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Drainage of the Ravne Tunnels (Bosnia and Herzegovina) Compared with Roman, Historic, and Modern Drainage Engineering

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Abstract: Water enters the Ravne 1 tunnel system near Visoko through the ceiling and runs down the walls. It flows out of the main entrance year-round and also out of a service opening, and no standing water forms on the walking floor. This paper reconstructs the floor geometry that carries this water and compares its gradients with drainage practice from antiquity to the present. We georeferenced 2,040 floor spot heights from the 2026 geodetic and laser-scanning survey, linked them into a passage network, and placed them on the official chainage of the main axis. The floor rises from 471.50 m above sea level (a.s.l.) at the main entrance to a broad high zone at about 473.5-473.9 m between chainages 340 and 540 m. It then falls to the service opening at 473.10 m (chainage 637.6 m). Gradients are 5.1% over the first 20 m and 1.0% to 100 m. The interior consists of near-level reaches separated by a short step, with a mean rise of about 0.14%. Toward the service opening, the floor falls at 0.35%. For the observed outflow of about 0.1 L/s, hydraulic scenarios give a flow a few millimeters deep, moving at 2.5-22.5 cm/s, with bed shear stress below 1.3 Pa. The interior mean gradient lies within the range measured on Roman aqueducts (0.13-0.16% on surveyed sections of Aqua Claudia and Anio Novus) and historic drainage adits. It is somewhat below modern minimums for railway drains and road tunnels (0.2-0.25%). The entrance gradients match surface-drainage practice. The reconstructed floor geometry is consistent with a predominantly gravity-driven drainage regime toward two observed outlets. Local elevation reversals, floor permeability, present-day modifications, and uncertain historical discharge prevent identifying deliberate hydraulic design from floor geometry alone.

Key words: Drainage gradient, tunnel hydraulics, gravity drainage, laser scanning, Roman aqueducts, qanat, Eupalinos tunnel, Ravne, Visoko, Bosnia and Herzegovina.

1. Introduction

Every channel that carries water by gravity needs a fall. Too little fall and water stands. Too much and it scours the bed and carries sediment away. Engineers have handled this trade-off for at least five thousand years. Roman writers set minimum falls for aqueducts [1]. Modern codes set minimum gradients for sewers, drains and tunnels, tied to pipe size and self-cleansing velocity. Field practice gives familiar rules of thumb: about 1% for buried drains, 1-2% for paved surfaces and gutters, and up to 2% for house drains.

The gradient of an old water-carrying structure is therefore a measurable trace of how it handles water. You can compare it directly with other structures, whatever their age, because the physics is the same.

The Ravne Underground Complex near Visoko has been investigated since 2005. Its archaeology, dry-stone walls, backfilling, dating and microclimate are published elsewhere [2-6]. In 2026, GNSS (Global Navigation Satellite System), UAV (Unmanned Aerial Vehicle) LiDAR (Light Detection and Ranging), and terrestrial laser scanning (TLS) surveyed all six tunnel systems in a single georeferenced frame [7, 8]. That survey showed mean floor gradients of 0.94-2.0% for the six systems. These figures are differences between

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the highest and lowest floor divided by length. They do not show the direction of fall, or where along a passage the fall occurs.

This paper takes the next step for Ravne 1, the longest system. It has three aims:

1. Reconstruct the longitudinal floor profile from the survey's floor spot heights.

2. Relate the profile to the observed water regime and estimate the flow hydraulics.

3. Compare the gradients with measured values from Roman aqueducts, ancient water tunnels, qanats, historic drainage adits, and modern drainage standards.

The question is functional: how does the floor handle water? The paper does not address who made the passages or when.

2. Site and Water Regime

The Ravne Underground Complex lies in the Ravne locality, Visoko, central Bosnia and Herzegovina (Fig. 1). Its six tunnel systems, Ravne 1-6, were surveyed in one coordinate frame in 2026 (Fig. 2). The passages are cut in Quaternary conglomerate that overlies marl and sandstone [6]. Ravne 1 is the largest system: 1,706.5 m of surveyed accessible passages, 2,465 m² of floor and 3,958 m³ of open volume. Its mean corridor width is 1.44 m and mean clear height is 1.61 m [7, 8]. The network branches repeatedly and includes several closed loops (Figs. 3 and 4).

Ravne 1 has two openings. The main entrance in the north-west is the visitor access and the principal outlet. A service opening lies at the south-western end of the main axis. Foundation staff laid a thin concrete layer at the main entrance to control mud. Elsewhere, the walking surface is the cleared passage floor.

Field observations by Foundation staff describe the water regime:

- Water enters through the ceiling and runs down the walls. There is no single inflow point.
- Water flows out of the main entrance all year. The discharge was estimated at about 1 liter every 10 seconds (0.1 L/s).
- Water also flows out of the service opening.
- No standing water forms on the walking floor of the drained passages.
- Several separate water bodies in other parts of the complex appear to be fed from below and do not drain to the outside. Some passages are water-filled and could not be scanned [8] (Fig. 5).

At 0.1 L/s, the main entrance discharges about 8.6 m³ per day, or roughly 3,150 m³ per year. This is an estimate from one timed observation, not a measured series.

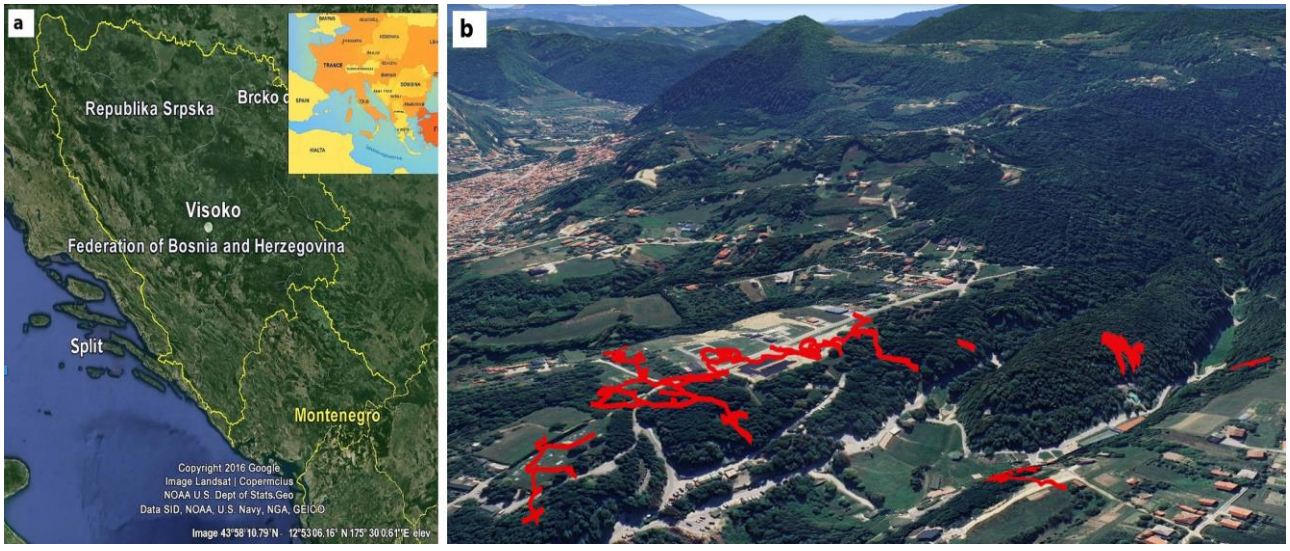


Fig. 1 Location of the Ravne Underground Complex. (a) Visoko in central Bosnia and Herzegovina; adapted from Osmanagich [4], CC BY 4.0. (b) Oblique view with the surveyed tunnel systems in red; Ravne 1 is the large network on the left. Source: GeoGIS studio [7]; base imagery © Google Earth.

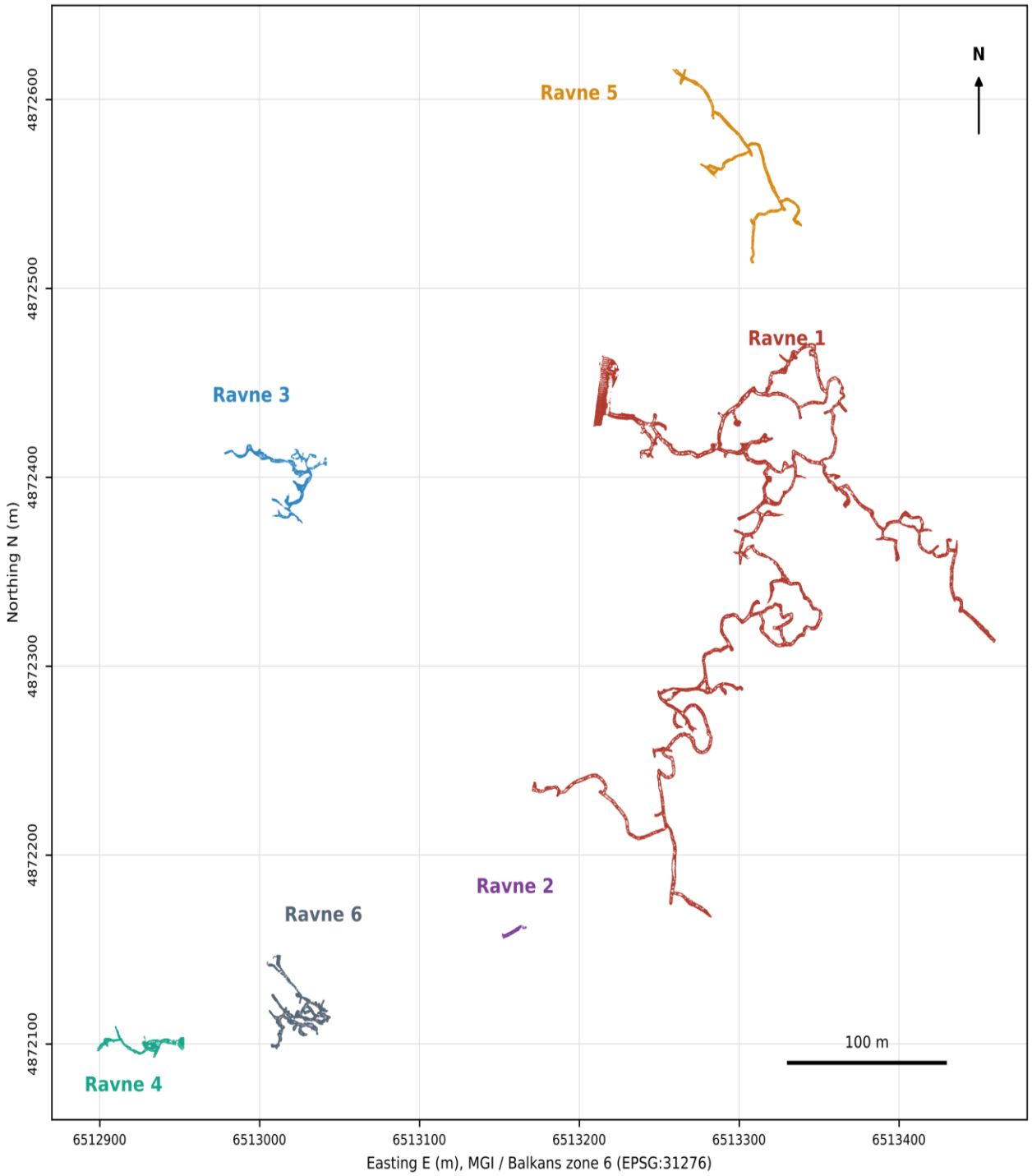


Fig. 2 Integrated plan of the six Ravne tunnel systems in MGI/Balkans zone 6 (EPSG:31276). Drawn from the georeferenced GeoGIS [7] survey sheets [8].

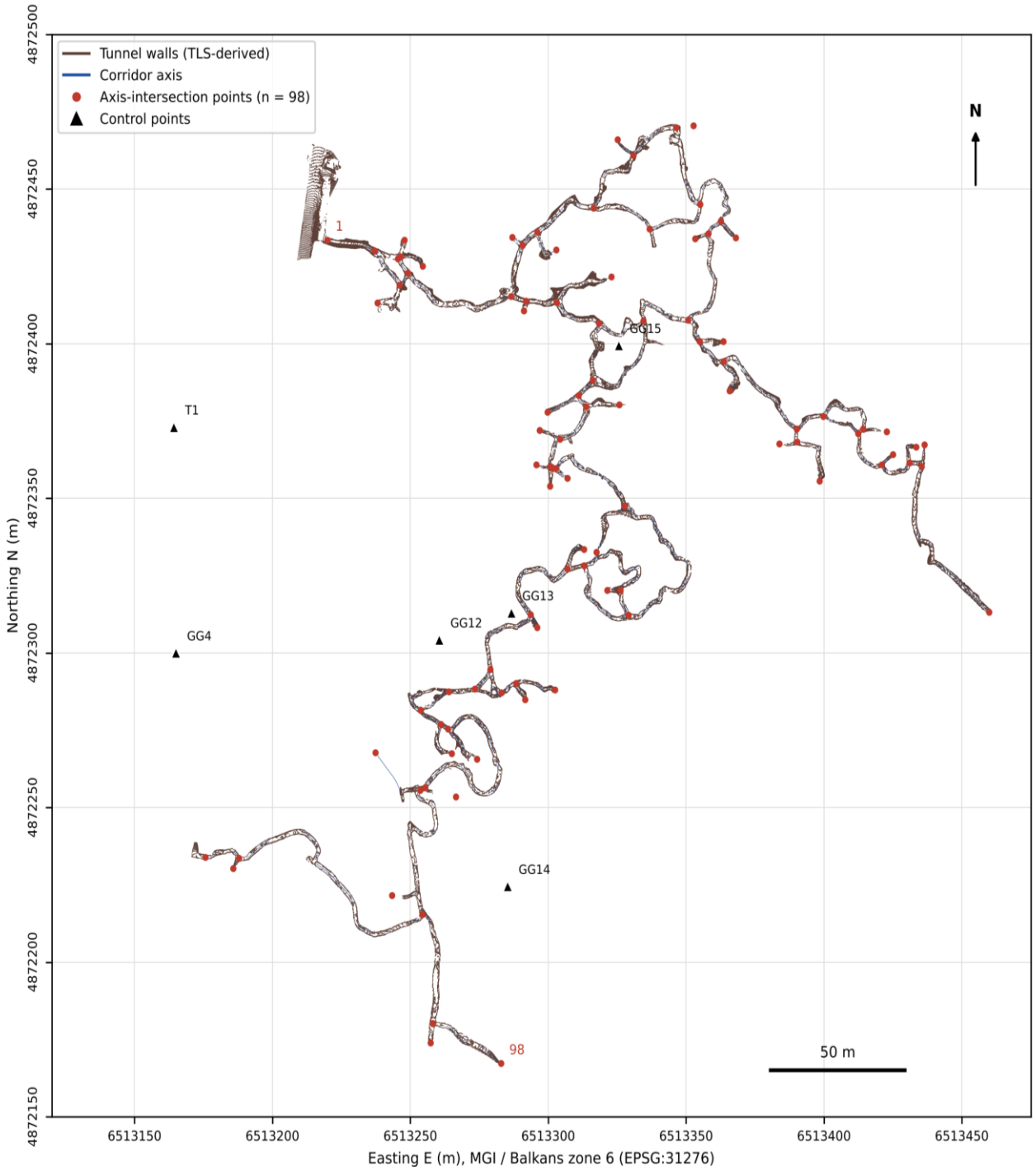


Fig. 3 Geodetic plan of Ravne 1: TLS-derived walls, corridor axis and 98 axis-intersection points, with nearby control points. Drawn from the georeferenced GeoGIS [7] survey sheets [8].

Fig. 4 Plan-view rendering of the Ravne 1 laser-scanning point cloud (≈550 stations, Trimble X7/TX8). Rendering prepared by the Foundation from the GeoGIS [7] point cloud; not to scale.

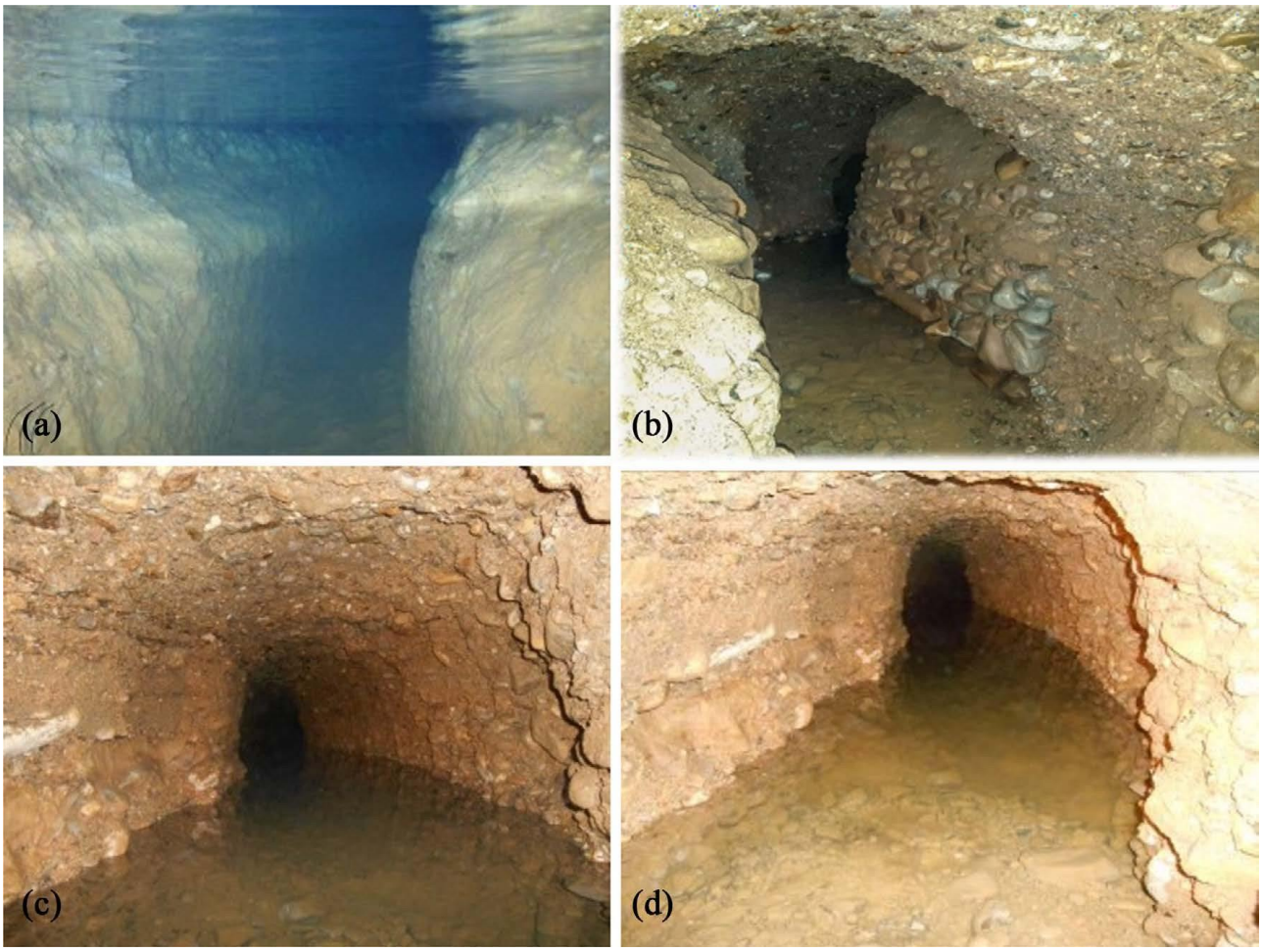


Fig. 5 Water in the Ravne network. (a) Dry-stone wall along a water-bearing passage; (b) partly submerged corridor; (c) clear water channel; (d) water-filled corridor. Adapted from Osmanagich [4], CC BY 4.0.

3. Data and Methods

3.1 Survey Data

The geometry comes from the 2026 survey by GeoGIS studio d.o.o., Sarajevo [7]. A 15-point GNSS control network was observed with a Tersus Oscar RTK (Real-Time Kinematic) receiver. The passages were scanned with Trimble X7 and TX8 scanners from about 550 stations in Ravne 1, registered in Trimble RealWorks and tied to the control network. The data were drafted in Autodesk Civil 3D in MGI (Militärgeographisches Institut, Military Geographic Institute)/Balkans zone 6 (EPSG:31276; EPSG = European Petroleum Survey Group). For Ravne 1 the survey delivered two A0 sheets showing walls, corridor axes with chainage, 98 numbered axis-intersection points with coordinates, and floor spot heights. The main axis runs from the main entrance (chainage 0+00.00) to the service opening (6+37.60). Survey details are given in Osmanagich and Žutić [8].

3.2 Extraction and Georeferencing of Spot Heights

The sheets were delivered as vector PDF files. Each floor spot height is a text label with a position on the sheet. We extracted all text labels and line work, along with their sheet coordinates in points.

Each sheet was georeferenced as follows:

1. The drawing scale stated on the sheet fixed the conversion from sheet units to meters. North-up orientation was assumed and then checked.

2. The translation was found by matching the vertices of the drawn corridor axes to the 98 listed axis-intersection coordinates. For each trial translation, we counted the listed points within 0.3 m of a drawn vertex, then refined the best translation by least squares.

3. The match confirmed the orientation. The first sheet matched 84 of 98 points and the second the rest of the network, with median residuals of about 2 mm. This residual measures how closely the drawn axes fit the listed coordinates. It is not the absolute geodetic accuracy of the survey, which has not yet been reported (Section 6.3).

A label was accepted as a floor spot height if its value lay between 450 and 499 m and it stood within 3 m of a drawn axis. Duplicates on the overlap of the two sheets were removed. This left 2,040 spot heights, from 471.42 to 475.50 m. The survey reports a floor range of 471.50-475.50 m for Ravne 1, so the extracted set covers the reported range.

3.3 Network and Chainage

The spot heights were linked into a network. Two spot heights were joined if they lay within 6 m of each other and at least 90% of the straight line between them fell inside the passage. The passage was defined, at 0.1 m resolution, as a 1 m buffer around the drawn axes and the spot heights. We computed distance from the main entrance along this network using the shortest path (Dijkstra's algorithm).

Shortest-path distance is not the same as the official chainage. It cuts across loops and short bends, so the route from the main entrance to the service opening measured 536.7 m in the network against 637.60 m of chainage. To report the profile on the official chainage, the chainage labels on the sheets were used. Each label was assigned the network distance of the nearest spot height (within 3 m). A monotonic relation between network distance and chainage was fitted through these pairs (106 pairs, overall ratio 1.19) and used to convert every spot height on the main route to chainage.

The main-axis profile uses all spot heights within 1.5 m of the shortest route from the main entrance to the service opening (n = 452). Section gradients were obtained by linear regression of elevation on chainage within fixed intervals. A 10 m running median shows the trend.

A gap in the spot heights left the south-eastern branch unconnected in the network, although it is connected in reality. Its floor lies at about 473.5-475.5 m, above the main entrance. It is shown on the floor map but excluded from the profile.

3.4 Local Reversals

For each spot height, the lowest possible crest on any route to either opening was computed as a minimax path through the network. A spot height lying more than 0.10 m below that crest marks a local reversal of the measured floor surface. This is a geometric test only. Whether water actually collects there depends on floor permeability and on micro-relief that spot heights do not resolve.

3.5 Hydraulic Scenarios

No flow depths or velocities were measured. Depth, velocity, and bed shear stress for the estimated discharge, Q = 0.1 L/s, were therefore calculated as scenarios. Manning's equation was used for a wide shallow channel:

$$V = (1/n) \cdot R^{2/3} \cdot S^{1/2},\ Q = b \cdot y \cdot V,$$
$$R \approx y,\ \tau = \rho \cdot g \cdot y \cdot S \quad (1)$$

Here V is mean velocity, n is Manning's roughness, R is hydraulic radius, S is gradient, b is flow width, y is flow depth, and τ is bed shear stress. Two widths bound the flow geometry: water spread over the whole floor (b = 1.4 m) and water gathered in a narrow rill (b = 0.3 m). Two roughness values bound the surface: smooth concrete (n = 0.013) and gravel-cobble floor (n = 0.030). For such thin flows, Manning's equation is only approximate. The scenarios were therefore checked against the laminar sheet-flow relation $y = (3\nu q/gS)^{1/3}$, with q = Q/b and kinematic viscosity $\nu = 1.3 \times 10^{-6}$ m²/s (about 10 °C). Both approaches give the same order of magnitude.

3.6 Comparison Data

Comparison gradients were taken from published sources that state numerical values (Table 3). Geodetic measurements were preferred where available. Ratios and historic units were converted to percent, and the conversion is stated. Design ranges and minimum standards are labeled as such, to distinguish them from measured gradients.

4. Results

4.1 The Main Entrance Is the Low Point

The main entrance is the lowest point of Ravne 1. Its floor is at 471.50 m. The lowest spot height in the system, 471.42 m, lies 5 m inside it. Of the 1,762 spot heights connected in the network, 99.5% lie above the entrance level. The floor map shows the lowest floors at the main entrance and the highest in the south-eastern branch and in the central-southern part of the network (Fig. 6a).

4.2 Two Outlets and an Internal High Zone

The main-axis profile has a clear structure (Fig. 6b, Table 1). From the main entrance, the floor rises steeply for 20 m, then at about 1% to chainage 100 m. Between 100 and 290 m, it is almost level at about 472.9-473.1 m. A short step between 290 and 340 m lifts it by about 0.7 m. From 340 to 540 m it is again almost level, at about 473.5-473.6 m, with the highest readings near chainage 400 m (median of a 10 m bin, 473.9 m). Beyond 540 m, the floor falls by about 0.4 m to the service opening at 473.10 m.

The high zone between 340 and 540 m therefore acts as a drainage divide. The floor on its entrance side falls toward the main entrance. The floor on its far side falls toward the service opening. Both openings discharge water, as observed. The divide is defined on the main axis. Because of the local reversals (Section 4.3), a continuous surface fall has not been demonstrated along every passage. Over the whole interior, from chainage 100 to 540 m, the floor rises by about 0.6 m over 440 m, for a mean gradient of about 0.14%.

The first 20 m include the thin concrete layer at the entrance. The network-wide trend changes by at most 0.02 percentage points when the first 10 or 25 m are removed (0.19% with all data, 0.18% and 0.17% without). The concrete does not control the result.

Table 1 Section gradients of the Ravne 1 main axis by official chainage. Positive values fall toward the main entrance.

Chainage (m)	Gradient	Median floor (m a.s.l.)	Description
0-20	+5.1%	471.67	Entrance ramp; thin modern concrete at the mouth
20-100	+1.0%	472.74	Steady rise
100-290	≈0 (-0.04%)	472.94	Near-level reach
290-340	+1.5%	473.43	Short step
340-540	≈0 (-0.02%)	473.51	High zone, drainage divide
540-637.6	-0.35%	473.25	Falls to service opening
100-540 (interior mean)	≈+0.14%	—	Net rise ≈0.6 m

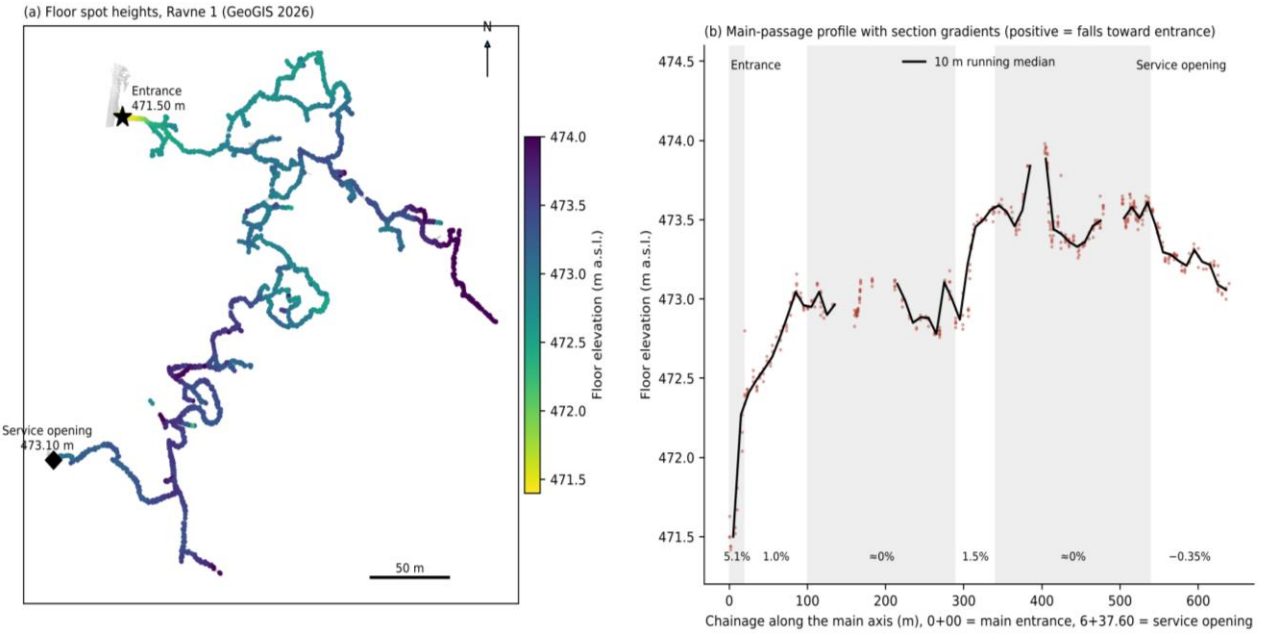


Fig. 6 Ravne 1 floor. (a) Floor spot heights (n = 2,040) colored by elevation, with the main entrance and the service opening. (b) Main-axis profile on the official chainage (0+00 at the main entrance, 6+37.60 at the service opening), with the 10 m running median and section gradients. Data: GeoGIS [7] survey sheets; analysis in this paper.

4.3 Local Reversals in the Measured Floor

The spot heights also show many small reversals. Taking both openings as outlets, 40% of connected spot heights lie more than 0.10 m below the lowest crest on their route out, and 23% more than 0.20 m. Most reversals are 0.1-0.4 m deep; 95% are shallower than 0.36 m and 99% shallower than 0.52 m. One isolated spot, 1.4 m below its surroundings, is probably a drafting error and was excluded.

These reversals are a property of the measured surface. In the field, no standing water forms in these places. Two factors can explain the difference. The floor is cobble conglomerate, and the spot heights sample a rough surface rather than the line along which water runs. The floor is also permeable, so a few-millimeter-deep film can pass through the gravel and joints beneath a local crest. The drainage regime is therefore described as predominantly, not uniformly, gravity-driven toward the two outlets.

4.4 Hydraulic Scenarios

Table 2 gives the scenario results for Q = 0.1 L/s. They describe what such a discharge would do on the measured gradients. They are not measured depths or velocities.

The laminar check gives similar values, for example, 2.7 mm and 2.6 cm/s at 0.14% with the whole floor wetted. Three conclusions follow, within the limits of the scenarios:

- In the scenarios, a small consistent fall is enough. At 0.14%, a film of this discharge still moves at a few centimeters per second. A gradient of 1-2% is not needed to keep the floor free of standing water at present flows.
- The modeled flow would not scour the floor. Bed shear stresses up to about 1.2 Pa are well below the values needed to move gravel and cobbles. In the interior, they barely reach the range of silt and fine sand.
- Travel time is hours. From the divide to the main entrance, about 400 m along the main axis, water at 3-5 cm/s would need roughly 2-4 hours.

4.5 The Other Five Systems

The same extraction was applied to Ravne 2-6 (Fig. 7). In every system, the entrance is the lowest point or lies within 0.1 m of it, and most of the floor stands above it. Ravne 4 and Ravne 5 rise fairly steadily from their entrances, with overall gradients of about 2.6% and 1.7%. Ravne 6 rises steeply along its entrance passage and is almost level in its inner cluster of corridors. Ravne 3 is irregular because several branches at different levels meet near the entrance. Ravne 2 is too short (13.9 m) for a meaningful trend. These systems were not analyzed further, but they show the same basic pattern as Ravne 1: lowest at the entrance, rising inward.

Table 2 Hydraulic scenarios for Q = 0.1 L/s. Ranges span flow width (1.4 m film to 0.3 m rill) and roughness (n = 0.013-0.030).

Section	Gradient	Depth (mm)	Velocity (cm/s)	Bed shear stress (Pa)
Interior mean	0.14%	1.7-7.2	2.5-7.7	0.02-0.10
20-100 m	1.0%	1.0-4.0	4.5-13.8	0.09-0.39
Step, 290-340 m	1.5%	0.8-3.5	5.1-15.6	0.12-0.52
Entrance, 0-20 m	5.1%	0.6-2.4	7.4-22.5	0.29-1.22

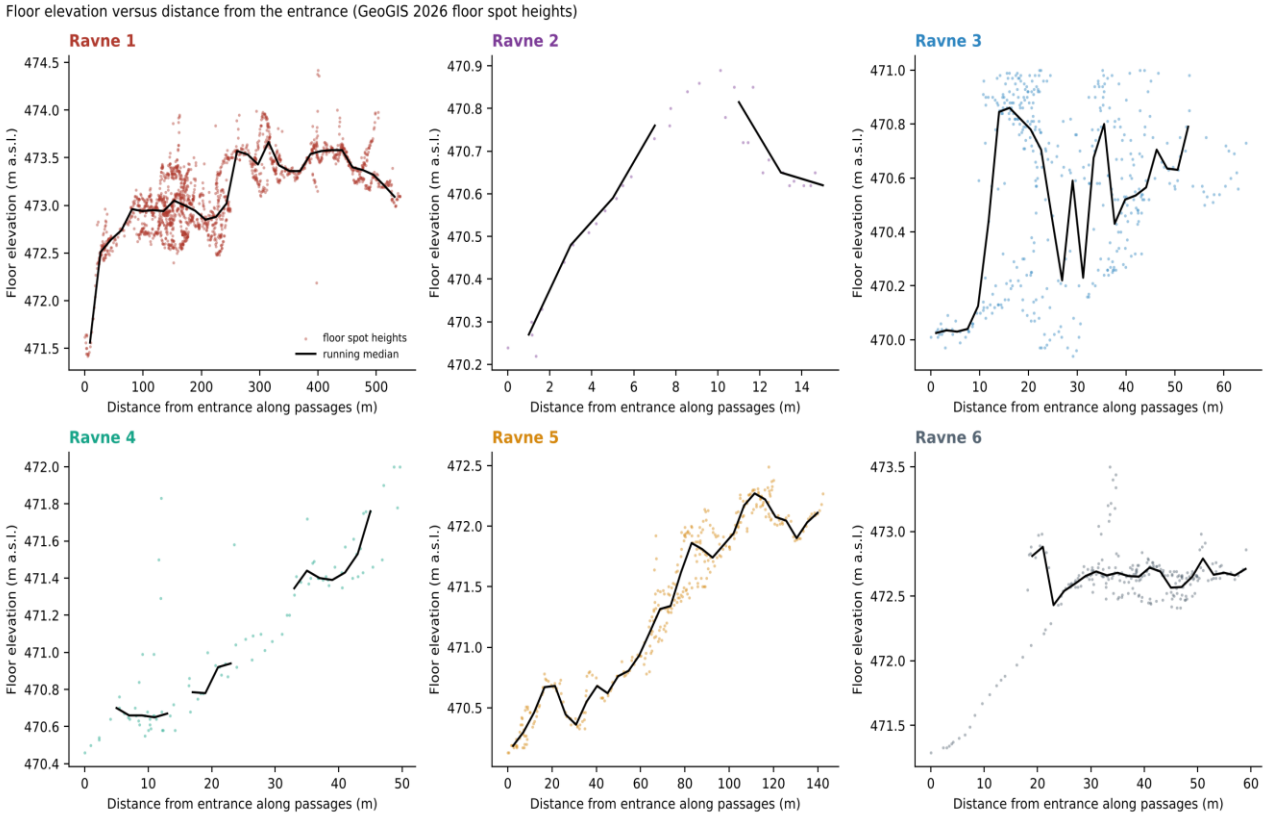


Fig. 7 Floor elevation against distance from the entrance for all six Ravne systems (GeoGIS 2026 floor spot heights). Distances are along the passage network; for Ravne 1 they are shorter than the official chainage (Section 3.3).

5. Comparison with Ancient, Historic and Modern Drainage Gradients

Table 3 lists gradients of structures that move water by gravity, from the Iron Age to current standards. Fig. 8 plots them on a common logarithmic scale.

5.1 What the Comparison Shows

The Ravne 1 gradients fall into two groups, and each has counterparts.

The interior mean of about 0.14% sits among long water-carrying channels. It lies between the two Roman aqueducts surveyed geodetically near Rome, Anio Novus (0.131%) and Aqua Claudia (0.163%) [9]. It is close to the Tiefer Georg-Stollen (≈0.19%) and well above the Siloam tunnel (≈0.06%), the Nîmes aqueduct, and the Ernst-August-Stollen. It lies below the recommended range for qanats (0.3-0.5%) and somewhat below the modern minimums for railway drains (0.2%) and road tunnels (0.25%). The Siloam tunnel shows that even 0.06% carries water over 533 m under steady flow.

The entrance gradients, 1.0% and 5.1%, belong to surface drainage. They match buried drains and gutters (about 1%) and paved surfaces and ramps (1-5%).

The Eupalinos tunnel adds a methodological point. Its walking floor is horizontal, and the water runs in a separate channel cut at 0.36% [12]. The gradient of a passage floor and that of the water path need not be the same. At Ravne 1, no separate channel is known, and the measured floor is also the water path. That is why the spot-height reversals in Section 4.3 matter, and why thalweg leveling would be a useful next step.

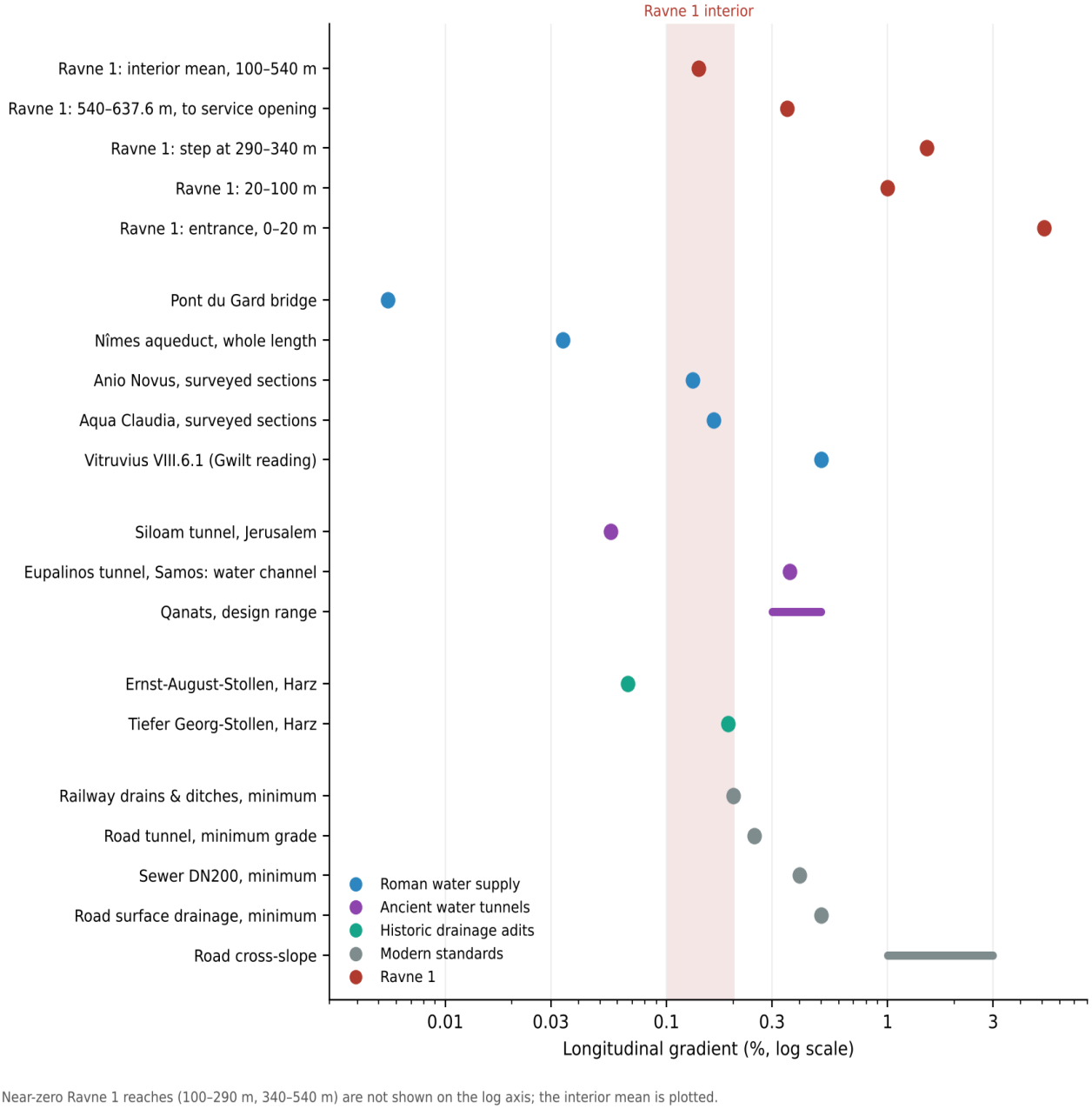
Table 3 Gradients of comparison structures and standards. M = measured on a structure; D = design value, recommendation or code minimum. Values from historical records (note b) are not geodetic measurements.

Group	Structure or standard	Gradient	Type	Source
Roman aqueduct	Pont du Gard bridge	0.0055% (1:18,241)	M	Ortloff [10]
Roman aqueduct	Nîmes aqueduct, whole length (≈50 km)	0.034% (≈1:3,000)	M	Ortloff [10]
Roman aqueduct	Anio Novus, surveyed sections near Rome	0.131%	M	Alimonti et al. [9]
Roman aqueduct	Aqua Claudia, surveyed sections near Rome	0.163%	M	Alimonti et al. [9]
Roman text	Vitruvius VIII.6.1, minimum fall	0.5% in the Gwilt translation[a]	D	Vitruvius [1]
Roman text	Pliny, minimum fall	≈0.02% (one *sicilicus* per 100 feet)	D	Smith [11]
Ancient water tunnel	Siloam tunnel, Jerusalem (533 m)	≈0.06% (≈0.3 m fall)	M	See note b
Ancient water tunnel	Eupalinos tunnel, Samos: water channel	0.36% (tunnel floor horizontal)	M	ASCE [12]
Qanat	Qanat tunnels, recommended range	0.3-0.5%	D	Saatsaz & Rezaei [13]
Historic drainage adit	Tiefer Georg-Stollen, Harz (1777-1799)	≈0.19% (15 Zoll per 100 Lachter)[c]	D	See note b
Historic drainage adit	Ernst-August-Stollen, Harz (1851-1864)	0.067% (1:1,500)	D	See note b
Modern railway	Track drains and ditches, minimum	0.2% (recommended 0.4%)	D	Rail Baltica [14]
Modern road tunnel	Minimum longitudinal grade	0.25% (maximum 3-4%)	D	Oyenuga [15]
Modern sewer	Gravity sewer DN 200 (nominal diameter 200 mm), minimum	0.40%	D	GLUMRB [16]
Modern road	Road surface drainage, minimum	0.5%	D	AASHTO [17]
Modern road	Normal cross-slope	1-3%	D	AASHTO [17]
Ravne 1	Interior mean, chainage 100-540 m	≈0.14%	M	This study
Ravne 1	Toward service opening, 540-637.6 m	0.35%	M	This study
Ravne 1	20-100 m	1.0%	M	This study
Ravne 1	Entrance ramp, 0-20 m	5.1%	M	This study

[a] English translations of Vitruvius VIII.6.1 differ; the value depends on the manuscript reading and should be treated as indicative. [b] Values from encyclopedic summaries of historical records [18]; primary engineering records were not accessible. [c] Conversion by the author, taking 1 Lachter ≈ 1.92 m and 1 Zoll ≈ 2.4 cm.

5.2 Mohenjo-Daro and Egypt

Two early traditions of planned drainage could not be placed in Table 3. At Mohenjo-Daro the floor of the Great Bath slopes toward a small outlet that leads into a corbelled drain, and the city's covered street drains carried wastewater by gravity [19, 20]. The mortuary temple of Sahure at Abusir had more than 380 m of copper drain pipe beneath its floors, ending at an outlet along the causeway [21]. Secondary literature cites numerical gradients for these systems, but they could not be verified against the excavation records for this study. They are therefore not used quantitatively here.



Near-zero Ravne 1 reaches (100–290 m, 340–540 m) are not shown on the log axis; the interior mean is plotted.

Fig. 8 Longitudinal gradients of Ravne 1 compared with Roman aqueducts, ancient water tunnels, historic drainage adits and modern standards (log scale). The shaded band marks 0.10-0.20%. Near-level Ravne 1 reaches are not shown on the log axis; the interior mean is plotted.

6. Discussion

6.1 A Predominantly Gravity-Driven Drainage Regime

The reconstructed floor of Ravne 1 is consistent with a predominantly gravity-driven drainage regime toward two observed outlets. Water enters along the network through the ceiling and walls. Along the measured main axis, it can reach the nearer outlet on either side of a broad internal high zone. The floor is steep close to the main outlet and almost level over long interior reaches. At the present discharge, this geometry keeps the walking floor free of standing water, while the estimated shear on the floor stays well below erosion thresholds. Drainage design also aims to avoid both ponding and scour by setting a minimum gradient to prevent standing water and a maximum velocity to prevent erosion. The Ravne gradients fall within the ranges found in surveyed aqueducts, water tunnels and historic adits, and near modern minimums (Table 3).

The regime is predominantly, not uniformly, gravity-driven. A large share of the measured floor shows local reversals of 0.1-0.4 m (Section 4.3). In the field, these do not hold water, suggesting permeability and micro-relief. They still show that the floor is not a smoothly graded channel.

6.2 What the Geometry Can and Cannot Show

A floor that falls toward its outlet is not, on its own, proof of design. Passages formed or enlarged by flowing water also tend to fall toward their outlets, because the water grades the bed. Three observations bear on the question without settling it:

- The divide. A single stream passage normally falls in one direction. Ravne 1 falls in two directions from a broad internal high zone, to two separate openings.
- The gradient break at the entrance. The fall steepens sharply in the last 100 m before the main outlet, from near level to 1.0% and then 5.1%. The modern concrete covers only the immediate entrance and does not account for the break.
- The present discharge. A flow of about 0.1 L/s, with estimated shear stress below about 1.3 Pa, is far too weak to cut passages in cemented conglomerate, under the modeled conditions and the assumed resistance of the rock. The present water regime may maintain the passages but is unlikely to have formed them.

The last point applies to present conditions only. Discharge may have differed in the past, for example under a wetter climate, before parts of the network were blocked or backfilled, or before the entrance zone was opened. The present flow does not exclude stronger flows in the past.

The archaeological record of dry-stone walls, infill and sealed side passages [2, 3, 5] is relevant to these questions but is not re-examined here. Within the scope of this paper, local elevation reversals, floor permeability, present-day modifications, and uncertain historical discharge prevent the identification of deliberate hydraulic design from floor geometry alone.

6.3 Limitations

- Discharge. The value of 0.1 L/s is a single timed estimate at the main entrance. The service opening was not gauged, and year-round outflow there has not been documented. Repeated timed measurements across seasons, ideally with a small V-notch weir, are needed.
- Hydraulics. Depths, velocities, and shear stresses are scenarios for assumed widths and roughness. They were not measured. For such shallow flow over a rough, possibly permeable bed, flow regime and resistance are uncertain.
- Present floor. The analysis uses today's walking surface. We cleared parts and laid a thin concrete layer at the entrance. Where the surface is a cleared floor rather than an original one, the profile describes present drainage, not necessarily the original.
- Spot heights. Spot heights sample a rough cobble surface. They resolve the trend well but overstate small reversals. Thalweg leveling along the water path would refine Section 4.3.
- Chainage conversion. Profile positions were converted from network distance to chainage through

the chainage labels on the sheets. Local errors of a few meters in position are possible, but they do not change the section gradients materially.

• Survey accuracy. The 2026 survey accuracies have not yet been reported [8]. The section gradients rest on height differences of 0.4-0.8 m over tens to hundreds of meters and are robust to errors of a few centimeters.

• Comparison data. Some comparison values come from encyclopedic summaries of historical records (Table 3, note b). Numerical gradients for Mohenjo-Daro and Old Kingdom Egypt could not be verified against primary records.

• Other water bodies. The separate water bodies fed from below do not drain to the surface. They belong to a different hydrological regime and are outside this analysis.

7. Conclusions

1. The floor of Ravne 1 falls toward two openings that both discharge water. The main entrance (471.50 m) is the lowest point of the system. A broad high zone at about 473.5-473.9 m, between chainages 340 and 540 m, separates it from the service opening (473.10 m).

2. Gradients change systematically along the main axis: 5.1% over the first 20 m, 1.0% to 100 m, near level from 100 to 290 m, a short step of 1.5%, near level across the high zone, and -0.35% toward the service opening. The interior mean is about 0.14%.

3. For the estimated present discharge of about 0.1 L/s, hydraulic scenarios give a flow a few millimeters deep at 2.5-22.5 cm/s, with bed shear stress below about 1.3 Pa. In these scenarios, any consistent fall drains such a flow, and the modeled shear stress is too low to scour the floor.

4. The interior mean gradient lies between those measured on Anio Novus and Aqua Claudia (0.131-0.163%), close to historic drainage adits, and somewhat below modern minimums for railway drains and road tunnels. The entrance gradients match surface-drainage practice.

5. The other five Ravne systems share the basic pattern: lowest at the entrance and rising inward.

6. The reconstructed geometry is consistent with a predominantly gravity-driven drainage regime. Floor geometry alone cannot establish deliberate hydraulic design.

Next steps include seasonal discharge measurements at both openings, thalweg leveling along the water path, and measured drain profiles from Indus and Egyptian excavation records.

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Conflicts of Interest

The author is the founder of the Foundation that manages the site and commissioned the survey.

Data Availability

The survey report, drawings, point clouds, and the extracted spot-height dataset are held by the Archaeological Park: Bosnian Pyramid of the Sun Foundation and are available from the author on reasonable request.

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