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GEO-ARCHAEOLOGICAL STUDY OF THE TERRITORY OF BURNUM'S ROMAN SITE (CROATIA) THROUGH LANDSAT MULTI-TEMPORAL SATELLITE IMAGES AND HIGH RESOLUTION GEOEYE

1. The site

The archaeological site of Burnum (administrative district of Sibenik-Knin, Croatia) rises within a vast karstic plateau that develops on the right-hand side of the middle course of the river Krka (Fig. 1). Built at the beginning of the Imperial Age as the permanent seat of the occupation army of Dalmatia, was occupied by several legionary contingents (*legio XX valeria victrix, legio XI claudia pia fidelis, legio IV flavia felix* and *legio VIII augusta*), which alternated with the defence of the province until 86 AD (Campedelli 2012). Crossing point of important road routes between some of the main colonies of the Dalmatian coast (Iader and Salona) and the centers of the Danubian provinces, the settlement continued to grow even after the legions were transferred, until it became municipium at the beginning of the 2nd AD. The new Roman city, the political focal point of a large portion of the Krka high valley (the *Titius* in Latin historical sources), experienced a certain vitality and economic flourishing especially during the 2nd and 3rd century AD. It was only around the first half of the 5th century AD that, together with the intensification of the military tensions and migratory flows that characterize the northern part of Dalmatia, the city experienced a slow but gradual abandonment. The subsequent involvement of the province in the Gothic conflict ensured Burnum's definitive disappearance from history (537 AD).

2. Introduction to the Burnum Project

Since 2005, thanks to a collaboration between Italian-Croatian scientific institutions, the Burnum area has been the subject of experimental and innovative researches with the general purpose of understanding the dynamics of population and urban development which have affected this particular territory of the Roman province of Dalmatia (Campedelli, Vecchietti 2009; Giorgi 2012). The research activities promoted by scholars and researchers of the Department of History and Cultures (DiSCi) – Archaeology section of the University of Bologna, in synergy with the Croatian colleagues (Dept. of Archaeology, University of Zadar and the Museum of Drniš), and with the support of the Italian Foreign Affairs Ministry and the Krka National Park,

Fig. 1 – The site of Burnum, today called "Šupljaja" (ruins), for the remains of Roman arches still visible *in situ*, is located on the right bank of the river Krka (*Titius flumen* in the historical documents).

are aimed to a better knowledge of the site through the implementation of integrated methodologies that make it possible to collect reliable data on the archaeological deposit with the least possible use of the excavation (Boschi, Campedelli 2008; Giorgi, Boschi 2012; Giorgi 2016). The results obtained so far, not only clarify the appearance of organized castrum in the first half of the 1st century AD and its subsequent transformation into municipium (early 2nd century AD), but also refer to the identification of archaeological evidence beyond the physical limits of the city. These results enlarge our understanding of the occupation forms of the area in ancient times. Specifically, the paper's aim is to propose part of the results obtained through the application of specific methodologies of remote sensing, with particular attention to the use of high resolution pictures and multi-temporal processing of the same through the Geomatics techniques.

A.C.

3. Method and data acquisition

The principle of remote sensing relies on the ability to differentiate the majority of elements or objects on the territory (soil, vegetation, water, urbanized, etc.) trying to describe the spectral characteristics of each of them at different wavelengths, to which the different sensors consistent with their spatial resolution are sensitive. The collection and distribution of information is made possible by the development techniques relating to the construction of the sensors, the transmission of data and distance and their processing. The sensors enable the measurement at a distance, which is based essentially on the behavior of the surfaces of the bodies relatively to the reflection of electromagnetic waves coming from the source of radiation (sun) within the portion of the visible spectrum, infrared and microwave (thermal). Such measures are directed to indirect recognition of the structure of spatial elements, or upon detection of some physical characteristics such as, for example, the temperature or the spatial distribution of an element (Lillesand, Kiefer, Chipman 2015). According to this concept, remote sensing allows both qualitative and descriptive analysis of the images.

Several satellite images, already subjected to orthorectification, have been used for the analysis of the study area (Leprince *et al.* 2007). The data used for this study cover a wide time span, ranging from 1972 to 2010. The Landsat images belong to an on-line store of the site (http://www.landcover.org/index.shtml), while the high-resolution GeoEye-1 image was acquired as a "demo" for research purposes by the E-geos. For the 1970s period, two Landsat Multispectral Scanner (MSS) satellite images were acquired. Then they have been mosaicked even if they belong to two different times, because all the specific multi-temporal sequences were not in the archive. For Landsat Thematic Mapper (TM) three pairs of images respectively dated to the years 1984, 1992, 2010 were mosaicked. For the Landsat Enhanced Thematic Mapper (ETM) images dated to the year 2000 belong to the same date of acquisition, while those of 2005 differ a month (Fig. 2). All images were then resized or cropped to the study area, i.e. the park's northern area of Burnum archaeological site.

At the beginning, in order to realize these analysis, we had to estimate the parameters for the georeferentiation of the images within the selected cartographic reference system, UTM33-IGS08 (WGS84). For this valuation 14 points on the ground were measured directly. To do this, these points were measured directly and are well recognizable on the images themself. As measuring system dual frequency (L1, L2) in differential mode Global Navigation Satellite System (GNSS) was used, it means that the individual coordinates have been determined (post-processing data) with respect to a reference station placed in a predefined point of known coordinates. In this case the so-called "master" station has been positioned within the Burnum archeological site, at a materialized point on the ground, having geographic coordinates 44° 01' 00.03047" N and 16° 01' 30.86652" E (Geodetic Datum IGS08). This point of known coordinates turned out to be materialized within the area of investigation and previously measured and connected to the Permanent Station of Croatian Geodetic Network and EUREF (Dubbini, Curzio, Campedelli 2016). The 14 points were positioned especially where irregular spots of different and

	Landsat MSS	Landsat TM	Landsat ETM+
Risoluzione	80 m	30 m	30 m
Green	1 (0,5-0,6 µm)	2 (0,52-0,6 µm)	2 (0,52-0,6 µm)
Red	2 (0,6-0,7 µm)	3 (0,63-0,69 µm)	3 (0,63-0,69 µm)
Infrared	3 + 4 (0,7-1,1 µm)	4 (0,76-0,9 µm)	4 (0,76-0,9 µm)

The Landsat sensors with their resolution and features for nearby green, red, and infrared bands.

Bands	Pixel size (m) Landsat TM	Pixel size (m) Landsat ETM +
Band 1, 2 , 3, 4, 5 e 7	30 x 30	3 0x 30
Band 6	120 x 120	60 x 60
Band 8	-	15 x15

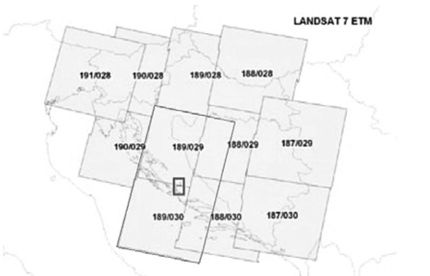
Earth pixel resolution sizes for all the two Landsat sensor bands.

Satellite and sensor	Path and row	Data picture
Landsat MSS	203-029	18/09/1979
	203-030	8/08/1972
Landsat TM	189-029; 189-030	27/06/1984
	189-029; 189-030	20/08/1992
	189-029;189-030	22/08/2010
Landsat ETM +	189-029;189-030	2/08/2000
	189-029	29/06/2005
	189-030	15/07/2005
GeoEye1	-	15/06/2010

The table shows the satellite imagery acquired for the study of the area. The table fields refer to the name of the satellite and its sensor, the path and row of images, and the date of acquisition.

Imaging Mode	Panchromatic	Multispectral
Spatial Resolution	0.41 meter GSD at Nadir	1.65 meter GSD at Nadir
Spectral *Range*	450-900 nm	450-520 nm (blue) 520-600 nm (green) 625-695 nm (red) 760-900 nm (near IR)
Swath Width	15.2 km	
Off-Nadir Imaging	Up to 60 degrees	
Dynamic *Range*	11 bit per pixel	
Mission Life	Expectation > 10 years	
Revisit Time	Less than 3 day	
Orbital Altitude	681 km	
Nodal Crossing	10:30 am	

GeoEye-1 satellite features [source: *www.landinfo.com*]



Landsat 7 ETM images cover (also corresponding to TM sensor). The slimmer black line highlights the images with the relative Path and Row used in the study of the area, inside the same, is displayed in bold, in the smaller black polygon, the territory of the National Park of Krka.

Fig. 2 – Technical data of the satellite images used: Landsat images belong to an available archive at http://www.landcover.org/index.shtml, while the high resolution GeoEye-1 image has been acquired as a "demo" for search purposes from E-geos company (http://www.eurimage.com).

nuanced tone were detected. These irregularities are generally due to different variations and frequent moisture and / or particle size of the deposits. In fact, these inhomogeneities are usual in sandy and not very thick deposits, in areas subject to solifluction, to leaching and also in karst areas. The coordinates of the control points were so obtained (GCP, Ground Control Point) from the GPS measurements and the subsequent processing. The average accuracy of each point is of the order of 2-5 cm magnitude. The georeferencing of the high resolution ortho-image was performed with QuantumGIS software.

M.M.

4. The image processing

The Image Processing procedures performed on images have the aim of increasing their quality in order to improve the extraction of information about the objects that make up the scene, if they are not clearly visible in the original image. The application software for processing satellite images, taken to perform all the processing calculations, is ENVI 4.4, which provides visualization tools, spectral analysis, geometric correction, and also can enable to work in vector environment. On the image you can operate satellite punctual transformations on a single pixel, or spatial ones which involve more pixels. The punctual transformations, also called radiometric transformations, enable to change the radiometry or Digital Number (DN) associated with the pixels so that the new value depends only on the corresponding original. The spatial or geometric transformations lead, instead, to the modification and to the improvement of the images' geometric details. Compared to point transformations used for the improvement of the radiometric contrast, the improvement of the image geometric techniques are characterized by operations that involve both the pixel to be processed and those close to it. When it comes to enhancement of an image, reference is made to law enforcement instruments, particularly the Stretch Contrast (Contrast Enhancement). This is a technique which applies in automatic or manual manner, without requiring special knowledge of quantitative type of noise or degradation phenomena that the image may contain, and is often used to a first general analysis, in order to facilitate the identification of subscenes of interest. Applying the linear stretching (Interactive Stretching), it is possible to work on the histogram of frequency in a dynamic manner; this allows to identify elements that the elaboration alone is not able to highlight.

The Stretching of the Linear algorithm consists of a transformation function that allows to expand (stretching) the range of the gray levels in the original image recorded up to cover the entire dynamic range of the display device (256 in the case of display 8-bit): this translates into a contrast increase. The same transformation function allows to obtain conversely the opposite result, that is, to compress the histogram, in order to decrease the number of gray tones and the contrast (Lillesand, Kiefer, Chipman 2015). The purpose of emphasizing techniques or improvement of contrast is to assist the interpretation in terms of characteristic parameters such as contrast, texture, shape and color. If the operator is expert and the color levels are adjacent and well separated, the human eye can distinguish 20 or 30 levels of gray from black to white (Gomarasca 2004); the contrast ratio enhancement encourages the appreciation of subtle variations of gray of an image, especially when the distribution of DN is comprised in a narrow range of values.

In order to interpret the available images, they were viewed through different compositions RGB (Red, Green, Blue). The most significant and useful one appeared to be the one in false colors, 4-3-2 sequence of bands, which means that the near infrared band is associated with the channel of the red color, the red band is associated with the green channel and the green band associated to the blue channel.

M.D.

5. Image classification and analysis method

The classification procedure performed by the ENVI software consists of two phases: the definition of Region of Interest (ROI) and the application of the type Maximum Likelihood classifier.

During the working phases other operations (NDVI, i.e. Normalized Difference Vegetation Index; Dencity Slice; Band Ratio) were correlated in order to grant a wider knowledge of the area and further information; a complete synoptic table to assign the right keys of interpretation, both from the spectral point of view and from the geographic-territorial one (Vishnu, Nidamanuri, Bremananth 2013). The Landsat images (TM and ETM) were classified according to the following classes: vegetation, water, urbanized-bare soil, rock (Fig. 3). The class "urbanized-bare soil" has not been divided into two separate classes. Indeed, through Landsat images you can not get a clear-cut distinction between the two elements but they are useful for a wide territorial framework and an overview of the whole. The class called rock, also includes plots of arable land, but precisely with a rocky substrate.

After defining the classes we estimated their spectral separability, through Jeffries Matusita's separability size (Bruzzone, Roli, Serpico 1995), which associates the values (0 to 2) with the ROI; then we evaluated how much the values of each class were correlated. For a good classification result these values should be higher than 1.8 (Zhilin, Qiming, Wolfgang 2004). Once the classifications were obtained, they were critically evaluated through the elaboration of the confusion matrix in order to establish the accuracy of the classification process and to compare the results obtained. Each class belonging to the classification of the individual images was then vectorized through ENVI 4.4 software. These vector files (shape files, .shp) were then overlaid and displayed as layers with the open source program Quantum GIS 1.6., so we could point out the changes between the same classes (such as vegetation class), extracted from different images in a more immediate way.

Before the classifications, the satellite images were processed through other analytical procedures. For example, a vegetation index was applied to each image. The NDVI is the index used as a benchmark when one wants to study the vegetation through the remote sensing images (Tucker, Sellers 1986). This type of analysis is based on the spectral properties of the vegetation and in particular on the phenomena of reflection and absorption of natural radiation. The reflectance curve of vegetation presents the peaks, specifically in the regions of visible Red, between 0.6 and 0.7 pm, Near InfraRed (NIR), between 0.9 and 1.35 μm and IR Medium, between 1.35 and 2.70 μm. As already said, the most common factors, which can vary the shape and amplitude of these maxima, are the leaf segments and the water content. Through the NDVI command a coefficient (between -1 and 1) is elaborated and it

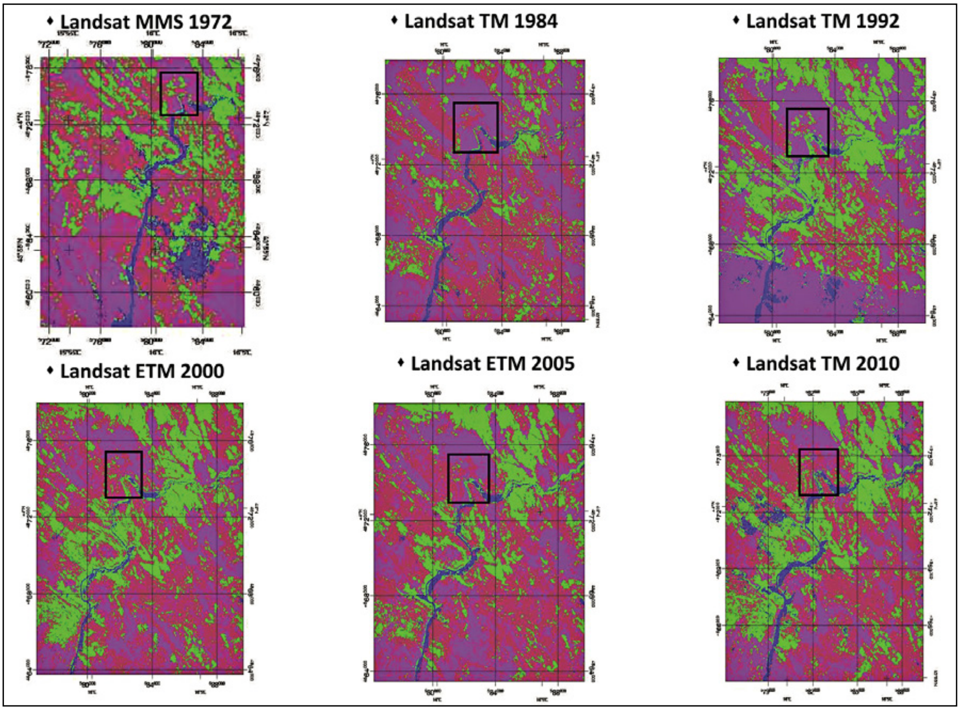


Fig. 3 – Landsat images processing and classification according to the following classes: vegetation (green), water (blue), urbanized-bare soil (purple), rock (red).

expresses the density of vegetation within the area of investigation through an algorithm of calculation which considers the two reflectance peaks. Here is the formula of this algorithm: NDVI = NIR-Red / NIR + Red, where Red is the band relative to the range of spectral visible Red. Also in this case the processing was performed using Landsat MSS for the intervals of the bands 2 and 4, Landsat 5 for the spectral ranges of the TM3 and TM4 bands, Landsat 7 for the intervals ETM3 and ETM4 bands. The Slice Density was applied at various vegetation indices; it consists of an analysis of density levels that enables to divide the continuous scale of tones in a single band of an image, grouping them in a single layer and assigning them a new DN (Lillesand, Kiefer 1986). The result will be a color image or encoded pseudo colors, which will not have a direct feedback with digital colors of the scene, as in fact the color is arbitrary and represents a certain interval of DNs, and then a certain amount of radiance intensity interval.

Another procedure used for the analysis of the images is the one of the relationship between bands (Band Ratio) (Lillesand, Kiefer 1986). After defining two bands of interest, the relationship between bands consists in dividing each DN of each pixel relative to a band for the corresponding DN of the pixels inside the second. The real number obtained as a result of the division is multiplied by a normalization factor that converts to an integer between 0 and 255; in this way in the report image obtained, the extreme darker and lighter gray levels correspond to the maximum of spectral reflectivity differences of the two bands considered (Gomarasca 1997). High-resolution image GeoEye 4/1 was usefully applied to investigate the moisture content of soils. At this report between bands was applied a 2% linear stretching to enhance the contrast and subsequently a density slice in order to highlight the difference in texture, which, in turn, could suggest a variation of soil moisture. By comparing the images processed with the same false-color RGB 432 it has in fact highlighted a darker place.

M.D.

6. Results and archaeological interpretation

As already mentioned above, the Burnum archeological site is located on the northern shore of the middle reaches of the river Krka, within the area of Bukovica, a plateau that is about 250 m above sea level. This region, dominated by carbonate rocks that favor the rainwater penetration in depth, is characterized by the peculiar phenomena of the karst. The almost total disappearance of a surface water network, therefore, makes the landscape almost bare from vegetation. The study of morphological, physical and chemical properties of the soil that characterize the area of the Krka valley, indicates that the thickness of the surface layer marly and colluvial varies generally from 15 to 70 cm (Vrbek, Pilaš 2007). The most important factors that determine this differentiation of the thickness of the surface soil layer are due to natural petrographic modifications of the substrates, to processes related to karst and anthropogenic influences. In particular, the anthropogenic and zoogena influences represent one of the main elements of the exogenous process of a karst environment (Perica, Orešik, Trajbar 2007). For several centuries, and until a few decades ago, the pastoral economy has been the main activity of the relatively dense population throughout the course of the Krka river. This practice has been the main cause of degradation of its forest cover. The grazing of sheeps and goats has subsequently destroyed the turf, thereby stepping up the process of soil erosion. Lacking almost completely the role played by the vegetation as a protective cover against exogenous processes, the dryness of the soil has greatly influenced the hydrological conditions giving rise on one hand to a greater evaporation of the water contained in the substrate, on the other to a more fast leaching of the same. However, this general information on geo-morphology of the Krka Valley does not seem to reflect the environmental situation of the Burnum site, or at least that portion of the territory, about 8 ha, in which we recognize the physical limitations of the castrum/municipium. Inside the area, in fact, the campaign plan appears to be characterized not only by a dense turf, but also by bushes and shrubs that reach discrete size. Geophysical surveys conducted within the limits of the site had led to the conclusion, since the first years of the project, that the Burnum underground preserves traces of a significant amount of ancient buried structures. The different essays about stratigraphic testing, conducted during the annual research campaigns, not only confirmed the geophysical data, but also allowed to document the presence of a significant level of underground, a stratigraphy that in some areas also reaches 2 m (Boschi 2011; Giorgi *et al.* 2012). Inside the Burnum site, therefore, the anthropogenic influence has affected the natural environment not only in a negative way, that is with "destructive" interventions such as deforestation, but especially with soil accretion actions. The choice of the site in the Roman period, dictated by strategic control needs of one of the few ford points on *Titius* river (Krka), and the need to regularize, through artificial terraces, a morphologically uneven ground, characterized by a significant gradient from N to S (i.e. in the direction of the canyon), have led to the realization of masonry structures directly on the bedrock and the ground carryover to create the necessary walking surfaces. If we add to these initial requirements the subsequent transformation from a military camp to the municipium and a continuity of settlement documented until the 5th century AD, this has further contributed to the growth of the archaeological deposit.

As a result of this awareness, at least as far as the restricted area of the site was concerned, we decided to expand the research to a larger portion of the territory, in order to check if the human presence in the area was limited to the already known urban context of Burnum. To carry out the research on a larger scale, also in consideration of the fact that in a karst environment as precisely the Bukovica, the presence of vegetation was somehow linked to the presence of man, we decided to apply methods of remote sensing of the surrounding territory of the Burnum site both to get an estimate of the spatial distribution of the vegetation and the moisture levels of the soil. As emerged above, the spectral characteristics of the images used have permitted to see and locate the structural and textural changes of the soil within the study area. In particular, the elaboration of the GeoEye image according to the parameters of the infrared band, pointed out a darker colored chromatic area (blue-green) compared to a slightly accentuated or totally absent chromatism of the remaining territorial context. This color change is due to the presence of a higher level of moisture in the soil (Thenkabail 2015). The soil moisture not only characterizes the restricted site of Burnum (as might be expected from the underground documented by the excavations), but also

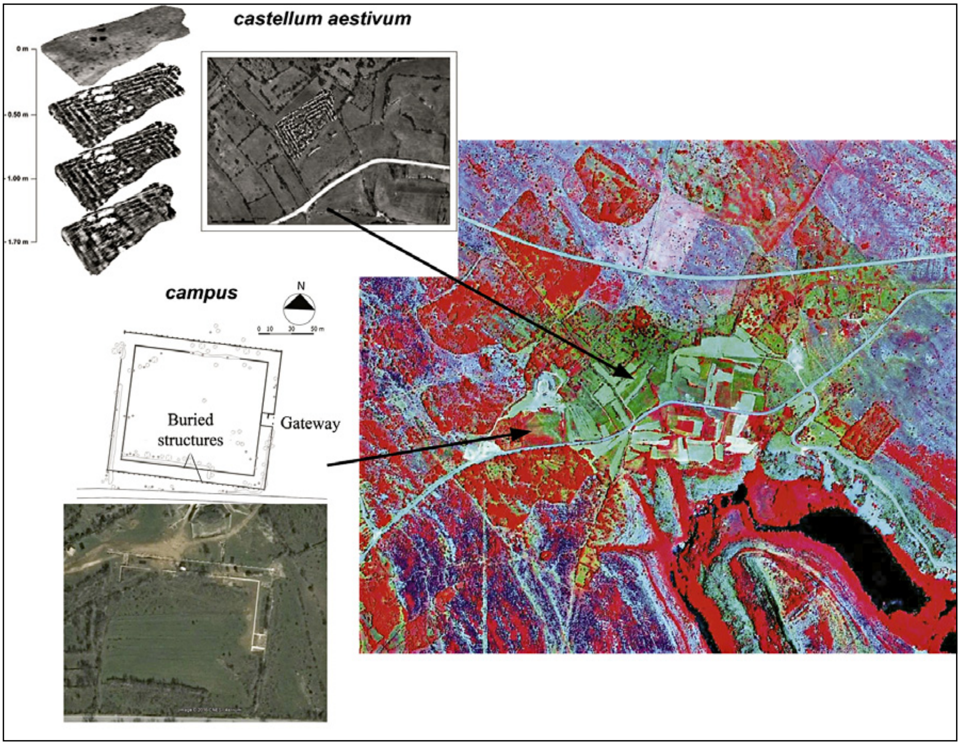


Fig. 4 – The GeoEye image in false color (RGB combination 432) and the identification of buried archaeological contexts in the western part of the site.

different areas of the southern sector of the western and northern Europe. In addition, this coloration assumed radial patterned forms in correspondence of the outermost limits, thereby forming narrow bands that progressively became thinner. Probably all these portions of the *extra-moenia* territory, characterized by a higher percentage of humidity and therefore characterized by a greater level of underground, could preserve traces of ancient buried structures. In order to verify the reliability of this hypothesis, first we conducted geophysical prospecting and then we proceeded with excavations in some sectors of the western part characterized by fields of natural obstacles (shrubs, trees, etc.) and artificial ones (modern dry walls used as legal division of the plots). Thanks to the results of these researches, the anthropogenic origin of the underground and the presence of ancient infrastructure such as a *campus* or *palestra exercitoria* for military exercises (Miletić 2010) and traces of an earlier temporary camp *(castrum aestivum)* were confirmed. In addition to these findings, the results that have further enriched our knowledge of the ancient employment of Burnum are given by those long and narrow areas that radially develop from the site to the periphery (Fig. 4). Basing on comparisons with other military camps sites (Doneus, Gugl, Doneus 2013), in these areas we must recognize the *canabae legionis* which are portions of territory under military command, within which non only essential facilities (amphitheater, gym, spa baths) were erected, but also houses, shops and other kind of private dwellings, occupied by artisans, blacksmiths and merchants who followed the army in order to be able to exploit its economic potential: the soldiers' wages, trade and procurements related with military requirements (Piso 1991). Since groups of people spontaneously formed, more buildings arose, developped and concentrated especially in correspondence of the busiest areas, and then near the edge of the extra-urban roads and in correspondence of public buildings such as the amphitheater and spas. The plan, the type and the quality standard of private structures relevant to *canabae* in Burnum must be checked in the future through archaeological excavations. However, thanks to the results of this methodological approach is now possible to focus resources and energies on these areas.

A.C.

7. Conclusions

The analysis conducted thanks to the satellite images allowed to extract data and territorial information and to analyze the archaeological area from different points of view. In general, it can be argued that the territorial morphology remained the same throughout the entire time investigated through the satellite images (1972-2010) since, being a karst area, it maintains its arid and "harsh" characteristics unchanged. As far as vegetation is concerned, a normal seasonal variation has been observed, as well as annual climatic changes, but it does not seem to concern the area of Burnum site, which is almost completely bare of vegetative coverage. Based on the geomorphological context and the exogenous effects that characterize the karst environment, this lack of vegetation is probably due to the anthropic action which began several centuries ago. What we can imagine is that on the occasion of the Roman occupation of this sector of the Krka middle valley, and in particular the river's turning point, the construction of the Roman camp involved a preventive deforestation of the area. The continuity of life and the demographic growth that took place during the transition between military camp to municipium expanded this phenomenon, favoring a further process of "reclaiming" the surrounding space. After the abandonment of the site up to the present days, this land "reclaimed" by the vegetation continued to be exploited for pasture, with the ultimate result of fossilizing the arid aspect of this part of the territory, marginal and less frequented. The Archaeological information, on the other hand, was obtained by analyzing the spectral characteristics of GeoEye images, which not only allowed the visualization and identification of structural and textural variations of the soil associated with increased humidity but also to recognize the presence of buried anomalies linked to the construction of a series of defensive trenches pertaining to the construction of a provisional temporary camp and traces of extra-urban roads. Burnum's *canabae legionis* occupy a special place in the category of civilian settlements near the Roman forts. Although a detailed picture of their organization is still unavailable, it is now possible to identify their extent and location thanks to the remote-sensing results, especially along the external connection paths to the castrum, and focusing resources and energies on these areas. The future commitment is to gain further evidence of the history of their development and the use of the individual sectors, coming to define the residential areas, the most economically viable sectors, and the spaces destined for the funerary sphere. At a more general level, this research methodology and this interpretative approach, if it could be supported by other data, can be extended to other areas of the Krka valley with the aim of intercepting sectors that might show other forms of occupation: above all rural settlements such as rustic villas, proved by numerous epigraphic testimonies pertaining to retired military in various areas from Bukovica.

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ABSTRACT

The object area of the study was analysed with a geographical and geo-archaeological approach, integrating the data by using geomatic techniques (Satellite Remote Sensing and Geographical Information System). The processing of the data of the high resolution Satellite images allowed us to discover that in the karst environment, like the one in which Burnum was established, the areas with a higher humidity and vegetation concentration are the results of the anthropic action due to frequentation in the Roman Age. The infrastructure and buildings, the earth moving conducted to raise the original natural surface levels, and the subsequent collapse of buildings during the stage when the site was abandoned, determined the formation of a significant substrate in the area. Thanks to the results of the surveys and data, the positive responses of the image analysis through the Band Ratio and the enhancement procedures highlighted the differences in the soil's patterns/weaving. This method of investigation, the results of which will be verified by carrying out targeted surveys, suggests the presence of residential infrastructure (*canabae*) in the area surrounding the Roman site and especially along the main roads. Therefore, the archaeological site of Burnum, today corresponding to approximately 8 ha, could be doubled, adding even further to the importance of the role that the city had in this part of the Roman province of Dalmatia.