Lidar and Satellite Data for Climate Monitoring and Archaeology Management in The Yaxha' Lagoon Landscape in Guatemala

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Abstract

The Yaxhà lagoon is located in Guatemala, within the Maya Biosphere Reserve, in the 'El Triangulo Cultural' National Park, a protected area bordering Belize and several indigenous concessions. The park contains three monumental archaeological citadels, Yaxhà, Nakum, and Naranjo, including a wetland's landscape protected by the Ramsar treaty. Additionally, there is a large artificial wetland, Poza Maya, and a series of small settlements covered by earth and tropical vegetation. The park requires ongoing management of archaeology, testimonies of Maya civilization. The Author proposes preserving biodiversity and controlling vegetation together with the conservation of archaeology to achieve the sustainability of this goal. Climate change exacerbates environmental and anthropogenic threats, particularly water stress, which will increase in the next decade according to IPCC and RCP Scenarios, making the preservation and fruition of sites increasingly difficult. A potential approach to monitor climate by examining parameters and indicators relevant to heritage (rain erosion) and biodiversity preservation (vegetation and water stress) is proposed. The tropical canopy was surveyed by VTOL UAV with LiDAR by the University of Jaén, with the University of San Carlos, and a German company for VTOL and pilot expertise. LiDAR produced an accurate topography of archaeological landscape and vegetation in a competitive time. It penetrates through foliage, making it possible to monitor vegetation and rain erosion impacts on cultural heritage. Together with satellite data analysis, this method provides a change detection of the landscape, georeferencing all the expected changes due to climate variability. That greatly benefits park managers, conservators and researchers.

1. Introduction

This paper is the result of a broader study conducted for the spatial archeology Ph.D, at the University of Jaén, Spain, and stems from an archaeological survey campaign carried out in 2022 in the northern region of Guatemala. The Petén, particularly the area known as the Cultural Triangle, includes the Archaeological Park of Yaxhá, Nakum, and Naranjo, which are monumental ancient Maya city-states. LiDAR technology is especially relevant in these regions where the forest is so dense that it almost completely covers the ancient Mayan architecture. For millennia, the Maya settled in the heart of these rainforests, adapting and domesticating the landscape in ways exemplary for our civilization. LiDAR technology has shown its effectiveness in tropical contexts, known for being covered by very dense vegetation. In Mesoamerica, LiDAR has mainly been employed by archaeologists and anthropologists using UAVs and airplanes (hence the term airborne laser scanner, or ALS). Significant results have been obtained regarding the governmental organization of city-states and their relationship with minor settlements, leading to important demographic conclusions. However, in a context where archaeology has been brought to light, the urgent issue arises of how to conserve and manage this heritage, which is exposed to weathering and anthropogenic threats compromising preservation. Looking at the literature, we see that very little has been published on cultural heritage management, while many works address the application of LiDAR technology to archaeology. Our work therefore fits into a very precise context: how to preserve heritage threatened by climate change, especially water stress and erosion caused by rainfall, and how to use LiDAR technology to develop and present to site stakeholders an effective monitoring methodology that can inform park management.

2. Background: the survey by VTOL UAV

In April 2022, the Universities of Jaén (Spain) and San Carlos de Guatemala carried out an aerial survey in the tropical forests of El Peten, within Yaxhà-Nakum-Naranjo National Park, also called "El Triangulo Cultural." The mission used a Vertical take-off and landing (VTOL) UAV equipped with both a LiDAR sensor and an RGB oblique camera, in collaboration with the German company Quantum Systems
(Collaro and Herkommer, 2025). The process included detailed documentation of the expedition's phases, showcasing results from both high-resolution data acquisition and subsequent processing and interpretation. The advanced methods allowed for direct georeferencing of LiDAR and RGB datasets of the three Maya main citadels and their transects, streamlining data analysis; this is feasible with PPK technology, which provides this crucial capability. The expedition's primary objective was to identify previously undocumented archaeological settlements in this 38,000-hectare, predominantly inaccessible park, and to cross-validate the discoveries with those made by earlier

archaeologists with traditional tools. Although no new archaeological sites were discovered, the high-resolution data of two to three centimeters allows us to develop accurate management plans for the park administrators, who enabled us to carry out the VTOL overflight (fig.1). The present study concerns the Acropolis of Yaxhà prospicient the lagoon.

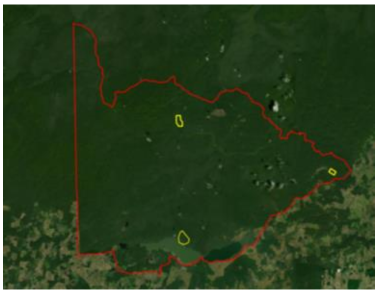

Figure 1. the VTOL survey area of the three monumental acropolises.

3. Datasets elaboration and integration

We analyzed data related to global warming, clearly observable even when downscaling to the specific Yaxhá Park area (tab.1). The graph shows over the past 45 years that the area analyzed has seen a steady increase in average temperature, rising from about 25.2°C to over 27°C. This trend, evident in both annual graphs and climate stripes, demonstrates how global climate change has concrete impacts at the local level on ecosystems and communities.

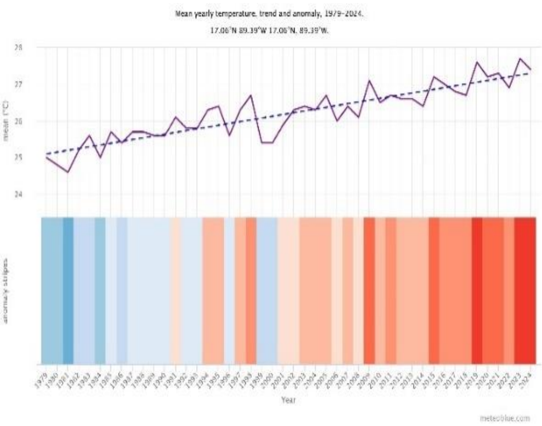

Table 1. Global Warming in Yaxhà archaeological area (source Meteoblue): the temperature trend from 1979- 2024 for the location 17.06°N, 89.39°W.

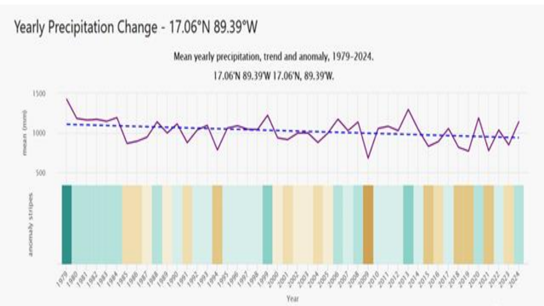

Table 2. Chart concerning precipitation for the same location (17.06°N 89.39°W) and the same period (1979–2024).

In comparison with temperature trends, the precipitation picture appears more complex (tab.2): there is marked annual variability, with an alternation of very rainy and extremely dry years, typical of tropical regions. The trend line indicates a slight but progressive decrease in average annual rainfall, estimated at about 200 mm over the span of 45 years (from 1979 to 2024). Furthermore, the frequency of intense drought episodes seems to increase in the second half of the analyzed period, suggesting a possible intensification of climate extremes. The combined analysis of temperature and rainfall data for the location 17.06°N 89.39°W over the period 1979–2024 highlights a gradual increase in temperatures accompanied by a slight but steady decrease in average annual precipitation. This trend results in increased evapotranspiration, which accentuates soil aridity and raises the frequency and intensity of drought events. The combination of higher heat and lower water input therefore represents a growing risk factor for water resource availability. These climate risks and their impact on the park area are acknowledged in the local park management plans, but an effective adaptation and mitigation strategy has not yet been achieved. The lagoon waters are monitored, with the nearest hydrological station located in Tikal. There is an ongoing commitment from local managers to prevent further incidents of archaeological heritage looting and illegal logging of natural resources, as well as close attention to frequent wild fires. While the most pertinent studies acknowledge the significant impacts of climate, vegetation dynamics, and soil erosion on the conservation of archaeological stone structures, it is noteworthy that such research has yet to be systematically translated into practical management strategies. A scientific approach to park management should particularly consider erosion (Wischmeier and Smith, 1978), which is exacerbated by the loss of vegetation cover and the intensification of extreme weather events; erosion threatens the structural stability of many monuments. Torrential rains seeping into the structures cause the detachment of painted plasters and the collapse of architectural elements, while soil erosion can compromise the foundations of buildings (Matarredona Desantes, 2017). We therefore developed climate analyses for two areas: the Yaxhà lagoon, with a buffer of 5 km per side (mesoscale) totaling 25 km², and the acropolis area of about 140 ha (microscale)
(tab.3) , using monthly CHIRPS precipitation data (Du, Tan and Zhang, 2024), which provide cumulative rainfall in mm, and monthly ERA5 Land for temperature data.

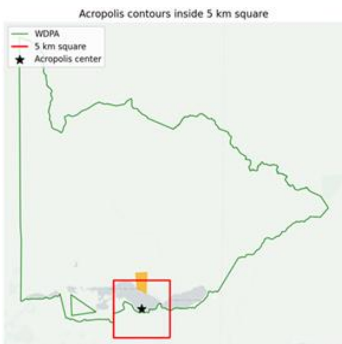

Table 3. The Yaxhà acropolis contour and the lake buffer area

However, in this paper, we examine only rainfall data, to which we added soil moisture and NDVI values obtained from Sentinel2 L2A The specific aim of this study was to compare the topographic LiDAR metrics provided by the DEM with rainfall and soil moisture data, to identify areas most at risk of erosion—both already excavated zones and those with archaeological potential—thus enabling park managers to base ongoing monitoring on scientific analysis. From the CHIRPS climate datasets for both mesoscale and microscale, we compared forty-year climatology with the 2024–2025 season, which is updated through May 2025; this allowed us to calculate climate anomalies for these 2024-2025 years and any differences between the two analysis scales (meso and micro-scale). We have utilized monthly datasets; however, the analysis of precipitation at the pentad scale proves particularly suitable for fields such as detailed hydrological studies (and, for example, evaluating flash floods and erosion), linking rainfall to environmental indicators (like NDVI or lagoon levels), and building “onset/cessation” indicators for the rainy season, as pentads represent the FAO standard. However, the procedure can become time-consuming when applied to large data series. To optimize the process, it is advisable to automate file reading and analysis using scripts such as Python and R, that enable rapid extraction and aggregation of information. As for the choice of climate data, we considered the 1981–2020 period for the microscale; the CHIRPS series begins in 1981, so climatologies cannot extend further back. Standard reference periods are 30–40 years (such as 1981–2020), which are already available and suitable for statistics. Climatology must be independent from the data being evaluated; including recent years like 2024, currently under examination, would introduce bias into anomaly calculations, as would including the current months of 2025. By combining the 1981–2020 climatology calculated on the same area of interest (AOI), we obtain anomalies: all drastically negative (–97 to –99%), thus the start of 2024 was exceptionally dry compared to the historical norm for the Yaxhà Acropolis.

3.1 Precipitation at micro and meso scale

For a better explication, the precipitation anomalies at the microscale of the Yaxhà Acropolis, were aggregated by season and by year (tab.4), and produced the following results: the four seasons of 2024 (DJF, MAM, JJA, SON) all show very pronounced negative anomalies (–79 mm to –186 mm), with percentage deficits ranging from –96% to –99%. For 2025, only DJF is currently available, and it remains in deficit, though slightly less extreme (–66 mm, –94%). The analysis of the average annual anomaly gives for 2024: –129 mm of rain on average compared to the 1981–2020 climatological mean (–97%); for 2025 (partial data): –64 mm (–96%), indicating that the drought persists. We can conclude that 2024 stands out as one of the most deficit years of the entire local climatological series, in line with the strong El Niño in the Pacific Ocean. The year 2025 begins dry but coming months need to confirm the trend. The persistent deficit (< –90%) justifies the hydro-geotechnical issues (soil fissuring, reduced surface cohesion).

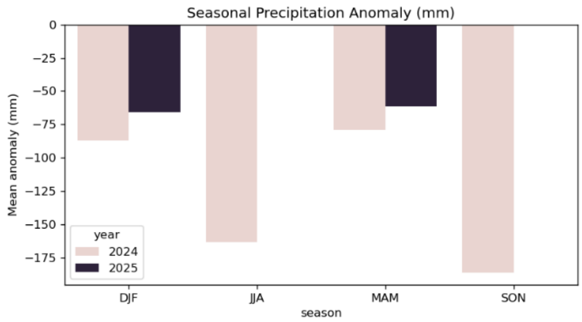

Table 4. Seasonal anomalies in Yaxhà Acropolis.

The seasonal distribution of precipitation, characterized by minimums between December and April and maximums between September and October, is also confirmed in the 25 km² area, with a marked and prolonged rainfall deficit at the beginning of 2024 (tab.5), like what was observed for the Acropolis alone. In our findings, the analyses could be further developed by comparing them with climate indices such as ENSO and other large-scale indices that may be related to rainfall anomalies in Central America, and which can be correlated with the climate series available for our case study. We then have proposed as methodological analysis, namely the comparison between the forty-year climatology and datasets from the last two years to identify anomalies, just as we did for the 141,50-hectare area of the Yaxhà Acropolis, to the 25 km² mesoscale area centered along the lakeshore, as already indicated in the tab.3.

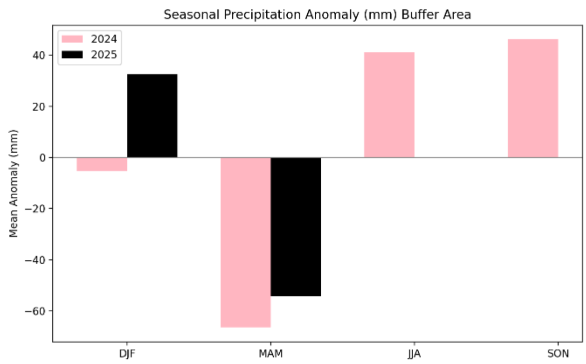

Table 5. Seasonal anomalies in the lake buffer area.

Following the analysis, we compared the two series of climatology/anomaly analyses for 2024–2025, referring to both the microscale and the 25 km² mesoscale; thus, both series are evaluated according to their respective climatologies. Below, the graphs displaying the calculations carried out (tab.6).

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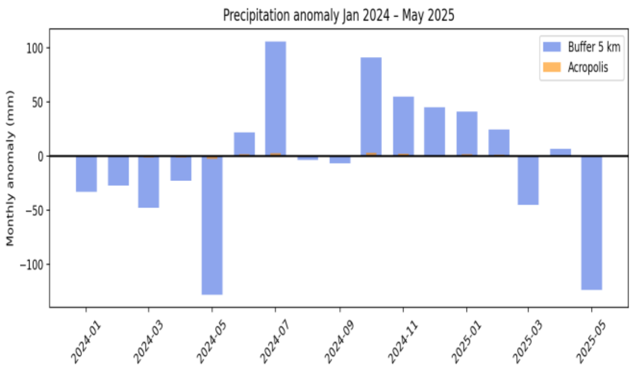


Table 6. Buffer area and Acropolis anomalies versus climatology.

The graph shows the monthly anomaly (mm) from January 2024 to May 2025: Blue bars = 5 km buffer, Orange bars = Acropolis. January–May 2024 is well below average in both areas; the relative anomaly is more severe on the Acropolis, but the absolute deficit (missing mm) is obviously greater in the larger buffer area. (tab 6)

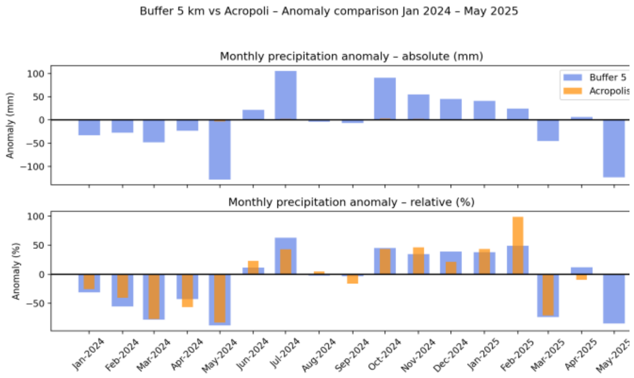


Table 7. Absolute and relative anomaly/climatology data.

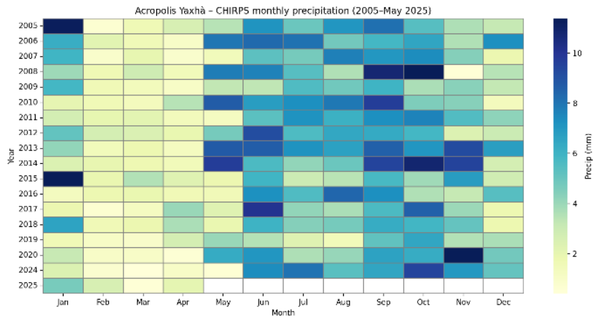
The analysis of rainfall anomalies between the Acropolis and the mesoscale buffer reveals that, although the absolute deficits in millimeters are more pronounced on the buffer (tab.7), the percentage severity of the recent drought is almost identical at both scales, with peaks reaching the –80% in the most critical months. During rainy periods, the Acropolis systematically receives less precipitation than the buffer, confirming the presence of a stable and recurring spatial gradient over time. The analysis carried out highlights that, although the drought recorded in the first five months of 2024 was significant, over the entire period from January 2024 to May 2025, the average precipitation within the buffer returns close to the climatological norm, thanks to the rains that occurred at the end of 2024. The Acropolis area, on the other hand, stands slightly above the reference climate average. This behavior confirms the slight divergence already identified in the ratio

$$Precipitation\text{-}acropoli / Precipitation\text{-}buffer$$

suggesting that the micro area can be subject to local variations (for example, convective showers) that do not necessarily reflect mesoscale conditions. The issue is of relevance for local managers and workers.

3.2 Heat map for data climate readings

By using colored "heat-map" matrices, it is easy to compare the precipitation data for the two areas (tab.8), and for a more immediate analysis, we start from 2005 for both.



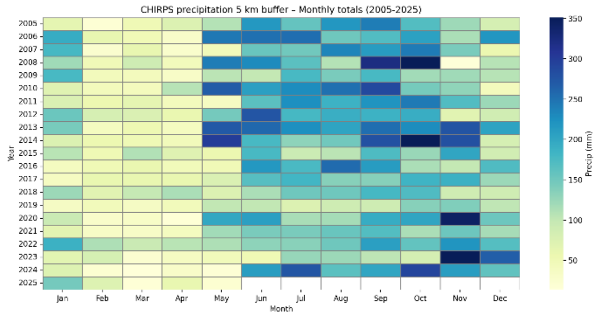


Table 8. Heat maps of precipitation data for the two areas.

4. Digital Terrain Model for topographic metrics by LiDAR

The next steps to connect altitude and rainfall distribution involve extracting elevation profiles along topographic sections of the Acropolis, as provided by the LiDAR survey. Concerning the accuracy, the goal of assessing Lidar's accuracy in registering archaeological features is "to know if Lidar data are reliable enough to be used as a substitute for extensive pedestrian and topographic survey and mapping" (Reese-Taylor et al.,2016) In particular, this study aims to present and validate a multiscale monitoring methodology to address these challenges by integrating high-resolution LiDAR data acquired with the VTOL , together with multi-temporal satellite data analysis. From the LiDAR data, a digital terrain model (DTM) of the archaeological landscape is generated (tab.9).

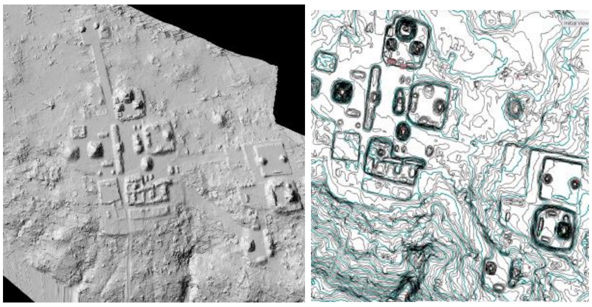


Table 9. DTM from ground .las classification and Autocad 3D Civil plot

4.1. Derivating Methods

The DTM enables the identification of specific landscape structures and features that are highly vulnerable to rain-induced erosion, by extracting appropriate topographic metrics and replacing traditional on-the-ground surveys, which are very complicated in such impenetrable environments. Concurrently, satellite images from Sentinel2-L2A and Landsat, when analyzed, reveal quantifiable changes in vegetation health and the available water quantity, allowing for the georeferencing of climate-driven impacts. The fusion of these datasets has produced a comprehensive risk map, benefiting park managers as well as conservationists and restorers by highlighting the priority areas for intervention. This data-driven approach supports the development of targeted conservation strategies that contribute to the sustainable preservation of the invaluable cultural and natural heritage of the Yaxhà site, in the context of climate change (tab.10) (fig.2).

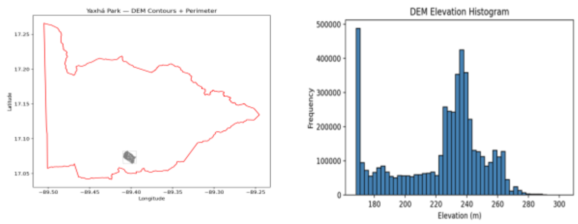


Table 10. Survey area over Yaxhà. Placement of the DEM within the El Triangulo cultural area- DEM Histogram.

Statistic	Value
Minimum altitude	≈ 168 m
Maximum altitude	≈ 302 m
Average	≈ 223 m ± 29 m (σ)
Variance	≈ 837

Figure 2. Statistic and values of Yaxhà area.

The Elevation Histogram from the DTM shows how elevations are distributed within a given geographic area—in this case, the Yaxhà overflight area. The X-axis represents Elevation in meters (m), while the Y-axis (vertical) indicates frequency, meaning how many points (pixels) of the model are located at a certain altitude. The most striking feature of this histogram is that it displays two main peaks, indicating a bimodal distribution. This reveals that the analyzed landscape has two predominant altitude ranges.

Peak	Altitude	frequency	Meaning
First Peak	~170 m	almost 500,000	A very large portion of the area is at this altitude, typical of a surface facing a lake
Second Peak	~220-250 m	over 400,000	Represents a hilly area or with more varied altitudes compared to the flat area
Valley between Peaks	~180-215 m	lower	Few areas at these intermediate altitudes, they are the slopes connecting the lake area to the hilly area

Figure 2. Yaxhà landscape morphology.

The landscape of the Yaxhà acropolis displays a clear morphological separation between its lower and higher areas. We completed the digital terrain analysis of Yaxhá by calculating the slopes and aspects of the DTM.

4.2 The Usefulness of the Elevation Histogram

The elevation histogram of a DTM is a fundamental diagnostic and descriptive tool—a kind of morphological “identity card” for the landscape (tab.11). It identifies Landscape Forms (Morphology): the histogram immediately reveals the nature of the terrain. If it is unimodal and narrow, it indicates a very uniform landscape, such as a vast plain or a plateau; unimodal and broad suggests a hilly or mountainous landscape with a more gradual distribution of elevations; bimodal or multimodal (as in Yaxhà) points to a complex landscape with two or more dominant morphologies. In Yaxhà, there is a distinctly separated flat, lacustrine area and a hilly/mountainous zone. If the distribution is flat (uniform), the landscape has a constant slope, where each elevation is represented almost equally. Moreover, the histogram is useful for data quality check: before any complex analysis, the histogram is the first tool to use to verify the DTM’s quality and the presence of any errors. Additionally, the histogram is crucial for understanding the hydrological potential of an area. A large frequency at low elevations, as in this case, indicates the presence of wide basins or floodplains—areas potentially prone to flooding. Many plant and animal species live within specific altitude bands (ecological niches). The histogram shows “how much habitat” is available at a given elevation, allowing us to estimate the potential distribution of species.

The main limitation of the histogram is that it completely loses spatial information: it tells us how much area is at a certain elevation, but not where. For this reason, it should almost always be paired with other graphs and maps, the most important of which are:

1) The Map of the DTM itself: displaying the histogram alongside the DTM map with a matching color scale immediately allows you to connect the histogram peaks to geographic areas on the map.

2) the Slope Map: derived from the DTM, it shows the steepness of the terrain. Comparing the elevation histogram with the slope histogram is extremely powerful. You might discover that the area at 170 m (first peak) has almost zero slopes (0°), confirming that it is a plain or a lake, while the area between 220-250 m has variable slopes, typical of a hilly region.

3) Aspect Map: This map shows the direction that slopes are facing (North, South, East, West) and can add valuable

information, for example for studies on sunlight exposure or the distribution of vegetation.

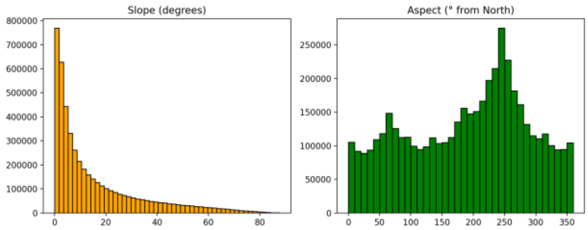


Table 11. Histograms of slope (°) and aspect (° from north).

4.3.Satellite Data

Using Sentinel2-L2A data, validated through comparison with Landsat data, we derived NDVI, SAVI, and EVI index values from the analysis of the respective bands. The dataset, covering the area of the Yaxhà acropolis (140 sq km) from 2020 to 2025, revealed that, because the entire Triangulo area is very vast and satellite images are not always available daily, there can be biases. Therefore, it is preferable to subdivide the area into smaller zones unless using satellite images with a broader spatial resolution. NDVI data correlated with the CHIRPS series did not provide significant indications, whereas a more meaningful correlation was found with soil moisture data. This suggests that, since the Pearson correlation coefficient is nearly zero, NDVI responds more to local vegetation factors (tree cover, phenology) rather than very short-term moisture. It is planned to deepen the study by considering a lag time between rainfall and vegetation vigor of more than a month, to test for any delayed response. Furthermore, the analysis can be repeated by applying pentadal CHIRPS precipitation data.

Our analysis continued by examining soil moisture data from the USDA SMAP series, which provides NetCDF data for the subsurface soil layer (0–5 cm). From this dataset, I correlated the data for NDVI and precipitation; the area remains the Yaxhà acropolis, and the period is 2020–2025, as the NDVI data refer to this timeframe. From the resulting graph and examined correlation matrix, we can affirm that a clearer correlation is found between rainfall and soil moisture data. Here too, a deeper analysis using lag time is recommended. Soil moisture was also analyzed using the Soil Moisture Profile series, which provides data for different soil depths up to 30–60 cm, confirming the seasonal trend with a decrease in April-May and a rapid increase with the June rains. The central question is: To what extent are rainfall and soil moisture data useful for assessing soil erosion in the Yaxhà area? In summary, precipitation and soil moisture provide two fundamental pillars for modeling erosion: one quantifies the kinetic power of water, the other the initial hydrological response of the soil. By combining them with topography, texture, and vegetation cover, a robust framework emerges to assess where and when Yaxhà's heritage is most exposed to erosive processes.

5. Archaeology and Vegetation Data Integration for monitoring

We have verified that the cultural triangle park hosts several thousand plant species, creating a rare and diverse flora. We extracted from online portals the species found specifically within the park, for which collectors reported geographic coordinates; these data were then related to cartographic information provided by the Guatemalan Geographic Institute, the Ramsar site—which recognizes this park as a wetland of international importance—and topographic surveys carried out by the author in 2022 using VTOL LiDAR. Once these digital datasets, sourced from the GBIF and Tropicos databases, were collected, we homogenized the georeferenced species with the same coordinate units (latitude and longitude in this case, though UTM could also be used) to encourage managers and local communities, through the use of open-source platforms such as iNaturalist, to also georeference their own observations. Archaeological use and conservation thus become drivers for the preservation of intangible heritage. According to the UNESCO definition intangible cultural heritage includes knowledge, traditional practices, and cultural spaces that are continually recreated by communities (Bakar, Aisyah and others, 2011). Intangible Cultural Heritage: Understanding and Manifestation. The analysis of plant species present in the Park reveals that many of them, already used by the ancient Maya for food and medicinal purposes, still hold great cultural significance for local stakeholders: the ancient Maya not only practiced milpa agriculture (Ford and Nigh, 2013), ensuring the forest they inhabited was not unsustainably deforested, but also made use of edible plants to prepare their daily meals. These data suggest a sustainable management model for the Maya forest, based both on the conservation of the archaeological heritage and on the enhancement of ethnobotanical heritage, elements that are now fundamental for integrated strategies of protection and promotion of the territory. An example comes from Guadua longifolia, for which FLAAR Guatemala (Hellmuth et al. 2022) have reported numerous observations and explored its ecological-cultural significance, face to environmental and anthropogenic threats. Guadua longifolia is a bamboo species native to Guatemala and neighboring regions, with a significant impact on the subsistence systems of the Classic period Maya. It primarily grows in areas subject to seasonal flooding, especially along rivers such as the Holmul and near ancient Maya cities like Naranjo and, likely, Tikal. The widespread presence of G. longifolia suggests that the Maya adopted sustainable agricultural strategies alternative to traditional milpa farming, using this bamboo both as a food source and as a building material, thus contributing to a more durable management of natural resources. In tab.12 , we observe: a cluster to the northeast (lat ≈ 17.055, lon ≈ -89.387) with 19 records; a second cluster to the west (lat ≈ 17.051, lon ≈ -89.439) containing the majority of species (44 records); and a single isolated marker to the southwest (Fissidens elegans, 17.01666 / -89.46666). The data come from the GBIF database and were georeferenced within our perimeter using Python software.

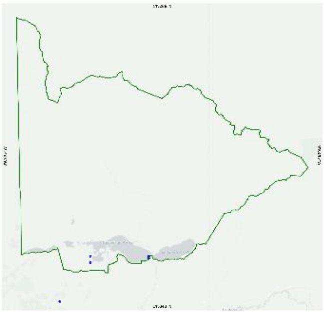


Table 12. Clusters of species of vegetation along Yaxhà lagoon.

Haematoxylum campechianum, commonly known as Palo de Tinte, is a tree species of notable cultural significance. This tree is particularly renowned for producing hematoxylin, a natural blue-violet dye widely used by pre-Columbian civilizations, especially the Maya, not only for dyeing textiles and artifacts but also in ritual practices. Specimens of Palo de Tinte have been observed along the bajos, typical floodplain areas formed following prolonged rainfall events, which are abundant throughout the park (thesis reference). However, to investigate the existence of a statistical correlation between the distribution of H. campechianum and the location of archaeological sites, we should consider a much larger area, extended to include the region of Tikal where it is also present. It is possible, in fact, that the presence of this plant species may be more common near formerly inhabited settlements. Given the lack of management based on scientific data for the Park, in order to protect our archaeological and natural heritage, it is necessary to regularly monitor the cultural landscape. At the moment, we have three monthly hydrological datasets for the Acropolis:

- CHIRPS rainfall (erosive energy)
- SMAP surface (0–5 cm) – rapid response to the event
- Deep SMP (0–100 cm) – state of the soil water reserve.

Together with NDVI and LiDAR DTM, we can evaluate whether areas with thin soil (such as building peaks or terrace edges) consistently show lower SMP values, indicating a higher risk of drought and cracking. Additionally, we have highlighted the importance of lagged correlations between rainfall, surface soil moisture, deep SMP, and NDVI to better understand eco-hydrological dynamics. Since this is an initial approach to a complex issue, we describe here how managers might also include the extraction of LiDAR metrics in this analysis to link LiDAR profiles to elevation/slope for each CHIRPS/SMAP pixel and investigate whether topography controls water retention and which areas are most at risk of erosion.

6.Conclusion for Park heritage management

At the end, we will have outlined a workflow to be followed and discussed for more proactive conservation of the park. High-resolution LiDAR data provides us with quality, accurate DTMs, from which vegetation can be filtered and ground DTMs obtained at intervals to be determined with monitoring and vulnerability analysis. Comparing DTMs taken at different times will allow us to assess the work carried out. From the DTM, we derive useful metrics such as S (slope), L (slope length), and their product LS factor, an indicator of how susceptible a terrain is to erosion, and TWI, the Topographic Wetness Index. TWI is an index that helps us understand how likely an area is to be wet or subject to waterlogging. It is based on both slope and flow accumulation: flatter areas and those where more water accumulates will have a higher TWI, indicating greater moisture. Applying this workflow, with Python, R codes and GIS, we proceeded with our case study, generating Slope/LS/TWI based on our DTM of Yaxhà. The detail of the causeway that connects the most impervious part of the acropolis is highlighted separately and plotted with the following raster (tab.13).

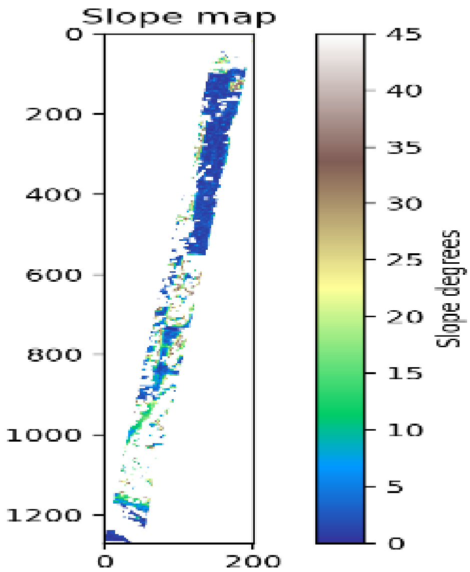


Table 13. The map highlights the corridor connecting the lake with the North Acropolis and the Mahler Pyramid Group. Slope values are shown in degrees, with inclines up to 45° indicating the steep escarpments of the platforms.

From the DTM of the entire archaeological area, 1,411 polygons were extracted by coding, and for each polygon, statistics on the LS factor were calculated, including key statistical variables such as the mean erosive potential (LS mean), the maximum value (LS max), and the 90th percentile (LS p90), in order to analyze the most critical areas, identifying structures most exposed for contours >95°. These values, once analyzed, can be compared with those of the TWI to determine whether areas with steep slopes also coincide with zones of saturation that increase the risk of soil landslides. Within the limits of this study, we analyzed the hillshade of the archaeological area, displaying the LS factor values and the resulting classification. The map shows, alongside the main corridor in grey, separately analyzed, the erosion risk classes identified for the different LS values, here mapped in UTM 16 coordinates. In red there are the highest risk zones, including the important South Acropolis area, which still preserves stucco graffiti and the typical vaulted roofs of the Maya.

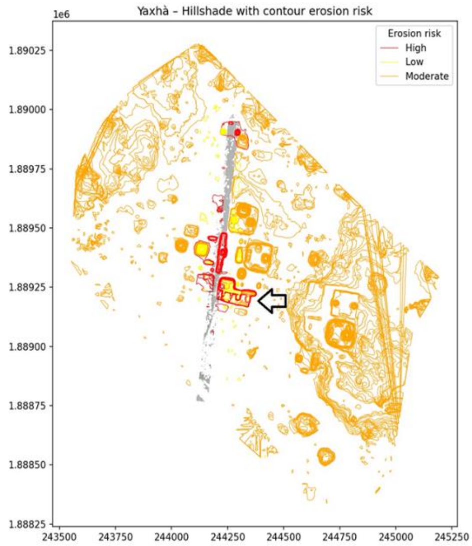


Table 14. Classification of erosion risk.

The areas colored red correspond to the steepest slopes or to depressions between platforms. These are the priority zones for drainage or stabilization interventions. In orange there are the moderate classes, which often surround the red ones, suggesting a risk gradient linked to micro-topography. The yellow contours show generally negligible LS values, where ordinary maintenance is sufficient. There are also very small geometries where the erosion risk is high and where extremely high LS values are present. These geometries will need to be carefully verified in the field. The role of innovative technologies such as LiDAR and satellite data in addressing the challenges posed by climate change to archaeological sites in Guatemala is significant. By integrating accurate derived DTMs and related metrics and indexes into management practices, stakeholders can strengthen their efforts to preserve the rich cultural heritage of the Maya civilization while ensuring the conservation of biodiversity in the Yaxhá Lagoon landscape.

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