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Using GPS-surveyed intertidal zones to determine the validity of shorelines automatically mapped by Landsat water indices

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ABSTRACT

Satellite remote sensing has been used extensively in a variety of shoreline studies and validated using aerial photography. This ground truth method only represents an instantaneous depiction of the shoreline at the time of acquisition and does not take into account the spatial and temporal variability of the dynamic shoreline boundary. Landsat 8′s Operational Land Imager sensor's capability to accurately delineate a shoreline is assessed by comparing all known Landsat water index-derived shorelines with two GPS-surveyed intertidal zones that coincide with the satellite flyover date, one of which had near-neap tide conditions.

Seven indices developed for automatically classifying water pixels were evaluated for their ability to delineate shorelines. The shoreline is described here as the area above and below maximum low and high tide, otherwise known as the intertidal zone. The high-water line, or wet/dry sediment line, was chosen as the shoreline indicator to be mapped using a handheld GPS. The proportion of the Landsat-derived shorelines that fell within this zone and their alongshore profile lengths were calculated. The most frequently used water index and the predecessor to Modified Normalized Difference Water Index (MNDWI), Normalized Difference Water Index (NDWI), was found to be the least accurate by a significant margin. Other indices required calibration of their threshold value to achieve accurate results, thus diminishing their replicability success for other regions. MNDWI was determined to be the best index for automated shoreline mapping, based on its superior accuracy and repeatable, stable threshold value.

1. Introduction

Landsat imagery has been used for decades to study various earth system processes; one of significant importance is shoreline change. With the onset and acceleration of climate change and measured increases in global air and sea surface temperatures, sea level is rising at an alarming rate due to thermal expansion and ice melt (IPCC, 2014; Nicholls and Cazenave, 2010). The positions of global shorelines are expected to transgress as sea level rises, posing a significant threat to public health (Mendez-Lazaro, 2012; Ziska et al., 2003), socio-economics of coastal communities (Lane et al., 2013; Stern, 2006), coastal ecosystems (Gontz et al., 2013; Hernández-Delgado, 2015; Maio et al., 2014), and sites of cultural heritage (Gontz et al., 2011; Maio et al., 2012). Applications of various remote sensing techniques have been used to delineate variable shoreline positions to confront these issues. Remote sensing data was used to analyze the fifty-year evolution of the Guianese shoreline to understand the dynamics of mangroves (Fromard et al., 2004), impacts of river dams on coastal erosion processes and ecological equilibrium of the Niger Delta (Kuenzer et al., 2014), and to understand the impacts of a reduction in river sediment discharge on the Chongming Dongtan National Nature Reserve coastline in China as a prerequisite for an integrated management plan (Li et al., 2014).

High-resolution aerial photography has been used as reference data for decades in various coastal studies such as analyzing short-term shoreline changes (Ford, 2013; Jimenez et al., 1997; Pradjoko and Tanaka, 2010), projecting future shoreline positions (Addo et al., 2008; Fenster et al., 1992; Leatherman, 1983), and calculating long-term shoreline recession rates (Dolan et al., 1979; Dolan et al., 1991; Smith and Zarillo, 1990). Although aerial photography provides a very high-resolution image of the shoreline, it only captures the instantaneous position at the time of acquisition. This poses a problem for analyzing changing shoreline positions in areas where the land/water boundary can fluctuate tens of meters across the beach face daily (Romine et al., 2009). Other survey methods have been employed to delineate the position of shorelines including LiDAR (Light Detection and Ranging; Liu et al., 2007; Yang et al., 2012), SAR (Synthetic Aperture Radar; Trebossen et al., 2005; Yu and Action, 2004), and beach profiling (Corbella and Stretch, 2012; Ruggiero and List, 2009). While all of the

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above techniques offer fine spatial resolution, the cost and/or time of data acquisition are excessively high and all but prohibit them as practical methods for change analysis with high spatial variability over short temporal scales.

In response to the limitations of previous survey methods, satellite remote sensing has been used extensively in a variety of shoreline studies (Garcia-Rubio et al., 2015; Kuleli et al., 2011; Pardo-Pascual et al., 2012). This method provides a more practicable approach to delineating shoreline positions over various spatial and temporal scales (Almonacid-Caballer et al., 2016; Hegde and Akshaya, 2015; Li and Gong, 2016). Several spectral indices have been developed for automatically extracting water pixels from Landsat imagery. Zhai et al. (2015) compared the performance of these spectral indices and concluded that the Automated Water Extraction Index (AWEI) and Modified Normalized Difference Water Index (MNDWI) indices perform better than the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI) by comparing extraction results to shorelines manually interpreted from high-resolution DigitalGLobe Quickbird imagery. Fisher et al. (2016) performed a similar comparative analysis using high-resolution imagery and concluded that $AWEI_{sh}$, MNDWI, and their newly developed index, WI_{2015}, were the most accurate water classification indices.

Like Zhai et al. (2015), the majority of Landsat shoreline studies use high-resolution aerial photography to validate the shoreline location derived from the various extraction techniques (Almonacid-Caballer et al., 2016; Ghoneim et al., 2015; Li and Gong, 2016). Some studies did not even attempt to corroborate their shorelines with reference data (Dada et al., 2016; Hegde and Akshaya, 2015). A separate ground-based dataset is essential to understanding and validating the performance of any remote sensing product (Lillesand et al., 2015).

The biggest complication of using high-resolution aerial photography as validation data is that the instantaneous depiction of the shoreline at the time of acquisition does not consider the spatial and temporal variability of the shoreline boundary. The assumption that the shorelines observed in these images represent "normal" conditions is the most substantial and likely incorrect assumption in many shoreline investigations (Boak and Turner, 2005), even more so for those using Landsat. Over a given tidal cycle and depending on beach geometry, a shoreline can fluctuate centimeters to hundreds of meters in a horizontal direction. Over longer time scales (months to years), major storms and anthropogenic activities can move a shoreline significantly landward. As such, the shoreline is an extremely dynamic boundary that exhibits significant short and long-term spatial fluctuation (Morton, 1991). In most published Landsat shoreline studies, aerial photography used as validation data is not collected during the same day as the satellite flyover. It can reasonably, and should be, assumed that the actual shoreline position during the aerial photography and Landsat acquisition days are not identical based on the natural variability of the boundary through the stage and range of tides, wind, and prevailing wave energy (Pajak and Leatherman, 2002). Therefore, using aerial photography as validation data for Landsat-extracted shorelines is likely not ideal.

1.1. Purpose

To overcome this limitation and truly test the capability of using Landsat to accurately define and describe changing shoreline positions, this paper uses GPS surveying to validate Landsat-derived shorelines. The shoreline boundary is best described as the area above low and below high tides and as such, the maximum of both of these stages is mapped using GPS. The intertidal zone GPS survey data and Landsat 8 imagery were collected within hours of each other to ensure the best possible temporal correlation. Seven water indices are assessed for their ability to delineate the shoreline with the overarching goal of identifying an index best suited for the task.

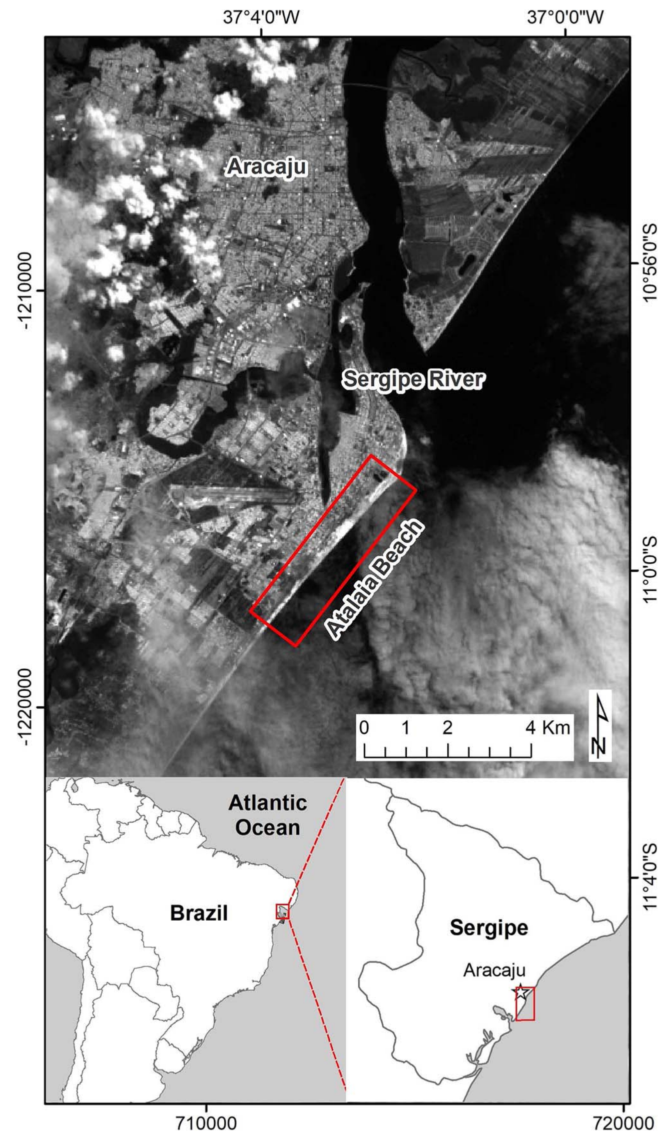

Fig. 1. Aracaju, Brazil – Location of the study area, Atalaia Beach, Aracaju, Sergipe, Brazil. Landsat 8 band 7 used as basemap (acquired on July 11, 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

1.2. Study areas

This analysis was applied to a 5 km stretch of Atalaia Beach in Aracaju, Sergipe located in the northeastern region of Brazil (Fig. 1). This region of Brazil is a classic example of a wave-dominated coastline with minimal tidal and river influence (Bhattacharya and Giosan, 2003; Dominguez, 1996; Wright and Coleman, 1973). The beach consists of clastic sediment predominantly composed of fine grained, well-rounded and well-sorted quartz with small amounts of feldspar and trace amounts of mica and magnetite grains. The shoreline experiences a micro- to meso- tidal range (up to 2.5 m) and a falling sea level since the mid-Holocene highstand around 5.1 kya (Dominguez et al., 1992; Martin et al., 2003). The low-lying urban area of Aracaju is located adjacent to the beach and is at the greatest risk of flooding in northeastern Brazil (Muehe, 2010).

A second shoreline was surveyed along a 5 km stretch of the Salisbury State Beach Reservation in Salisbury, Massachusetts, USA (Fig. 2). The beach is a part of the larger Merrimack barrier system that extends to Cape Ann, Massachusetts to the south and Great Boars Head, New Hampshire to the north and has been well studied (Costas and