Ocean & Coastal Management 102 (2014) 458–470

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Potential of remote sensing in management of tidal flats: A case study of thematic mapping in the Korean tidal flats

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ARTICLE INFO

Article history:
Available online 26 March 2014

ABSTRACT

Tidal flats in Korea are increasingly being changed by various construction projects. This report reviews the remote sensing techniques used to monitor tidal flats and suggests appropriate techniques for meeting monitoring targets for the effective management of tidal flats. The application of remote sensing to studies of tidal flats and the characteristics of the preferred satellite data for a particular monitoring target were examined from a statistical analysis of peer-reviewed journals and case studies of Korean tidal flats. Specifically, three different monitoring targets were examined: topography, sedimentary facies, and biofacies. To date, the Landsat thematic mapper (TM) and the enhanced thematic mapper (ETM+) have been most widely used for this purpose due to the large amount of archived data, the convenience of time-series analysis, and the minimal or no-cost data acquisition. Sedimentary facies of the tidal flats can be classified into the three categories mud, mixed, and sand, at a spatial resolution of 30 m. A potential map for macrobenthos was generated with high accuracy based on the spatial variables. High-resolution, space-borne, and X-band synthetic aperture radar (SAR) systems such as TerraSAR-X and Cosmo-SkyMed were used to improve the accuracy of tidal flat digital elevation model (DEM) generation and halophyte distribution mapping. The details of those data can be further enhanced by the use of a high-spatial-resolution image. The legislation regarding the monitoring of tidal flats in Korea and Germany was compared to the potential application of remote sensing to the monitoring of tidal flats. Thematic maps based on remote sensing can help improve policy decisions from a management perspective.

1. Introduction

Tidal flats, which are a mixture of seawater and fresh water environments, have economic, social, and ecological value as habitats for a diverse range of living organisms, as costal protection against storms, and as buffer zones for seawater from land-based pollutants (Brooks et al., 2006; Kirwan and Murray, 2007). However, tidal flats have been significantly restructured and damaged by human activities on a large scale and are threatened by a rise in sea level (Kirwan et al., 2010; Ryu et al., 2004).

Field surveys for monitoring aspects of tidal flats (e.g., topography, benthos distribution, sedimentary facies) can be restricted due to the time limitations of capturing the ebb/flood tide characteristics, physical difficulties with the work, and limited numbers of investigators (Ryu et al., 2002). Moreover, field surveys are constrained because a few survey lines may not adequately represent changes in large tidal flats (Boak and Turner, 2005). To overcome these limitations, remote sensing data combined with field surveys have been used as complementary data since the late 1980s (Cracknell, 1999). The advantages of using remote sensing include the potential to perform time series analysis and the use of archived images for the monitoring of tidal flats where survey data are not available. Remote sensing is a particularly suitable technique for the ecological monitoring of vast tidal flats on a periodic basis, and is effective for the quantitative analysis of areas larger than 10 km^2 (Choi et al., 2010a,b). Thus, many studies of tidal flats have used remote sensing techniques (Heygster et al., 2010; van der Wal and Herman, 2007; Zhao et al., 2008).

Vast tidal flats have formed along coastal areas of Korea. The tidal range in Incheon, located in the central coastal area, is ~7.3 m, whereas the tidal range in Mokpo, located in the south, is ~3 m. There are various types of tidal flats, including closed tidal flats in Hamhae, Haenam, and Muan, semi-closed tidal flats in Gomso, and open tidal flats in Baeksu. Moreover, Korean tidal flats have two

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http://dx.doi.org/10.1016/j.ocecoaman.2014.03.003
0964-5691/

distinctive features: (a) they are composed of fine grains, and (b) the sand barriers are poorly developed (Ryu et al., 2008). The total area of tidal flats along the Korean coast has decreased due to reclamation projects that have occurred since the Japanese colonial period. In the 1990s, the total area of tidal flats was ∼2 800 km^2, representing almost 3% of the nation's total land area (Koh, 2001). By 2010, it had decreased to 2 489 km^2 (almost 2.4% of the nation's total land area) due to large-scale reclamation projects in areas such as Sihwa and Saemangeum (MLTM, 2010).

In Korea, the use of remote sensing techniques to monitor tidal flats began in 1986 (Yoo, 1986). Ryu et al. (2002) used remote sensing to study the Gomso tidal flat. The study introduced waterline extraction, the concept of effective exposed area, and a consideration of the remnant surface water effect with respect to spectral reflectance measurements. Despite the limited number of researchers using remote sensing to study Korean tidal flats, a diverse range of remote sensing techniques have been used to study tidal flats, and the results have been published in peer-reviewed journals.

Since the mid-1990s, many studies have used remote sensing techniques to provide complementary data or to help determine the status of tidal flats. In the present study, we review the remote sensing techniques that have been used to monitor tidal flats and attempt to identify the most appropriate methods for facilitating effective tidal flat management in an efficient and cost-effective manner. Peer-reviewed papers, largely published since 1996, were reviewed to determine the characteristics of the sensors that were used. Specific case studies of tidal flats in Korea were examined. We focused on remote sensing techniques related to topography, sedimentology, and ecology with applications to coastal areas because tidal flats interact with coastal water. Examples of remote sensing-based management schemes for tidal flats in Korea and Germany were examined.

2. Overview of remote sensing techniques used in studies of tidal flats

To review the remote sensing techniques used in studies of tidal flats, a statistical analysis was conducted on peer-reviewed papers and the characteristics of the satellites and sensors used in the research were summarized.

2.1. Interactions of environmental factors within tidal flats

The sensors can be divided into optical systems, which measure the reflection of sunlight in the visible and infrared regions of the electromagnetic spectrum, and radar systems, which measure the receipt of an actively transmitted microwave pulse (Vrieling, 2006). A large number of optical and radar systems have been used to provide imagery of tidal flats. From the analysis of information expressed by the DN value in satellite images, which represents the end result of interactions with various factors in tidal flats, the characteristics of tidal flats can be investigated according to the sensors loaded on satellites.

Fig. 1 shows the environmental factors that affect the remote sensing reflectance (Rrs) of optical data and the backscattering coefficient of SAR data. These factors, including topography, biofacies, sedimentary facies and tidal wetness, are closely connected. For example, living organisms such as halophytes and benthos have their own distinct habitats. Each species inhabits a location with unique temperature and salinity conditions according to the level of the ebb/flood tide. Topographic conditions such as the tidal flat elevation, slope angle, and the existence of channels also influence the habitat of each species. The water content of surface sediments and the amount of remnant water, which are determined by the

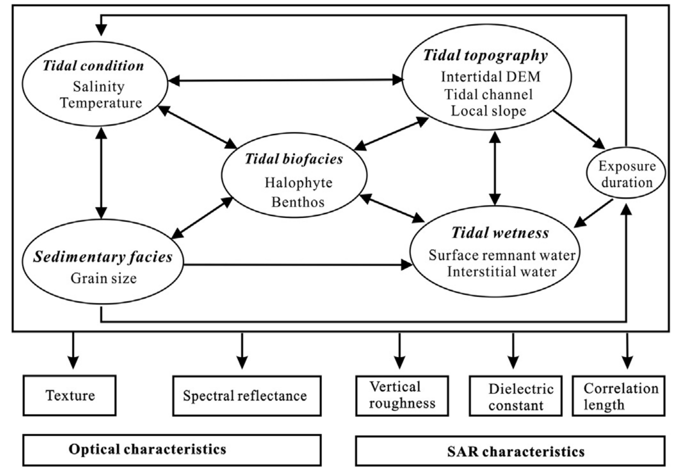

Fig. 1. Environmental factors such as tidal biofacies, tidal topography, tidal wetness, sedimentary facies in tidal flats, and their interactions determine texture and remote sensing reflectance in optical imagery. Physical parameters such as roughness, dielectric constant, and correlation length affect the backscattering coefficients in SAR imagery.

duration of exposure to the atmosphere, also affect the environments inhabited by different species. The sedimentary facies, which differ according to the tidal wetness, determine the locations of living organisms. Various environmental factors and their interactions within tidal flats can affect the radiance of targets in the flats, which must be converted into an Rrs value after atmospheric corrections. The texture and reflectance of channels in tidal flats can be analyzed by using an optical sensor with high spatial resolution.

In SAR, the digital number (DN) value recorded at the sensor is converted into a backscattering coefficient through radiometric calibration. The tidal flat environment (i.e., the topography, biofacies, sedimentary facies, and tidal wetness) affects physical parameters such as roughness, dielectric constant, and correlation length. Backscattering coefficients are determined according to the interactions of physical parameters. Higher surface roughness values are recorded in the presence of halophytes, for example, due to the structure of the plants, compared with non-vegetated tidal flats. The exposure duration differs according to the topography of the halophyte location, such as the local slope. The dielectric constant is affected by variations in the moisture content and the amount of remnant water. The correlation length depends on the dielectric constant, according to the grain size under the halophytes. Thus, a comprehensive study is required to understand the tidal flat environment fully due to the interconnectedness of the physical and environmental parameters.

In LiDAR, the distance to feature is measured. The topography or bathymetry of tidal flat can be determined. Laser profilers are unique in that they confine the coherent light energy within a very narrow beam. Providing pulses of high peak intensity allows LiDAR system to penetrate much moderated turbid coastal water. The water depth is derived based on comparing the travel times of the LiDAR pulses in blue–green laser reflected from the bottom and the sea surface.

2.2. Statistical analysis of peer-reviewed papers

Published papers with the keyword "tidal flats" in the "ISI Web of Knowledge" and "SCIRUS" databases were selected, and then papers with the keyword "remote sensing" were reselected (http://app.isiknowledge.com/; http://www.scirus.com/). After removal of