**Recognition and mapping of lacustrine relict coastal features using high resolution aerial
photographs and LiDAR data**

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Abstract

Shallow lakes in semiarid regions experience frequent water level fluctuations. Each long-lasting episode of water-level lowering leaves behind abandoned littoral forms and deposits whose identification and mapping is hampered by their smooth relief. Given the difficulty of recognising these possible relict forms using traditional geomorphological techniques, two sources of information were employed in the present work: high resolution (1:15 000) aerial photographs and a digital terrain model (DTM) generated from LiDAR data. The improved definition of surface elevation enhanced the quality of geomorphological mapping as well as the accurate delineation of subtle geoforms. The method was applied to Gallocanta Lake, a highly fluctuating shallow lake 14 km² in area and less than 3 m deep located in a mountainous semiarid area of NE Spain. As a result, a sequence of relict coastal features (RCF) with high lateral continuity has been identified around the lakebed. These include well-preserved spits with recurved hooks, counter-spits, bays closed by barrier islands, beach ridges, deltas and cliffs. The highly precise LiDAR-derived topographic maps suggest a much greater extension of the lacustrine environment during the Late Pleistocene, reaching at least 51 km² of water surface and about 13 m of depth above the present lake bottom. The method presented in this paper generates very detailed palaeogeographical maps that are particularly useful for reconstructing lake changes in semiarid environments as a function of climate change.

Key words: DEM; Coastal mapping; Lake margin; Photointerpretation

Introduction

Water level fluctuations in shallow lakes generate coastal forms with subtle relief that are difficult to distinguish using traditional geomorphological methods. Identifying these littoral landforms requires high-resolution topographic data and their processing requires both advanced digital data and analysis methods. Digital elevation models (DEM) are important inputs to geomorphometric studies, especially thanks to the general increase in the amount of DEM data available through different collection techniques (Smith 2011). The widespread use of geographic information systems and the availability of high-resolution digital land surface data have led to a revolution in the geomorphological methods used to recognise and map geoforms (Otto et al. 2013).

High-resolution DEMs generated from light detection and ranging (LiDAR) systems, in combination with detailed orthophotographs, have been used to refine geomorphological interpretation, increasing the level of detail of traditional geomorphological maps (Newell and Clark 2008). Through LiDAR DEMs more accurate geomorphometric characterisations of the surface and greater detail in mapping can be achieved, as well as new capabilities in morphometry (Bishop et al. 2012). Beyond the obvious utility of LiDAR data for land-use planning and assessments of resources and hazards (Saksena and Merwade 2015), high resolution topography has been used for the automatic extraction of landform curvature (Tarolli et al. 2012), surface hydrology (Jones et al. 2008; Schumann et al. 2008, Skorko et al. 2012; Barber and Shortridge 2005) and coastal geomorphology (Woolard and Colby 2002; White and Wang 2003).

Closed basin lakes commonly experience rapid and frequent water level fluctuations, especially under semiarid environments, and they are very sensitive to climatic changes (Burrough and Thomas 2009; Goudie 2013). After long-lasting periods of flooding, drought episodes cause the water levels in shallow lakes to drop, leaving behind strand lines comprising perched, inactive landforms surrounding the new, reduced, lake perimeter (Schuster et al. 2005; Burbank and Anderson 2012). Sometimes these perched forms are preserved, forming stepped levels of narrow flat surfaces such as lacustrine terraces s.s. (Bowman 1971; Mermut and Acton 1984; Ocakoglu et al. 2013). These are formed during periods of water level stability (Abu Ghazleh and Kempe 2009), when waves cut a coastal platform that may later be covered by shoreline sediments. Flattened tops may be produced by a number of coastal processes both during and after their generation (e.g., wave cutting and aeolian deposition). In other cases the abandoned levels have irregular tops and the original coastal palaeoforms are well preserved as beach ridges (Otvos 2000), with smooth convex to undulating surfaces (Burrough et al. 2007; Hudson et al. 2015). Since water level fluctuations are frequent in such environments, many semiarid lakes develop numerous stepped

strand lines or shoreline levels with small ($< 1\text{ m}$) height difference between consecutive levels, making them very difficult to study. For this reason, there is a significant lack of published work on historical lacustrine shorelines mapped at detailed scales.

These kinds of issues can be successfully tackled by using high resolution DTMs (Hare et al. 2001; Ghienne et al. 2002; Tarolli and Fontana 2009; Gomez et al. 2015). LiDAR high-resolution topographic data sets enable the remote identification of submetre-scale geomorphic features, providing valuable information on both the landscape and geomorphic markers of water level fluctuations in fluvial and marine terraces (Jara-Muñoz et al. 2015). Recent studies of marine terraces (De Gelder et al. 2015) and lacustrine shores (Turmel et al. 2015) using LiDAR data have demonstrated that these landforms can be readily isolated from other landscape geoforms.

The present study provides an integrated (multi-scale) method based on high-resolution LiDAR data used in combination with traditional geomorphological mapping to identify relict coastal features, and demonstrate the previously larger size of Gallocanta Lake (NE Spain). Smooth surfaces in the field that were either missed, or only vaguely recognised by stereoscopic photointerpretation at a scale of 1:15 000, presented sufficient relief to be recognised, mapped and interpreted using DTMs derived from LiDAR data.

Site description

Gallocanta Lake is located in the Iberian Range, NE Spain, at 992 m a.s.l. It is one of the largest and best-preserved saline lakes in Europe (Fig. 1). At present, the lake is elongated in the dominant wind direction (NW-SE). It is 7.7 km long and 2.8 km wide, and extends over 14 km². The lake is located in a 543 km² endorheic basin whose origin has been interpreted by Gracia et al. (2002) as a polje formed during the Pleistocene and developed on sub-horizontal Jurassic limestones. The almost complete dissolution/corrosion of carbonate units led to the outcropping of the underlying Triassic clays, rich in gypsum and soluble salts. The bottom of the depression became impermeable, hosting a string of lakes of which Gallocanta Lake is the largest. The lacustrine conditions were established in the Upper Pleistocene. Luzon et al. (2007) indicates an uncalibrated date of $26,369 \pm 320$ years BP for lakebed sediments taken in a core at a depth of 130 cm. These authors palaeoenvironmentally and palaeoclimatologically reconstructed the lake, concluding there had been progressive and continuous desiccation over the last 10,000 years.

The slopes of the NE and the SW lake shores differ (Castañeda et al., 2015). The depression presents a marked asymmetry controlled by the structural geometry of the different bedrock

lithological units. This asymmetry makes the northern margin short with a mean slope of 4%, while the southern margin has a longer, gentler slope (mean <1%). Gallocanta Lake has developed segmentation along the lake axis, parallel to the direction of the prevailing wind (Fig. 1), a typical process in elongated lakes (Zenkovich 1967). Many coastal forms have been identified, including beaches, spits, barrier islands, lagoons, deltas and low cliffs (Castañeda et al. 2013, 2015), indicating active erosion and sedimentation. These coastal landforms are associated with dominant currents directed towards the SE and controlled by NW winds (Gracia 1995; Castañeda et al. 2015). During the Late Pleistocene, gravels and sands transported by waves and currents accumulated along the lake shores, particularly on the leeward side, forming a complex lunette about 4 m thick located 8–10 m above the present lakebed (Gracia, 1995).

The climate is semiarid, with a mean annual rainfall of 450 mm and a mean annual temperature of 10.5 °C. The Gallocanta basin is exposed to frequent, high intensity winds in winter, >100 km h⁻¹ (Martínez-Cob et al. 2010). At present, the lake is intermittently flooded with a maximum water depth of about 3 m, and becomes dry in the summer. It is an ephemeral saline lake with highly fluctuating levels dependent on rainfall oscillations (Comín et al. 1992; Castañeda et al. 2015). Unlike other lakes in the endorheic basin, Gallocanta Lake has high salinity due to the groundwater contributions flowing over and through the salt-rich Triassic units (Gracia 2014).

Material and methods

Stereoscopic photointerpretation and a digital terrain model were the two main high-resolution data sources used in this work, and these were analysed using a geographic information system (GIS). Aerial photographs and LiDAR data were provided by the PNOA (Spanish National Aerial Orthophotography Program) project which has complete national coverage and is freely and openly published under the Inspire Directive (2007/2/EC) (Directive INSPIRE, 2007).

Photointerpretation

Geomorphological stereoscopic photointerpretation was performed using pairs of colour aerial photographs from 2006, taken during the dry season with a film-based camera at a scale of 1:30 000. Photointerpretation was performed on enlarged prints of 0.48 × 0.48 m resulting in a 1:15 000 scale. The resulting geomorphological map was then scanned and georeferenced using the

orthophotographs from the same 2006 flight as reference. All geomorphological features were digitised directly on screen and analysed within the geographic information system ArcGIS® 10.3.

Digital terrain model

A high-resolution digital terrain model (DTM) generated from airborne LiDAR data with an absolute vertical accuracy of 0.20 m and a density of 0.5 points m⁻² was used to complement the geomorphological interpretation. LiDAR data were obtained from the Spanish Geographical Institute in ASCII files corresponding to the 1:50 000 scale National Topographic Map system with geodetic projection ETRS89. The four ASCII files covering the study area were merged and converted to raster BSQ interleaved data type using ArcGIS. The DTM was managed within ENVI® as a floating point data type with the prism colour table on HSL (Hue, Saturation, Lightness) mode (Fig. 2a). In order to identify subtle topographic differences a standard linear stretch was applied to adjust the dynamic range of the DTM to successive altitudes from 992 m at the lake bottom to 1005 m on the perilacustrine plains. The contrast stretch of the prism colour table was also tailored in selected areas to highlight the topographic signatures.

The entire perimeter of the lake was examined on the screen at different spatial scales (multi-scale analysis). The DTM areas with relict coastal features (RCF) of interest were directly exported to ArcGIS as RGB colour maps (Geotiff) in order to integrate them with the colour orthophotographs and ancillary data.

Geographic information system

A 0.20-m interval contour map was generated from the raster DTM in ArcGIS to enhance topographic contrast and, in particular, to help identify continuous linear features parallel to the lakeshore (Fig. 2c). The RCF colour maps were overlain on the reference orthophotograph using variable transparency, the LiDAR derived 0.2-m-spaced contour lines, and the georeferenced geomorphological map for analysis. The integration of these data in ArcGIS allowed the resolution of inconsistencies. This method, based on the synergy of ArcGIS and ENVI tools, enabled the detailed mapping of relict littoral features (Fig. 2). A mosaic of A3-sized RCF maps covering the entire lake was created at a printed scale of 1:15 000, similar to the scale of aerial photographs. The DTM-derived features were assessed through stereo photointerpretation and using complementary topographic profiles created from the DTM with the ArcGIS line interpolation tool. Finally,

fieldwork was conducted at selected sites representative of the most continuous ridge levels. Field observations identified subtle topographic changes, surface stoniness and gravel roundness.

Results

Small linear features were distinguished from aerial photographs. These mainly include coastal ridges parallel to the present lake border, distributed at different elevations roughly parallel to the contour lines. These were recognised due to their elongated shape and whiter colour, as well as by their arrangement. This latter is basically a longitudinal arrangement paralleling the current shoreline, and a curvature similar to that of hooked spits, which currently develop along the lakeshore. This first examination of aerial photographs allowed a detailed preliminary map of relict coastal features to be drawn up.

From the RCF colour maps, a series of ridges were differentiated over the perilacustrine plains extending from the lake border, located at about 992 m, up to the enveloping contour line of 1005 m. The uppermost relict features are up to 13 m above the current lake bottom and represent a lake with a minimum extent of 51 km², five times the current area of the lakebed.

The ridges are arranged concentrically around the lake and distributed as stepped levels with significant lateral continuity. In fact, most of the ridges can be followed all the way round the lake basin. Each particular level is represented by topographic markers mainly consisting of topographic knicks or flattened to smoothly convex surfaces. Ridge height usually ranges from 0.3 to 2 m, and the width varies between 20 and 100 m. Due to the gentle slope of the southern margin of the lake, there the ridges often appear separately and well-developed, many exhibiting smooth, low topography. The steeper slope of the northern margin conditioned a tightly-packed arrangement of ridges, many of them with significant relief (> 1 m high), as well as poorly-developed spits.

Ridge forms include parallel ribbons, isolated elongated ridges similar to coastal barrier islands, associated embayments resembling lagoons / bays, and rectilinear and recurved spits. Other forms identified on the RCF maps include cusped forelands, aeolian deposits, river deltas, and microcliffs (Figs. 3, 4).

Field inspections confirmed the littoral origin of the mapped deposits. Most of the deposits comprise small, elongated accumulations of sands and gravels overlapping former geomorphological units, frequently Pleistocene alluvial fans surrounding the lake. The soil profiles show about 1 m of medium and fine quartzite gravels (< 1 cm) alternating with poorly-sorted coarse sands arranged in dm-thick sets, gently dipping 10-20° (Fig. 5) and radially oriented towards the

lake. Some profiles show cross-laminated deposits with sets sloping about 30° towards the inland side. All these accumulations present dominant rounded and subrounded gravels and pebbles, while soils developed on the nearby alluvial fans have heterometric angular- or subangular-shaped clasts including larger (> 6 cm) cobbles. Finally, aeolian deposits comprise accumulations of well-sorted medium to fine sands less than 0.5 m thick with no internal lamination, giving a smoothly undulate surface topography.

Discussion and conclusions

The combination of high-resolution and high-precision DTMs with geomorphological photointerpretation provides consistency when delineating subtle relict lacustrine coastal landforms like beach ridges, spits, barriers, bays, deltas and cliffs at different heights and of different sizes. The sound interoperability between ArcGIS and ENVI was crucial for enhancing and detecting the subtle topographic expression of the lacustrine deposits by adapting the histogram stretching and colour scale. Moreover, this interoperability results in not only an illustrative process but also a major research tool for gaining a better insight into the past geomorphological variability of Gallocanta Lake. The management of high-resolution topography in the context of geomorphological interpretation, results in an advantageous procedure for overcoming the difficulties associated with traditional geomorphological mapping. This combined method is substantially time-saving and inspires the production of more-refined, spatially-accurate and cost-effective morpho-topographic models (Chiverrell et al. 2008).

The LiDAR-derived RCF maps overcome the limitations of geomorphologically mapping lacustrine coastal features in areas with smooth relief. The identification of lacustrine coastal landforms in the field was hampered by four main factors: 1) the subtle relief of the area; 2) the location of the coastal landforms far from the present lake border; 3) the fading of the landform expression due to historical agricultural activity and land consolidation; and 4) degradation or geomorphic decay affecting these landforms through partial coverage by aeolian, colluvial and pedogenic materials (Currey 1994). Geomorphic decay is also related to the lateral migration of streams which may erode perched shoreline deposits.

The sedimentological characteristics of the ridge deposits agree with the geomorphological interpretation made after their mapping: most comprise alternating sets of gravel and sand laminae that dip gently towards the lake, while other sets with steeper laminae dip inland. The former represent prograding beach deposits, while the latter can be interpreted as landward migrating

sublittoral bars, quite similar to those previously described and interpreted by Blair (1999) in Lake Lahontan, and by Bowman et al. (2000) in the Dead Sea. Gracia (1995) described this sequence in quarries located in the perilacustrine area of Gallocanta Lake and interpreted the deposit as representing a sequence of small-scale water level fluctuations (seasonal to pluriannual cycles) around a generally stable level. Once the lake experienced a substantial water level change to become established at a different height, the following stabilisation period would lead to the generation of a new episode of ridge formation and coastal deposits. If the water level rose to a significantly higher position, the former, abandoned set of coastal forms and deposits would become permanently flooded and would probably disappear due to wave-induced erosion and/or would be covered by new lacustrine sediments (Lees and Cook 1991). If the water level dropped to a lower position, the former abandoned coastal ridges would remain as perched relict forms above the new lake shore (Ocakoglu et al. 2013).

The continuity and complexity of the mapped RCF, together with the sequences of coastal ridges, barriers and associated beaches, reveal a very dynamic lacustrine environment and indicate that the Gallocanta palaeolake was much more extensive. As a provisional model, Fig. 6 shows the extent of Gallocanta Lake during the maximum water level reached by the lake, 13 m above the present lakebed. Luzón et al. (2007) analysed sediment cores from the bottom of Gallocanta Lake and interpreted a progressive and continuous desiccation of the lake from the last full glacial period until the present. It is very likely that the highest water level inferred in this work may represent the moment of maximum flooding during the Upper Pleistocene. This situation was very probably associated with the more humid period occurring in the Iberian Peninsula during the last glaciation at the end of the Upper Pleistocene (between 22,000 and 19,000 years BP according to Bañuls-Cardona et al. 2014), in accordance with the age of about 23,000 years BP obtained from cores dug in the centre of the lake (Luzón et al. 2007).

In humid regions littoral features form slowly due to processes acting uniformly over and extensive period of time (Timms 1992). In semiarid regions lake water levels fluctuate frequently favouring the preservation of ancient landforms that were abandoned during the desiccation of the lake. In these environments, the high preservation potential of lacustrine coastal forms is related to the lack of highly energetic wave episodes associated with the common prevalence of shallow waters.

The detailed geometry of the ridges, spits and barriers mapped can be used to infer prevailing wave and current dynamics at different moments in the evolution of the lake. As a further step, palaeogeographical maps of each level must be developed and studied in detail with a

palaeodynamic focus (Goy et al., 2003). Parameters such as ridge and barrier dimensions, shoreline curvature in spit hooks, and the total or partial closure of former bays can be very useful for interpreting the amount of sediment transport by waves and currents, the relative duration of lake water levels in each episode (Thompson and Baedke, 1995; Suanez and Provansal, 1998), relative wave energy and current intensity, among other things (Giese et al., 2009), which may improve the reconstruction of palaeoclimatic variables (e.g., prevailing wind direction/intensity and lake water volume).

The method presented in this work allows the comparison of relict coastal features and present coastal forms. A detailed study of the present forms and the associated genetic processes would help to infer the processes prevailing during the generation of the mapped relict coastal forms and deposits (Kumar et al., 2010). After dating the ridge levels identified in the maps, the resulting palaeogeographical and palaeoenvironmental reconstruction would complement that obtained previously from sediment cores (Blair, 1999).

The LiDAR-derived RCF maps can be considered palaeogeographical maps. They reveal new details of the coastal dynamics prevailing throughout the evolution of the lake. This type of information, difficult to obtain only using sediment coring, is very valuable from a palaeogeographical point of view since it provides a more realistic three-dimensional reconstruction of the palaeolake. In Gallocanta Lake, these littoral forms are highly continuous and can be followed throughout the entire lacustrine depression. The mapping of the different stepped relict ridges helps reconstruct the detailed geomorphological evolution of Gallocanta Lake as it experiences a progressive desiccation.

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Figures

Fig. 1 Delimitation of Gallocanta Lake on the DTM. Wind rose indicates the relative frequency of moderate winter winds (2 to 5 m s⁻¹) (modified from Martínez-Cob et al. 2010). Polygons show extent of Figs. 3, 4, and the star pinpoints the photo in Fig. 5

Fig. 2 DTM colour maps highlighting relict coastal features across the entire extent of Gallocanta Lake (a) and in a selected area (b): 0.20 m contour lines overlaying the DTM map (c1); relict coastal features resulting from photointerpretation and DTM analysis (c2) and 2006 reference orthophotograph (c3)

Fig. 3 Examples of different relict coastal features identified below 994 m a.s.l. highlighted on the LiDAR-derived RCF maps (left column) and corresponding orthophotographs from 2006 with contour lines superimposed (right column). Location of a, b, c maps from Fig. 1

Fig. 4 Examples of different relict coastal features identified above 995 m a.s.l. highlighted on the LiDAR-derived RCF maps (left column) and corresponding orthophotographs from 2006 with contour lines superimposed (right column). Location of a, b, c maps from Fig. 1

Fig. 5 Lacustrine coastal deposits in the quarry located on the SW margin of Gallocanta Lake (Fig. 1)

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 447 **Fig. 6** DTM map showing the hypothesised maximum area of Gallocanta Lake during the Upper
 448 Pleistocene and selected LiDAR-derived contour lines. The current lakebed corresponds to the 992
 449 m contour line.