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Review of satellite resources to assess environmental threats in rammed earth fortifications

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Abstract: The nature of rammed earth fortifications and the environmental conditions where they are located determine the pathologies that these structures suffer in the presence of humidity sources and strong winds. The objective of this project is to revise the main mechanisms of deterioration of rammed earth fortifications and evaluate the use of remote detection as a tool to register environmental threats that affect their preservation. The selected images and satellite results offer information about precipitation, ground humidity, temperature, wind intensity and direction and the presence of particles in the wind. The use of statistical analysis methodologies for large volumes of satellite images makes it possible to acquire daily, monthly and yearly maximums, averages and minimums of these variables. The application of satellite resources GPM, SMAP, MODIS, Merra-2 and the statistical analysis of large volumes of images for preventive conservation in Andalusia has become useful to monitor the main threats that affect rammed earth fortifications on a global level: humidity, wind and temperature.

Keywords: vulnerability, fortifications, hazards, rammed earth, remote sensing products

Revisión de recursos satelitales para evaluar amenazas ambientales en fortificaciones de tapia

Resumen: La naturaleza de las fortificaciones en tapia y las condiciones ambientales del entorno en el que se ubican condicionan las patologías que estas estructuras sufren ante la presencia de fuentes de humedad y fuertes vientos. Este trabajo tiene como objetivo revisar los principales mecanismos de degradación de las fortificaciones en tapia y evaluar el uso de la teledetección como herramienta de registro de las amenazas medioambientales que afectan a su preservación. Las imágenes y productos satélites seleccionados ofrecen información sobre precipitación, humedad del suelo, temperatura, intensidad, dirección y presencia de partículas en el viento. El uso de metodologías de análisis estadístico de grandes volúmenes de imágenes satelitales permite obtener máximas, medias y mínimas diarias, mensuales y anuales de estas variables. La aplicación de los recursos satelitales GPM, SMAP, MODIS, Merra-2 y el análisis estadístico de grandes volúmenes de imágenes para la conservación preventiva en Andalucía resulta de utilidad para monitorear las principales amenazas que afectan a las fortificaciones en tapia a nivel global: humedad, viento y temperatura.

Palabras clave: vulnerabilidad, fortificaciones, peligrosidades, tapia, productos satelitales

Introduction

Historically, tapia—or rammed earth—has been a constructive technique widely utilised in different time periods and cultural contexts. Its use has become widespread in the construction of houses, palaces, fortifications and religious buildings, and its remains are common in archaeological sites and vernacular structures, the result of constructive richness and diversity that rammed earth heritage features (Jaquin *et al.* 2008). In practice, of the 150 earth constructions that are declared World Heritage Sites, at least 39% preserve rammed earth structures (Gandreau & Delboy 2012). In Spain, a large part of traditional architecture and medieval fortifications are constructed in rammed earth, its presence is common in the walls of many historical centres.

Concern about environmental problems is motivating a return to the use of traditional materials, like rammed earth, that do not implicate CO_2 emissions in the process of manufacturing and it is an interesting option to reduce the carbon footprint of construction (Arrigoni *et al.* 2017; Kariyawasam & Jayasinghe 2016).

Traditionally, the knowledge related to rammed earth constructions has been passed on orally (Ávila *et al.* 2021). Although its current use as a construction material has required the development of studies that standardise its characterisation, hydromechanical performance and evaluate the deterioration processes it undergoes (Quoc Bao Bui *et al*. 2014b; Giuffrida *et al.* 2019; Jiménez Delgado & Guerrero 2007).

The fact that conserved rammed earth fortifications in many cities of the Iberian Peninsula have lasted for centuries makes it interesting to study which factors affect its resistance and durability, especially in the face of threats that are considered more aggressive, such as strong and prolonged rain, or water access through capillarity from the subsoil (Beckett *et al.* 2020).

While in contemporary constructions water access can be controlled using stabilizers and designing constructive elements that protect the rammed earth, in heritage buildings, the continuous exposure to water creates serious pathologies over time that are difficult to resolve and are the main cause of reparation interventions and maintenance in historical rammed earth (Avram *et al.* 2001; Mileto & Vegas 2013). In archaeological sites, coverings are usually carried out and sacrificial mortars and consolidating agents are used to insure the conservation of the rammed earth in the long term (Correia *et al.* 2016). Interventions in medieval fortifications have mainly included the reintegration of lost areas and eroded walls and filling cracks. The use of incompatible restoration mortars has produced its own pathologies such as lack of adhesion, which is one of the main problems that the intervened areas present. Canivel and Graciani (2012) attribute its cause to incorrect installation, which hinders the bond between screed mortars and the original rammed earth, while the laboratory tests carried out about restoration mortars (Gomes *et al.* 2016, 2018) and grouts for filling cracks (Silva *et al.* 2018) associate these pathologies with the addition of Portland cement as a stabilizer. In their archival review about restorations of rammed earth fortifications conducted between 1980-2010 in Spain, García Soriano and Mileto (2015) highlight the frequent use of mortars stabilised with Portland cement and the problems with installation in many of these interventions. The appearance of displacements and erosion are very common pathologies that minimize the durability of the rammed earth. Identifying the direct causes of these alteration indications in restored walls creates controversy, especially when the materials and installation have been respectful of the originals. It is about the complex deterioration models in which the original rammed earth, the completed restorations and the environmental conditions must be kept in mind. Ground-breaking work like that of Gutiérrez Carrillo and Oliveira (Gutiérrez-Carrillo *et al.* 2021; Oliveira *et al.* 2019) registers the factors of environmental danger that influence the deterioration of rammed earth fortifications. However, studies that determine the impact of the environment in the behaviour of historical structures and their restorations are still scarce, so the of the development of studies that analyse how these environmental mechanisms determine the durability of the rammed earth is fundamental, especially if they allow the full expanse of the fortifications to be covered.

Facing the described problems, this study aims to contribute to the knowledge about the benefits that remote detection offers for the collection of environmental data and monitoring of heritage buildings. As an analysis technique, remote detection enables gathering land coverage data according to its emission spectrum (Chuvieco 2016; Perez & Muñoz 2006). Its application in walls and fortifications would allow insight into the surroundings of the rammed earth and its environmental conditions. In fact, as a consequence of technological advances, analysis models are being used for statistical work on large volumes of satellite data and large geographical areas over long periods of time (Awange & Kiema 2019; Chuvieco & Emilio 2007; Gorelick *et al*. 2017; Lasaponara & Masini 2020). Today the satellite images are a very useful tool for the analysis of heritage environments, the gathering of information about its recent past and the decision-making for its preservation (Agapiou *et al*. 2020; Cuca & Hadjimitsis 2017; D. G. Hadjimitsis *et al*. 2020; Luo *et al*. 2019b).

From this perspective, this study is intended to identify the main factors of danger and deterioration mechanisms of rammed earth and evaluate the main satellite resources and analysis methods that make monitoring those threats possible.

Methodology

Satellite resources have been tested for monitoring precipitation, ground humidity, temperature and wind for the evaluation of the threats that affect the preserved rammed earth fortifications in Andalusia (Spain). The precipitation data has been acquired from Global Precipitation Measurement (GPM), that of ground humidity from Soil Moisture Active Passive (SMAP), that of temperature from the result MOD11A1.006 derived from Aqua-MODIS and that of wind from the result M2TMNXAER derived from Merra-2.

All of the satellite data has been acquired by the use of the Worldview and Giovanni viewfinders and the processing software in the Google Earth Engine cloud. The location of the 216 rammed earth fortifications in Andalusia has been acquired from the IAPH Digital Heritage Guide (IAPH, s.f). Subsequently, all of the data has been migrated to a Geographical Information System like ArcGIS, to identify the exposure of the fortifications to the registered dangers.

Rammed earth: compositional characteristics and deterioration processes

Rammed earth is an architectural structure composed of a mixture of sand, gravel and clay that is compacted by tamping it down inside wooden formwork. When only clay is used as a binding agent it is called unstabilised rammed earth. In these unstabilised rammed earth structures, it is the clay, due to its small particle size (<0.0.002 mm), which provides cohesion to the mixture. If different binding agents are added to the rammed earth other than clay, it is designated stabilised rammed earth (Avram *et al.* 2001; Mileto & Vegas 2013).

While almost any type of local soil can be used to make rammed earth, it is necessary to control the particle size distribution and the proportion of the materials used to ensure the aptitude of the soil. In spite of this, the proportion in which the materials are mixed can vary enormously in the making of rammed earth. The percentage of clay used varies between 8-20% and that of sand between 50-75% of the dry weight of the mixture(Ávila *et al.* 2021; Giuffrida *et al.* 2019; Niroumand *et al.* 2021). Within these margins, the content of clay determines the resistance of the rammed earth walls. While proportions close to the minimum offer a higher resistance due to the high capacity of the clay to retain water, proportions close to the maximum increase plasticity and favour workability and the compressive strength of the wall (Gomes *et al.* 2014). The type of clay also determines the behaviour of the rammed earth. While kaolinite, illite or chlorite are non-expandable clays, montmorillonite, smectite and vermiculite are expandable clays that, in the presence of water, expand and contract, creating cracks. The addition of silt, sand or straw reduces the effects of expandable clays, and the addition of gravel and pebbles increases the durability (Reddi *et al.* 2012). Among these components, natural fibres make the behaviour of the rammed earth in seismic areas better (Giuffrida *et al.* 2019; Jiménez Delgado & Guerrero 2007).

To increase the durability and resistance of the rammed earth, since ancient times, a large variety of stabilisers and additives have been put in to modify texture, structure and physio-mechanical properties of the rammed earth in a controlled way. The main stabilisers used have been lime and cement (Ávila *et al.* 2021; Hall *et al.* 2012; Toufigh & Kianfar 2019). The masonry of medieval fortifications is an example of stabilised rammed earth that is called soil and lime concrete. In turn, the mortars used in its restoration usually employ lime and cement as stabilisers in different proportions (Gomes *et al.* 2016).

The studies of rammed earth characterization identify the materials that make up different historical masonry. Different methodological proposals and local studies exist (Avram *et al.* 2001; Canivell García de Paredes 2011; Hamard *et al.* 2016, 2020), of which the objective is to compositionally characterise the material nature of the fortifications (Martín-del-Rio *et al.* 2018; Mota-López *et al.* 2021; Ontiveros Ortega *et al.* 2008). The methodology developed by Gomes *et al.* (2014) in the south of Portugal makes it possible to establish relationships between the compositional characteristics and the aptitude of the vernacular rammed earth structures in relation to current structural regulations (Jiménez Delgado & Guerrero, 2007). The results acquired by Gomes *et al.* (2014) conclude that the contents of the organic matter and the maximum particle size is greater in historical rammed earth structures than in current ones due to the use of local soil and the scarce processing of the soil used in historical rammed earth structures.

In respect to the constructive technique, the compaction of the rammed earth allows the rigidity and mechanical resistance of the soil to improve. This process reduces air pockets and increases the dry density in the rammed earth (Cuccurullo *et al.* 2021). The difference in working method and compaction energy determine the resistance of the resulting rammed earth (Ávila *et al.* 2021), while the optimal water content favours the compaction of the soil to maximum dry density. Currently, the optimal amount of water can be calculated by means of Proctor tests or modified Proctor tests and it is common to use mixtures with 5-15% dry weight (Ávila *et al.* 2021; Gerard *et al.* 2015; Reddi *et al.* 2012). The distribution, the size and shape of the grains and the amount of clay-like minerals also determine compaction (Cuccurullo *et al.* 2021; Jiménez Delgado & Guerrero 2007). According to Ávila *et al.* (2021) course-grained soil reaches a higher density than finer-grained soil. In summary, properties such as water content, particle size, chemical and mineralogical composition, or constructive technique determine the dry density and resistance, varying in modern rammed earth between 1700-2200 kg/m^3 and in historical rammed earth between 1770-1990 kg/m^3 (Niroumand *et al.* 2021). As a consequence, the compaction and raw materials used in the making of rammed earth determine its hydro-mechanic behaviour in the environment (Giuffrida *et al.* 2019; Jiménez Delgado & Guerrero 2007).

At the design level, the stone bases that many of the historical rammed earth buildings exhibit act as a layer of isolation that protects against water access from the subsoil and rain splashes. The lime linings are also permeable protective elements that minimize water access to the interior of the wall (Hall and Djerbib 2005). The presence of stone finishings and laterite roofing material are designed with a similar function of protection. Figure 1 presents different typologies of rammed earth works preserved in medieval Spanish fortifications. After the XI century, along with simple rammed earth [Figure 1B and 1C], mixed works are starting to be used that include the use of brick walls [Figure 1A], a change in metrical spacing after the XII century and a stone and laterite lining of the structures [Figure 1D] in subsequent time periods (Garcia *et al.* 2008). The constructive technique model used and the state of conservation of the materials determine the durability of these rammed earth structures (Moreno *et al.* 2019).

During their useful lifespan, rammed earth walls behave as an unsaturated geomaterial that exhibits water and

Figure 1.- A) Rammed earth lined with stone, Alcalá de Guadaira Castle (Seville); B) View of simple rammed earth, Alcalá de Guadaira Castle (Seville); C) View of simple rammed earth, Palmar del Río (Seville); D) Rammed earth lined with brick and stone, Alcazaba of Málaga.

gas-filled spaces. For this reason the internal capillary suction processes have a major influence on the degree of resistance that the structures present (Gerard *et al.* 2015; Laloui *et al.* 2013). Changes in environmental humidity and temperature mean that the earth walls undergo constant absorption and desorption processes. The high water retention capacity depends on open porosity, micropores and the hygroscopicity of the clays (Quoc Bao Bui *et al.* 2014a; Giuffrida *et al.* 2019; Pauporté & Sgambi 2019). According to Cuccurullo *et al.* (2021) a decrease in environmental humidity means an increase in capillary suction, a decrease of water in the pores and an increase in the resistance and rigidity of the rammed earth. Conversely, an increase of water content in the surroundings produces reduced suction, an increase of ductility and a decrease in the mechanical properties of the material. Otcovska et al. (2019) describes this phenomenon on a microscopic scale and indicates that an increase in water means a decrease in the uniting forces between clays, sand and gravel that varies depending on the type of soil. On a macroscopic scale, various authors (Avram *et al.* 2001; Morel *et al.* 2012; Moreno *et al.* 2019) relate humidification and drying acts to the reduction of the mechanical resistance, expansion of the clay minerals or swelling of the walls. These processes materialize in cracks and displacements [Figure 2] that increase vulnerability and facilitate water access to the interior of the material and erosion processes.

In the explained alteration processes, the deterioration of the rammed earth is generally due to durability problems from their materials (Beckett *et al.* 2020), mechanical failures caused by load levels are less common (Serrano-Chacón *et al.* 2021). The durability, understood as the resistance to deterioration over long time periods, defines the ability to resist wear generated by environmental and adverse anthropogenic effects. In the case of rammed earth structures numerous authors (Q. B. Bui *et al.* 2009; Giuffrida *et al.* 2019; Morel *et al.* 2012; J. Richards *et al.* 2019) agree that the durability of the walls is mainly determined by the resistance to water and wind.

The factors related to the decrease in resistance that rammed earth undergoes facing an increase in water content have been investigated from diverse perspectives: laboratory testing that recreate controlled environmental conditions (Cuccurullo *et al.* 2021; Villacreses *et al.* 2021); field tests that reproduce simulated rainfall events (Richards *et al.* 2019); and long-term studies that have

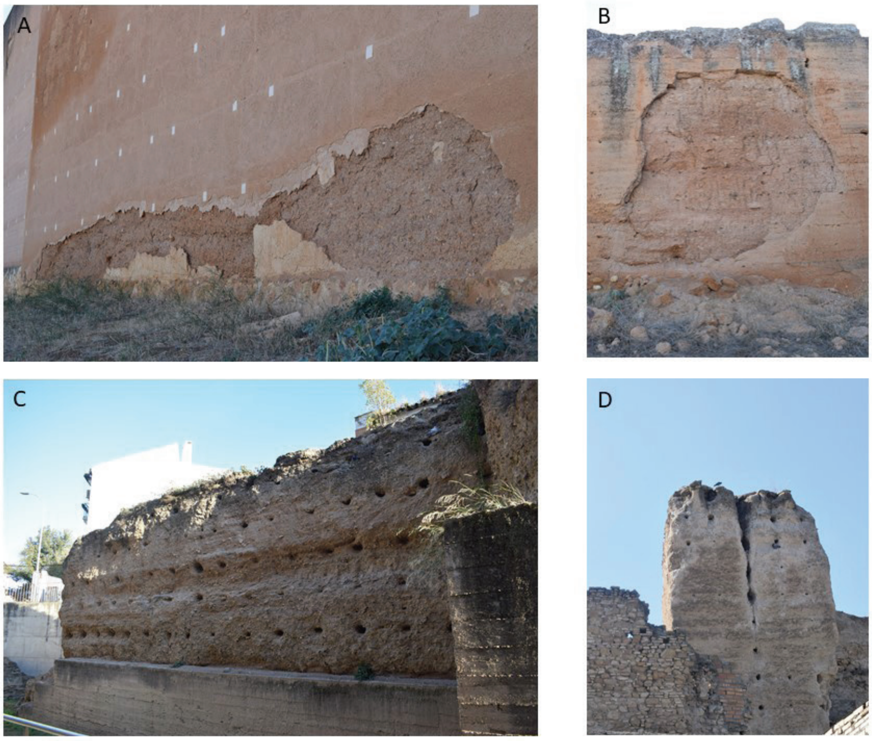

Figure 2.- A) and B) Displacements identified in the urban wall of Niebla; C) Erosion identified in the Alcazaba of Córdoba; D) erosion and fragmentation in the fortress of Marchena.

allowed evaluation of ageing processes over 20 year time periods (Bui et al., 2009). According to Hart *et al.* (2021) prolonged rainfall is more detrimental for a rammed earth structure than a short, intense rainfall, although, an increase in the kinetic energy of the raindrops due to the intensity and the angle of incidence due to wind action determine the erosive power of the rain (Jenny Richards *et al.* 2020). In short, it is the changes in mechanical resistance level that rammed earth undergoes as it moistens which determine the deterioration process. During a prolonged rain event, the water penetrates to a greater depth in the wall, reduces its mechanical resistance and makes it more vulnerable to the erosive effect of rain. As a consequence, the risk of precipitation and the vulnerability of the structure increase with exposure time, intensity and wind.

The use of geomorphic signatures (Richards *et al.* 2020) and vulnerability matrices that are adapted to work with rammed earth (M. Moreno *et al.* 2019) make it possible to establish relationships between deterioration processes, alteration factors and the current state of vulnerability. The established relationship between identified deterioration patterns and climate conditions is of great interest to understand the deterioration processes of these types of structures. The studies developed by Richards *et al.* (2020) relate the presence of delamination and strong erosion processes to the humidification-drying cycles accompanied by strong winds that occur in semi-arid climates. In Mediterranean climates, the studies completed by Moreno *et al.* for Seville (2019) identify deterioration patterns that cause differential erosion in 89% of the 199 evaluated sections of walls due to the effects of rain and wind; while water access through capillarity causes displacements and granular disintegration in 56% of the evaluated sections.

The studies carried out until now highlight the necessity to analyse the existing correlation between surrounding climate factors and the pathologies that reduce durability in rammed earth structures. Therefore, tools such as remote detection and the use of geographical information systems, which offer continuous and consistent geo-reinforced climate data, are especially useful for the analysis of threats that affect rammed earth structures due to the reliance on meteorological conditions and their large expanse in the area.

Satellite resources and methodologies for monitoring the environment of heritage structures

As an analysis technique, remote detection acquires land cover information depending on the interactions that occur between the objects being studied and a source of illumination (Awange & Kiema 2019; Rodríguez Pérez, D., Sánchez Carnero, N., Domínguez Gómez, J. A., & Pastrana 2015). If the sensor that registers that interaction is carried by a satellite it is called remote spatial detection and if it is a small aircraft or an unmanned plane it is called remote airborne or photogrammetry detection. One of the main advantages of satellite data is that it allows near-global and consistent coverage to compare data gathered in areas that are far away from each other. For this reason it has been used a lot in cartographic updating and in the automatic detection of land use changes, the type of land coverage or climate changes (Sobrino 2001).

Table 1 summarizes the main satellite resources available for monitoring the danger factors that affect rammed earth fortifications. These have been included: (1) satellite images that are produced directly from the radiance/reflective values gathered by satellite instruments; and (2) algorithms that indirectly produce climate reanalyses and estimated results based on mathematical calculations applied over satellite images. The time period covered, the temporary spatial resolution, the available bands and the existence of derivative results have been analysed with the goal of evaluating environmental threats in heritage structures. It must be taken into account that the temporal resolution can decrease for areas outside of Europe in the

Satellite/ Instruments/ Algorithms	Types of data	Period	Spatial Res.	Temporal Res.	Bands/ Polarisation/ Result	Danger factors analysed
Landsat/ currently OLI and TIRS	Multispectral passive satellite VIS-SWIR	1979-present	30-15-100 m	15 days	7 spectral bands, 1 panchromatic band and 2 thermal bands. It also has derivative results with vegetation bands, burned areas, etc.	Urbanisation and asphalt in heritage environments (Elfadaly *et al.* 2017; Elfadaly & Lasaponara 2019; D. Hadjimitsis *et al.* 2013)
						Changes in the vegetative development of green areas and ground humidity (Titolo 2021; Wellmann *et al.* 2020)
						Ground temperature, fires and burned areas (Agapiou & Lysandrou 2021; Cook *et al.* 2014a)
Sentinel 2/MSI	Multispectral passive satellite VIS-SWIR	2017-present	10-20-60 m	5 days	10 spectral bands	Urbanisation and asphalt in heritage environments (Elfadaly & Lasaponara 2019)
						Changes in the vegetative development of green areas and ground humidity (Abate & Lasaponara 2019; Chen *et al.* 2020).
Sentinel 1	C band active radar satellite	2014-present	10-25-40 m	6 days	2 dual and simple VV, HH, VV + VH, HH +VV polarisation bands	Flooding in non-urban lands (Lopez *et al.* 2020)
						Land displacements and seisms (Chen *et al.* 2020; Kosta *et al.* 2020b; Themistocleous & Danezis 2020a)
Aqua EOS, Terra EOS/ MODIS	Passive satellite. Spectroradiometer.	2000-present	250-500-1000 m	1 day	36 spectral bands. It also has derivative results with vegetation bands, the earth's surface temperature, burned areas, etc.	Changes in the vegetative development of green areas and ground humidity (Gu *et al.* 2007)
						Changes in ground temperature, risk of fire and burned areas (Bisquert *et al.* 2014; Quintero *et al.* 2019)
						Concentrations of aerosols and sandstorms (Sarikhani *et al.* 2021; Xie *et al.* 2017)
ERA 5 Land	Climate reanalysis	1981-present	11.132 m	1 day/ 1 month	50 bands with different estimated climate variables	Monitoring of climate variables: precipitation, air and ground temperature, solar radiation, evaporation, velocity and direction of the wind, etc. The data is reliable in time periods over 1 year (Liu *et al.* 2020)
GLDAS-2.2	Climate reanalysis	2000-present	27.830 m	3 hours	36 bands with different estimated climate variables	Monitoring of climate variables: precipitation, air and ground temperature, solar radiation, evaporation, wind speed, ground humidity at different depths, etc. The data is reliable in time periods over 1 year (Cai et *al.* 2017).
CHIRPS	Estimated result	1981-present	5.566 m	1 day	1 precipitation band	Precipitation and meteorological droughts. The data is reliable in time periods over 1 year. (Alahacoon & Edirisinghe 2021; Funk *et al.* 2015; A. Kumar *et al*. 2021; Moreno *et al.* 2022)
PERSIANN-CDR	Estimated result	1983-present	27.830 m	1 day	1 precipitation band	Precipitation and meteorological droughts. The data is reliable in time periods over 1 year (Santos *et al.* 2021)

GPM	Active-passive satellite. Dual frequency precipitation radar/microwave camera. Estimated result	2000-present	11.132 m	1 month/ 3 hours	4 precipitation bands	Precipitation and meteorologic droughts over short and long time periods (Retalis *et al.* 2022; Tang *et al.* 2020)
GSMaP	Estimated result	2000-present	11.132 m	1 hour	2 precipitation bands	Precipitation and meteorologic droughts over short and long time periods (Retalis *et al.* 2022)
SMAP	Active-passive satellite. Estimated result	2015-present	10.000 m	3 days	5 ground humidity bands	Ground humidity, subsoil humidity and anomalies in the registered humidity levels (Lopez *et al.* 2020)
Aqua EOS/Air/ DM2TMNXAER	Infrared probe. Estimated result	1980-present	60,000 m	1 month	1 surface dust mass concentration band	Presence of dust particles in the air and sandstorms (Ghazal 2020)

Table 1.- List of the main satellites, instruments and algorithms available to assess environmental threats in rammed earth constructions.

case of the Sentinel 1 and 2 satellites. The available bands and satellite results can vary in all satellites depending on the image processing level. Throughout this study the differences between the stated resources and their possible use for the study of rammed earth structures are explained.

— *Current use of satellite resources and methodologies for heritage monitoring*

In the analysis of risk and vulnerability of cultural heritage, the studies completed with remote detection raise a special interest because of the use of satellites with passive instruments and multispectral images for the research and analysis of risks in archaeological complexes and historical landscapes (Cuca & Hadjimitsis 2017; Luo *et al.* 2019a). The Landsat (1979-present) and Sentinel 2 (2014-present) series are the most used satellites (Table 1) due to the fact that they carry multispectral sensors. They produce groups of images in layers (or bands) based on the radiance/reflectance registered at a given wavelength in the area of study. Their application to the analysis and monitoring of rammed earth fortifications allows the identification of humidity levels in green areas or urban growth processes that affect the immediate context of the fortifications. Their main advantage is high spatial resolution, 30 m on Landsat and 10 m on Sentinel, which enables their use in limited environments like urban areas. The main disadvantage of these satellites is that they carry passive sensors that do not capture information from the earth's surface in the presence of clouds or the absence of solar light, for this reason their use in context of heavy rainfalls is limited.

The analysis methodology used on these types of satellite images has been based on the use of false-colour combinations (blue, green and red), standardised indices and classifications based on the levels of reflectance registered in different bands (Abate & Lasaponara, 2019). Landsat has derivative results like Global Human Settlement Layers (GHSL) which include the results of using urbanisation indices and construction date classifications for certain periods of time. Unlike the bands, the derived results can be consulted without needing to execute any type of analysis. Figure 3A shows the result of applying the combination of bands B7, B6 and B4 from Landsat 8, which identifies the asphalt ground in purple and, therefore, the possible areas where there could be difficulties to drain water from the subsoil in the city of Seville. Figure 3B shows the results of using the Normalized Difference Vegetation Index (NDVI) from a Landsat 8 image to identify the green areas in the city of Seville and their proximity to the medieval fortifications that are outlined in black. This type of index is very useful for monitoring urban irrigation systems and recreational areas where fortifications are often located.

Since 2010, the use of new satellite resources in heritage has diversified (Agapiou *et al.* 2020; Luo *et al.* 2019b). The LiDAR flights enable the gathering of information from the earth's surface with a high spatial resolution in areas of dense vegetation (Lieskovský *et al.* 2018; Rodríguez-Gonzálvez *et al.* 2017; Trier *et al.* 2021); and synthetic aperture radars (SAR radar) work at very high wavelengths and capture data in almost any climatic and environmental condition (Chen *et al.* 2017; Iadanza *et al.* 2013; Lopez *et al.* 2020; Tapete & Cigna 2017b; Themistocleous & Danezis, 2020a). The active sensors carried by LiDAR and the SAR radar go through the clouds and capture information from the earth's surface in situations where a passive satellite is not capable, such as a rain event, the presence of smoke associated with a fire or volcanic activity. As an example, the active satellite Sentinel 1 (5.405GHz, C band) offers information available since 2014 with 3 different spatial resolutions (10, 25 or 40 metres) and simple or dual (HH+HV, VV+VH) polarisation (Table 1). By way of example, Figure 4 shows the differences between two satellite images taken on the same date over the city of Granada, one through a passive satellite (Landsat 8) and another through an active satellite (Sentinel 1). While the information captured by the passive sensor that day is minimal, the active sensor goes through the clouds and acquires information about the city centre, which is

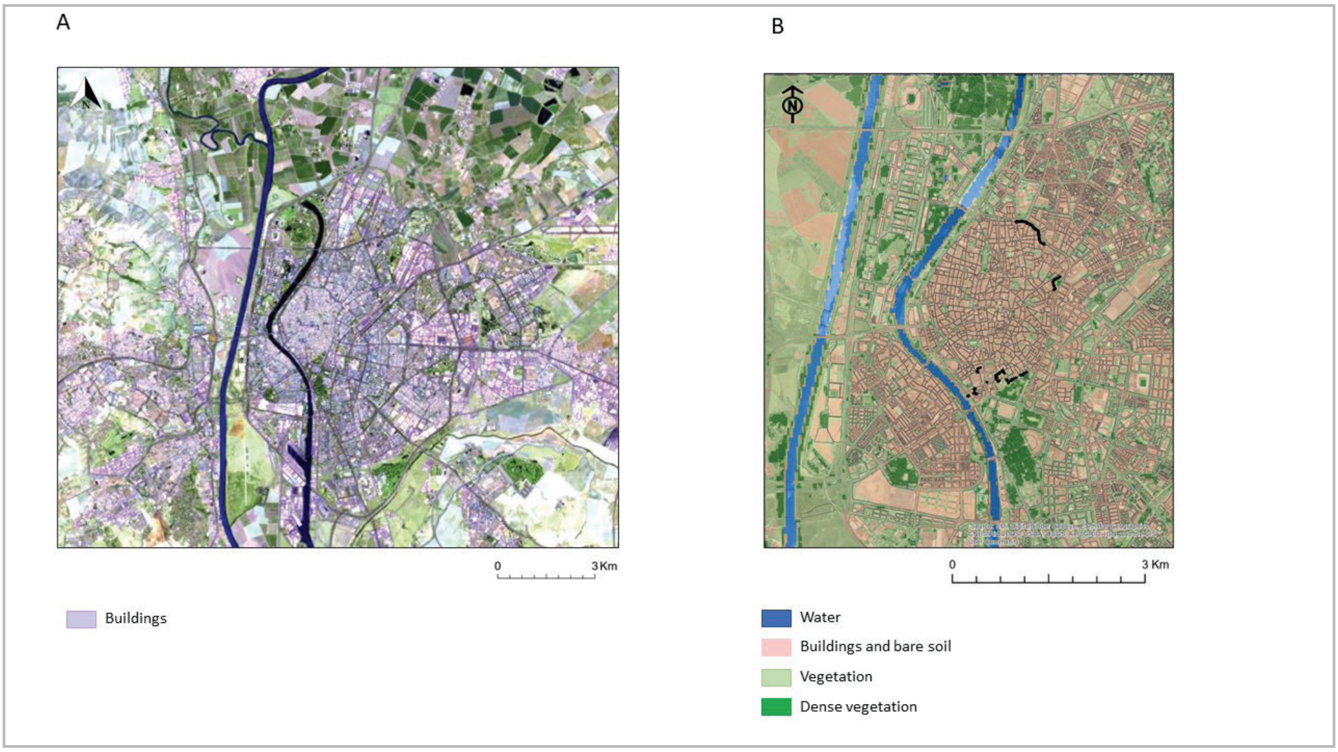

Figure 3.- Images acquired from the multispectral Landsat 8 satellite for the city of Seville: A) combination of urban false-colour bands (B7, B6 and B4); B) and of land coverage classification from the Normalized Difference Vegetation Index (NDVI): (B5-B4)/(B5+B4)). Satellite images downloaded on the Google Earth Engine and processed in SMAP and ArcGIS.

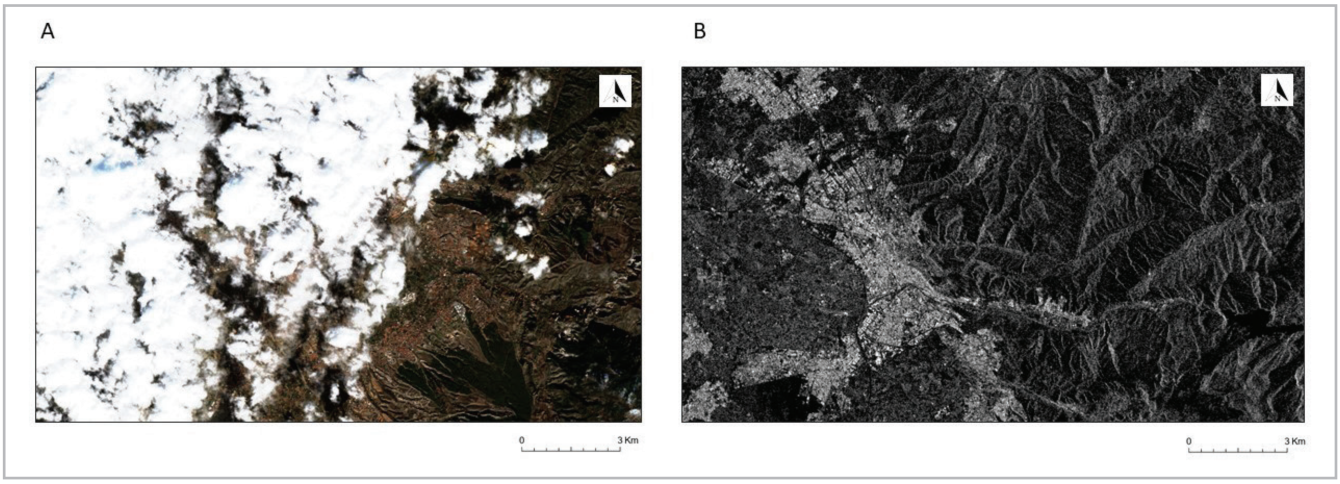

Figure 4.- Satellite images in the city of Granada, Spain: A) Passive satellite Sentinel-2; B) Active satellite Sentinel-1 (November 2021). Images acquired from the EO Browser viewfinder.

highlighted light grey in figure 4B. For this reason, the applied use of active sensors in the management of rammed earth fortifications can be very useful to monitor floods and vegetation in non-urban areas.

Another application of SAR radar satellites is the interferometry that acquires very accurate topographic measurements by analysing the differences in backscatter and existing stages between two measurements (Kosta *et al.* 2020b; Themistocleous & Danezis 2020b). The possibilities offered by its application in patrimony have generated numerous studies to analyse the effects of seismic waves and land displacements (Chen *et al.* 2020; Kosta *et al.* 2020a; Tapete & Cigna 2017a; Themistocleous & Danezis 2020b). Applied to the study of rammed earth fortifications, it is key to identifying the origin of failures in the mechanical behaviour of rammed earth, cracks and collapses.

— *Capabilities of satellite resources and methodologies for preventative conservation studies*

Estimated meteorologic satellite results and climatic reanalysis are widely used today (Geer *et al.* 2017; Hersbach *et al.* 2020a), nevertheless, their application to heritage conservation has only been considered on a theoretical level (Lasaponara & Masini 2020) and scarcely used on a practical level.

The appearance of new satellite results from the reflective data and algorithms or numerical calculation models that acquire indirect measurements of parameters such as temperature or precipitation is becoming increasingly common. Once devised, these estimated results are calibrated by comparison with direct measurements from ground-based meteorological stations to adjust the mathematic models. Examples of such results would be CHIRPS (Shen *et al.* 2020), PERSIANN(Ashouri *et al.* 2015b), Era5 (Hersbach *et al.* 2020b)or GSMaP (Aonashi *et al.* 2009; Kubota *et al.* 2017). As Table 1 shows, in these types of reprocessed results, the available bands are no longer related to the different levels of radiance or reflectance but to the meteorological parameters estimated indirectly from the calculations made (temperature, wind, precipitation, etc.).

At present, the great challenge is how to implement tools and methodologies capable of analysing statistically large volumes of satellite information and acquire essential information for the monitoring and conservation of heritage structures (Agapiou 2017; Ma *et al.* 2015). In contrast to the analysis of one reduced group of images, the statistical work with large volumes of historical satellite series generates maps and graphs with daily, monthly and annual maximum values, averages, cumulative amounts, etc. (Cuca & Hadjimitsis 2017; Lasaponara & Masini 2020). In recent years, advances in the development of viewfinders and processing software in the cloud have made this new work option possible, diversifying the possibilities that satellite images offer as a source of information and favouring their use in many different disciplines (Mutanga & Kumar 2019).

Table 2 synthesises a list of the main free access resources for the analysis of satellite images and highlights which of them can be used to work statistically with large volumes of data. New software like Google Earth Engine (https://earthengine.google.com/) offer the possibility to consult and statistically analyse complete historical series from main satellites such as Landsat, MODIS, Sentinel, etc. (Agapiou 2017; Agapiou & Lysandrou 2021) and facilitate work with estimated satellite results or climatic reanalysis with data on precipitation, ground humidity, wind, temperature and other factors closely related to the deterioration of the heritage assets.

Furthermore, the use of viewfinders facilitates the access and use of satellite resources to people who do not specialise in remote detection work. EO Browser (https://apps.sentinel-hub.com/) allows acquiring combinations of bands and indices for unit analysis of images pertaining to passive and active satellites; WorldView (https://worldview.earthdata.nasa.gov/) makes it possible to visualise historical series of a large part of the displayed reprocessed resources and Giovanni (NASA) (https://giovanni.gsfc.nasa.gov/) carries out simple statistical operations (averages, maximums, accumulated values, correlations...) on large volumes of images (Table 2).

In summary, the introduction to the statistical study of satellite images as a humidity, precipitation and temperature monitoring tool, would make it possible to develop preventative conservation plans in territories with a large number of heritage structures and its application would help with decision-making for the redistribution of available technical, professional and economic resources, minimising the risk of losing the structures. Satellite resources with environmental parameters offer continuous and global coverage of the planet that allows relationships

Name of software	Description	Unit analysis of satellite images	Statistical analysis of satellite images
Quantum GIS (QGIS)+ Google Earth Engine plugin for QGIS	Geographical Information System. Desktop software from the Open Source Geospatial Foundation (OSGeo)	Yes (Titolo 2021)	Yes (Rufin *et al.* 2021)
Sentinel Application Platform (SNAP)	satellite image processing programme. Desktop software from the European Space Agency (ESA)	Yes (McGarragh *et al.* 2015)	No
Google Earth Engine (GEE)	Geo-spatial processing platform in the Google cloud	Yes	Yes (Gorelick *et al.* 2017; L. Kumar & Mutanga 2018)
EO Browser	Satellite image viewfinder developed by the European Space Agency (ESA)	Yes (Fedoniuk *et al.* 2021; Kim *et al.* 2009)	No
Giovanni	Satellite image series viewfinder developed by the National Aeronautics and Space Administration (NASA)	Yes	Yes (Ghane Ezabadia et al., 2021; Jamali *et al.* 2022)
Climate Engine (Huntington *et al.* 2017)	Climate satellite image series viewfinder run by Google	Yes	Yes (Huntington *et al.* 2017)

Table 2.- Open access software available for the analysis of satellite images

to be established between variables detected in very distant places. In spite of this, the absolute variables acquired from these images must be validated with land-based meteorological station data before being used.

Application of satellite resources to the evaluation of environmental threats for rammed earth fortifications in Andalusia

Because of the possible uses that the employment of environmental satellite resources offers and the scarce use they have had up to this point in patrimony, hereafter, the characteristics of satellite resources listed in table 1 for the gathering of climate and environmental variables are explained in detail. The GPM precipitation, SMAP subsoil humidity, MODIS temperature and Merra-2 wind resources have also been tested by their application to the case study of conserved rammed earth fortifications in Andalusia.

Within the satellite results that estimate environmental parameters, multiple precipitation algorithms exist that work on infrared and microwave wavelengths (Sun *et al.* 2018). The data from the Global Precipitation Measurement (GPM) satellite is an example of this (Table 1) and it offers precise and accurate values according to the data taken in land-based stations for monitoring rain events. The derivative images from this network of satellites offer estimated precipitation data in mm/h every 30 minutes for an almost global spatial coverage of the planet (60ºSx60ºN) and a spatial resolution of 0.1º (10km) since 2014. To recover previous precipitation data, it is possible to access the images acquired through its predecessor, the TRMM (1998-2015) or consult GSMaP. Applied to patrimony, the statistical analysis of these series of satellite results offers graphics that register the intensity of heavy rain events in different contexts and favours the access to maximum, minimum and average daily, monthly and annual data in the immediate surroundings of a fortification.

Identifying climate characteristics and evaluating the effects of climate change requires working closely with the available information for long periods of time known as climate normals. The reproduced satellite results offer a climatic reference of more than 30 years to compare current observations and identify climate anomalies. These tools, applied to the management of rammed earth fortifications, help to identify areas located in rainier climates and areas especially affected by strong storms or long droughts. They are essential for monitoring and planning preventative conservation activities in territories that are affected by climate change.

As table 1 shows, Era5 reanalysis is available to carry out climate studies; algorithms such as: PERSIANN, calculated by the use of artificial neural networks from satellite sensors that operate in infrared and microwave; and CHIRPS, calculated from infrared observations and land-based station data. The validation studies carried out to date show that this data is acceptable for annual analysis and reliable for long climatic periods, not for daily data (Ashouri *et al.* 2015a; Funk *et al.* 2015; Hsu *et al.* 2021; Tetzner *et al.* 2019; Moreno *et al.* 2022). As an example, figure 5A shows the results acquired from the calculated average of 240 monthly precipitation images from GPM between 2001 and 2021. The resulting image from the statistic calculation of satellite images is very similar to that generated by the Spanish Meteorological Agency (AEMET) from the interpolation of data gathered by land-based stations (http://agroclimap.aemet.es/), and easily identifies the high precipitation areas in the Iberian Peninsula. Galicia, the Cantabrian strip, the Pyrenees and Cádiz. The acquired precipitation data allows clearly defined areas to be identified, although the absolute pixel values (mm/h) must be validated on a local level with land-based meteorological stations before being used. Image 5B provides a detailed view of the Andalusian area and the conserved rammed earth fortifications. 9% of the 216 fortifications analysed are located between Cádiz and Málaga in the area highlighted in dark blue in the image, so they are exposed to greater danger from rain and they will be more prone to suffer humidity problems. 7% of the fortifications located in the light blue area are situated in Almería, where there is a lesser danger of precipitation and, in similar conditions of vulnerability, they should have a higher durability.

Era5 offers estimates of more than 50 climate variables such as ground humidity, evapotranspiration, air temperature, intensity and direction of the wind, etc. (table 1) since 1979 with a spatial resolution of 0, 28º (approx. 30 km) and 3 temporal resolutions (hour, day or month). Era 5-Land is an improved model of Era-5 (Muñoz-Sabater *et al.* 2021) and it offers data as far as 1981 with a spatial resolution of 11x11 km. The data is reliable for annual analysis and long climate periods, not for daily data. Applied to the study of rammed earth fortifications, its use makes it possible to categorize distinct climate contexts and evaluate existing threats for rammed earth structures in an area.

To quantify ground humidity and evaluate possible water access through capillarity, Soil Moisture Active Passive (SMAP) is available, which has 2 measurement instruments, a radar and a microwave radiometer functioning at 1,2 GHz. The measurement of superficial and subsurface humidity in land coverage is based on existing differences in backscatter between dry and/or humid soil (Entekhabi *et al.* 2010; Zhang *et al.* 2017). From this satellite data, the GLDAS model has contributed humidity data from different depths since 1948 with a 27 km spatial resolution and a 3-hour temporal resolution (Table 1). This type of information can also be consulted in Era 5. Its use in patrimony identifies changes in ground humidity and predicts droughts and floods. In rammed earth structures, it is very interesting to monitor the drying of the soil after a heavy rain event and identify the higher risk areas due to drainage problems in the subsoil. As an example, image 6A presents the registered humidity levels in the subsoil on a

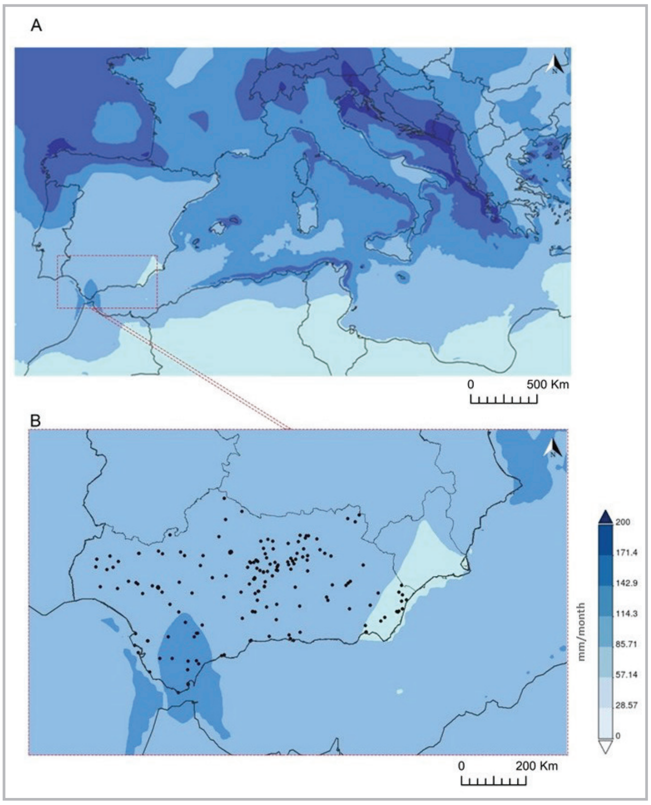

Figure 5.- A) Average of the precipitation satellite images from 2001 to 2021. Data acquired from the monthly GPM IMERG model and statistically analysed in the Giovanni viewfinder; B) Detail of the Andalusian area with the location of rammed earth fortifications marked with black dots.

winter day and image 6C, the registered humidity levels on a summer day in the Mediterranean. As figure 6D illustrates, the Mediterranean climate in Andalusia determines that a large part of the rammed earth fortifications suffer low levels of ground humidity and drought events that can favour the appearance of ground settlement issues and fracturing in clay soils (Santos 1997). In forested areas, low subsoil humidity also increases the risk of fire. As figure 6B shows, in winter months, subsoil humidity increases across the board with the exception of the southeast coastline and the area of Almería, which continues to present low humidity levels. This area corresponds to the area identified in figure 5B as the area with the least risk of precipitation, so the fortifications located here will be more affected by periods of severe droughts and will be more prone to showing cracks associated with ground movements. Applying statistical calculation methodologies to the daily ground humidity images would allow the identification of geographic areas with very dry summers or very humid winters that debilitate rammed earth structures.

To acquire temperature data, Era5 and GLDAS are available. The Aqua and Terra satellites also have the MODIS sensor that recovers daily data on the land surface temperature (LST) with a 1,2 km spatial resolution. In turn, it is possible to calculate LST from the bands on the Landsat 8 satellite (Table 1) with a 30 m resolution, but the parasitic light problems detected generate errors that must be assessed before its use (Cook *et al.* 2014b). Figure 7 shows the LST

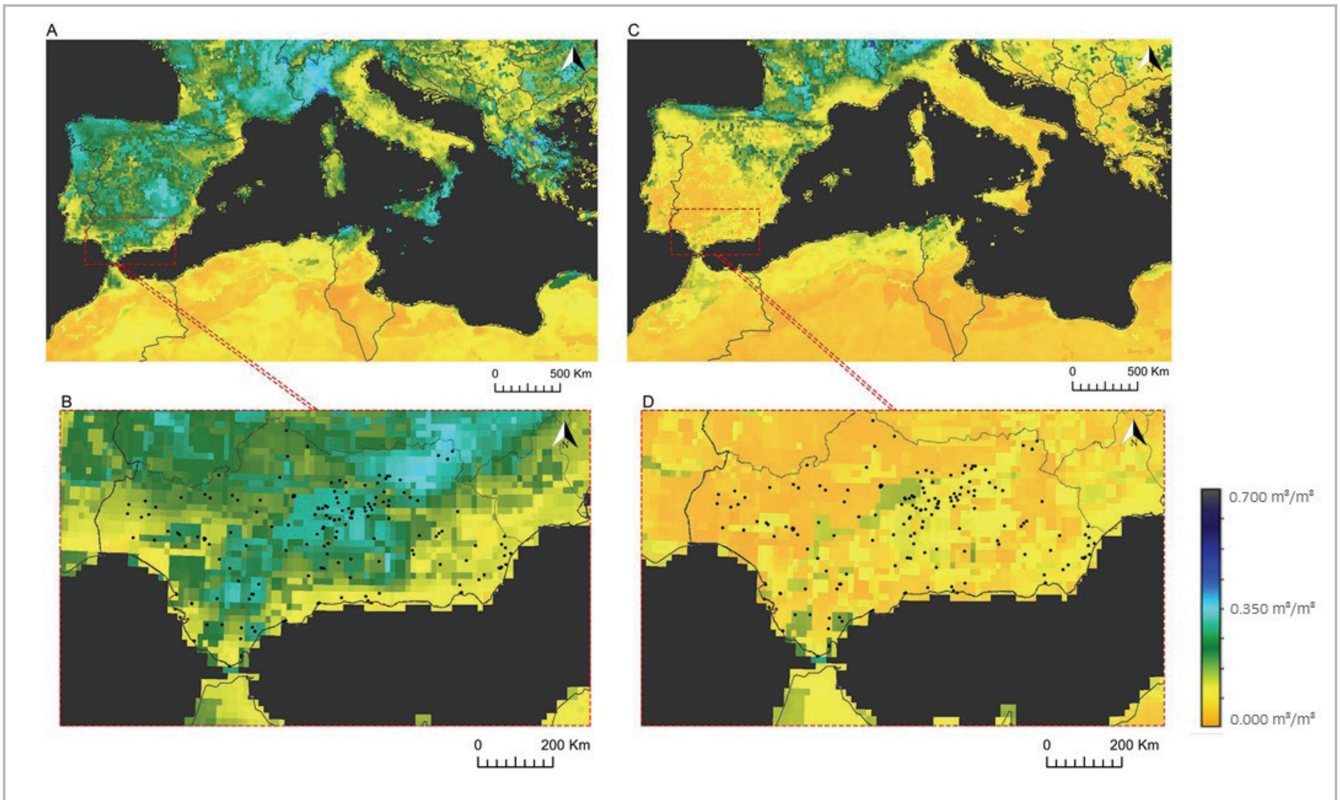

Figure 6.- Superficial humidity model images calculated from SMAP data: A) in summer (1st of August 2020); C) in winter (1st of November 2020). C and D) Detail of the Andalusian area with the location of rammed earth fortifications marked with black dots. Images acquired from the Worldview viewfinder.

reached in the Mediterranean area in the summer of 2021 and makes the registered high temperatures in the north of Africa and the southern half of the Iberian Peninsula visible. In particular, image 7B shows the registered temperatures in Andalusia and registers the highest temperatures in the Guadalquivir river valley and the Almería area. 45% of the studied fortifications are found in areas that, in the summer of that year reached average LSTs above 29ºC, while only one of the analysed fortifications is located in surroundings with average temperatures lower than 27ºC, a situation that reflects the high registered temperatures in the summertime in Andalusia. LST monitoring, especially after periods of rain and long dry periods, is essential to understand the wet and dry cycles of rammed earth and the occurrence of droughts. The combination of the use of LST, air temperature and precipitation values and vegetative coverage maps such as Corine LandCover or the image-based classifications made from Landsat and/or Sentinel-2 images makes evaluating the risk of fire possible. Along these lines, the cartography made based on the Fire Weather Index (FWI) is very useful for preventing fires in heritage landscapes (Moreno *et al.* 2021).

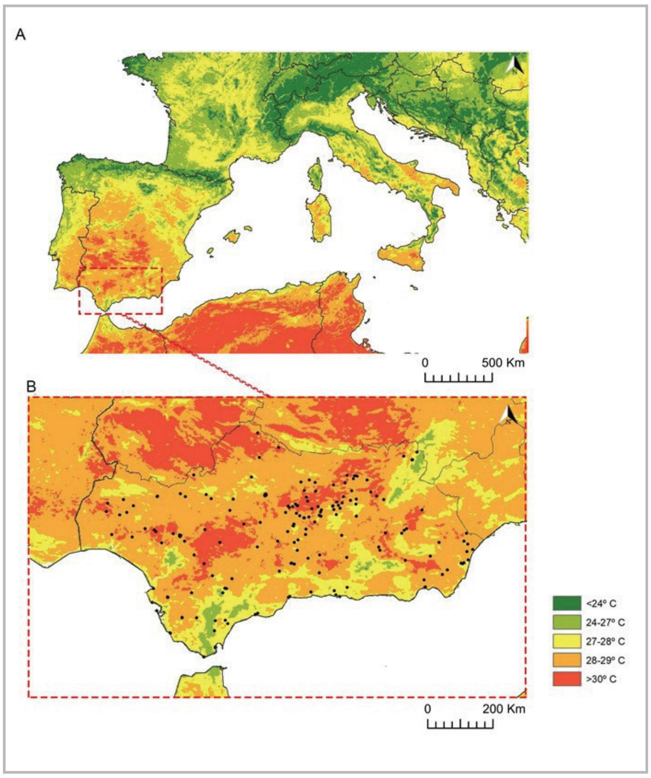

Figure 7.- Average temperature on the earth's surface registered between July and August 2021. Map calculated on Google Earth Engine from the surface temperature result (MOD11A1.006) made from the data gathered by the MODIS sensor.

In relation to the presence of wind, existing free access resources offer indirect measurements of wind intensity from models like GLDAS. Era 5 offers the possibility to identify the intensity and direction of the wind. The acquired data covers a height of 10 meters above the earth's surface and differentiates between the north wind and the east wind. Applied to the monitoring of rammed earth fortifications, knowing the intensity and direction of the wind favours comprehension of the erosion processes. This type of resource must be revised with care in fortifications in urban environments where the presence of taller buildings conditions the winds and must be complemented by the use of wind roses and orientations of the structures (Ortiz 2014).

In turn, the number of solid particles transported increases the erosive power of wind currents. Sandstorms can be observed in the images acquired with MODIS since 2000. This sensor transported on the Aqua and Terra satellites, has algorithms that calculate the average optical density (AOD) of aerosols, a variable related to biomass burning, pollution and the presence of dust. In practice, the results of AOD offered by the sensors express the amount of light removed from a beam by dispersion and/or absorption during its journey through a medium. At the same time, Aqua EOS/ Airs and Merra-2 have specific estimated results for the measurement of dust in the air. Figure 8A makes the high presence of windblown particles from North Africa visible and the long distances over which they are transported. For the case of the Andalusian area, image 8B shows how 3% of the fortifications located in Huelva were not affected by the sandstorm, while 24% of the fortifications located in Almería and Granada, the area highlighted in darker brown in the image, were the most affected by these types of very erosive winds during the month of September in 2021. In the most affected areas, in addition to the erosive effect, an increase in dust deposits on the horizontal surface of rammed earth

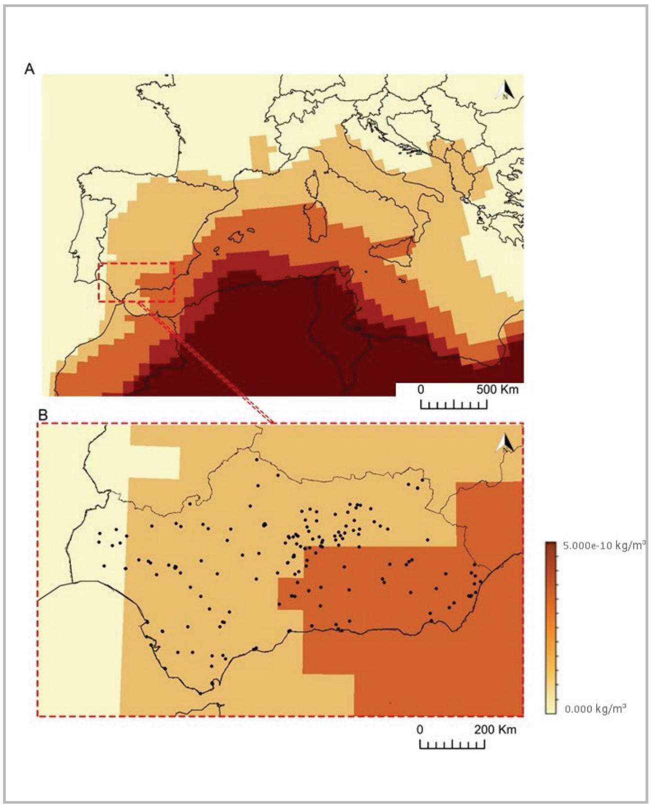

Figure 8.- Images from the monthly surface dust mass concentration model calculated from Mera-2 (M2TMNXAER) in September 2021. Imaged acquired from the Worldview viewfinder.

is expected.
In summary, the study carried out so far corroborates that satellite resources offer useful data to identify environmental threats on heritage environments. As has been noted in the brief analysis given for the Andalusian fortifications, the use of satellite resources has allowed the differentiation of 3 geographic areas which present discernible surroundings and dangers: (1) the Cádiz-Málaga area presents a higher risk of precipitation and humidity access from the subsoil; (2) the Almería area presents a greater risk of drought and highly erosive winds; (3) the rest of Andalusia presents average levels of danger for these factors. The information collected coincides with the cartography generated by AEMET according to the land-based meteorological stations and validates the results acquired by the use of satellite resources.

The application of the presented resources to the monitoring of rammed earth fortifications allows global climate studies of widespread territories to be carried out and to differentiate danger levels based on registered precipitation, temperature and wind values in recent years. In turn, its use favours the analysis and evaluation in settings of previous risk, the prediction of future risk situations and rapid gathering of information after an emergency situation. For the future, it is necessary to encourage the development of studies that define the usefulness and reliability of existing resources, normalise workflows and methodologies applied to the gathering of data in heritage settings and validate the existing satellite resources for comparison with the data collected by land-based meteorological stations.

Conclusions

The more frequent deterioration processes in rammed earth fortifications generate erosion, displacements and delaminations. The durability of rammed earth and the appearances of these pathologies are strongly affected by rain, the presence of humidity in the subsoil and the humidification and drying cycles that imply changes in the mechanical resistance of the walls. In arid and semi-arid climates, the intensity of solid-particle-laden winds favours the erosion processes and the existence of long dry periods that increase the risk of mechanical damages due to the alteration of the balance between the foundation of the wall and the environment.

Remote detection allows the monitoring of water and wind presence, the main environmental threats that affect rammed earth fortifications, through the use of diverse satellite resources: (1) GPM and GSMAP for monitoring daily precipitation; (2) CHIRPS, PERSIANN, and Era 5 for monitoring precipitation in long climate periods; (3) Era 5, SMAP and GLDAS to acquire ground humidity data; (4) Landsat, MODIS and Era 5 for temperature data; (5) Era 5, Merra-2 and Terra- EOS-AIRS to identify the intensity and direction of the wind and the transported particles. In turn, satellites such as (6) Landsat and Sentinel-2 allow the changes in land coverage; (8) and Sentinel-1 land displacements in seismic situations to be identified. The policy of free and open access to exposed satellite resources promotes their incorporation as monitoring tools in preventive conservation plans.

The correct choice of satellite resources depends on the necessities of spatial resolution, temporal resolution and differences displayed between passive and active satellites and calculated algorithms. Scale is a very important issue in remote sensing that is closely related to the resolution of satellites and the objectives of a study (Weng, 2014). Thus, analyzing anthropogenic changes in land cover requires satellite resources with higher spatial resolution, while analyzing climatic variables requires higher temporal resolution. Generally, opting for a higher spatial resolution also implies having a lower temporal resolution and vice versa.

For monitoring meteorological variables and the study of the consequences of climate change in heritage structures, statistical analysis methodologies of historical series of satellite images are required. The Google Earth Engine is the most recommended software due to the high capacity for working in the cloud on a petabyte scale with geospatial data that it offers. This software offers a free access technical solution for the development of this type of study.

In the case of rammed earth fortifications in Andalusia, the application of statistical studies on the satellite series GPM, MODIS and GLDAS have allowed three areas with discernible dangers to be identified: the Almería area which is more prone to droughts and erosive winds; the Cadiz-Málaga area with a higher level of danger from rain and subsoil humidity; the rest of Andalusia with average levels of danger from rain, wind and drought. Future studies should carry out a comparison of the data obtained by satellite resources and ground stations to develop methodologies that enable optimal use of satellite resources in the monitoring of heritage landscapes.

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