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Spectral Characteristics of Shallow Turbid Water near the Shoreline on Inter-tidal Flat

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Abstract : Extraction of waterline in tidal flat has been one of the main concerns in the remote sensing of coastal region. This study aimed to define the spectral characteristics of turbid water near the shoreline and to find the appropriate spectrum to delineate the waterline at the inter-tidal flat in the western coast of Korean Peninsula. Spectral reflectance curves were obtained by the field measurements under the diverse condition of water depth and turbidity at the study area in Kyong-gi Bay. Spectroscopy measurements showed that reflectances of the exposed mudflat, shallow turbid water, and normal coastal water were significantly different by wavelength. Shallow water near the waterline showed diverse conditions of turbidity. Spectral reflectance tends to increase as turbidity increases, particularly at the visible and near infrared spectrum. At the middle infrared wavelength, tidal water showed very little reflectance regardless of the turbidity and water depth and was easily distinguished from the exposed tidal flat. The exact waterline between exposed tidal flat and seawater should be extracted from the image data obtained at the middle infrared wavelength.

Key Words : spectral reflectance, spectro-radiometer, inter-tidal flat, turbidity, coastal remote sensing

1. Introduction

The western coast of Korean Peninsula has one of the largest and well-developed tidal flats in the world. Inter-tidal flat is a shoreline landform resulting from the deposition process of suspended sediments by tidal action. Inter-tidal flats in this region have been valuable sources of very productive shellfish industry and the habitat for thousands of adopted species. Although the geomorphology of inter-tidal flat changes constantly due to tidal actions, the rate of change has been accelerated by human activities such as reclamation, embankment, coastal developments, and inland watershed managements. Continuous monitoring of the coastal line is very important for the conservation of such susceptible ecosystems, as well as the management practices in fishery industry and coastal development planning.

Due to the large area and the difficulty in accessing it, field surveying of the inter-tidal zone is very difficult and time consuming. Satellite remote sensing has been an attractive alternative for mapping and monitoring the environmental and morphological status of the coastal area (Welch *et al.*, 1992). Multi-temporal satellite images

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have been utilized to analyze the morphologic changes in coastal areas and wetlands where the seasonal variations were significant (Frihy *et al.*, 1994; Lunetta and Balogh, 1999). Construction of three dimensional terrain surfaces in shore areas has been the main interest of several studies related to the coastal change detection (Wang and Koopmans, 1996). There have been a few attempts to construct the digital elevation model (DEM) data of the shoreline areas using various types of multi-temporal satellite images (Ahn *et al.*, 1989; Chen and Rau, 1998; Ryu *et al.*, 2000). In these studies, several lines of land-water boundary were delineated from multi-temporal satellite images collected at different sea levels and were used as contour lines to construct three-dimensional surfaces of the inter-tidal zone. However, it is not very simple to delineate the exact boundary between the land and water body over the tidal flat in particularly at the tidal mudflat zone.

The objectives of this study are to analyze the spectral characteristics of the tidal flat area, in particular near the waterline, and to define the suitable wavelength spectrum to delineate the waterline between seawater and tidal flat. Initially we focus on our analysis to characterize the spectral reflectance of the tidal flat by field measurements using spectro-radiometer. Based on the results obtained from the field spectroscopy, Landsat Thematic Mapper (TM) multispectral data were examined to determine the waterline on the tidal flat area.

2. Methods

1) Study area

Field measurements of spectral reflectance as well as the collection of field samples were conducted at several tidal-flats in Kyong-gi Bay. The Seoul and Incheon metropolitan areas, having a population of approximately twenty million, are attached to Kyong-gi Bay and have a continual impact on the biophysical and chemical conditions of the tidal mudflats. During the last decades, a large area of the tidal flat has been converted to industrial, transportation, agricultural, and residential uses. Land reclamations, sedimentation discharges, and the high dynamics of tidal currents would be major forces to bring about the geomorphologic changes in the tidal mudflat zone. This area is also famous for the large range in tidal heights, which closes up to 9 meters. Due to the high variation of tidal elevation over the large area of tidal flat, it is often difficult to define the exact waterline from the satellite imagery.

To delineate the waterline between seawater and exposed mudflat, it has been common to use a single band image of visible or near infrared band. However, from the visual interpretation of the color composite of multispectral satellite data as well as a single band display, we found that the waterlines were quite different according to spectral bands. Fig. 1 shows the exposed inter-tidal mudflats on three spectral bands of TM data captured at low tide on June 20, 1999. The waterlines shown among the three bands of visible, near infrared, and middle infrared images did not correspond with each other. The waterline seen in the band 5 image seems to be clear and positions differently as compared to the band 3 and 4 images. Field measurements were carried out to determine the spectral characteristics along the waterline between the exposed tidal flat and shallow tidal water.

TM band 3 (red)

TM band 4 (near IR)

TM band 5 (middle IR)

Fig. 1. Different shape and boundary of the inter-tidal flat in southern part of Yongjong Island. The TM images were captured at low tide on October 22, 1991.

2) Measurements of Spectral Reflectance and Turbidity

Shallow tidewater flowing over the tidal flat becomes very turbid as they mix with the thick layers of clay, silt and sand particles. The turbidity decreases as the water depth of water increases. Tidal water becomes clear when it reaches beyond a certain depth. To define the relationship between the turbidity and the water depth, water samples were collected at the tidal-flat in Yongjong Island. A small boat was launched twice at the time of both ebb and flood tides from the nearest wharf and traveled to the study site. Water sample was collected at several depths ranging from one meter up to three meters. It appeared that the color and turbidity did not changed at the points where the water depth was deeper than three meters. Since the boat could not approach to shallow water, water samples near the waterline where the water depth is less than one meter were collected directly on the field. At each water depth from 10cm to about 4meters, two or three samples were collected. The turbidity was measured by using a DRT-15CE portable turbidimeter in which the turbidity measure was the nephelometric turbidity units (expressed as NTU). The NTU tends to have a direct linear relationship with the concentration of suspended solids.

It was rare to find the field measured spectral reflectance on inter-tidal mudflats. Spectral measurements were initially conducted at the inter-tidal flat in the study area. A portable field spectroradiometer used for this study can measure the percent reflectance at 640 continuous wavelength bands ranging from 350nm to 2,500nm and use a barium sulfate ($BaSO4$) coated plate as a reference. The field measurements were made at several places in the study area on relatively sunny days from September 2000 to May 2001. Spectral measurements were made at one meter above the target, which gave us about a 10cm field of view (FOV). Once the first measurement was made on the surface of the completely exposed mudflat, the subsequent measurements were collected from the same surface that was gradually covered by tidewater.

After the field measurements were made at the tidal flats, soil samples were taken to the laboratory to simulate the waterline condition of the tidal flat. The tidal flat in the study area, as well as the other tidal flat in western coast of Korean peninsula, are mainly mud and mud-sand flat that is consisted of thick layer of mud, clay, and sand. The spectral reflectance of soil samples was measured as they correspond to the condition of exposed tidal flat. Soil samples were then used to formulate the turbid water by mixing with clear water. Varying the concentration of suspended soil particles made several water samples with different turbidity. Turbidity level ranged from 25 NTU to 600 NTU, which were similar to the ones that found at the shallow tidewater along the waterline in the tidal flat.

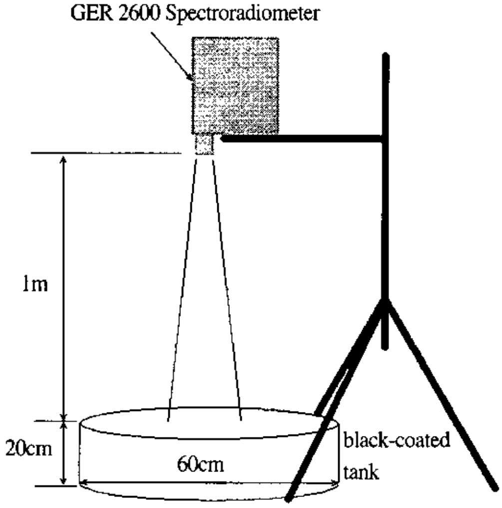

Fig. 2. Laboratory setup for measuring spectral reflectance of varying turbidity (spectral reflectance was measured under the sun illumination at the outside).

Second set of spectral measurements of turbid water was made using a simple setup over the small water tank (Fig. 2). The inside of the water tank (60cm in diameter and 20cm in high) was black coated to avoid any influence from the side and bottom reflectance. Spectral measurements were made under the bright sun illumination at the outside. At the time of measurement, sun elevation angle was close to 80 degree and the spectroradiometer was placed one meter above the water surface.

3. Results and Discussions

1) Relationship between Turbidity and Water Depth

Shallow tidewater moving in and out near the waterline looks very turbid. Assuming that the spectral reflectance of tidewater is heavily influenced by the turbidity, it would be useful to define the relationship between the turbidity and water depth. Fig. 3 shows the relationship between the turbidity and the water depth obtained from the samples collected at the tidal mudflat and the sand beach. Turbidities were not much different by the water depth at the sand beach although it was rare to find relatively large area of sand beach in the study area. In fact, the transparency of tidewater looked almost the same regardless of the water depth over the sand flat. However, it showed quite different pattern over the mudflat site, in which the turbidity was inversely proportional to the water depth. Concentration of suspended sediments decreases

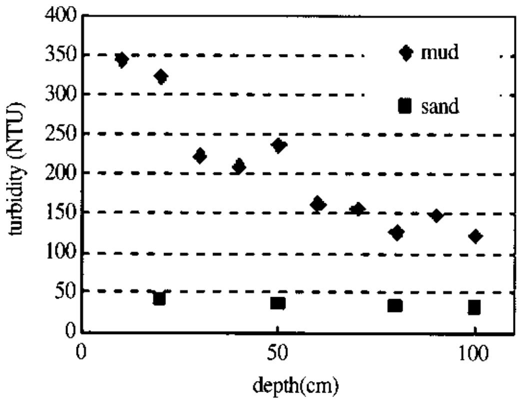

Fig. 3. Relationship between turbidity and water depth found from the tidal mudflat and sand beach.

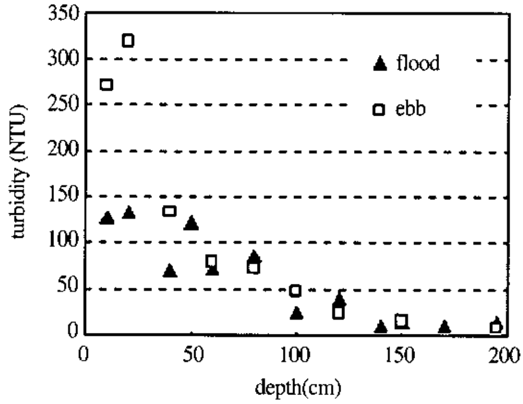

Fig. 4. Relationship between turbidity and water depth found over the mudflat during both flood and ebb tides.

as the water depth increases. Shallow water has higher concentration of suspended sediments than deep water. Although the amount of soil particles activated from the surface of tidal flat is about the same, the volume of water to restrain the sediments is quite different by the water depth. Therefore, the shallow water has higher turbidity than rather deep tidewater.

Ebb tide has more interactions with the surface of mudflat than flood tide since it brings the suspended solids that have been activated from the upper portion of the mudflat. Fig. 4 shows the relationship between the turbidity and depth on both ebb and flood tides. As expected, the ebb tide showed higher turbidity over flood tide at shallow water. Once the tidewater was deeper than about 50cm, turbidity was not different each other. Again, Fig. 4 shows the inverse relationship between turbidity and water depth. Although we collected water samples from the sites where the water was deeper than 2 meters, the turbidity did not change very much from the one at the 2 meters. It looked very clear for the water having the turbidity level of 50 NTU or less. When tidewater had a certain depth above the mudflat, the water color and turbidity appeared the same as the normal coastal water. The marginal water depth, in which the upper level of tidewater does not mix with the solids of the mudflat surface, might be between 50 to 150 centimeters depending on the solid materials composing the tidal flat.

2) Spectral Characteristics near the Waterline

The turbidity has been a major concern to the remote sensing of water quality. It has been known that turbid water has higher spectral reflectance over clear water. Fig. 5 shows the spectral reflectance curves measured directly on the tidal flats. Due to the high level of noise, reflectance data collected at the strong atmospheric water absorption bands (near 1,400nm and beyond 1,900nm) were omitted. The exposed tidal flat showed the highest spectral reflectance as compared to other measurements of shallow waters. Spectral reflectance of shallow seawater is influenced by complex interactions of several parameters including water depth, substrate reflectance, and suspended sediments and dissolved substances.

In this study, the spectral reflectance of water

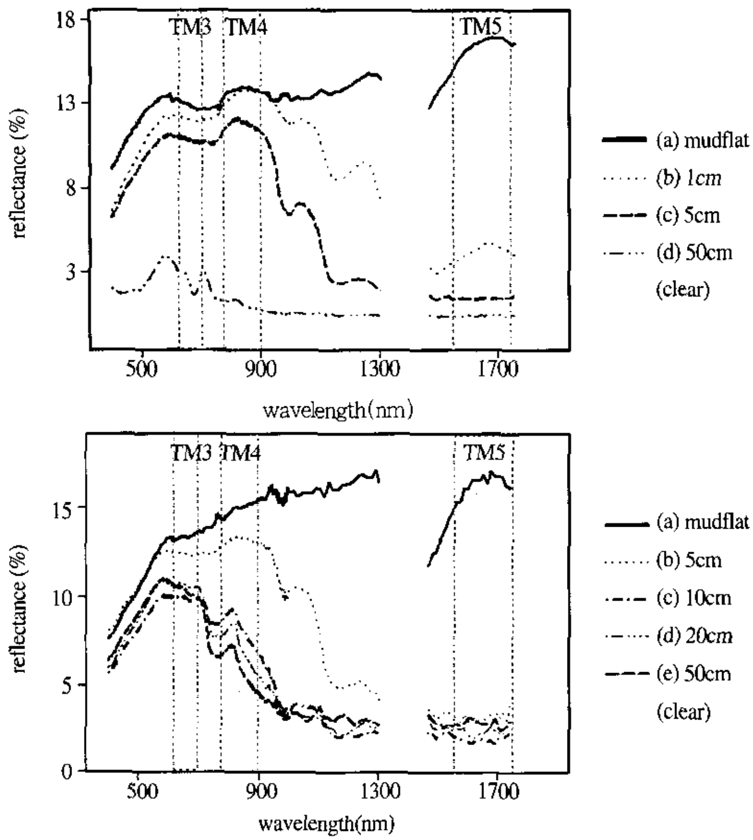

Fig. 5. Field measurements of spectral reflectance, which were made at the two sites of inter-tidal mudflat. One site showed relatively clear water beyond 50cm in depth (a) and the second site showed turbid water at 50cm in depth (b). Vertical dot lines indicate the spectrum of three spectral band 3, 4, and 5 of Landsat TM data.

body above the mudflats varied according to the turbidity and water depth. In general, the spectral reflectance of the tidewater decreases as the water depth increases. The reflectance values of the exposed mudflat and the tidewater of less than 5cm depth are very similar at visible and near infrared wavelengths. However, the reflectance of relatively clear water of 50cm depth showed very low reflectance in all wavelengths (Fig. 5-a). At the second measurement site, the turbid waters of 10cm, 20cm, and 50cm depth did not show such low reflectance as the clear water case (Fig. 5-b). They showed somewhat lower reflectance than the exposed tidal flat while the 5cm-depth water showed similar reflectance to the exposed tidal flat at the wavelengths shorter than 1,000nm. Regardless of the water depth, the spectral reflectance of shallow tidewater showed a sudden decline at near infrared wavelength longer than about 1,000nm and was very low at the middle infrared wavelength.

Fig. 6 shows the spectral reflectance curves measured under the laboratory condition, which turned out to be similar to the field measurements. Spectral reflectance of the exposed mudflat was almost the same as the highly turbid water covering the mudflat with 2cm in depth at the wavelength below the 1,000nm. While the

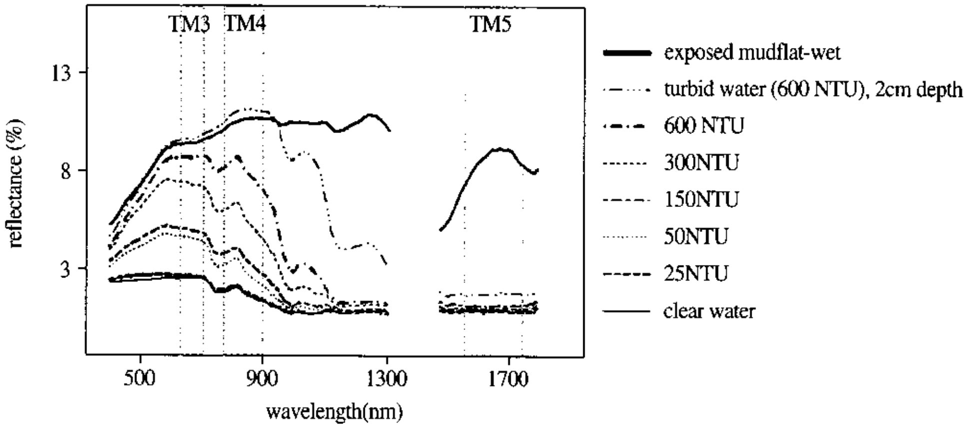

Fig. 6. Laboratory measurements of spectral reflectance, which were made under the sun illumination on the samples of simulated tidal flat surface and turbid waters. Except for the first two measurements on the exposed mudflat and the shallow turbid water covering the mudflat in 2cm depth, all other samples were measured on the black-coated water tank by changing the turbidity.

reflectance of exposed mudflat remained relatively high at the wavelength longer than 1,000nm, the highly turbid water showed sudden decline and almost no reflectance at the middle infrared spectrum. The other measurements were made on the water samples of 20cm in depth within the black-coated water tank by varying the turbidity. Spectral reflectance was proportional to the concentration of suspended solids. As several previous studies have reported, the visible and near infrared wavelengths are highly correlated with the turbidity (Bhargava and Mariam, 1990; Liedtke *et al.*, 1995). In this graph, it appears that the reflectance of different turbidity is better depicted at the near infrared wavelength. At the middle infrared wavelength, all water samples had very low reflectance no matter how deep or how turbid they are.

It has been well recognized that clear water has very little reflectance beyond the wavelength of 700nm. Using the spectral characteristics of water, infrared images have been widely used in the survey of water bodies. This could be the reason why several studies have used the near infrared band for delineating the shorelines from satellite imagery. However, the spectral measurements in this study showed that the actual boundary between the tidal flat and seawater was well distinguishable at the middle infrared spectrum rather than at the near infrared spectrum.

Using the spectral characteristics obtained by the field measurements, we can explain why the waterlines appearing in the three images of TM data in Fig. 1 are so different. Note that the spectral range marked by vertical dot lines in Fig. 5 and 6 indicates the spectrum of the three bands of Landsat TM data. In TM band 3 and 4 images, the boundary between seawater and tidal flat was not quite clear while the band 5 image showed clear distinction. As can be seen in Fig. 5 and 6, the shallow tidewater near the waterline has relatively high concentration of suspended solids and, therefore, higher reflectance than normal coastal water. Since the reflectance at the red and near infrared wavelength is directly proportional to the turbidity that is also correlated with the water depth at the inter-tidal flat, TM band 3 and 4 images show the gradual change in tonal value

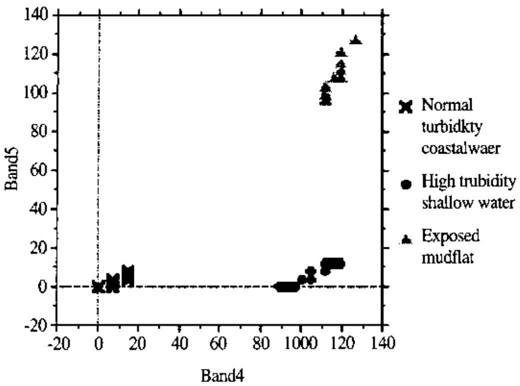

Fig. 7. TM band 4 and band 5 pixel's DN values of the exposed mudflat, normal coastal water, and shallow tidewater near the boundary.

between the exposed tidal flat and seawater. The boundary between the mudflat and seawater appearing in the TM band 3 and 4 might be the borderline between the normal coastal water and the high-turbid shallow water.

In the middle infrared spectrum of TM band 5, the exposed mudflat maintained a relatively high reflectance while the tidewater showed very low reflectance regardless of the depth and turbidity. Therefore, the true waterline separating seawater from the mudflat should be seen at the middle infrared wavelength and can be found in TM band 5 or 7 images. Fig. 7 clearly shows the actual values of digital number (DN) of two TM bands for the samples of exposed mudflat, shallow turbid water, and normal coastal water. In TM band 4, normal coastal water could be distinguished from the exposed mudflats and the shallow turbid tidewater while these two features were not different from each other. On the other hand, in TM band 5, the exposed mudflat was very distinct from the other two water surfaces regardless of their turbidity and depth. Consequently, the correct waterline between mudflat and seawater can be extracted from the middle infrared image of TM band 5. If we want to delineate the exact shorelines in the coastal area of inter-tidal mudflats, we should use the images obtained at the middle infrared spectrum.

4. Conclusions

Extraction of waterline in inter-tidal zone has played an important role for the construction of geomorphology of the tidal flat, the management of estuary ecosystems, and the planning of coastal developments. In this study, we found that the waterlines extracted from the optical imagery could vary depending on the spectral band used. In particular, the waterline extracted from the near infrared band was quite different from the middle infrared band. From the field measurements of spectral reflectance under various conditions of the turbidity and water depths, the following conclusions can be inferred.

- Shallow tidewater near the waterline has diverse turbidity level as a function of the water depth. Turbidity of tidewater is inversely proportional to the water depth.
- There is a significant relationship between spectral reflectance and turbidity, in particular at the wavelength between 600 and 1,000nm. Reflectance increases as the turbidity increases at the visible and near infrared spectrum. Such relationship is not seen at the middle infrared spectrum.
- At the middle infrared wavelength, tidewater shows very little reflectance regardless of the turbidity and water depth. Even the shallow and very turbid water has significantly low reflectance and can be distinguished from the exposed tidal flat only at the middle infrared spectrum.

- The waterline, appearing on the near infrared image (such as TM band 4), is actually the boundary between normal coastal water and shallow turbid water covering the tidal flats. The true waterline can be found from the middle infrared image (such as TM band 5).

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