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Topographic mapping on large-scale tidal flats with an iterative approach on the waterline method

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ABSTRACT

Tidal flats, which are both a natural ecosystem and a type of landscape, are of significant importance to ecosystem function and land resource potential. Morphologic monitoring of tidal flats has become increasingly important with respect to achieving sustainable development targets. Remote sensing is an established technique for the measurement of topography over tidal flats; of the available methods, the waterline method is particularly effective for constructing a digital elevation model (DEM) of intertidal areas. However, application of the waterline method is more limited in large-scale, shifting tidal flats areas, where the tides are not synchronized and the waterline is not a quasi-contour line. For this study, a topographical map of the intertidal regions within the Radial Sand Ridges (RSR) along the Jiangsu Coast, China, was generated using an iterative approach on the waterline method. A series of 21 multi-temporal satellite images (18 HJ-1A/B CCD and three Landsat TM/OLI) of the RSR area collected at different water levels within a five month period (31 December 2013–28 May 2014) was used to extract waterlines based on feature extraction techniques and artificial further modification. These 'remotely-sensed waterlines' were combined with the corresponding water levels from the 'model waterlines' simulated by a hydrodynamic model with an initial generalized DEM of exposed tidal flats. Based on the 21 heighted 'remotely-sensed waterlines', a DEM was constructed using the ANUDEM interpolation method. Using this new DEM as the input data, it was re-entered into the hydrodynamic model, and a new round of water level assignment of waterlines was performed. A third and final output DEM was generated covering an area of approximately 1900 km^2 of tidal flats in the RSR. The water level simulation accuracy of the hydrodynamic model was within 0.15 m based on five real-time tide stations, and the height accuracy (root mean square error) of the final DEM was 0.182 m based on six transects of measured data. This study aimed at construction of an accurate DEM for a large-scale, high-variable zone within a short timespan based on an iterative way of the waterline method.

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1. Introduction

Tidal flats are areas inundated during high tide and exposed during low tide (Chen et al., 2008). They are present at various locations worldwide and constitute an invaluable spatial resource, an abundant materials resource, and a significant environmental resource. However, vast world-famous tidal flats, such as the German Wadden Sea, Jiangsu coast of China and the western coast of the Korean peninsula, are being developed by land reclamation (Ma et al., 2014). Such reclamation development will bring positive and negative impacts to the environment including hydrodynamic condition, sediment transport, and also ecosystem (Nicholas et al., 2014), yet the changing nature of tidal flats beyond local scales remains largely unknown. Therefore, accurate and up-to-data topographic maps or digital elevation models (DEMs) of large-scale tidal flats are important baseline resources for coastal development and wetland conservation.

Mapping vast and often inaccessible intertidal areas is a difficult task that requires considerable logistical and financial efforts. Ground and ship-based surveys are not feasible when dealing with large areas because of their high cost and harsh working conditions,

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such as severe weather, difficult terrain, and changing tide conditions. Remote sensing has become a widely used and easily available technique for the measurement of topography over tidal flats. The most representative methods are based on airborne LiDAR (light detection and ranging) (Flood and Gutelius, 1997; Deronde et al., 2006; Guo et al., 2010) and airborne/satellite InSAR (interferometric synthetic aperture radar) (Madsen et al., 1995; Wimmer et al., 2000; Hoja et al., 2000; Slater et al., 2006). LiDAR can achieve relatively high vertical (centimeter-level) and planimetric accuracies (decimeter-level), but it can be difficult to obtain a synchronized DEM over a large area under changing tidal conditions. InSAR is able to cover large areas, monitor across the full tidal range, and fly in adverse weather conditions. However, its vertical and planimetric accuracies are relatively low (meter-level) (Mason et al., 2000).

Another remote sensing method for generating topographic maps of the intertidal zone is the waterline method, which is currently considered to be the most useful approach (Ryu et al., 2008; Mason et al., 2010). The waterline method makes use of the ever-shifting boundary between tidal flats and adjacent water areas, whose position can be regarded as a quasi-contour line of the topography (it is not a true contour line because the water level of the tidal wave varies horizontally). The waterline method has been widely applied in many regions throughout the world: the Humber and Wash coasts and Morecambe Bay in England (Mason et al., 1995, 1998; 1999, 2000; 2001, 2010), the Holderness coast in England (Lohani, 1999), the coast of French Guiana (Anthony et al., 2008), the Wadden coast in northern Europe (Heygster et al., 2010), Gomso Bay in Korea (Ryu et al., 2008), and the Yangtze Delta and Dongsha sand ridges in China (Zhao et al., 2008; Liu et al., 2010, 2012; 2013a, b). In previous studies, the waterline method has usually been applied to small, stable regions, such as an estuary or bay. Application of the waterline method is more limited in large-scale, shifting tidal flats areas, where the tides are not synchronized and the waterline is not a quasi-contour line.

Two key issues need to be discussed with respect to the application of the waterline method. One is the time interval between adequate quality satellite images. When there are few high quality satellite images across various tidal levels, the time interval must be extended for up to a year or more (Ryu et al., 2008; Zhao et al., 2008; Mason et al., 2010; Liu et al., 2012), which is not short enough to neglect the variation of topography. The second is how to assign accurate water level values to the waterlines. For large-scale tidal flats, the sea surface is not flat at any given moment, so that one or two tide stations or transects cannot be applied to a wide range of height assignments, except for the hydrodynamic tide model. However, simulation accuracy of the tide model is always lower due to the absence of actual terrain and real-time, measured tidal level data (Liu et al., 2012).

The objective of this study is to overcome these two challenges and apply the waterline method to a large-scale, variable, complex intertidal zone. Taking a case study area of the Radial Sand Ridges (RSR), we proposed an iterative way to modify the hydrodynamic model stepwise in the process of waterline method and based on which a high accurate DEM was acquired within a short time span.

2. Study area and data sets

2.1. General description of RSR

The RSR is made up of very large continental shelf sand bodies that spread in fan-shaped spatial patterns over the Jiangsu Coast, China. It covers a vast area that is approximately 200 km long and 140 km wide. The RSR was considered to be formed by the interaction between the existing, stable tidal wave system and the ancient coastline that was formed during the Holocene regression (Wang et al., 2012). Moreover, this tidal wave system, which covers the Southern Yellow Sea, is thought to be the major hydrodynamic factor that influences the formation and maintenance of the modern RSR (Xing et al., 2012). The semidiurnal M2 constituent is the dominant tidal component. Part of the progressive tidal wave, which is reflected by the Shandong Peninsula, forms an anticlockwise rotational tidal wave with the amphidromic point located to the north of the RSR (121.37°E, 34.62°N, according to Xu et al., 2016). This rotational tidal wave encounters a subsequent progressive tidal wave and leads to the formation of an approximately stationary tidal wave system along the Jiangsu Coast. As a result, the tidal ranges, which reach 9.36 m in a tidal channel south of Tiaozini (Kang et al., 2015), and the magnitudes of the tidal current, up to 2.5 m/s, are considerably larger in the RSR (Yan et al., 1999). The waves in the study area are mainly governed by local winds, with an annual average wind speed of approximately 2.7 m/s. The wind direction is typically ESE-SE, and the wave height is generally less than 1.0 m (Chen et al., 2006).

As shown in Fig. 1, water depths in the RSR range between 0 and 30 m (lowest normal low water datum), and there are large-scale tidal flats distributed across three main sand ridges, namely the Dongsha, Tiaozini, Gaoni, which emerge and submerge as the tide fluctuates. Intertidal flats are typically dozens of kilometres wide with an average slope of approximately 0.2%, and an increase in slope to 1.5% near the tidal creeks (Liu et al., 2012). The total study area within this region is 90 km × 70 km, and the exposed tidal flats area is more than 2000 km^2.

2.2. Data sets

For our study, we acquired a series of satellite images from Landsat TM/OLI and HJ-1 CCD. Landsat imagery contains relatively high-resolution (30 m) earth observation data and allows for a wide range of applications. However, because its revisit period is relatively long (approximately 16 or 18 days), the number of images that are available is insufficient for relatively short periods (e.g. five months, in this study). The HJ-1 CCD data have a nadir pixel resolution of 30 m, a width of view of 360 km, and a temporal resolution of two days (Wang et al., 2010). Thus, these data have good potential to be applied to the waterline monitoring. This study collected 18 HJ-1 images and three Landsat images acquired at different tidal stages from 31 December 2013 to 28 May 2014 (Table 1). False color composite images (RGB three channels respectively with shortwave infrared (0.76–0.90 μm), red (0.63–0.69 μm), green (0.52–0.60 μm)) were used to extracted waterline in the next step.

A topographic map (1:50,000) of the Jiangsu coastal zone was collected for geometric rectification of the satellite images. As shown in Fig. 1, a 1:100,000 bathymetric map of the ocean area (1979) combined with underwater topographic survey data from the 2006 'Jiangsu offshore investigation and assessment,' were used as input data for the hydrodynamic model. To validate the hydrodynamic model simulation result, between October 2010 and December 2013, five new automatic tide level telemetry stations were established around the central area of the RSR: Dafenggang (DFG), Dongdagang (DDG), Tiaoyugang (TYG), Yangkougang (YKG) and Dongshagang (DSG) (Fig. 1). Table 1 displays the tide heights of those five stations on the acquisition dates of the 21 remotely-sensed images. Six transect lines of topographic measurement data obtained during a ground survey in March 2014 were compared with the derived DEM result to test the height accuracy (Fig. 6e). The datasets used in the study have different vertical datums: the lowest normal low water datum (LNLW) was adopted by the bathymetry map of 1979 (seen in Fig. 1). The Chinese

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