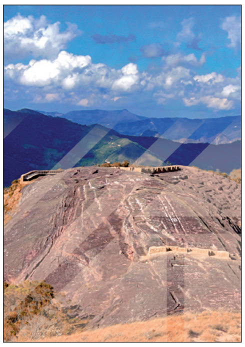

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Integration of project results on a GIS platform and its impact on conservation strategies

Integracja wyników projektu na platformie GIS i jej wpływ na strategię konserwatorską

Introduction

The geographic information system (GIS) is an important utility that can be considered as a perfect tool to combine the study of the spatial dimension with the study of human activities. In archaeology, GIS platforms have been used since the early nineties of the last century [1]. The GIS environment allows large volumes of data to be processed, spatial queries to be made, and different types of datasets to be analysed, so it is a cost effective, fast tool. It helps to organise documentation and is efficient and precise in aggregating spatial data, especially in architectural and archaeological conservation [2]. This helps to provide more information on the formation of a site and its changes in time, which allows complex spatial analysis to be conducted.

GIS environments are able to store, manipulate, and combine multiple types of data sets, for example, satellite images, LiDAR point clouds, TLS point clouds, CAD files, photo images, GPS coordinates, multiple types of databases (SQL, Access, Oracle), raster images, DTMs, DSMs, and 3D models. This diversity of data allows complex analyses to be conducted and different possible scientific hypothesis to be made. There are many publications in the form of manuals for GIS technologies [1], [3], [4].

This paper presents the development of a complex 2.5D GIS database, which was built for the project "Architectural examination and complex documentation of Samaipata (El Fuerte de Samaipata/Bolivia) site from the World Heritage List" funded by the Polish National Science Centre. The current condition of Samaipata rock and its progressing erosion[1] is caused by several factors. One of these is precipitation and the impact of rainwater flowing down the slopes of the rock or accumulating locally. This problem has already been addressed by earlier studies [5]–[7], but a more general approach that also encompasses the detailed topography of Samaipata rock seems to be necessary. The main features of the rock surface need to be considered, especially the areas of local depressions and natural cracks through which water seeps into the rock.

Methods

The main objective of this research was to combine spatial data acquisition technologies and a GIS in order to create multidisciplinary documentation and make a quan-

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[1] Cf. W. Bartz, J. Kościuk, M. Gąsior, T. Dziedzic, *Petrographic, mineralogical, and climatic analyses, and risk maps for conservation strategies*, in the same issue of "Architectus".

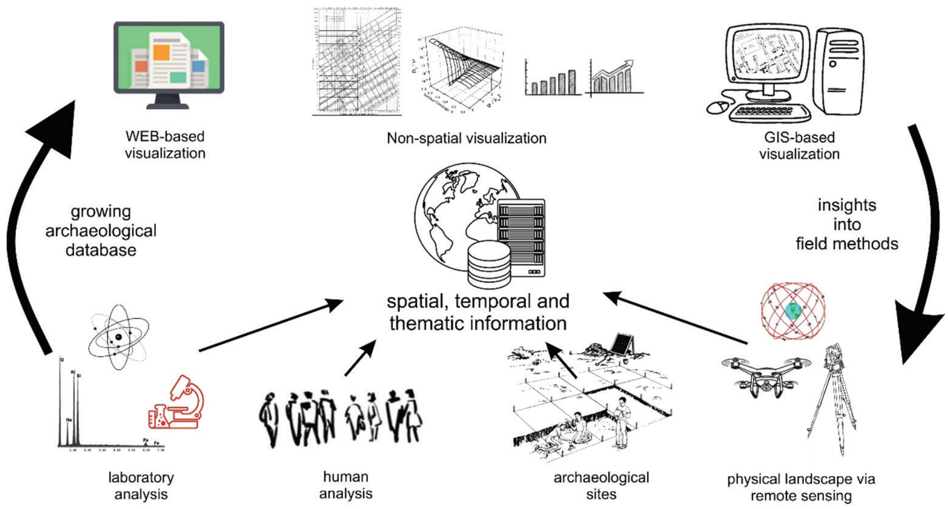

Fig. 1. A representation of the cyclical relationship between collecting data from the archaeological field, information integration, and data visualization and interpretation (adopted from [21])

titative assessment of the damage to an archaeological site caused by nature or human activity. The study followed the typical process of information transmission, starting with a topographic survey and finishing with analysis from non-specialists. These typical steps are described below.

1. Survey and documentation.

There are several techniques for documenting archaeological sites. The most effective method for acquiring spatial data is remote sensing technology [8], [9]. Over the last twenty years, the development of ground, aerial, and space equipment and technologies have proven the efficiency of remote sensing technology for documenting archaeological sites and heritage monuments [10]–[12]. In particular, the fast and huge progress of space technology, including a higher spatial resolution and hyperspectral data, has created new opportunities for better and accurate analysis, often resulting in many unexpected discoveries [13]–[15].

2. Specialist interpretation.

The GIS environment can be treated as the best visualisation platform for combining different types of datasets [16], [17]. It has a very big impact on multiple analyses performed on cultural heritage [1], [3]. In particular, the use of such platforms as ESRI or QGIS allows complex models derived from laser scanning [18], [19] or photogrammetry [20] to be combined with more traditional datasets. Such data overlays allow the broader context of the analysed material to be seen.

3. Map development.

After analysis and summarising, the GIS environment can create thematic maps (both 2D and 3D) of a very high quality and with high spatial resolution.

4. Community.

The first three steps require specialist knowledge and skills; the last step is the work with the developed material by the community, and the creation of their own analyses and hypotheses.

Neha Gupta and Rodolphe Devillers [21] compare GIS environments to the classic relationship between the collection of data in the archaeological field, information integration, and data visualization and interpretation (Fig. 1). This comparison shows the main advantage of GIS databases is that they can integrate different types of datasets. Even if we do not have geolocations due to specific types of data (for example, text descriptions), we can easily add our data to a larger spatial database regarding the particular project. Additionally, if in a text description we can highlight some specific factors, later we can perform spatial analysis using them.

For example, hydrological analysis allows potential surface runoff routes made by natural erosion and people to be identified [22], [23]. The ArcMap application with the ArcHydro extension [24] was used in the hydrological analysis of this study. The goal was to identify potential surface runoff routes in the natural terrain and those developed by people. The basis of the study was a digital terrain model (DTM) with a 5 cm spatial resolution. Altitude data from TLS (point spacing 0.01, ca. 425 million points[2], were used to create a spatial spacing 5 cm DTM in a grid format.

When preparing data for analyses, special attention was paid to the hydrological correctness of the numerical terrain model [25], [26]. For this purpose, the function Fill Sinks in ArcHydro [24] was used. This corresponds to the Fill function in the Spatial Analyst extension [27]. The purpose of Fill Sinks is to fill in drainage areas, the occurrence of which, even on a microscale, can limit the continuity of runoff routes. The Fill Sinks function aligns and fills places with the biggest depressions to the level of the surrounding area.

The natural step before Fill Sinks is the use of the DTM Reconditioning function in ArcHydro. Its task is to stamp the watercourse beds into the DTM to indicate the main runoff routes. However, due to the characteristics of what was being analysed, this was abandoned in the first step and was used only after filling the drainage areas. Using the DTM Reconditioning function identified natural cracks, terrain cracks, and intentional human-created runoff routes. It was decided to take this step simultane-

[2] Cf. J. Kościuk, B. Ćmielewski, M. Telesińska, A. Kubicka, *3D terrestrial laser scanning of El Fuerte de Samaipata*, in the same issue of "Architectus".

ously to take into account runoff through natural forms of the terrain, and to demonstrate the flow of water channels made by people. Then in ArcHydro, a runoff direction model was developed (Flow Direction [28]) based on the DTM, and a runoff accumulation model (Flow Accumulation [27], [28]), was created to determine the hydrological conditions of surface runoff. By using subsequent modules in the ArcHydro extension, potential runoff routes were developed. Following this, the Stream Definition and Stream Segmentation (to develop concentrated runoff routes) and Catchment Grid Delineation (to determine areas from which concentrated runoff occurs) functions were used.

The algorithm conditioning the accuracy of the results obtained was the Stream Definition function, in which the minimum surface area of the catchment area of a single water route was taken into account. An even surface was assumed to be 4000 pixels, which in the case of spatial resolution in the DTM corresponds to an even surface of 10 m^2. Ultimately, potential runoff routes were determined by taking into account natural forms of terrain, including cracks formed over the years, and forms created by people to manage water on the site. As a result, a layer of microcatchment areas was created.

Results and discussion

GIS in fieldwork

During the survey, especially during the photogrammetric acquisitions of images, the mobile GIS was a very useful supporting tool. Due to very bad atmospheric conditions, especially extremely strong winds, it was not possible to fly a drone, so we were forced to acquire images from the ground by placing cameras on long telescopic sticks ca. 3–4 m above our heads. Even when we created virtual lines of walking on the rock, sometimes it was not possible to avoid errors and create gaps or very poor longitudinal and transverse coverage. Due to this, every day, we estimated the positions of images in the global coordinate system and checked the coverage. If we found gaps, we exported the .shp file to a mobile phone application (Locus Map on Android) and navigated to this area using mobile phone GPS.

A similar workflow was used when we captured the multispectral images. This workflow forced us to create temporary layers such as:

1. RGB camera position reconstructed each day (Fig. 2).
2. Temporary orthoimages from each day.
3. Position of multispectral images reconstructed each day.

Additionally, during the field survey and inspection by Giuseppe Orefici, we created two temporary layers to organize the data. One was the schematic plan of the site (Fig. 3) and the second was used to collect data from analysis of objects found on the rock such as petroglyphs, water tanks, seats and terraces, and other important features (Fig. 4).

Cameral work

After fieldwork seasons were completed, final documentation was prepared. Several groups of researchers contributed to delivering data for particular thematic layers of the GIS. They all used three basic deliverables that were prepared in advance: DEM, orthoimages from TLS, and RGB and multispectral orthoimages from the photogrammetric project. The final product was vector (CAD) documentation of the site as well as detailed analysis of more specific features such as unclear (eroded) petroglyphs. A description of the final layers of the whole GIS is presented in Table 1.

The basic set of data (layers from 1–23) presented above was further used to produce more advanced analysis that was also incorporated into the GIS project (layers 24–32). Some of these analyses are presented below.

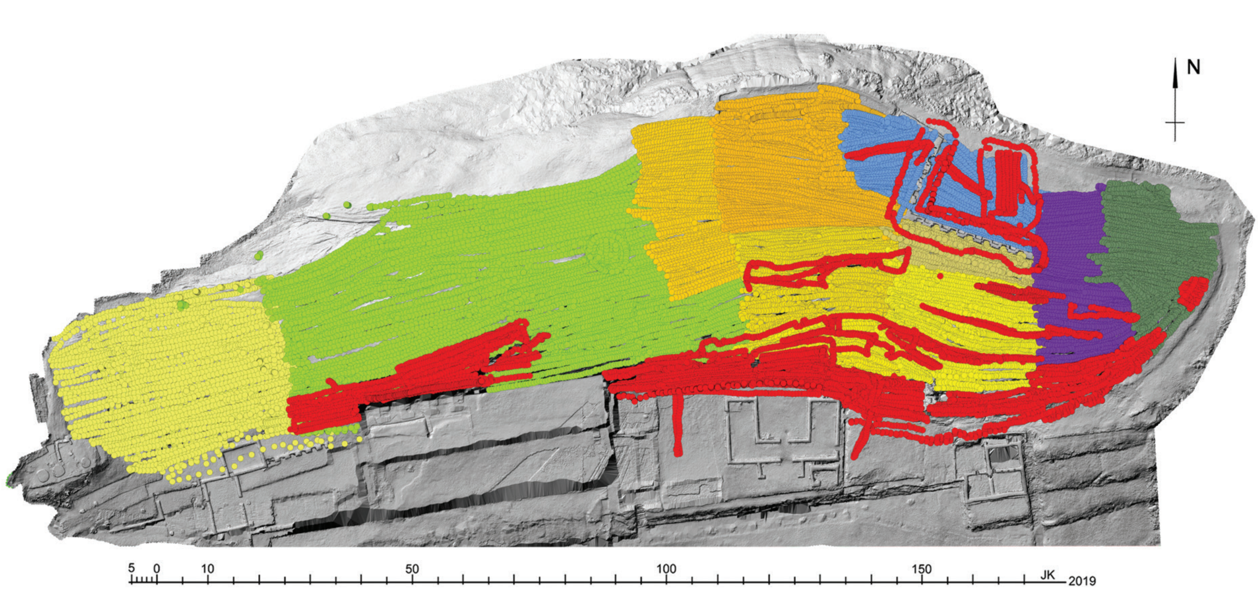

Fig. 2. RGB camera position reconstructed each day. Each day is shown with a different colour (elaborated by B. Ćmielewski)

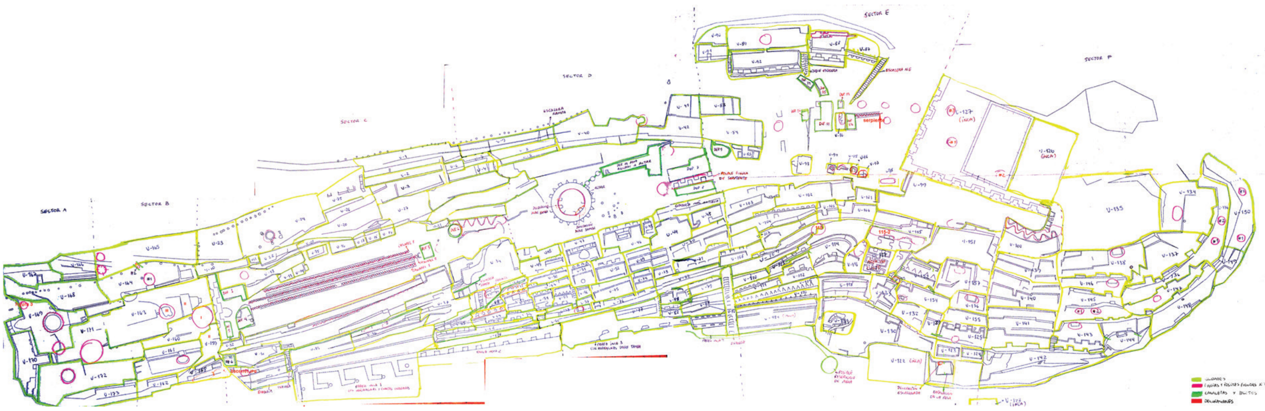

Fig. 3. Schematic plan of the site during the 2016 survey season
(elaborated by G. Orefici)

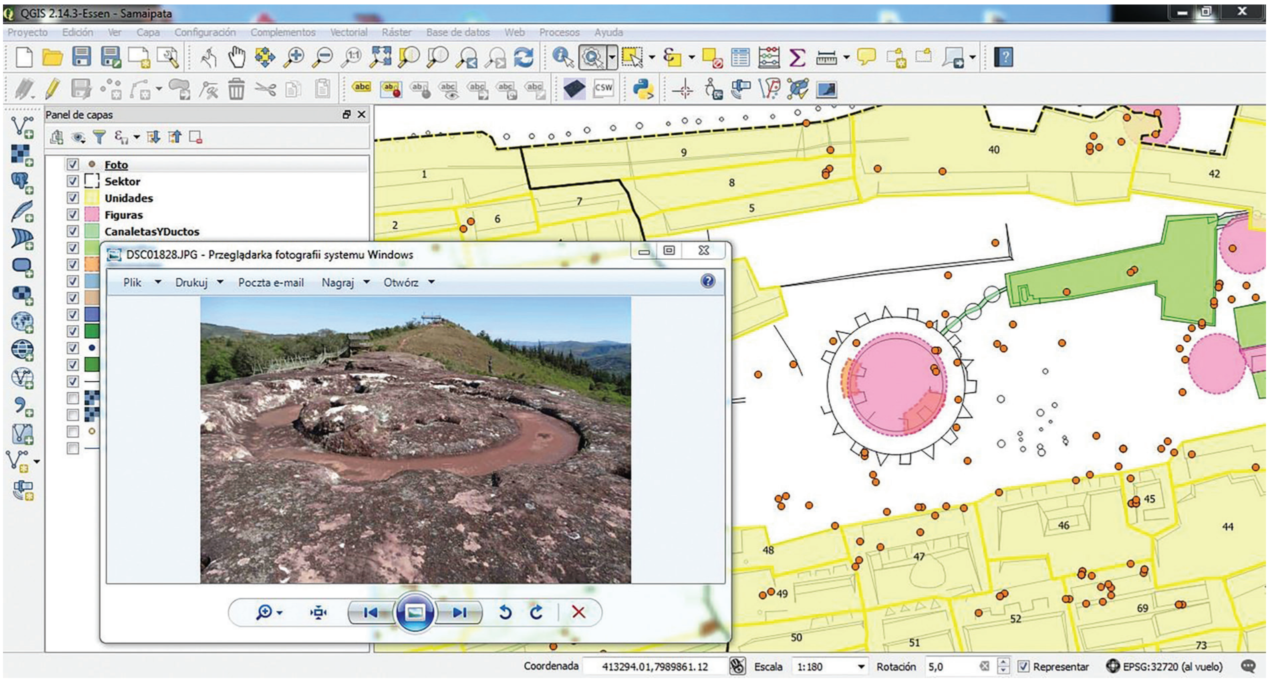

Fig. 4. Organisation of iconographic fieldwork data during the 2016 survey season
(elaborated by I. Wilczyńska)

Hydrological analysis

Local depressions were searched for in a Bentley MicroStation V8i environment – contour lines were generated every 10 cm and those that formed enclosed areas were selected. The results were presented in colour scale reflecting the maximum depth of accumulated water (Fig. 5).

The ArcMap environment was then used to automatically select depressions without a drain and to smooth them as required for hydrological analysis, for which the first step was the calculation of water catchments. The biggest ones were of 719.08 m^2, and the mean area was 164.42 m^2. The number of catchments calculated for the whole site of Samaipata rock is presented in Table 2. Most of the catchment areas were between 0 and 300 m^2.

The next step in the hydrological analysis was to determine the water flow direction. This resulted in the creation of a drainage line model (Fig. 6) with lines along which rainwater will most likely flow down.

Spatial analysis

The drainage line model was used to check the interaction between rainwater flowing down the slope of the hill and existing natural cracks of the rock. These places are of particular interest for conservation because of the negative impact of rainwater infiltrating the rock. All the main cracks were selected as well as the drainage lines, and a 25 cm buffer zone was automatically created around their intersections, thus pointing to the places with the highest risk of rainwater infiltration (Fig. 7). This analysis was further used to prepare risk maps for conservation that could cumulatively calculate degradation factors. This kind of data is of big importance for any conservation

Table 1. Final GIS layers developed for the project
(elaborated by I. Wilczyńska)

Numbers	Final GIS layers	Short description
1	Borders of examination	Range of examination area
2	Sectors	New borders of sectors were determined during office work
3	Sector name	Each sector was given a name
4	RGB orthoimages	RGB orthoimages from the photogrammetric project of Samaipata rock
5	Multispectral orthoimages	Multispectral orthoimages from the photogrammetric project of Samaipata rock
6	TLS DTM hill-shade	A hill-shaded DTM developed from a filtered 3D point cloud created using TLS
7	Niches and terraces	Niches and terraces carved on the rock
8	Offering holes	Offering pits
9	Water channels	Traces of water channels
10	Inca walls	Inca architecture built on Samaipata rock
11	Inca tracing lines	Lines traced on the rock by Inca builders
12	*Quincha* walls	Walls constructed using the *quincha* technique
13	Colonial walls	Buildings from the colonial period
14	Stairs	Stairs carved in the rock
15	Wall negatives	Traces of no longer existing walls
16	Post holes	Holes in the rock for the construction of *quincha* walls
17	Contemporary constructions	Contemporary platforms for visitors
18	Landscape rock	The rock formation
19	Petroglyphs	Location of petroglyphs
20	Petroglyph description	Text describing a petroglyph based on analysis from the iconographic survey in 2016
21	RAW image of petroglyphs	Images taken during the iconographic survey in 2016
22	RTI/PTM models of selected petroglyphs	Models from the RTI/PTM of selected petroglyphs
23	Main natural cracks	Main lines of natural cracks
24	Hydrology major lines	The main watercourses
25	Hydrology minor lines	The minor watercourses
26	Depressions without drains	Permanent deposits of rainwater
27	Mineralogical samples	Places from where the mineralogical samples were collected
28	Risk map – green vegetation	The areas of green vegetation
29	Risk map – lichens	The areas attacked by lichens, fungi, and algae
30	Risk map – loose lithic material	Deposits of loose lithic material
31	Risk map of thermal shock	The areas exposed to the risk of thermal shock during daily temperature changes
32	Risk map of wind erosion	The areas exposed to abrasive wind
33	Restoration risk zones	The areas of particular restoration risks

strategy. For example, juxtaposing the petroglyphs and areas where many different degradation factors accumulate can show which petroglyphs are most at risk from degradation (Fig. 8). In the future, using our GIS can allow further analysis of this kind to be developed in line with any new requirements of site management.

Conclusions

In the last decades, the use of GIS platforms for cultural heritage management has become very important. These environments make it possible to develop an effective spatial database for archaeological sites and architec-

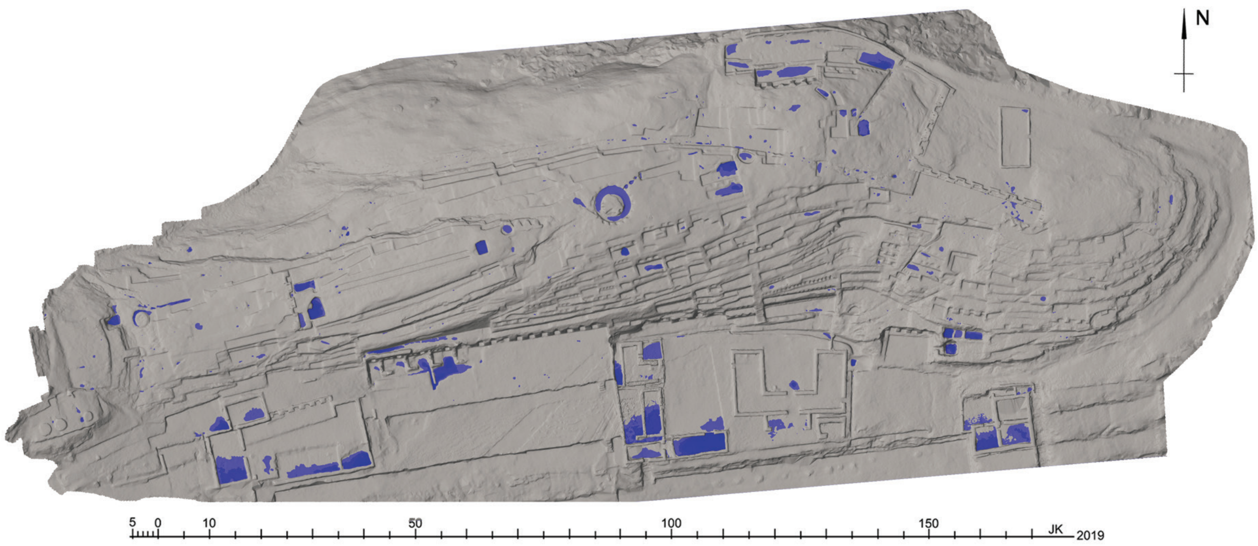

Fig. 5. Depressions without drains (elaborated by J. Kościuk)

Table 2. Statistic of catchments on Samaipata rock (elaborated by P. Dąbek)

Area [m^2]	Number of catchments
0–50	39
51–100	13
101–200	95
201–300	33
301–400	15
401–500	3
501–600	4
601–700	1
701–800	1

tural objects. This creates a powerful toolset of analytical instruments both for a micro and macro scale. The case of El Fuerte de Samaipata shows how effective a GIS can be, both in fieldwork during the data collection process and later in office analysis.

Using GIS environments allows very quick and precise spatial analysis to be made, which is especially important for conservation and site management strategies at all archaeological sites.

From the point of view of conservation strategy, the study provided very important results. Risks related to atmospheric precipitation consist of three different factors:

– Rainwater accumulated on the rock surface for a long time causes hydrolysis and the subsequent washing-out of the binder of the sandstone rock;

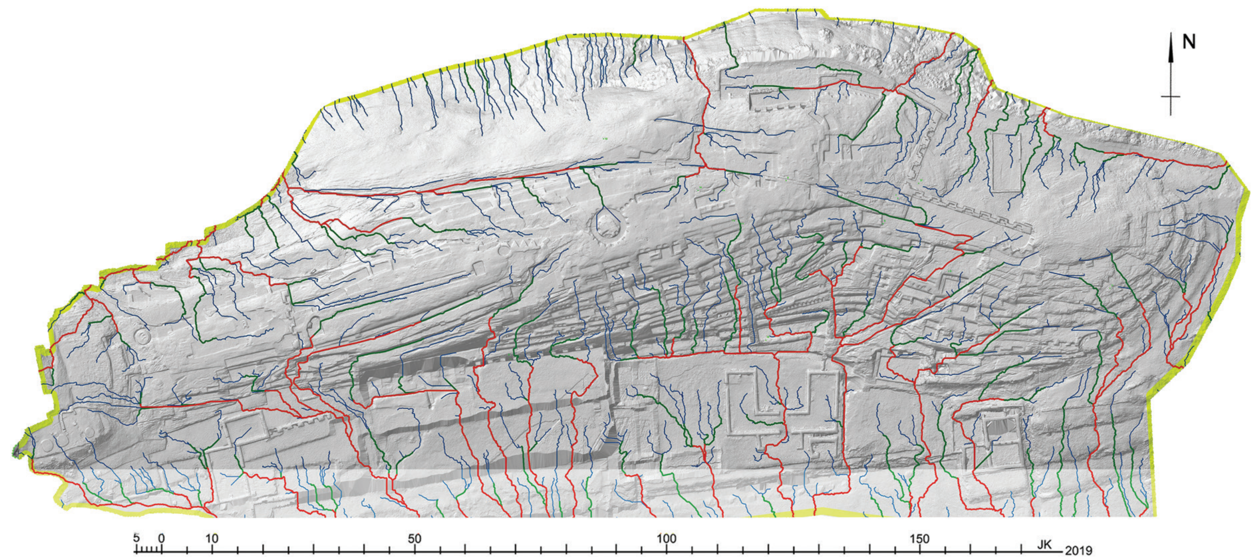

Fig. 6. Model of drainage lines (where colours of drainage lines mean the size of catchment area: red 100 m^2, green 40 m^2, blue 10 m^2) (elaborated by P.B. Dąbek)

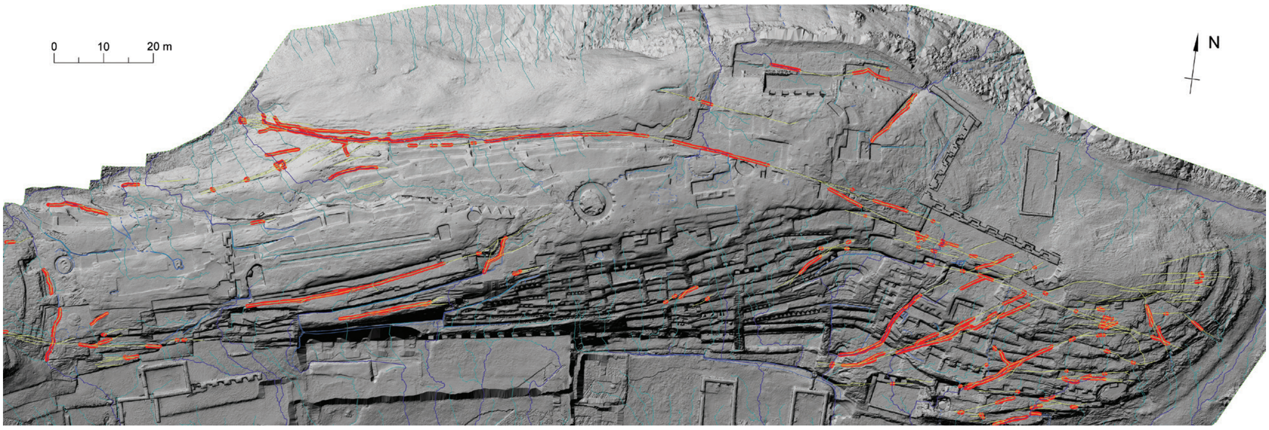

Fig. 7. Map of rainwater infiltration risk. Buffers around intersections between the main cracks (red) in the rock and rainwater runoff lines (blue) (elaborated by B. Ćmielewski)

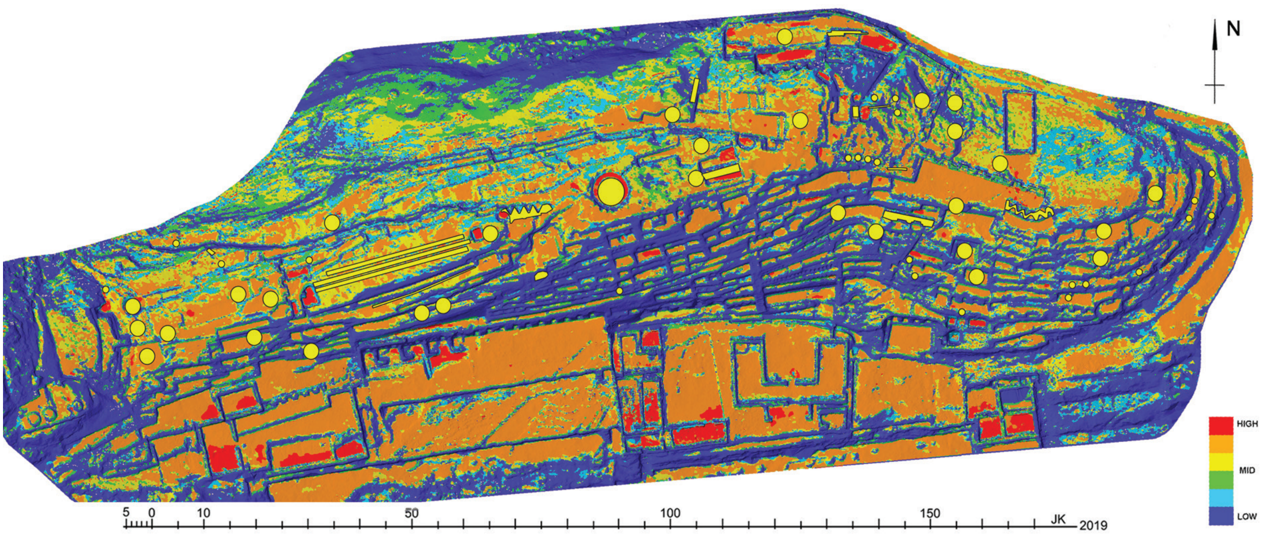

Fig. 8. Juxtaposition of petroglyphs (yellow) and zones of cumulative degradation factors (blue – low, green – medium, red – high) (elaborated by B. Ćmielewski)

– Water leaking into the rock through natural cracks also washes out the binder, and in addition, its local effusions in the lower parts of the slopes are where rock-destroying lichens, mosses, and algae develop;

– Water freezing in the rock crevices, which causes the rock to break.

In the light of the described climatic and topographic factors, as well as the results of petrographic and mineralogical studies of local sandstone [13], it is necessary to consider the problem of water retained in local depressions. The other recommendation to consider is to seal the most important natural cracks in the rock (Fig. 7).

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Abstract

The geographic information system (GIS) has become a very popular and useful tool to aggregate and process spatial data. In this paper, the implementation of data obtained during survey seasons at the El Fuerte de Samaipata (Bolivia) archaeological site and results of data analysis on the GIS platform are presented. In addition to the thematic layers, a description of the sectors and archaeological relics was added to the whole system. The implemented layers are related to orthoimages created from terrestrial laser scanning (TLS) and from close range photogrammetry (in visual, spectral, and infrared light), raw photos of petroglyphs, a highly detailed vector plan of the site, conservation risk maps, new spatial divisions, description layers, and a digital terrain model (DTM) based on the results of TLS. Such a system, with an implemented DTM, allows rainwater runoff and its impact on the archaeological site to be analysed. Thus, the paper presents a study on some hydrological conditions of the Samaipata rock. It is part of the larger research project "Architectural examination and complex documentation of Samaipata (El Fuerte de Samaipata/Bolivia) site from the World Heritage List". The results of this study are considered mainly from the point of view of conservation recommendations and strategies. Same aspects, however, may influence future studies on the chronology and cultural affiliation of the Samaipata rock carvings.

Key words: GIS, spatial analysis, data integration, conservation, hydrology

Streszczenie

System informacji geograficznej (GIS) stał się bardzo popularnym i użytecznym narzędziem do agregowania i przetwarzania danych przestrzennych. W niniejszym artykule przedstawiono implementację danych uzyskanych podczas sezonów badań na stanowisku archeologicznym El Fuerte de Samaipata (Boliwia) oraz wyniki analizy danych na platformie GIS. Oprócz warstw tematycznych do całego systemu dodano opis sektorów i zabytków archeologicznych. Zaimplementowane warstwy są powiązane z ortoobrazami utworzonymi z naziemnego skanowania laserowego (TLS), fotogrametrii bliskiego zasięgu (w świetle wizualnym, spektralnym i podczerwonym), surowych zdjęć petroglifów, bardzo szczegółowego planu wektorowego, map ryzyka, nowego podziału przestrzennego stanowiska, warstw opisowych oraz cyfrowego model terenu (DTM) opartego na wynikach TLS. Taki system przetwarzania danych z wdrożonym DTM pozwala na analizę spływu wody deszczowej i jej oddziaływania na stanowisko archeologiczne. W związku z tym w artykule przedstawiono badania niektórych warunków hydrologicznych skały Samaipata. Badania są częścią większego projektu „Badania architektoniczne i kompleksowa dokumentacja stanowiska Samaipata (Fuerte de Samaipata/Boliwia) z Listy Światowego Dziedzictwa”. Wyniki tych prac rozpatrywane są głównie z punktu widzenia zaleceń i strategii ochrony skały. Te same aspekty mogą jednak wpłynąć na przyszłe badania dotyczące chronologii i przynależności kulturowej rzeźb skalnych Samaipata.

Słowa kluczowe: GIS, analizy przestrzenne, integracja danych, konserwacja zabytków, hydrologia

Measuring GPS cooridates
(photo by M. Gąsior)

Pomiar współrzędnych GPS
(fot. M. Gąsior)