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Catchment controls and human disturbances on the geomorphology of small Mediterranean estuarine systems

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ABSTRACT

Geographic signatures are physical and human-induced characteristics or processes that identify comparable or unique features of estuaries along latitudinal gradients. In Mediterranean areas, the microtidal regime and the strong seasonal and inter-annual contrasts cause an alternation between relatively high runoff and arid conditions. Furthermore, the long history of human settlement also increases the complexity in the study of these estuarine systems. This study investigates these signatures of the estuaries located within the Mallorcan eastern coast, which are geomorphologically homogeneous because of a similar bedrock geology and Holocene history. A multi-method approach focused on the integration of geomorphometry, hydraulics, historical sources and statistics was used. We explore the role played by catchment morphometric parameters, severe flash flood events and human disturbances in controlling the geomorphology of 10 beach-barrier enclosed, fluvial incised lagoons. Most of the lagoons discharge into 'calas', ranging in size from 1345 to 17,537 m^2 and their related catchments are representative of the Mediterranean hydrological systems. Multiple regression models illustrate that the size, slope and drainage network development of the catchments explain the variance in length ($r^2 = 0.67$), volume ($r^2 = 0.49$), area ($r^2 = 0.64$), circularity ($r^2 = 0.72$) and average width ($r^2 = 0.81$) of the lagoons. Depending on these catchment morphometric variables, the shape of the lagoons is also determined by the occurrence of catastrophic flash floods, which cause scouring and dredging, whereas the ordinary flood events and sea storms promote refilling and sedimentation. A historical analysis since 1850 documented 18 flood events, 5 of which were catastrophic with destructive effects along the catchments and large morphological changes in coastal lagoons. High intensity rainfall (up to 200 mm in 2 h), the geomorphometry of the catchments and the massive construction of terraces and transverse walls are involved in the generation of catastrophic flood events. Additionally, the lagoons were altered considerably by human intervention for flood control and to allow for an increased amount of human activities within the surrounding areas, although the high recurrence of catastrophic flood events causes a persistent difficulty in the human battle to dominate these ecosystems. Therefore, the area occupied by lagoons increased between 1956 and the present time from 31,981 m^2 to 63,802 m^2 because of the high recurrence of catastrophic flood events. Furthermore, tourism demand and a social conservation consciousness have promoted restoration and preservation since the 1990s. This study has improved the geomorphological knowledge of small Mediterranean estuaries affected by human disturbances in the high-energy environment found in Mallorca.

1. Introduction

Geomorphologically, estuaries occupy a transitional position between land and sea and act as an interface between terrestrial and marine environments. Many estuaries are highly dynamic environments in which geomorphological change may occur at time scales that range from nearly instantaneous (for example, during river floods) to a progressive change due to sediment infilling and the rise in sea level. All estuaries have an interface between the fluvial and the marine processes, although the nature and intensity of the processes operating at this interface may vary considerably. In certain systems, the sea water may extend many kilometres upstream, whereas in other systems, it may be restricted to inputs from barrier overwash and be confined to areas

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adjacent to the barrier (e.g., Tagliapietra et al., 2009; Potter et al., 2010). Moreover, catchment processes act as controlling factors of the geomorphology of estuaries (cf. Rich and Keller, 2012); therefore, the morphometric characteristics of drainage basins provide a means for describing the catchment hydrological behaviour and its outlet to the sea. In turn, the morphometry of the estuaries influences the habitat type distribution, the nutrient cycling and the water quality as well as the inlet dynamics (e.g., Roy et al., 2001).

In Mediterranean areas, the microtidal regime and the strong seasonal and inter-annual contrasts cause an alternation between relatively high runoff and arid conditions in estuarine systems. This very high spatial and temporal variability of fluvial processes and the long history of human settlement also increase the complexity of the study of these systems (e.g., Hooke, 2006). Firstly, natural variations are especially severe, so the dominant processes may change throughout and between years. Secondly, in recent decades, changes in land uses have transformed these hydrological systems and have increased the pressure on the coastal ecosystems. Tourism affects environmental degradation by placing excessive demands on water supplies and creating waste management problems, which are common issues throughout the coastal areas of the Mediterranean basin (cf. Rodríguez-Rodríguez et al., 2011); however, these problems are amplified on islands (cf. Vogiatzakis et al., 2008). Many of these problems will be compounded by global change and may, in turn, affect socio-economic activities including tourism. The island of Mallorca, which is located in the middle of the Western Mediterranean basin, amply illustrates the transformation of the economy, society, and environment of tourist resorts during the 20th century in the Mediterranean basin. The island has been affected by intense land use changes, transformation of hydrological systems through urban effluents, intensive agricultural activity and forest management in addition to the soil and water conservation practices applied historically and recently. Similarly, severe flash floods are an inherent Mediterranean characteristic (e.g., Grimalt, 1992; Llasat et al., 2005), and because of the occurrence of extreme events in ungauged catchments, there is generally no measured discharge information or formal records of the magnitude of the events. Consequently, flash floods and, especially, geomorphic processes affecting the coastal behavioural remain poorly understood because their influence is frequently viewed in terms of causing inundation rather than inducing morphological change (cf. Cooper, 2002).

To address the gap in the available information of floods and morphological changes in small Mediterranean estuarine systems, it is possible to explore how the catchment dynamics and processes control estuary geomorphology, i.e., morphometric parameters and severe flood events. In addition, it is essential to evaluate the human disturbances related to urbanisation and tourism in the geomorphological evolution over the last 60 years. Hence, by studying the Mallorcan eastern coast, here we aim (a) to assess the role played by catchment morphometric parameters and severe flash flood events in controlling the geomorphology of 10 beach-barrier enclosed, fluvial incised lagoons, ranging in size from 1345 to 17,537 m^2; and (b) to determine the anthropic disturbances in the geomorphological evolution of these lagoons from the middle of the 20th century to the present time, when tourism has emerged as the primary economic activity.

2. Study area

The drainage basins of the Mediterranean region are dominated by relatively short and steep-gradient river systems formed in limestone and erodible Tertiary sedimentary rocks (cf. Woodward, 1995). The surface hydrology of Mallorca Island (3640 km^2) is primarily composed of catchments with these characteristics and is an area with an absence of rainfall during the summer, a porous substrate, and an overexploitation of groundwater resources that generate ephemeral or intermittent flows (e.g., Menció and Mas-Pla, 2008). Estuaries are formed at the sea outlet of a significant portion of these streams. These waterbodies may be defined as coastal lagoons (cf. Ward and Ashley, 1989; Dalrymple et al., 1992), as they are physically separated from the sea, to a greater or lesser extent, by a berm of sand or pebbles. Their morphodynamics are primarily determined by the lack of exchange with the sea based on ephemeral or intermittent flows and a microtidal regime with a spring range of less than 0.25 m, although the combination of the astronomic and barometric oscillations with advections from E may generate sea-level increases closed to 1 m (cf. Basterretxea et al., 2004). Therefore, the connection with the sea is only caused by occasional river flooding and sea storms during the winter (e.g. Sanjaume and Pardo, 2000).

These small lagoons are spread along the Mallorcan coast. However, on the eastern coast, the catchment rock-strength and rock-type, precipitation and catchment hypsometry are similar, favouring the development of a high concentration of lagoons, most of which are fitted in karstic canyons and discharging into 'calas' (Fig. 2), mouths of steep sided valleys (cf. Bird, 2008). Depending on the hydrological river regime, the lagoons are separated from the Mediterranean Sea by a beach berm during a different temporal range throughout the year (see the table within Fig. 1). The altitude ranges from 300 to 500 m a.s.l. in the headwaters of the catchments, which are generally composed of two relief units (cf. ITGME, 1992): (1) The Llevant Ranges, which occupy the headwater parts, constitute a series of alpine mountains and hills that are primarily constructed of Jurassic limestones and dolomites and Cretaceous marls, and (2) The Marinas, a reefal Upper Miocene tabular platform composed of calcarenites, calcisiltites and terra-rossa post-reef sediments affected by significant karstic processes endorsed to the eastern slopes of the Llevant Ranges. Most of the streams that drain the Llevant Ranges have incised the Miocene platform since the Pleistocene through E–W striking (e.g., Silva et al., 2005), forming canyons as an interdependent activity of tectonics, karst and fluvial processes (e.g., Gelabert et al., 2005). During Quaternary glacial periods, the coastal zone was displaced seaward onto the continental shelf, with the river cutting to new base levels (cf. Rose et al., 1999). Meanwhile, during interglacial periods with high sea levels, similar to the current conditions, coastal valleys were drowned to form lagoons. These lagoons subsequently began filling with sediment from the land and sea. This cut and fill cycle has been repeated many times, and most coastal valleys thus contain remnants of previous interglacial deposits in addition to those deposited over the Holocene period (the last 10 ka). The most recent phase of coastal lagoons sedimentation was initiated nearly simultaneously throughout the Western Mediterranean region near the end of the Post-Glacial Marine Transgression approximately 7–8000 years ago (cf. Fleming et al., 1998). Since the Post-Glacial Marine Transgression, the rates of infilling have varied depending on the sediment load carried by the river and the hydrodynamic conditions that transport the sediment into the fluvial outlets to the sea.

The climate in the Mallorcan eastern coast is Mediterranean, with a sub-arid climate in the southern catchments and a sub-humid in the northern catchments. The mean annual rainfall for the period from 1960 to 1990 was 525 mm, with an interannual coefficient of variation of 26.8%. Data are available for 14 rain gauges that are maintained in the catchments by AEMET, the Spanish Meteorological Agency. Autumn is the rainiest season, followed by winter, spring and summer. Topographical and latitudinal differences across the catchments yield a spatial coefficient of variation for the annual rainfall of 22.4%, with a maximum value