Integration of spatial variables derived from remotely sensed data for the mapping of the tidal surface sediment distribution

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ABSTRACT


The sedimentary environments of tidal flats on the west coast of Korea are subjected to continuous change due to both natural and artificial causes. Thus, knowledge of the spatial distribution of surface sediments in a tidal flat is important in understanding the nature of coastal environmental change. This paper reports on a preliminary study of a novel approach to classifying the surface sedimentary facies in a tidal flat. A map of sedimentary facies was compiled by integrating spatial variables related to the facies. The digital number value of the IKONOS NIR band, which is a remotely sensed image with high spatial resolution, was constructed as a spatial database that represents spectral reflectance. The distribution of the tidal channel network was extracted from the IKONOS image and the density of tidal channels was built as a spatial database. The relative weighting of two variables, i.e. IKONOS NIR band and the density of tidal channels, was determined based upon a previous study, and a group of grain-size samples was analyzed to estimate the boundaries between sedimentary facies. The classification showed a relatively high level of accuracy in terms of comparison with another group of grain-size samples. The results demonstrate that the proposed method is applicable to the mapping of surface sedimentary facies in a tidal flat based on remote sensing images with high spatial resolution. The use of sufficient control factors and a suitable model for quantitative estimates of the weighting for each factor is expected to enable precise mapping of the distribution of surface sedimentary facies in tidal flats.

ADDITIONAL INDEX WORDS: Surface sediment distribution, Spectral reflectance, Tidal channel, Spatial variables, Remote sensing

INTRODUCTION

Tidal flats, which are widely distributed on the west coast of Korea, have economic, social, and ecological value as diverse habitats, food sources for neighboring marine areas, and removers of pollution in circulating seawater. The surface sedimentary facies in tidal flats of this region show continuous change due to natural causes such as the northwest monsoon and seasonal cycles of sedimentation and erosion (Woo and Je, 2002). Human activities (e.g., land reclamation) also result in marked changes in the facies of surface sediments (Ryu et al., 2004). Thus, studies on the surface sedimentary facies in tidal flat environments are important to understand changes in the coastal environment (Rainey et al., 2000). Previous studies of this type have employed remote sensing techniques (Doerfert and Murphy, 1989; Van der Wal et al., 2005).

Many studies have examined the relationship between the distribution of surface sedimentary facies and the related environment, based on remotely sensed data (Rainey et al., 2000; Ryu et al., 2004). Choi et al. (2011) reported that sedimentary environments in a tidal flat are characterized by diverse variables with complex interactions among them, and showed a significant spatial relationship between the distribution of surface sediment in a tidal flat and topographic features. In addition, Choi et al. (2010) reported that the distribution of surface sedimentary facies in a tidal flat on the west coast of Korea had a significant spatial relationship with the spectral reflectance of a high-spatial-resolution remotely sensed image.

It is important to select a suitable classification method when analyzing surface sedimentary facies in a tidal flat, taking into account the heterogeneous characteristics and spatial resolution of remotely sensed data. It is possible to map the tidal surface characteristics solely from spectral reflectance in remotely sensed images with low to medium spatial resolution. Hence, pixel-based classification methods have been commonly employed to map the distribution of surface sedimentary facies in tidal flats (Yates et al., 1993; Rainey et al., 2003). However, data acquired at high spatial resolution provide information on the surface texture, which is controlled mainly by the tidal channel network. Thus, new approaches, such as object-based classification (Blaschke and Strobl, 2001), have been used in mapping the distribution of surface sedimentary facies in tidal flats based on high-spatial-resolution satellite images (Choi et al., 2010). The object-based approach is suitable for classification based on high-spatial-resolution images and has the advantage of greater accuracy compared with pixel-based methods (Blaschke and Strobl, 2001). However, to perform a classification using an object-based approach requires specific software; i.e., Definiens® Developer 7, which is commercial software developed by Definiens Imaging Co as an object-based image analysis tool. Hence, it is necessary to

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convert a spatial database into input data for the software, and it is difficult to understand the details of the classification process.

In this study, as a first step in developing a novel method of classification by integrating the spatial variables related to the distribution of surface sediment in a tidal flat, the distribution of surface sedimentary facies is mapped using spectral reflectance and the distribution of tidal channels. Choi et al. (2011) reported that the distribution of surface sedimentary facies is closely related to the tidal topography and consequently to tidal wetness (e.g., surface water and interstitial water within surface sediments). These features of the tidal surface can be easily identified from high-spatial-resolution satellite images as the spectral reflectance and the network of tidal channels. The present study focuses on the mapping of sedimentary facies by integrating two variables including the spectral reflectance of the satellite image and the distribution of tidal channels induced by high-spatial-resolution satellite images. The integration process is based on the spatial relations between the variables and in situ grain-size data.

The proposed method was applied to the tongue-shaped Hwango tidal flat of Cheonsu Bay, Korea. Cheonsu Bay, which is characterized by a shallow water depth of less than 25 m, is located on the central western coast of Korea, surrounded by the districts of Anmyeondo (Taean County) and Kanweoldo (Seosan City) (Figure 1a). The total area originally covered by tidewater was 380 km², but this was reduced to 180 km² as a result of the construction of embankments during land reclamation since 1984 (So et al., 1998). The water depth around Cheonsu Bay has been maintained at above 10 m since the embankments were constructed. The tides in the study area are semi-diurnal, with a mean tidal range of 4.59 m (spring tide = 6.33 m, neap tide = 2.86 m). The maximum tidal-current velocities in the main tidal channel are ~1.0 ms⁻¹ during flood tide and ~0.7 ms⁻¹ during ebb tide (Kim and Kim, 1996). Sand dunes located in the northwestern part of the bay are extensively exposed during ebb tide (Lee and Park, 1998). The central Hwango tidal flat is characterized by complex channels. The tidal flat is 1.65 km wide and 5.15 km long (Figure 1b), and consists of the following sedimentary facies (from the high tide waterline to the low tide waterline): mud flats, mixed flats, and sand flats. The mud flat facies is dominant in a relatively elevated area with a steep slope, whereas the sand flat facies is located in a lower area with a gentle slope and upwardly concave relief (Choi et al., 2010). Figure 1b shows the result of the classification of surface sedimentary facies using the object-based method approach, based on an IKONOS satellite image (Choi et al., 2010).

**MATERIALS AND METHODS**

**Field Campaign**

Forty-one samples for grain-size analysis were collected in March 2004. A shipboard grab sampler acquired 27 samples at flood tide, and 14 field samples were collected by hand along the middle part of the study area at ebb tide. At least three samples were taken within a 10-m radius at each site by scraping material from the top 5 mm of the surface sediment. A differential GPS (Trimble Co, Pathfinder Pro XR) with a horizontal accuracy of 1 m was used for accurate positioning of the sampling sites. The sites labeled “G” in Figure 1b are the locations of the 27 flood-tide samples, and those labeled “C” are the locations of the 14 ebb-tide samples. Grain size data for each of the 41 sample sites were classified following Folk (1968). According to the percentage of grains larger than 0.0625 mm, samples were classified into three facies types: sand flat (>70% of grains larger than 0.0625 mm), mixed flat (30%–70%), and mud flat (0–30%). The grain size data for the 14 samples from the C sites were used as the training dataset for classification of the surface sediment facies.

**Satellite Image**

A high-resolution IKONOS satellite image was used to map the distribution of surface sediments. The spatial resolution of the image is 4 m, and it was acquired at 11:20 AM (local time) on 26 February 2001, which was 0.5 h before low tide, when the tide was 0.78 m (Boryeong station). The study area is a semi-closed bay in which changes in the sedimentary environment due to erosion/sedimentation are negligible, except in the summertime rainy season, when the floodgates of the Seosan breakwater are opened (Kim and Kim, 1996). Thus, we did not consider the time difference between the field campaign and satellite acquisition. Geometric rectification was performed using 13 ground control points (GCPs) acquired at the dyke or the floodgate around Cheonsu Bay in October 2003. The survey measurements for the 13 GCPs were carried out using a differential GPS (Pathfinder Pro XR; Trimble) with a minimum horizontal accuracy of <1 m at ground level.

Table 1 lists the band characteristics of the IKONOS data. Choi et al. (2010) reported that the distribution of surface sedimentary facies is closely related to the digital number (DN) value, which

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (μm)</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Blue</td>
<td>0.45-0.52</td>
<td>4</td>
</tr>
<tr>
<td>2. Green</td>
<td>0.52-0.60</td>
<td>4</td>
</tr>
<tr>
<td>3. Red</td>
<td>0.63-0.69</td>
<td>4</td>
</tr>
<tr>
<td>4. Near-IR</td>
<td>0.76-0.90</td>
<td>4</td>
</tr>
<tr>
<td>5. Panchromatic</td>
<td>0.45-0.90</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 1.** (a) The Landsat ETM+ image of the Cheonsu Bay and Hwango tidal flat acquired on 14 February 2002. (b) The distribution map of surface sedimentary facies in the Hwango tidal flat derived from the IKONOS image acquired on 26 February 2001 based upon the object-based classification method overlaid with 41 sampling positions for sedimentary facies acquired in March 2004.
the authors used instead of optical reflectance from the IKONOS satellite image, in particular for the Hwangdo tidal flat. Their investigation was performed using the DN value of IKONOS band 4, because the near-infrared (NIR) band may indicate the sedimentary environment in a tidal flat (e.g., water content and remnant surface water), and this band is effective in terms of classifying sediment (Ryu et al., 2004). In the present study, the DN value of the IKONOS NIR band was used as a layer for compiling a map of the distribution of surface sedimentary facies.

Tidal Channel Network

The distribution of surface sediments in a tidal flat shows a strong spatial relationship with topographic features, especially with the tidal channel network in the case of tidal flats on the west coast of the Korean Peninsula (Choi et al., 2011). Thus, the tidal channel network was considered as a variable for mapping the sediment distribution in the present study area. The tidal channel network was extracted from the IKONOS image. A multi-spectral image (spatial resolution, 1 m) was generated from the panchromatic band image with a spatial resolution of 1 m, combined with the visible-to-NIR band image (spatial resolution, 4 m) using an image sharpening technique. The tidal channels were extracted and digitized from the spectrally enhanced image. A map of the tidal channel density for the study area was constructed from the tidal channel database via surface analysis, and was employed as a layer for compiling a map of the distribution of surface sedimentary facies.

Integration of Variables

The spatial relationship was established between the surface sedimentary facies and the two variables. The mud flat facies shows a strong spatial relationship with the IKONOS DN value, whereas the sand flat facies shows a strong negative correlation (Choi et al., 2010). These results indicate that the percentage of grains in the surface sediment that are larger than very fine sand, increases with increasing DN value of the IKONOS NIR band. The mud flat facies shows a significant positive relationship with the density of tidal channels, whereas the sand flat facies is concentrated in areas with a low density of tidal channels (Choi et al., 2011). This finding indicates that the percentage of sand grains increases with increasing tidal-channel density. Based on these relationships, the two variables were integrated in a single map to produce a map of the distribution of surface sedimentary facies. To apply this scheme, the IKONOS data were converted into a raster image as an ArcGIS grid file with a cell unit of 4 × 4 m, and each cell was assigned a DN value for the IKONOS NIR band (Band 4). For data processing, we used ArcGIS 9.3 with the optional Spatial Analyst and the 3D Analyst application. The DN values of the grid file were re-categorized into 10 classes by a quantile method in which each class has an equal area. Re-categorization of 10 classes was considered appropriate in examining the trend of IKONOS DN values according to the change in the predominance of each sediment facies, and the quantile method is effective in intuitively understanding the spatial relationships among the variables.

As shown in Figure 2a, the area classified as mud flat facies by Choi et al. (2010) (Figure 1b) shows a high value of tidal channel density. The map of tidal channel density was also converted into an ArcGIS grid file with cell dimensions of 4 × 4 m, with each cell containing a density value. The grid file was reclassified into 10 groups by a quantile classification method, assigning each group an equal area. The DN value is higher for the mud flat facies than for other facies (Figure 2b), indicating that the mud flat facies shows relatively high spectral reflectance in the IKONOS image.

RESULTS AND DISCUSSIONS

Map of Surface Sedimentary Facies

Based on the relationships between the surface sedimentary facies and the two variables, we assigned the relative weighting related to the occurrence of a high percentage of sand grains for each subgroup of each variable. For each of the 10 subgroups of tidal channel density, a weighting with a value from 1 to 10 was assigned, with a value of 1 being assigned to the subgroup with the lowest density. The DN value of the IKONOS NIR band was
Table 2: Error matrix of the surface sedimentary facies classification derived from the IKONOS image of the study area.

<table>
<thead>
<tr>
<th>Reference data (in situ samples)</th>
<th>Row total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud flat</td>
<td>2</td>
</tr>
<tr>
<td>Mixed flat</td>
<td>1^</td>
</tr>
<tr>
<td>Sand flat</td>
<td>1^b</td>
</tr>
<tr>
<td>Sand shoal</td>
<td></td>
</tr>
<tr>
<td>Column total</td>
<td>4</td>
</tr>
</tbody>
</table>

Overall accuracy = 70.4%

Mud flat (0-30%), Mixed flat (30-70%), Sand flat (above 70%)

^A16G17:26.8%, ^B1:27.6%, ^C10:53.6%, ^D18:51.7%, ^E25:36.4%, ^F27:67.0%, ^G8:75.5%, ^H12:89.1%

also assigned a weighting from 1 to 10 for each of the 10 subgroups, with a value of 1 being assigned to the subgroup with the lowest DN value (i.e., the lowest spectral reflectance). Then, the weightings of the tidal channel density and the DN value of the IKONOS NIR band were combined using an ArcGIS overlay method to construct a map showing the distribution of the percentage of sand grains in the sediments. The map showed values in the range [2, 20], as an integer, in each cell; this value presents the degree of predominance of sand grains in the surface sediment at each cell location. Finally, the combined single values were re-categorized as mud flat facies, mixed flat facies, and sand flat facies based on a comparison with the training dataset (i.e., grain-size data for the 14 samples from the C sites in Figure 1b). For example, the combined single values at the location of mud flat samples (C1, C2, and C3) are 15, 18, and 17, respectively, as derived from the map showing the distribution of the percentage of sand grains. Thus, cells with values above 15 were categorized as mud flat facies. Similarly, cells were categorized as mixed flat and sand flat facies. Areas of sand shoal could be clearly identified from satellite images; consequently, sand shoals were classified separately based on visual inspection. Ultimately, the Hwangdo tidal flat was classified into four surface-sediment facies (Figure 3). Figure 3 shows similar trends with the result of object-based classification (Figure 1b), in that the mud flat facies is distributed mainly in the western part of the study area near the area of high waterline, whereas the sand flat facies is located mainly in the eastern part, in the area of the low waterline.

Verification of the Classification Map

The map showing the distribution of surface sedimentary facies was verified by generating an error matrix based on the spatial relationship between the classification map and grain-size data. The 27 samples acquired by the shipboard grab sampler at flood tide (from the G sites in Figure 1b) were used for the validation. Table 2 shows the error matrix generated from the classification. Among the four grain-size samples of mud flat, only two samples were classified accurately in terms of comparison with the in situ data. One sample at point G17 was misclassified as mixed flat, and the percentage of grains larger than 0.0625 mm in the sample was 26.8% (Table 2). A sample from point G1, which contains 27.6% sand, was misclassified as sand flat. For the samples with grain-size data corresponding to mixed flat, five samples were classified accurately, three were misclassified as mud flat, and one was misclassified as sand flat. Samples at points G10, G18, and G25 were misclassified as mud flat (sand percentages of 53.6%, 51.7%, and 36.4%, respectively). A sample at G27 was misclassified as sand flat (67.0% sand grains). Among the 11 samples of sand flat, two samples at G8 and G12 were misclassified as mixed flat (75.5% and 89.1% of grains larger than very fine sand, respectively). Three samples of sand shoal were classified accurately (compared with in situ data).

The examples of misclassification were due mainly to classification errors; however, the sample at G17 showed a sand percentage close to that of the mixed flat facies (30%-70%), even if the sample belonged to the mud flat. Thus, we can infer that it could represent the characteristics of mixed flat in the IKONOS image. Similarly, the sample at G25 was close to mud flat in terms of the percentage of sand grains, sample at G27 was close to sand flat, and the sample at G8 was close to mixed flat. Accordingly, although some samples were misclassified relative to the sedimentological standard, the optical characteristics of the IKONOS satellite image show good agreement with the results of the surface sediment classification in the study area. The overall accuracy was 70.4%, which is a relatively high level of agreement.

In conclusion, the proposed method is applicable in mapping the distribution of surface sedimentary facies in tidal flats based upon remote sensing images with high spatial resolution.

CONCLUSIONS

A preliminary study was made using a new approach to mapping the distribution of surface sediment facies in a tidal flat. The method involved integrating thematic maps generated from a remotely sensed image with high spatial resolution. Compared with existing methods, the new approach has the advantage of being easily incorporated into commercial GIS software, thereby enabling a better understanding of the classification process. However, to obtain a more accurate result, it is necessary to develop suitable control factors relating to or affecting the surface sedimentary environment in tidal flats, and to develop an appropriate model that can quantitatively estimate the weighting for each control factor. Sedimentary environments in a tidal flat are characterized by diverse variables with complex interactions among them. The construction of a spatial database of such variables, based on high-spatial-resolution remote sensing images, would enable the compilation of accurate thematic maps of the benthic environment, if combined with appropriate field campaigns in tidal flat areas, which are characterized by limited accessibility and cyclic aerial exposure.

LITERATURE CITED


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