PYRGI: ANALYSIS OF POSSIBLE CLIMATIC EFFECTS ON A COASTAL ARCHAEOLOGICAL SITE

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Abstract – This work refers to an interdisciplinary study on the archaeological site of Pyrgi, an Etruscan harbour still under excavation, located on the Lazio's coast in Santa Severa, in the province of Rome. The site in question is subject to frequent flooding which compromises its accessibility and delays the archaeological excavation operations. The study is based on the combined use of geomatic technologies, meteorological and climatic models, and hydrogeological knowledge of the examined site, to have a global view of the hazard to which it is exposed. Different geomatic techniques at different scales are used in the analysis. Large scale surveys are carried out to define the water networks and to monitor the site using satellite images. On a small scale, drone photogrammetry techniques are used to assess the morphology of the territory and eventual protection from natural hazards present in the site. Using these images, a detailed digital surface model (DSM) has been generated.

The objective of the research is to assess the main cause of the floods and the time the water stays in the site and to determine if the floods are periodic phenomena over time or random events. The study was conducted using images captured by Sentinel 2 satellites processed at level 2-A. These images enabled the identification of the flooding periods of the site for the years of monitoring. The study was conducted by comparing the captured images with rainfall data, paying attention to extreme weather phenomena that occurred from 2012 to date. The rainfall data are provided by the National Department of Civil Protection to CNR-ISAC by an agreement between the two institutions. The same images have been compared with the wind data recorded by the anemometer located in the Civitavecchia harbour and the wave height data available from ERA5 reanalysis. Knowledge of the main cause of the floods and a possible periodicity will allow to plan correct conservation of the site through specific protection measures designed according to the hazards to which it is exposed.

Introduction

The cultural heritage is subject to continuous interaction with the surrounding territories, with consequent exposure to different types of hazard, both manmade and natural, which affect its conservation over time. Due to changes in climatic conditions demonstrated in recent years, with a consequent increase in the frequency and intensity of

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extreme weather phenomena, hydrogeological instability is causing increasing damages to cultural heritage [4] [5] [10]. This has a potential impact on the built and landscape heritage, which frequently fails to have appropriate protection systems [14] [18] [19] [20]. As a peninsula, Italy shows part of its cultural heritage located along the coasts, where important dangerousness of sea storms exists. Any area close to the coastline, as well as suffering flood damage, can be subject to coastal erosion and absorption of saltwater into the site, which undermines the fragile balance between monument and land, or even to permanent submersion of part of the area [5] [10] [17].

The case study is Pyrgi, an Etruscan harbour still under excavation, supervised by the Sapienza University of Rome, Department of Classic in particular under the Scientific Responsibility of Professor Laura Michetti, located along the Lazio coast in Santa Severa (RM) (Figure 1) [2]. As can be seen in Figure 1 the site is located only a few meters from the coastline.

Pyrgi was the harbour of an ancient Etruscan city, Caere, and played a fundamental role in maritime transport, being frequented by Greek and Phoenician ships. The emerged area includes a ceremonial district and two different sanctuary areas: Monumental and Southern (Figure 1) [2] [8] [12]. A consistent part of the area is completely submerged by the sea that includes the harbour site [1] [2] [7] [16].

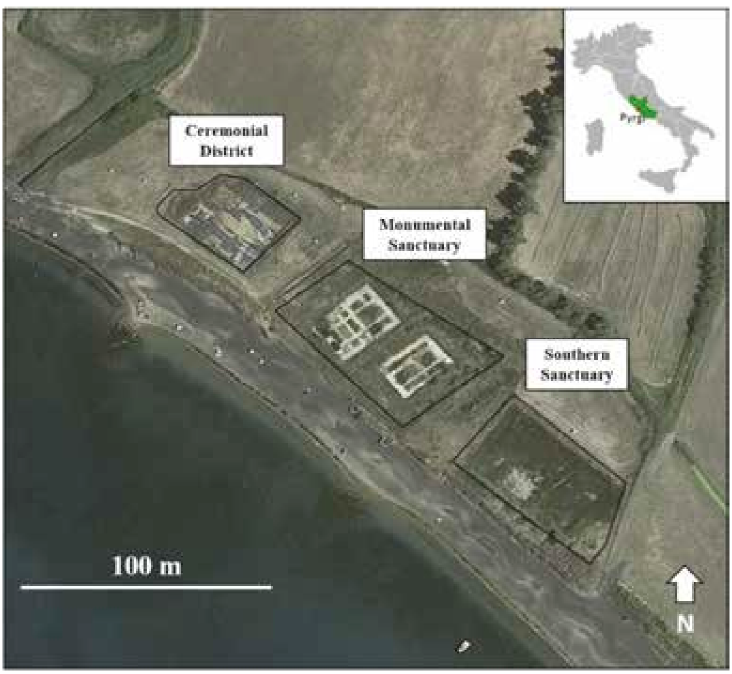

Figure 1 - Geo-localization of Pyrgi and subdivision of the sanctuary complex: at the top left Ceremonial District; in the centre the Monumental Sanctuary; at the bottom right the Southern Sanctuary. (Google Earth Image © 2020 TerraMetrics ©2020 Google).

Over the years, the site has suffered repeatedly flooding events, characterized by a strong transport of solid sludge and permanence of water in the site, which can cause damage, delay of the archaeological excavation work, and a complete submersion of the site in the future [1]. In the area under consideration, as can be seen in Figure 1, no structures built over the ground exist, but ruins located at lower ground level, potentially transforming into large basins of water after a heavy storm and consequent floods (Figure 2).

Aim of this study is to investigate the causes of flooding, deepening how long the water covered the site, and the incidence of flooding events over the years (return period) in order to estimate whether they are sporadic or permanent phenomena. The aim is achieved by an interdisciplinary approach based on exploring meteorological datasets, performing hydrogeological investigations, and examining site images at different scales. Satellite images provided by Sentinel-2 level-2-A (S2-A) were used to monitoring the area and its surroundings [11] [6], and drone images helped to construct a Digital Surface Model (DSM) [15]. All this information was analysed, meteorological data have been correlated with satellite images and geological surveys to have a global view of the site and flooding conditions.

a) Ceremonial District

b) Monumental Sanctuary

Figure 2 - View of the flooded archaeological site after the thunderstorm of 15th November 2019 (photos by the authors taken on 20th November 2019).

Materials and Methods

In the frame of this investigation, a Digital Surface Model (DSM) was generated from drone images[1] taken on October 5, 2017. These images were collected to inspect the morphology of the terrain. In particular were captured 777 images from different height through a DJI FC6310 camera (resolution of 5742 x 3648 pixel, ground resolution 8 mm/pixel). The images were thus processed by the Agisoft Photoscanner®, a photogrammetric software, to generate a DSM of the archaeological area. For georeferencing the area, 20 Ground

[1] Images provided by Professor Alessandro Jaia, Sapienza University of Rome, Department of Classic.

Control Point (GCP) were used, so that the DSM is georeferenced in the World Geodetic System (WGS84) reference frame with orthometric heights referred to the Earth Gravitational Model 2008 (EGM2008) geoid model [15]. As GCP have been inserted points clearly visible on the ground and to them have been associated the elevations collected by Google Earth Pro, in which the elevations have a vertical accuracy around 2 m [3]. In the DSM three sections have been generated in front of the main areas of the site starting from the sea and crossing the whole area. These have been designed to assess the morphology of the terrain, along the same sections, and to reveal the presence of possible protections (also anthropogenic) of the site from sea dynamics, such as dunes or protective works as hearsay knows.

S 2-A[2] satellite images were used to monitor the site and its surroundings.

Sentinel-2 is part of the Sentinel family of satellites developed by the European Space Agency, specifically designed for the operational needs of the Copernicus program. Copernicus is the most ambitious Earth observation program to date. It will provide an Earth observation program that is accurate, timely and easy, accessible information to improve the management of the environment, understand and mitigate the effects of climate change and ensure civil security. Copernicus is the new name of Global Monitoring for Environment and Security Program, formerly known as GMES. This initiative is led by the European Commission (EC) in partnership with the ESA [6].

Sentinel-2 is equipped with a multispectral sensor with 13 spectra having a spatial resolution between 10 m and 60 m; therefore, it is part of the category of optical/passive sensors. It acquires the reflected electromagnetic waves of sunlight and/or infrared radiation emitted by objects on the ground. The objects, being of different materials, reflect and absorb different wavelengths in different ways. In a multispectral sensor, each channel is sensitive to radiation within a narrow wavelength band. The resulting image is a multi-layer image that contains both brightness and spectral (colour) information of the objectives observed. Since visible/infrared radiation does not pass through the clouds, the images of the terrain cannot be captured during cloudy days[3].

S2-A images were used in the investigation. The Level-2A operational processor generates, from algorithms of scene classification and atmospheric correction, Level-2A (BOA reflectance) products from Level-1C products. From the mid-March 2018, the Level-2A became an operational product, beginning with coverage of the Euro-Mediterranean region. Global coverage started in December 2018[4].

In the images used in this investigation, the following bands (B) were used: SWIR 2 (B12 resolution 20 m), SWIR 1 (B11 resolution 20 m), Blue (B2 resolution 10 m), Green (B3 resolution 10 m), Red (B4 resolution 10 m).

Being these data heavy, we used Google Earth Engine[5] for the elaboration. It is a cloud computing platform released by Google for petabyte-scale scientific analysis and visualization of geospatial datasets, both for the public benefit and for business, and government users. Earth Engine stores satellite imagery organizes it and makes it available

[2] https://sentinel.esa.int/web/sentinel/missions/sentinel-2
[3] https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/copernicus-sentinel-2
[4] https://earth.esa.int/web/sentinel/technical-guides/sentinel-2-msi/level-2a-processing
[5] https://www.geoinformers.com/post/2018-01-13-google-earth-engine-for-scientific-analysis-and-visualization-of-geospatial-datasets

for the first time for global-scale data mining. The public data archive includes historical earth imagery going back more than forty years, and new imagery is collected every day. Earth Engine also provides APIs in JavaScript and Python, as well as other tools, to enable the analysis of large datasets [9].

In addition to aerial and satellite imagery, ground data were used. The rain gauges precipitation data have been provided by the National Department of Civil Protection[6], based on a specific agreement with CNR-ISAC. Hourly rainfall and overall daily precipitations were collected from January 2012 until December 2019, specifically considering days with more than 60 mm of rain. To have further information over the site, also correcting missing data caused by incorrect sensor performance, in addition to the rain gauge located in the Santa Severa station, we also examined the data of the rain gauges in Civitavecchia (north-west), Bracciano (north-east) and Cerveteri (south-east) of Lazio Region.

For the wave heights, the ERA 5 reanalysis was used on a site near Civitavecchia. ERA 5 is the fifth generation of the ECMWF's atmospheric global climate reanalysis, covering the years from 1979 to the present with hourly resolution and a horizontal resolution of 0.25° x 0.25° [7].

For wind and tide data, those provided by the national maritime network have been used; the measurements are related to the anemometer and the buoy in the port of Civitavecchia[8]. Concerning wind and wave heights analysis, the specifics directions were previously selected, i.e. can affect the coast and therefore cause sea storms, then daily average and maximum wind velocity and wave height were calculated.

Previous analyses[9] of soil stratigraphy of the Monumental Sanctuary show, from the top, the following sedimentary sequence: (1) the archaeological layer, at least 2 m thick; (2) a silty-sandy alluvial layer, 3÷5 m thick; (3) a predominantly sandy layer, 2.5÷7 m thick, often interbedded by silty-sand levels; (4) a much more coherent layer, between 4 m and 7 m thick, including cemented deposits similar to beach rock; (5) a very stiff clay layer at the bottom [13].

Once all the information has been collected, the different data have been related to each other to achieve the goal of this study.

Results and Discussion

Different possible causes for the recurrent flooding of the archaeological site of Pyrgi were analysed: flooding of water bodies, rising of groundwater, heavy rains, sea storms. In this research we assess what is the main cause of the flooding of the Pyrgi site, the time the water stays in the site and whether the phenomenon occurs with a certain periodicity.

Considering the single causes of flooding, the hydrogeological maps elaborated by the Lazio Region, does not evidence the presence of rivers with high flow or important aquifers in the area of interest[10], what seems excluding considerable contributions to the

[6] http://www.protezionecivile.gov.it/
[7] The data are provided in grid version available on Copernicus website: https://cds.climate.copernicus.eu/
[8] https://www.mareografico.it/
[9] Analysis carried out by Professor Luciana Orlando, Sapienza University of Rome, Department of Civil, Constructional and Environmental Engineering.
[10] Map available at the following link:
http://www.regione.lazio.it/prl_ambiente/?vw=documentazioneDettaglio&id=8672

flooding related to rivers and aquifers. To confirm this, in figure 3-b it can be observed that floods occur only along the coast and not in the hinterland.

Figure 3 - Comparation of images captured by Sentinel 2-A and processed with Google Earth Engine of the same area in summer, image captured on 19 August 2019 (a), and in autumn, image captured on 30 November 2019 (b).

Once the component associated with rivers and aquifers was excluded as the main cause of flooding, the contribution of rainy events was examined. The days of heavy rainfall (greater than 60 mm/day) were correlated with the first available satellite image (S2-A) after the event. In this text only one heavy rain event is reported as an example, considering that for all the other analysed heavy rainfall events (from 2012 to date have been identified 17 heavy rainfall events) the site showed the same response. As can be seen from Figure 4, the site is not flooded after the single heavy rainfall event. Considering the extent of the flooded area and the permeability characteristics of the soil [13], the single heavy rainfall event is not sufficient to cause the flooding of the site.

Table 1 - Rainfall event greater than 60 mm/day in Santa Severa registered from all pluviometer around the site.

Date	**S. Severa**	**Cerveteri**	**Bracciano**	**Civitavecchia**
	[mm]	[mm]	[mm]	[mm]
04-10-2018	0.00	0.00	0.00	0.00
05-10-2018	14.80	12.30	10.10	16.60
06-10-2018	78.80	50.00	87.30	15.80
07-10-2018	3.20	3.00	2.70	0.40
08-10-2018	0.00	0.00	0.80	0.00

Figure 4 - Image, captured in data 13th October 2018, by satellite Sentinel 2-A after a rainfall greater than 60 mm.

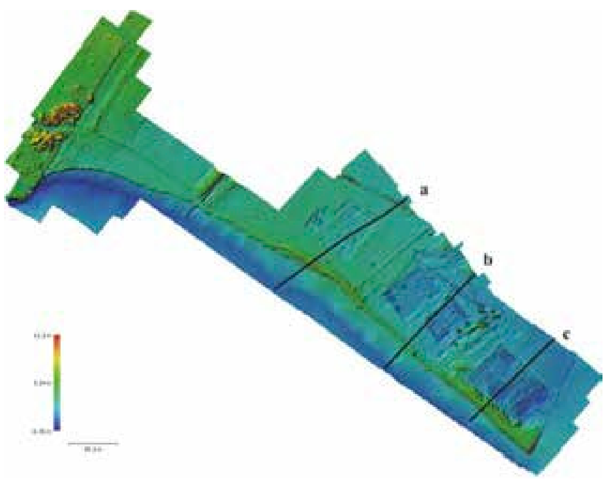

Figure 5 - Digital Surface Model developed with Agisoft®.

Excluding hydrogeological events and severe rainfalls as the principal causes of flooding, sea storms should be analysed. As a first study, it was considered if the site was equipped with sea storm protections. For this purpose, a DSM of the study area was built from drone images (Figure 5), with a resolution of 1.6 cm/pix and point density of 0.391 point/cm^2. Three sections have been generated, in front of the three principal areas, to highlight the presence of sea storm protection. This specific analysis is derived from the visit to the archaeological site, in which the remains of some dunes were evident, that were created by

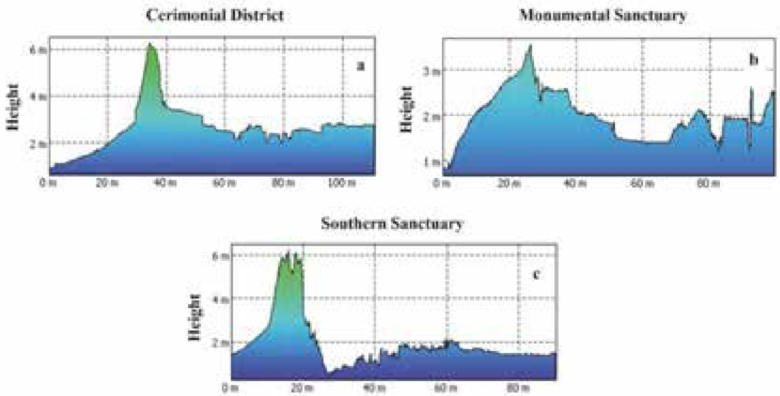

Figure 6 - Surface development in the three different sections shown in Figure 5: Ceremonial District; Monumental Sanctuary; Southern Sanctuary.

accumulating digged ground. Figures 6-a and 6-c show elevations with heights up to 6 m in the boundary line between the site and the beach, associated with storm protection in the area. This, however, is absent in figure 6-b where there are no high elevations and consequently no protection, so the site is exposed to sea dynamics.

To assess if the sea is the primary cause of the flooding of the site the period in which the site is submerged has been identified through S2-A (Figure 7); the site is mainly flooded from November to May. Wind speeds and wave heights are intense during the same months. In particular, the monthly maxima of wave heights are very high, up to 3 m high waves. Also the wind speeds are very high, with peaks over 9 m/s in particular during the autumn and winter months. The data reported do not take tides into account, being the tide variations around 30 cm and so they have been considered negligible in this study.

Table 2 - Monthly data for flooded period of 2018-2019.

Date	Average Wind Speed	Maximum Wind Speed	Average Significative Wave Height	Maximum Significative Wave Height
	[m/s]	[m/s]	[m]	[m]
September	1.67	10.10	0.46	1.97
October	2.60	14.20	0.99	5.71
November	2.47	10.00	0.97	2.78
December	2.02	10.20	0.87	2.99
January	2.79	11.00	1.02	2.56
February	2.34	10.20	0.90	2.80
March	2.81	9.50	0.83	3.44
April	3.49	13.00	0.73	3.31
May	2.87	8.90	0.82	3.30
June	2.90	9.00	0.45	1.92
July	2.70	9.00	0.44	1.32
August	2.43	7.70	0.34	1.22

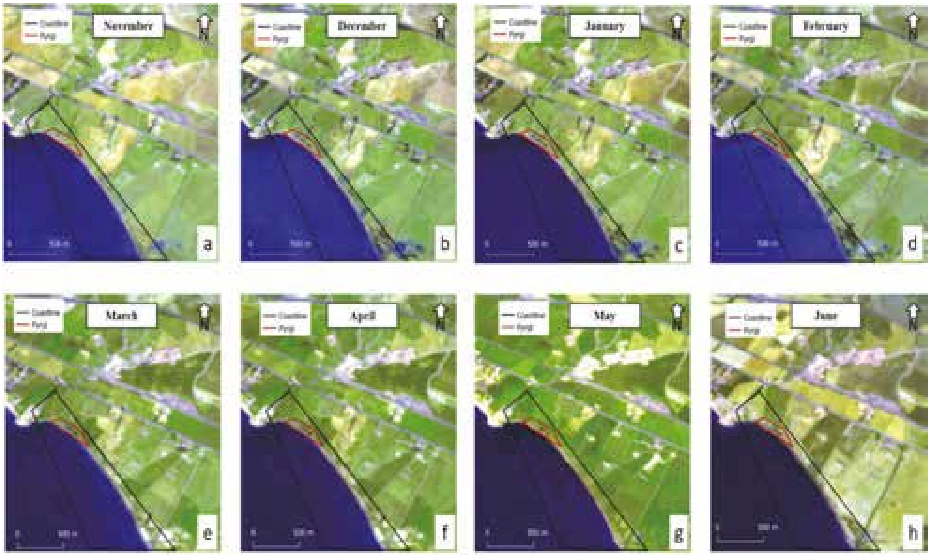

Figure 7 - Pictures taken by Sentinel 2-A and processed with Google Earth Engine for the month of November 2018 (a), December 2018 (b), January 2019 (c), February 2019 (d), March 2019 (e), April 2019 (f), May 2019 (g), June 2019 (h).

Upstream of all the analyses, it can be said that the main cause of the flooding at the archaeological area is the maritime component. since the area in which it is exposed to storm surges and the site without adequate protection. It is also noted that in June wind speeds and wave heights decrease and the drying up period of the area begins, lasting several weeks (Figure 7 h).

Conclusion

The aim of this interdisciplinary work, in collaboration with the Sapienza University of Rome, Department of Classics, and the Soprintendenza archeologica, belle arti e paesaggio per l'area metropolitana di Roma, la provincia di Viterbo e l'Etruria meridionale, has been to assess the period of flooding of the archaeological site of Pyrgi and the main cause of the flooding. The combination of different disciplines as geomatics, meteorology, and hydrogeology, in relation to the data coming from the historical-archaeological and geological researches, has been used to conduct a complete study and continuous monitoring of the area and the hazards that expose it to specific dangers.

The archaeological site of Pyrgi is one of the largest Etruscan harbour in Italy, with inestimable archaeological value, still under excavation by the Sapienza University of Rome, Department of Classics. Its position on the coast exposes this site to many risks that potentially compromise its conservation, fruition, and valorisation.

Currently, part of the archaeological area is completely flooded, while the ruins that have emerged, based on the analysis reported in this work, are covered by water for seven months, during the eighth month the physical forcing decreases in intensity and the air begins the drying phase.

The other result highlighted in this study is the role of the sea as the main risk factor for flooding rather than local rivers or aquifers and rainfall due to its short duration. The DSM shows that the site is currently fully exposed to meteorological and hydrogeological instabilities so that, in the absence of protective measures, it could easily be compromised. The presence of water in the long term could compromise the fragile balance between the monumental ruins and the ground, delaying excavations and leading to total submersion of the area soon.

Future studies will focus on the creation of a higher resolution DEM including bathymetry to develop wave propagation and simulate a sea storm event. Statistical studies will be carried out covering all the maritime components to suggest possible protection of the site. In addition, further geological analysis will be conducted to calculate the absorption velocity of the soil and the actual contribution of rainfall and groundwater to the flooding of the site will be assessed.

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