



SPATIAL AND HYDROLOGICAL ANALYSIS OF THE WATER SUPPLY SYSTEM IN AS-SILA'/SELA (TAFILA, JORDAN) BASED ON A 3D MODEL

ANÁLISIS ESPACIAL E HIDROLÓGICO DEL SISTEMA DE ABASTECIMIENTO DE AGUA EN AS-SILA'/SELA (TAFILA, JORDANIA) BASADO EN UN MODELO 3D

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Highlights:

- A new methodology, previously unused in the region, is presented for conducting spatial and hydrological analysis of the hydraulic supply system based on a 3D model.
- By creating a photogrammetric model of the site based on aerial photographs, new surface structures, settlement density zones, and flood-prone zones have been located.
- The newly identified structures analysis suggests spaces for access, management, and use of available water resources in a water scarcity context.

Abstract:

The research described below proposes a spatial analysis of the hydraulic infrastructure, and settlement remains, as well as a topographic analysis of the site of as-Sila'/Sela on the southern Transjordan plateau. The authors designed Sela's first photogrammetric model from aerial photographs provided by the "Aerial Photographic Archive for Archaeology in the Middle East (APAAME)" project. This modelling has enabled the research team to locate new hydraulic structures, settlement remains, marks on vertical facing, and elevated or levelling platforms hitherto unidentified by a pedestrian survey; it was also possible to obtain more detailed direct and indirect relationships between these features. The 3D model has provided a reference for locating the various elements and correlating their surface with the topographic coordinates recorded by the total station during fieldwork. Additionally, a Digital Elevation Model (DEM) was derived from the 3D model to depict the flow direction of run-off. Through our analysis, we identified spaces for accessing, managing, and utilising available water resources, including settlement density and flooding zones. The hydrological analysis revealed potential run-off and flood-prone areas, guiding the location of hydraulic structures to prevent water contamination. This study highlights the importance of Sela's water supply systems and the technical expertise of ancient communities in their construction and management. The applicability and feasibility of the applied methodology emphasise its use as a powerful and indispensable tool to obtain a complete overview of the site. The results yield a comprehensive site mapping with a broader scope than previous research and provide a basis for further research, as well as for understanding the site's water supply and settlement patterns. Thus, this study enhances the hydro-technological investigation of Sela's water management and culture and contributes to its holistic analysis. Future studies can use the data to propose effective water management strategies and shed light on the social structures involved in water supply practices.

Keywords: archaeology; digital aerial photography; hydraulic infrastructures; hydrology; photogrammetry; 3D model

Resumen:

La investigación aquí descrita propone un análisis espacial de las infraestructuras hidráulicas y los restos de construcciones, así como un análisis topográfico del yacimiento de as-Sila'/Sela, en la meseta sur de Transjordania. Diseñamos el primer modelo fotogramétrico de Sela a partir de fotografías aéreas proporcionadas por el proyecto "Aerial Photographic Archive for Archaeology in the Middle East (APAAME)". Este modelo nos ha permitido localizar nuevas estructuras hidráulicas, restos de construcciones, marcas en paramentos verticales y plataformas elevadas o de nivelación hasta ahora no identificadas por una prospección pedestre sobre el terreno, y obtener relaciones directas e indirectas más detalladas entre estas infraestructuras. El modelo 3D ha proporcionado una referencia para localizar los distintos elementos y correlacionar su superficie con las coordenadas topográficas registradas por la estación total durante el trabajo de campo. Además, se ha generado un Modelo Digital de Elevación (MDE) a partir del modelo 3D para representar la dirección del flujo de escorrentía. A través de nuestro análisis, hemos identificado espacios para acceder, gestionar y aprovechar los recursos hídricos disponibles, incluyendo zonas de densidad urbanística y áreas propensas a

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inundaciones. El análisis hidrológico reveló áreas potenciales de escorrentía e inundaciones, guiando la ubicación de estructuras hidráulicas para prevenir la contaminación del agua. El estudio destaca la importancia de los sistemas de abastecimiento de agua de Sela y la pericia técnica de las antiguas comunidades en su construcción y gestión. La aplicabilidad y viabilidad de la metodología aplicada enfatizan su uso como herramienta potente e indispensable para obtener una visión completa del yacimiento. Los resultados ofrecen una cartografía completa del yacimiento, con un mayor alcance que las investigaciones anteriores, y sientan las bases para seguir estudiando y comprendiendo el abastecimiento de agua y los patrones de asentamiento del yacimiento. Así pues, este estudio profundiza en la investigación hidrotecnológica de la gestión y la cultura del agua de Sela y contribuye a su análisis holístico. Futuros estudios pueden utilizar estos datos para proponer estrategias efectivas de gestión del agua y arrojar luz sobre las estructuras sociales involucradas en las prácticas de abastecimiento de agua.

Palabras clave: arqueología; fotografía aérea digital; infraestructuras hidráulicas; hidrología; fotogrametría; modelo 3D

1. Introduction

An increasing number of scientific teams are using documentation techniques based on advanced digital tools (Forte & Campana, 2017), such as digital photogrammetry (Magnani, Douglas, Schroder, Reeves, & Braun, 2020), laser scanning (Lercari, 2017) or LiDAR (Light Detection and Ranging). Digital photogrammetry enables rapid documentation of vulnerable or inaccessible historical heritage. In addition, this method acquires 3D information in cases where 3D scanners are impractical due to accessibility constraints. Archaeologists are increasingly utilising this technique due to its outstanding outcomes, versatility, and relatively low costs, especially Structure from Motion (SfM). According to several authors, the aerial SfM-based mapping approach is currently the most effective method for comprehensive site mapping (Howland, Liss, Najjar, & Levy, 2015).

GIS technology has been instrumental for hydrological modelling in many scientific, engineering, and planning research applications. Digital elevation models (DEMs) are extensively employed for characterising land surfaces and analysing topographic attributes using hydrological models (Chowdhury, 2023).

In Jordan, digital documentation was used mainly for documentation purposes, rescue archaeology (Richter, Kuester, Levy, & Najjar, 2012), or heritage documentation (Al-kheder, Al-shawabkeh, & Haala, 2009). The hydrological modelling has focused on studying irrigation (Harrower, 2008, 2009, 2010), land use in arid regions (Bolten, Bubenzer, & Daris, 2006), floods and settlements dynamics (Gillings, 1995), archaeological restoration (Hamarneh et al., 2022), as well as waterscapes and social relations (Williams, 2003).

1.1. Structure from motion and georeferencing of archaeological aerial photographs

One of the most effective remote sensing techniques for locating and interpreting archaeological sites is aerial photographic survey from low-flying aircraft. Verhoeven, Doneus, Brise, & Vermeulen (2012) and Magnani et al. (2020) argue for an increased emphasis on detailed site interpretation. Georeferencing methods are crucial for automating the generation of orthophotos. SfM is a technique that enables the simultaneous computation of relative projection geometry and a 3D point cloud using overlapping photographs captured by a moving camera (Robertson & Cipolla, 2009). SfM calculates the location

of points of interest and presents them as a sparse 3D point cloud, representing the geometry/structure of the scene in a local coordinate frame. Thus, orthophotography provides sufficient accuracy for archaeological mapping interpretation.

1.2. GIS for hydrological analysis

Several software packages, including ArcGIS, ILWIS, and SAGA GIS, include hydrological analysis tools. These are essential resources for defining how the geographic scope of an area interacts with water. Hydrological analysis makes it possible to identify the source and pathway of groundwater, delineate watersheds and identify flood-prone areas (Aksoy, Kirka, Burgan, & Kellecioglu, 2016). By using GIS, it becomes possible to characterise how ancient communities managed water resources and conduct a broader analysis of traditional methods (McKinney & Cai, 2002).

1.3. The site of as-Sila'/Sela and the interest in water management

As-Sila'/Sela rises above a steep outcrop of Cambrian sandstone (Umm Ishrin Formation) overlain by Ordovician sandstones (Disi Sandstone Formation) (Lindner, 1989; Lindner, Hübner, & Gunsam, 2001; Raz, Raz, & Uchitel, 2001; Bandel & Salameh, 2013) on the southern highlands of Transjordan (Figs. S1-S3). This region, with an area of about 6900 km², lies on the eastern edge of the Wadi Arabah-Jordan Graben, which slopes gently toward the central plateau to the east and, more steeply, toward the Dead Sea Rift fault to the west. In the southern part of the plateau, the wadis flow northward into the Wadi al-Hasa and westward into the southern Ghors and the northeastern Wadi Arabah system (Burdon, 1959; MacDonald, 2015).

Sela is located at an important crossroads in antiquity: about 4 km southwest of the King's Highway, around 50 km north of Petra (the ancient Iron II settlement of Umm al-Biyara), and approximately 3 km northwest of Bozrah, the modern city of Busayra and the ancient capital of the ancient kingdom of Edom (Fig. 1). From ancient times, the King's Highway was an important thoroughfare for north-south trade (Lipiński, 2013). Its location to this main north-south route in the Transjordan area and other routes connecting east-west, such as the route to the copper-mining area of Feinan (Levy, Najjar, & Ben-Yosef, 2014), became the focus of interest for several researchers (Lipiński, 2013; Bienkowski, 2014; MacDonald, 2015).

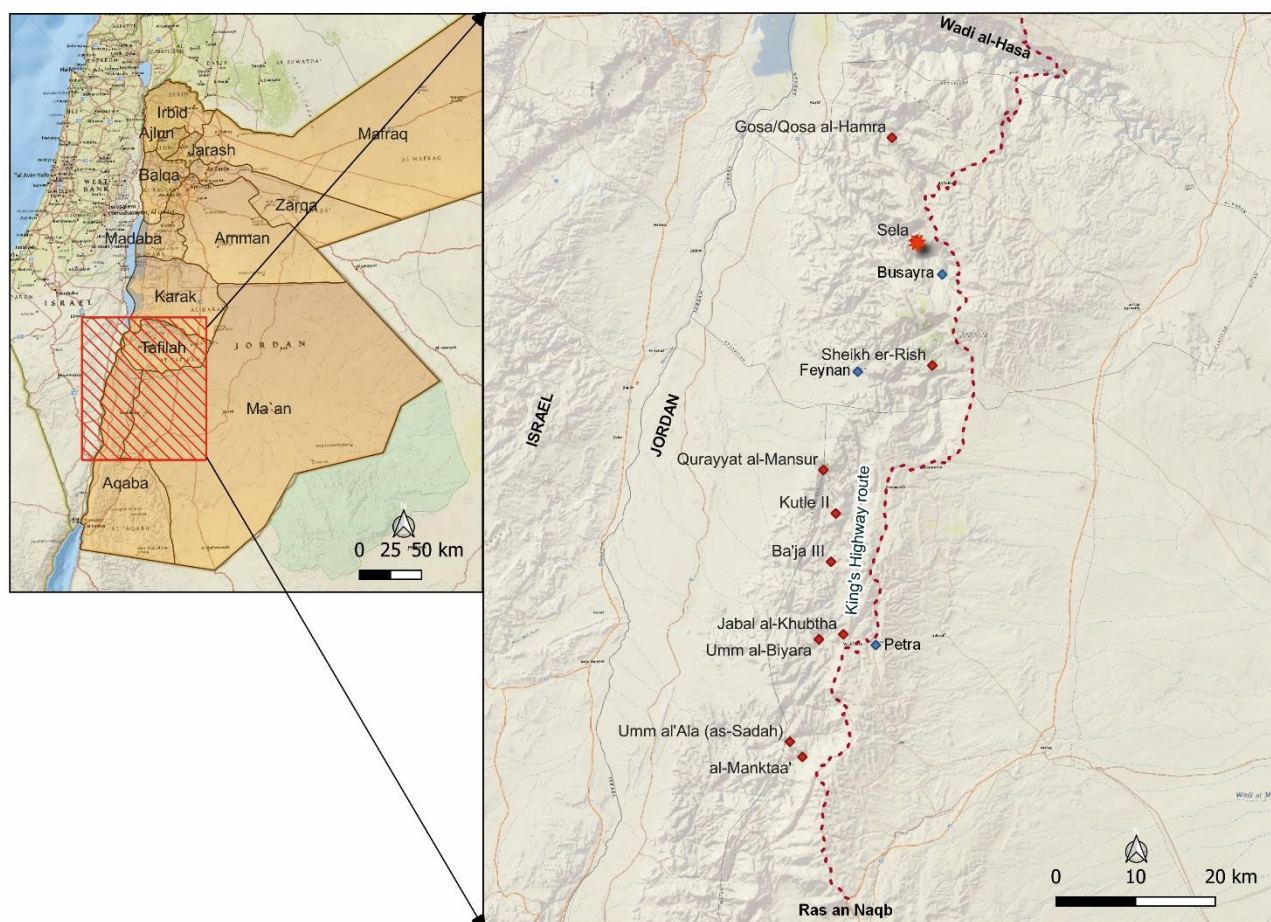


Figure 1: Map showing Sela's location in the Transjordan area.

The highlands of southern Transjordan have a mainly Mediterranean climate, with average annual temperatures of between 14-18°C per year. It is the so-called "Mediterranean island" (Smith, Najjar, & Levy, 2014), whose climate varies from subhumid conditions, with an average of 3 °C in January to 27-33 °C in August, to semi-arid conditions, with average temperatures of 3-7 °C in January to 30-35 °C in August (Bender, 1974). Springs are found in the wadis along the 1200-1100 m altitude range (MacDonald, 2015). The average annual rainfall in this region is 300 mm, although, in the south, it is much lower (Barker & Gilbertson, 2000).

Studies conducted at Sela have proposed a chronological framework extending from the Bronze Age (ca. 3rd millennium BCE) (Marsal, 2023) to the Mamluk period (14th-15th century BCE), although the Iron II period has been in the spotlight (Glueck, 1939; Lindner, 1989; Hart & Falkner, 1985; Hart, 1986; Lindner et al., 2001; MacDonald et al., 2004).

1.4. Long-term hydraulic systems at Sela

The hydrotechnological approach of the hydraulic systems at Sela has proved the capacity of the communities that inhabited the settlement to take advantage of a limited resource in a semi-arid region (Marsal, 2021, 2023).

Carbon-14 dating of lime-based mortars found in various structures has confirmed the use of hydraulic infrastructures since the Final Bronze Age, providing evidence of long-term occupation spanning from the Late Bronze Age to the Mamluk period (Marsal, 2023).

The initial study developed in Marsal's (2021) doctoral research, partially published (Marsal, 2023), enabled the georeferencing of each structure, resulting in extensive 2D planimetry and some specific 3D reconstructions. The structures were identified during an archaeological survey conducted in 2016, and their spatial documentation was accomplished using a Leica TC 407 total station, AutoCAD, Agisoft Metashape, and Autodesk 3D Studio Max software were employed to create 14 photogrammetric models of the most significant water-holding installations for the study of the hydraulic systems.

In this study, a 3D model of the site was created to assess the functionality of the hydraulic systems and their correlation with topography. The 3D model facilitated the identification of previously undiscovered archaeological structures associated with the settlement on the promontory. Additionally, the generation of an orthomosaic covering the entire surface enabled a comprehensive analysis of the architectural intricacies of known structures and the identification of new ones. The 3D model greatly enhanced the understanding of the site's topography. The high-resolution photographs enabled the generation of contour lines with a 1 m equidistance, resulting in a significantly more detailed and accurate topographic model compared to the previous model based on lower-resolution satellite images, which only allowed for a minimum equidistance of 10 m. The previous model's accuracy was found to be imprecise when compared to Global Positioning System (GPS) points collected during fieldwork.

The comprehensive understanding of the relationship between preserved remains, spatial layout, and detailed DEM facilitated an extensive hydrological analysis. The 3D model, with its higher-resolution imagery, enabled precise contour line extraction and the development of a terrestrial elevation model for local hydrology analysis. The main goal is to explore the relationship between hydraulic infrastructure, settlement remains, and the topography of the site to propose spaces for acquiring, managing, and using available water resources.

2. Methodology

The data used in this study were collected through an extensive archaeological survey carried out in 2016, focusing on the documentation and analysis of the hydraulic infrastructures at the site (Marsal, 2021). The survey involved a thorough pedestrian exploration, which enabled the identification, documentation, and subsequent analysis of various hydraulic installations (Marsal, 2023). The hydraulic system comprises 136 facilities (66 cisterns, 9 entire canals, 42 fragment canals, 10 sedimentation basins, 1 dam, 4 pools, 1 reservoir, and 3 undetermined hydraulic facilities).

The 2D graphic documentation of the archaeological remains, as described by Marsal (2021), was accomplished using the AutoCAD 2015 software. The field-collected coordinates were imported into AutoCAD, and drawings, annotations, and photographs from the survey were used as references. This process resulted in the creation of multiple 2D vector drawings depicting the hydraulic and architectural structures. Each structure was assigned a specific number based on its typology, and a colour code was applied to identify the elements according to their typological classification. Regarding the canals, a distinctive colour was assigned to represent the extant sections, while hypothetical layouts were depicted using a slightly faded version of the same colour. To organise the prominent facilities at the site, they were grouped by sectors (denoted as "S") within each survey area. This categorisation facilitated the analysis and interpretation of the archaeological remains.

The network of structures was established based on the planimetry created. The conduction canals were crucial in examining potential connections with adjacent water collection and storage facilities. In certain instances, hypothetical sections were suggested to verify inflows and outflows, considering the direction of the slope and gradient of the terrain. As a result, a comprehensive planimetry of the site was created, enabling the extraction of individualised plans for each area. Each plan provides a detailed view of the remains, depicting the various elements with the assigned colour code, corresponding numbers, and types. This systematic approach facilitates the identification and organisation of the elements within the databases, ensuring efficient data management and analysis. In addition to the planimetry, the topographic elevations of each structure, as well as the starting and ending elevations of the canals, were incorporated. Sections and cross-sections were created to illustrate the gradients of the network within each section, followed by its location, a topographic scale, and represented with dashed lines and by dimming the colour assigned to the canals.

Photogrammetry techniques were employed using aerial photographs taken during flight 2018-1014 of the Aerial Photographic Archive for Archaeology in the Middle East (APAAME) project in 2019 to enhance the 2D planimetry. A collaboration was established with this project, led by David Kennedy and Robert Bewley, to obtain a comprehensive overview of this extensive site of more than 42 ha. This archive, established in 1978 by Kennedy, consists of over 91000 photographs from different countries in the Middle East. The photographic material can be viewed online in a digital archive at the APAAME Flickr page (<https://www.flickr.com/people/apaame/>). These images were taken from a helicopter provided with a Nikon D750 24 mm focal length camera following a spiral trajectory around the outcrop. All the photographs are in DNG format with dimensions of 1024 x 684 pixels, a resolution of 96 dpi, and GPS coordinates. The result was a 3D model created using 114 oriented photographs from the 116 taken during the flight. Reference points identified by the total station during the survey were used for its orientation (Fig. 2).

Using software that uses SfM (Structure from Motion) techniques, the aerial images require an overlap between shots of at least 60% for vertical and between 40-60% for side shots. Orthogonal shots of the terrain and vertical planes formed by cliffs and oblique shots of the remaining surfaces were required (Kyriou, Nikolakopoulos, & Koukouvelas, 2021; Ozimek, Ozimek, Skabek, & Łabędź, 2021). It is because the topography of the rocky outcrop is very rugged, the dispersion of archaeological structures, both in the horizontal plane delimited by the top of the promontory and in the vertical faces formed naturally by the steep slope towards the wadi and by the volumes of rock that protrude abruptly from the surface. Following these parameters, the photogrammetric model of the site was created using the photographs taken during the APAAME flight. The 3D model is available in Supplementary File_2. Despite not adhering to the typical procedure in photogrammetry work, the unique characteristics of the spiral route taken during the helicopter flight around the promontory have generated a reasonably accurate model. All the shots were coordinated by GPS so that the program could orient 114 of the 116 photographs obtained. To improve the orientation of the model, the topographic work carried out during the fieldwork has been handy.

Regarding the limitations of this specific case, overhead shots of the surface of the promontory have been missing, which would have allowed obtaining a higher quality texture and resolution of the orthomosaic, in such a way that in some areas, it has not been possible to recognise the existence of structures with a minimum degree of certainty. Despite the lower resolution and challenges in identifying smaller remains, we believe that aerial images not intended for photogrammetry can still benefit drone-restricted areas. This approach offers a significant resolution improvement compared to models based on satellite images.

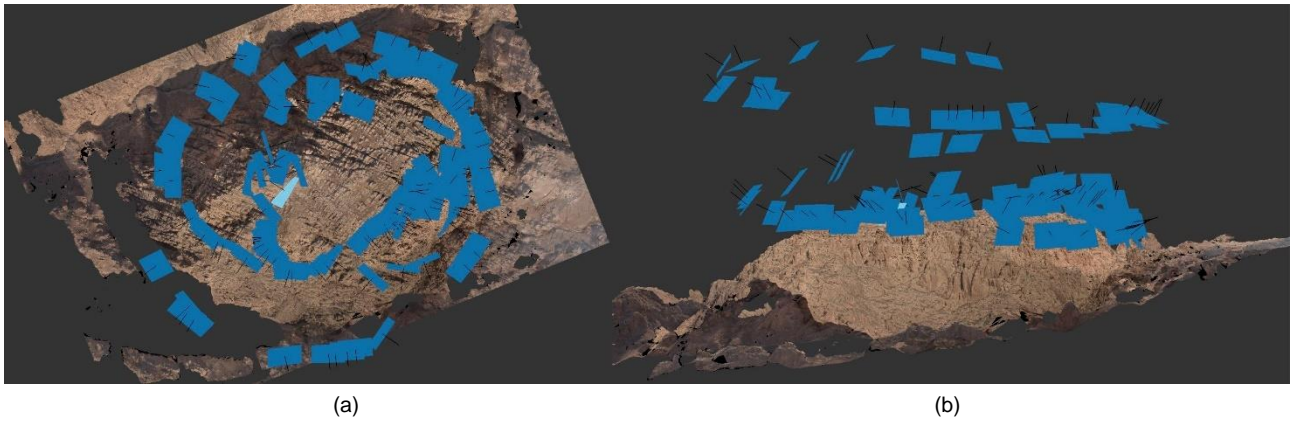


Figure 2: Camera positions used in photogrammetric model processing: a) top view; b) Side view from the east.

After processing the dense point cloud and polygonal mesh (Fig. S4), contour lines and an orthomosaic plan were extracted from the entire complex to identify new structures. For this purpose, the image was imported into the AutoCAD 2021 software. All the elements documented in Marsal's (2021) thesis were first located on the orthomosaic (Fig. S5), and then, the new structures were detected. At the same time, a visual inspection was carried out directly on the 3D model to detect archaeological remains that could not be identified in an overhead image, such as those present in vertical planes or under any natural or artificial cover.

The photogrammetric model was imported and uploaded into the Autodesk 3D Studio Max 2021 software. Mesh optimisation and cleaning have been carried out using the available tools in the program to conduct an analysis based on its morphology (Verhoeven, 2017). In this way, it was possible to detect archaeologically relevant areas, such as those prone to flooding due to their topography. Thus, the whole 3D nature of the source data has been considered, which has resulted in a general planimetry of the entire site, which shows the detected structures grouped according to their features and the areas that could have had relevance due to their topography or location.

A DEM was created in QGIS v. 3.22.10 for hydrological analysis using contour lines extracted from the 3D model (Conolly & Lake, 2006) (Fig. 3a). The high-resolution photographs allowed the generation of contour lines with a 1-m equidistance, unlike satellite imagery from Google Earth Engine, EO Browser, USGS Earth Explorer (Fig. 3b), CORONA, or ASTER, which only allowed a minimum equidistance of 10 m (Altaweel, 2005). Moreover, while CORONA or ASTER satellite images have a 3601 x 3601 pixels resolution, the DEM derived from the photogrammetric model is 29484 x 24616 pixels (Casana & Cothren, 2008). Thus, the resulting DEM (Fig. 3c) provides sufficient detail for studying local hydrology.

The hydrological model for this study was created using SAGA's terrain processing tools within QGIS (Passy & Théry, 2018). To identify and remove sinks and peaks for automated DEM-based surface run-off modelling (Wang & Liu, 2006), we have used the "Fill sinks Wang & Liu" tool. A hillshade layer was created to enhance the visualisation of the DEM. To show the flow directions of water run-off over the terrain's topography, we used the Strahler Order tool. This tool uses the stream ordering system developed by Strahler (1952), which consists of the streams' hierarchical representation and shows the stream's position in the tributary hierarchy.

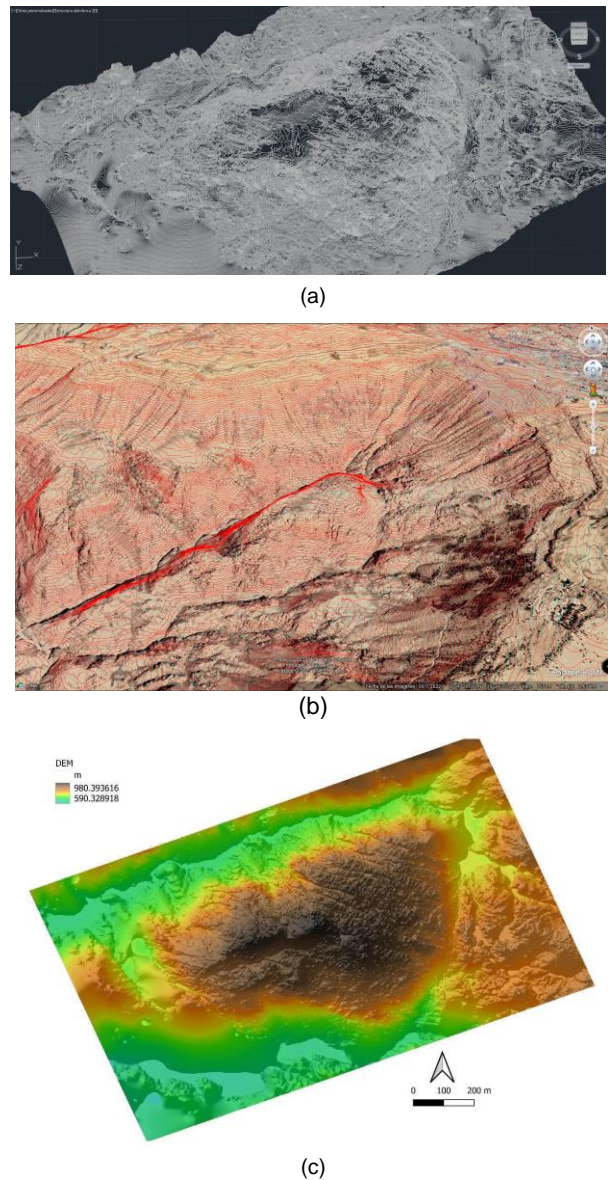


Figure 3: Sela area: a) Contour lines generated from the photogrammetric model; b) Satellite image obtained from Google Earth Engine; c) Resulting hillshade DEM.

A stream polyline was generated to improve the representation and clarity of the stream network. The Channel and Catchment Network tool, based on Strahler's methodology (Strahler, 1964), was utilised to

create the polyline. Specifically, streams were separated and filtered based on their Strahler Number. A threshold value 5 was chosen to isolate streams with a number greater than or equal to this threshold. The flow was determined with the algorithm by differentiating where a given pixel would go based on the elevation and height values of the cell.

3. Results

Based on the photogrammetric model and its analysis, we have identified new surface structures, settlement density zones, and flood-prone zones at the top of Sela. Statistical analyses of the data generated by the GIS hydrological model have identified flood and run-off zones, providing new information on the distribution of hydraulic structures.

3.1. New surface structures

Several new surface structures have been identified from the raster image (Supplement File_3).

Evidence of embedding, casting, or surface preparation has been located on the vertical faces by direct observation of the 3D model. These are the following elements:

A) Settlement remains: structures that delimit spaces (i.e., walls, stairs, etc.), the use of which is uncertain but which can be associated with residential constructions or occupation areas.

B) Marks on vertical facing: marks that show some preparation of the facing (i.e., hollow out, recesses, smoothing of the surface, etc.) but are not associated with any surface structure of the previous type.

C) Elevated platforms with regular linear marks: small horizontal surfaces with no signs of construction upon them.

D) Platforms/ground levelling: surfaces that appear to have been horizontally levelled, potentially serving as a form of pavement but lacking surrounding structures or enclosures.

E) Hydraulic infrastructures: water catchment and water transport facilities.

The distinguishing feature between the elevated platforms with regular linear marks and the platforms/ground levelling is the presence of specific marks, although their exact function remains unknown. An example is illustrated in Figure 4a, and some identified incisions on the vertical facing are shown in Figure 4b.

The new surface structures were found in the designated areas identified during the pedestrian survey: E, F, G, H, I, K, and L. Because the aerial photography by the APAAME Project was focused on the summit of Sela, it has not been possible to locate new structures in area C or to identify clear structures in area D, except for marks on the vertical faces such as those found throughout the site (Fig. 4b). Table S1 provides an overview of the main features identified during the pedestrian survey and the 3D model survey. Supplementary File_3 contains all maps depicting the identified areas and structures below.

Area E reveals significant activity with the identification of numerous platforms, settlement remains, and hydraulic structures. The area showcases over fifteen scattered platforms, primarily concentrated in the north and east. Three of them have small incisions at the base (approximate length of 0.40 m) at regular intervals whose function cannot be established. In the central area, two

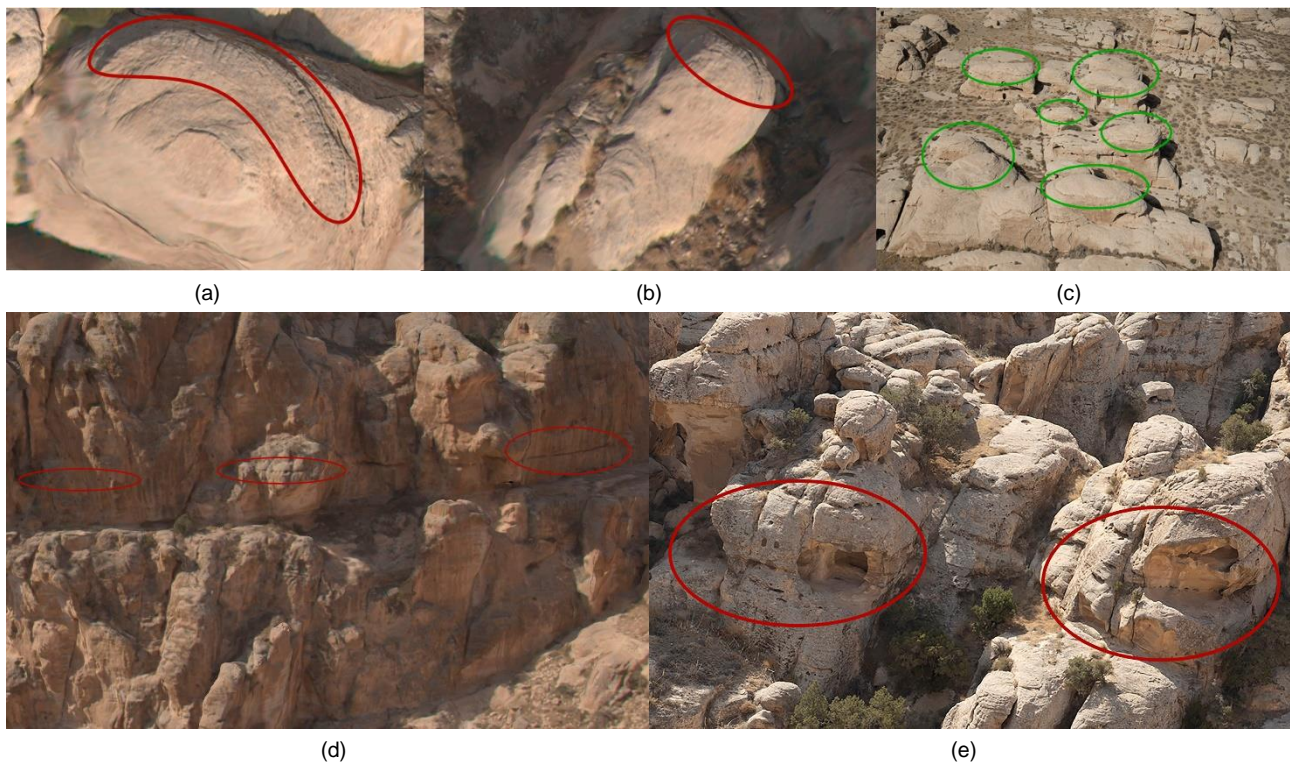


Figure 4: a-c) Example of elevated platforms with regular linear marks (red) and platforms/ground levelling (green). Photo source from left to right: Orthophoto capture (x2) and APAAME_20181014_RHB-0361. d-e) Example of marks on vertical facing. Photo source from left to right: Model 3D capture and APAAME_20181014_RHB-0381.

large surfaces of 46 x 11 m and 25 x 13 m of unknown use have been identified, framed by the natural rock modified to act as a facing. At some points, outcroppings of the pavement created in the same way can be seen. A staircase carved into the rock has been found to the north of the larger surface, providing access, and bridging the height difference with the adjacent area. Additionally, a nearby platform includes two connected canals leading to a water-holding structure measuring about 8 x 5 m. However, the exact function of this structure is uncertain due to the degree of silting up. Additionally, 32 new hydraulic structures have been documented, including a possible feeding canal for the D21 reservoir, new cisterns associated with canals, canal fragments, and two large water storage tanks. One would have two water supply canals located to the NW of S1. The other, situated in structure E1, could be related to the sedimentation basin D72, located SW of this facility. Water supply systems have been identified, consisting of one or more cisterns, the sedimentation basin, and water conduits leading to these facilities, primarily located to the east of the area.

Likewise, it has been better to visualise the C77 and C108 canal sections. In the southern zone, bordering on area K, what appears to be a water-holding structure carved out of the natural rock itself has been identified, which would collect the water taking advantage of the terrain's natural slope. Again, due to the silting up of the feature, its function is not wholly clear without ground-truthing at the site. Furthermore, this area is a depression, and the resolution in the 3D model is insufficient due to the darkness generated by the shadows cast.

Area F has a high settlement remains density, although most structures were registered during the 2016 pedestrian survey. The newly identified features obtained from the 3D model are primarily located in areas that are challenging or unsafe to access on foot. Despite the expansive size of the site (ca. 42 ha), the survey work conducted in April 2016 involved only one or two researchers for 19 days. During this time, the dense vegetation cover often hindered the identification of potential structures. Consequently, the new structures identified in this study were not described in the 2016 fieldwork.

In the southern sector, a group of structures has been identified, consisting of two platforms at different levels connected by a staircase and associated with a wall on the higher platform. Another two rock-cut stairs with no apparent connection to any other structure have also been recorded in this area. In the central part of the area, three wall sections have been identified that delimit a rectangular space of about 7.60 x 6.60 m and various fragments of scattered walls to the west. These structures seem to have emerged from the ground due to recent excavations showing the marks that can be seen on the ground. Finally, to the east, under H2 and directly overlooking the main access to the promontory, there is a platform with multiple marks on its vertical face. Regarding hydraulic structures, a new canal fragment has been traced out, which could correspond to the prolongation of C104. On the northern side of S5, two structures have been detected, potentially used for water storage and, to the SW of this sector, a possible cistern with an associated canal has been identified. Additionally, some canal fragments have been found.

In area G, a new canal fragment has been identified, which connects with the D63 cistern on its northwest side, and another possible canal fragment has been observed to the west of the D70 sedimentation basin. At least three new settlement remains have been found in this area, including stairways, walls, and new platforms with regular linear marks.

In area H, the newly identified structures are concentrated towards the south, where stands out a surface of 28 x 7 m of unknown function is delimited by some sections of walls that have been preserved and preparations of natural rock as facing. Two water storage structures have been identified south of the area, one whose shape could correspond to a cistern, and both have associated canals. Other canal fragments without connection to other hydraulic infrastructures and a fragment of the D26 cistern canal have also been identified. A platform with its access staircase, another surface of 6 x 3 m framed as the previous one by walls, and preparation of the natural rock and some possible scattered canals with unknown connections have been identified. A platform with two access stairs in the central area and another small platform to the north have been placed in the remaining area.

In area I, 15 new hydraulic structures have been revealed. Their shape and dimensions could correspond to 3 pools or sedimentation basins, a cistern, a water-holding structure, and an undetermined facility with two possible associated canals facility in S20. In S21, they correspond to two canal fragments and a sedimentation pool or water-holding structure; in S22, a pool or sedimentation basin with an associated canal; in S23, a large water storage facility; and a possible cistern and a sedimentation basin or pool in S24.

Regarding the remains of settlement planning, area I contains one of the most significant accumulations of such structures. The housing is organised around two complexes articulated through a road of about 7 m in width that runs between both in an east-west direction (Fig. 5). The northern complex (S20), measuring approximately 39 x 18 m, is formed by a wall that runs along the boundary of the platform in an east-west direction, creating the façade with the track described above. Although some sections of the wall have been lost in certain areas, it appears to have been a continuous element, maintaining the same direction and thickness throughout its entire extent. The interior distribution is organised in the eastern area through elongated rectangular rooms with a north-south orientation that alternate with others of quadrangular type in the western part. The dimensions of the rooms are variable (those of elongated type around 2.18 - 5.33 m wide and quadrangular of 4 - 5 m) as well as the thicknesses of the walls (between 0.50 - 0.90 m). The surfaces associated with these rooms are built using the natural rock of the platform on which it sits, presenting different types of hydraulic structures in different places.

The southern complex follows a similar pattern to the previous one but is organised around three platforms at different elevations. The platform corresponding to S22 measures approximately 41 x 14 m and is accessed solely from the main road via a staircase that bridges the height difference. While few interior partitions have been preserved, it appears evident that there is a linear arrangement, indicating the shared use of specific spaces for accessing different areas. In the central region, another platform rises with a height difference of 2-3 m, dividing the space, although no access points have been documented.

The second platform identified in this work is situated in the eastern area (S21), rising about 1 m from the previous one. The characteristics of the settlement are comparable to those of the northern complex: elongated rooms between 1.58 - 2.40 m wide, walls of variable thickness between 0.40 - 0.80 m, natural rock soils, and various hydraulic structures at various points of the surface. The layout is also linear, requiring first going through some rooms to get to others. It also has a single access using a staircase to communicate the complex with the central road.



Figure 5: Diagram showing possible routes of physical movement across the complex.

In area K, the central area has a platform distributed on two different levels with dimensions of around 40 x 10 m, which would have been accessed via a staircase. In the lowest terracing, there appear to be two canals leading to a water tank, which is very difficult to identify due to the degree of silting up. In the western area, two connected water tanks have been placed, which indicates a possible sedimentation basin and a cistern connected by a canal. Nearby, there is an undetermined water-holding structure of larger dimensions. In the space between the elements described above, an area of about 14 x 8 m has been detected, delimited by a natural rock modified in its contour to adapt it as a facing, but whose function is unknown. Towards the north, around S28, we have identified two small water storage tanks with associated canals of small dimensions. To the northeast, at the highest point of a small rocky outcrop, two tanks connected by a canal have been identified, which again is evidence of the existence of a sedimentation basin and its corresponding cistern. Finally, around S33, there is a platform and a possible cistern in the eastern sector.

Finally, in area L, a large surface stands out in the central area. It is a space of approximately 68 x 23 m delimited by the topography of the promontory on which it sits, and which preserves a continuous masonry wall 57 m long at its southern limit and an irregular thickness between 1.10 - 1.30 m. At one point in its development, it presents a quadrangular shape of 5.75 x 4.30 m, whose characteristics resemble a tower. They have also detected many masonry fragments scattered throughout the surface and the natural slope of the promontory that would form part of the collapse of the walls that have not been preserved. All these characteristics, together with the fact that it sits on an area that topographically dominates a large part of the central area of the site, lead us to believe that it is a control or observation point. A large rectangular structure that could correspond to a water storage tank has been identified. At this point, the

orthophoto is distorted, and the image quality has not been improved, so we can only speculate that this was its function. In addition, a canal has been identified to the south of cistern D59, which connects with a possible hydraulic installation, whose shape and dimensions could correspond to a sedimentation basin or another cistern. In this area, it has been possible to delimit the stairways and three elevated platforms, one of which is a possible watchtower (T2) in S34. To the northeastern (NE) of S34 and southwestern (SW) of S35, a new staircase cut into the rock has been identified. In area S36, new settlement remains are associated with hydraulic installations and three access stairways to an elevated structure. Finally, in S37, various remains of housing planning and elevation platforms have been located. To the north of this sector, one has a hydraulic system of water inlet canals to a sedimentation basin and a cistern. To the south, there is a framework of walls, the spaces of which are distributed in two rooms and an access opening.

As a result of this work, several new structures have been identified beyond the boundaries of the previous survey areas. In the eastern part of area F, two potential water storage structures with associated canals, a fragment of a canal, rock-cut stairs, and a levelled platform have been documented. To the south of area H, in a space with great difficulty of access and at a height much lower than the surface of the promontory, three large platforms have been detected with multiple marks of having housed structures. A cistern and a canal fragment have also been documented in the northwestern part of area L. Additionally, new raised platforms and marks have been recorded on the vertical face of area J, one less intensively surveyed area. Besides all the structures described above, it is worth noting the large number of marks identified on the natural rock to adapt it as vertical walls, vaults, large hollows and multiple remains of slots for roofing. This class of elements has a greater incidence even outside the limits of the designated areas, in the places that correspond to the vertical rock slopes, in what seems to be a use of the orography to create platforms at different levels. As this work focuses on the areas that could be prospected to compare them with the elements detected from the 3D model, everything outside of them has only been reflected superficially. A more in-depth investigation would be necessary as the basis for future research.

3.2. Settlement density zones

By combining our findings from the pedestrian survey and the 3D model, we have identified and classified five settlement density zones (a-d). These zones represent spaces closely associated with urban development (Supplementary File_4).

a) Located at the southern part of the site, which extends NE-SW on the site's western side, various land levelling platforms are found with remains of urban planning and associated hydraulic structures. Most of the platforms have associated rock-cut stairways.

b) The area located southeast of area "a" and south of the promontory has the most significant settlement remains. Archaeological remains are in two elevated parts, divided by a large avenue. In the northern area, we have located wall remains, some of which we have reconstructed their hypothetical layout, which would

delimit a residential place. In the southern area, there are three platforms, higher from east to west, with a related hydraulic system. In addition, numerous marks on vertical surfaces in the southern part of this area may be connected to these infrastructures.

c) Located to the hilltop's northeast area and southwest of zone "d", it has several raised platforms, settlement remains, and associated hydraulic installations.

d) Located in the northeastern hilltop area, this zone features multiple hydraulic facilities (cisterns, canals, and a sedimentation basin), various elevated platforms with stairways for access, and two potential domestic structures (H1 and H2). H1, located in the northwest corner of this area, includes an undetermined hydraulic structure D115. H2, measuring 8.55 x 6.30 m, has traces of stucco painted in green, purple, red, and blue (Lindner et al., 2001: 256). Due to the topography, we have determined that all the settlement density zones are located in non-floodable areas. The area's rainfall record supports this assessment, indicating sporadic but heavy rainfall in Sela (Sharadqah, 2014). All areas are on the outer limits at the top of the promontory, with the central area showing minimal traces of structures except for hydraulic facilities. Large dimensions and a significant accumulation of masonry in the surrounding area characterise the only relevant structure in the central area. As discussed below, these characteristics, together with its situation, could be associated with a defensive or control structure. The identified zones are scattered around the promontory, so no unitary grouping suggests an independent organisation. The location of the settlement density zones on the outcrop's perimeter,

along the cliffs/vertical drop-offs, could correspond to a defensive structure, perhaps related to the visibility over the wadi. Finally, hydraulic facilities are distributed throughout the promontory, with a higher concentration in areas associated with settlement remains. This evidence suggests individual water collection within dwellings and collectively managed water collection in areas not linked to specific structures.

Based on the analysis of the settlement remains identified and their possible reconstruction, it was possible to identify two areas with similar living space structures.

A complex with rectangular and quadrangular rooms has been identified in settlement density zone "b", where it has been possible to trace a more significant number of housing remains (S20). The thickness of the walls is 0.73-0.86 m for the thicker ones and 0.40-0.54 m for the thinner ones. However, further examination is required to establish connections between rooms and transit areas. The wall dimensions are the same as those found in density zone "c". In this case, the settlement remains are associated with the promontory on the opposite side (next to S16). Its facing is worked in a very similar way, and the heights of the upper platforms are practically the same. The thickest walls are between 0.73-0.80 m, and the thinnest walls are between 0.44-0.48 m. The U-shaped staircase serves as a connection between one of the upper platforms and one of the lower enclosures, while both platforms are part of the same assemblage (refer to the green dashed lines in Fig. 6).

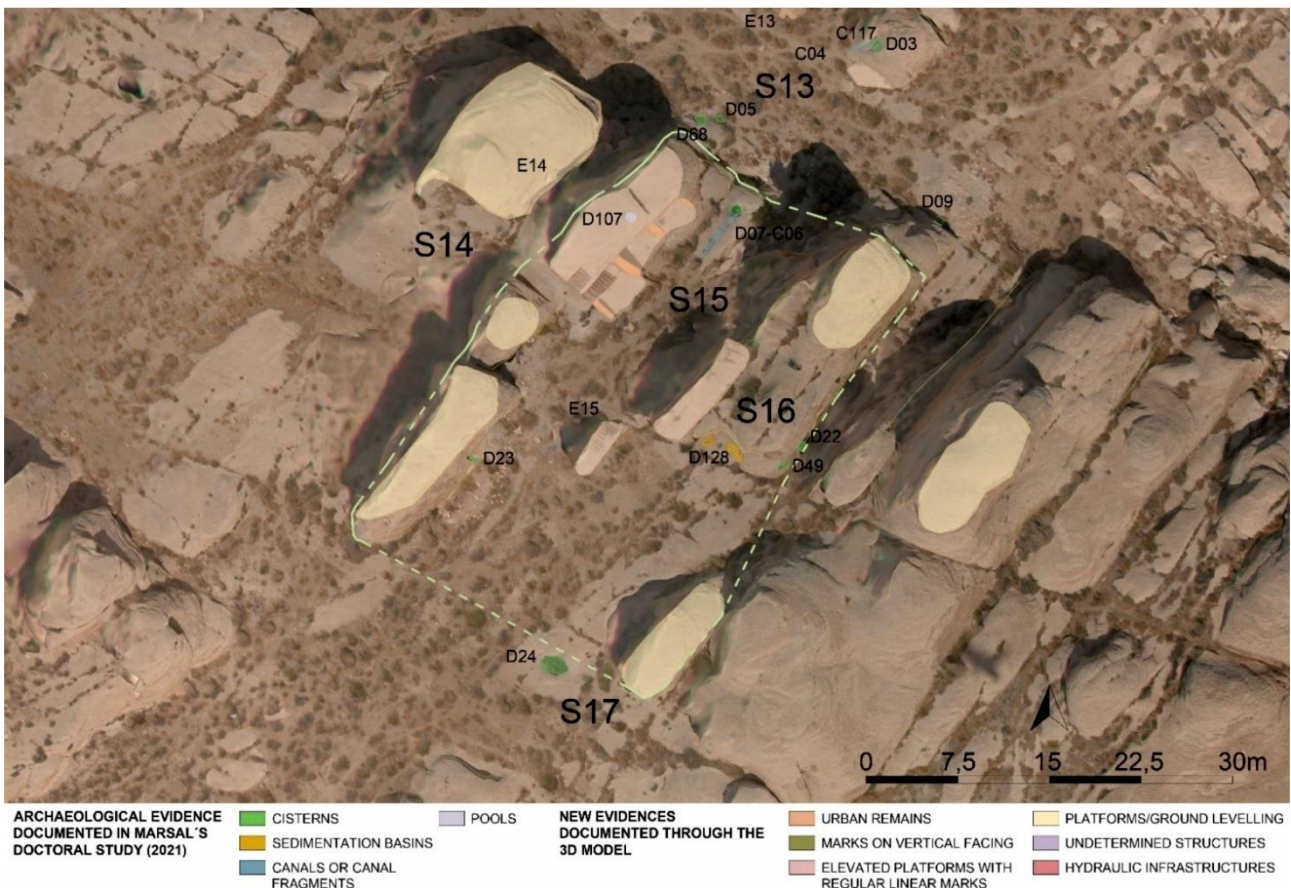


Figure 6: Urban complex identified in settlement density zone "c".

3.3. Run-off and flood-prone zones

Using the 3D and hydrological models, we have detected the potential orientation to water flow and propose run-off and flood-prone areas due to the orography.

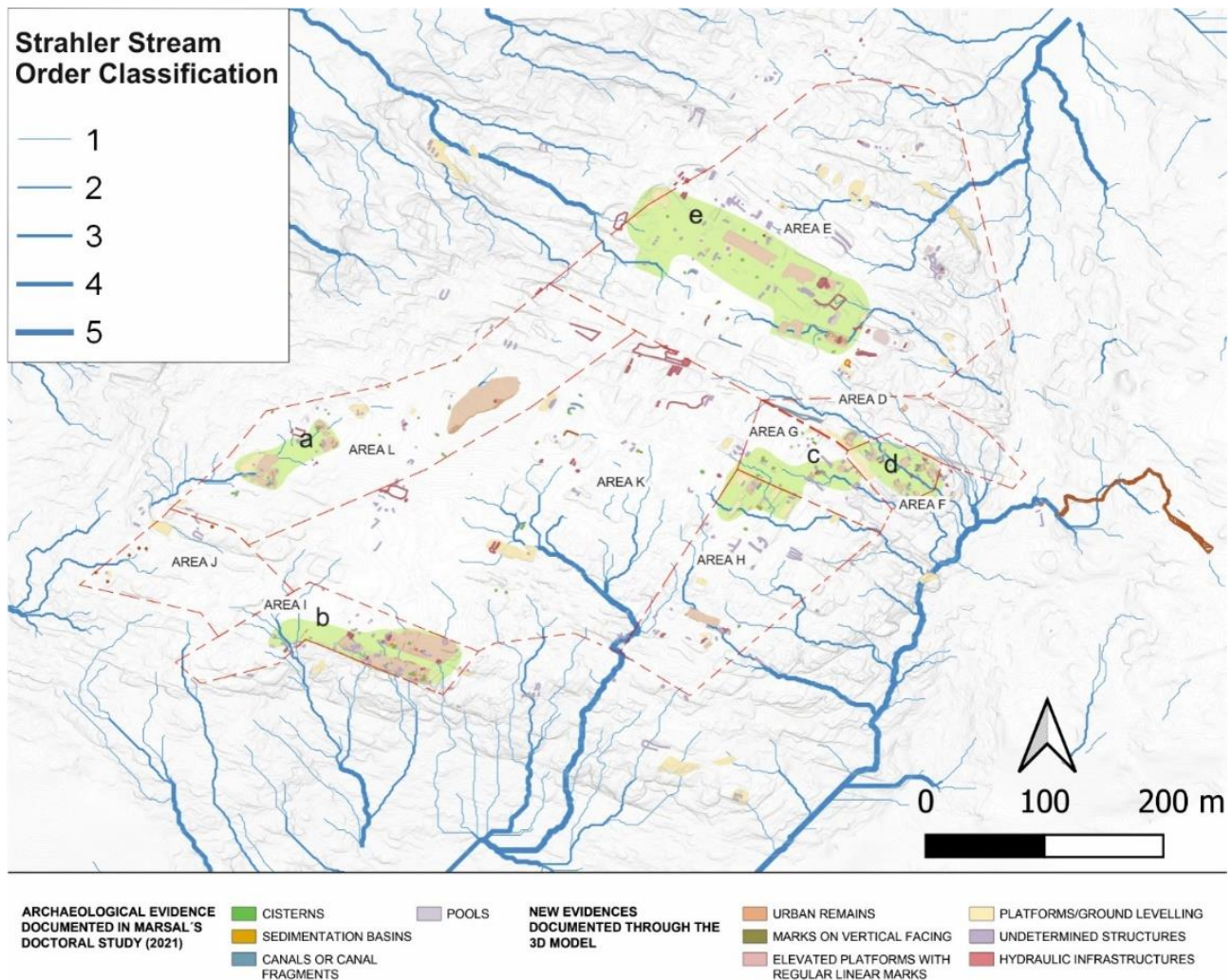
The main run-off areas are concentrated on the promontory slopes and in the northeastern, central, and southwestern regions of the summit. These areas are prone to flooding during rainfall events due to natural depressions and the terrain's slope. Notably, there are no associated hydraulic structures in almost all these areas, except the large area further north (Fig. 7). The absence of hydraulic structures in the higher-intensity water flows indicates that the hydraulic systems were arranged where run-off water could accumulate and be collected with a lower content of transported contamination. In water flows where sediment and material transport are high, it causes sediment and material to accumulate in the cisterns, quickly silting up them and rendering them unfit for human consumption.

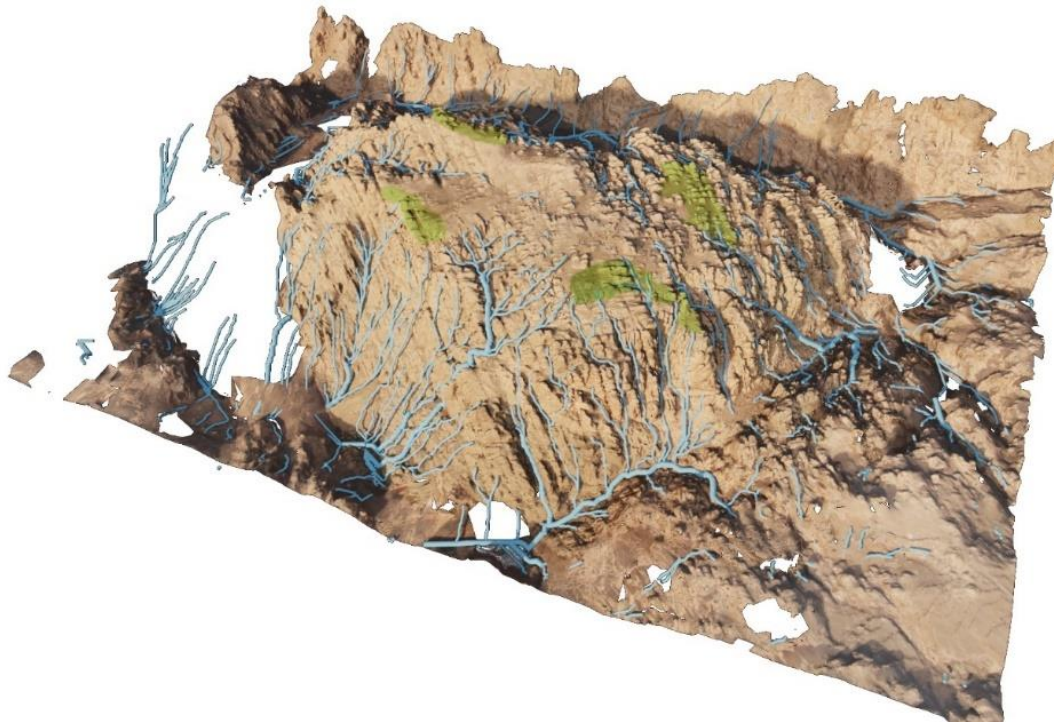
From the hydrological analysis of the settlement, it has been determined that all the cisterns are in optimal places

to store run-off water without inputting materials and sediments. These locations are at lower elevations than their catchment areas to ensure water entry through uneven terrain slopes. The absence of canals associated with many of the cisterns is evidence of the use of the rock faces of the hills to transport water from the top to the cisterns built below. The cisterns on the cliff's edge, such as D75, D51, D52, D59, and D75, confirm this. However, the current topography may have varied from the past because of natural erosion over centuries.

The analysis also suggests that natural depressions in the terrain may have served as water retention reservoirs. The naturally formed water reservoirs would contain many washed-out materials, and these are spaces where a large volume of water could be collected with minimal construction effort. However, these water flows would carry abundant materials and sediments, contaminating the water for human consumption.

Eventually, the water run-off would cause the only access to the promontory, the stairs carved into the rock leading to the top, to be wholly flooded during rainy periods.





(b)

Figure 7: Sela hydrological model: a) Map displaying the main flows according to threshold 5 of Strahler's order; and b) 3D hydrological model.

4. Discussion

Based on the results of this study, new surface structures, settlement density, and flood-prone zones at the top of Sela have been identified. The statistical analyses through the GIS hydrological model identified flood and run-off zones and provided new information on hydraulic structure distribution.

The vast number of new structures identified extends previous studies related to this site (Glueck, 1939; Hart, 1986; Lindner, 1989; Lindner et al., 2001; Raz et al., 2001; MacDonald et al., 2004; Kołodziejczyk, 2015; MacDonald, 2015) and provides additional data on the water supply system in Sela (Bagg, 2006; Marsal, 2021, 2023). Among the twenty or so hydraulic structures identified by the first explorers (Glueck, 1939; Lindner et al., 2001), the examination of the promontory's surface and the exhaustive analysis of the hydraulic systems by foot survey in 2015 and 2016 (Da Riva & Marsal, 2017) revealed more than a hundred hydraulic structures. As a result of this study, at least 91 potential new hydraulic structures, over 60 housing remains, and numerous undetermined structures have been identified.

4.1. Water run-off and flood-prone zone management and use

The study area is in a semi-arid zone characterised by low annual rainfall, seasonal and short-term extreme precipitation events (Sharadqah, 2014). Extreme precipitation events in the form of short-lived storms cause flash floods (Migón & Goudie, 2014), and the water infiltrated and retained in the ground is subsequently affected by high evaporation rates. These are due to the high temperatures and low humidity typical of the region's Mediterranean climate (Bender, 1974). According to Migón

& Goudie (2014), the Ordovician sandstone that shapes the geological landscape where Sela is located within a highly permeable rock type. The rock's permeability and the scarce vegetation generated by the area's climatic conditions would produce high water infiltration. However, high-intensity precipitation events probably reduced the infiltration rate and increased water run-off.

Climatic factors such as the rainfall pattern and regime, as well as the evaporation rate, hydrogeological factors such as the level of infiltration, and topographical factors were decisive in the configuration of Sela's water supply system (Marsal, 2021). The location of settlement density zones in non-floodable areas suggests that water availability also played a key role in the construction of housing zones. Most hydraulic structures were situated in areas with less-intense water flows, indicating a strategy to collect run-off water with lower contamination. Hydrological analysis of the site confirms that most cisterns are in optimal locations to capture run-off water without contributing materials and sediment. These spaces are located at lower altitudes than their catchment areas to ensure water inflow through the uneven slopes of the terrain. The absence of canals associated with many of the cisterns is evidence of the use of the rocky slopes of the hills to transport water from the summit to the cisterns built below. Cisterns on the cliff edge, such as D75, D51, D52, D59, and D75, confirm this.

According to the available information on floods in the southern Transjordan area, there are flash floods (Al-Qudah, 2011; Farhan, Anaba, & Salim, 2016). They are characterised by their short duration, suddenness, and unexpectedness. These factors render it an extremely destructive phenomenon. According to Bagg (2012), flash floods generally occur on small to moderate-sized catchment basins in watersheds with large impervious areas, sparse vegetation, and steep slopes.

To manage this surplus water in arid and semi-arid regions (Lin, 1999) such as the Negev (Kahana, Ziv, Enzel & Yan, 2002), Israel (Khavich & Ben-Zvi, 1995) or Jordan, communities implemented flood prevention measures through efficient hydraulic engineering (Nydahl, 2002). These were mainly based on the establishment of reservoirs and dams. The site of Petra is undoubtedly one of the best examples of the use and development of this type of technology to protect the water supply system (Bellwald, 2004; 2006; Abdelal, Al-Rawabdeh, Al Qudah, Hamarneh, & Abu-Jaber, 2021). In addition, natural hollows, gutters, and gorges were used to divert rainwater, such as those identified at Sela and in other sites such as Sabra. At this city, located about 5-7 km southwest of Petra, a complex water-supply system was found that includes such systems to prevent damage caused by flash floods by storing and directing run-off water. Similar constructions have also been found at es-Sadeh, Umm Latam, and ed-Deir Plateau in Petra (Lindner, 2005). In addition, natural depressions in the terrain may have served as water retention reservoirs. These spaces could store a large volume of water with minimal construction effort. The presence of pools and water-holding structures as open reservoirs and flood-prone areas suggests water supply for livestock. Water availability for the animals grazing workable and reduce the time and energy required to travel long distances in search of water (Hammer, 2018).

The findings of this study suggest that the main run-off areas on the promontory are located on its slopes and in the northeastern, central, and southwestern regions of the summit. These areas are prone to generating flood zones due to water flow. Only a few large-scale installations have been found in these areas of higher water flow intensity, probably for storing the water produced by episodes of high-intensity flash floods. This would be the case for the newly identified water storage facilities in area E. Water collected in open water storage structures, as with naturally formed water reservoirs, would carry high sediment transport rates (Cohen & Laronne, 2005). According to Schick, Grodek, & Lekach (1997), the sediment loads consist mostly of bed material, often pebbles and cobbles, reaching 10% or more concentrations.

Likewise, in the northern area of the site, where water would accumulate after heavy rainfall, we can conclude that canal C17 had the function of evacuating the waters from accumulated precipitations on the terrain of the promontory. In this work, we have traced its complete layout of about 52 m. It leads the flow directly over the natural slope on which the access staircase is located.

As this study has shown, the hydraulic systems of Sela are distinguished by a great diversity of installations whose spatial position seeks to exploit all the topographical advantages of the outcrop. Additionally, the inclusion of numerous sedimentation basins ensures the quality of water for human consumption. Throughout the study, various water reservoirs have been identified. Based on their morphology and proximity to a cistern, they appear to be sedimentation basins in previously undocumented areas. This is particularly true for areas E and K, where the existence and utilisation of these facilities were previously unknown (Marsal, 2021). Thanks to the 3D photogrammetric model, these areas have been identified for the first time. The identification of systems to guarantee and increase water quality in Sela suggests that the cistern was mainly for human consumption, followed by sedimentation basins and covered canals. Their location may correspond to areas with more significant material

entrainment. In area F, differences have been found. These are the sections of covered canals (C14, C118, C119, C120, and C121) and the intermediate regulation cistern (D13). These elements suggest a system for collecting, conveying, and storing water to satisfy the quality requirements necessary for human consumption.

In addition to implementing hydraulic engineering measures to mitigate the impact of flash floods, it has been shown that the main settlement density zone is strategically situated on elevated ground to prevent areas of run-off and flood-prone because of the orography. The location of the settlement density zones delimits the spaces of occupation and highlights the need of the communities that inhabited Sela to control the territory. The choice of the location of settlement density zones on the perimeter of the promontory is not random. Their distribution seems to correspond to a system of territorial control. The defensive constructions on the cliffs/vertical slopes could be related to the visibility over the wadis and, therefore, the control of the surrounding valleys.

4.2. Communal and house-based water management

The identified structures reveal new, hitherto unknown places at the top of the promontory. In contrast to the previous view of the occupation of Sela, this work proposes further water use and management spaces. The locations of settlement density zones are scattered around the promontory, so no single grouping suggests an independent organisation. Although hydraulic installations are found all over the promontory, the more significant accumulation of these in the settlement density zones offers different water management spaces. The collection and management of water in a particular way are carried out in the housing areas. This would be the case of the settlement density zone "d" and "c", where architectural structures probably related to residential use have been identified.

In contrast, the collective catchment and management seem to correspond to areas where hydraulic structures were not associated with any buildings. This is the case of settlement density zone "e", where no architectural structures are related to hydraulic installations. The large amount of water flows that converged in this area could be the leading cause. In this area, the large reservoirs identified would allow the storage of large quantities of water, and its use and management could be communal.

Regarding the specific water management spaces, the results of this work have facilitated a comprehensive analysis of the architecture identified at Sela and a comparison with that documented in the region. Considering other regional architectural examples as mountain-top sites such as Jabal al-Qseir (Lindner, Knauf, Zeitler, & Hübl, 1996), as-Sadeh, Tawilan (Bennett & Bienkowski, 2005), or Umm al-Biyara (Brown, 2018), the predominant architecture is the longhouse. These are long corridor-like rooms interspersed with small, square, or rectangular rooms (Fig. 8b). Long rooms are associated with food storage. In contrast, quadrangular rooms of certain dimensions are related to residential use (Baxter, 2011). Whilst systematic excavation is needed to shed further light on interpreting these spaces, we can suggest that the structures located north of density zone "b" could be households (Fig. 8a,b). Notably, we believe the complex S20 would have a domestic function because corridor-shaped rooms are standard in the domestic architecture of the Jordanian plateau, such as those found in Um al-

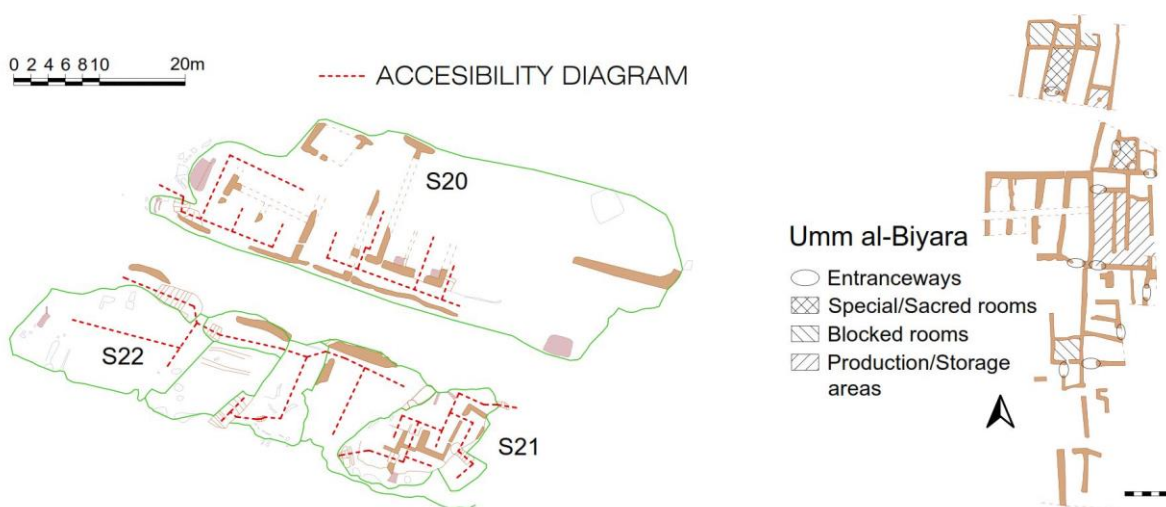
Biyara. In addition, movement within the interior is linear, meaning that to access a specific room, one must pass through others beforehand. This design suggests that those who inhabited a specific area were likely members of a close kinship-based group. Providing water supply facilities in these areas is significant evidence for this hypothesis. Also, the standard dimensions found seem to correspond to this type of building from the Iron Age in southern Jordan (Baxter, 2011).

In density zone "d", the hydraulic structures found in H1 and H2 (Fig. 9a,b) could indicate domestic use. H1, dated to the 16th century AD (Da Riva et al., 2019), would be an example of water use in a domestic space. Within the H1 complex, structure D115 may have functioned as a small tank-like reservoir for storing water or other liquids. The well-preserved domestic space is house H2. In this space, there is a system of conduction (canals C14, C131, and C135), decanting (D111), and water storage (D15) system D15 cistern may resemble the domestic cisterns of Hellenistic houses on Delos (Hodge, 2000; Mays, Antoniou, & Angelakis, 2013). In these domestic units, the central courtyard or peristyle has a cistern that stores rainwater from the roofs or the courtyard's surface (Karvonis, 2023).

In the settlement zone "b", documented pools stand out. Furthermore, no cisterns are fully or partially excavated in the rock, and all their internal forms have been proposed as cylindrical. These forms have only been observed in this area (Marsal, 2023). Additionally, excavated platforms associated with the hydraulic system are present. Various authors have studied the use of this area (Lindner, 1989: 280-281; Kołodziejczyk, 2015: 107). Lindner (1989: 282) suggests that these excavated platforms may have served as the foundations for domestic structures. This hypothesis was discarded as they were considered too significant for this purpose. According to Lindner, the stair's symmetrical layout and the space arrangement could correspond to an ancient place of worship like those identified at Petra or in the urban centre of Hegra (Lindner, 1989; Dentzer, 2010) or the acropolis of Sepphoris (Israel) (Galor, 2006). Based on our results, neither hypothesis can be ruled out. It could correspond to a habitational or ritual use. It is confirmed that this is a specific use of water management at the site, where the hydraulic structures are confined within architectural structures, whatever their final use.



(a)



(b)

Figure 8: a) The northern part of the density zone "b". Source: APAAME_20181014_RHB-0367. b) Architectural example of a longhouse in Umm al-Biyara and architectural example of the household complex in density zone "b". Sources: Baxter, 2011: 54 and Jesús G. Carpallo.



Figure 9: Examples of Sela's water facilities for domestic and collective use. a) Hydraulic facility D115 in H1; b) Hydraulic system in H1; c) Location of cistern D07; and d) Location of cistern D75. Sources: Marsal, 2021.

Furthermore, communal spaces can be distinguished in this work. In density zone "c", the location of the D07 cistern is outside the limits of the structures carved into the rock that could correspond to domestic units (Fig. 9c). In addition, a fragment of a canal (C06) leading the water from the southwest, in a sort of "avenue" is also discernible. The reservoirs that collect a larger volume of water, such as the D21 reservoir, or facilities that function as a reservoir and retaining walls, such as the M130 dam, could also have communal use (De Feo, Laureano, Drusiani, & Angelakis, 2010). The hydraulic systems comprising water collection and storage outside settlement density zones could correspond to collective use (Fig. 9d).

The new structures identified in this work and their location give the site a greater spatial complexity. Although only a very brief excavation campaign has been carried out in area F of the site (Da Riva et al., 2019), the new findings through the study of the 3D model place Sela as one of the so-called mountain strongholds on the southern Transjordan plateau. Until now, as suggested by different authors, mountain strongholds were Umm al-Biyara, Ba'ja III, Jabal al-Qseir, Umm al'Ala (as-Sadah), Kutle II, Jabal al-Khubtha, Sheik er-Rish y Qurayyat al-Mansur (Lindner, 1986; Lindner & Farajat, 1987; Lindner et al., 1988, 1990; Lindner, 1992; Lindner et al., 1996; Bienkowski, 2014). According to Glueck (1939) and Ben-David (2001), the site of Gosa / Qosa al-Hamra, located northwest of Sela, could also be included as a mountain stronghold. However, there is no reference to hydraulic structures.

Lindner & Knauf (1997) consider that these settlements are located on the rocky peaks of the Edom plateau and share two main characteristics: no direct access to springs and the presence of water collection and storage facilities in all of them. In addition to these features, mountain strongholds are located in an environment that does not encourage permanent settlement; they are difficult to access; they have a large number of storage facilities for agricultural products, the so-called "communal houses"; they are located between terraces and small fields that are suitable for small-scale agriculture, horticulture, viticulture, and pastoralism; there is a partial or total absence of so-called "fine pottery"; and they are Iron II period settlements. A further aspect of the mountain strongholds in the Sela area is that they form a mountain range that connects the Gulf of Aqaba area with the Dead Sea area. This trade route, according to Nigro (2014), may have been in operation since the Early Bronze Age. Finally, another feature is the security and defence provided by the natural properties of the promontories. In addition, defensive structures such as the watchtower at Umm al-'Ala have also been found at some of these sites (Lindner et al., 1988, 1990).

4.3. The role of Sela as a mountain stronghold

This study provides a more detailed analysis of the defensive character of Sela through the study of structures already identified and the documentation of new ones. Area D stands out, where the main element in this area is the grand staircase that allows the only access

to the promontory from the wadi overcoming the 110 m of height that separates them. This is developed by adapting to the topography, generating multiple bends during the ascent, and combining sections of stairs with landings. In the space created by the highest bend from which all the access is dominated stands a structure of 3 walls that create a surface area of 3.15 x 3.70 m. Given its location and characteristics, it seems to be a tower or surveillance post that would control the entrance. The other housing structure that we find in this area is a raised platform that would dominate the final section of the access to the promontory, and that is made up of two rooms delimited by walls of variable thickness (H3) with characteristics and dimensions very similar to structure H2, located in area F.

Towers documented in Area F (T1) and J (T2) stand out as defensive elements. Both are located to the northeast and southwest of the promontory, in strategic positions to control the surrounding valleys from which the summit of the promontory is accessed, Wadi Hirsh and Wadi Jamal, respectively. According to Lindner et al. (2001: 275), the masonry and mortar ceramics of T1, which defended the access from the stairway, date from the Ayyubid-Mamluk period. However, the surface pottery and the pear-shaped cisterns suggest that its use could correspond to an Iron II period or earlier phase.

Finally, the new defensive structure located in area L has a shape whose characteristics resemble a tower. Its location in an area that topographically dominates a large part of the central area of the site suggests a space for the control and defence of the promontory. Since Sela has hardly been excavated, it is challenging to determine the specific functions of these spaces. However, such structures emphasise the importance of the site, which had to be protected. According to Lindner (1986, 1992), these sites were first established in the 7th century BCE and functioned as areas for safely storing food or other valuables. Mouton & Schmid (2013: 28) argue that the absence of typical Edomite 'fine' or painted pottery (Oakeshott, 1983), as well as the evidence of ceramic storage assemblages, could corroborate this interpretation. For these authors, the economy of its occupants would be based on the exchange of agricultural products with other settlements on the plateau. On the other hand, this and other authors (Lindner, 1986; Lindner & Farajat, 1987; Lindner et al., 1988, 1990; Lindner, 1992; Lindner et al., 1996; Ben-David, 2001) do not rule out the possibility that these were shelters in case of threat to the inhabitants of the permanent settlements in the region or to the robber bands of the caravans that crossed Edom. However, the history and interpretation of the function of these settlements, as well as their chronology, is still under discussion.

There are numerous theories about Sela's role. Undoubtedly, the settlement is similar to the Iron Age mountain-top sites in southern Jordan (Lindner & Knauf, 1997). Sela's defensive characteristics and geostrategic location are the main factors that have allowed researchers to propose different hypotheses about its function. Sela could be a "central place" for non-sedentary groups (Lindner et al., 1996), a stronghold or refuge from danger (Ben-David, 2001, Lindner et al., 2001, Raz et al., 2001; Kołodziejczyk, 2015, MacDonald, 2015), a satellite of settlements on the plateau (Hart & Falkner, 1985) or a habitation place with sequences of rooms used as storage and distribution facilities (Lindner, 1989, Lindner & Knauf, 1997). According to Lindner (1989, 1992), Sela functioned as a dwelling place and a temporary settlement.

There are numerous theories about Sela's role. Undoubtedly, the settlement is similar to the Iron Age mountain-top sites in southern Jordan. Unlike previous proposals, in this study, we have added water availability, distribution, and control to these factors. All together, these features determined the density, intensity, and continuity of human occupation at Sela.

Following Hart & Falkner's (1985) proposal, depending on the area's security, this settlement could have housed the surrounding communities, who would reside permanently in areas close to the site. Ben-David (2001) suggests that it was a refuge for the inhabitants of Busayra. According to this author, the proximity of Busayra -only 4 km away- supports this hypothesis. Similarly, Starcky (1966) considers Sela, well provided with water storage tanks, a safer refuge than Busayra, built on a plateau-bound spur. However, insufficient information indicates whether Sela was a refuge for Busayra's inhabitants or a settlement without a relationship to a higher level of organisation. Based on this hypothesis, it is a matter of speculation about the causes of the need for refuge. According to Ben-David (2001), the groups could take refuge from different external enemies, such as the kingdom of Judah, the tribes of Arabia, or the kingdoms of Assyria and Babylon. From Diodorus of Sicily (XIX, 95, 1-2), it is also known that at the end of the 4th century BCE, the Nabataeans protected themselves against the Seleucid king Antigonos on a rock, which was interpreted to be Sela (Kołodziejczyk, 2015: 102-103). Despite this, many researchers consider that this event should be linked to Petra rather than Sela.

The diversity of hydraulic installations for storing, transporting, and controlling water and the design of Sela's hydraulic networks suggest ongoing use. The inhabitants of Sela have taken measures to ensure a guaranteed water supply through different hydraulic systems, indicating continuous long-term use. These facilities would only be able to operate with some, albeit minimal, maintenance. Hydraulic structures require constant cleaning due to the non-watertight canals carrying sediment into the reservoirs. Whether this cleaning was done regularly at fixed intervals or irregularly each time the promontory was reoccupied cannot be confirmed, as both possibilities are plausible. If cleaning is irregular, water storage becomes inefficient when the reservoirs become filled with sediment, especially in a location with occasional and heavy rainfall.

Furthermore, the canal network served not only as a water supply for storage systems but also played a role in preventing flooding in certain areas of the promontory. Without regular maintenance, any canals would likely malfunction due to sediment accumulation. This suggests the potential for a permanent year-round occupation at the site. Thus, contrary to the assumptions about the mountain strongholds of Lindner & Knauf (1997), the present study suggests that the site was occupied permanently and continuously. However, it cannot be ruled out that it was temporarily unoccupied. The numerous remains of solid architecture and domestic pottery from the Bronze Age to the Mamluk period (Lindner et al., 2001) would support this hypothesis. In addition, the number of hydraulic structures suggests that one of the valuables that could be stored at Sela was water. We may therefore be looking at a water bastion in the region.

5. Conclusions

The methodology proposed in this study has demonstrated the feasibility of analysing long-term hydraulic systems and has yielded highly positive results. The high-quality images generated offer new potential for researching and presenting the water supply systems at the site of Sela.

The visual inspection carried out directly on the 3D model has enabled the identification of new archaeological structures not previously identified by the pedestrian survey. These newly identified structures and their locations contribute to the site's spatial complexity and facilitate the detection of archaeologically relevant areas based on their features, topography, and placement.

The 3D model was the basis for creating a DEM, which provides adequate resolution for studying local hydrology. The hydrological analysis confirms that flood-prone areas align with the spaces detected by the 3D model. It also demonstrates that the main settlement density zones correspond to elevated locations to avoid the facilities' collapse due to flooding and ensure their entire operation. Therefore, it can be suggested that the communities that built the Sela supply system had specialists of great constructive and technical capacity (Marsal, 2023).

The newly acquired data significantly enhances the comprehensive mapping of the site, surpassing the previous findings regarding the investigation of the water supply systems. Future research can use the interpretation of these spaces to propose strategies and practices for ensuring the successful operation of hydraulic systems, encompassing their construction, usage, and the social structures involved in water supply and management.

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Supplementary files

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