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Journal of Maps

ISSN: (Print) 1744-5647 (Online) Journal homepage: http://www.tandfonline.com/loi/tjom20

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To cite this article: Fernando M. G. Martins, Helena M. Fernandez, Jorge M. G. P. Isidoro, Antonio Jordán & Lorena Zavala (2016) Classification of landforms in Southern Portugal (Ria Formosa Basin), Journal of Maps, 12:3, 422-430, DOI: 10.1080/17445647.2015.1035346

To link to this article: https://doi.org/10.1080/17445647.2015.1035346

Journal of Maps, 2016
Vol. 12, No. 3, 422–430, http://dx.doi.org/10.1080/17445647.2015.1035346

SCIENCE

Classification of landforms in Southern Portugal (Ria Formosa Basin)

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(*Received 22 December 2014; resubmitted 18 March 2015; accepted 25 March 2015*)

A Geographic Information Systems-based tool is used for macro-landform classification following the Hammond procedure, based upon a Digital Terrain Model (DTM) created from ordinary Kriging. Gentle slopes, surface curvature, highlands and lowlands areas are derived from the DTM. Combining this information allows the classification of terrain units (landforms). The procedure is applied to the Ria Formosa basin (Southern Portugal), with five different terrain types classified (plains, tablelands, plains with hills, open hills and hills).

Keywords: landform classification; Hammond; Dikau; DTM; Ria Formosa

1. Introduction

Geomorphic events (e.g., erosion, sedimentation, landslides) may represent threats to people and economic activities. A deeper knowledge of the genesis of these events is thus crucial for finding adequate tools able to mitigate those threats. Within the last decades, Geographic Information Systems (GISs) supported by Digital Terrain Models (DTMs) have shown a marked importance in environmental and land management. DTMs are also important resources for the identification and modelling of geoforms, that is, the land units resulting from the endogenous and exogenous (natural) processes that shape the Earth's surface.

The Mediterranean region is characterised by having seasonal climate and specific ecological and edaphic conditions that make it one of the most vulnerable ecosystems in Europe, this is, namely, due to the fragility of the ecosystems and the low rates of biomass production during dry periods (e.g. Zachar, 1982). A profound knowledge of Mediterranean topography, at different scales, is thus essential to, for example, set control, prevention and correction measures for soil conservation, and to mitigate the occurrence and intensification of desertification. This process, which can become irreversible, has already occurred in some areas of the Mediterranean region (e.g. Kosmas, Danalatos, & Gerontidis, 2000; Rubio & Calvo, 1996).

Geomorphic studies allow for a deeper knowledge of the natural environment. One example is the modelling of geomorphic terrain units (landforms), considered important for the study of

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environmental and ecological processes (Martins, 2012), with several approaches to classifying landforms. Early studies were mostly manual-based and supported by the analysis of land surface parameters on topographic maps, or directly through field measurements (e.g. Crozier & Owen, 1983; Hammond, 1954, 1964a, 1964b; Linton, 1968; Wallace, 1955). According to Hammond (1964a), the best methods for classification require a systematic analysis of the terrain, describing each component individually. Hammond's geomorphometric and geomorphic studies were conducted in large areas (small scale), using quantitative variables and hierarchical classification. Later, with the emergence of GIS, Dikau updated and automated Hammond's procedures, ranking the landforms in terms of size, order and geometric complexity (e.g. Dikau, 1989; Dikau, Brabb, & Mark, 1991). Since then several researchers have followed this methodology (e.g. Barka, Vladovič, & Máliš, 2011; Brabyn, 1998; Jordán & Bellinfante, 2000; Jordán, Zavala, Bellinfante, & González, 2005; Tinós, Ferreira, Riedel, & Zaine, 2014).

In addition to the Hammond-based procedure, several other methodologies have been used with accurate results to analyse and classify landforms (Martins, 2012). Pellegrini (1995) developed a classification algorithm using eigenvectors and Fourier transformation. Maguire (2005) used principal component analysis (PCA) to evaluate which topographic features were relevant for landform definition (e.g. slopes, bends, aspect, roughness, local relief). This landform definition was used to train a fuzzy ARTMAP neuronal network for landform classification. Drăguţ & Blaschke (2006) used fuzzy logic algorithms to process the segmentation of homogeneous regions derived from a DTM. Oliveira and Santos (2009) applied high-pass and low-pass spatial filters to a DTM with different levels of information used for intensity-hue-saturation (IHS) image fusion or segmentation-by-region growing techniques.

The aim of this research is to develop a methodology, based on the Hammond and Dikau procedures, for the classification of landforms in the Ria Formosa basin in Southern Portugal (Figure 1), following other studies on the south of the Iberian Peninsula (e.g. Martinez-Zavala, López, & Sanmiguel, 2007; Paixão, 2012). The Ria Formosa basin landform map is presented at a 1:60,000 scale (see: Main Map). The 17 terrain units are shown with different colours: green, gentle and low-lying areas; pink, intermediate zones; yellow and red, rougher areas and highlands. To enhance the virtual sense of relief, the colour representation is draped over a hillshade with a solar elevation of 45° and an azimuth of 30°. The map includes the position of 10 localities to assist spotting the landforms.

2. Study area

The Ria Formosa basin is located in the extreme south of mainland Portugal (N 36° 57′ to N 37° 15′ and W 7° 28′ to W 8° 04′) and has an area of 86,400 ha and a perimeter of 166 km, including a complex of coastal saltwater lagoons and barrier islands with an area of about 16,000 ha. The coastal lagoons are protected by European Union and Portuguese Laws and classified as a Wetland of International Importance under the RAMSAR convention (PORTUGAL Ramsar

Figure 1. Ria Formosa basin (view from Monte Figo to S).

Site 212). This area is of particular importance for numerous species of breeding, wintering and staging waterbirds.

The basin is characterised by a gentle and homogenous topography without abrupt changes in altitude. The average slope is 11% and the elevation ranges from 0 to 530 m above sea level. The region is divided into three distinct geological areas (from N to S): the mountains of Serra do Caldeirão with lithosols are mainly shale-greywacke and shale-clay; the sections with calcareous soils are called Barrocal; the coast with the system of barrier islands and a sandy coastline extending to the outlet of the Guadiana River into the Atlantic Ocean.

3. Methods

The basic source of information for this study was a 1:25,000 map with contour lines and discrete elevation points (Geographical Institute of the Portuguese Army; IGeoE, 2004). The DTM of the Ria Formosa basin (10 m resolution) was created using ordinary Kriging, with the variogram based on a spherical model (Figure 2). Several land surface parameters such as gentle slope, local relief, curvature and relative vertical position were modelled for each point of the DTM. The automatic classification of landforms was carried out following the methodology established by Hammond and Dikau, with some modifications: (1) slopes below 4% were classified as 'gentle slopes' to produce results homogenous and comparable to the obtained by Hammond and Dikau; (2) a curvature map was used to create the relative vertical position map with less steps than the original method, where the low and high areas (as defined by Hammond and Dikau) were represented, respectively, by concave and convex surfaces; (3) adjustments to the classes of landforms were required due to the resolution of the DTM and the smoothness and

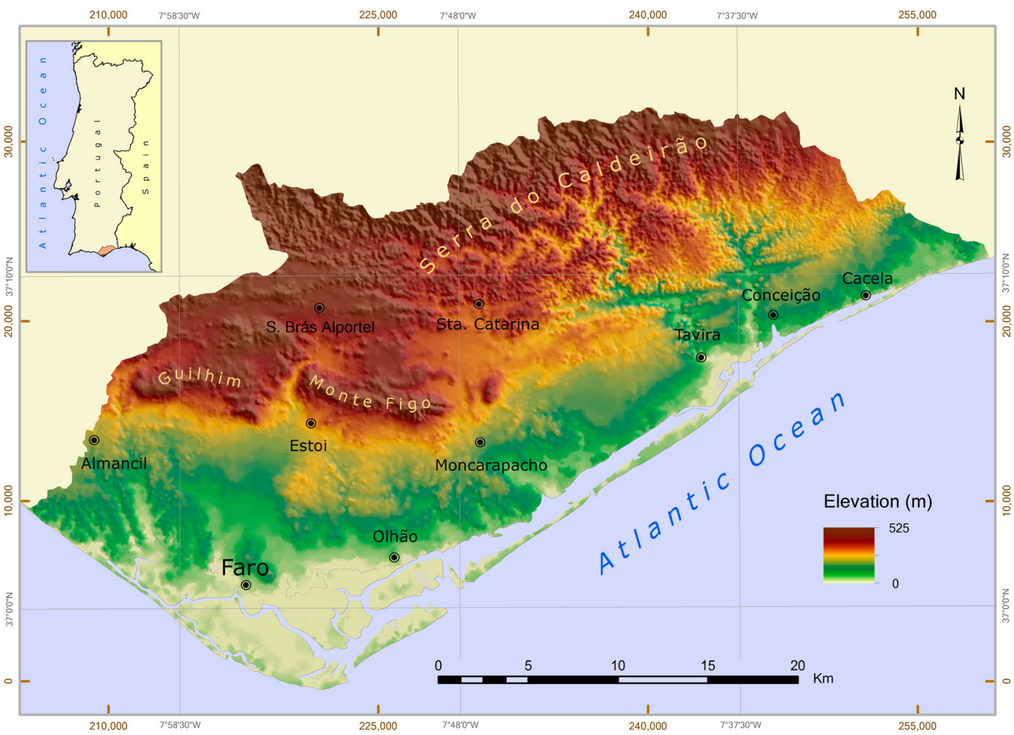

Figure 2. DTM of the Ria Formosa basin.

Table 1. Classes of gentle slopes in the Ria Formosa basin.

Code	Gentle slopes (%)
A	>80
B	50–80
C	20–50
D	<20

regular relief of the Ria Formosa basin. 'Very irregular plains', 'very low and smooth open hills' and 'very low and smooth hills' classes were created. 'Flat or nearly flat plains' were split into 'flat plains' and 'nearly flat plains'. 'Tablelands and plains with hills' were not divided into subclasses.

3.1. *Gentle slope map*

The slope of each pixel of the basin area was calculated using the elevation values of its neighbouring pixels, at the spatial resolution of the DTM (see Monmonier, 1982). A 'moving window' technique with a matrix of 7 × 7 was then used over the slope map. For each window, the percentage of gentle slopes (below 4%) was found and assigned to the central pixel of the window. After this process, the 'gentle slopes' categories were reclassified (Table 1) and the corresponding map produced (Figure 3).

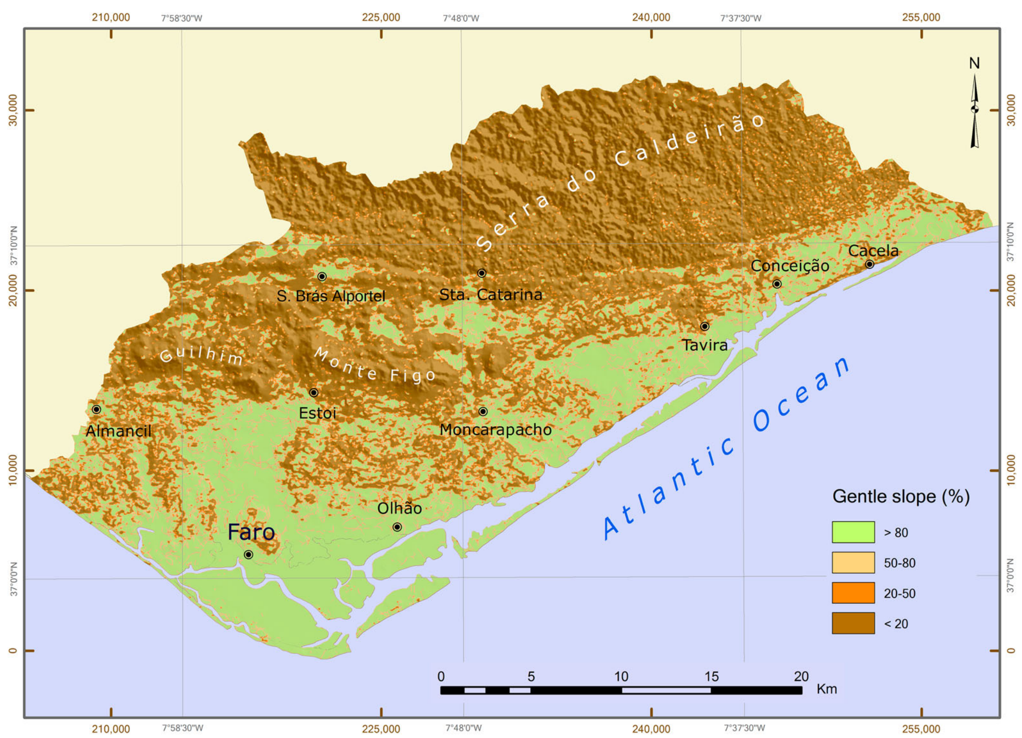

Figure 3. Gentle slope map of the Ria Formosa basin.

Table 2. Classes of local relief in the Ria Formosa basin.

Code	Local relief (m)
1	0–15
2	15–30
3	30–90
4	90–150
5	150–220

3.2. *Local relief map*

A ‘moving window’ technique with a 7 × 7 convolution matrix was used to obtain the range of elevations directly from the DTM. The range of elevations was reclassified according to Table 2. The local relief map was generated following this procedure (Figure 4).

3.3. *Relative vertical position map*

A 7 × 7 Laplacian filter was used over the DTM to find the slope’s rate of change (curvature). The negative and positive values indicate, respectively, concave and convex surfaces. According to the Hammond procedure, only areas with a majority of gentle slopes were considered (to divide the gentle slope shapes of the terrain, separating the ‘tablelands’, as upland units, from the ‘plains with hills’, as lowland units, see Dikau et al., 1991). Table 3 shows the classes of gentle slopes on concave and convex hillsides.

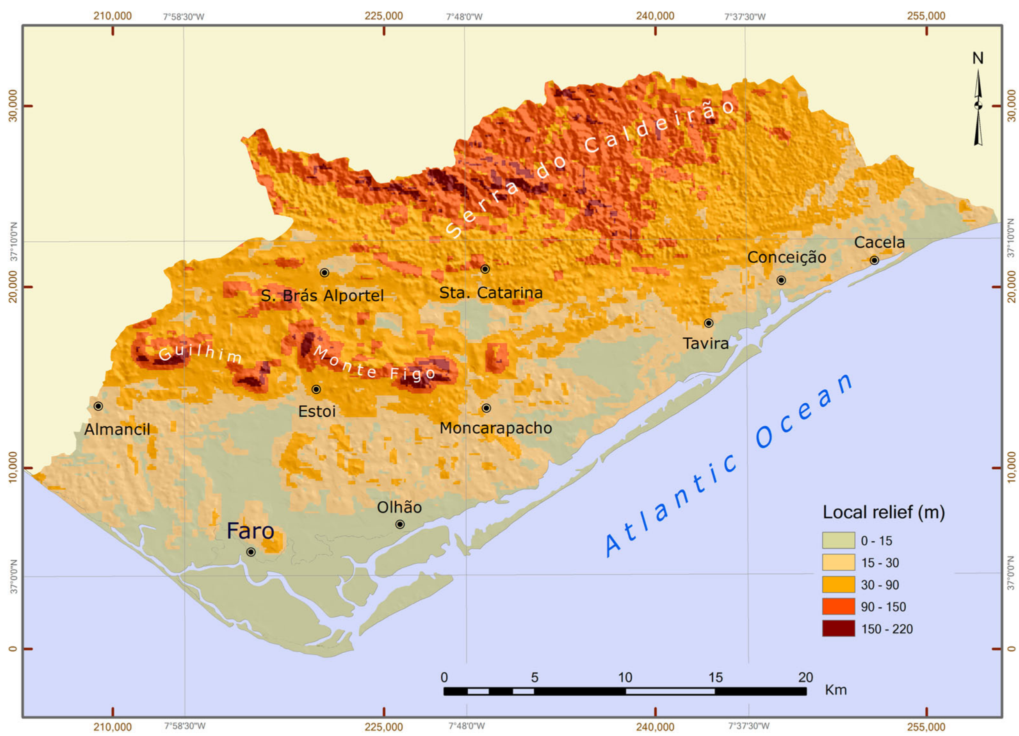

Figure 4. Local relief map of the Ria Formosa basin.

Table 3. Classes of relative vertical position in the Ria Formosa basin.

Code	Relative vertical position
a	>50% of gentle slopes on concave hillsides
b	>50% of gentle slopes on convex hillsides

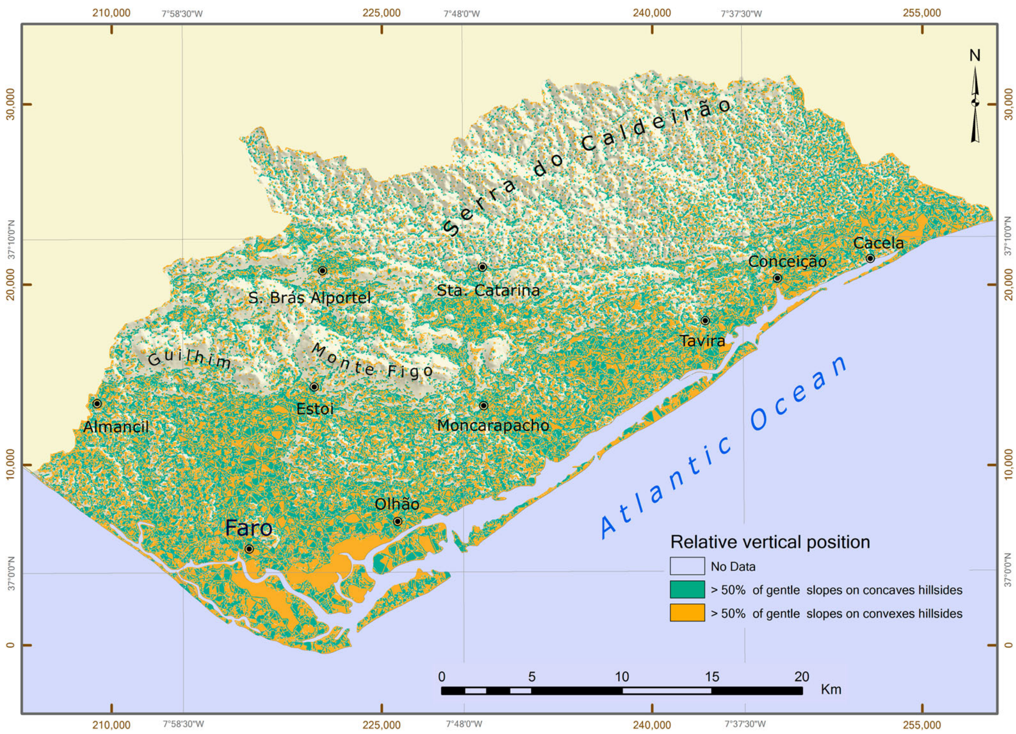

Figure 5. Relative vertical position map of the Ria Formosa basin.

Overlaying the curvature and gentle slope maps, it was then possible to produce the relative vertical position map (Figure 5).

3.4. *Landforms map*

The map of landforms was obtained by overlaying the maps of gentle slopes (Figure 3), local relief (Figure 4) and relative vertical position (Figure 5). Five main landforms were mapped: plains, tablelands, plains with hills, opens hills and hills. These were divided into 17 subclasses (Table 4). The nomenclature follows Hammond (1964a) and Dikau, Heidelberg, Mark, Pike, and Park (1995) with slight changes.

The three most representative landforms in the basin area are low hills (27.4%), flat plains (17.3%) and moderate hills (15.6%). The low hills and moderate hills are mainly on the mountains of Serra do Caldeirão. The flat plains are on the coast, next to the coastal lagoons and along the leeward coast.

Table 4. Classes, subclasses, codes and areas of landforms in the Ria Formosa basin.

Class	Subclass	Code	Area (%)
Plains	Flat plains	A1	17.3
	Nearly flat plains	A2	8.0
	Smooth plains	A3	1.9
	Slightly irregular plains	B1	3.3
	Irregular plains	B2	6.4
	Very irregular plains	B3	3.0
Tablelands	Tablelands	A4b,A5b,B4b,B5b	0.1
Plains with hills	Plains with hills	A4a,A5a,B4a,B5b	0.1
Open hills	Very low and smooth open hills	C1	0.5
	Very low open hills	C2	3.9
	Low open hills	C3	4.5
	Moderate open hills	C4,C5	0.4
Hills	Very low and smooth hills	D1	0.3
	Very low hills	D2	5.6
	Low hills	D3	27.4
	Moderate hills	D4	15.6
	High hills	D5	1.7

4. Conclusions

This paper presents a methodology based on GIS tools for the detection and classification of landforms in the Ria Formosa basin (southern of Portugal). A DTM is used as the starting point for an automatic classification of landforms based on the procedures of Hammond and Dikau. The spatial distribution of gentle slopes, local relief and relative vertical position are combined to automatically identify distinct landforms. This methodology has shown to be effective for the classification of landforms. Also, it allows for easy and fast visual analysis. The results show that this method allows the reliable identification of the main landforms, with high-detail. In this particular example, the final map presents 17 subclasses of landforms.

The resulting map, which reflects the main physical and structural differences of the Ria Formosa basin, can be of substantial interest for the definition of hazard mitigation strategies (e.g. prevention and fighting of forest fires and control of the consequential soil, hydrological modelling for flood management purposes).

At the present stage, the authors are working with higher-resolution DTMs with which it will be possible to distinguish landforms with a smoother relief (e.g. saltmarshes, usually classified as flat plains surfaces).

Software

IDRISI Taiga software (Clark Labs, Clark University, 2009) was used as the analysis platform for modelling landforms. Esri ArcGIS 10.1 was used to design the maps.

Acknowledgements

The authors wish to thank the MED_SOIL Research Group for all support offered during fieldwork and the IGeoE for providing the information needed to create the DTM.

Disclosure statement

No potential conflict of interest was reported by the authors.

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