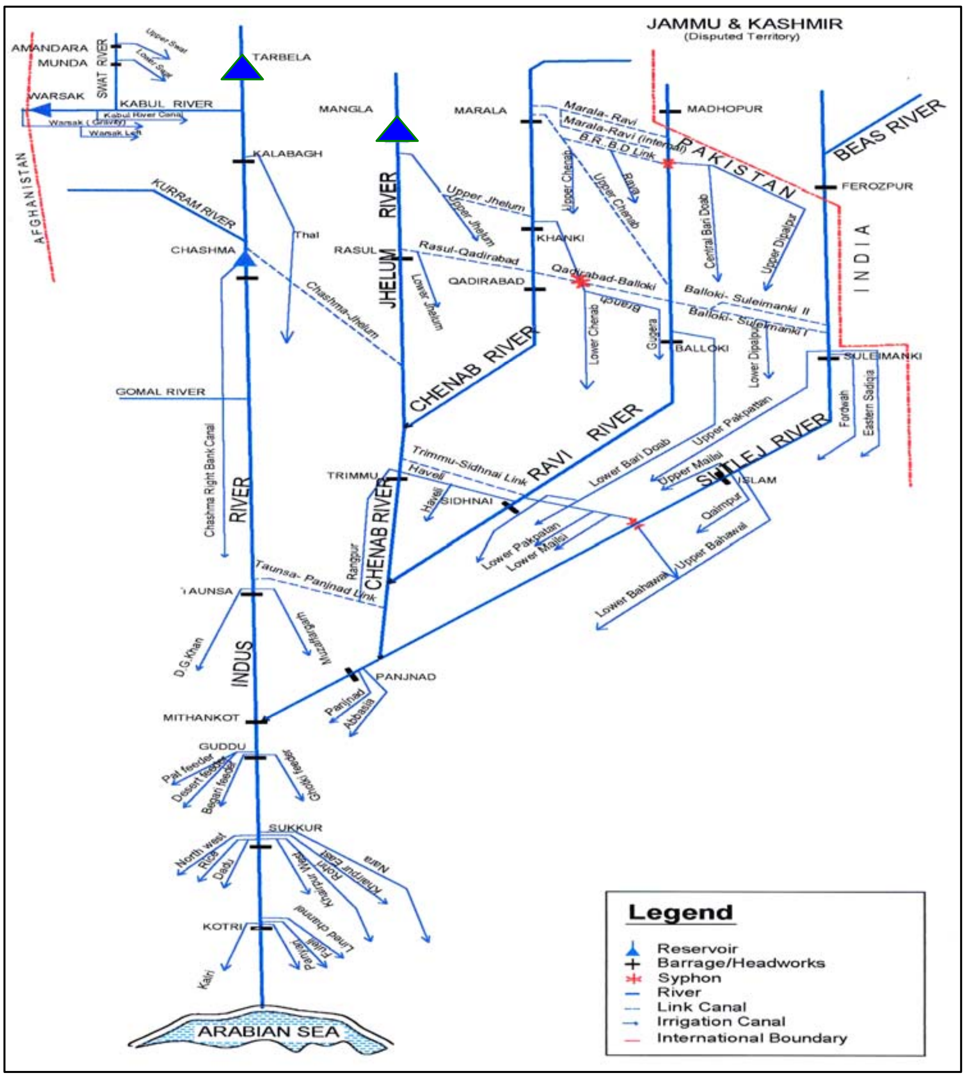

Figure 1: Schematic diagram of Indus Basin Network

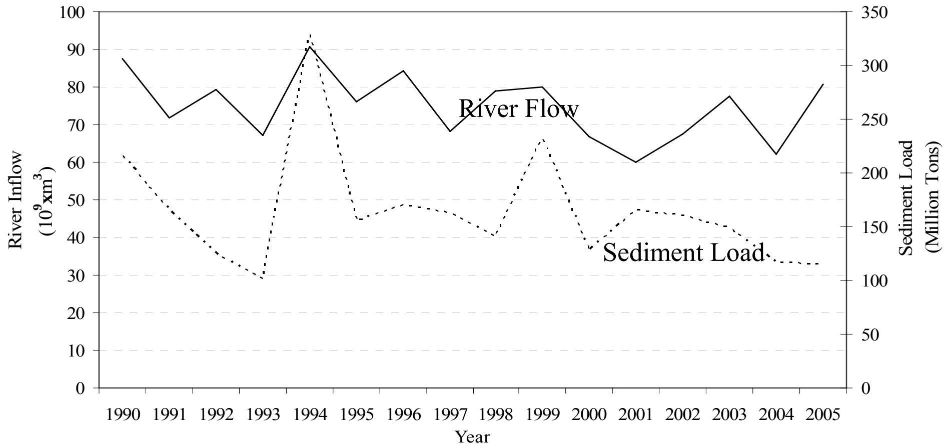

Figure 2: Annual sediment load computed from hydrograph survey

3- MATERIAL & METHODOLOGY

3.1 Landsat TM Image Processing

Two images were examined in this research study to quantify the suspended sediment load and its spatial and seasonal variation along the river. Among them, one Landsat TM images was acquired on 22nd June, 1994 and SPOT 2 image was acquired on 10th May, 2005 covering the Tarbela dam reservoir and gauging station. The images acquired in June 1994 correspond to high discharge period (June to September) and the images acquired in May correspond with the medium discharge period. The images were geometrically corrected. In order to estimate the SSC from the satellite images, Digital Counts (DC) are converted to at-satellite radiance and then radiance is converted to reflectance. The equation to convert satellite DCs to at-satellite radiance is:

$$L = (DC+A)\ S$$

where L is the at-satellite spectral radiance for the given spectral band ($Wm^{-2}\ sr^{-1}\ \mu m^{-1}$), DC is the digital count at a given pixel for a given spectral band, A is the offset for a given spectral band in the unit of DC, and S is the slope for a given spectral band in $Wm^{-2}\ sr^{-1}\ \mu m^{-1}/DC$ [11]. The offset and slope values were taken from header file. Atmospheric correction was applied to the at-satellite spectral radiance and then converted to surface reflectance. The suspended sediment concentration is very high ranging from 500mg/l in May to 2000mg/l in August. As suspended sediments in the river is high, and 0% reflectance or completely dark objects are not likely to exist. The improved dark-object subtraction technique [12][13] was adopted to remove atmospheric path radiance or haze DC value from the images. Also, correction for atmospheric transmission coefficient due to atmospheric absorption was carried out based on the COST model of Chavez (1996). The following equation was used to calculate reflectance from radiance data [11].

$$R = \frac{\pi(L_s - L_a)}{TAU_V\,(E_o Cos(TZ) TAU_Z + E_d)}$$

where *R is s*pectral reflectance of the water surface, L_a is atmospheric path radiance($Wm^{-2}\ sr^{-1}\ \mu m^{-1}$). TAU_v is atmospheric transmittance along the path from the ground surface to the sensor, TAU_z is atmospheric transmittance along the path from the sun to the ground surface, *TZ* is Solar zenith angle in degree. E_o is solar spectral irradiance on a surface perpendicular to the Sun ray's outside the atmosphere ($Wm^{-2}\ sr^{-1}\ \mu m^{-1}$). E_d is the downwelling spectral irradiance at the water surface due to scattered solar flux in the atmosphere($Wm^{-2}\ sr^{-1}\ \mu m^{-1}$).

3.2 SPOT 2 Image Processing

The SPOT image was acquired on 10 May, 2005 during that time in situ measurement of turbidity was taken along the river. The digital numbers (DNs) was converted the into radiance units by using the equation 1;

$$L = DN/A_k$$

where L (Wm^{-2} sr^{-1} μm^{-1}) is the top of atmosphere (TOA) upwelling radiance and A_k ($W^{-1}m^2$ sr µm) is the calibration factor for spectral band k. Lwas converted to TOA reflectance R using the following relationship [14]:

$$\frac{R(XSi) = \pi L(XSi)}{\mu_s E_s(XSi)}$$

Where i = 1, 2, or 3 for XS1, XS2, XS3; $\mu_s = \cos(\theta_s)$, θ_s is the solar zenith angle; Es(XSi) (Wm^{-2} µm) is the solar TOA irradiance. The TOA measurements were then corrected for atmospheric effects. R is related to the above water reflectance (R_w, unitless) by following the relationship:

$$R = T_g (R_{aer} + R_{ray} + T_d R_w)$$

where R_{aer} and R_{ray} are the aerosol and Rayleigh reflectances, respectively; T_g and T_d (unitless) are the gaseous and diffuse transmittances, respectively. The atmospherically corrected reflected was calculated by using the following equation;

$$R_{ac} = \frac{R_w}{1 + SR_w}$$

Where S (unitless) is the total spherical albedo. This atmospherically corrected reflectance, divided by π steradians, can be compared to the remote-sensing reflectance: 1/ π $R_{ac}(\lambda)R_{rs}(\lambda)$ [15].

3.3 Laboratory Experiments

Water and soil samples were collected from the study area. Soil samples were collected from the catchement area in order to investigate the relationship between Suspended sediment concentration and reflectance from the water surface. The experiments were conducted in a black painted room to measure the reflectance from water surface and water with varying concentration of collected soil samples. The samples were air dried and sieved to ensure a uniform sediment size. A hyperspectral Field SpecPro FR Spectroradiometer (Analytical Devices, Inc., Boulder, CO) was used to collect the upwelling radiance from the water surface. The depth of water column was 40 cm. Initial reflectance readings were taken for the water tank prior to the addition of any suspended sediments and sediments were added systematically to the water-filled tank to enable spectra to be collected for a range of SSC. To study the SSC and reflectance relationship, the mean of ten scans was used for analysis. Data from 400 to 900 nm was used because noise was pronounced at wavelength shorter that 400 nm and longer than 900 nm. Reflectance was calculated as a simple ratio between target and reference panel using following equation.

$$\% \; R(\lambda) = \frac{L(\lambda)}{S(\lambda)} \times Cal(\lambda)$$

Where L (λ) is the radiance measured from the water surface, S (λ) is the radiance from the reference panel measured under the same illumination conditions and Cal (λ) is the calibration factor for the reference panel.

4. RESULT AND DISCUSSION

The determination of the statistical variance in the spectral reflectance is a tool for measuring the information content in the spectra. The spectral reflectance of water with varying concentration of collected soil samples are shown in figure 3. With the increase in suspended sediment concentration the spectral reflectance increase and the peak reflectance shifts towards longer wavelength. The spectral reflectance of suspended sediment in surface water is a function of both the quantity and characteristics (particle size, texture, absorption) of sediments and is strongly affected by other optically active water components. The average reflectance value of selected soil sample with the SSC of 1000 mg/l was 6 %. The low reflectance value is caused by the black wall and bottom of the experimental tank. Most of light is absorbed by the black bottom causing the low reflectance. The hyper

The Landsat TM was acquired almost 12 years before and the atmospheric condition at the site was not known. In case of SPOT the sky was clear on the day of acquisition of image and the also there was no wind. We assumed that the factor affecting the images on two different times with long time span was not very much different. For the purpose of this study the TM band 3 (630 - 690 nm) and band 4 (760 - 900 nm) was selected as suspended sediment concentration is strongly correlated with red and NIR domain. The average reflectance value of TM band 3 was 21% and SPOT X3 was 14 %. The concentration was found to be low in case of SPOT image because of dry season. However the month of June is considered to be rainy with many flash floods. This scenario closely matches with the seasonal pattern of SSC in the river. The in situ suspended sediment measurements are shown in table 3.

Table 3 : In Situ Suspended Sediment Concentration Measurements

Date	Discharge (m^3/s)	SSC (mg/l)	% Average		
			Sand	Silt	Clay
22nd June, 1994	7690.7	1700	20	57	23
10th May, 2005	3015	473	10.1	76.1	13.8

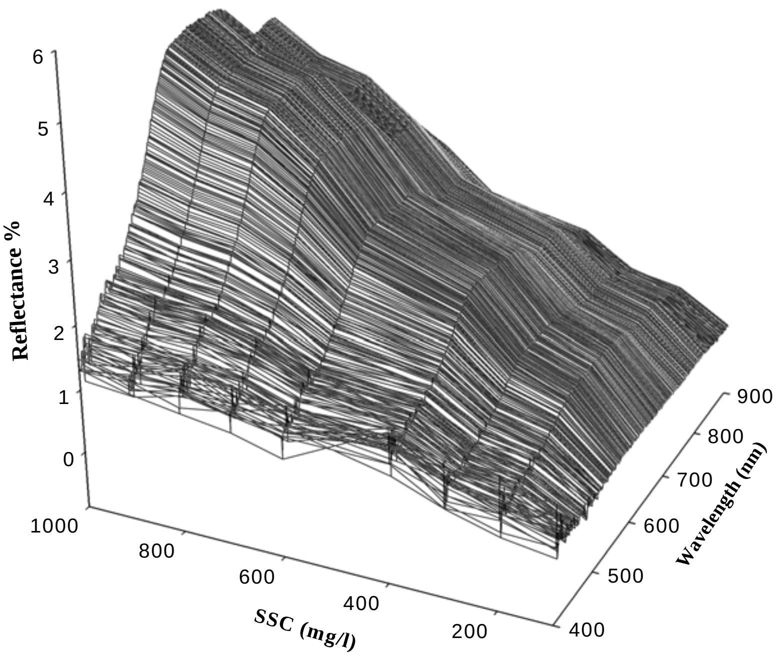

Figure 3. Spectral Reflectance of Water With Varying Concentration of Collected Soil Sample

The simulated TM bands, individually and in combination, was used with regression techniques to examine the relationship between reflectance and SSC to provide solution for the field application of remotely sensed data for assessment of suspended sediments. The correlation coefficients (R^2) were computed between SSC and simulated TM band (Table 4).

Table 4: Correlation between simulated TM bands and SSC

TM Bands	R^2
1	0.93
2	0.98
3	0.99
4	0.99

The NIR region (Band 4) seems to be more useful than the visible region for measuring the SSC in water. The reflectance of band 4 can be used to develop a linear regression model of the following form for estimation of SSC.

$$SSC\ (mg/l) = (R\ (Band\ 4) + 0.0412)/\ 0.004$$

The spectral reflectance, in the NIR domain (Band 4), as a function of varying SSC in water is shown in figure 4.

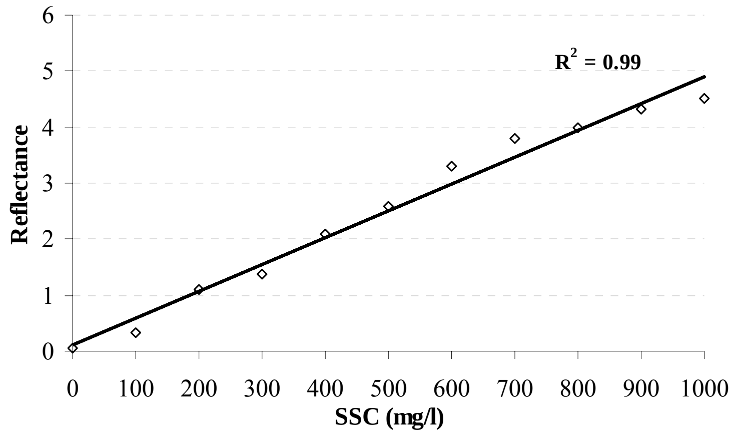

Figure 4. Correlation between simulated TM bands and SSC

Reflectance was estimated from the pixel of different location alone the river. The SSC is higher in the upstream of the river and lower in the reservoir on the Tarbela dam because the velocity of the river inflow containing sediments decreases upon entering Tarbela reservoir, which reduces the sediment carrying capacity of the river water. The coarse sediment tends to deposit in the upper reaches of the reservoir, while the finer particles travel downstream towards the dam and settle in the reservoir. The reason for success of remote sensing in such surveys is the strong positive relationship that exists between SSC and remotely sensed spectral reflectance. It is also easy to update remote sensing data, which allows continuous monitoring. Many authors have developed the empirical relationship to estimate the SSC. However no standard algorithm was developed to estimate the SSC from the reflectance.

5- CONCLUSION

Seasonal and spatial variations of reflectance for TM band 3 and 4 and SPOT image were observed along the courses of the Indus River and compared with on-site SSC measurements. In the high discharge period (June) reflectance values are higher than during the medium discharge period (May). It is concluded that in the red and near infra red band's reflectance increase with the increase in SSC. For the same concentration, the experimental reflectance value was found to be less than the estimated reflectance of TM band 3. The rational is because the experimental tank was black panted and it absorbs most the incident light. Also, the water quality parameter targeted here, namely suspended sediments are strongly influenced by the environmental factors. Comparisons of satellite-derived sediment concentration indicated several areas of similar relative concentrations. The study has shown that it is possible to use hyperspectral and multispectral data to estimate the suspended sediments in the surface water of rivers and reservoirs. The water and environmental engineers could concentrate on the water bodies and their watersheds with the most significant suspended sediment problems. In the future, it will be important to incorporate sediment assessment as an integral part of water resources and environmental planning, development and management. Without this approach the problems of the water & environmental sector are going to compound in the future.

Acknowledgement

The authors wish to acknowledge the cooperation and financial assistance provided by Kochi University of Technology (KUT), Japan.

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