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Early water management systems on the southern Transjordan plateau

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ABSTRACT

The efficient management of water resources to supply the needs of societies in territories where water is a scarce and limited resource has been essential throughout time. The site of Sela on the southern Transjordan plateau is unique for understanding water management in this semi-arid area. The analysis of hydraulic installations has allowed us to characterise its hydro technology and spatial distribution in the settlement. To this end, the hydraulic facilities have been identified, documented, and analysed in detail through two archaeological surveys (2015 and 2016). Spatial analysis has been carried out by preparing extensive 2D planimetry and 3D reconstructions. The results obtained have made it possible to reconstruct the water supply system necessary for the subsistence of the societies that inhabited Sela over time. The system consists of canals, cisterns, and sedimentation basins for the collection, conduction, storage, and preservation of water, mainly from rain. Some of Sela's hydraulic structures may have originated in the Bronze Age (mid-late 2nd mill. BCE), but more secure dating is needed to substantiate this possibility.

1. Introduction

Water acquisition, distribution, and conservation techniques and strategies have been fundamental over time, especially in areas where the search for water is essential to the lives of human groups. Each specific natural environment offers different access to water and requires different strategies and techniques to manage it (Al-Dbiyat and Mouton, 2009). In the arid or semi-arid areas of the Ancient Near East, the main limiting factor is the low and erratic availability of rainfall. Therefore, rainwater harvesting was fundamental for the communities that inhabited these areas (Sanlaville, 1981). They developed an efficient water technology to make the most of this scarce resource (Berking, 2018).

The large number of archaeological remains of hydraulic structures at Sela has been a focus of attention for the authors who have studied this site prior to the project, Sela Archaeological Project led by Rocío Da Riva (Glueck, 1939; Hart, 1986; Lindner, 1989, 1999; Lindner et al., 2001; Bagg, 2006; Kolodziejczyk, 2015; MacDonald, 2015). However, a detailed and comprehensive study of its water management system had never been addressed until this author conducted a survey and analysis for her doctoral research.

This study highlights the particularity of Sela in understanding the strategies and techniques developed over time for water gathering, storage, and supply. The investigation had three main objectives. The first is to define the systems that enabled water resources management. The second is to establish the hydraulic networks of the site through the analysis of the spatial organisation of the hydraulic facilities. The third is to evaluate the hydraulic systems according to the technical, typological, and stylistic comparison of the Sela water structures with the water facilities of other settlements in southern Transjordan, also in relation to radiocarbon dating by Accelerator Mass Spectrometry (AMS) of the mortars lining some of the structures (Table 3).

2. Study area and archaeological context

Sela is located on the southern Transjordan plateau, in the highlands of the eastern edge of the Wadi Arabah-Jordan Graben, about 7 km south of at-Tafila (Fig. 1c) (Da Riva and Marsal, 2017). The rainfall regime (from 1938 to 2007) at at-Tafila can reach 200–250 mm per year. Rainfall is erratic, intense, and concentrated during the rainy season. There is a large variability of precipitation from year to year, and this factor was probably more significant in the past (Sharadqah, 2014).

The site rises on a steep outcrop of Cambrian sandstone (Umm Ishrin Formation) covered by Ordovician sandstones (Disi Sandstone Formation) (Bandel and Salameh, 2013). The promontory of Sela (at 877 m a.s.l.) is elevated about 200 m above Wadi Hirsh, to the south, and Wadi

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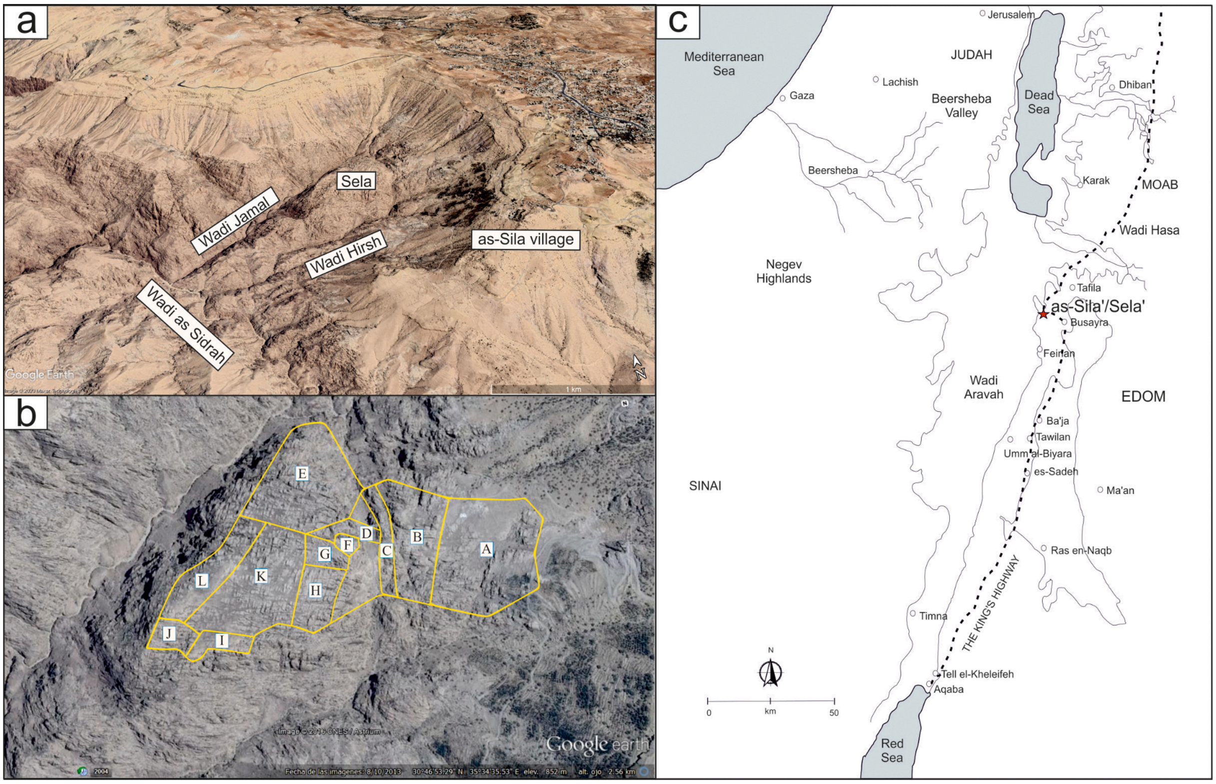


Fig. 1. a) Location of Sela with the surrounding wadis and the present-day village of as-Sila. Source: Google Earth 2020. Image © 2020 Maxar Technologies, modified by the author. b) Map of the different areas of the site. Source: Google Earth 2016. Image © 2016 CNES / Astrium, modified by the author. c) General map of the location of Sela. Source: Marsal, 2021.

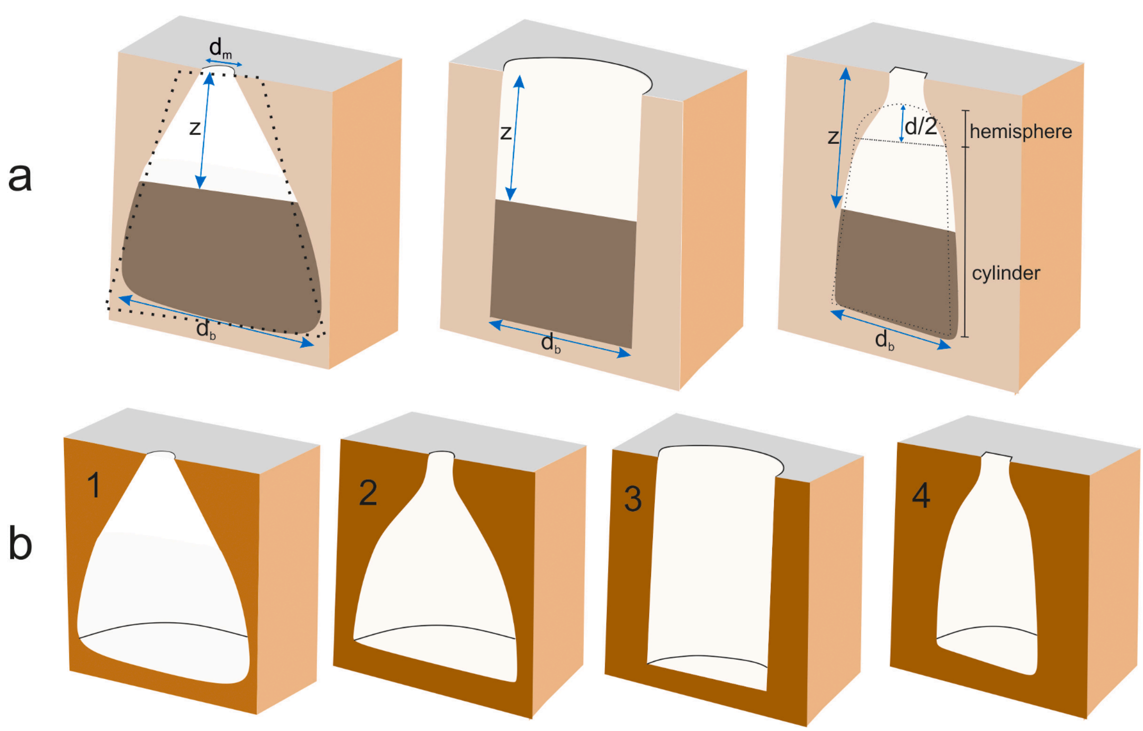


Fig. 2. a) From left to right: dimensions taken to calculate the current free capacity of a pyriform, cylindrical, and bottle-cylindrical cistern (d = diameter; z = depth; d_m = average diameter and d_b = base diameter. b) Proposed shapes of the cisterns of Sela: 1) pyriform; 2) bottle; 3) cylindrical and 4) bottle-cylindrical. Source: modified from Marsal, 2021.

Table 1
Classification of cisterns by types and subtypes. Ud = Undetermined.

Type	Total	%	Subtype	Total	%	Structure
1. Cisterns excavated in flat terrain	26	39	**a.** With neck	10	38	D03, D07, D15, D38, D45, D57, D58, D73, D79, D99
			b. Without neck	9	35	D44, D46, D75, D53, D91, D18, D24, D25, D26
			c. With the diameter of the mouth regular or enlarged when the storage chamber is excavated	1	4	D33
			d. Dug into the vertical walls for support	3	11	D34, D36, D86
			e. Dug into the vertical walls for support and enlarged below them	3	12	D35, D87, D90
2. Cisterns excavated inside a vertical cavity	4	6	**a.** With steps	3	75	D09, D23, D83
			b. With access corridor	1	25	D95
3. Cisterns partially excavated on a flat surface and in a vertical rock wall	15	23	**a.** By recessing the vertical rock wall as the mouth opening	5	33	D01, D16, D27, D47, D76
			b. By using the intersection between a flat surface and the vertical rock wall	6	40	D02, D05, D20, D22, D63, D98
			c. By recessing the vertical rock wall, which has the same diameter of the opening as that of the storage chamber	4	27	D30, D49, D64, D88
4. Cisterns excavated completely into the standing boulders	3	5	**a.** With one opening	2	75	D10, D52
			b. With two openings	1	25	D55
Ud	18	27				D13, D43, D59, D51, D67, D78, D82, D97, D100, D103, D37, D41, D80, D81, D96, D40, D68, D85

Jamal, to the north, which connects with Wadi as Sidrah on its western side (Glueck, 1939) (Fig. 1a). The total surface area of the site covers about 42 ha (Da Riva et al., 2017) (Fig. 1b).

The location of Sela, about 4 km southwest of the King's Highway, which was the main north–south route through the Transjordan area during antiquity (Lipiński, 2013), has been the focus of interest of many researchers (Fig. 1c).

The pottery recovered from the site suggests a framework of occupation from the Early Bronze Age (ca. 3rd millennium BCE) to the Mamluk period (14th-15th century BCE) (Hart and Falkner, 1985; Hart, 1986; Lindner, 1989; Lindner et al., 2001). Architectural archaeological evidence suggests significant occupation during the Iron Age period, specifically Iron II (Lindner, 1999; MacDonald et al., 2004; MacDonald, 2015). The presence of a Nabonidus inscription, king of the Neo-Babylonian empire (556–539 BCE), on the eastern slope of the outcrop indicates the referential position of this site during this period (Dalley and Goguel, 1997; Qatamin, 2001; Raz et al., 2001; Crowell, 2007).

3. Materials and methods

The hydraulic structures analysed in this work are the outcome of the archaeological surveys carried out in 2015 and 2016 in Sela. A base map of the topographic data was drawn up using AutoCAD 2015 software. According to the defined areas, all structures were described and numbered on the base map. Each water-related facility was characterised with a letter according to its type: C = canal; D = water-holding structure; M = wall. Water-holding structures are differentiated into cisterns, reservoirs, sedimentation basins, and pools. Following Bagg's (2017) proposal, the difference between the first two is their maximum storage capacity, more than 100 m^3 for reservoirs and less than 100 m^3 for cisterns. Pools refer to open artificial water-holding structures for storing rainwater, whose width and length are more relevant than their depth. Lastly, the hydraulic facilities and other architectural structures were grouped by sector (S).

During the fieldwork, each structure was recorded according to the location, form, construction techniques, materials, orientation, slope, dimensions, state of conservation, and their relationship with the adjacent structures. The types of hydraulic facilities at the site were described: cisterns, canals, sedimentation basins, dams, pools, and undetermined hydraulic structures. In addition, specific typologies have been established for each type of structure.

For the study of the cisterns, the level of silting up was measured, and an estimate of current free capacity in litres (L) was conducted (Oğuz-Kirca, 2016) as neither access nor excavation was possible. For this purpose, the proposal of Lancaster (2006, 133, appendix 3, equation 9b) was followed according to the geometric shapes that may correspond to the primary forms of cisterns. Following Watt and Wood (1979), the base diameter has been considered 1 m, which is the minimum diameter for an operator to build a cistern. Due to the silting up, their classification has also been done by extrapolating the documented evidence of the most common shapes: pyriform, bottle-shaped, cylindrical, and bottle-cylindrical (Oleson, 2001, 2008, 2010; Keilholz, 2007, 2014; Shqiarat, 2019; Ore et al., 2020) (Fig. 2, Appendix A).

For the study of the canals, the mean value of their slope (P) was established according to P= (initial height-final height)/(Length) × 100.

Based on the topographic plan of the site (including contour lines) and the information on the hydraulic structures, the three-dimensional digital modelling of Sela was carried out. Also, the photogrammetric models of the fourteen most representative water-related facilities were created using AutoCAD 2015 and 3D Studio Max software. The 3D model allowed the display of the theoretical connection network of hydraulic facilities, especially canals and water-holding structures. Section maps showing the unevenness of the network in each of its sections were also carried out using the AutoCAD 2015 program.

To detect changes or similarities in the production of mortars lining some hydraulic facilities and select samples with little contamination for

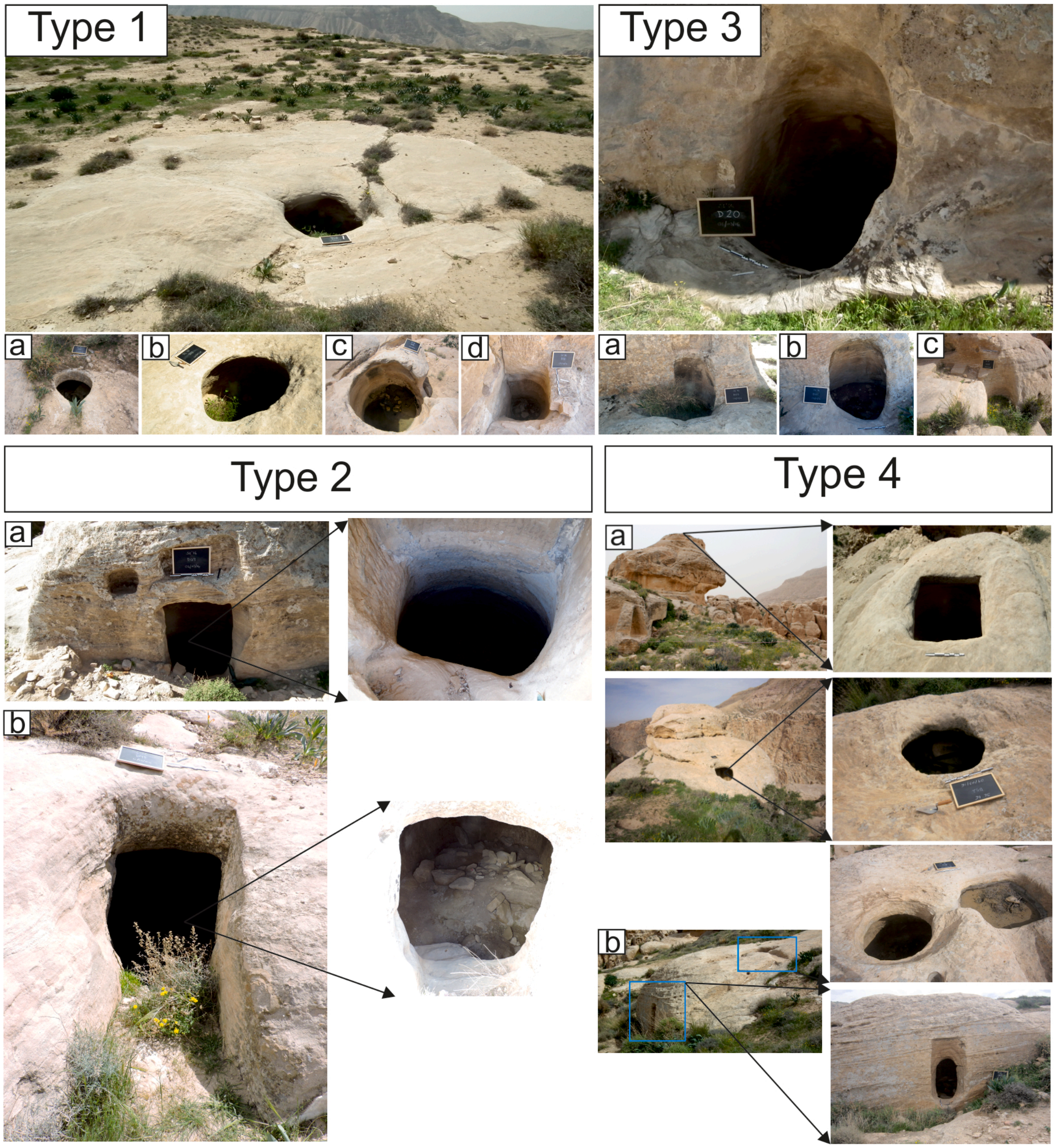


Fig. 3. Main types and subtypes of defined cisterns. Source: modified from Marsal, 2021.

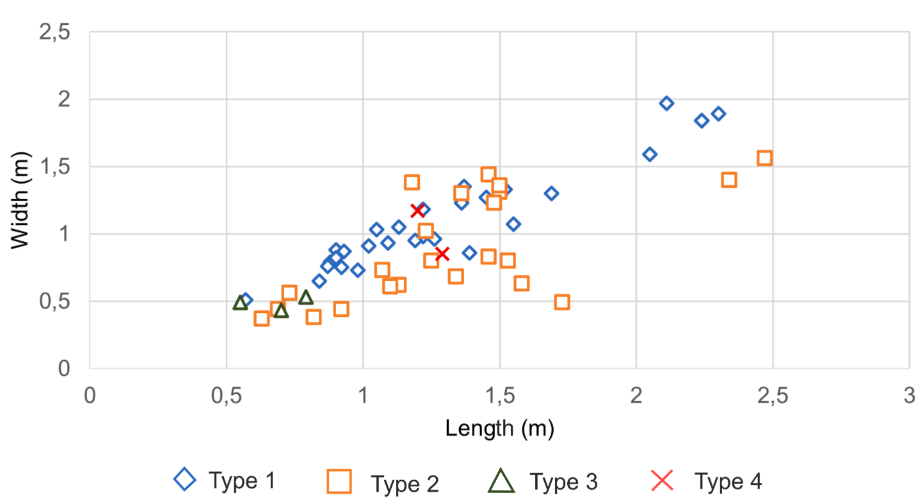


Fig. 4. Graphic representation of the width and length of the mouth of the cisterns according to the typology. Source: modified from Marsal, 2021.

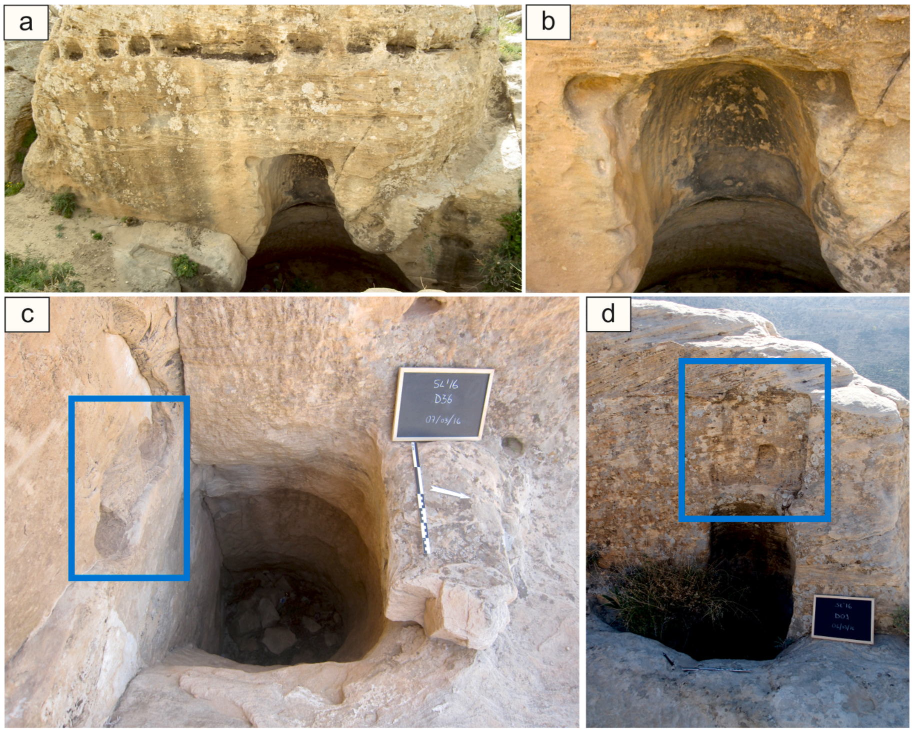


Fig. 5. a) Cistern D16. b) Detail of the "dome" of cistern D1 with two holes on both sides of the structure. c) Box showing the two holes in cistern D36. d) Box showing the recess on cistern D02. Source: modified from Marsal, 2021.

dating by 14C AMS, 14 structures were petrographically and mineralogically characterised. The samples correspond to 11 cisterns, one undetermined facility, probably related to water storage, and two levels of the H1 structure (Marsal, 2021). The variability of structures and levels allowed the determination of the differences in the composition of the mortars depending on each installation. The elaboration of thin sections for petrographic and mineralogical characterisation was carried out following the guidelines of the Geoarchaeology laboratory of the Institut de Paleoecologia Humana i Evolució Social (IPHES) in Tarragona (Soto, 2017). In addition, microdiffraction (μXRD) to thin sections has been carried out at the Servei de Recursos Científics i Tècnics (SRCiT) facilities of the Universitat Rovira i Virgili in Tarragona.

4. Results

4.1. Hydraulic structures

The total number of hydraulic structures documented at Sela is 136. The cisterns ($n = 66$) and the canals ($n = 51$) are the most abundant. All the structures are excavated in the sandstone bedrock and show intense alterations due to erosion (84.3% of canal fragments) and silting up (100% of the cisterns, pools, reservoirs, and sedimentation basins, and 54.9% of canal fragments). Both factors are considered in the hydraulic network's documentation at Sela, as discussed above, concerning the current free capacity of cisterns.

4.1.1. Cisterns

The cisterns have been classified according to their shape and location. According to their form, eleven pyriform, eleven bottle-shaped, four cylindrical, and two cylindrical-bottle-shaped cisterns have been identified. However, the rest have been classified as undetermined due to the extent of the silting up. Based on their location, four types were established with a further category for undetermined types (Table 1 and Fig. 3).

According to their location, cisterns excavated in flat terrain are the most significant (type 1, 39%), followed by cisterns partially excavated on a flat surface and in a vertical rock wall (type 3, 23%). A large percentage of undetermined cisterns is due to their silting up (Ud, 27%). Regarding subcategories, the most significant type 1 cisterns are those with or without a neck (a and b, 38 and 35%, respectively). Subcategories 3a and 3b (33% and 40%, respectively) also stand out.

The mouths of the cisterns have the following shapes: oval ($n = 30$), circular ($n = 11$), semi-oval ($n = 5$), semi-circular ($n = 5$), square ($n = 2$), pointed ($n = 1$), or indeterminate ($n = 12$) (Table A.1). Type 1 cisterns have a length ranging from 1 m to 1.5 m, except for cases exceeding 2 m (D13, D24, D25, and D67). The exception of cistern type 1 is cistern D15, with an axis between 0.82 m and 0.63 m. Type 2 cisterns have an axis between 0.5 and 1 m, type 3 cisterns between 0.5 and 1.7 m, and type 4 cisterns between 1 and 1.5 m (Fig. 4).

In total, the current free capacity of 16 cisterns has been calculated. The huge volume belongs to the pyriform cisterns (7300–2200 L), followed by the bottle-shaped cisterns (3400–1800 L). On the other hand, the cylindrical ones have a volume of less than 1000 L (Table A.1). Their current capacity needs to be determined concerning the sedimentation volume of the cistern. Although we do not know what it was, it can be assumed that cisterns with sedimentation basins in the network would have less sediment than larger basins carrying a larger volume of sediment.

Recesses or sockets cut into the bedrock have been identified related to hydraulic structures. Most of them are arranged horizontally on cistern walls (Fig. 5a), on both sides of the opening of its mouth or the entrance that gives access to it (Fig. 5b), on the vertical wall where it is built (Fig. 5c), or on the top of its mouths (Fig. 5d). Their role will be discussed below.

Finally, 27 cisterns have extant lime-based mortars to waterproof their walls and prevent water leaks due to the high absorption coefficient of the Disi Sandstone that shapes the landscape where Sela is located (Migón and Goudie, 2014). They are mainly preserved in the storage chambers, although they can also be found lining the entire structure.

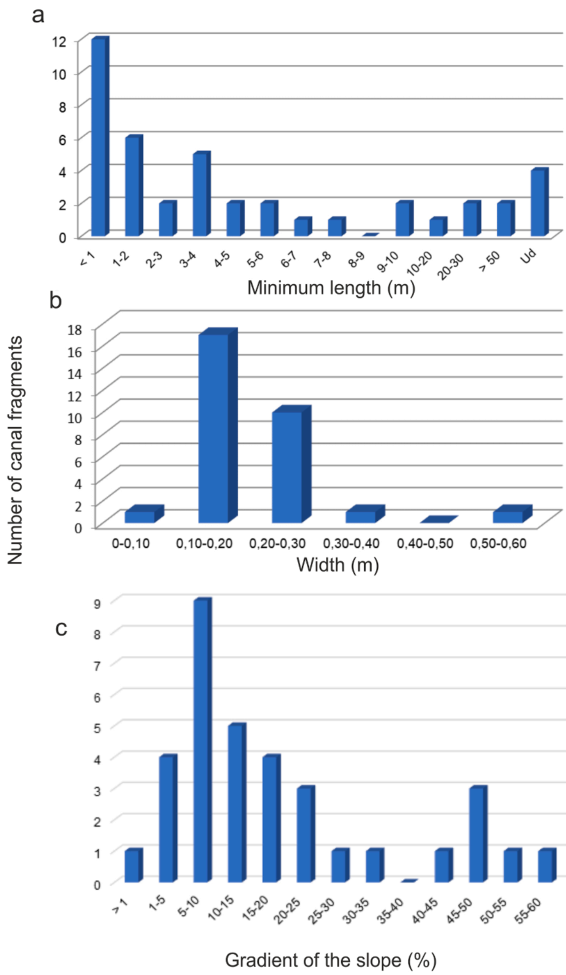


Fig. 6. Graphical representation of a) the minimum length of the canal fragments; b) the width of the canal fragments according to ranges of 0.1 m; and c) the gradient of the canal fragments. Source: modified from Marsal, 2021.

4.1.2. Canals

A total of 51 canal fragments have been documented, of which it was possible to establish that C104, C12, C121, C119, and C14 belong to the same facility. Four types, according to their design, slopes, and connections, have been established: catchment (type 1), conduction (type 2), overflow (type 3), and connection between two structures (type 4). In Sela, the most representative is type 2 (n = 28, 54.9%), followed by type 3 (n = 6,11.76%), type 4 (n = 10, 19.61%), and type 1 (n = 7, 13.73%).

The catchment canals (type 1) collect the runoff water gathered on the large rocky surfaces. Except for canal C17, they all have standard features: a length of more than 10 m, an open section, an angle of the wall of the section of about 100 or 110°, and no evidence of lime-based mortars or signs of covering. The conduit canals (type 2) supply water from one structure or connect a water catchment area to a water storage or retention area. Most of them have very varied cross-sections and dimensions. The longest canals are more than 50 m long, as in the case of canal C50, and some were covered with slabs and lined with mortars. Due to this lining, the canal would be waterproofed to prevent water loss, reduce deterioration due to the action of water flows and ensure that the water would have less friction on the canal's walls. Overflow canals (type 3) carried water from cisterns to other hydraulic structures when they were full. They are open and have mainly semi-circular sections. Finally, the connecting canals (type 4) link two hydraulic structures, particularly a sedimentation basin with a cistern (78% of the canals identified in Sela). The characteristics (dimensions, slope, and section) of the types defined are presented in Table A.2.

The dimensions of the canal fragments (length, width, depth) have revealed only nine that have preserved their entire course (between 0.26 and 0.60 m in length and 0.10–0.26 m in width). Canal fragments are between 1 and 50 m in length and have a modal width of 0.10–0.20 m. Their modal gradient is 5–10% (Fig. 6), although slopes of less than 1% and between 55 and 60% have been identified.

The variability of construction techniques of the canal fragments has led to their classification in: open (n = 42) and covered canals (n = 8). The C32 canal is the only one with both open and closed stretches. Among the open canals, there are canals excavated directly into the bedrock (n = 38) and canals that take advantage of fissures in the ground for their layout (n = 5) (Fig. 7a-d). Although some canals do not directly preserve the slab, some conserve the marks of the recesses where they were inserted to cover them. In the canals dug into the bedrock, different sections have been observed according to the type of excavation or whether they are open or covered (Fig. 7f).

The canal fragments excavated through partitions or fissures in the rock have an angle of the wall of the section of about 100 or 110° (n = 5). In contrast, canals dug directly into the bedrock are in cross-section semi-circular (n = 14), rectangular (n = 3), trapezoidal (n = 1), square (n = 1), square with slab (n = 1), and triangular (n = 1). There are eight canal fragments with different sections, although it is not known what it corresponds to, and 15 with an undetermined section produced by the disintegration and alveolarization of the sandstone at Sela due to erosion. As a comparative example, the canals excavated in the Cambrian sandstone of the Umm al-Biyara site are better preserved due to the greater hardness of the sandstone compared to the Ordovician sandstone of Sela (Schmid and Bienkowski, 2011).

4.1.3. Sedimentation basins

The ten documented sedimentation basins have been classified into two types (Fig. 8), with a further category for undetermined types (n = 4):

Type 1: they have inlet and outlet canals (n = 3), divided into two subtypes according to the presence (type 1a, n = 1) or absence (type 2b, n = 2) of small openings or holes to transfer the decanted water from the water-holding structure to the canal.

Type 2: they only have an outlet canal (n = 3). They have been divided into two subtypes according to the presence (type 2a, n = 1) or absence (type 2b, n = 1) of a quadrangular-shaped elevation on one of the sides or corners of the facility. It is unknown what function this element would have had; it has been suggested that it allowed access to the water-holding structure for maintenance.

They have been considered undetermined when the identification of inlet or outlet canals could not be documented. Their dimensions (between 1.84 and 0.97 m in length and 1.19–0.49 m in width), estimated volume, type, orientation, slope, and relationship to other structures are presented in Table A.3.

4.1.4. Dams

Only one structure (M130) has been identified as a dam. It is on the slope leading down to the Wadi Hirsh from the modern village of Sela. It consists of a wall of sandstone blocks covered with thick layers of mortar arranged in at least five courses to a height of about 2.15 m (Fig. 9).

4.1.5. Pools and reservoirs

Four pools have been described, characterised by rectangular shapes associated with possible water catchment areas (Fig. 10a). These structures are between 1.45 m long and 1.20 m wide and could have stored between 680 and 1100 L of water (Table A.4). The openings of their inlet or outlet canals could be below the debris levels. However, we have no evidence because these structures have not been excavated. It may be suggested for use as a watering trough for livestock.

The only hydraulic structure identified as a reservoir (D21) has on its

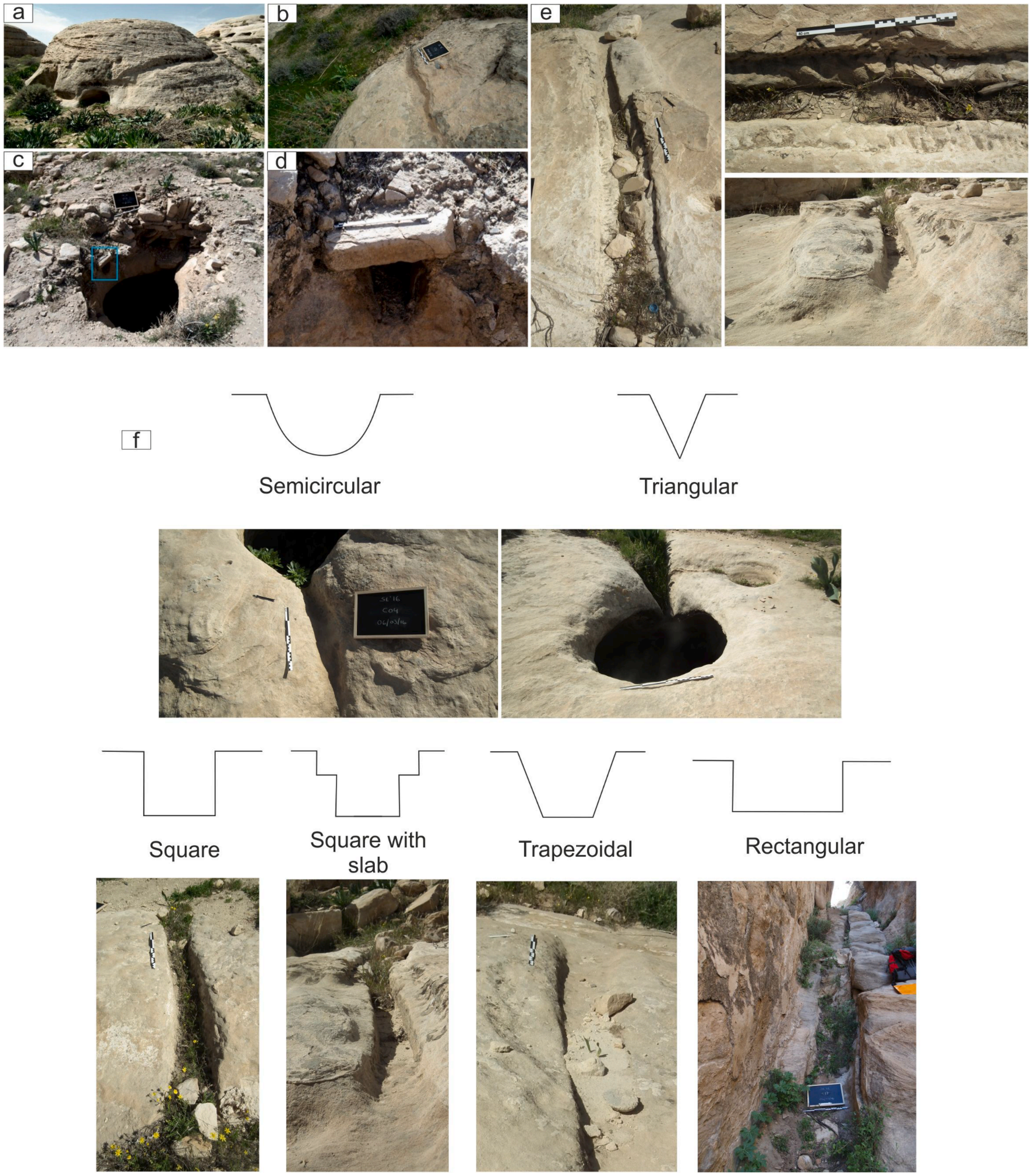


Fig. 7. a) Canal C39 dug through fissures in the rock. b) Canal C56 dug directly into the bedrock. c) Cistern D13 and canal C119. d) Detail of canal C119. e) Extension of documented canal C11 (left); detail of the marks for inserting the slabs that covered it (top right) and detail of the section of the canal (bottom left). f) Sections of canal fragments. Source: modified from Marsal, 2021.

walls remains of lime-based mortars and sockets arranged in one or two courses, which could correspond to supports for a perishable construction (Fig. 10b). The east wall is 4.23 m long, and the south wall is 5.16 m long. The hydraulic structure is 3 m deep up to the silting level, so the structure's current free capacity would be about 7100 L. Assuming that the facility could be considerably deeper, it has been given the status of a reservoir (Table A.4). A perishable covering could be related to the desire to reduce evaporation and preserve water in optimal conditions for consumption.

4.1.6. Undetermined hydraulic facilities

Finally, three structures were documented according to their rectangular morphology, the location of other hydraulic installations, and the application of lime-based mortars to avoid percolation, which could be associated with water management (Fig. 11). Its features, dimensions, and volumes are presented in Table A.5.

4.2. Spatial analysis of hydraulic structures

Table 1 shows that the areas with the highest number of hydraulic structures are L (27), E (21), G (20), I (20), F (18), and K (17) and that the majority variety of types is concentrated at the top of the outcrop (areas E-L). In contrast, the area occupied by the Wadi Hirsh (A) and the access to the top of the outcrop through stairs cut into the bedrock (D) have only two and one water installation, respectively. Areas A and B have no hydraulic structures and are not included in this study.

Among all the distribution maps of the hydraulic structures drawn up for each area (Marsal, 2021), a more significant relationship between

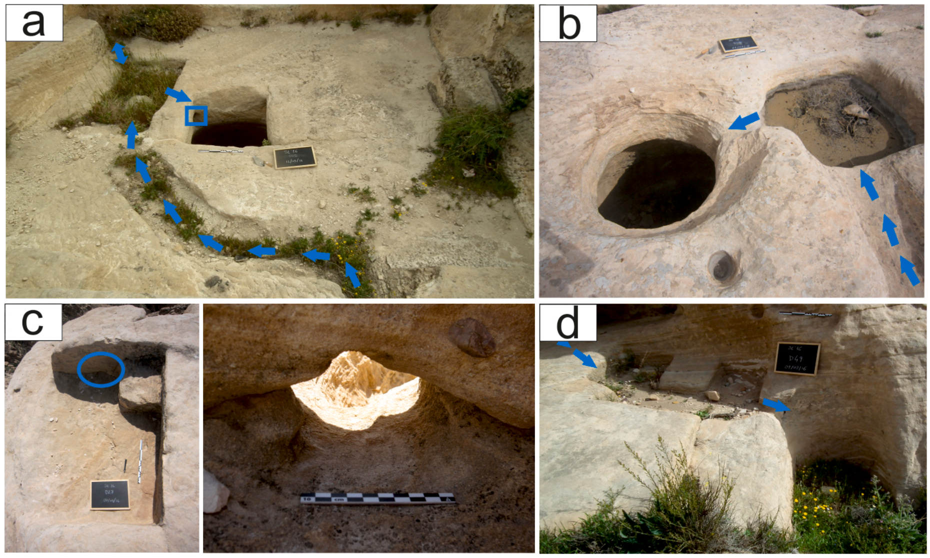


Fig. 8. a) Sedimentation basin D111 with its respective water inlet and outlet canals. b) Inlet and outlet canals of sedimentation basin D112. c) Indication of the location of the opening of sedimentation basin D28 (left) and detail of the opening (right). d) Outlet canal and possible water catchment area of sedimentation basin D128. Source: modified from Marsal, 2021.

Fig. 9. Dam in Wadi Hirsh (left) and the dam wall (right) detail.
Source: Marsal, 2021

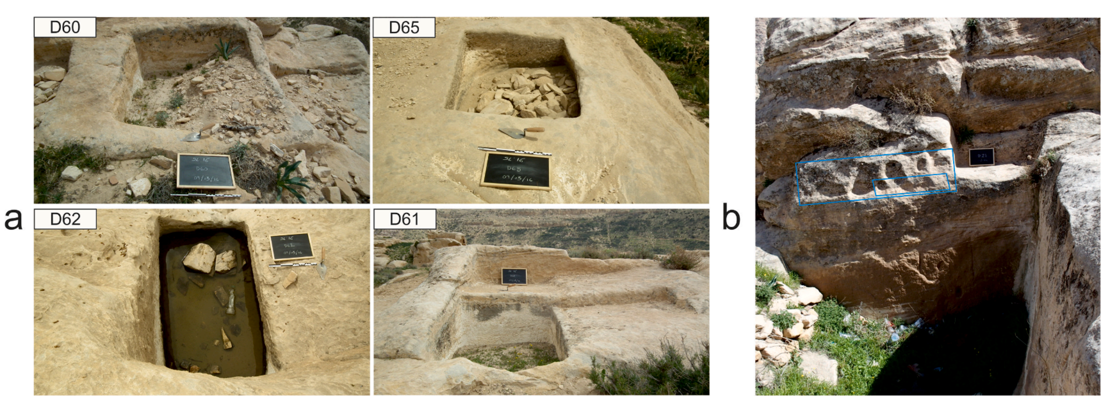


Fig. 10. a) Documented structures possibly associated with water catchment areas. b) In the box, sockets of the east wall of reservoir D21. Source: modified from Marsal, 2021.

Sela's architectural and hydraulic structures can be observed in areas F and I. In area F, it has been possible to determine hydraulic facilities related to undetermined architectural structures and two possible domestic structures (H1 and H2). The clearest is H2, where painted stucco remains were found (Da Riva et al., 2017). Just to the southeast of this is structure E10, an elevated platform structure with two staircases

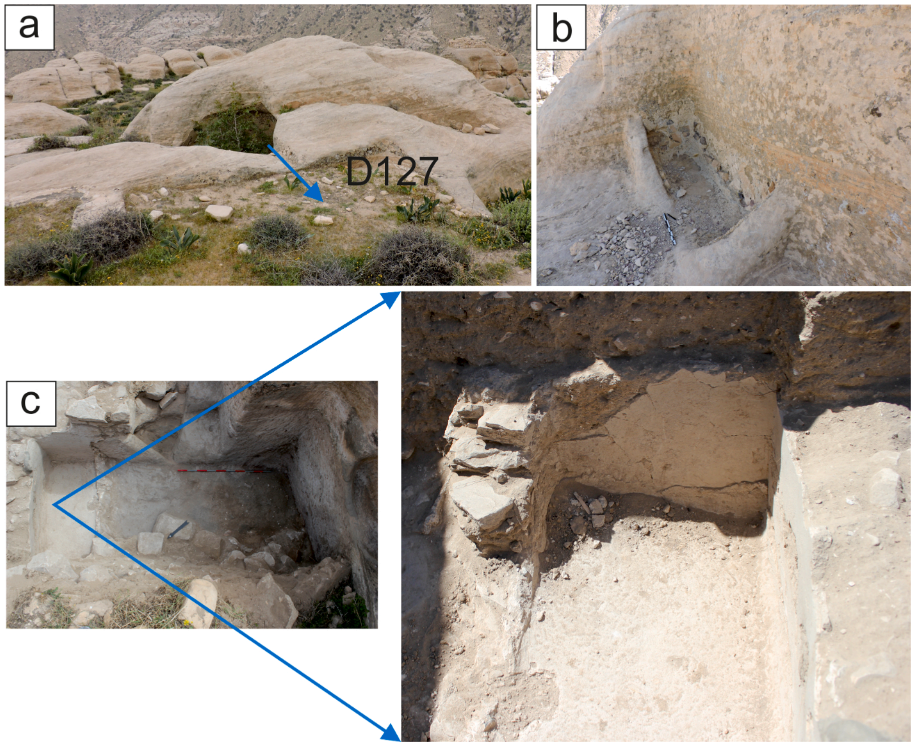


Fig. 11. a) Structure D127, where the slope of canal C92 is indicated. b) Structure D107. c) Structure D115. Source: modified from Marsal, 2021.

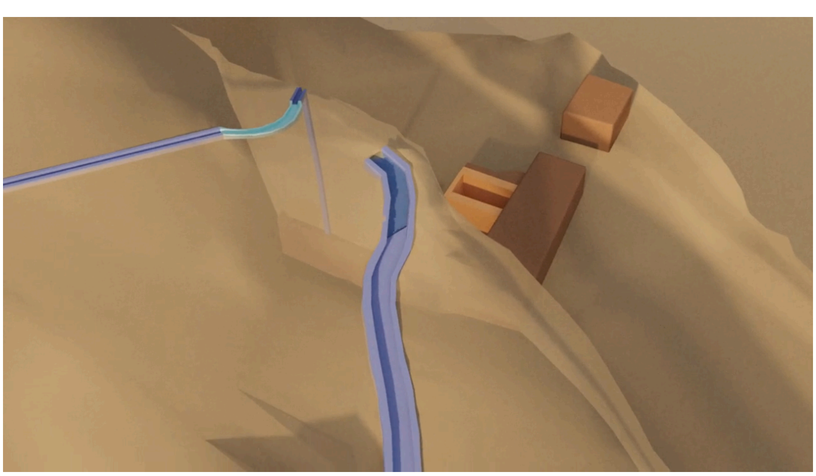
for access (to the northwest and southeast), and structure E11 which presents two associated staircases. However, its function is unknown. The same occurs in area I, where hydraulic systems associated with rock-cut stairways and doubtful structures have been identified (Fig. 12). It is noteworthy that all identified pools are located in this area. According to Lindner (1989), the rock-cut stairways' symmetrical layout and the space's arrangement could correspond to an ancient cult place similar to those identified at Petra or in the urban centre of Hegra (Dentzer, 2010). The use of these pools could, therefore, be very diverse: supplying livestock, human consumption, or possible ritual use.

However, the absence of architectural features in the other areas related to most of these hydraulic systems suggests exclusive water catchment and storage spaces. These installations are part of small assemblies consisting mainly of a cistern type 1, 3, or 4, an inlet and outlet canal, and, in some cases, a sedimentation basin (Fig. 13).

The distribution of the main types and sub-types of hydraulic structures analysed in this work, which are unevenly distributed, are presented in Fig. 14.

A hypothetical 3D reconstruction was carried out based on the direct (Table 2) and indirect connections of the hydraulic structures identified to check whether there is a relationship between the hydraulic installations in area F.

A complete canal consisting of the canal fragments C104, C12, C119, C121, and C114 has been traced according to canal orientation and the topography of the area. The catchment area of this canal system could not be documented due to lack of evidence. Following this reconstruction, all these canal fragments would join, with a drop of 5 m from its head, with the D15 cistern, after passing by the D13 cistern, acted as a regulating water-holding structure to reduce the velocity in the canal (Video 1). It has also been proposed that cistern D10, located on the tower in this area, could have been a rainwater collection cistern. According to Glueck (1939), the top of this tower was encircled by a sandstone block wall. It probably raised the outer level of the tower and thus helped divert rainwater that fell on its top towards the cistern.



Video 1. 3D model of the hydraulic system of area F. Source: Jesús García Carpallo.

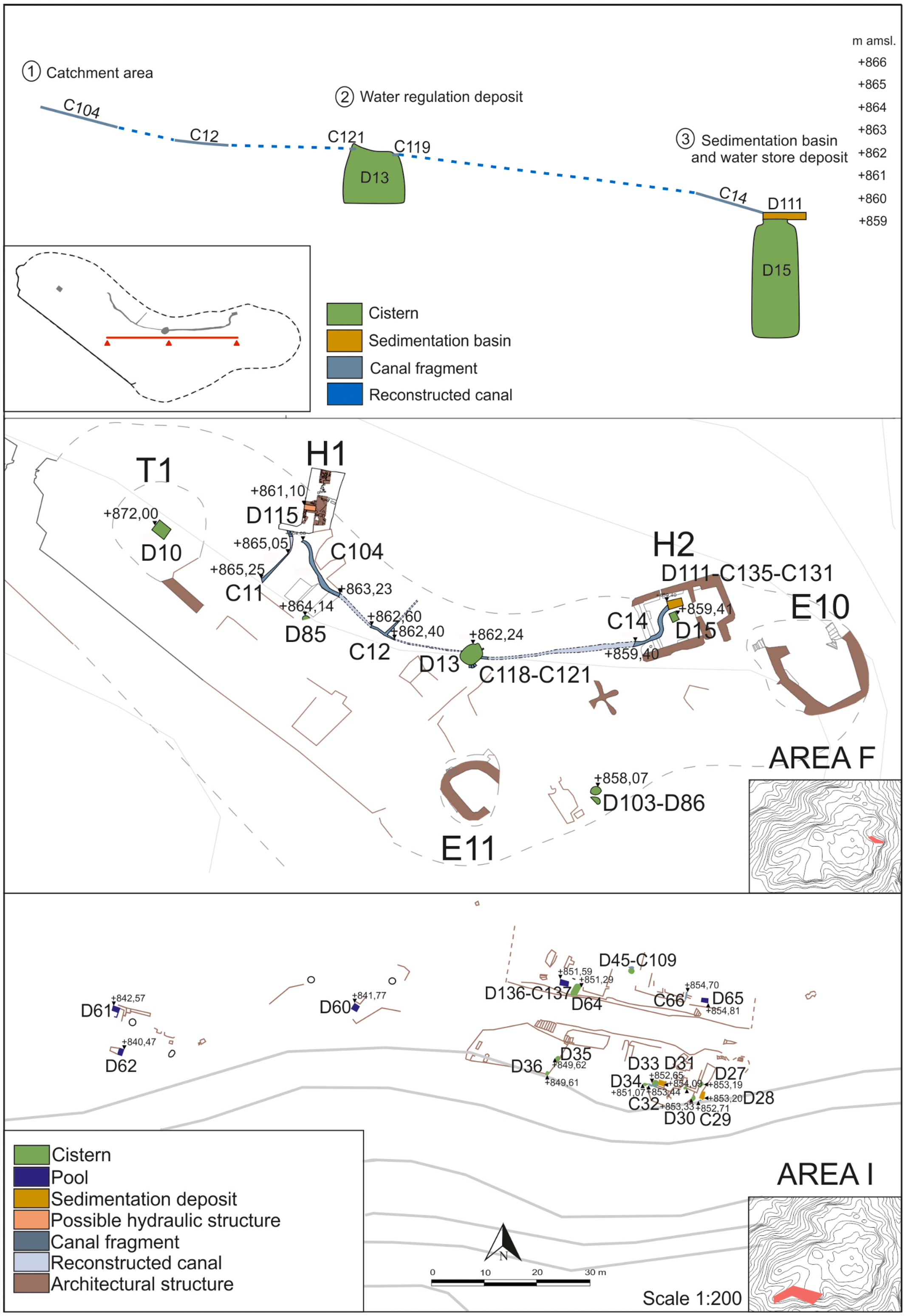


Fig. 12. Map of the distribution of hydraulic structures in areas F and I. Source: modified from Marsal, 2021.

4.3. Lime-based mortar technology

As shown in Table 4, five types of mortar have been identified according to their composition (Marsal, 2021). Among them, types 1–3 are hydraulic mortars (Figs. B.1-B.3). They have a binder composed of micritic and microsparitic calcite and clay minerals. Lime is water-resistant and has a higher malleability, with minimal shrinkage (Elsen, 2006). In addition, mineral clays give lime specific hydraulic properties. As aggregates, pottery fragments and charcoals have been observed as well as ashes in types 1 and 3 and flints in types 1–2. All these components increase its hydraulic property. Quantitatively the binder/aggregate ratio is 3:1, the most common ratio for lining hydraulic installations, mainly cisterns (Sha'er, 2004). These proportions and their composition indicate that types 1–3 are very similar and were made for

Fig. 13. Different perspectives of the three-dimensional model of the sedimentation basin D28, canal C29, and cistern D30. .
Source: Marsal, 2021

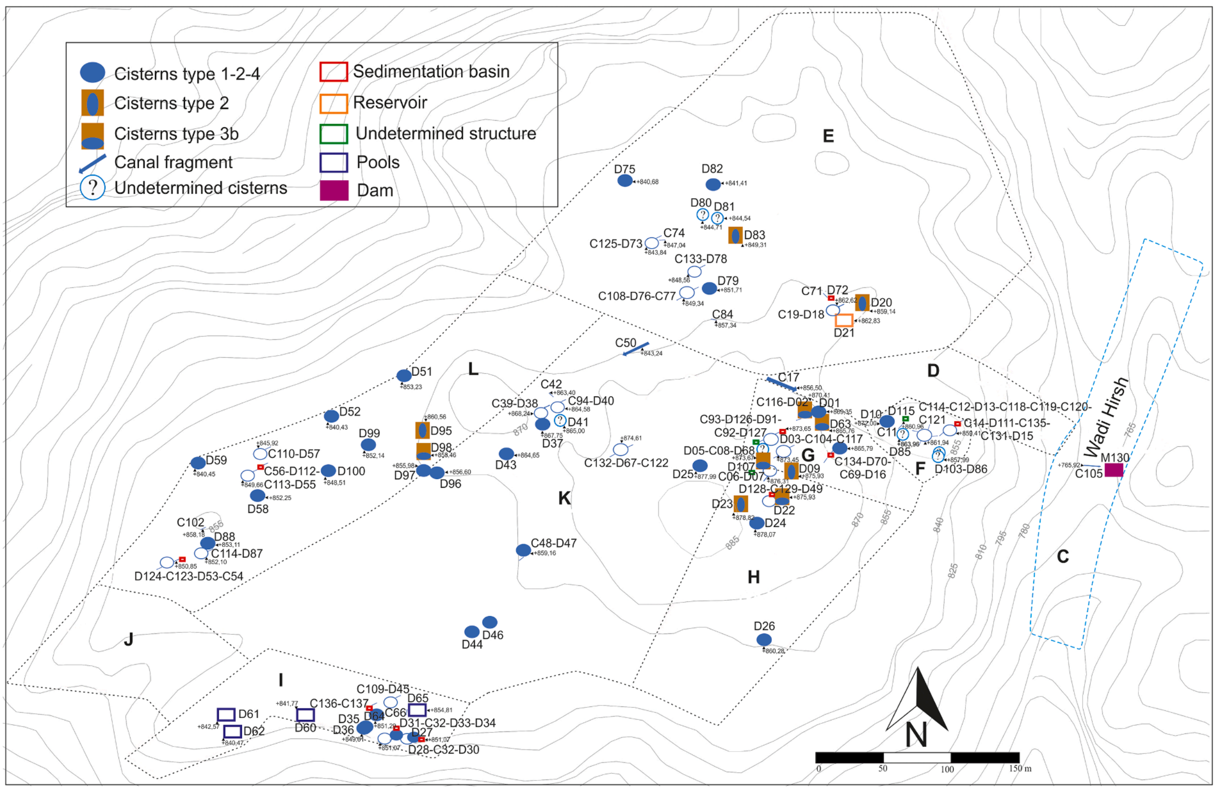


Fig. 14. Spatial distribution of the leading hydraulic structures analysed. Source: modified from Marsal, 2021.

lining hydraulic installations. Whereas types 4 and 5 (Figs. B.4-B.5) were probably produced to line pavements or floors. Furthermore, the μXRD of thin section results have shown that no significant differences in the mineralogical composition of the different types of mortars identified can be inferred (Table B.1). These results indicate a continuity over time of lime-based mortar production practices.

The binder of all the samples analysed is composed of calcite, quartz, and clay minerals. The μXRD results reaffirm the presence of these minerals in almost all samples. As for micro-aggregates, the main ones observed are sandstones, detrital quartz, limestones, and flints. The local Umm Ishrin Sandstone and Disi Sandstone formations are composed of these minerals (Mouton and Schmid, 2013), confirming the use of locally available minerals. Bonazza et al. (2013) have documented similar compositions in the Petra area, which are characterised by the same sandstone formations. Remarkably, a limestone outcrop was detected in area L of Sela, located on the western part of its hilltop. Thus, it cannot be ruled out that this outcrop was used as a source of lime to line the hydraulic facilities (Da Riva and Marsal, 2017).

5. Discussion

Research of the hydraulic structures and their spatial distribution at Sela has allowed us to propose the primary sources that could have been exploited and established the water supply system. This last includes conduction, storage, and control of the quality and quantity of water systems.

The territorial study has established that rainwater, surface water from the Wadi Hirsh during rainfall events, and groundwater from the Moyet Dleib spring were the three water supply sources for Sela. The main advantages and disadvantages of each water source are listed in Table 5.

The hydraulic facilities included in the catchment system are canals (type 1) and cisterns (type 1, 3, and 4), which are in the surroundings of the catchment areas. Regarding the rainwater collection canals (type 1), their gradual slope and length would contribute to water transport, preventing the rock's erosion. The absence of mortar remains suggests that their use was unnecessary, as the water circulated for a shorter time. According to Al-Muheisen (2009), this system effectively collected

Table 2
Summary of the distribution of hydraulic structures by area. C = Cisterns; Ca = Canal fragments; SB = Sedimentation basins; Ud = Undetermined hydraulic structures; P = Pools; R = Reservoir; D = Dam. .

	C	Ca	SB	Ud	P	R	D
C	–	C105	–	–	–	–	M130
D	–	C17	–	–	–	–	–
E	D18, D20, D73, D75, D76, D78, D79, D80, D81, D82, D83	C19, C71, C74, C77, C84, C108, C125, C133	D72	–	–	D21	–
F	D10, D13, D15, D85, D86, D103	C11, C12, C14, C104, C118, C119, C120, C121, C131, C135	D111	D115	–	–	–
G	D01, D02, D03, D05, D09, D16, D63, D68, D91	C04, C08, C69, C92, C93, C116, C117, C134	D70, D126	D127	–	–	–
H	D07, D22, D23, D24, D26, D49	C06, C129	D128	D107	–	–	–
I	D27, D30, D33, D34, D35, D36, D45, D64	C29, C32, C66, C109, C137	D28, D31, D136	–	D60, D61, D62, D65		–
K	D25, D37, D38, D40, D41, D43, D44, D46, D47, D67	C39, C42, C48, C50, C94, C122, C132	–	–	–	–	–
L	D51, D52, D53, D55, D57, D58, D59, D87, D88, D90, D95, D96, D97, D98, D99, D100	C54, C56, C89, C101, C102, C110, C113, C114, C123	D112, D124	–	–	–	–

Source: Marsal, 2021

rainwater during the region's short and scarce precipitation episodes. Exceptionally, the C17 canal, located in the siq of Sela, is thickly plastered and has a staircase on its side to access it. These characteristics indicate that this canal may have collected rainwater from the upper part of the rock and diverted it through other canals to the lower part. Its use, therefore, could be related to agricultural supply (Bruins, 2012; Oweis et al., 2012). This type of canal has been documented in the Petra region (Amr et al., 1998; Bellwald, 2008), in the Wadi Feinan (Newson et al., 2007; Crook, 2009), in the Negev (Avner, 2002; Bruins, 2012) and Umm al-'Ala (Lindner et al., 1988). Regarding the cisterns, the small dimensions of their mouths show that they were not designed to collect water directly. At Jabal al-Qseir, Khirbat Masala, ARNAS 146, SAAS 259, and Bronze and Iron sites in the Negev Highlands (Ore et al., 2020), small entrance mouths around 1–1.5 m as at Sela have also been documented. In addition, the analysis of the composition of mortars reveals a homogeneous technology in the fabrication of the plaster, which could indicate a cultural tradition of water management resources.

The conduction systems at Sela facilitated water transport from the catchment area to the storage area to increase its capacity. Their study has made it possible to document water transport networks throughout the settlement's summit as a network of communicating vessels. This network is based on water transport channels from one structure to another, mainly cisterns with a sedimentation basin or connecting a catchment area with water storage or retention. Square-section canals closed by a slab and the mean slope of the canals (5–10%) show that

Table 3
Summary of the direct relationships between the identified hydraulic structures and the 11 radiocarbon dates (Da Riva et al., 2021) in relation to the hydraulic structures from which the lime mortar samples were obtained.

Area	Sector	N° of related structures	Reference	Type of structure	Radiocarbon dates from lime-based mortars (n° structure, n° lab, age BP and calibrated ranges)
D	–	0	–	–	–
E	S1	2	C19-D18	Canal-cistern	–
	S2	2	C133-D78	Canal-cistern	–
	S3	2	C125-D73	Canal-cistern	–
		3	C108-D76-C77	Canal-cistern-canal	–
F	S2	5	C14-D111-C135-C131-D15	Canal-sedimentation basin-canal-canal-cistern	–
	S8	0	D115	Undetermined hydraulic facility	D115 (CNA# 4189.1.1) 980 ± 30 993–1055 CE (51.0%) 1077–1153 CE (49.0%) D115 (CNA# 4391.1.1) 1000 ± 30 983–1049 CE (82.2%) 1086–1124 CE (14.5%) 1137–1150 CE (3.3%)
	S13	5	C118-C119-C120-C121-D13	Canal-canal-canal-canal-cistern	D13 (CNA# 4397.1.1) 910 ± 25 1035–1189 CE (99.1%) 1199–1202 CE (0.9%)
G	S13	3	D05-C08-D68	Cistern-canal-cistern	–
	S11	2	C116-D02	Canal-cistern	–
	S10	4	C134-D70-C69-D16	Canal-sedimentation basin-canal-cistern	D16 (CNA# 4192.1.1) 3150 ± 30 1498–1382 BCE (90.0%) 1340–1310 BCE (10.0%)
	S12	5	C93-D126-D91-C92-D127	Canal-sedimentation basin-canal-canal-cistern / undetermined hydraulic structure	D91 (CNA# 4396.1.1) 2300 ± 30 404–356 BCE (82.1%) 286–235 BCE (17.9%)
		3	D03-C117-C04	Cistern-canal-canal	D03 (CNA# 4393.1.1) 2890 ± 30 1192–1170 BCE (3.3%) 1165–1144 BCE (3.3%) 1131–977 BCE (93.4%)
H	S14	0	D107	Undetermined hydraulic facility	D107 (CNA# 4193.1.1) 2660 ± 30 895–868 BCE (8.7%) 857–854 BCE

(continued on next page)

Table 3 (*continued*)

Area	Sector	N° of related structures	Reference	Type of structure	Radiocarbon dates from lime-based mortars (n° structure, n° lab, age BP and calibrated ranges)
					(0.6%) 850–794 BCE (90.7%)
	S15	2	C06-D07	Canal-cistern	–
	S16	3	D128-C129-D49	Sedimentation basin-canal-cistern	–
		0	D22	Cistern	D22 (CNA# 4392.1.1) 2500 ± 30 787–699 BCE (27.9%) 696–540 BCE (72.1%)
I	S20	2	C109-D45	Canal-cistern	–
	S21	3	D28-C29-D30	Sedimentation basin-canal-cistern	–
	S21	4	D31-C32-D33, D34	Sedimentation basin-canal-cistern-cistern	–
K	S29	2	C48-D47	Canal-cistern	–
	S27	2	C39-D38	Canal-cistern	D38 (CNA# 4191.1.1) 2980 ± 30 1371–1359 BCE (1.2%) 1297–1113 BCE (98.8%)
	S27	2	C94-D40	Canal-cistern	–
	S27	2	D37-D38	Cistern-cistern	–
	S31	3	C132-D67-C122	Canal-cistern-canal	–
L	S35	4	D124-C123-D53-C54	Sedimentation basin-canal-cistern-canal	–
	S36	2	C114-D87	Canal-cistern	–
	S37	2	C110-D57	Canal-cistern	D57 (CNA# 4394.1.1) 2650 ± 30 894–870 BCE (6.3%) 849–792 BCE (93.7%)
		0	D59	Cistern	D59 (CNA# 4395.1.1) 1260 ± 25 670–778 CE (92.9%) 791–805 CE (2.1%) 812–826 CE (1.7%) 840–862 CE (3.3%)
		4	C56-D112-C113-D55	Canal-sedimentation basin-canal-cistern	–

water transport was carried out in such a way to guarantee its quality, avoiding the transportation of solid particles and the erosion of the canal. The presence of sedimentation basins would have prevented a greater amount of transported sediment from accumulating in the cisterns during heavy rainfall. Likewise, the identification of lime mortar in the conduction canals indicates the existence of technology suitable for preventing water infiltration and erosion.

The water storage systems in Sela allowed water harvesting during rainy periods to supply the demand during long periods of drought. These include underground facilities and open reservoirs, especially cisterns, whose large number at Sela is remarkable. In the case of reservoir D21, some similar ones have been documented at Jabal al-Qseir, Ba'ja III, and north of al-Beq'ah (Lindner et al., 1996). For cisterns, their typological variability related to their location shows clear parallels with the cisterns of the mountain strongholds, dated to Iron II (Lindner and Knauf, 1997) at Umm al-Biyara (Schmid and Bienkowski, 2011), Jabal al-Qseir (Lindner et al., 1996), Umm al-'Ala (Lindner et al., 1988; Lindner, 2003), Kutle II (Lindner et al., 1988) and Ba'ja III (Lindner and Farajat, 1987; Bienert et al., 2000), Sheikh er-Rish (Glueck, 1939) and with a large number of cisterns from the sites surveyed by different projects throughout the southern Transjordan area[1] (MacDonald, 1988, 1992; MacDonald et al., 2001, 2012, 2016) (Fig. C1). Most of these sites have not been precisely dated and have different phases of occupation, some of which have chronologies beginning in the Bronze Age period (Bir al-Bitar, Kh. Al-Hamah, Kh. Al-Hateh, SAAS 271, Al-Shraifihe Shmaliya, SAAS 305, Khirbat Harir, SGNAS 49, Muafa, WHS 182, 196, 287 and 855). The preference for pyriform and bottle shapes, characterised by small mouths (0.6–1 m), indicates an efficient technology for sheltering stored water from solar exposure and facilitating covering installations. The covers would have minimised evaporation and reduced the risk of contamination (Hodge, 2000). In addition, both shapes are the largest in water storage, around 2000–7000 L, since the storage chamber is enlarged. Both morphologies have been observed at many sites in the southern Transjordan region, where Ba'ja III, Umm al-Biyara, and Jabal al-Qseir stand out by number. Cylindrical forms have also been documented at sites such as Khirbat Masala, ARNAS 146, and SAAS 259.

Related to the goal of preserving the maximum quantity of water, the presence of sockets concerning hydraulic structures, as suggested by Lindner et al. (2001), would allow the installation of mechanical devices such as winches, traction or lifting devices like pulleys, or the insertion of covers, enclosure devices or other lightweight structures. These relate mainly to type 2 cisterns excavated in a vertical-cavity with no supply canals. For them to have been in use, water transport would have had to be carried out manually. As Wåhlin (1997) points out, many such cisterns have been associated with natural caves used as cisterns found throughout the Negev and the southern Levant since the Middle Bronze. Here, the water would be more protected, cleaner, and fresher, being less exposed to possible contamination caused by animals and less exposure to sunlight, and therefore less likely to evaporate or be contaminated by bacteria. Their shape might suggest an alternative use, being used as provisions storage. However, such facilities are prevalent in southern Transjordan and are often associated with their use as cisterns (Lindner, 1992; Shqiarat et al., 2010). These storage facilities indicate the accumulation of water for human consumption.

Nevertheless, two types of structures may have had another purpose. Firstly, the Wadi Hirsh dam (M130) demonstrates the need to store large volumes of surface water, although its total capacity is unknown. Its use would be related to agricultural and livestock supply (Charbonnier and Schiettecatte, 2013). These kinds of dams, located in the fissures of the mountains, are typical of the studied area, as shown by the different dams of the Petra siq, which have been widely studied (Bellwald, 2004, Oleson, 2018) or the Rekhemtein dam (Glueck, 1935; Oleson, 1995; Nydahl, 2002). Secondly, the pools and the reservoir could be used for water supply for livestock. According to Hammer (2018), implementing such structures would have reduced time and energy spent fetching water, making local grazing feasible.

[1] These are The Wadi al-Hasa Archaeological Survey (WHS); The Southern Ghors and Northeast 'Arabah Archaeological Survey (SGNAS); The Tafila-Busayra Archaeological Survey (TBAS); The Ayl to Ras an-Naqab Archaeological Survey (ARNAS) and The Shammakh to Ayl Archaeological Survey (SAAS).

Table 4
Binder/aggregate composition and binder/aggregate ratio of the five lime-based mortars and the number of the sample. Source: modified from Marsal, 2021.

Type	Sample number	% Binder	Binder	% Aggregates	Main aggregates	Binder/ aggregate ratio
1	SL'16.H1. UM3.1 SL'16.H1. UM3.2 SL'16.H1. UM3.498 SL'16.H1. D01.4 SL'16.D13.1	70–80	Micritic and microsparitic calcite, micrite, sparite, microsparite, microsparite and clay minerals	30–20	Sub-rounded or sub-angular detrital quartz, microsparitic and micritic calcite, chert fragments and iron oxides, probably hematite	3:1
2	SL'16.D05.7 SL'16.D09.6 SL'16.D16.2 SL'16.D03.5	60–80	Micrite, microsparitic and micritic calcite and clay minerals	40–20	Sub-rounded and sub-angular detrital quartz and micritic, sparitic and microsparitic calcite, pottery fragments and organic matter	3:1
3	SL'16. D57.10 SL'16.D22.8 SL'16. D59.11 SL'16.D63.3 SL'16.D38.9	70–80	Micrite and microsparitic calcite and clay minerals	30–20	Sub-angular and sub-rounded detrital quartz and microsparitic and sparitic calcite, pottery fragments and organic matter	3:1
4	SL'16. H1.6.169	50–60	Microsparitic calcite	40–60	Fragments of microsparitic limestone, sub-rounded quartz, organic matter, pottery fragments, charcoal, ashes, possible phytoliths, bones and adobe fragments	2:1
5	SL'16. D107.10	50–60	Micritic calcite	50–40	Microsparitic limestone fragments, sub-rounded detrital quartz, secondary gypsum, ash, and massive hematite	2:1

Table 5
Main disadvantages and advantages of operating water sources in Sela. Source: modified from Marsal, 2021.

Sources of water supply	Disadvantages	Advantages
Rainwater	• Possible contamination in collection and storage • Variability depending on rainfall patterns	• Access to the resource without the need to travel • Management of storage • Control of usage
Surface water (Wadi Hirsh)	• Intermittency • Limitation of water quantity by transport • Water quality and need for treatment	• Location • Relatively easy water catchment
Groundwater (Moyet Dleib)	• Possible reduction of flow in dry seasons • Water quantity depends on the hydrology of the area and the aquifer	• Quality of water

Finally, the water conservation systems, designed to regulate its flow and preserve water for consumption, were water evacuation, treatment, retention, and regulation facilities. The water evacuation facilities were mainly overflow canals to transfer water from one cistern to another when one of them overflowed. However, the existence of internal canals between cisterns cannot be ruled out. The water treatment facilities documented in Sela were all sedimentation basins. Their presence attested in all the areas of the site, except for areas E and K, indicates an intention to purify the water from the solids it carries and thereby improve its quality. Thus, stored water over long periods could be used for human consumption (Chatzakis et al., 2006). The presence of an intermediate regulating cistern (D13) and systems for covering the water-holding structures and canals are also evidence of water regulation systems at Sela. The only water retention facility was the dam, which could have been used as a retaining wall and store water. Agricultural terraces and wadi barriers cannot be ruled out to regulate water flows. As Oleson (2018) suggests, perhaps the wadi flow was so intermittent that it was unnecessary to implement them.

The distribution of hydraulic structures has revealed that their location was related to natural catchment basins provided by irregularities, slopes of the terrain, and natural formations. Fig. 14 illustrates how the hydraulic installations are distributed in different areas with elevations ranging from 878 to 870 m amsl (areas H and G) to 850–840 m amsl (areas D, E, and I). As Migón and Goudie (2014) indicated, the sandstone's permeability and the scarce vegetation in the area would produce a high water infiltration into the ground. However, during episodes of high-intensity rainfall, the infiltration rate was probably reduced, increasing water runoff (Bender, 1974; Salameh et al., 2018). Both factors would contribute to optimising the total volume of runoff water that could be harvested and stored. In line with what Crouch (1993) calls "geological determinism", these features may have favoured the choice of the outcrop of Sela as a place of settlement with its water supply system. However, as Mouton (2009) suggests, although water may have been a decisive factor, other factors such as protection, trade routes, or proximity for acquiring additional resources were considered to choose the location. The difficult access, easy defence, and control position of Sela, in addition to its proximity to different trade routes crossing the region from north to south (Lipiński, 2013) and from east to west (Riehl and Shai, 2017), and the proximity to the Feinan copper mining region (Levy et al., 2014), were probably relevant factors for its occupation.

The location of the three water sources of Sela (the top of the outcrop, the Wadi Hirsh area, and the vicinity of the present-day village of as-Sila'), the hydraulic systems, and the water conservation features indicate that the water was intended for local use, mainly for human consumption. Based on Geyer's (2009) proposal on the patterns of social structuring around water access and exploitation, the absence of a network of centralised distribution canals and large reservoirs for its storage suggests a single community managed the domestic and communal use. Although traditional historiography emphasises the existence of state power behind significant hydraulic engineering works, as argued by LaBianca (2006), Lafont (2009), and Kaptijn (2018), ancient societies were able to manage water at local level without the need for higher-order regulation or control.

The settlement on the top of the outcrop of Sela, permanent or temporary, would be unlikely without the existence of hydraulic systems that guaranteed the water supply. The reuse of water systems over time can mask the construction date of the hydraulic installations. Nevertheless, it can be suggested that some of them were in use from the earliest occupations at Sela. Based on the only published study of pottery from Sela (Lindner, 1989), this would correspond to the Bronze Age (ca. 3rd millennium BCE). AMS radiocarbon dates of the lime-based mortars from cisterns D16 (CNA# 4192.1.1) and D38 (CNA# 4191.1.1) (Da Riva et al., 2021) may indicate cisterns in Sela having plaster of the 14th-12th centuries, if the lime was not contaminated with older carbonate rock fragments, such as insufficiently burnt limestones or micro-fossils or limestone fragments of geogenic origin present within calcareous or siliceous aggregates (Hayen et al., 2017). Although contamination cannot be ruled out, the selection of samples based on the petrographic and mineralogical analysis of lime-based mortar minimises the risk that the samples were contaminated and increases the reliability of the results.

Contrary to Tebes (2020), who discards the mid-late 2nd millennium BCE time horizon of the Sela mortar dating, I propose that the lime-based radiocarbon dates involved may in fact be correct, indicating the presence of cisterns used during the Late Bronze Age. The two mortar samples yielding Late Bronze Age dates have been processed with the same methodology (standard carbonate pretreatment, Daugbjerg et al., 2021) as the samples that have provided chronologies ranging from Iron II to the Middle Islamic period (Table 3). Moreover, both samples were selected to be prepared and measured at the dating lab (Centro Nacional de Aceleradores, CNA) in the first batch as petrographic and mineralogical analysis of the samples showed less recrystallisation and post-diagenetic process and the presence of abundant charcoal (Soto, 2017). Unfortunately, the charcoal was not dated separately by AMS, which would have given valuable additional dating information.

Some researchers date the hydraulic installations (cisterns) in the Negev highlands to the Iron Age II (Evenari et al., 1958, 1982) and suggest a considerable increase in the number of cisterns in the Transjordan area in this period, following the application of linings (Wåhlin, 1997; AbdelKhaleq and Alhaj Ahmed, 2007). However, in the southern Levant, Hesban lined cisterns are dated to the Iron Age I (LaBianca, 1990), and even the site of Tell Ta'annek, one of the lined cisterns has been dated to the Middle Bronze or early Late Bronze Age (Lapp, 1969). Likewise, many of the designs of Sela's hydraulic structures, notably the rock-cut canals and pyriform cisterns, are present from the Bronze Age throughout the eastern Mediterranean and the Levant (Negev, 1972; Braemer, 1988; Oleson, 2001, 2008, 2010, 2018; Mays et al., 2013; Graßhoff and Meyer, 2018; Ore et al., 2020).

Furthermore, at Sela, unlike other sites in the region, the gradient of the hardness of the sandstone would have allowed the first hydraulic structures to be carved with tools that did not necessarily have to be made of iron (cf. Tebes, 2020). Thus, this study suggests for the first time that communities with nomadic lifestyles (transhumant pastoralists) could have built the first water catchment and storage structures to increase water availability expanding the amount of usable pasture. As Hammer (2018) argues, these communities were the first to manage water resources to capture and store rainwater. Therefore, these groups may have temporarily occupied Sela during the Bronze Age. Subsequently, depending on the socio-political and economic conditions and needs of each period, they designed and developed the set of hydraulic facilities that have survived today.

6. Conclusions

This work is the first systematic and detailed analysis of all the hydraulic installations at Sela, which has revealed a complete water supply system unparalleled in the southern Transjordanian plateau. The results have shown that the main objective of the hydro technology at Sela was to implement facilities to collect, conduct, store and preserve water, mainly rainwater. The Sela water technology reflects specialised responses that denote efficient systems to maximise the quality, conservation time, and water storage for consumption, with additional use for agricultural and livestock supply. Furthermore, Sela is a unique example in the region of developing efficient local water management techniques that may have originated from semi-nomadic communities. The direct dating of mortar, the archaeological context of the site, and the regional context suggest that the first use of cisterns, and probably the rock-cut canals, may have originated already during the Late Bronze Age. The lime-based mortar analysis demonstrates the reuse of these facilities and the continuation of mortar manufacturing practices over time. It denotes the sustainability of these structures and the resilience of the local communities that managed them.

The study contributes to the current knowledge on water culture studies in the southern Transjordan region, where Sela can be considered a model of regional water technology in different periods, as suggested by radiocarbon dating of lime mortars. In addition, the complete analysis of the entire supply system is unique in the region, which can serve as a potential guide to investigate other areas in terms of water supply; the socio-cultural dimensions of its management; and population dynamics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data are included as annexes (Annex A, B and C) in the manuscript.

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Appendix A

Methodology of cisterns

When the cistern has no neck and the diameter of the storage chamber is larger than the mouth, they are proposed as pyriform. On the other hand, when the cisterns have a well-marked neck and the walls of the storage chamber are wider than the neck, they are considered bottle-shaped. Finally, when the cistern has no neck and the diameter of the mouth remains constant in the storage chamber, they are considered cylindrical. This classification incorporates the combination of bottle and cylindrical shape (Fig. 2b).

Table A.1
Description of type, the shape of the mouth and inlet of the cisterns, dimensions and orientation of its mouths, presence or absence of neck, proposed shape, and current free capacity (in L). Ud = Undetermined. Structures that were not measured are indicated by three asterisks (***). .

Structure reference	Type	Mouth shape	Comments	Dimensions of the mouths (length × width, in m)	Mouth orientation	Presence of neck			Storage chamber	Proposed shape	Depth (m)	Current free capacity (L)	Elevation (m amsl)
						Yes	**No**	**Ud**					
D01	3a	Ud	The NE part is semicircular, but the rest is irregular.	1.23 × 1.02	NE-SW			x	Ud	Ud	0.79	Ud	869,35
D02	3b	Oval	The entrance mouth is dug into the vertical wall.	1.46 × 1.44	NW-SE			x	It could widen about the mouth.	Ud	0.73	Ud	870,41
D03	1a	Oval	It has the most pronounced neck in the SE part.	1.22 × 0.98	N-S	x			It widens about the mouth.	Bottle shape	1.41	973	873,45
D05	3b	Pointed shape	The entrance mouth is dug into the vertical wall.	1.5 × 1.36	NE-SW			x	Ud	Ud	0.66	Ud	873,67
D07	1a	Oval	It has the most pronounced neck in the SW part.	1.13 × 1.05	NE-SW	x			It widens about the mouth.	Bottle shape / pyriform shape	1.69	1193	876,31
D09	2a	Oval	The mouth has long oval sides and straight short sides. The façade of the entrance to the cistern has sockets of other structures built of perishable materials. Access to the cistern is via a step.	0.70 × 0.43	NE-SW		x		It could keep the same diameter as the mouth.	Ud	3.23	Ud	871,47
D10	4a	Quadrangular	The mouth has a slightly irregular quadrangular shape.	0.8 × 0.67	NW-SE	x			It widens about the mouth and neck but subsequently maintains its diameter.	Cylindrical bottle shape	3.66	2744	872,00
D13	1Ud	Oval	The NE part of the mouth is irregular.	2.05 × 1.59	NE-SW			x	It widens about the mouth.	Pyriform shape	1.3	5509	861,94
D15	1a	Quadrangular	The mouth has a slightly irregular quadrangular shape.	0.82 × 0.63	NW-SE	x			It widens about the mouth and neck but subsequently maintains its diameter.	Cylindrical bottle shape	4.5	3403	859,41
D16	3a	Semi-oval	It has a “domed” recess at the top.	2.47 × 1.56	NW-SE		x		It widens about the mouth.	Pyriform shape	1	7381	865,79
D18	1b	Oval	The C19 canal is in the SW part of the mouth.	1.55 × 1.07	NE-SW		x		It widens about the mouth.	Pyriform shape	***	3642	862,62
D20	3b	Oval	The entrance is dug into the vertical wall.	0.92 × 0.44	NE-SW			x	Ud	Ud	0.57	Ud	859,14
D22	3b	Ud	It has a recess at the top rectangular with angled sides, and the lower part is narrowed.	0.73 × 0.56	NE-SW		x		Ud	Ud	***	Ud	875,93
D23	2a	Oval / oval	The upper part of the entrance opening is slightly wider than the lower part, and it has two steps leading to the mouth of the cistern.	0.55 × 0.49	E-W			x	Ud	Ud	0.66	Ud	878,82
D24	1b	Oval	The N part is irregular.	2.24 × 1.84	E-W		x		It could widen about the mouth.	Ud	***	Ud	878,07
D25	1b	Oval	The NE part is irregular.	2.11 × 1.97	N-S		x		It widens slightly about the mouth.	Ud	***	Ud	877,99
D26	1b	Oval	The NE part is irregular.	1.52 × 1.33	N-S		x		It widens about the mouth.	Ud	***	Ud	860,28
D27	3a	Oval	The NE and SW part is quite irregular.	1.25 × 0.80	NE-SW		x		The diameter relative to the mouth is maintained.	Cylindrical	1.17	917	853,19
D30	3c	Oval	The SW part is very irregular, and it is probably destroyed.	1.07 × 0.73	NE-SW		x		The diameter relative to the mouth is maintained.	Cylindrical	1.11	870	853,33
D33	1c	Oval	The mouth is quite regular.	1.45 × 1.27	N-S		x			Cylindrical	***	Ud	852,65

(*continued on next page*)

Table A.1 (*continued*)

Structure reference	Type	Mouth shape	Comments	Dimensions of the mouths (length × width, in m)	Mouth orientation	Presence of neck			Storage chamber	Proposed shape	Depth (m)	Current free capacity (L)	Elevation (m amsl)
						Yes	**No**	**Ud**					
									The diameter relative to the mouth is maintained.				
D34	1d	Semi-oval	The SE side rests on the wall, and the NE has a slightly pointed part.	0.65 × 0.49	NW-SE			x	Ud	Ud	0.59	Ud	851,07
D35	1e	Semicircular	The E side leans against the wall.	1.02 × 0.91	NE-SW	x			It widens about the mouth.	Bottle shape	***	Ud	849,62
D36	1e	Semicircular	The E side rests against the wall.	0.63 × 0.82	NE-SW		x		The diameter relative to the mouth is maintained.	Semi-cylindrical	***	Ud	849,61
D37	3Ud	Semicircular	The part that has been documented appears to be semi-circular.	1.13 × 0.62	NE-SW			x	Ud	Ud	***	Ud	867,75
D38	1a	Oval	The SW part is irregular.	1.09 × 0.93	NW-SE	x			It widens about the mouth.	Bottle shape	***	Ud	868,24
D40	3Ud	Ud	It looks like an oval shape, but it is too silted up.	1.10 × 0.61	NW-SE			x	Ud	Ud	***	Ud	864,58
D41	3Ud	Ud	It looks like a semicircular shape, but it is too silted up.	1.73 × 0.49	N-S			x	Ud	Ud	0.12	Ud	865,00
D43	1Ud	Oval	Although it seems to correspond to an oval shape, the vegetation cover does not allow more precise documentation of the mouth.	1.39 × 0.86	NW-SE			x	Ud	Ud	0.55	Ud	864,65
D44	1b	Circular	It seems quite regular.	***	E-W		x		It widens about the mouth.	Pyriform shape	***	Ud	***
D45	1a	Semi-oval	Its S side is straight.	1.22 × 1.18	NW-SE	x			It widens about the mouth.	Bottle shape	***	Ud	852,33
D46	1b	Circular	It seems quite regular.	***	E-W		x		It widens about the mouth.	Pyriform shape	***	Ud	***
D47	3b	Semi-oval	Its NE side is relatively straight.	1.34 × 0.68	N-S		x		It widens about the mouth.	Pyriform shape	***	Ud	859,16
D49	3c	Semi-oval	It has not been possible to document the mouth precisely.	0.69 × 0.44	NW-SE		x		It widens about the mouth.	Cylindrical	***	Ud	877,91
D51	1Ud	Circular	It has a more pointed shape on the W side.	1.26 × 1.26	NW-SE			x	Ud	Ud	***	Ud	853,33
D52	4a	Oval	It is irregular in the NE part.	1.29 × 0.85	NW-SE		x		It widens about the mouth.	Pyriform shape	***	2826	840,42
D53	1b	Oval	It has a pointed shape at the connection to the C54 canal.	***	NE-SW		x		It widens about the mouth.	Pyriform shape	***	Ud	***
D55	4b	Circular	It is quite regular.	1.20 × 1.20	N-S	x			It widens about the mouth.	Bottle shape	***	Ud	849,66
D57	1a	Oval	It has a pointed shape at the connection to the C110 canal.	0.84 × 0.65	NE-SW	x			It widens about the mouth.	Bottle shape	1.15	775	845,92
D58	1a	Circular	It is quite regular.	0.88 × 0.88	E-W	x			It widens about the mouth.	Bottle shape	***	Ud	852,25
D59	1Ud	Oval	Its shape is quite irregular.	1.19 × 0.95	NE-SW			x	Ud	Ud	0.98	Ud	840,45
D63	3b	Ud	The inlet of the cistern is irregular and has an elongated shape, straighter at the top and more curved at the bottom.	1.38 × 1.18	N-S		x		Ud	Ud	***	Ud	865,76

(*continued on next page*)

Table A.1 (*continued*)

Structure reference	Type	Mouth shape	Comments	Dimensions of the mouths (length × width, in m)	Mouth orientation	Presence of neck			Storage chamber	Proposed shape	Depth (m)	Current free capacity (L)	Elevation (m amsl)
						Yes	**No**	**Ud**					
D64	3c	Ud	It could be a very elongated oval mouth.	2.34 × 1.4	NE-SW		x		It could have the same diameter throughout the structure.	Ud	1.34	Ud	851,29
D67	1Ud	Oval	Its shape is rather irregular.	2.30 × 1.4	NW-SE			x	Ud	Ud	***	Ud	874,61
D68	3Ud	Ud	The mouth is very silted up and could be rather circular or oval.	1.50 × 1.31	N-S			x	Ud	Ud	0.76	Ud	874,00
D73	1a	Circular	It is quite regular.	0.90 × 0.90	NE-SW	x			It widens about the mouth.	Bottle shape	1.97	1415	843,84
D75	1b	Circular	It is quite regular.	1.05 × 1.05	N-S		x		It widens about the mouth.	Pyriform shape	1.32	2167	840,68
D76	3a	Circular	It is quite regular.	1.36 × 1.36	NE-SW			x	Ud	Ud	2.18	Ud	849,34
D78	1Ud	Oval	Its shape is rather irregular.	1.37 × 1.35	NW-SE			x	Ud	Ud	0.8	Ud	848,56
D79	1a	Circular	It is quite regular.	0.93 × 0.93	E-W	x			It widens about the mouth.	Bottle shape	2.75	2029	851,71
D80	3Ud	Ud	The documented part is semicircular.	0.82 × 0.38	NE-SW			x	Ud	Ud	0.3	Ud	844,71
D81	3Ud	Ud	The documented part is semicircular.	1.46 × 0.83	NW-SE			x	Ud	Ud	0.36	Ud	844,54
D82	1Ud	Oval	The vegetation cover prevents better documentation of this water-holding structure.	1.36 × 1.23	NE-SW			x	Ud	Ud	4.07	Ud	841,41
D83	2a	Oval	The entrance is rectangular at the top and more rounded at the bottom. The façade where it is located has sockets of other structures built with perishable materials. There is a step leading to the mouth of the cistern.	0.79 × 0.53	NE-SW			x	Ud	Ud	2.37	Ud	849,31
D85	3Ud	Ud	The documented part has a semi-oval shape.	0.63 × 0.37	NE-SW			x	Ud	Ud	0.2	Ud	863,96
D86	1d	Semicircular	A vertical wall supports its SW side.	0.57 × 0.51	NW-SE			x	Ud	Ud	0.98	Ud	858,07
D87	1e	Oval	It is quite regular.	0.90 × 0.82	NE-SW	x			It widens about the mouth.	Bottle shape	2.17	1575	852,10
D88	3c	Ud	The documented part has a semi-oval shape.	1.53 × 0.80	NW-SE			x	Ud	Ud	1.74	Ud	853,11
D90	1e	Circular	It is quite regular.	***	E-W		x		It widens about the mouth.	Pyriform shape	***	Ud	***
D91	1b	Oval	It is quite regular.	1.69 × 1.30	NW-SE		x		It widens about the mouth.	Pyriform shape	2.38	4125	874,62
D95	2b	Oval	The access to the entrance is quite oval.	***	NW-SE		x		It could widen about the mouth.	Ud	***	Ud	860,56
D96	3Ud	Ud	The documented part has a semi-oval shape.	1.58 × 0.63	NW-SE			x	Ud	Ud	***	Ud	856,60
D97	1Ud	Oval	The shape can be guessed from the vegetation inside it.	***	NE-SW			x	Ud	Ud	0.41	Ud	855,98
D98	3b	Oval	It is quite regular.	1.48 × 1.23	NW-SE		x		It could widen about the mouth.	Ud	***	Ud	858,46
D99	1a	Circular	It is quite regular.	0.87 × 0.76	E-W	x			It widens about the mouth.	Bottle shape	***	Ud	853,14
D100	1Ud	Semicircular	Boulders and vegetation heavily cover it.	0.98 × 0.73	NW-SE			x	Ud	Ud	***	Ud	848,51
D103	1Ud	Oval	It is quite regular.	0.92 × 0.75	NE-SW			x	Ud	Ud	0.31	Ud	857,99

Source: Marsal, 2021

Table A.2
Dimensions, main features, sections, orientation, slope, and type of canal fragments. .

Structure reference	Length (m)	Width (m)	Depth (m)	Excavated directly or through the:		Open	Close	Section	Presence of plaster	Orientation	P	P %	Type	Elevation (m amsl)
				Rocky surface	**Rock fissuring**									
C04	>2.50	0.24	0.15–0.20	x		x		Semicircular		NE-SW	SW	10.92	3	873,46
C06	>3.35	Ud	Ud	x		x		Ud		NE-SW	NE	18.20	1–2	876,95
C08	>0.60	Ud	Ud	x		x		Ud		E-W	Ud	Ud	4	873,63
C11	>3.20	0.16–0.36	>0.10	x			x	Square with slab		NE-SW	NE	6.6	2	865,18
C12	>0.96	0.12–0.25	>0.10	x		x		Square		NE-SW	SW	4.17	2	862,42
C14	>5.20	0.37–0.53	Ud	x			x	Square / Square with slab?		NE-SW	NE	8.63	2	859,40
C17	>28.11	0.57–1.28	>0.30	x		x		Rectangular	x	NW-SE	SE	25.77	1–2	856,50
C19	>0.93	0.10–0.70	0.20–0-30	x		x		Triangular		NE-SW	NE	34	2	862,52
C29	*1.36	0.10–0.28	0.10–0.20	x		x		Semicircular (connection with D28) / Square (connection with D30)		NE-SW	SW	49	3	852,71
C32	*2.66	0.11–0.31	0.10–20	x		x	x	Ud (connection with D31) / Square with slab (in the middle) / Semicircular (connection with D34)		E-W	W	40.74	3	853,44
C39	>12.65	0.26–0.42	Ud		x	x		Angle 100°-110°		E-W	W-SW	6.68	1–2	868,64
C42	>3.04	0.28–0.31	0.10	x		x		Trapezoidal		NW-SE	SE	16.1	2	863,40
C48	>10.04	0.3–1.10	Ud		x	x		Angle 100°-110°		NE-SW	SW	8.72	1–2	859,87
C50	>60.17	0.2	Ud	x	x	x		Angle 100°-110° / rectangular / square		NE-SW	SW	54.16	2	843,24
C54	>6.08	0.10–0.20	0.10	x		x		Semicircular	x	E-W	W	4.57	3	850,85
C56	>2.24	0.50–0.60	0.24 / 0.10	x		x		Rectangular / Square		NE-SW	NE	6.21	2	850,18
C66	>1.73	0.15	Ud	x		x		Square		NE-SW	SW	22.43	2	854,70
C69	*2.13	0.15–0.20	Ud		x	x		Angle 100°-110°		NE-SW	NE	58.69	4	867,92
C71	>1.86	0.23	0.10	x	x	x		Trapezoidal / Angle 100°-110°		NW-SE	SE	18.28	2	864,66
C74	>7.61	0.20–0.40	0.15–0.20		x	x		Angle 100°-110°		E-W / NW-SE	W / SW	10.56	2	847,04
C77	>3.57	0.10–0.15	0.10	x		x		Semicircular		NE-SW	NE	0.34	3	849,24
C84	>24.28	0.20–0.25	0.10	x		x		Rectangular		E-W /N-S	W / N	12.1	2	857,34
C89	>5.67	0.2	0.10	x		x		Semicircular		NE-SW	SW	8.7	2	853,24
C92	*0.61	0.08–0.15	0.05	x		x		Ud		NE-SW	SW	9.57	3	874,29
C93	*0.27	0.12–0.15	0.08–0.10	x		x		Semicircular		NW-SE	SE	6.67	3	873,85
C94	>10.06	0.11–0.42	Ud		x	x		Angle 100°-110°		NE-SW / SW-SW	NE / SE	23.10	1–2	866,03
C101	>1.50	0.2	Ud	x		x		Ud		NW-SE	SE	21.01	1–2	853,86
C102	>2.69	0.37–0.56	0.20–0.30	x		x		Rectangular / Square / Semicircular		NW-SE	SE	45.1	2	858,18
C104	>6.17	0.19–0.66	Ud	x		x		Ud		NW-SE	SE	13.9	2	863,91
C105	>16.5	0.15–0.20	0.15–0.10	x		x		Trapezoidal / Square		E-W	Ud	Ud	2	765,92
C108	>1.37	0.10–0.15	Ud	x		x		Semicircular		NE-SW	NE	3.62	2	849,39
C109	>1.04	0.10–0.20	0.05–0.08	x		x		Rectangular		E-W	W	16.4	2	852,45
C110	>0.40	0.15–0.20	Ud	x		x		Semicircular		NW-SE	Ud	Ud	2	845,92
C113	*0.32	0.22–0.26	0.10–0.15	x		x		Semicircular		E-W	W	29.69	3	849,80
C114	>0.25	0.1	Ud	x		x		Ud		E-W	Ud	Ud	2	852,10
C116	>0.10–0.15	0.08–0.10	0.08–0.10	x		x		Semicircular		NE-SW	Ud	Ud	2	870,19
C117	>0.60	Ud	Ud	x		x		Ud		NE-SW	Ud	Ud	2	874,44
C118	Ud	0.15	0.10	x			x	Semicircular		NE	Ud	Ud	2	861,85
C119	Ud	0.15	0.10	x			x	Semicircular	x	E	Ud	Ud	2	861,88
C120	Ud	0.15	0.10	x			x	Semicircular		S	Ud	Ud	2	861,92
C121	Ud	0.15	0.10	x			x	Semicircular		SW	Ud	Ud	2	862,34
C122	>0.73	0.30–0.38	0.08–0.10	x		x		Ud		E-W	E	11.23	3	874,64
C123	*0.45	0.20–0.25	0.08	x		x		Ud		E-W	Ud	Ud	4	850,91
C125	0.50	0.15	0.05	x		x		Ud		NW-SE	NW	Ud	2	843,79
C129	*0.26	0.16	0.10	x		x		Semicircular		NW-SE	SE	9.23	4	877,75
C131	>0.30	0.15	Ud	x		x		Ud		NE-SW	Ud	Ud	2	859,44
C132	>0.65	0.23–0.65	0.08–0.10	x		x		Ud		E-W	W	2.46	3	874,47
C133	>0.60	0.20–0.25	0.10–0.12	x		x		Ud		E-W	Ud	Ud	2	848,35
C134	>0.60	Ud	Ud	x		x		Ud	x	NE-SW	NE	Ud	2	868,73
C135	*0.36	0.09–0.13	Ud	x			x	Semicircular (connection with D111) / Circular (connection with D15)		NE-SW	SW	Ud	4	859,42
C137	Ud	0.20	Ud	x			x	Ud		Ud	Ud	Ud	4	851,56

Source: Marsal, 2021

Table A.3
Dimensions, current free capacity (in L), type and subtype, orientation, and connections of the sedimentation basins. .

Structure reference	Dimensions			Current free capacity (L)	Type and subtype	Orientation	Connecting structure	Elevation (m amsl)
	Length (m)	**Width (m)**	**Depth (m)**					
D28	1.54	0.93	0.59	591	2a	Slightly NE-SW	Cistern D30 and output canal C29	853,20
D31	1.5	1.05	0.51	803	2b	Slightly NW-SE	Cisterns D33-D34 and output canal C32	854,09
D70	0.97	0.78	0.38	159	1b	Slightly NE-SW	Cistern D68, input canal C134 and output canal C69	868,76
D72	1.34	0.64	0.21	159	Ud	Slightly NE-SW	Ud	862,38
D111	1.32	0.74	> 0.20	174	1a	NE-SW	Cistern D15, input canal C14 and output canal C135	859,39
D112	1.36	1.05	0.48	685	1b	Slightly NW-SE	Cistern D55, input canal C56 and output canal C113	850,05
D124	Ud	Ud	Ud	Ud	Ud	Cistern D53 and output canal C123	***	
D126	1.25	1.14	Ud	Ud	Ud	NE-SW	Cistern D91 and output canal C93	873,65
D128	1.33	0.80	0.16	163	2b	NW-SE	Cistern D49 and output canal C129	877,76
D136	1.84	1.19	0.36	788	Ud	NW-SE	Ud	851,59

Source: Marsal, 2021

Table A.4
Dimensions, current free capacity (in L), and orientation of the pools and reservoirs. Source: modified of Marsal, 2021.

Structure reference	Structure type	Dimensions			Current free capacity (L)	Orientation	Elevation (m amsl)
		Length (m)	**Width (m)**	**Depth (m)**			
D60	Pool	1.31	1.20	0.49	770	NE-SW	841,77
D61	Pool	1.44	0.98	0.58	818	NW-SE	842,57
D62	Pool	1.43	0.96	0.55	1101	NE-SW	840,47
D65	Pool	1.45	0.87	0.54	681	E-W	854,81
D21	Reservoir	5.16	4.23	3	71,000	NW-SE	862,83

Table A.5
Dimensions, current free capacity (in L), and orientations of undetermined hydraulic structures. .

Structure reference	Dimensions			Current free capacity (L)	Orientation	Elevation (m amsl)
	Length (m)	**Width (m)**	**Depth (m)**			
D107	1.51	0.72	0.45	490	NE-SW	880,61
D115	1.04	0.54	0.48	270	NW-SE	860,96
D127	2.44	1.27	Ud	Ud	NW-SE	873,74

Source: Marsal, 2021

Appendix B

Table B.1
Main mineralogical components of each sample. Source: Marsal, 2021, based on the results obtained from the XRD of the Servei de Recursos Científics i Tècnics (SRCiT) of the Universitat Rovira i Virgili. Source: Marsal, 2021.

Type	Sample	Quartz	Calcite	Dolomite	Kaolinite
1	SL'16.H1.UM3.1	x	x	x	
1	SL'16.H1.UM3.2	x	x		x
1	SL'16.H1.2.498	x	x		
1	SL'16.D01.4	x	x		
1	SL'16.D13.1	x	x		x
2	SL'16.D05.7	x	x	x	x
2	SL'16.D09.6	x	x		
2	SL'16.D16.2	x	x		
2	SL'16.D03.5	x	x		
3	SL'16.D22 8		x		
3	SL'16.D57.10	x	x	x	
3	SL'16.D59.11	x	x		
3	SL'16.D63.3	x	x		
3	SL'16.D39.9	x	x		
4	SL'16.H1.6.169	x	x		
5	SL'16.D107.13	x	x	x	

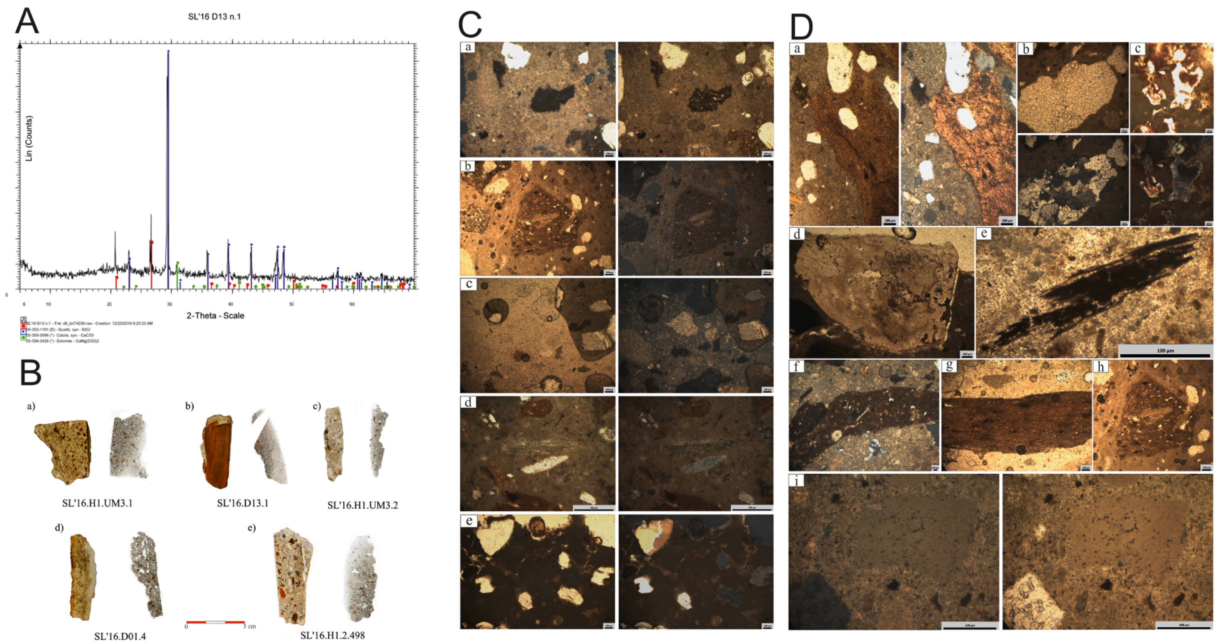

Fig. B.1. A) Diffractogram of the sample SL'16.D13.1. B) Hand samples of the mortars identified as type 1 and the resulting thin film scan. C) MLP photographs of the binder of the type 1 samples (left: PPL and right: XPL). a) SL'16.H1.UM3.1; b) SL'16.H1.UM3.498; c) SL'16.H1.UM3.2; d) SL'16.D01.4 and e) SL'16.D13.1. D) MPL photographs of the most prominent aggregates of type 1 samples. a) Detrital quartz from SL'16.H1.UM3.1 (left XPL and right PPL); b) micritic-microsparitic calcite from SL'16.2.498 (top PPL and bottom XPL); c) iron oxides from SL'16.D13. 1 (above PPL and below XPL); (d) thermoaltered flint (PPL) from SL'16.D01.4; (e) vegetal residue (PPL) from SL'16.D01.4; (f-g-h) ceramic residue from SL'16. H1.UM3.1 (XPL), SL'16.H1.UM3.2 (PPL) and SL'16.H1.2.498 (PPL), respectively, and (i) ash from SL'16.H1.UM3.3 (left XPL and right PPL). Source: Marsal, 2021. Photographs: J. Vallverdú and M. Soto (Geoarchaeology Laboratory, IPHES).

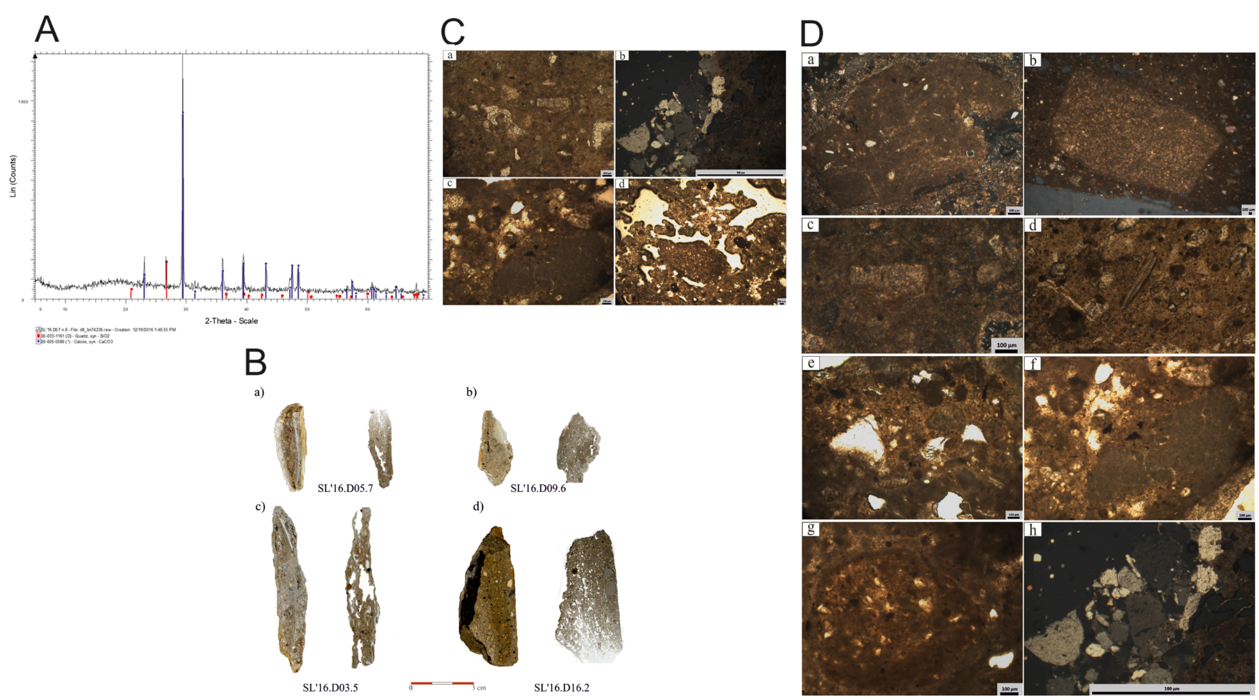

Fig. B.2. A) Diffractogram of the sample SL'16.D16.2. B) Hand samples of the mortars identified as type 2 and the resulting thin film scan. C) MLP photographs of the binder of the type 2 samples. a) SL'16.D05.7 (PPL); b) SL'16.D09.6 (XPL); c) SL'16.D03.5 (PPL) and d) SL'16.D16.2 (PPL). D) a) micritic-microsparitic calcite from SL'16.D05.7 (XPL); b) sparitic calcite from SL'16.D16.2 (XPL); c-d) possible vegetal aggregate replaced by microsparitic calcite and vegetal debris, respectively, from SL'16. 7 (PPL); e) secondary gypsum from SL'16.D05.7 (PPL); f) micritic-microsparitic calcite from SL'16.D03.5 (PPL); g) ceramic fragment from SL'16.D03.5 (PPL) and h) gypsum and detrital quartz crystals from SL'16.D09.6 (XPL). Source: Marsal, 2021. Photographs: J. Vallverdú and M. Soto (Geoarchaeology Laboratory, IPHES).

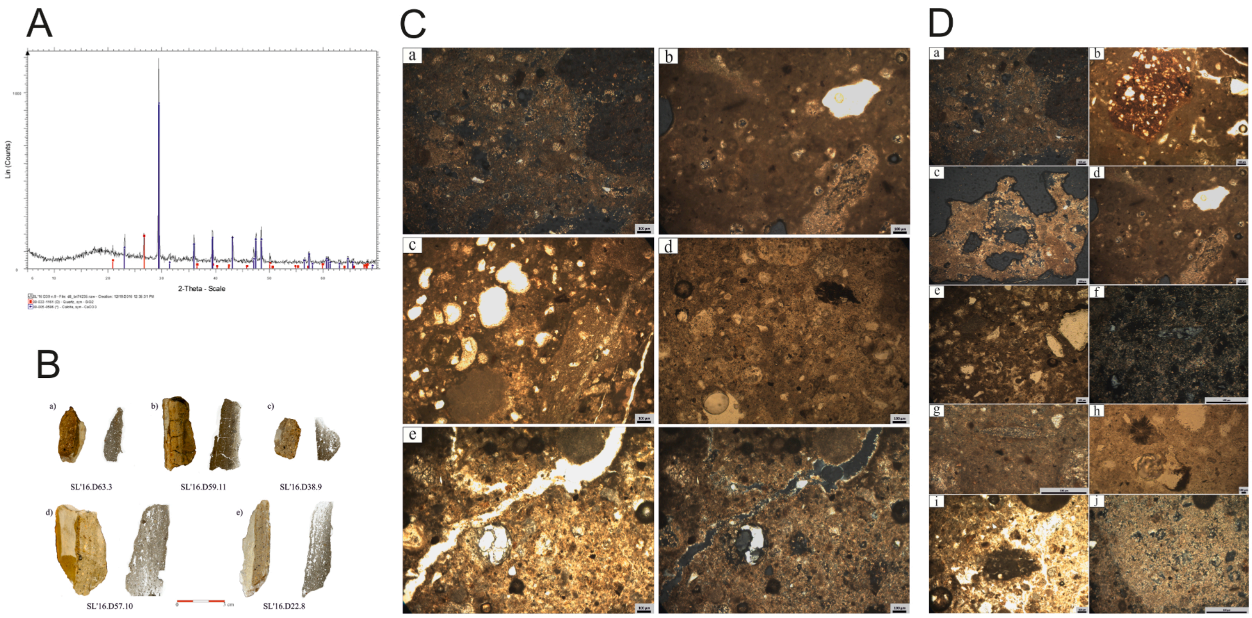

Fig. B.3. A) Diffractogram of the sample SL'16.D38.9. B) Hand samples of the mortars identified as type 3 and the resulting thin film scan. C) MLP photographs of the binder of the type 3 samples. a) SL'16.D57.10 (XPL); b) SL'16.D22.68 (XP); c) SL'16.D63.3 (PPL); d) SL'16.D38.9 (PPL) and e) SL'16.D59.11 (left PPL and right XPL). D) a) detrital quartz from SL'16.D57.10; b) detrital quartz and ash with possible ceramic residue from SL'16.D63.3; c-d) ash and massive hematite, respectively, from SL'16.D22.8 (XPL); e) gypsum from SL'16. 10 (PPL); f) subhedral and lenticular gypsum from SL'16.D59.11 (XPL); g) replaced phytolith or possible plant remains (XPL); h) plant debris from SL'16.38.9 (PPL); i) micritic mud from SL'16.D59.11 (XPL) and j) rock aggregate with biomicritic texture (XPL). Source: Marsal, 2021. Photographs: J. Vallverdú and M. Soto (Geoarchaeology Laboratory, IPHES).

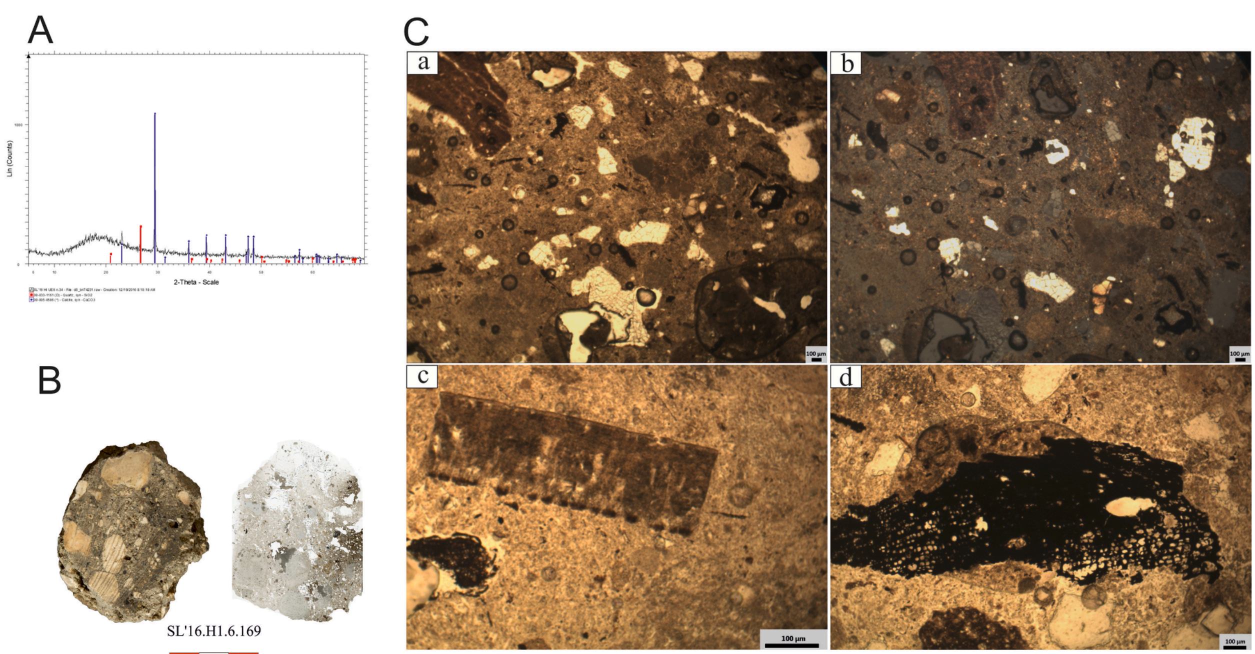

Fig. B.4. A) Diffractogram of the sample SL'16.H1.6.169. B) Hand sample of the mortars identified as type 4 and the resulting thin film scan. C) MLP photographs of the binder and the most prominent aggregates of sample SL'16.H1.6.169, defined as type 4 (PPL). a) detrital quartz and micritic mud; b) binder composed of microsparitic calcite with possible gypsum as aggregate; c) possible phytolith/diatomite and plant debris and d) charcoal. Source: Marsal, 2021. Photographs: J. Vallverdú and M. Soto (Geoarchaeology Laboratory, IPHES).

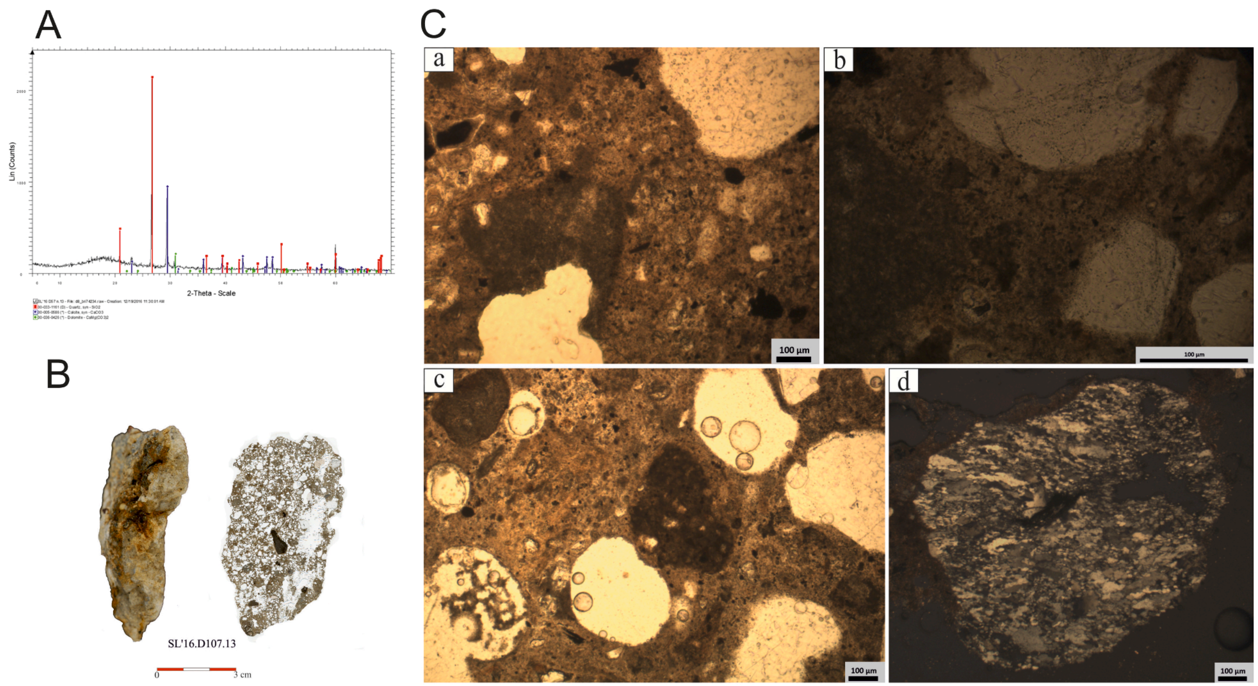

Fig. B.5. A) Diffractogram of the sample SL'16.D017.13. B) Hand sample of the mortars identified as type 5 and the resulting thin film scan. C) MLP photographs of the binder and the most prominent aggregates of sample SL'16.D107.13, defined as type 5. a) Binder composed of micritic calcite (PPL); b-c) possible ash and this together with massive hematite, respectively, as aggregates (PPL) and d) feldspathoid fragment. Source: Marsal, 2021. Photographs: J. Vallverdú and M. Soto (Geoarchaeology Laboratory, IPHES).

Appendix C. Supplementary data

Fig. C.1. General map of the region showing the sites mentioned in the text. Source: Map created by the author on the base map of Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Scale: 1:1,000,000. URL: https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer [Accessed: 27/12/2022].

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