REMOTE SENSING OF SUSPENDED SEDIMENTS IN SURFACE WATERS, USING MODIS IMAGES.

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ABSTRACT:

Collecting information about (**S**uspended **S**ediment **C**oncentration) **SSC**, in coastal Waters and estuaries is vital for proper management of coastal environments. Traditionally, SSC used to be measured by time consuming and costly point measurements. This Method allows you to accurately measure SSC only for a point in space and time. Remote sensing from air-borne and space-borne sensors have proved to be a useful method to such studies as it provides an instantaneous and synoptic view of sediments that would otherwise be unavailable. The reason for success of remote sensing in such surveys is the strong positive relationship that exists between SSC and remotely sensed spectral radiance L_λ . This Spectral radiance could be in the sun reflected and/or scattered or thermal terrestrial wavelength bands.

Many workers have shown that the relationship between SSC and L_λ strongly depends on the intervening atmospheric constituents as well as the suspended material and depth.

To find an algorithm relating SSC to L_λ over Bahmansheer River Estuary at the North-West of Persian Gulf, a three-month field measurement (April to June 2003) were conducted while we had MODIS sensor on board of Orbview-3 over-passed the scene simultaneously. Ninety samples in fifteen trips were collected. Also the environmental parameters such as atmospheric visibility, air and water temperature, current direction and speed of water at the sampling point, wind speed and humidity were measured simultaneously.

The collected samples were analyzed thoroughly by measuring density, diameters of the sediment particles and determining the sediment constituents. Total density were ranging between 30 to 500 (mg/lit), the range of particle diameter were from less than a micrometer to more than 20 micrometers and finally it was found that the sediment were composed of Quartz, Kaolinite, Orthoclase, Chlorite, Calcite, Gypsum, Muscovite, Halite, Anhydrite, Apatite, Biotite, and low amount of Albite. It is found that the spectral characteristics of these compositions are partly responsible for the reflected and/or scattered energy in different bands while the correlation between larger suspended particle density and L_λ were profound. Also the effects of environmental parameters on the results were discussed. It is believed that the atmospheric aerosols are the main reason for the poorness of the correlation coefficients.

1- Introduction

Since the late 1970's remote sensing studies of suspended sediments have been made using the fact that suspended sediments increase the radiance emergent from surface waters in the visible and near infrared region of the electromagnetic spectrum (Ritchie and Schiebe 2000). Most researches that had a large range (i.e., 0-200+ mg/l) of suspended sediment concentration has found a curvilinear relationship between suspended sediments and radiance or reflectance (Ritchie et al. 1976, 1990; Curran and Novo 1988) because the amount of reflected radiance tends to saturate as suspended sediment concentrations increase. The point of saturation is wavelength dependent, with the shorter wavelength saturating at lower concentrations.

If the range of suspended sediments is between 0 and 50 mg/l, reflectance from almost any wavelength will be significantly related to suspended sediment concentrations (Ritchie and Schiebe 2000). As the range of suspended sediments increases to 200 mg/l or higher, curvilinear relationships have to be developed with reflectance in the longer wavelength. Significant relationships have been shown between suspended sediments and radiance or reflectance from spectral wave bands or combinations of wave bands on satellite sensors. Ritchie et al. (1976) using in situ studies concluded that wavelengths between 700 and 800 nm were most useful for determining suspended sediments in surface waters. Many studies have developed algorithms for the relationship between the concentration of suspended sediments and radiance or reflectance (Mobasheri, 2003). A few studies have taken the next step and used these algorithms to estimate suspended sediments for another time or place (Ritchie and Cooper 1988).

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 (Doxaran et al., 2003).

. The six MODIS channels centered at 0.55, 0.66, 0.86, 1.24, 1.64, and 2.1 m are being used for aerosol retrieving algorithm and deriving aerosol models and aerosol optical depths. Water leaving reflectance is assumed to be zero in the 0.86-, 1.24-, 1.64-, and 2.13- m channels (Rong-Rong et al., 2003). The reflectance at channel 1 and 4 was assumed to be the typical clear water reflectance. Any unaccounted elevated values of the water leaving reflectance were interpreted as an increase in the optical thickness of the fine aerosol particles. Sediments and shallow waters provided such unaccounted high reflectance and resulted in systematic overestimate of the aerosol optical thickness. It is believed that the main differences between the two types of waters are located in the 0.4–0.7 m spectral range (Rong-Rong et al., 2003) 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. The penetration depths at the level of 90% light attenuation is as high as 40meters for channel 3 and as low as less than a millimeter for channel 7 (Mobasheri, 1995). Thus, the turbidity in water can affect reflectance in visible channels and even at 0.86 μ.

However, for the longer wavelengths (1.2, 1.6, and 2.1 μ) the penetration depths of sunlight into the water are very small, eliminating the possibility of the reflection by sediments. On the other hand, the blue channel (0.47 μ) is very sensitive to atmospheric molecular scattering, but less sensitive to the additional reflection by sediments. For coastal waters, this channel is not nearly as sensitive as the 0.55μ channel to sediment reflection because of strong absorption by dissolved organic matters (yellow substances) at 0.47μ. In summary, the MODIS measurements over the ocean at 0.47, 1.2, 1.6, and 2.1 μ are influenced mainly by aerosol scattering and absorption and can be used to derive the atmospheric spectral power law (Rong-Rong, et al., 2003). Measurements at 0.55–0.86 μ are influenced both by the aerosol and the sediments. The excess reflectance at 0.55–0.86 μ beyond the power law values can be associated to the presence of sediments and consequently is used for their detection in this work.

2- Methodology and Data Collection

Bahmansheer River is situated at the southwest of Iran and is 80 km long parallel to Arvand River, which is the border of Iran and Iraq (fig 1). This river carries large amount of sediments to the Persian Gulf (varies with tide). The tidal current influences the water level even at the junction of this river with the Arvand River some 80 km far from its estuary.

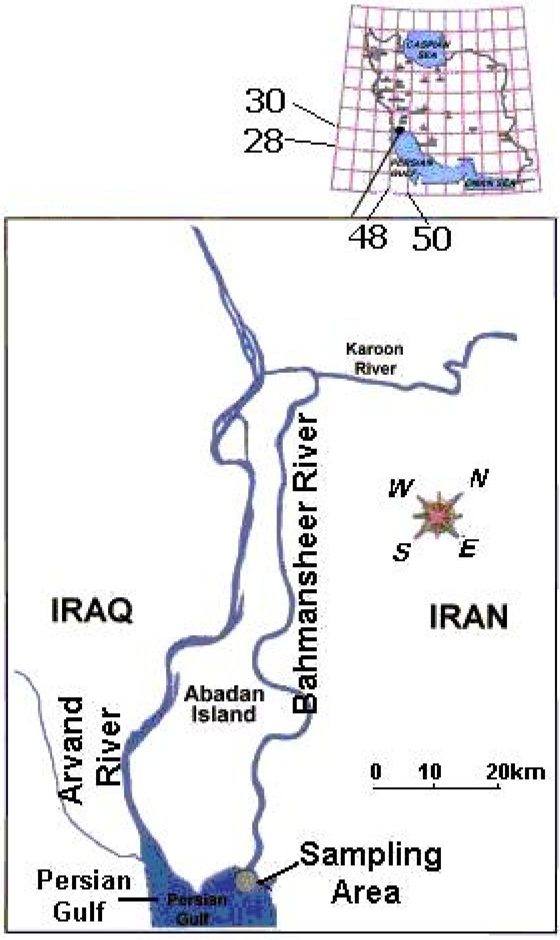

Fig.1 Map of sampling area, northwest of Persian Gulf.

This usually keeps the water at the estuary, turbid for the most of the time. This turbidity may extend up to few kilometers far from the estuary out in to the deeper region, where heavier particles reside to the substrate and will not return to the estuary even with the tidal currents.

We have collected our samples at the vicinity of the estuary (Fig.1), while MODIS sensor onboard of Terra was passing over the region. Each sample was a minimum distance of 500 meters apart. Along with the sample collection, latitude and longitude of the sample were determined (using a GPS set). Also parameters like current speed and direction profile (for determination of tidal state), water temperature, wind speed and direction (in the nearest meteorological station) and visibility were collected. These data were used for quality assessment of the images. Then the collected samples were taken to the laboratory for measurement of density, particle size distribution and composition analysis. The density of the collected samples were as low as 30 and as high as 500 mg/lit. Between 1 to 15% of the particles had diameters of less than 1 μ, consequently Rayliegh scattering is not responsible for the reflection and scattering. On

Table 2- Sediment constituents, with chemical name and formula
(Courtesy, Amethyst Gallery URL *http://mineral.galleries.com*)

Name	Formula	Presence in Nature and/or Industry	Interaction with light
Albite	NaAlSi3 O8	Ornamental stone, ceramics and mineral specimens	Translucent to Transparent
Anhydrite	CaSO4	In the manufacture of some cement	Transparent to Translucent
Apatite	Ca5(PO4)3(OH,F,Cl)	As a source of phosphorous to be used in fertilizer	Transparent to Translucent
Biotite	K (FE, Mg)3 AlSi3 O10 (F, OH)2	Heat insulator for industrial purposes	Transparent to Translucent
Calcite	CaCO3	In cements and mortars, production of lime and some other industries	Transparent to Translucent
Chlorite	(Fe, Mg, Al)6(Si, Al)4O10(OH)8	As a mineral specimen and some industrial uses	Transparent to Translucent
Gypsum	CaSO4-2(H2O)	some cements, fertilizer, paint filler, ornamental stone	Transparent to Translucent
Halite	NaCl	Major source of salt and as mineral specimens	Transparent to Translucent
Kaolinite	$Al_2Si_2O_5(OH)_4$	In the production of ceramics and some other industry uses	Translucent
Muscovite	KAl2(AlSi3O10)(F, OH)2	Heat and electrical insulator for industrial purposes	Transparent to Translucent
Orthoclase	KAlSi3O8	Mineral specimens and in the porcelain industry	Opaque to Translucent
Quartz	SiO2	Silica for glass, electrical components	Transparent for visible

the other hand diameter of more than 45% of the particles was between 0.1 and 9 micrometer. These particles may undergo Mie scattering in the channels 1, 2, 3 and 4 of MODIS. The rest of particles may have Nonselective scattering. As a result, assumption of a Lambertian reflection for those samples, with low wind speed conditions and high SSC is reasonable. Of course, those cases where the light is specularly reflected to the sensor is excluded.
It is found that at low tide situation (flood), the particle size distribution is more toward higher values and as a result an increase of reflections in channels 1, 2 and 4 were detected.

Table (2) shows compositions content detected in sediment samples. As it shows almost all sediment constituents are translucent to the visible and near infrared portion of the sun spectrum. Most of these compositions may be found in building materials and/or minerals.

3- Results and Discussions

Fig. (3) shows spectral reflectance of the sediment constituent compositions, where the center bands of the first 7 MODIS channels are also shown. For three channels 1, 2 and 4 that their sensitivities to the sediments are presumed, eight of compositions have reflectance more than 0.80. This reflectance had more influence on the aforementioned channel's output when the surface sample density was higher. Reflectance in channel 3 that is centered at 0.47μ, and is strongly scattered by the atmosphere constituents, was weakly affected by these compositions and cannot be suitable for SSC detection. In channels 5, 6 and 7, composition's reflectance decreases gradually but is not ignorable when the surface sample density is high. This brought some difficulties in the deployment of Rong-Rong, et al., (2003) method especially for channels 5 and 6. Channel 7 due to strong absorption by water and sediment particles (Fig. 3), was much less affected by the sediment. This means that four channels 3, 5, 6 and 7 did not make straight line in all cases as presumed by Rong-Rong Li, et al., 2003. The linear fit to these channels reflectance had correlation coefficients ranging as low as 0.15 for higher densities and as high as 0.999 for lower density values. This may

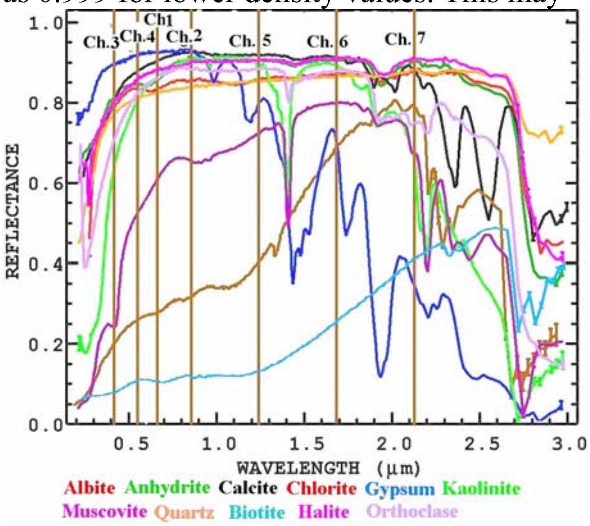

Fig. (3) Reflectance curves of the sediment's constituents (Courtesy of USGS)

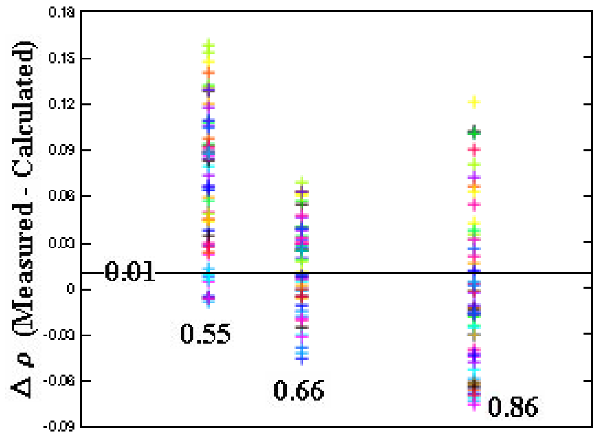

Fig. (4) Reflectance difference between calculated by the Rong-Rong Li, et al., 2003 method and measured by the MODIS channels 1, 2 and 4.

enables one in estimation of higher surface SSC values by using channels 5 and 6 reflectance.

The difference of the calculated reflectance by the Rong-Rong Li, et al., 2003 method and the one extracted from MODIS data (Δρ) in channels 1, 2 and 4, for all samples were shown in Fig. (4). Negative values are for higher densities. Channel 4 (centered at 0.55μ) has lesser negative values, which means it has better correlation with densities of different values. Channel 1 (0.66 μ) has more negative values that means it has less deviated from the straight line produced by channels 3, 5, 6 and 7 for higher density values and consequently is less correlated with them. Channel2 (0.86μ) has the worst correlations with the higher values of densities as it has highest negative values of $\Delta\rho$.

Fig. (5) shows measured densities versus channel 1 reflectance, where red points are below the threshold ($\Delta\rho$=0.01) suggested by Rong-Rong Li, et al., 2003.

A linear fit is run with the accepted data and a poor value of correlation coefficient of 0.59 was found. The fitted line has the equation of the form

Density (mg/lit) = a (ρ_{ch1})+b **(1)**

where **a** is equal to 4160, **b** is 106 and ρ_{ch1} is reflectance in channel 1.

Fig. (6) shows the same story but for channel 4 reflectance. As expected, a better correlation of 0.77 between density and reflectance in this channel was found. The algorithm for channel 4 data is of the form

Density (mg/lit) = c (ρ_{ch4})+d **(2)**

with **c** = 2396 and **d** = 33.9.

The minimum density that can be detected by algorithm 1 is about 150 mg/lit, while this value for channel 4 (algorithm 2) is 57 mg/lit. This makes algorithm 2 suitable for detection of coastal turbid waters as well as turbid estuaries, while using relatively low spatial resolution sensors such as MODIS channel 4(500m).

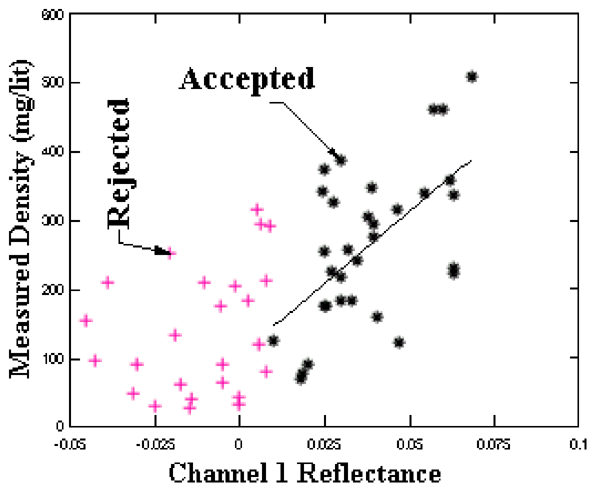

Fig. (5) Measured density versus reflectance in channel 1 of MODIS sensor.

Larger sediment particles concentration did not show a well-defined correlation with the total sediment density due to its dependence on the tidal state.

At the flood situation, more than 95% of the sediment particles had diameters more than 1 micrometer, where in the ebb, less than 75% of particles had diameter of 1µ and more. This shows that the heavier particles have resided in the ebb situation. The correlation between channel 4 reflectance and density of sediment particles with diameter more than 1 µ was about 0.81 that shows some improvements.

The effects of environmental parameters on the results were investigated. It was found

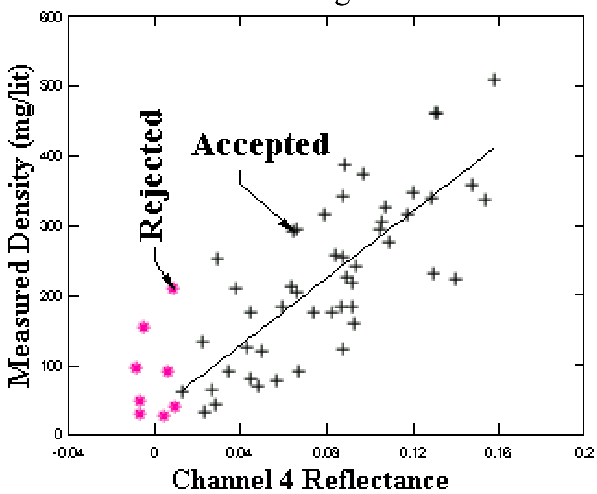

Fig. (6) Measured density versus reflectance in channel 4 of MODIS sensor.

that the visibility had strong influence on the correlation coefficients values of the line fit between channels 3, 5, 6 and 7, where higher visibility values coincide with higher correlation and better prediction of density values using channel 4 reflectance. It is believed that the atmospheric aerosols are the main reason for the poorness of the results, while the effect of poor spatial resolution is not of lesser importance i. e. each sample represents an area of minimum 25 acres. So this sample may hardly represent the turbidity of that vast area unless we have strong mixing of the water in that region. This could be the case at the flood or ebb conditions at the vicinity of estuaries.

Due to low wind speed, uniformity of temperature and humidity during expeditions, no serious effects of these parameters on the results were detected.

4- Conclusion

A line fit through channels 3, 5, 6 and 7 of MODIS and calculation of channel 4 reflectance from this line suggested by Rong-Rong et al., (2003) is approved. The difference between this value and the one extracted from MODIS channel 4 is found to be in a good correlation with the total density especially in high visibility situations. Algorithm (2) is highly recommended for turbid estuaries and coastal waters. Atmospheric aerosols and low spatial resolutions are the main reasons for the poorness of the results. Sediment constituents should be determined once for each region. This has an important role in the determination of suitable channel/channels in each region for SSC estimation.

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