Applied Geography 55 (2014) 278–291

Contents lists available at ScienceDirect

Applied Geography

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

A public, open Western Europe database of shoreline undulations based on imagery

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A R T I C L E I N F O

Article history:
Available online

Keywords:
Shoreline undulations
Open data
Western Europe
Geographic feature
Data-mining

A B S T R A C T

Beaches around the world frequently exhibit a wide variety of shoreline morphological features of different dimensions, and increasing attention has been focused on shoreline undulations in recent years. Shoreline undulations (SUs) are medium to large spatial-scale features with longshore dimensions ranging from hundreds to thousands of meters and cross-shore widths ranging from tens to hundreds of meters. This work presents a public, open database with a total of 294 sites showing SUs identified using Google Earth Imagery along 50,000 km of Western European and Northwestern African coasts. Insights from regional, geometrical and hydrodynamic analyses are also presented to explore the potential of using the methodology for geographic studies occupying large extensions. The database contains information on 17 fields and is shared in a suitable and open format. Denmark exhibits the most features, followed by Spain and Italy. SUs ranging from 50 to 100 m in length and below 25 m in width are predominant, whereas SUs larger than 1000 m in length and 50 m in width are of minor importance. A total of 223 (76%) sites exhibit a series of one, two or three individual undulations, whereas the rest show more than three. The existence of SUs greatly depends on the tidal range, with lower (higher) tidal ranges indicating a higher (lower) number of undulations. A detailed analysis for the Spanish case was performed focusing on the relation between the presence of SUs and climate variables. The results show that SUs are more frequent where the wave energy is lower and the wave periods are shorter. An additional data mining analysis with association rules was conducted to corroborate the relationships between variables.

Introduction

Coasts represent some of the most dynamic environments on earth, and 84% of the countries of the world have a coastline adjacent to open oceans, inland seas or both (Martínez et al., 2007). Coastlines develop a wide range of morphologies depending on many factors, such as forcing conditions, characteristics of the forming materials and regional geology (Carter & Woodroffe, 1997; Woodroffe, 2002). Bird (2010) recently published an extensive updated revision of worldwide coastal morphologies. Global and regional studies have identified and analyzed the main characteristics of such coastal morphologies (e.g., cliffs, beaches, estuaries, lagoons). Among them, beaches have been the most studied because of their social, economic and environmental interest (Davis & Fitzgerald, 2009). Beaches are frequently found on rectilinear or slightly curved coasts, although they can also appear in other environments, such as estuaries, deltas or river mouths (Bird, 2011). Beaches have been intensively analyzed morphologically, with special attention given to both the beach form and profile (Dean & Dalrymple, 2002) and the morphological state (Masselink & Short, 1993).

Many studies have also analyzed the generation, evolution and characteristics of secondary shoreline features (Coco & Brad Murray, 2007) that many beaches exhibit. Secondary features can be parallel or perpendicular to the shoreline and may have different geometrical characteristics (Pethick, 1989). Recent attention has focused on shoreline undulations (hereafter referred to as SUs), which can be defined as medium to large spatial-scale shoreline features that have longshore dimensions ranging from hundreds to thousands of meters and cross-shore widths ranging from tens to hundreds of meters (Ortega-Sánchez, López-Ruiz, Baquerizo, & Losada, 2015; see Fig. 3). SUs are generally classified as rhythmic

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http://dx.doi.org/10.1016/j.apgeog.2014.09.018
0143-6228/

coastline features, although some are neither periodic nor regularly spaced (López-Ruiz, Ortega-Sánchez, Baquerizo, Navidad, & Losada, 2012). SUs are frequently associated with sudden changes in the orientation of the coast, such as at spits (Kaergaard & Fredsoe, 2013), and are often located in proximity to human infrastructures (López-Ruiz, Ortega-Sánchez, Baquerizo, & Losada, 2012). Many authors have referred to SUs as shoreline sand waves; however, shoreline sand waves are generally considered to be rhythmically spaced, and they migrate alongshore (Davidson-Arnott & Van Heyningen, 2003; Stewart & Davidson-Arnott, 1988).

The mechanism(s) behind the formation and the dynamics of SU are not well understood, but the working hypothesis adopted in recent years is that coastlines with a wave climate dominated by very oblique incidence waves may be unstable and commonly feature large-scale undulations (Ashton & Brad Murray, 2006; Ashton, Brad Murray, & Arnault, 2001; Medellín, Medina, Falqués, & González, 2008). Recent advances reveal that variation in the alongshore sediment transport with the angle formed by the wave crests and the coastline plays a major role in the development of SU (López-Ruiz, Ortega-Sánchez, Baquerizo, Navidad, et al., 2012). In this respect, the curvature of the coastline seems to play a key role in the formation of such features (López-Ruiz, Ortega-Sánchez, Baquerizo, & Losada, 2014).

Compared to other general beach characteristics, such as the morphological state (Scott, Masselink, & Russell, 2011), or other shoreline features, such as beach cusps (Coco, O'Hare, & Huntley, 1999), a global compilation of sites that contains SU information for scientific and management purposes is not available. Stakeholders, managers and politicians are all involved in preserving coastal features. From an operational perspective, a massive sample collection of shoreline features can aid in understanding how coastlines form and developing new tools.

The advances in modeling the natural processes responsible for geographic processes are strongly related to the quality, availability and temporal and spatial scale of the data, such as in the cases of forests (Song, 2013), benthic habitats (Godet, Fournier, Toupoint, & Olivier, 2009) and soil mapping (Dewitte, Jones, Elbelrhiti, Horion, & Montanarella, 2012). They are generally studied by remote sensing and by the analysis of statistical surveys and field data integrated with historical maps (Carretero, Braga, Kruse, & Tosi, 2014; Messerli, Giger, Dwyer, Breu, & Eckert, 2014). Satellite remote sensing is valuable for providing cost-effective information (Borrelli et al., 2014; Emel, Plisinski, & Rogan, 2014; Kuenzer, van Beijma, Gessner, & Dech, 2014). Nevertheless, the satellite spatial resolution can be too coarse for detailed mapping and for distinguishing local variability, while very high-resolution satellite imagery is very expensive. Additionally, the inclusion of this type of data into large and readily accessible geo-referenced databases is rapidly growing, but the methodological frontiers are still advancing.

Developing large databases is not a trivial task because raw data are frequently unavailable, and accumulating and verifying the data are lengthy and tedious tasks (Gajewski, 2008). Additionally, the movement towards open-source databases is not straightforward (Goff & Chague-Goff, 2014). Although databases related to paleoenvironmental, hydrological or land-use are growing (MacDonald et al., 2008; Maetens et al., 2012; Wan et al., 2014), many works demonstrate the frequent absence of databases related to morphological and terrain features, both at regional and global scales (Bhambri & Bolch, 2009; Butler, Hewes, Liknes, Nelson, & Snyder, 2014; Rozenstein & Karnieli, 2011). Although many advances have been made during the last few years at local, regional or country scales (i.e., Brown, 2012; Messerli et al., 2014), such databases are frequently based on satellite images covering very few years and commonly have inconsistencies that have to be revised (Portillo-Quintero, Sanchez, Valbuena, Gonzalez, & Larreal, 2012). Despite these issues, their potential and interest for the scientific community keeps growing with many different examples and applications (i.e., Delmelle, Zhu, Tang, & Casas, 2014; McCool, 2014; Widener & Li, 2014; Yu et al., 2013).

The main objective of this work is to explore the potential of using imagery for geographic studies implicating large extensions, with a particular emphasis on coastal studies. To that end, we present a database of identified and characterized SUs created after reviewing a total of approximately 50,000 km of coast in Western Europe and Northwestern Africa. This database is free, public and available for the scientific community and can be used to gain deeper insight into coastal morphodynamic processes. This paper also presents analyses that can be obtained using the collected data; this information constitutes a valuable dataset for coastal areas.

Methodology

Region of study

We analyzed the coastlines of Western Europe and Northwestern Africa to identify SUs (Fig. 1). A total of approximately 50,000 km of coast was investigated. For the analysis, we used images from the Google Earth imagery database. Google Earth maps the earth by the superimposition of images obtained from satellite imagery, aerial photography and GIS 3D globe and is freely available. The resolution for the sites analyzed in this work is <1 m/pixel; certain images had a resolution on the order of cm/pixel. For sites where the visibility or quality of the images was inadequate, satellite images from other virtual globes such as Bing or Nokia were reviewed.

Google Earth hosts high-resolution imagery and allows the development of practical methods for studying the regions of interest in which a coarser resolution is insufficient. Google Earth has been recognized for its potential to significantly improve the visualization and dissemination of scientific data since its origin in the year 2005 (Butler, 2006).

Thus, several scientific works have been published that use and compare this new tool with existing systems. Yu and Gong (2012) presented a review of Google Earth in earth sciences research. However, several concerns related to the limitations of Google Earth (Thenkabailc et al., 2007) were briefly noted (i.e., the absence of very-high resolution imagery for every location in the world or the presence of images from varying dates).

Although Google has been unwilling to release detailed information on any of these aspects of their holdings, Potere (2008) stated that the positional accuracy is more than sufficient for medium-scale features and that no geo-correction is required. This study addressed the trustworthiness issue in Google Earth's horizontal positional information via a comparison with that of Landsat GeoCover. The study was carried out in 2008 with 436 control points. Our area of study (i.e., Europe) had an accuracy of 25.7 m RMSE.

Furthermore, due to the constant evolution of this platform, the imagery has been improved several times over the last few years. Google Earth has attempted to overcome some of the initial limitations. For example, Google has attempted to enhance the imagery with new providers and better resolution. Most of the current providers offer spatial resolutions of less than 10 m. A more recent work studied Google Earth's accuracy compared with that of high-precision field measurements in a region of Texas (Benker, Langford, & Pavlis, 2011), and a horizontal position accuracy of 2.46 m RMSE was determined. This value is an order of magnitude greater than the smaller dimensions of SUs (see the definition of SUs in Section 1).