**Geo-environmental evaluation for the preventive conservation of open air archaeological sites:
the case of the Roman Necropolis of Carmona (Spain)**

Short title: Preventive conservation of open air archaeological sites.

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Abstract

The Necropolis of Carmona, which has more than 600 tombs carved in calcarenites, is among the most important Roman burial sites preserved in Southern Spain. The tombs in the Necropolis show severe alteration and multiple weathering processes after being excavated at the end of the 19th Century without a preventive conservation plan. The archaeological site shows strong anthropic modifications related to different excavation stages and in relation to the construction of facilities for the visiting public. In particular, the exposure of the buried tombs to meteoric conditions and anthropic modification of the natural drainage have led to an important acceleration of the tombs' deteriorations. The conservation status of the Necropolis was defined through a comprehensive geo-environmental study that combined field observations and laboratory data, modelling and digital mapping and environmental monitoring. Results allow to develop a methodology providing guidelines to minimize potential risks when excavating new tombs (now buried) in the future. Moreover, there can be defined the most suitable prospective areas inside the Necropolis in terms of the environmental, geological and geomorphological conditions which will enhance the preservation of newly exhumed tombs. Geo-Environmental preventive conservation methods that

we propose can be entirely applied to other large archaeological sites completely exposed to open air atmospheric conditions.

Keywords

Preventive conservation, GIS modelling, environmental monitoring, Roman Necropolis of Carmona, South Spain.

1. Introduction

The Necropolis of Carmona (Seville, Spain) comprises more than 600 tombs, most of which were carved in calcarenites between the 1st century BC and the 1st century AD (Fig. 1). This is one of the most important Roman burial sites preserved in Southern Spain. The archaeological excavations in the Necropolis began at the end of the 19th century. Surveys were performed without prior planning for the preservation and organization of the post-excavation site (Cañaveras et al. 2015, Sánchez-Moral et al, 2018). In addition, the area also shows important modifications that are related to the construction of facilities for visiting, mainly earthworks and trails that were built to protect the tombs from massive public visits. Nevertheless, archaeological sites are not only threatened by physical deterioration due to visitors but are also threatened by natural deterioration caused by weather and pollution (Díaz-Pedregal & Diekmann 2013). For the Necropolis of Carmona, the evaluation of the conservation state in previous studies (Ariño & Saiz-Jiménez 1997; Laiz et al. 2009; Benavente et al. 2011; Cañaveras et al. 2015) allowed the main indicators of the currently active deterioration phenomena to be detected and to conclude that the main factor of the current deterioration of the tombs is meteoric water. Unfortunately, the exposure of the buried tombs to atmospheric conditions and modification of the natural drainage has led to an important acceleration of the deterioration phenomena in this exceptional burial site (Sánchez-Moral et al, 2018).

Water related deterioration processes in archaeological sites and historical buildings are relatively well known (Camuffo 2014). Additionally, Geographic Information Systems (GIS) techniques have been widely used in the land-planning and risk assessment of cultural heritage (Siart, Eitel & Panagiotopoulos, 2008; Lazzari, Danese & Masini, 2009; Elez et al. 2013; Lazzari et al., 2014; Ortiz et al. 2014). However, the use of GIS based hydrological analysis and modelling in combination with geomorphological and geological studies has only focused on the prospecting and reconstruction of

archaeological sites (Siart et al. 2010; Espa, Benedetti, De Meo, Ricci & Espa, 2006; French, Duffy & Bhatt, 2013; Harrower 2010, among others). Additionally, there are no previous works that integrate the entire set of scales of observations and techniques (also including climatic monitoring and modelling and petrophysical characterization), to unravel the main water-related factors involved in the deterioration of large archaeological sites.

Fig. 1. Location map of the Roman Necropolis of Carmona and the selected tombs. The main post burial anthropic modifications in the area are also mapped and include parterres, quarries, walls, ways and roads, the modern museum and other facilities.

This study addresses a complete assessment of the conservation status of the Roman Necropolis of Carmona based on a comprehensive Geo-environmental study. The main objective of the present study is to identify the main triggering geofactors influencing the state of preservation of the site and offer a scientific research framework for preventive conservation.

One of the short-term objectives of the managers of this archaeological site is the exhumation of Roman tombs that have been mapped with electrical resistance and seismic techniques and remain unexcavated (Peña, Teixidó & Carmona, 2005). The present study provides guidelines to minimize potential risks when excavating new tombs in the future that are currently buried and, consequently, to yield higher probabilities of retaining good preservation conditions over longer times.

2. Study site and conservation state of the necropolis

The Necropolis of Carmona occupies today an area of c. 100.000 m² at the top of a small hill and is surrounded by walls and fences. These remains of the original and broader Roman burial site (Bonsor, 1931) are now enclosed inside the town of Carmona and surrounded by houses, streets and two small quarries, one of which is integrated into the modern enclosure of the Necropolis. Hence, the Necropolis is currently located in an urban area and has a strongly modified environment ([location here](#)).

The modern enclosure of the Necropolis (Fig. 1) can be divided into two main sectors: (1) the Roman amphitheatre to the northeast, which is separated by a road from (2) the main sector of exhumed tombs and holds the museum and other visitor's facilities. This second sector presents later modifications and tombs carved along terraces and is where most of the archaeological activities have been undertaken since the end of the 19th Century.

In detail, the current topography of the Necropolis is very complicated because numerous modifications have been performed along the different stages of land-use. Late Roman use as a burial site led to an abandonment stage in which natural processes again partially buried the site and decline took place. At the end of the 19th Century, archaeological excavations and conditioning work for tourism strongly modified the area, and French style parterres were built (c. 1-1.5 m high and gardened) that accumulated the debris of the archaeological excavations. Modern works include the construction of a museum, a visitor's centre, accesses, awnings, fences and walls surrounding the site (Fig. 2). Inside the Necropolis, a relevant number of tombs have been identified that remain buried and unexcavated (Peña et al. 2005). At this burial site, most tombs were contained in collective mausoleums with underground chambers that are accessed by a well, typically with some steps to access the inner parts. Only few tombs still preserve part of their surface buildings. The degree of deterioration of most tombs in the Necropolis is moderate to

severe (Fernandez-Cortés et al., 2014; Sánchez-Moral et al., 2018). For this work, we selected 8 tombs that are representative of the main conservation problems: Four Columns, Circular Mausoleum, Three doors, 118, Garlands, Servilia, Elephant and Postumius. The last three characterize large tombs with outer courtyards (Fig. 1).

Fig. 2. Representative features of the Roman Necropolis of Carmona, including post-burial anthropic modifications mainly related to archaeological excavations and enabling visitors. A) General view from the S of the Necropolis, museum, parterres with gardening and tracks for visitors. B) Detail of Parterres and access for visitors. C) Aerial view of the amphitheatre. D) Tomb of Servilia, a representative example of monumental burials with entrances/patios. E) Typical aspect of the entrance to a hypogean tomb, in this case an unnamed tomb south of Servilia, usually surrounded by parterres. F) 3d view of the obtained DEM from the Servilia tomb.

The main mechanisms of deterioration detected in the Necropolis are (Sánchez-Moral et al., 2018) (1) cyclic dissolution/crystallization of salt minerals in the superficial and sub-superficial pore

system of the different support of the tombs, leading to a physical disaggregation of the supports (host rock and stuccos), (2) microbial colonization and the development of biofilms, and (3) dissolution of the host rock components. All these deterioration phenomena (see Fig. 3) have a common factor: the presence of meteoric water in the tombs in sufficient quantities and continuity to activate the deterioration mechanisms.

Fig. 3. Examples of detailed deterioration features at Carmona Necropolis. A) Globulitic crust and associated microorganisms (cyanobacteria and algae) (Circular Mausoleum Tomb). B) Gypsum efflorescence showing a characteristic 'mikado'-like texture on both the stucco and paintings in the Three Gates Tomb. C) Powdery salt efflorescences on the ceiling of the main chamber of the Circular Mausoleum Tomb. D) Granular disintegration and crumbling products at the facade of the Postumius Tomb. E) Fragmentation of calcarenite slab in Tomb 118. F) Local ceiling collapse at the Four Columns Tomb. G) Phototrophic biofilms on a rough substrate (due to spalling and disaggregation) in the Circular Mausoleum Tomb. H) Biocolonization on walls and steps at the entrance of the Three Gates Tomb. (Scale bars: A and B, 5 cm; C and G, 10 cm).

3. Materials and methods

The acquisition of the data followed a workflow involving several field campaigns in the Necropolis and accounting for more than 60 days of fieldwork. Weather monitoring in the Necropolis covers two annual cycles and field campaigns were done in all the seasons of the year, yet mostly in spring. First campaign was devoted to the recognition of the Necropolis, the selection of the studied tombs, overall overview and lithological identification, search of locations for the weather station, etc., and following ones advanced in the field identification and geological mapping, sampling and assembly and installation of the weather station. At the same time, geological photointerpretation, GIS modelling and laboratory work were carried out. Preliminary laboratory results helped guiding the latest stages of the field based labor, allowing a more precise geological fieldwork and sampling.

3.1. Climate monitoring

The local weather conditions were monitored by means of a HOBO Weather Station HWS (Onset Computer Corporation) that was installed on the flat roof of the museum. This station was equipped with a tipping-bucket rain gauge (S-RGB model) for rainfall measurements (measurement range: 0-12.7 cm, resolution: 0.2 mm); a S-BPA-CM10 barometer that provided average barometric pressure for each logging interval (measurement range: 660 mbar to 1070 mbar, accuracy: ± 3.0 mbar, resolution: 0.1 mbar); a 12-bit Smart Sensor (S-THB model from Onset Computer

Corporation) to measure the relative humidity and air temperature with an accuracy of ± 0.2 °C from 0° to 50 °C, and $\pm 2.5\%$ from 10% to 90% RH, to a maximum of $\pm 3.5\%$ (above 95%); a silicon pyranometer sensor that measured solar radiation (measurement range: 0-1280 W/m², accuracy: ± 10 W/m², resolution: 1.25 W/m²); and, finally, a Davis® Wind Speed and Direction Smart Sensor based on a weather-vane and a cup-revolution device to measure the wind and gust speeds (measurement range: 0-76 m/s, accuracy: ± 1.1 m/sec, resolution: 0.5 m/sec).

3.2. Petrophysical characterization of the host rocks and buildings

Petrophysical characterization of the host rocks was performed to evaluate their water transport properties. Two types of samples were collected: (1) samples from the selected tombs, picking unaltered parts, and (2) samples in outcrops outside of the archaeological area for petrophysical analysis. As a consequence, each lithostratigraphic unit was characterized using a large number of samples (from 5 to 10).

The pore structure of host rock was described in terms of porosity and pore size distribution via mercury intrusion porosimetry (MIP). An Autopore IV 9500 Micrometrics mercury porosimeter was used and the studied pore radius interval ranges from 0.001 to 200 μm .

Field capacity was estimated from MIP. It is the percentage of the volume of infiltration water that is retained by the rock after excess water has drained away. Capillary and gravitational forces mainly produce water flow in porous materials. Capillarity is active for pore sizes up to 0.1 μm , although the pore-size range between 1 μm and 1 mm provides high-water absorption rates. For smaller pores, water tends to remain in the rock, and its movement is hindered. Thus, field capacity is linked to the smallest pore fraction.

3.3. Methods for water balance calculations: daily reference evapotranspiration and effective condensation.

The water inputs to tombs potentially arise from two main processes: 1) either direct rainfall or runoff and 2) the effective condensation of water vapour on the inner surfaces of tombs, i.e., walls and ceilings (Sánchez-Moral et al., 2018). The meteorological conditions primarily determine evapotranspiration in the case of allochthonous water, whereas the daily and seasonal variations in the microclimatic parameters inside tombs control the condensation process.

The daily reference evapotranspiration (ET_0) was estimated with the Penman–Monteith FAO-56 (PM-56) parameterization scheme (Allen, Pereira, Raes, & Smith, 1998). In this case, estimation includes the use of standard climatological records of solar radiation (sunshine), air temperature, relative humidity and wind speed provided by the meteorological station, including their daily maximum and minimum values. Also, secondary parameters were calculated from the barometric pressure, humidity and temperature records, from the solar radiation records and by considering some other intermediate parameters as functions of the geographical coordinates and year period.

The results obtained by FAO Penman-Monteith method were compared with a 'photoperiodic effective daily temperature' version of the Thornthwaite scheme for estimating daily evapotranspiration rates (Pereira and Pruitt, 2004). The Penman–Monteith model had a performance almost identical to that of the simpler Thornthwaite scheme, but with a higher and reliable daily variability.

Once the potential evapotranspiration was calculated, we integrate the temporal rainfall record for the adjustment of the water balance in the outcrop. The result is a temporary series, on a daily scale, of the evolution of surface runoff and infiltration that affects to calcarenite banks on which the tombs are excavated. The combination of the reference evapotranspiration data (ET_0) and the precipitation in the form of rain (R) in order to calculate the real evapotranspiration and the "useful rainfall". Real evapotranspiration (ETR) is the amount of water (in mm) that actually returns to the atmosphere. Its value depends on its availability in the form of rain or stored in the ground. The upper limit of ETR is determined by the ET_0 . The "useful rain" (UR), also called effective rain or surplus, corresponds to the amount of water that runs off on the surface (runoff) plus the amount that infiltrates.

In short, the rock into which the tombs are carved can store a maximum amount of rainwater (Maximum Reserve, expressed in mm or L/m^2) before its percolation into the tombs or is incorporated in surface runoff. For the specific quantification of the Maximum Reserve (R_{max}) for the rock-type of the Necropolis of Carmona (calcarenite), information on the petrophysical properties of the 7 different cartographic units has been integrated, specifically that information referring to the typology and distribution of the porous system of the rock (Table 1).

Cartographic Unit	Field capacity [%]: ($P_{total} - P_{eficaz} \cong P_{ads}$)	Maximum water retention capacity (mm)
7	1.30	1.56

6	2.18	2.62
5	5.74	6.89
4	2.15	2.58
3	3.26	3.91
2	1.77	2.12
1	1.52	1.82
average	2.56	3.07

Table 1. Water retention capacity according to the characteristics of the porous system of the representative samples of each cartographic unit.

3.4. GIS-based data integration: digital mapping and modelling

The understanding of the complex action of the water through the Necropolis requests a GIS based integration. This study combines geological fieldwork, including field mapping, with the use of digital mapping and modelling. A Digital Elevation Model (DEM) was obtained from an existing conventional digital topographic map in CAD format and at a 1:1000 scale. For this work, the DEM was built in a TIN (Triangulated Irregular Network) format using Delaunay algorithms. This algorithm allows the construction of vector based topographic models with very sharp edges, which is entirely in concordance with the complex topographic details at the burial site and mainly responds to the anthropic modifications of the relief (e.g., buildings, parterres, tombs, and quarries). The whole area was divided into several sectors that were modelled individually and iteratively to obtain the best fit to the real volumetric conditions. From this DEM were computed several derived models, hillshade, slope, hydrological models, etc.

4. Results

4.1 Geology and geomorphology of the Necropolis

The Roman Necropolis of Carmona was built into the uppermost Messinian shallow marine calcarenites (González-Delgado et al. 2004). Currently, the Carmona calcarenites show a-cuesta-type relief constrained by gentle dips shaping a characteristic scarp in the area of Carmona city, where the typical thickness is approximately 40 m. In the area occupied by the Necropolis, the outcropping calcarenites reach approximately 30 m thick and present a complex internal

architecture as most units laterally disappear but in general terms are arranged in decimetre to metre scale beds of massive aspect. Those are separated by lutitic and/or marly beds ranging from millimetres to a few metres in thickness that are mostly discontinuous. Seven lithostratigraphic units (mapping units 1 to 7 in Fig. 4C) were identified and mapped in the Necropolis, which are grouped into four thinning and fining upward depositional sequences (I to IV in Fig. 4A). The location of the studied tombs in the stratigraphic section is also displayed in Figure 4. Calcarenites beds are N10° directed, and dips range from 5 to 15° towards the north.

The computed slope distribution model (Fig. 5A) shows a dominant slope of less than 12° in 90% of the surface of the Necropolis. Areas with slopes less than 1° and areas with slopes above 15° typically coincide with the anthropic modifications of the natural landscape, either Roman or later in age. The topography (Fig. 5B), which is only disturbed by anthropic modifications, is smooth and shows a continuous landscape and, consequently, the hypsometric distribution along the Necropolis only shows differences in height of a few tens of metres.

Currently, erosion and sedimentation are active but at small scales and low intensities. These processes are primarily related to the ubiquitous but ephemeral drainage network that is typical of a semiarid climate. In the headwaters, the outcropping calcarenites are disaggregated and dispersed. These processes are the only important source of sediments in the Necropolis. Sediments are transported from headwaters and distributed all over the Necropolis. Ripples and small fans are usually developed in the areas where water is discharged, mainly in the inner areas of the exhumed tombs. Moreover, the successive flooding after strong rainfall events have covered the floors of many tombs with impermeable clay deposits that in some cases show thicknesses of several centimetres.

Fig. 4. Stratigraphy and geology of the Roman Necropolis of Carmona. A: Lithostratigraphic column showing Mapping units (1 to 7 and equivalent to the Lithostratigraphic units described in section 4.1) and depositional sequences (I to IV). The column also shows the location of the studied tombs in the lithostratigraphy of the Necropolis. B: Porosity obtained using mercury intrusion porosimetry, P(Hg), and pore size distribution types in the lithostratigraphic column. C: Geological map of the central area of the Roman Necropolis of Carmona with the location of the selected tombs (numbers in white) and mapping units (numbers in black). Note that Mapping units 1, 6 and 7 do not lie within the selected frame.

Fig. 5. Derived model obtained from the DEM; A) Slope distribution in the vicinity of the Necropolis, in degrees, and B) Hypsometric distribution, 2 metre colour interval. Note that high slope gradients correspond with anthropic activities, either Roman or later.

4.2. Petrophysical characterization

All the host rocks (calcarenite beds) of the Necropolis are very porous (20-40%) and have a polymodal pore size distribution (Fig. 5B). Table 1 shows the values of field capacity and water retention capacity according to the characteristics of the porous system of the representative samples of each cartographic unit. Those parameters are necessary to calculate the water balance as a function of rainfall, average temperature and evapotranspiration. Most of the calcarenite beds show an important pore fraction of 0.001-0.5 μm and, consequently, a high field capacity. These materials constitute calcarenite banks on which the studied tombs are excavated and serve as the roofs and walls of the tombs. However, if water reaches a tomb, the pore structure characteristics provide water condensation and retention within porous materials and consequent high bioreceptivity (Sánchez-Moral et al. 2005). Benavente et al. (2011) showed that all the host rocks have a very low resistance to simple compression (2.95-11.79 MPa). Salt crystallization durability tests also showed that all the studied rocks have very low durability. These materials are present in most of the tombs (Circular Mausoleum, Garlands, Three Doors, Four Columns and Postumius) and are the most susceptible to deterioration.

In Tomb 118, the bed of calcarenite located on the roof has high field capacity values and prevents filtration to the tomb (Fig. 4). However, the walls are excavated in other high porous calcarenite beds that exhibit large pores (2-20 μm and 20-100 μm). This pore structure is appropriate for the circulation of fluids but not for their retention. As a consequence, if meteoric water achieves the tomb, the alteration processes will be less aggressive than in other tombs. This could be related to the good state of preservation of Tomb 118, and it may be an excellent geological criterion for excavating new tombs in the future.

4.3 Drainage network and hydrogeological features

We performed a twofold analysis in order to obtain a detailed and reliable map showing the drainage network in the Necropolis. First, systematic observations of the geomorphological and sedimentological features in the Necropolis indicating current direction of surficial water flow were mapped (Fig. 6A). This map shows the location, direction and sense of the observed evidence of water flow and the depressed areas acting as sinks. Later, the theoretical model of the surficial drainage was obtained (Fig. 6B) by extracting the channel networks and determining the flow directions and upslope areas from digital elevation data (Tarboton, 1997). The original DEM of the Necropolis was transformed to a proper raster format (0.2 m pixel) in order to process the related computations. The comparison of the observations with the computed model allowed the GIS-based model to be validated.

As stated, the surficial drainage network is remarkably complex, is far from a typical natural one and has plenty of deflected streams due to the presence of anthropic elements. In the areas that are highly modified by human activities, meandering morphologies with very short lengths dominate, whereas in contrast, in the pristine areas (e.g., the barely modified valley west of the Necropolis), the dendritic morphologies with straight and larger streams prevail. The headwaters are located mainly near the museum (at the highest topographic point), at the hill SW of the Necropolis and in the western part of the amphitheatre (due to its disconnection from any natural drainage system). The main stream runs to the west along the mentioned valley and finally discharges into the public sewage. No drainage network drains from the outside of the enclosure of the Necropolis due to its location at the top of a hill.

Fig. 6. A) Field map based on direct observations of the geomorphological and sedimentological features indicating the current sense of drainage runoff in the observed localities. The areas acting as sinks (endorheic) are also displayed. B) Obtained model of surficial drainage. Both maps show a drainage network that is strongly constrained by human-related modifications to relief.

Typically, the hypogeal parts of the Roman tombs (exposed to direct rainfall throughout their main entrances) act as sinks, and all of them lack natural (or anthropic) pour points or drains at their bottoms. In some cases, broader areas grouping several tomb entrances act as sinks as well (e.g. Elephant tomb; Fig. 6A). It is not rare that individual streams after a strong rainfall flow into those poorly drained areas and discharge inside the tombs (e.g. Four Columns, Garlands and Tomb 118). In some cases, the existing parterres and other modern works contribute to enlarging the catchment area draining to each individual tomb. All these features significantly increase the amount of water potentially discharging inside the tombs along a discrete event of rainfall/storm. This accumulative effect is more noticeable in the biggest tombs (e.g., Elephant, Servilia, and Postumius), with more accumulated later anthropic modifications in its vicinity. Only the few tombs with entrances raised over the substrate or located in a well-drained area avoid this increase in water contribution. This is more common in smaller tombs in which any minor irregularity in the terrain surface can deflect the water streams away. Additionally, smaller tombs typically present smaller surface open to direct rainfall and hence accumulate less water at their bottoms. However,

there are zones that are completely endorheic, for example the amphitheatre and the area with mid-sized tombs located north of the museum.

4.4 Climatic monitoring of the Necropolis, rain excess and hydric balance

The area has a semiarid Mediterranean climate (Csa type in the climatic classification of Köppen-Geiger). The average annual temperature is approximately 18°C, and the minimum values are recorded in the winter months of December / January / February with averages of the minimum of approximately 9-11°C and the highs in the summer months of June / July / August with absolute values higher than 40°C. Figure 7 shows the evolution of the daily average values of air temperature, relative humidity, rains and solar radiation in the Necropolis of Carmona during the monitoring period.

Rainfall in the area is typical of a semi-arid climate (<400 mm/year). It has a very marked dry season in the summer, a period in which more than 3 months can be registered without any precipitation. During the rest of the year, precipitation events are very scarce and distributed between winter, spring and autumn. Low rainfall on an annual scale is opposed to the existence of some torrential events that can exceed 70 mm in one day.

Climate monitoring allowed the calculation of the monthly distribution of the water balance (deficit, reserve and surplus water in mm) in the Carmona Necropolis during the monitoring period (Fig. 7). For the precise calculation of the water balance, the average water retention capacity of the support rock was taken into account based on the average values of its porous system (field capacity = 2.56% and maximum water reserve = 3.07 mm). The results obtained during the monitoring period and its contrast with previous time series show a temporary predominance of water deficit in the outcrops of the Necropolis, with a daily average deficit of 4.3 mm/day and extreme droughts that raise it to 11.5 mm/day. The total deficit during the analysed hydrological cycle was 1386 mm.

Fig. 7. Air temperature, relative humidity, rains and daily water balance in the Necropolis of Carmona during a biannual monitoring period.

5. Discussion

The studied tombs are a good representation of the state of conservation of the whole Necropolis, three of them (Servilia, Postumius and Elephant) represent Semi-Hypogeal environments and the other five (Tomb 118, Three Doors, Circular Mausoleum, Garlands Tomb and Four Columns Tomb) completely Hypogeal. Table 2 shows the extensive list of the deterioration features and damage categories observed for each one for both the hypogeal and non-hypogeal parts of the tombs.

UNDERGROUND CHAMBERS

DETERIORATION FEATURES AND PROCESSES		Servilia	Postumius	Elephant	Four Columns	Circular Mausoleum	Three doors	Garlands	118
SURFACE DEPOSITS	CRUSTS	Little; disperse	Little; disperse	Little; disperse	Little; disperse	frequent; disperse	Little; disperse	Little; disperse	Little; disperse
	EFFLORESCENCES	Abundant; linked to restored areas; gypsum	Abundant; linked to restored areas; gypsum, salts	Little; disperse	Little; disperse	Abundant; linked to restored areas; gypsum	Little; disperse; gypsum	Frequent; disperse; gypsum, Na-carbonates, oxalates	Little; disperse; gypsum
DETACHMENT & LOSS OF MATERIAL	VOIDS	Little; disperse	Abundant; clumped	Abundant; clumped	Little; disperse	Little; disperse	Little; disperse	Little; disperse	Little; disperse
	GRANULAR DISINTEGRATION	Little; disperse	abundant; extended	abundant; extended	abundant; extended	abundant; extended	abundant; extended	abundant; extended	Little; disperse
	BLISTERING	No visible	No visible	No visible	No visible	abundant: on stuccos	frequent: on stuccos	No visible	little: on stuccos
	FRAGMENTATION	Little; disperse	Little; disperse	frequent; disperse	frequent; disperse	frequent; disperse	frequent; disperse	Little; disperse	Little; disperse
	SCALING	Little; disperse; on ceiling and walls	Frequent; disperse; on ceiling and walls	Frequent; disperse; on ceiling and walls	abundant; disperse; on ceiling and walls	abundant; disperse; on ceiling and walls	abundant; disperse; on ceiling and walls	abundant; disperse; on ceiling and walls	Little; disperse; on ceiling and walls
BIO-COLONIZATION	PHOTOTROPHIC MICROORGANISMS	Frequent; linked to moisture zones and percolation water	Little; linked to voids	Frequent; linked to voids, moisture zones and percolation water	Abundant; linked to voids, moisture zones and flooding fringe	Little; disperse (more abundant linked to voids)	Little; linked to voids, moisture and flooding fringe	Abundant; linked to voids, moisture zones and flooding fringe	Little; linked to voids, moisture and flooding fringe
	NON-PHOTOTROPHIC MICROORGANISMS	No visible	No visible	No visible	No visible	Little; disperse; on mortar/stucco	Little; disperse	No visible	No visible
	INVASION (ANIMALS, PLANTS)	Little; disperse	Little; disperse	Little; disperse	Little; disperse	Little; disperse	frequent; disperse	frequent; disperse	frequent; disperse

OUTDOOR BUILDINGS/PATIOS

DETERIORATION FEATURES AND PROCESSES		Servilia	Postumius	Elephant
SURFACE DEPOSITS	CRUSTS	Little; disperse	Little; disperse	Little; disperse
	EFFLORESCENCES	Little; disperse	Little; disperse	Little; disperse
	SOILING	Frequent; localized on soil	Frequent; localized on soil and niches	Frequent; localized on soil and niches
DETACHMENT & LOSS OF MATERIAL	VOIDS	Frequent; disperse	Frequent; disperse	Frequent; disperse
	GRANULAR DISTINTEGRATION	Abundant; localized on columns and some walls	Frequent; disperse	Abundant; localized on cleaned/restored areas
	CRACKS	Little; localized	Little; disperse	Little; disperse
	FRAGMENTATION	Little; disperse	Little; disperse	Little; disperse
	SCALING	Frequent; localized	Little; localized	Frequent; localized
BIOCOLONIZATION		Abundant; linked to soil and moisture zones	Abundant; linked to soil and moisture zones	Abundant; linked to moisture zones

Damage categories in function of frequency and pattern of deterioration features:
0-No visible
1-slight
2-moderate
3-severe

Table 2. Deterioration features and damage categories detected in the selected tombs.

As later evidenced, the external climatic features determine the overall hydric balance of the Necropolis and the alteration processes in the outcropping rock formations. In addition, the climatic features directly influence the micro-environmental parameters inside the tombs, those been determinant in the processes deteriorating the walls and roofs of the individual tombs in the Necropolis. Under those circumstances, a proper land-use planning focused on preventive conservation appears as the most suitable instrument to reduce the vulnerability of the Necropolis.

5.1. Causes of the deterioration

Results from the environmental monitoring in the Necropolis confirm that the pluviometric regime corresponds to a semiarid climate. Rain is scarce, sporadic and torrential. This, when combined with the high temperatures recorded, determines high evapotranspiration rates and an overall deficit in

the water balance (a mean value of 4.3 mm/day rising to 11.5 mm/day values in the driest seasons). However, the short rain episodes are concentrated in a few strong rainfall events along the year, accelerating the deterioration phenomena. The main agents responsible for the rapid deterioration suffered by the Roman Necropolis are water-related and include: 1) flooding by direct rainfall or by direct discharge of the ephemeral small water streams formed during storms and draining into the tombs, 2) active physical erosion due to the activity of the water streams and 3) supplies of sediments and debris mainly into the subterranean areas of the tombs. Furthermore, the fine sediments that are filling the tombs' floors act as seals and retard or impede the natural infiltration of the floodwaters. These issues cause a more effective and long-lasting rise in water by capillarity throughout the walls of the tombs. In addition, those important increases in the residence times of the water at the bottoms of the tombs entails a more lasting and gradual water evaporation and an important increase in the overall humidity. It also increases the activity and timespan of the effective condensation process.

The results from the analysis of the several tombs, before and after different land-use activities, confirm that effective condensation is a key factor in the deterioration process (e.g., Benavente et al. 2011, 2013; Fernandez-Cortés et al., 2014; Cañaveras et al., 2015). Effective condensation processes occur at least during a quarter of the year in many tombs (Fernandez-Cortés et al., 2014; Sánchez-Moral et al., 2018). It yields/comprises a great timespan with water available in the different supports (e.g., host rock, mortars, stucco, and paints) for the activity of the main deterioration processes. Under these environmental conditions, short period cycles of effective condensation and evapotranspiration develop, determining too short effective condensation intervals. This implies an elevated hydric stress with constant processes of wetting and drying. According to our findings, the most favourable conservation conditions will occur when:

- The minimum thickness of the natural rock cover is 1 metre without external soil and externally covered with lichens;
- The rock of the tomb roof has high values of field capacity whereas the walls present low water retention capacities; and
- The tombs have high ventilation rates favoured by southern orientation with subsequent moderate-high winter insolation that enhances the drying of the supports.

As we only can modify anthropic factors, land-use planning and management arise as a determinate tool to diminish, as far as possible, the overall decay in the Necropolis.

5.2 Land-use planning and preventive conservation methodology

As stated, the environmental conditions in the area occupied by a tomb are essential to its preservation or deterioration along the time. The exhumation of unexcavated tombs will certainly modify the terrain's surface and will create new depressed areas and sinks. With the here provided methodological tools, the arising problems related to the flooding of the newly excavated areas can be anticipated. This land planning method should be a first order criterion when deciding whether a tomb should be exhumed. Its potential preservation along a long-lasting period of time remains truly in the decrease to a minimum the mentioned risk geofactors.

To maximize its preservation, the election of a new tomb for potential exhumation should then rely largely in choosing a location coinciding to the best environmental conditions. This would ensure the best a priori settings for a prolonged preservation of optimal conditions. While also showing the criteria and workflow applied, here are defined a number of prospective areas inside the Necropolis in which the environmental conditions are most appropriate to enhance the preservation of a newly exhumed tomb.

Criteria. To maximize the preservation of a tomb, the main objective is to minimize the percentage of relative humidity and water in liquid state in the interior of the tomb. The most favourable/recommendable relative humidity is below 70% along the whole year and with as few anthropic actuations as possible. This would cause the tombs to not accumulate humidity and/or water in liquid state above the hydric balance corresponding to the overall climate conditions of the Necropolis. Then, the most favourable environmental conditions are related to high values of insolation, high field capacity and minimum surficial runoff.

The four criteria for delimiting the best prospective areas in order of importance are as follows.

- Regardless of the environmental parameter, areas in which all the tombs are exhumed are excluded (e.g., the amphitheatre, several quarries, and the central area with the museum).
- Preferred areas are oriented to the south (selected interval from N112.5 to N247.5) because there is an important difference in insolation (and temperature) along the year between the sunny south-facing and shady north-facing settings.
- The field capacity must be high; the substrate in which the potentially exhumed tomb is located should hold the maximum possible amount of water.

- The area in which the tomb is located must have the minimum possible surficial runoff. There, the drainage system should not be evolved, and the best areas are headwaters or should be easily modifiable (this not causing any related problems downstream).

Workflow. Once the criteria for delimiting the prospective areas are established in a GIS environment, the workflow involves two steps.

- Step 1 is based on aspect (direction that a slope faces) and the potential presence of unexhumed tombs. Here, three areas are mapped (Zones 1, 2 and 3 in. 7A). Each one delimits spaces where there are tombs to be exhumed with slopes facing southward.
- In Step 2, inside the previous 1 to 3 Zones, we mapped some narrower areas based on the field capacity and runoff features. Mapped areas are grouped into categories “a” and “b”. The “a” zones are located headwaters, without a developed drainage system, and their field capacity is high (values from 5.74 to 3.26%). Note that the drainage system displayed in Figure 8B is categorized following Strahler (1957) and that orders 1 to 4 have been eliminated because they had no correlation with field observations. In the “b” zones the field capacity is medium-high (5.78 to 2.18%) and its location in the drainage system remains adequate, with a drainage network that is not very evolved and easy to modify due to the broad areas without important anthropic modification.

Although the zones from category “a” meet all the best delimiting criteria (south oriented, low field capacity and good position in the drainage system), they are small. Instead, the area from category “b”, although less favourable, still shows acceptable field capacity values and offers broader areas to adequately exhume new tombs (see the summary in Fig. 8C). The remains of zones 1 and 2 and the entirety of zone 3 remain less favourable, and potential archaeological activities there will require major attention, mainly to surficial runoff. From the preservation standpoint, these are the best options, but for the rest of the Necropolis, the situation is adverse.

Another important feature to consider when selecting a tomb to exhume is the orientation of the entrance towards the hypogeal or semi-hypogeal environment. Certainly, the ideal option is that this entrance is south facing, reducing the relative humidity in the tomb by increasing insolation. However, this seems to not be a limiting factor as a newly exhumed tomb, regardless of the orientation of the main entrance of the tombs, should have a protective cover (similar to that proposed for the Circular Mausoleum tomb; Cañaveras et al. 2015). This seems mandatory to protect the exhumed tomb from direct rainfall and general weathering. In addition, the tomb’s

surroundings must present the appropriate measures to avoid direct runoff discharge into its interior.

Fig. 8. Results of the described workflow to delimit the best prospective areas to exhume a new tomb minimizing the environmental risk and hence deterioration. A) Best insulated zones outside the excavation area and with existing unexcavated tombs. B) Location of the studied tombs and field capacity map also incorporating the zones evidenced in A. C) Combination and summary of previous maps indicating zonation with the best zones to prospect.

6. Conclusions

As in many open air archaeological sites, meteoric water is the main agent of alteration in the Necropolis. Every intervention to restore the inside of any individual tomb must then be preceded by proper planning and a number of corrective measures aimed at the origin of the decay problems in the Necropolis and hence to diminish the water availability inside and near the tombs. In the short term, corrective measures are typically of local influence and are related to preventing the direct entrance of water inside the tombs (e.g., maintenance of the surficial drains and fixing the protective ledges of every tomb). Long term measures address the hydrological re-structuration focused on the surficial drainage system at the scale of the whole Necropolis.

Tombs exhumed throughout the 19th and 20th centuries underwent rapid deterioration processes due to the aforementioned phenomena and to the unawareness of the basic procedures for heritage conservation at that time, something again common in many large archaeological sites. The final objective of this work is to develop a land-use and management tool to minimize the deterioration in excavated tombs. The obtained result show a final qualitative zonification categorizing zones in the Necropolis ranging from areas more to less favourable to adverse. The final outline of the shown zonification is quite accurate as is based in a high resolution DEM, integrating extensive modelling, field mapping and sampling. Furthermore, this management tool is expected to assist in the decision-making course at the time of exhuming unexcavated tombs, potentially contributing to enhance its potential and preventive conservation.

As environmental conditions are key to the conservation of tombs over time, to favour their optimal preservation, the election of new tombs for potential exhumation should rely largely in choosing a location that coincides with the best environmental conditions. In the form of a recommendation, herein we have defined a number of prospective areas inside the Necropolis in which the environmental conditions are the most appropriate to enhance the preservation of newly exhumed tombs. Also, the developed methodology leading to the definition of the best prospective areas (preventive conservation) can be exported to other archaeological sites.

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REFERENCES

- Allen, R.G., Pereira, L.S., Raes, D. & Smith, M., (1998). Crop evapotranspiration – guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper 56*. Roma: FAO.
- Ariño, X. & Saiz-Jimenez, C. (1997). Deterioration of the Elephant tomb (Necropolis of Carmona, Seville, Spain). *International Biodeterioration & Biodegradation*, 40, 233–239.

Benavente, D., Sánchez-Moral, S., Cortés-Fernández, A., Cañaveras, J.C., Elez, J. & Saiz-Jiménez, C. (2011). Salt damage and microclimate in the Postumius Tomb, Roman Necropolis of Carmona, Spain. *Environmental Earth Sciences*, 63 (7-8), 1529-1543.

Bonsor, G.E. (1931). The archaeological sketch-book of the Roman necropolis at Carmona. *New York: The Hispanic Society of America*.

Camuffo, D. (2014). Microclimate studies for cultural heritage: conservation, restoration and maintenance of indoor and outdoor monuments. *2nd ed. New York: Elsevier*.

Cañaveras, J.C; Fernández-Cortés, A; Elez, J; Cuezva, S; Jurado, V; Miller A.Z; Rogerio-Candelera, M.A; Benavente, D; Hernández-Marín, M; Saiz-Jiménez, C & Sánchez-Moral, S. (2015). The deterioration of Circular Mausoleum, Roman Necropolis of Carmona, Spain. *Science of the Total Environment*, 518-519, 65-77.

Díaz-Pedregal, P. & Diekmann, A. (2013). Is It Possible to Reconcile Protecting Archaeological Sites with Opening Them to the Public? In: S. Sullivan and R. Mackay, eds. *Archaeological Sites: Conservation and Management*. Los Angeles: Getty Conservation Institute, 743-750.

Elez, J., Cuezva, S., Fernández-Cortés, A., García-Antón, E., Benavente, D., Cañaveras, J.C. & Sánchez-Moral, S. (2013). A GIS-based methodology to quantitatively define an Adjacent Protected Area in a shallow karst cavity: The case of Altamira cave. *Journal of Environmental Management*, 118, 122-134.

Espa, G., Benedetti R., De Meo, A., Ricci, U. & Espa, S. (2006). GIS based models and estimation methods for the probability of archaeological site location. *Journal of Cultural Heritage*, 7(3), 147-155.

Fernandez-Cortés, A., Elez, J., Cuezva, S., Cañaveras, J.C., Benavente, D., Rogerio, M.A., Saiz-Jimenez, C. & Sanchez-Moral, S. (2014). The conservation of the Carmona Necropolis (Sevilla, Spain). In: Saiz-Jimenez, C., (ed.) *The Conservation of Subterranean Cultural Heritage*. London: CRC Press, 45-50.

French, K. D., Duffy, C.J. & Bhatt, G. (2013). The urban hydrology and hydraulic engineering at the classic maya site of Palenque. *Water History*, 5 (1), 43-69.

635

636 González-Delgado, J.A., Civis, J., Dabrio, C.J., Goy, J.L., Ledesma, S., Sierro, F.J. & Zazo, C. (2004).
 637 Cuenca del Guadalquivir. In: J.A. Vera, ed. *Geología de España*. Madrid: SGE-IGME, 543-550.
 638

639 Harrower, M. J. (2010). Geographic Information Systems (GIS) hydrological modelling in
 640 archaeology: an example from the origins of irrigation in Southwest Arabia (Yemen). *Journal of*
 641 *Archaeological Science*, 37 (7), 1447-1452.
 642

643 ITGE, COPyT de la Junta de Andalucía y Ctel de la Junta de Andalucía (1998). *Atlas Hidrogeológico*
 644 *de Andalucía*. Madrid: ITGE.
 645

646 Laiz, L., Miller, A.Z., Jurado, V., Akatova, E., Sánchez-Moral, S., González, J.M., Dionísio, A., Macedo,
 647 M.F. & Saiz-Jiménez, C. (2009). Isolation of five *Rubrobacter* strains from biodeteriorated
 648 monuments. *Naturwissenschaften*, 96, 71–79.
 649

650 Lazzari, M., Danese, M. & Masini, N. (2009). A new GIS-based integrated approach to analyse the
 651 anthropic-geomorphological risk and recover the vernacular architecture. *Journal of Cultural*
 652 *Heritage*, 10, Supplement 1, 104–111.
 653

654 Lazzari M., Patriziano M.S. & Aliano A. (2014). GIS assessment and planning of conservation
 655 priorities of historical centers through quantitative methods of vulnerability analysis: an example
 656 from Southern Italy. In: B. Murgante et al. (Eds.): *ICCSA 2014, Part II, Lecture Notes in Computer*
 657 *Science* 8580, 677–692.
 658

659 Ortiz, P., Antúnez, V., Martín, J.M., Ortiz, R., Vázquez, M.A. & Galán, E. (2014). Approach to
 660 environmental risk analysis for the main monuments in a historical city. *Journal of Cultural Heritage*
 661 15 (4), 432–440.
 662

663 Peña, J.A., Teixidó, T. & Carmona, E. (2005). Prospección Geofísica en la Necrópolis de Carmona
 664 (Sevilla). *Estudio solicitado por el Conjunto Arqueológico de Carmona, Consejería de la Junta de*
 665 *Andalucía*. Ref. AGA-29.
 666

667 Pereira, A.R. & Pruitt, W.O. (2004). Adaptation of the Thornthwaite scheme for estimating daily
 668 reference evapotranspiration. *Agricultural Water Management* 66, 251–257
 669

670 Sánchez-Moral, S., Luque, L., Cuezva, S., Soler, V., Benavente, D., Laiz, L., Gonzalez, J.M. & Saiz-
671 Jimenez, C. (2005). Deterioration of building materials in Roman catacombs: The influence of
672 visitors. *Science of the Total Environment*, 349 (2005), 260– 276.

673

674 Sánchez-Moral, S., Cañaveras, J.C., Benavente, D., Fernández-Cortés, A., Cuezva, S., Elez, J., Jurado,
675 V., Rogerio-Candelera, M.A. & Saiz-Jiménez C. (2018). A study on the state of conservation of the
676 Roman Necropolis of Carmona (Sevilla, Spain). *Journal of Cultural Heritage*, 34, 185-197.

677

678 Siart, C., Eitel, B. & Panagiotopoulos D. (2008). Investigation of past archaeological landscapes using
679 remote sensing and GIS: a multi-method case study from Mount Ida, Crete. *Journal of*
680 *Archaeological Science*, 35 (11), 2918-2926.

681

682 Siart C., Hecht S., Holzhauer, I. Altherr, R. Meyer, H.P. Schukraft, G. Eitel, B. Bubenzer, O. &
683 Panagiotopoulos, D. (2010). Karst depressions as geoarchaeological archives: The
684 palaeoenvironmental reconstruction of Zominthos (Central Crete), based on geophysical
685 prospection, sedimentological investigations and GIS. *Quaternary international*, 216 (1-2), 75-92.

686

687 Strahler, A.N. (1957). Quantitative Analysis of Watershed Geomorphology. *American Geophysical*
688 *Union Transactions*, 38, 913-920.

689

690 Tarboton, D.G. (1997). A new method for the determination of flow directions and upslope areas in
691 grid digital elevation models. *Water Resources Research*, 33, 309-319.