# Mapping air pollution using Earth Observation techniques for cultural heritage sites

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## ABSTRACT

Air pollutants, together with climatic parameters, are of major importance for the deterioration of cultural heritage monuments. Atmospheric pollution is widely recognized as one of the major anthropogenic threats to architectural cultural heritage, in particular when associated with water absorption phenomena. Atmospheric particle deposition on surfaces of Monuments (of cultural heritage interest) may cause an aesthetic impact induced by a series of chemical reactions. Therefore there is a need for systematic monitoring and mapping of air pollution for areas where important archaeological sites and monuments are found. Earth observation techniques, such as the use of satellite image for the retrieval of Aerosol Optical Thickness (AOT), are ideal for this purpose. In this paper, all important monuments of the Paphos District, listed by the Department of Antiquities of Cyprus, have been mapped using Geographical Information Systems. Several recent (2012) MODIS satellite images (both Aqua and Terra) have been used to extract the AOT values in this area. Multi-temporal analysis was performed to identify areas of high risk where AOT values are considered to be high. In situ observations have been also carried out to verify the results.

**Keywords:** air pollution; MODIS satellite; AOT; cultural heritage; Paphos district

## 1. INTRODUCTION

The costs of deterioration and soiling of different materials due to air pollution are huge and the damage to culture targets endangers seriously the rich European cultural heritage [1]. Indeed as [2] argued, atmospheric pollution is widely recognised as one of the major threats to cultural heritage, in particular when associated with water absorption phenomena. In addition, as [3] report the corrosion of cultural heritage monuments is related to several factors such as the physical–chemical properties of building materials, the exposed meteorological conditions, and the level of atmospheric pollution. Therefore, the over time knowledge of atmospheric pollution concerning monuments ambient has become an increasingly important issue in preservation strategies [4].

The preservation of cultural heritage and its protection against possible damage due to air pollution have become the focus of well-deserved scientific interest [4]. In the last 35 years a noticeable effort has been dedicated to urban air pollution research. However, modeling air pollution especially in urban areas and even more in a regional scale is still pending [5]. In many cases [6-7] a network of ground air pollutants stations is set in the area of interest in order to record air pollutants. Yet, such methodology has a high cost (implementation and maintenance) while at the same time it is spatially limited (point measurements) [8]. On the other hand, satellite remote sensing of air quality has evolved dramatically over the last decade [9-12]. Spectral variations, recorded by satellite sensors are indicators of aerosol particles and therefore air pollution. When solar radiation undergoes through the atmosphere it produces a general decrease in the spectral irradiance which is related to the optical thickness of the atmosphere. These effects are due to the scattering and wide band absorption produced by both aerosol particles and atmospheric gases [5]. Several studies have

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shown that satellite data can be efficiently used to monitor air pollution and air pollution effects. For instance [13] compared vegetation land use maps and air pollution emissions data over a 15 year period and found major changes in the environment as a result of high air pollution values. In addition, Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data have been used by [12] in order to analyse the relationship between the aerosol optical thickness (AOT) and the PM10 as indicators of pollution. AOT represents the extinction of incoming solar radiation by aerosols over the atmospheric column and it is related to aerosol concentration, and vertical profile of the aerosol extinction coefficient. AOT can be retrieved from numerous sensors, including the MODIS [14], which is used in this study. The MODIS sensor has 36 different channels with varying spatial resolution of 250, 500 and 1000 m. Uncertainty above land is given by $0.05 + 0.2 \times AOT$ [15].

## 2. CASE STUDY AREA

Paphos district, located in the western corner of the island of Cyprus, was selected as the case study since several important monuments are found in this area. Indeed, all cultural heritage sites, listed from the Department of Antiquities of Cyprus, were mapped in a common geodetic system (WGS 84, 36 N) using Geographical Information Systems As it is shown in Figure 1, these monuments can be found both in urban and rural areas, in low altitude (nearly sea level) and high level (highest mountain-picks of the island), near and far from the coastlines, forest, industrial zones etc.

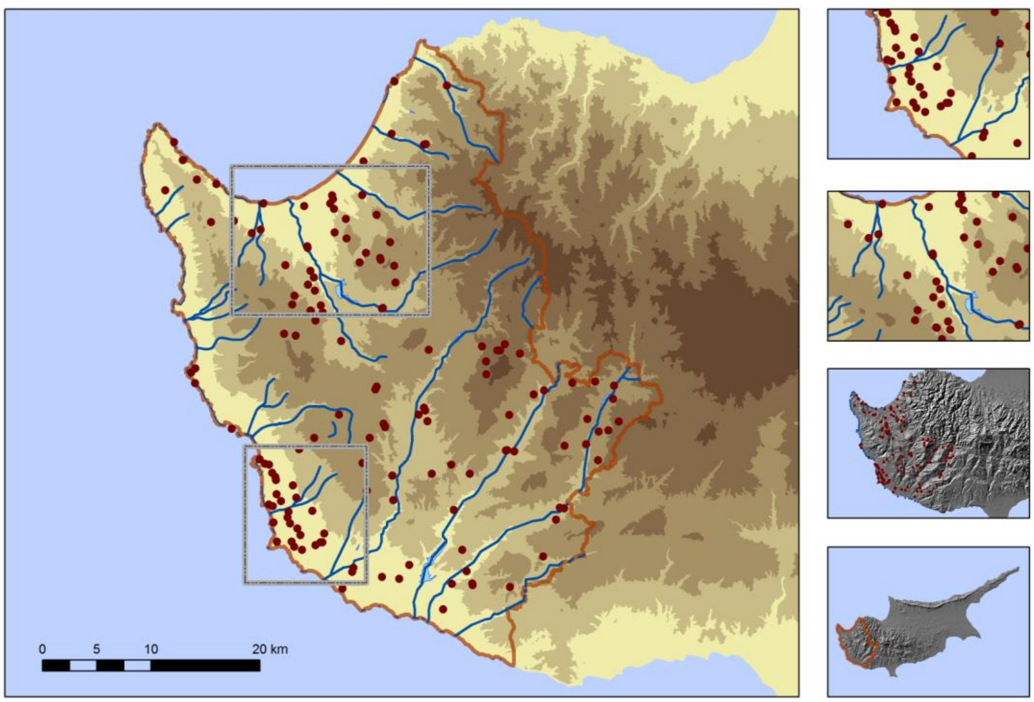


Figure 1: The archaeological sites and monuments of the Paphos district.

Two important archaeological sites of the Paphos district are also listed as World Heritage Monument by UNESCO. These are the *"Tombs of the Kings"* and *"Nea Paphos"* archaeological sites located in the SW part of Paphos District. *"Nea Paphos"* is situated on a small promontory on the southwest coast of the island. According to written sources, the town was founded at the end of the 4th century by Nicocles, the last king of *"Palaepaphos"*. In the beginning of the 3rd century B.C. when Cyprus became part of the Ptolemaic kingdom, which had its capital in Alexandria, *"Nea Paphos"* became the center of Ptolemaic administration on the island. Systematic excavations at *"Nea Paphos"* started in 1962 by the Department of Antiquities during which many of the ancient town´s administrative buildings as well as private houses and ecclesiastical buildings came to light (Figure 2, right). The *"Tombs of the Kings"* is a large necropolis lying about two kilometers (little over a mile) north-west of Paphos harbor in Cyprus. The underground tombs, many of which date back to the 4th century BCE, are carved out of the solid rock, and are thought to have been the burial sites of Paphitic aristocrats and high officials up to the third century CE (the name comes from the magnificence of the tombs;

no kings were in fact buried here). The impressive tombs are entirely cut and sculpted into the native rock (Figure 2, left).

Figure 2: Photos from the *"Tombs of the Kings"* (left) and *"Nea Paphos"* archaeological site (right).

## 3. METHODOLOGY AND RESOURCES

### 3.1 Mapping cultural heritage sites in Paphos district

In order to map all known sites and monuments of the Paphos District the necessary raw date from the Department of Antiquities of Cyprus were used. The authors explored the database of the «Cyprus Archaeological Digitization Programme», after the permission of the Department of Antiquities. In total more than 170 monuments and sites exist to Paphos District dated from the prehistoric to medieval times. Local cadastral maps were also used in order to map the cultural heritage sites. More than 300 detail photographs were taken from the Map Archive of the Department of Antiquities (Figure 3, left).

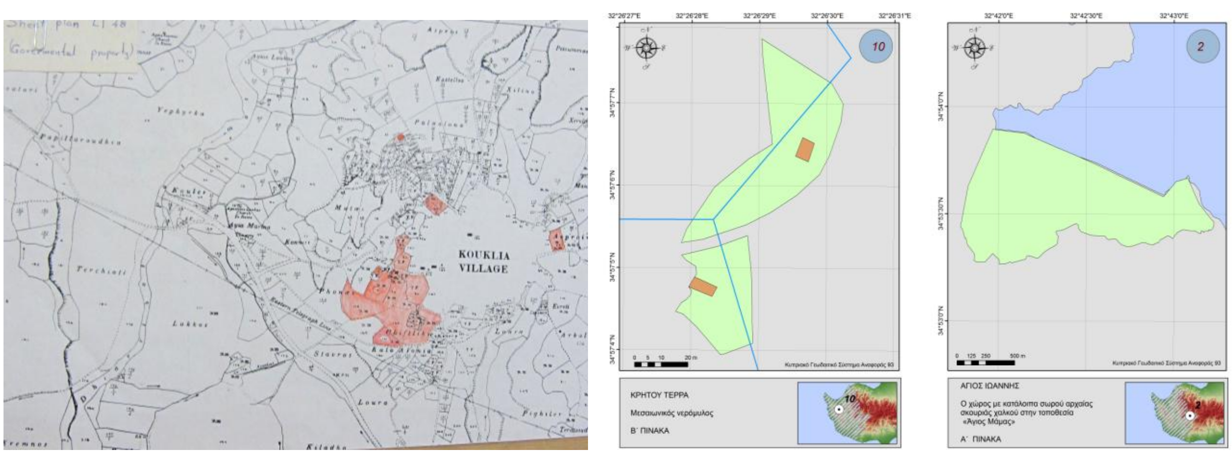


Figure 3: Photographs taken from the Archive Section of the Department of Antiquities showing the local cadastral maps. Archaeological sites and monuments are colored with red (left), Example of the mapping procedure using the GIS software (right).

All these data were stored in a customized GIS geodatabase. An important advantage of the GIS environment is the fact that both spatial information (e.g. place, coordinates) along with non-spatial information (e.g. type of the monument, chronology etc) can be connected. In this way all monuments were georeferenced in a common geodetic system (WGS 84, 36N) (see example in Figure 3, right).

### 3.2 AOT retrieval from satellite images

Monitoring air quality for urban and sub-urban areas using conventional methods requires expensive equipment. Air pollution measurements are always related to the area where the air quality stations are located. However, remote sensing images can fill this gap since satellite images cover vast areas [16]. This is possible to be performed if AOT values, retrieved from satellite sensors such MODIS, are related with PM10 and/or PM2.5. In order to retrieve the AOT values for the Paphos district, several recent (2012) MODIS satellite images have been used. Daily Level 2 data are produced at the spatial resolution of a 10x10 km (at nadir)-pixel array. In this study two MODIS Aerosol data product files have been used: MOD04_L2, containing data collected from the Terra platform; and MYD04_L2, containing data collected from the Aqua platform (HandBook MODIS). For the aims of this study the Paphos district was divided into seven main grids (from A – G) as shown in Figure 4.

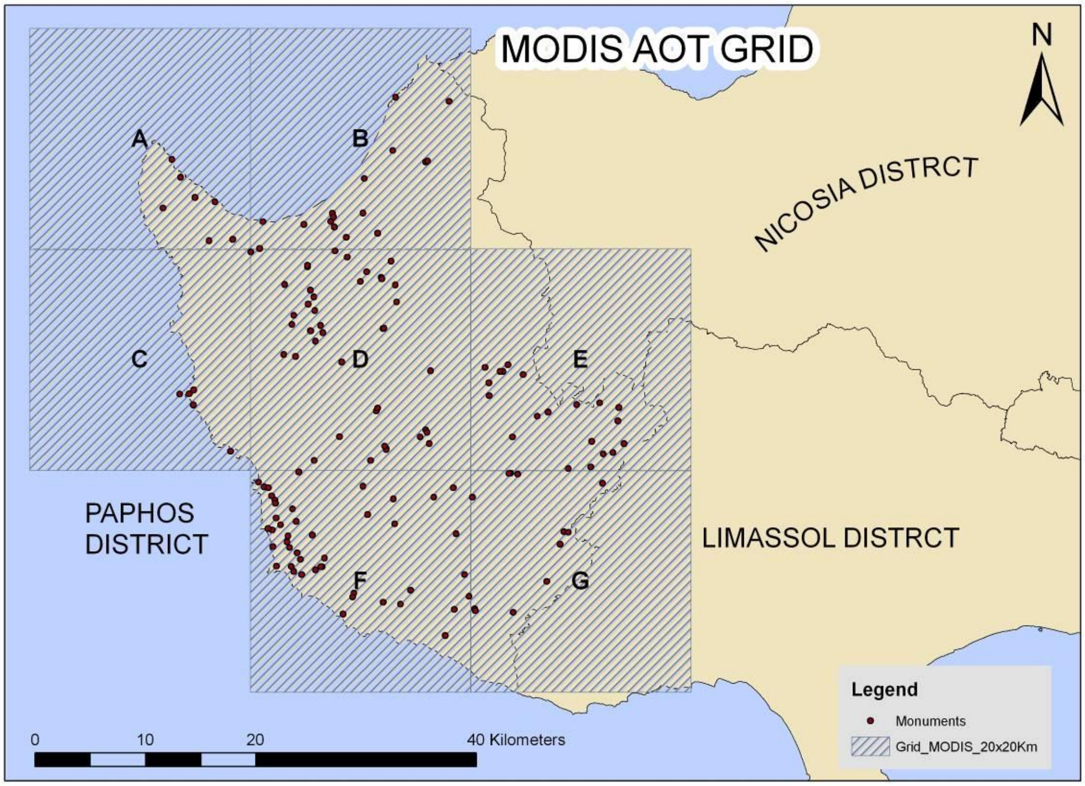


Figure 4: The archaeological sites and monuments of the Paphos district and the grid used for the retrieval of AOT

Finally, *in situ* observations were made in order to record any atmospheric particle deposition on surfaces cultural heritage site or even to map individual monuments with aesthetic alterations induced by air pollution.

## 4. RESULTS

### 4.1 AOT values using MODIS data

Figure 5, shows the AOT values as recorded from both Terra and Aqua platforms for the year 2012. As it is clearly indicated AOT values tend to give many fluctuations during the year. However, as it is shown in Figure 5, these fluctuations tend to be quite similar trends for all the grids of the Paphos district. In general high AOT values are recorded during dry periods (March – August), while lowest AOT values are recorded from the wet periods (September – February). In addition, as Figure 6 indicates the average AOT value for all grids is estimated to ≈0.20. Grid F (which includes the Paphos town) seems to give the highest average values (both from Terra and Aqua platform), while high AOT values are also observed in the "G" grid, where semi-urban areas exist along with the airport of Paphos. Nevertheless, high values (max values in Figure 6) of AOT can be also observed in the whole area of Paphos district.

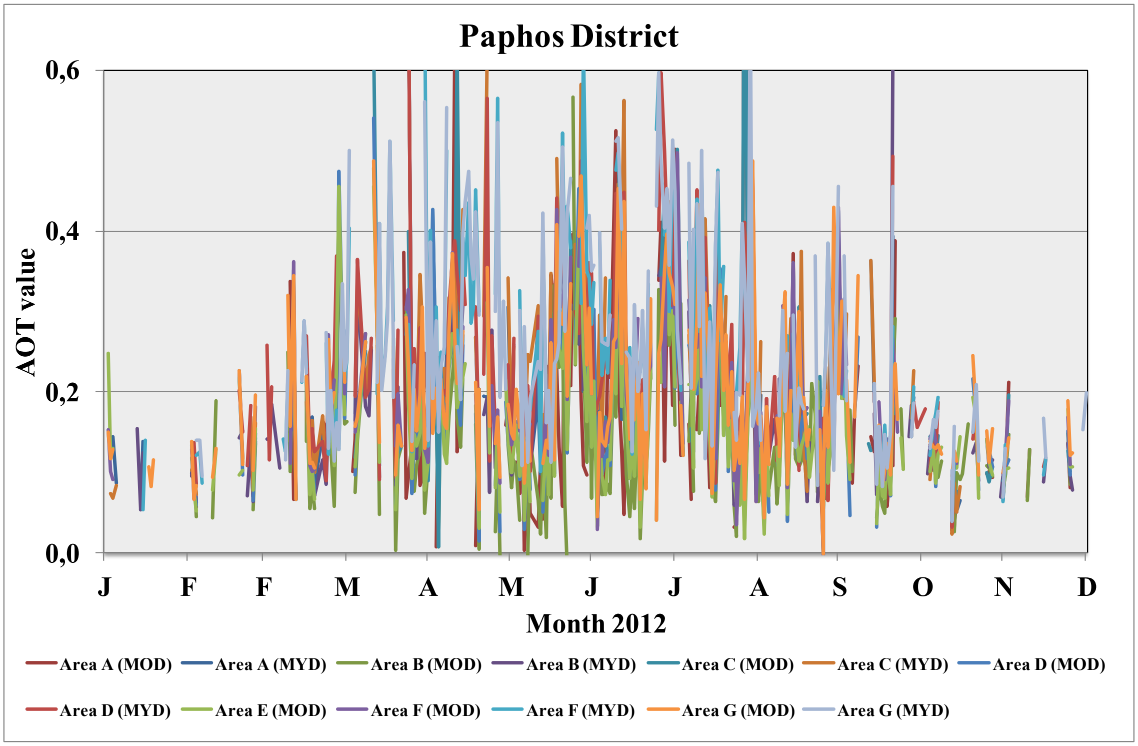


Figure 5: AOT values from Terra (MOD) and Aqua (MYD) platforms of 2012 for the Paphos district with regard to the grid used for MODIS images.

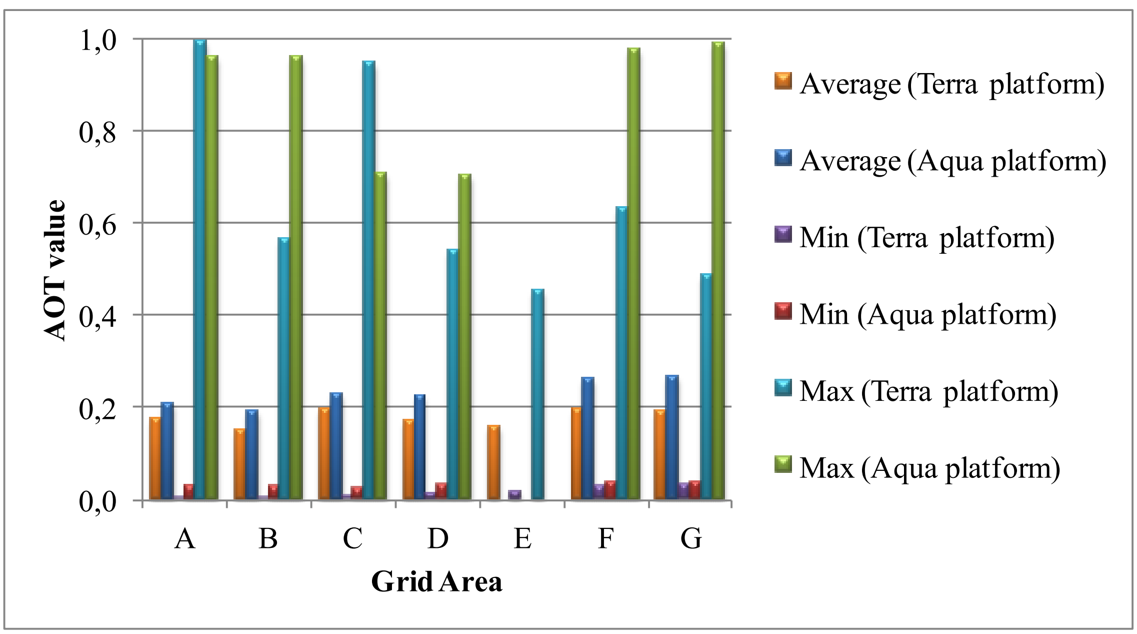


Figure 6: Statistics from AOT values of 2012, as recorded from the Terra and Aqua platform for the Paphos district with regard to the grid used for MODIS images.

In order to study the overall AOT values during the whole year (2012) as observed from both Terra and Aqua platforms, all AOT values were interpolated as shown in Figure 7. Each cell, in Figure 7, corresponds to a single day (beginning from top left to the right). In each cell, all measurements (from grids A to G), were interpolated using the kriging algorithm. As it shown from Figure 7, Terra platform (above the red dash line) tends to give much lower AOT values rather the Aqua platform (below the red dash line). This is not strange, since Aqua and Terra platforms have different hour of overpass. Terra platform over the equator is approximately estimated between 10:30 am and 10:30 pm each day, while Aqua platform passes over the equator at approximately 1:30 pm and 1:30 am. However, the sun-synchronous orbit allows the satellites to pass over the same area at the same time in every 24 hour period. High AOT values were recorded only for a few days, or a short period, from the whole year (2012) as it is shown in Figure 7.

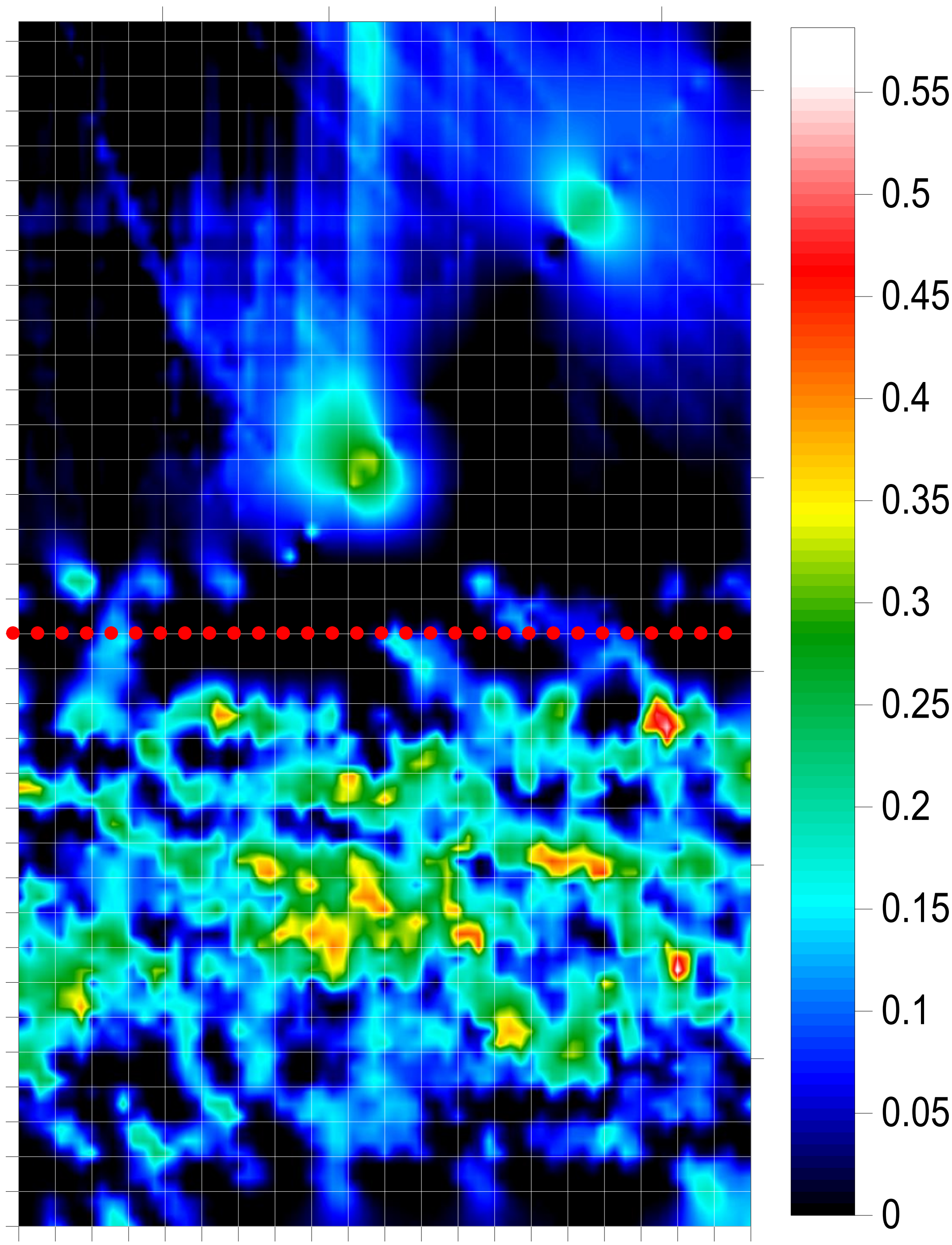


Figure 7: AOT values as recorded from both Terra (above red dash line) and Aqua (below red dash line) for the year 2012. Each cell corresponds to a single day (beginning from top left to the right).

Indeed, this is more obvious when using different threshold values for the AOT dataset. As it is observed in Figure 8, four different thresholds have been used for AOT values (0.1; 0.2; 0.3 and 0.4). AOT values over 0.2 threshold (top right in Figure 8) were recorded for only a few days, while in the next AOT threshold (0.3; lower left in Figure 8) the majority of the measurements is below this value. Finally, AOT values over 0.4 thresholds are very rare to be observed in the Paphos district.

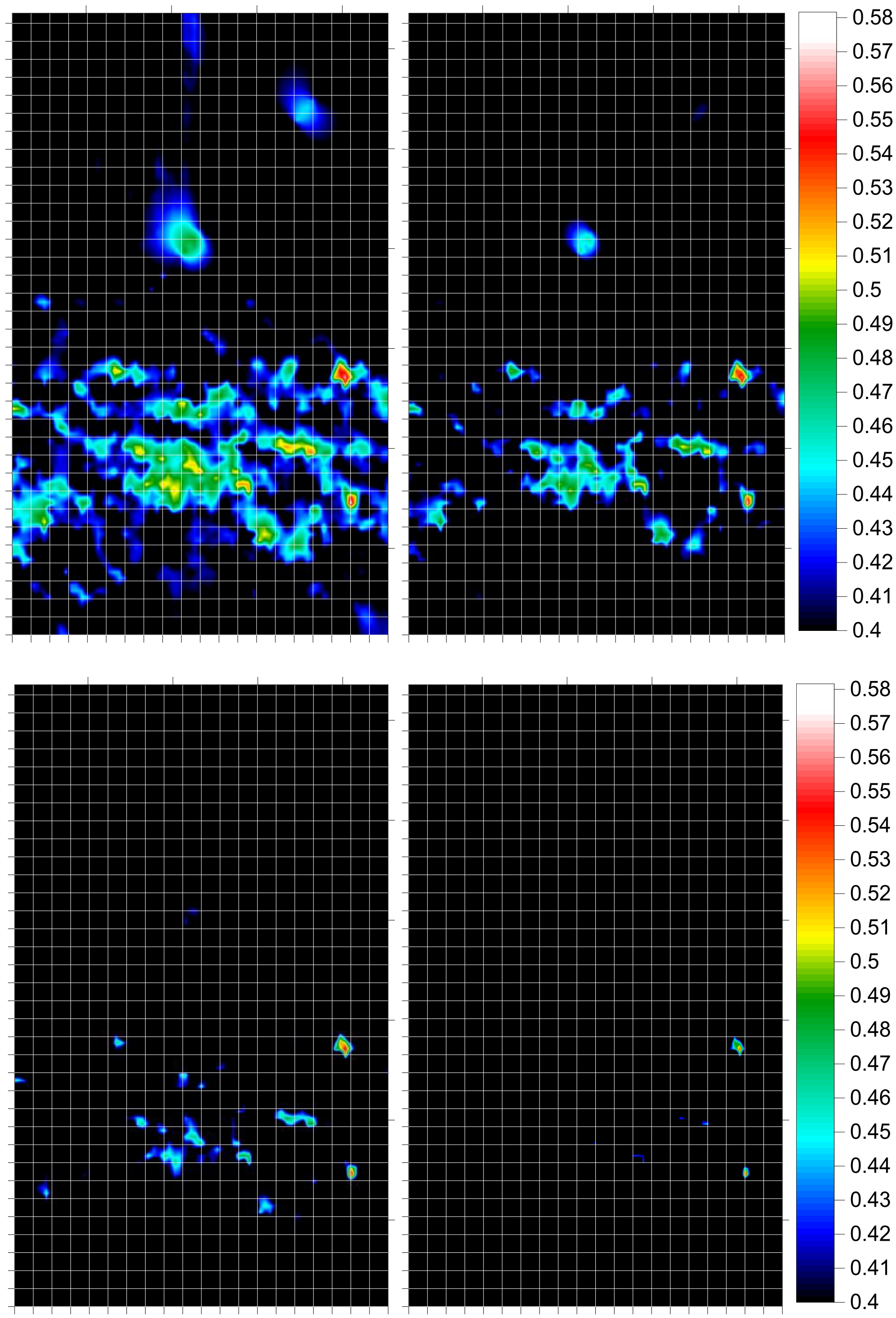


Figure 8: AOT values as recorded from both Terra and Aqua for the year 2012 using threshold values: 0.1 (top left); 0.2 (top right); 0.3 (lower left) and 0.4 (lower right). Each cell corresponds to a single day (beginning from top left to the right).

### 4.2 In situ observations

*In situ* observations were performed in the region of the Paphos town in order to record any possible changes of the monuments due to the air pollution. As it was found this threat is still very low in this area. Indeed, air pollution is not considered to be the primary hazard for cultural heritage sites of Paphos, compared to others such as urban expansion, salinity, rising humidity etc. Even though the great majority of the monuments of Paphos town are open air and thus directly exposed to environmental conditions and even more, are thickly surrounded by the modern town and its daily traffic life, they are little affected by air pollution factors. Deposits from airborne particles are rare and some cases of black colored incrustations are due to a combination of factors and mainly to fungus.

Paphos' monuments are almost entirely built out of local limestone native of the area. A stone of high porosity which in cases of severe air pollution could be destructively deteriorate. The positive results of the present research regarding the absence of air pollution in the cultural area of Paphos, does not equal complacency, but an efficient and inexpensive method of monitoring an eventual cultural heritage hazard.

## 5. DISCUSSION

Air pollution is a major threat for cultural heritage sites. In this study all monuments of Paphos district, as listed by the Department of Antiquities of Cyprus, were examined in order to evaluate their potential risk to this anthropogenic threat. For this reason, MODIS satellite data have been evaluated for the year 2012. The Paphos district was divided into seven main areas (grids) and then AOT values where extracted from the satellite data.

As it was found, air pollution, as a major parameter of AOT values, is still very limited in this area of Cyprus. Indeed, some high values of AOT where recorded rarely during the year. In addition, it was revealed that the maximum average AOT value was recorded over the Paphos town as it was expected. *In situ* observations verify the fact that monuments located within the town, are exposed to a low level of air pollution.

Finally, this study highlights the contribution of remote sensing techniques for monitoring AOT values in a systematic way, for protecting cultural heritage sites. Non contact data such as MODIS images may be systematically used for risk management along with other remote sensing data such as medium or high resolution satellite images. These non destructive for the monuments methods, may be a useful tool to the authorities for monitoring and managing the sites of archaeological interest and reenters in the sphere of preventive conservation, one of the key principles of conservation science.

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## REFERENCES

[1] de la Fuente, D., Vega, M. J., Viejo, F., Díaz, I. and Morcillo, M., "Mapping air pollution effects on atmospheric degradation of cultural heritage", Atmospheric Environment, 45 (6), 1242-1250, (2011).
[2] Nava, S., Becherini, F., Bernardi, A., Bonazza, A., Chiari, M., García-Orellana, I., Lucarelli, F., Ludwig, N., Migliori, A., Sabbioni, C., Udisti, R., Valli, G. and Vecchi, R., "|An integrated approach to assess air pollution threats to cultural heritage in a semi-confined environment: The case study of Michelozzo's Courtyard in Florence (Italy)", Science of The Total Environment, 408(6), 1403-1413, (2010).

[3] Karaca, F., "Mapping the corrosion impact of air pollution on the historical peninsula of Istanbul", Journal of Cultural Heritage, ISSN 1296-2074, 10.1016/j.culher.2012.04.011 (2013).
[4] Ghedini, N., Ozga, I., Bonazza, A., Dilillo, M., Cachier, H. and Sabbioni, C., "Atmospheric aerosol monitoring as a strategy for the preventive conservation of urban monumental heritage: The Florence Baptistery", Atmospheric Environment, 45(33), 5979-5987, (2011).
[5] Pujadas, M., Plaza, J., Terés, J., Art ano, B. and Millán, M. "Passive remote sensing of nitrogen dioxide as a tool for tracking air pollution in urban areas: the Madrid urban plume, a case of study", Atmospheric Environment, 34 (19), 3041-3056, (2000).
[6] Pfeffer, H.U., Friesel J., Elbers G., Beier R. and Ellermann, K., "Air pollution monitoring in street canyons in North Rhine-Westphalia, Germany", Science of The Total Environment, 169 (1-3), 7-15, (1995).
[7] Pummakarnchana, O., Tripathi, N., Dutta, J., "Air pollution monitoring and GIS modeling: a new use of nanotechnology based solid state gas sensors", Science and Technology of Advanced Materials, 6(3-4), 251-255, (2005).
[8] Ferradás, G. E., Mi arro, D. M, Morales, M. I., Terrés, M. M. I. and Martínez F. J. M., "An approach for determining air pollution monitoring sites", Atmospheric Environment, 44(21-22), 2640-264 (2010).
[9] Hadjimitsis, D.G., "Aerosol Optical Thickness (AOT) retrieval over land using satellite image-based algorithm", Air Quality, Atmosphere & Health - An International Journal, 2 (2), 89-97, (2009), doi 10.1007/s11869-009-0036-0.
[10] Hadjimitsis, D.G., "Description of a new method for retrieving the aerosol optical thickness from satellite remotely sensed imagery using the maximum contrast value principle and the darkest pixel approach", Transactions in GIS Journal, 12(5), 633-644, (2008), doi: 10.1111/j.1467-9671.2008.01121.x
[11] Hadjimitsis, D.G., Retalis, A. and Clayton, C.R.I., "The assessment of atmospheric pollution using satellite remote sensing technology in large cities in the vicinity of airports", Water, Air & Soil Pollution: Focus, An International Journal of Environmental Pollution, 2 (5-6), 631-640, (2002), doi: 10.1023/A:102130541700.
[12] Themistocleous, K., Nisanzti, A., Agapiou, A., Alexakis, D.D., Hadjimitsis, D.G., Lysandrou, V., Perdikou, S., Retalis, A. and Chrysoulakis, N., "Long term monitoring of air pollution on monuments and cultural heritage sites in Cyprus using satellite remote sensing", International Journal Heritage in the Digital Era, 1(1), 145-167 (2012).
[13] Tømmervik, H., "Monitoring the effects of air pollution on terrestrial ecosystems in Varanger (Norway) and Nikel-Pechenga (Russia) using remote sensing", Science of The Total Environment, 160-161, 753-767, (1995).
[14] Péré, J.C., Pont, V., Mallet, M. and Bessagnet, B., "Mapping of PM10 surface concentrations derived from satellite observations of aerosol optical thickness over South-Eastern France", Atmospheric Research, 91(1), 1-8, (2009).
[15] Kaufman, Y.J., Tanri, D., Remer, L. A., Vermote, E. F., Chq, A. and Holben, B. N., "Operational remote sensing of tropospheric aerosol over the land from EOS-MODIS", Journal of Geophysical Research, 102, 17051–17068, (1997).
[16] Hadjimitsis, D. G., Nisantzi, A., Themistocleous, K., Matsas, A. and Trigkas, V., "Satellite remote sensing, GIS and sun-photometers for monitoring PM10 in Cyprus: issues on public health". Proc. SPIE 7826, 78262C, doi:10.1117/12.865120, (2010).