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Automatic extraction of shorelines from Landsat TM and ETM+ multi-temporal images with subpixel precision

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ABSTRACT

A high precision geometric method for automated shoreline detection from Landsat TM and ETM+ imagery is presented. The methodology is based on the application of an algorithm that ensures accurate image geometric registration and the use of a new algorithm for sub-pixel shoreline extraction, both at the sub-pixel level. The analysis of the initial errors shows the influence that differences in reflectance of land cover types have over shoreline detection, allowing us to create a model to substantially reduce these errors. Three correction models were defined according to the type of gain used in the acquisition of the original Landsat images. Error assessment tests were applied on three artificially stabilised coastal segments that have a constant and well-defined land-water boundary. A testing set of 45 images (28 TM, 10 ETM high-gain and 7 ETM low-gain) was used. The mean error obtained in shoreline location ranges from 1.22 to 1.63 m, and the RMSE from 4.69 to 5.47 m. Since the errors follow a normal distribution, then the maximum error at a given probability can be estimated. The results confirm that the use of Landsat imagery for detection of instantaneous coastlines yields accuracy comparable to high-resolution techniques, showing the potential of Landsat TM and ETM images in those applications where the instantaneous lines are a good geomorphological descriptor.

1. Introduction

The recognition of changes in the position of the shore is crucial for understanding the dynamics of coastal areas and especially the shorelines. The position of the shore can change for two reasons: (i) more or less predictable short-term variations in sea level that depend on astronomical and meteorological factors (Lisitzin, 1974; Pugh, 1996, 2004); and (ii) alterations in the shape and volume of sediments along the profile of the shore. These morphological changes are much less predictable because they are a response of the shore system to wave conditions.

There can be two types of morphosedimentary changes: (a) those that occur in the short-term (generally less than a year) and depend on whether the waves are pushing towards the land or sea; and (b) longer-term changes that can be detected after several years and are caused by accumulation or erosion.

Both types of changes are important in the management of coastal areas (DGC, 2008). The first type of change reveals the magnitude of the variability over the course of a year and so enables a coastal management analyst to define and establish protected shore areas without worrying about specific changes that may occur after, for example, a major storm. The second type of change reveals a definite trend and is more important as it enables predictions to be made about whether the shore could be subject to significant changes that may prevent some uses, or endanger spaces adjacent to the coast. On many coastal areas, where a major tourism industry is established based on beach resources, recognition of the meaning and speed of changes may be strategically important because such information would enable corrective action to be taken to avoid or minimise risk (Pérez-González, 2008).

For this reason it has been standard practice for many decades to track the position of the shore using aerial photography as the primary source of data (Jiménez et al., 1997; Leatherman, 1983; McCurdy, 1950; MOPU, 1979; Pardo-Pascual, 1991; Smith & Zarrillo, 1990; Stafford, 1971; Thieler & Danforth, 1994). One of the most useful types of data extracted from aerial photography is the location of the waterline at the same instant as the acquisition of the photograph. On a microtidal coast the changes of the instantaneous waterline position may be used as an indicator of long term trends, since they provide a dynamic measure of beach width. The task is more complex in tidal areas, since the location of the shore at a given moment is much less likely to reveal changes or trends. Many solutions have been proposed for this problem. Boak and Tunner (2005) described up to 44 different indicators of the location of the shore as used by different authors from the 1950s until today. Recently, the use of the LiDAR technology (Liu et al., 2007; Morton et al., 2005;

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Robertson et al., 2004; Stockdon et al., 2002; White & Wang, 2003) and SAR images (Lee & Jurkevich, 1990; Mason & Davenport, 1996; Niedermeier et al., 2000; Yu & Acton, 2004) allowed for the resolution of this limitation by determining the altitudinal lines. However, the use of LiDAR technology is new and few data sets are available periodically, making difficult to infer trend changes over the time.

Multispectral satellite imagery offers several advantages, such as: a large number of data records, the availability of repeated images of a single place at different times, and the fact that virtually the entire planet is covered. As a result, multispectral satellite imagery is potentially more useful than previously employed sources for recognising evolutionary trends in the medium and long-term. The Landsat images acquired by the TM and ETM+ sensors on the Landsat 5 and 7 series is the largest useable database of medium resolution images for studying the dynamics of coastal areas. Moreover, since 2008 the United States Geological Survey (USGS) has freely provided all archived Landsat images, along with newly acquired Landsat 7 ETM+ SLC-off and Landsat 5 TM images with less than 40% cloud cover , thereby enabling free access to multiple images of the same sectors.

Until now this information has been relatively little used for these purposes (Gens, 2010). This is because a 30 m spatial resolution is too coarse to detect most of the changes in the shoreline within the time-scale required for coastal management (Pardo-Pascual & Sanjaume, 2001). However, several exceptions are worth mentioning and these are usually found in places such as deltas that show abrupt changes of great magnitude. Applications to the Nile delta (White & El Asmar, 1999), the Maritsa delta on the Aegean coast of Turkey (Ekercin, 2007), or the Huanghe river (Yellow River) in China (Chu et al., 2006) are good examples. Landsat images have also been used to map the environments within tidal flats and describe the three-dimensional nature of these domains by determining the various shorelines (Ryu et al., 2002). A similar goal is found in applications to coral reef atolls in the Marshall Islands (Yamayo et al., 2006) where the aim is to describe the topography of the intertidal zone. Landsat TM and ETM+ images have also been used in various studies to build digital lines of complex coastal regions such as in Louisiana (Braud & Feng, 1998); locate wetlands in flood plains (Frazier & Page, 2000); detect changes in reservoirs (Manavalan et al., 1997); or monitor natural lakes such as the Rift Valley in Kenya (Ouma & Tateish, 2006). In all of these cases, it was assumed that the level of accuracy produced by mapping the shoreline would always be worse than the 30 m resolution of the original images.

Much of the effort made so far by researchers has been focused on defining an optimal method to reliably locate the position of the shore. Many types of solutions have been proposed — the use of a supervised classification (Espinosa & Rodríguez, 2009; Hoeke et al., 2001; Pardo-Pascual et al., 2008); unsupervised classified images (Ekercin, 2007; Guariglia et al., 2006); and various thresholding techniques (Bayram et al., 2008; Jishuang & Chao, 2002; Kuleli et al., 2011; Liu & Jezec, 2004; Maiti & Bhattacharya, 2009; White & El Asmar, 1999; Yamayo et al., 2006). Since these methods are based on hard classification, each of the pixels will ultimately be considered as sea or land, meaning they cannot be used to monitor small changes to the shoreline (<10 m) unless high resolution images are used.

Foody et al. (2005) propose the use of fuzzy logic to resolve this limitation inasmuch as the same pixel can be assigned partially for the sea and partially for land. Muslim et al. (2006, 2007) have presented in successive publications improved solutions to accurately determine how much of each pixel should be assigned to each of these two regions. In order to facilitate the evaluation, the authors use IKONOS images to delineate the actual position of the shore. These images are then degraded to pixel sizes similar to SPOT-3 images (20 m/pixel) (Foody et al., 2005; Muslim et al., 2006) or to Landsat TM images (30 m/pixel). The tests were conducted on a 125 m section along the coast of Indonesia. The root mean square error (RMSE) of the shoreline predictions from the two-point histogram method – the method that obtains the best results – is found to be in the range of 1.15–2.08 m and 1.71–5.11 m when imagery with 16 and 32 m/pixel of spatial resolution is used, respectively (Muslim et al., 2007). In previous works (Pardo-Pascual et al., 2008; Ruiz et al., 2007) a shoreline extraction algorithm at the subpixel level was proposed and evaluated using high-resolution imagery (QuickBird) degraded to 28 m/pixel to approximately emulate Landsat TM images. However, from a practical point of view, it is not enough to assess the shoreline detection algorithm from an image, as a minimum geometric accuracy in the georeferencing of the images is required to ensure the applicability between successive shorelines.

The aim of this paper is to propose a complete methodology to extract shorelines from successive Landsat images of the same location and to determine the level of precision that can be achieved. We describe a subpixel shoreline extraction algorithm, together with a high-precision image registration method, and evaluate the accuracy degree of the integrated methodology directly over Landsat TM and ETM images.

2. Evaluation area

A principal requirement for the selection of evaluation areas was to ensure that no changes occurred in the position of the shoreline during the period of acquisition of the Landsat image set available (1984–2010). A sector of the coast that was artificially and permanently stabilised was chosen for this purpose. This sector is 20 km long and is located on the Spanish Mediterranean coast, extending from the port of Castelló de la Plana to the port of Borriana (Fig. 1).

This is a microtidal coast, the average tidal range is less than 25 cm and the maximum positions of sea level over a year do not exceed 80 cm (Puertos del Estado, 2009). The average waves affecting the sector under study have relatively low energy levels (the average significant wave height is 0.7 m and the average peak wave period is 4.2 s). However, wave height during storms can reach up to 5 m and the peak period may extend to 15 s (wave data obtained from Spanish State Port Authority database: http://www.puertos.es/oceanografia_y_meteorologia/redes_de_medida/index.html). Artificial rock seawalls have been built over the past 50 years to stop erosion around the downdrift piers and thereby stabilising the shoreline. In fact, approximately 11 km of the 20 km of surveyed shoreline has been artificially protected with rock seawalls (Fig. 1).

The analyses were focused on three coastal segments permanently stable during the period 1984–2010. The first segment, termed Seawall 1, is located immediately south of the port of Castelló de la Plana and extends 2.9 km. The port of Castelló de la Plana was expanded after 2005 and a part of this breakwater was immersed in the port. Industrial facilities have been built on the coast and there are small installations such as piers and loading points. As a result, the shoreline is not completely continuous and appears curved in some places (an example can be seen in Fig. 10). The second segment – termed Seawall 2 – is 2.4 km long. Farmland borders the shoreline (Fig. 6). The third segment is 2.73 km long and starts immediately south of the docks at Borriana. The shoreline is also straight and the adjacent land is urban in the north and farmland to the south. In 2005, a detached breakwater was built enabling the creation of a small beach (indicated with a yellow circle in Fig. 1). This area was excluded from the evaluation after this date.

3. Data

All images used for the evaluation of the methodology were downloaded from the USGS database at: http://earthexplorer.usgs.gov/; and are catalogued by the Landsat program as L1T product (NASA, 2006). As reported by NASA, this product is georeferenced with a level of precision better than 0.44 pixels (meaning 13.4 m).