Hydraulics of Roman Aqueducts: Steep Chutes, Cascades, and Dropshafts

H. CHANSON

Abstract

This paper examines the archaeological evidence for steep chutes, cascades, and dropshafts in Roman aqueducts. It also presents comparative data on steep-descent water flow in aqueducts based on physical model tests. It is suggested that the Romans were aware of the hydraulic problems posed by supercritical water flows and that the technological solutions they imposed were rudimentary but sound: for example, they understood the need for energy dissipation devices such as the stilling basin and the dropshaft.*

The Roman aqueduct remains one of the best examples of hydraulic expertise in antiquity. Many aqueducts were used, repaired, and maintained for centuries, and some, such as the aqueduct of Carthage (Tunisia), are still partly in use today.[1] Most aqueducts consisted of long, flat sections interspersed by shorter steep drops. Despite arguments suggesting that Roman aqueducts maintained a fluvial flow regime,[2] the present study suggests that these steep drops produced supercritical flows requiring a technical response to ensure normal water flow; it also argues that the Romans employed three methods to address this problem: chutes followed by stilling basins, stepped channels, and dropshafts.

STEEP CHUTES AND STEPPED CASCADES: HYDRAULIC CONSIDERATIONS

A chute is characterized by a steep bed slope associated with torrential flow (figs. 1–3). This chute flow may be either smooth (fig. 2) or stepped (fig. 3). Roman designers used both designs as well as single drops along aqueducts (tables 1 and 2). There is archaeological evidence of smooth chutes along the Brévenne, Cherchell, Corinth, and Gorze aqueducts, and on the Anio Vetus, Claudia, Marcia, and Anio Novus aqueducts at Rome (table 1).[3] Although there is less information on stepped channels, those at Andriake and Beaulieu are well documented. Dam spillways also employed smooth and stepped-chute designs. The oldest known stepped spillway was built around 1300 B.C. in Greece,[4] and the famous Marib dam (Yemen) was equipped with an unlined rock chute on the left bank to spill flood waters. Roman engineers also built several significant spillway systems.[5]

The appendix provides some basic hydraulic calculations that I have applied to well-documented steep chutes. Tables 1 and 2 (column 4) summarize the results of these calculations. They were performed for "accepted" maximum flow rates (table 3) and demonstrate that high-velocity flows (velocities in excess of 8 m/s) occurred along several Roman aqueducts. The hydraulics of fluvial and torrential flows is distinguished by their fundamentally different behaviors. Torrential (supercritical) flows produce a much greater kinetic energy than fluvial flows. This value is normally expressed in terms of a "Froude number";[6] that is,

* I wish to acknowledge the following people (in alphabetical order) for their help and assistance: Professor C. Apelt, The University of Queensland, Australia; Mr. G. Berge Jussy, France; Dr. D. Blackman, Monash University, Australia; Ms. Chou Y.H., Brisbane, Australia; Dr. M.R. Gourlay, The University of Queensland, Australia; Dr. A.T. Hodge, Carleton University, Canada; Mr. G. Illidge, The University of Queensland, Australia; Mr. C. Lefebvre, Châtel-St.-Germain, France; Mr. P. Leveau, Université d'Aix-en-Provence, France; Mr. D. Murphy for information on Andriake cascade; Mr. J.L. Paillet, I.R.A.A., Aix-en-Provence, France; Professor N. Rajaratnam, University of Alberta, Canada; Dr. Y. Yasuda, Nihon University, Tokyo. In addition, I thank Dr. R.B. Hitchner, Editor-in-Chief of *AJA*, and Dr. S.R. Holman, former Associate Editor, for their helpful comments.

[1] Clamagirand et al. 1990, 423–31.

[2] That is, a tranquil flow regime such as the flow Froude number is less than unity (e.g., Chanson 1999).

[3] The Carthage aqueduct has a moderate slope (0.7%) upstream of the Oudna arcades, but the channel is technically termed "steep" because the flow was considered torrential.

[4] The overflow stepped weir in Akarnania, Greece, built around 1300 B.C., is an earthfill embankment, 10.5 m high, with a 25 m-long crest. The downstream slope is stepped (14 steps) with masonry rubbles set in mortar. The weir was used for several centuries. It is still standing, and flash floods spill over the stepped chute. See Chanson 1997; Knauss 1995.

[5] Roman dams equipped with a chute spillway system included: Cornalvo (Spain, second century A.D.), Al Khums (Libya, third century A.D.). Examples of drop spillway included Harbaka (Syria, third century A.D.). Examples of stepped spillway include the Kasserine dam (Tunisia), Oued Guergour dam (Tunisia, first century A.D.), Qasr Khubbaz (Syria, second century A.D.), and Tareglat dam (Libya, third century A.D.). See Chanson 1995a, 23–37.

[6] The Froude number for a rectangular channel is defined as the ratio of the velocity to the square root of the gravity acceleration times the flow depth: i.e., $Fr = V/\sqrt{gd}$.

American Journal of Archaeology 104 (2000) 47–72

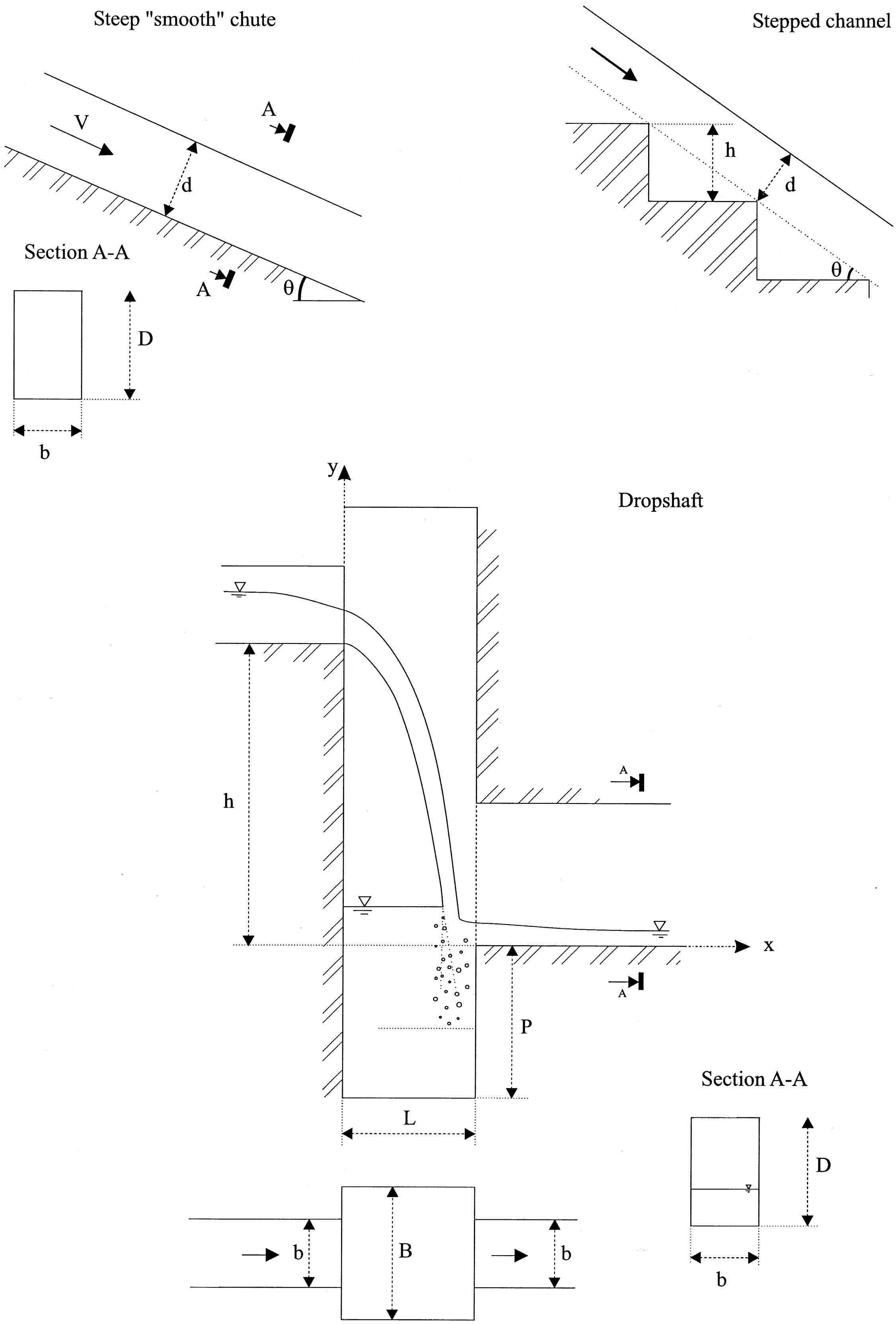


Fig. 1. Sketch of steep chute, dropshaft, and stepped channel observed in Roman aqueducts

Fig. 2. Photograph of chute flow in operation. Smooth chute flow, $Q = 0.075\ m^3/s$ (6,480 m^3/day), $\tan\theta = 7\%$, $b = 0.5$ m, $d \sim 0.035$ m, $V \sim 4.3$ m/s. View from downstream (flow from top to bottom).

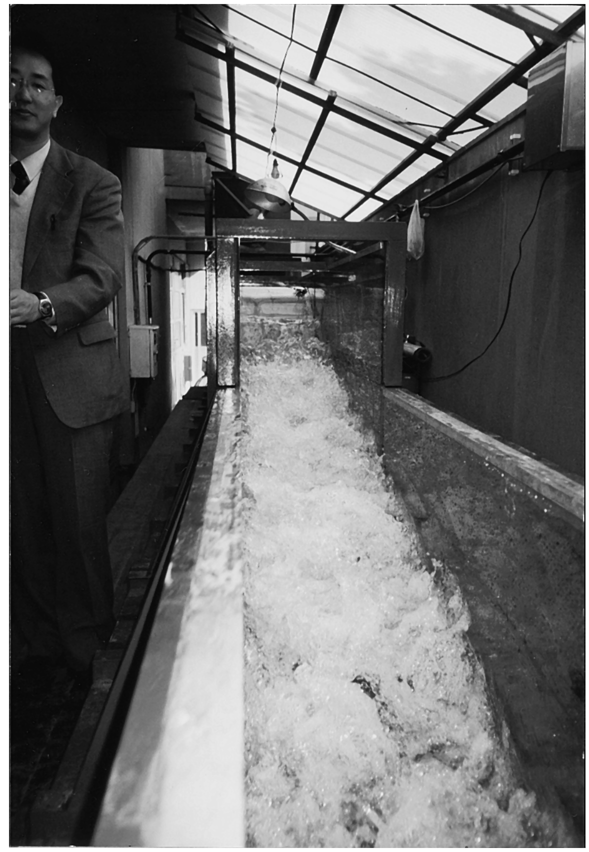


Fig. 3. Photograph of chute flow in operation. Stepped chute flow, $Q = 0.033\ m^3/s$ (2,850 m^3/day), $\tan\theta = 20\%$, $h = 0.1$ m, $b = 0.4$ m. View from downstream (flow from top to bottom).

the calculation of the properties of fluvial (lower energy) flows will produce a Froude number less than 1, while the properties of torrential flows produce a Froude number greater than 1. Supercritical torrential flow was consistently present along the entire channel of each investigated chute (table 1, column 4). Downstream of the chute, the transition to a slower flow motion took place as a hydraulic "jump," characterized by strong energy dissipation (see appendix).

In modern engineering, hydraulic designers seek to avoid three types of hydraulic jumps: strong, oscillating, and undular jumps (fig. 4). Bed erosion and "scouring" is more likely whenever there is a strong hydraulic jump, abruptly increasing the scour potential of the water at any point. It is believed that Roman aqueduct mortar and concrete could never sustain the "uplift forces" that occur in the water just beyond these strong jumps.[7] Oscillating jumps present the risk that the position of the roller would be unsteady and fluctuate over great lengths. Further, the oscillating jump would be characterized by the unsteady propagation of the surge waves, highly undesirable in a narrow channel.[8] The third undesirable change in water flow pattern, the undular hydraulic jump, produces steady, stationary free-surface

[7] This comment is based upon my experience (associated with site inspections of several aqueducts) in several hydraulic studies related to concrete deterioration. I have discussed the issue of concrete resistance with world-known concrete experts and historians, who suggested similar results in Roman concrete and 19th-century concrete.

[8] "This type [of jump] has a pulsating action. . . . [It] is one of the most difficult [types of jump] to handle" (Bradley and Peterka 1957a, 1401–22). Bradley and Peterka's work also highlighted specific problems in confined channels: "In narrow structures, such as canals [and aqueducts], waves may persist to some degree for miles. . . . Structures in this range of Froude numbers are the ones which have been found to require the most maintenance" (Bradley and Peterka 1957b, 1404–20).

Table 1. Steep Smooth Chutes in Roman Aqueducts

(1) Steep Section	(2) Ref.	(3) Geometry	(4) Flow Conditions ΔH (m)	d_o (m)	V_o (m/s)	X (m)	(5) Remarks
Brévenne aqueduct	[Co3]						
Courzieu II/ La Verrière		b ~ 0.55 m, θ = 12.4°, mortar	44	0.05	4.24		Chute C1; 2.4 km upstream of the Basin of Sotizon
Chevinay/Plainet		b ~ 0.76 m, θ = 24.2°, paved stone	87	0.052	4.45		Chute C2
Lentilly II/Les Molières-Montcher		b = 45 m, D = 0.8 m, θ = 4.7°, mortar	33	0.0795	3.25		Chute C5
Limonest/ La Bruyère		b ~ 0.53 m, mortar	8				Chute C6
Cherchell aqueduct	[LP]						
Chabet Ilelouine		b = 1.3 m, θ = 38.0°	12.3	0.045	8		4 series of steep chutes followed by circular dropshaft
Corinth aqueduct	[Lo]						
Alepotrypes		b ~ 1.1 m, θ = 1.72°, mortar		0.29	3.62		Upstream of a large stilling basin (40 × 11 m²)
Gorze aqueduct	[Le]						
Bridge over Moselle		Two parallel canals, each: b ≈ 0.85 m, θ = 0.022°, mortar	4.3			1,100	Upstream calming basin (Ars-sur-Moselle) and downstream stilling basin (Jouy-aux-Arches)
				0.111	0.92		2 canals in operation
				0.177	1.15		1 canal in operation
Anio Vetus aqueduct							
Tivoli, Hadrian's Villa	[VD]	b = 0.8 m, D = 1.25 m, θ = 11.6°, rocks and bricks	0.7	0.332	8.3		Short section [VD, p. 40; AS, pp. 63–64]
Bridge at Mola di San Gregoria	[AS]	b ~ 1.05 m, D ~ 2.37 m, θ = 9.3°	4.09	0.236	8.9		[AS, pp. 68–70]
Claudia aqueduct							
below D. Cosimato cliff	[VD]	b = 1.15 m, D = 0.9 m, θ = 26.6°, coarse concrete with rough reticulate	5.48	0.18	10.7		Upstream of bridge below Vicavaro [VD, p. 196; AS, p. 196]
Marcia aqueduct							
Casale Acqua Raminga, Gericomio	[Bl]	b = 1.15 m, θ = 8.9°, rough concrete	3.98	0.329	5.75	25.4	Upstream section [AS, p. 115; VD, p. 92]
		b = 1.15 m, θ ≈ 6.13°, rough concrete	31.9	0.374	5.05	204	Downstream section
Anio Novus							
near Torrente Fiumicino	[Bl]	b = 1.25 m, θ ≈ 3.48°, brick work	6.8	0.315	5.58		[AS, p. 261; VD, p. 280]
Ponte dell'Inferno to Ponte Scalino	[AS]	b ≈ 1.06 m, θ = 0.604°	26.37	0.765	2.71		Unlined rock tunnel; cascades or steps? [AS, p. 287]
Ponte Scalino to Ponte Amato	[AS]	b ~ 1 m, θ = 0.94°		0.686	3.21		Unlined rock tunnel; cascades or steps? [AS, p. 287]
Fienile	[AS]	b ~ 1 m, θ = 0.76°		0.747	2.95		Unlined rock tunnel; cascades or steps? [AS, p. 287]
Carthage aqueduct	[Ra]						
upstream of Oudna arcades		b = 0.865 m, θ ≈ 0.40°, mortar		0.157	1.47		Immediately upstream of Oued Miliane plain arcades

d_o: normal flow depth; V_o: normal flow velocity; X: chute length; ΔH: total head loss. References: [AS] Ashby 1935; [Bl] Blackman 1978; [Co3] Conseil Général du Rhône 1993; [CQ] Coquet 1966; [Le] Lefebvre 1996; [LP] Leveau and Paillet 1976; [Lo] Lolos 1997; [Ra] Rakob 1974; [VD] Van Deman 1934.

Table 2. Stepped Cascades and Drops in Roman Aqueducts

(1) Steep Section	(2) Ref.	(3) Geometry	(4) Flow Conditions ΔH (m)	X (m)	(5) Remarks
Stepped cascades					
Oued Bellah, Cherchell aqueduct	[LP]		37		Upstream of bridge
					Cascade?
			18.6		Downstream of bridge
Beaulieu aqueduct	[CQ]		37		Combination of steep chutes and dropshafts
Petite cascade		5 steps: h = 0.5 to 5.0 m	2 to 2.5		Horizontal and inclined stepped faces
Andriake, Lycia	[Mu]	Pooled steps: h = 2.2 m, pool height = 0.78 m, b = 1.78 m, θ = 31.4°	11	18	Series of 5 pooled steps
Claudia aqueduct	[VD]	Single drop: h = 1.1 m			Near bridge below Vicavaro
Drops					
Brévenne aqueduct	[Co3]				
St-Pierre-La-Palud I		b ~ 0.45 m	30		
Lentilly II/Le Guéret-La Rivoire		b ~ 0.45 m	38		

b: channel width; X: cascade length; ΔH: total head loss. References: [Co3] Conseil Général du Rhône 1993; [CQ] Coquet 1966; [LP] Leveau and Paillet 1979; [Mu] personal communication, D. Murphy 1998; [VD] Van Deman 1934.

waves of significant length[9] that have no formed roller pattern and that extend far downstream.[10] Thus, for a flow depth of 0.5 m, these waves might extend for one kilometer or more. A similar wavy flow pattern may also occur with near-critical flows.[11] The waves generated by these undular and oscillating jumps can seriously interfere with the operation of the conduit downstream. Such problems in modern conduits include vibrations on downstream gates, disturbance of the discharge measurement devices, and changes in the way turbulent materials are dispersed within the channel.[12]

The free-surface profile at the downstream end of steep chutes is affected by both the high-speed chute flow and tailwater conditions. The latter are the flow conditions in the downstream canal.[13] Four flow situations may occur (fig. 5). With a supercritical tailwater depth, the flow remains supercritical after the change of slope and no jump occurs. When the tailwater depth is larger than the critical depth in the downstream conduit, a hydraulic jump takes place. Depending upon the chute and tailwater conditions, the jump may be located far downstream or close to the change in slope. For very high tailwater depths, the hydraulic jump becomes drowned and a plunging jet flow occurs at the change of slope.

For several of the Roman steep chutes (tables 1 and 4), the effects of tailwater conditions were investigated by performing backwater computations.[14] The results suggest that various types of jumps occurred, as well as plunging jet flows (table 4, column 3). These findings demonstrate that unfavorable flow conditions existed in these chutes, including oscillating hydraulic jump and undular flows, which were unsuitable for a proper operation of the aqueduct unless structures were built to dampen the surge waves. A sensitivity analysis was further performed for several chutes and aqueducts: table 4 contains a sample of the quantitative results for one of these. The study suggests no major change in backwater profiles for a broad range of discharge, from 30 to 120 percent of maximum flow rate.

---

[9] E.g., $X/d \geq 2{,}000$ where X is the longitudinal extent of the undular flow and d is the flow depth.

[10] Chanson and Montes 1995.

[11] Chanson 1995b.

[12] For more complete reviews, see Chanson 1995b, 1-1 to 1-4; for undular flows, see Montes and Chanson 1998; for oscillating jumps, see Bradley and Peterka 1957a and 1957b.

[13] Assuming a long prismatic downstream conduit, the downstream flow depth, or tailwater depth, is the uniform equilibrium flow depth in the downstream conduit.

[14] Standard step method, distance calculated from depth (e.g., Henderson 1966; Chanson 1999). See Chanson 1998 for further details on the calculations.

Table 3. Accepted Flow Rates and Details of Roman Aqueducts

(1) Name	(2) Location	(3) Length (km)	(4) Discharge (m^3/day)
Arles	France	48.0	8,000
Athens	Greece	25.7	
Beaulieu	Aix-en-P., France		
Brévenne	Lyon, France	70.0	10,000
Carthage	Tunisia	132.0	17,300
Cherchell	Algeria	>45	40,000/6,600*
Cologne	Germany	95.4	
Corinth	Greece	85.0	80,000
Cuicul	Algeria	5 to 6	
Dougga	Tunisia	12	
Gier	Lyon, France	86.0	15,000
Gorze	Metz, France	22.3	15,000
Gunugu	Algeria		
Mont d'Or	Lyon, France	26.0	2,000 to 6,000
Montjeu	Autun, France		
Nikopolis	Greece	70.0	
Nîmes	France	49.8	35,000
Yzeron-Craponne	Lyon, France	40.0	13,000*
Appia	Rome, Italy	16.6	73,000
Anio/Anio Vetus	Rome, Italy	81.0	190,080
Marcia	Rome, Italy	91.3	188,000
Tepula	Rome, Italy	17.7	18,000
Julia	Rome, Italy	22.9	48,000
Virgo	Rome, Italy	22.9	100,200
Alsietima	Rome, Italy	32.8	15,700
Claudia	Rome, Italy	69.7	190,900
Anio Novus	Rome, Italy	86.9	190,080
Trajana	Rome, Italy	57.0	114,000
Alexandrina	Rome, Italy	22.0	21,000

Column (4) = maximum discharges as estimated in some references below; * present study. References: Ashby 1935; Blackman 1979; Burdy 1996; Carton 1899; Conseil Général du Rhône 1987, 1991, 1993; Fabre et al. 1992; Hodge 1992; Lefebvre 1996; Leveau and Paillet 1976; Lolos 1997; Van Deman 1934.

Design of Stilling Basins Downstream of Steep Chutes

In discussing the design of these basins, it is necessary to consider their intended purpose, stilling basin design, and chute geometry.

Settling or Stilling Basins? The presence along aqueducts of basins (i.e., short, deeper sections of the canal), often associated with inspection shafts and manholes, has been well documented.[15] But were they settling basins or stilling basins? Some studies have proposed that these were "settling basins" built to trap mud, sand, and solid waste.[16]

Some basin systems, however, were clearly *not* designed to trap sediments. At Alepotrypes (Corinth), for example, the hydraulic power of the chute flow was about 9 kw and the downstream cistern functioned primarily as a dissipation basin.[17] Three

[15] For example, Hodge 1992, 103–5 and Chanson 1999, c-1. Examples of inspection shafts and manholes include: Cap Blanc at Hippo Zarite (0.3 m square shaft, P = 0.4 m [Gauckler 1902, 129]); Grand'Croix at Gier (0.9 m × 0.87 m rectangular shaft, P = 0.32 m [Burdy 1996, 209]); and Oudna at Carthage (Rakob 1974, 49–50). Gauckler (1897, 176) illustrated an aqueduct at Ksar Soudane (Tunisia) with circular manholes, possibly acting as basins. At Hippo Zarite (near Bizerte), the Aïn Nadour branch (B = 0.2 m wide, P = 0.3 m) had several circular basins (∅ = 1 m, P ~ 2.5 m? [Gauckler 1902, 126]). Gauckler's father, Philippe Gaspard Gauckler (1826–1905), was a French hydraulic engineer and member of the French Corps des Ponts-et-Chaussées. He reanalyzed the experimental data of Darcy and Bazin (1865), and in 1867 he presented a flow resistance formula for open channel flows (Gauckler-Manning formula), sometimes called improperly the Manning equation (Gauckler 1867).

[16] For example, Rakob 1974, 1979; Hodge 1992; Burdy 1996.

[17] The concept of a stilling basin was known prior to the Roman era. In Priene (Ionia), a large stilling basin was built at the downstream end of the sewer system during the 5th century B.C. (Ortloff and Crouch 1998). The basin was about 3.23 m long, 0.8 m wide, and 0.8 m deep, and the maximum discharge was probably about 0.425 m^3/s before spillage.

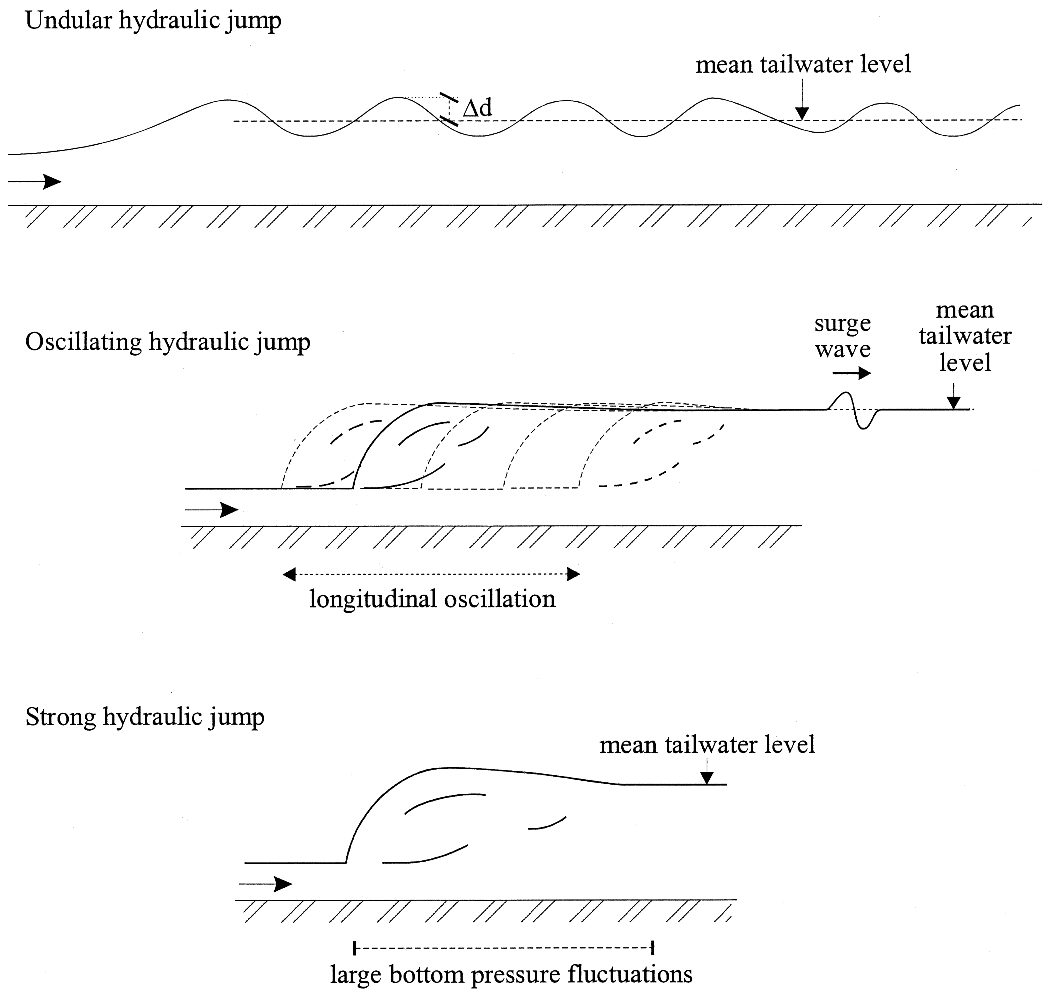


Fig. 4. Sketch of undular, oscillating, and strong hydraulic jumps

other, well-documented basin systems were built downstream of steep chutes: at Sotizon, 2,410 m downstream of the Courzieu II chute (Brévenne), at Jouy-aux-Arches, downstream of the Moselle bridge-canal (Gorze), and in the case of at least five circular basins at Oudna (Carthage)[18] (figs. 6–8). Moreover, it appears that the basin dimensions are inadequate for purposes of trapping sediments. All of these aqueducts were covered and lined with mortar. The intake channel was the only possible point at which sediments could enter the system. Roman engineers were, even by modern standards, highly expert at building intake structures, and several of these were designed with a de-silting device.[19] It is obviously most efficient to trap sediments directly at the point of entry rather than further downstream. Further, the water velocity in the aqueduct channels was too slow to carry coarse sediments very far.[20]

The degree to which a sedimentation basin may effectively trap sediment is related to the inflow properties, depth and length (geometry) of the basin, and the properties of the sediment itself.[21] My

[18] Sotizon is also called "Bac de Sotizon" or "Bac de nettoyage de Sotizon à En Triaume" (Conseil Général du Rhône 1993). For the Mosell bridge-canal see, e.g., Lefebvre 1996. The role of the basin was recognized early as a stilling device to calm the flow: "un espèce de puits, afin que les eaux y puissent tournoyer et prendre ensuite plus facilement leur direction" (François and Tabouillot 1974, 146). The five circular basins at Oudna were separated by 25 to 50 m at the start of the aqueduct arcades across Oued Miliane plain (Rakob 1974, pls. 36 and 37, fig. 11). Although further basins were found near and within Carthage, it must be noted that none existed upstream of the Oued Miliane plain arcades.

[19] E.g., the Gier aqueduct intake at Saint-Chamond (Burdy 1996).

[20] A complete set of calculations was developed in Chanson 1998, appendix E.

[21] E.g., Fair et al. 1971.

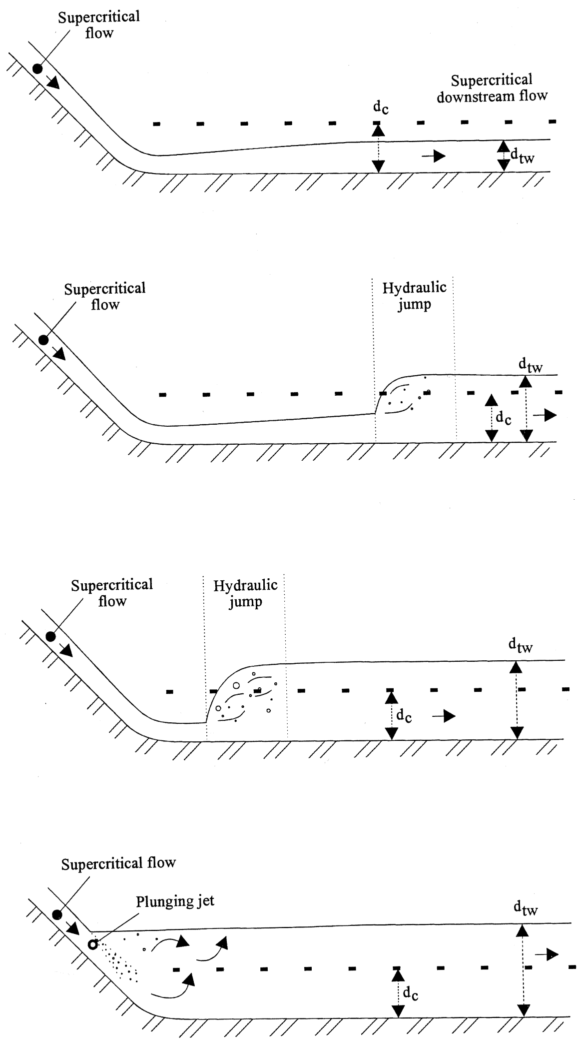


Fig. 5. Sketch of different tailwater flow conditions and associated backwater effects

calculations of maximum flow rates for the basins at Sotizon and Oudna suggest that sediment trap efficiencies were less than 50 percent. In addition, the basin volumes were small: 0.27 m^3 at Sotizon, 1.7 m^3 at Jouy, and 0.176 m^3 per basin at Oudna. With inflow sediment concentrations as low as 0.02 to 0.19 kg/m^3, these basins would have been filled in one day at maximum flow rates. To clean the basins one had to stop the flow, making it improbable that cleaning would occur on a daily basis.[22] It is unlikely, in fact, that the aqueducts were stopped more than once a month, and the cleaning process would have taken several days to complete. Thus it appears to me most likely that at least four of these basins were in fact not sediment traps but stilling devices.

Stilling Basin Designs. As the preceding discussion suggests, undulations and surge waves would create serious problems for the operation of an aqueduct. The purpose of the stilling basins was to dampen the wave energy. Calculations done of the backwater show the need for substantial energy dissipation at Alepotrypes and reveal unfavorable flow conditions at Courzieu II (undular jump), at Gorze bridge-canal (undular flow, Fr = 0.88) and at Oudna[23] (undular flow, Fr = 0.7) (table 4). At Sotizon, Jouy, and Oudna, the basins were primarily stilling basins to suppress downstream wave propagation (e.g., fig. 9). I believe that the Chevinay and Lentilly II chutes located downstream of the Sotizon basin were equipped with similar stilling devices, although no trace of the basin has yet been found (table 4).

Stilling basins work best when the basin itself is deep and long. The minimum length of modern hydraulic jump stilling basins is about three to six times the downstream flow depth although, for oscillating hydraulic jumps, the basin length must be longer: a length-to-depth ratio of about 6:1.[24] At Sotizon this ratio is approximately 4:1. At Jouy it is approximately 10:1, while at Oudna it is closer to 3.8:1, although the basins at Oudna are circular in shape. Clearly, the Jouy basin had the most efficient design while that at Oudna was less than optimal. The circular shape of the Oudna basins, associated with a small volume, may have been intended to induce three-dimensional wave motion, associated with cross-waves, wave impact on the walls, and wave reflection.[25] Consequently, a single basin would have been inadequate for dampening wave propagation. There are at least five basins at Oudna, and this quantity may represent an attempt by the Roman designers to address this problem.

Chute Geometry. In several instances, the design of the steep chutes differed from that of the main aqueduct channel. Some steep chutes were wider than the main channel, such as those at Chabet Ilelouine

[22] Rakob (1979) commented on the frequent cleaning task of the Carthage aqueduct basins. Lefebvre (1985) similarly mentioned the rate of sediment filling at Gorze.

[23] At the start of Oued Miliane plain arcades.

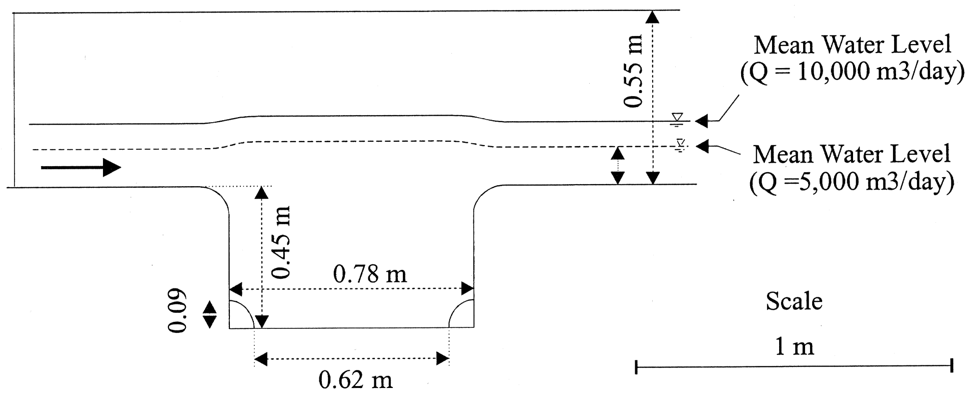
[24] See, e.g., U.S. Department of the Interior 1960 and Novak et al. 1996.

[25] A similar cross-wave pattern is experienced in undular hydraulic jumps and near-critical flows (Chanson and Montes 1995; Chanson 1995b).

Table 4. Tailwater Flow Conditions Downstream of Steep Chutes

(1) Steep Section	(2) Q (m^3/day)	(3) Tailwater Flow Patterns
Brévenne aqueduct		
Courzieu II/La Verrière	28,000	***Undular jump*** 15.4 m d/s of change in slope (d_{tw} = 0.418 m)
	10,000	Undular jump 8.5 m d/s of change in slope (d_{tw} = 0.197 m)
	7,000	Undular jump 6.4 m d/s of change in slope (d_{tw} = 0.154 m)
	5,000	Undular jump 4.6 m d/s of change in slope (d_{tw} = 0.123 m)
	3,500	Undular jump 3.4 m d/s of change in slope (d_{tw} = 0.097 m)
Chevinay/Plainet	28,000	***Undular jump*** 13 m d/s of change in slope (d_{tw} = 0.434 m)
	10,000	Undular jump 7.2 m d/s of change in slope (d_{tw} = 0.204 m)
	7,000	Undular jump 5.4 m d/s of change in slope (d_{tw} = 0.154 m)
	5,000	Undular jump 3.8 m d/s of change in slope (d_{tw} = 0.127 m)
	3,500	Undular jump 2.8 m d/s of change in slope (d_{tw} = 0.10 m)
Lentilly II/Les Molières-Montcher	28,000	Steady jump immediately d/s of change in slope (d_{tw} = 0.586 m)
	10,000	***Oscillating jump*** 1.5 m d/s of change in slope (d_{tw} = 0.268 m)
	7,000	Oscillating jump 1.2 m d/s of change in slope (d_{tw} = 0.208 m)
	5,000	Oscillating jump 1 m d/s of change in slope (d_{tw} = 0.165 m)
	3,500	Oscillating jump 0.7 m d/s of change in slope (d_{tw} = 0.130 m)
Gorze aqueduct	15,000	***Undular flow*** in bridge-canal (Fr = 0.88); identical flow pattern for operation with one and two canals
Carthage aqueduct		
Oudna, start of Oued Miliane plain arcades	17,300	***Undular flow*** d/s of change in slope: Fr = 0.7 (d_{tw} ~ 0.228 m)
Corinth aqueduct		
Alepotrypes	80,000	Plunging jet flow
Anio Vetus aqueduct		
Tivoli, Hadrian's Villa	190,080	Steady jump at sudden enlargement (d_{tw} ~ 1.7 m)
Bridge at Mola di San Gregoria	190,080	Plunging jet flow (d_{tw} ~ 1.8 m). Risk of ***undular flow*** in d/s conduit
Claudia aqueduct		
below D. Cosimato cliff	190,900	Steady jump at change in slope (d_{tw} ~ 2.2 m)
Marcia aqueduct		
Casale Acqua Raminga, Gericomio	188,000	Weak jump 9.1 m d/s of steep chute (d_{tw} = 1.32 m)
Anio Novus		
near Torrente Fiumicino	190,080	Critical flow in downstream conduit (Fr = 1.03, d_{tw} = 0.668 m)
Ponte dell'Inferno to Ponte Scalino	190,080	Subcritical backwater effect in steep chute associated with ***undular flow***
Ponte Scalino to Ponte Amato	190,080	Plunging jet flow (d_{tw} ~ 1.4 m). Risk of ***undular flow*** in d/s canal
Fienile	190,080	Plunging jet flow (d_{tw} ~ 1.0 m). Risk of ***undular flow*** in d/s canal

d_{tw} = tailwater normal depth; results based on backwater calculations (Chanson 1998); ***bold italic*** = unfavorable flow conditions.



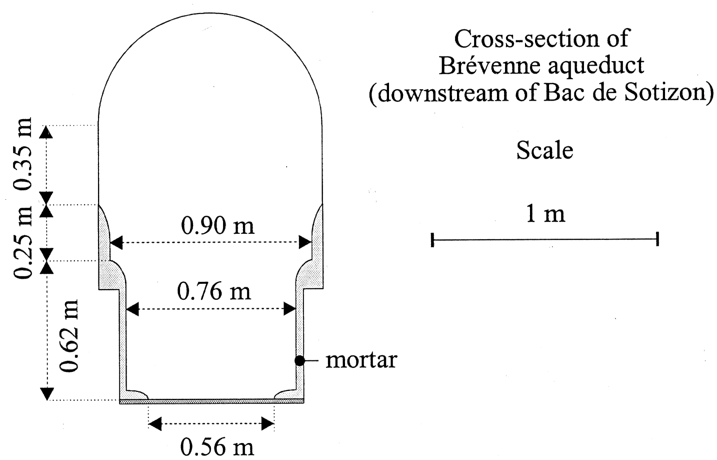


Fig. 6. Stilling basins in Roman aqueducts. Basin of Sotizon and a typical cross-section of Brévenne aqueduct. (After Conseil Général du Rhône 1993)

(Cherchell), and the Claudia aqueduct below D. Cosimato cliff. It has been suggested that this design was introduced to maximize flow resistance.[26] Other steep chutes were narrower than the main channel. This is the case at Courzieu II (Brévenne), Lentilly II (Brévenne), and Hadrian's Villa (Anio Vetus). Of interest, the chute outlet was often designed to be narrow at the point in which the water entered it and gradually expanding in width. This is evident at Courzieu II (Brévenne), Lentilly II (Brévenne), Alepotrypes (Corinth), Jouy (Gorze), Hadrian's Villa (Anio Vetus), and Fienile (Anio Novus). This corresponds to a transition from a cut-rock tunnel to an aqueduct bridge. In a few cases, the chute outlet design was a contraction: this occurs at the bridge at Mola di San Gregoria (Anio Vetus) and at the Claudia aqueduct below D. Cosimato cliff. The gradual reduction in breadth seems related to the chute's transition into a cut-rock tunnel. Modern hydraulics suggests that a channel expansion at the chute outlet would have assisted in dissipating the energy of the flow.[27] The evidence of the contrary, of gradual reduction, could suggest that those who did the construction were not aware of the problem.

DROPSHAFT CASCADES

In some aqueducts Roman engineers built a series of dropshafts (called dropshaft cascades) along the aqueduct's main branch. This technology is well documented for the Cherchell, Cuicul, Cologne, Montjeu, and Yzeron aqueducts (table 5).[28] In Rome, vertical dropshafts were used to connect aqueducts, particu-

[26] Leveau and Paillet 1976.
[27] E.g., Hager 1992; Novak et al. 1996.
[28] It may also be suggested by construction details in the Beaulieu, Dougga, Gunugu, and Rusicade aqueducts.

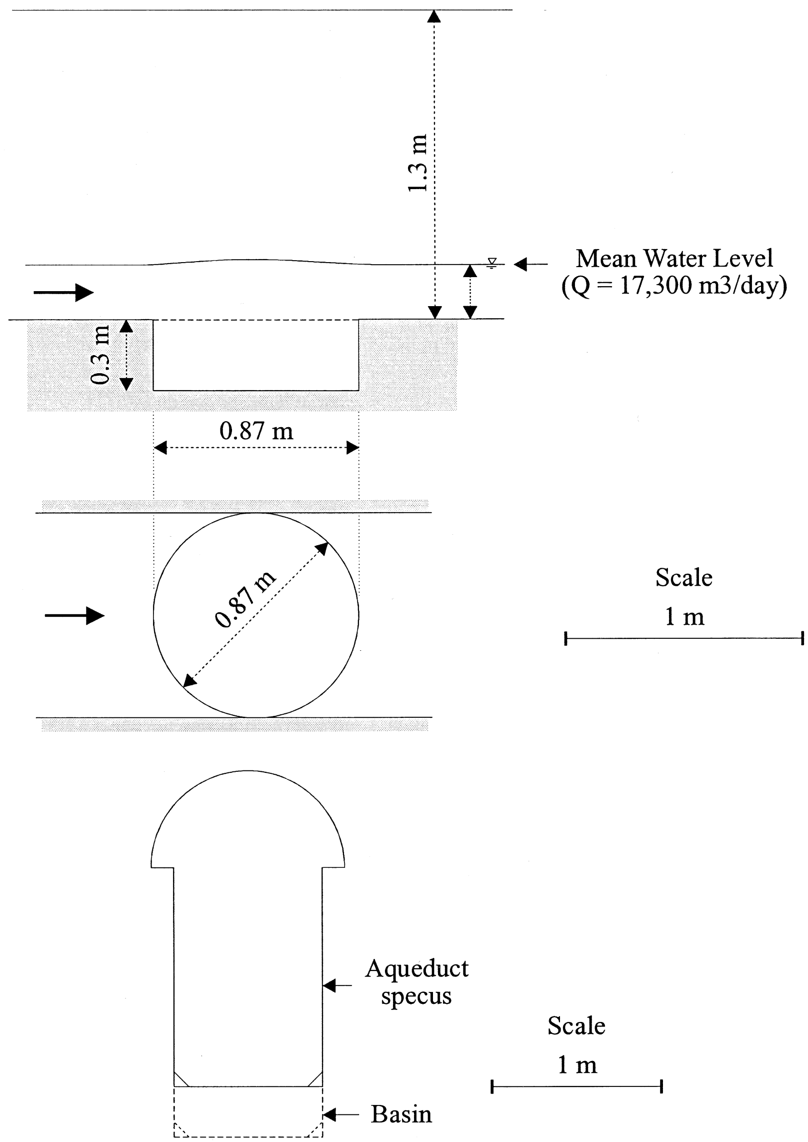


Fig. 7. Stilling basins in Roman aqueducts. Oudna, at the start of Oued Miliane plain arcades (Carthage aqueduct). (After Rakob 1974)

larly from newer, higher channels to older canals.[29] These shafts were sluice towers built primarily for water redistribution. It is believed that the design was probably a function of circumstances rather than a specific engineering feature of the newer aqueduct.

In modern hydraulics, there are at least three recognized purposes for designing dropshaft cascades. First, they may be used where the topography is especially steep. This is clearly the case for the Roman aqueducts at Recret and Grézieu-la-Varenne, Yzeron; and at Montjeu and Autun (table 5, figs. 10–15). Until now it has been believed that dropshafts were built to dissipate energy and possibly also, as dis-

[29] At Grotte Sconce (also spelled Grotte Sconcie), a branch of the Anio Novus aqueduct led to a circular dropshaft and into the Claudia aqueduct, and a second rectangular dropshaft led to the Marcia aqueduct (Ashby 1935, 277–9 and fig. 31; Van Deman 1934, 212–3, 302–3). At San Cosimato Gorge, a side channel connected the Claudia to the Marcia aqueducts through a 9.2 m-deep rectangular dropshaft (Ashby 1935, 101–2 and fig. 7; Van Deman 1934, 76–7). Other examples of "interconnection shafts" included a square dropshaft from Claudia to Vetus at Voltata delle Corrozze (Van Deman 1934, 213) and a rectangular shaft from Anio Novus to Claudia near the Fosso Arcese bridge (Ashby 1935, 275).

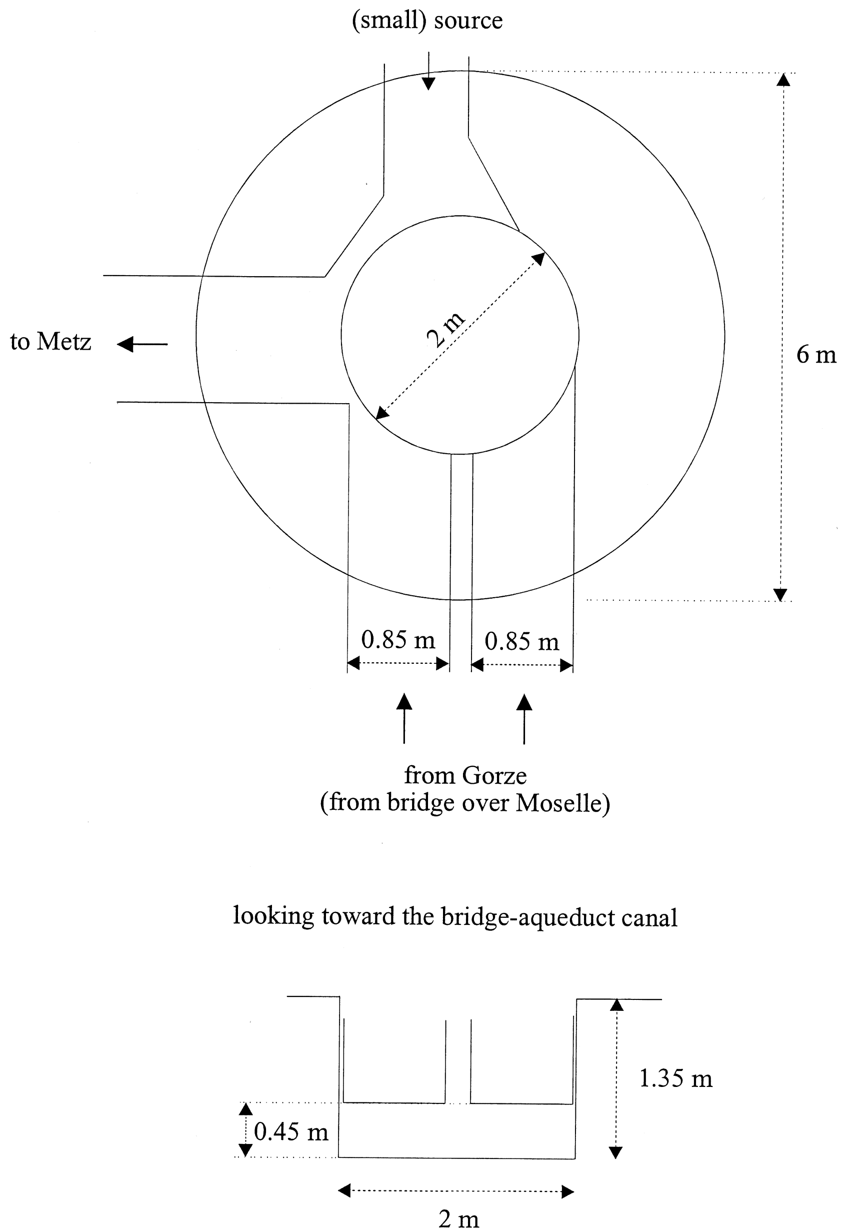


Fig. 8. Stilling basins in Roman aqueducts. Jouy-aux-Arches downstream of the Moselle bridge-canal, Gorze aqueduct. (After Lefebvre 1996)

cussed above in the context of basins, to trap sediment.[30] Regardless of purpose, a dropshaft by design provides a connection between two flat conduits, located at different elevations along the (usually short) length of the shaft. In contrast, a steep chute would require a much greater horizontal distance for the same drop height. A second application of the dropshaft is the dissipation of the kinetic energy of the flow. Such a design is still used today.[31] To work well this design must account for three factors: drop height, shaft geometry, and flow rate. If these are not properly considered, unacceptable scour and erosion may take place. A third application of the dropshaft cascade is the aeration (or reoxygenation) of

[30] Conseil Général du Rhône 1991, 80; Gauckler 1902, 129. Although there is some uncertainty whether the shafts at Hippo Zarite were dropshafts or inspection holes, Gauckler (1902) mentioned specifically that the shafts were designed with an invert drop of 0.4 m to trap impurities.

[31] E.g., Apelt 1984; Rajaratnam et al. 1997.

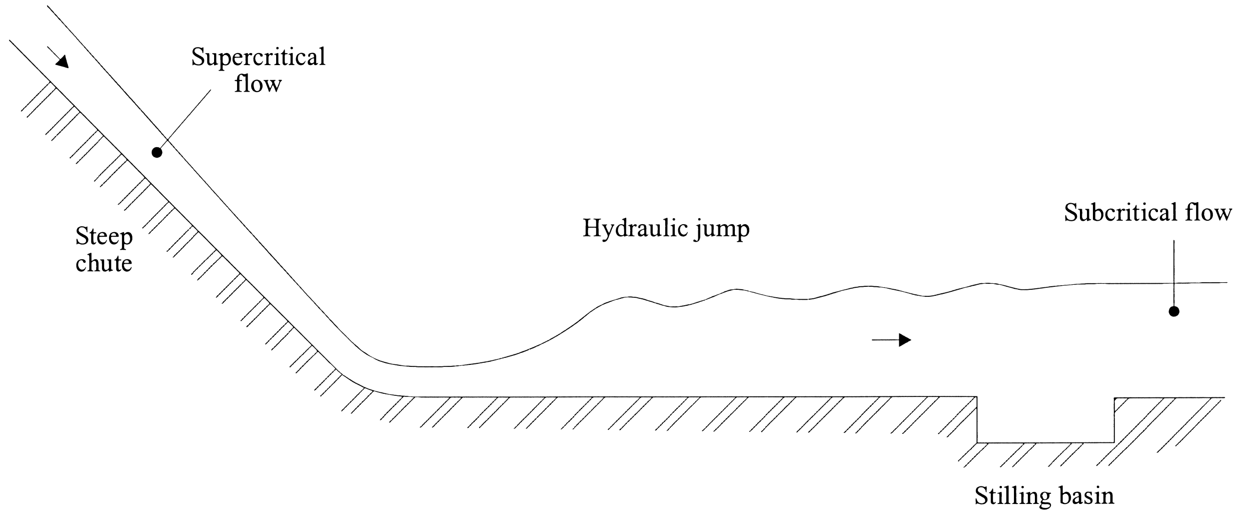


Fig. 9. Sketch of stilling basin operation in Roman aqueduct

the flow. This occurs via air bubbles entrained by plunging jet action into the shaft pool.[32]

Hydraulics of Roman Dropshafts

In the Hydraulics Laboratory at the University of Queensland, we investigated the hydraulics of the Roman dropshaft using a 1:4 scale model of the Recret dropshaft on the Yzeron aqueduct (figs. 11, 16–17). The results[33] highlighted several flow patterns with increasing flow rates. We expressed this in terms of d_c/L, which is the ratio of critical flow depth (the height of the drop, measured in meters) to the length of the dropshaft (also in meters).

At low flow rates (d_c/L is less than or equal to 0.15), the free-falling nappe (the water surface) impacts into the shaft pool; we categorize this scenario as regime R1 (fig. 16). In this flow, substantial air-bubble entrainment occurs in the pool. In the downstream channel, the flow is supercritical in the absence of downstream backwater effect. In situations where the discharge rate is greater (the d_c/L is greater than 0.15 but less than 0.30), the upper nappe of the free-falling jet impacts into the downstream channel, flowing in between the inlet invert and obvert; we categorize this as regime R2 (fig. 17). In R2 the rate of energy dissipation is smaller, the pool free-surface level increases significantly, and less air-bubble entrainment is observed in the pool. At large flow rates (where d_c/L is greater than or equal to 0.30), the free-jet impacts onto the opposite wall, above the downstream conduit obvert (regime R3). The pool free-surface rises up to the downstream channel obvert, and the water level in the pool fluctuates considerably. The third type of regime, R3, common in modern dropshafts, occurs only at large flow rates and was unlikely in Roman aqueducts.

Dropshaft Performance

The analysis of the dropshaft-model performances indicates that the optimum performances in terms of energy dissipation and flow aeration are achieved with a flow regime such as that illustrated in R1 (fig. 16). The experiments show that the flow regime R2 is characterized by poor energy dissipation, little flow aeration, and a high risk of scouring (figs. 17 and 18). In flow regime R2, extensive damage would occur very rapidly, typically in less than one day of operation. Most erosion would take place at the nappe impact and at the downstream conduit intake (fig. 18). The deterioration of modern concrete structures is well documented,[34] and worse damage would have occurred in Roman constructions. I suggest that, in fact, the dropshafts had to be overdesigned in order to prevent rapid and costly damage associated with the regime R2, and that the aqueduct dropshafts had to be built for an operation in a flow regime R1.

Table 6 summarizes the operation of well-documented dropshafts based on analytical calculations of the nappe trajectory and impact conditions.[35] At

[32] E.g., Ervine and Ahmed 1982; Chanson 1998.
[33] Chanson 1998.
[34] E.g., U.S. Department of the Interior 1965; Chanson 1995a, 198–201; Novak et al. 1996.
[35] The calculations are based on the nappe trajectory equation and shaft geometry (Chanson 1998). The results were validated successfully with the physical experiments.

Table 5. Dropshaft Cascades in Roman Aqueducts

(1) Steep Section	(2) Ref.	(3) Geometry	(4) Flow Conditions ΔH (m)	d_c (m)	X (m)	(5) Remarks
Dougga aqueduct	[Ca]					
Oued Melah		B ~ 3.3 m b ~ 0.35 m (tunnel)	4 to 5			Located downstream of 200-m-long bridge, upstream of tunnel
Vaugneray, Yzeron aqueduct	[Co2]		21.9			Vaugneray branch of Yzeron aqueduct
Puit du Bourg		Rectangular dropshaft: h = 2.55 m, b = 0.4 m, B = 1.14 m, L = 1.9 m		0.24		Downstream flow conditions: d ~ 0.35 m, V ~ 1.33 m/s
Recret/Grézieu-la-Varenne, Yzeron aqueduct	[Co2]	Rectangular dropshafts	38			Main branch of Yzeron aqueduct
Puit Gouttenoire		Square dropshaft: h = 2.55 m, b = 0.55 m, B = L = 1.18 m, P = 1.12 m		0.197		
Puit-en-bas		Rectangular dropshaft: h = 2.5 m, b = 0.55 m, B = L = 1.17 m, D = 1.26 m, P = 1.35 m		0.197		Downstream flow conditions: d ~ 0.15 m, V ~ 1.9 m/s
Chabet Ilelouine, Cherchell aqueduct	[LP]		12.28			4 series of steep chutes followed by circular dropshaft
Puit amont		Circular dropshaft: h ≈ 0.77 m, b ≈ 0.94 m, ∅ = L = 2.03 m, P > 1.75 m				Located downstream of steep smooth chute. Supercritical upstream flow: V ~ 8 m/s
Gunudu aqueduct			20			
Moulin Romain	[LP]	Circular dropshaft: h ~ 3.5 to 4 m, b ≈ 0.38 m, ∅ = L = 0.80 m				Upstream channel: 0.86 m wide
Rusicade aqueduct	[Ve]	Circular dropshafts				
Beaulieu aqueduct	[CQ]		37			Combination of steep chutes and dropshafts
Puit d'Olivari		Dropshaft: h = 6.2 m, b ~ 0.45 to 0.6 m				Rectangular or circular? 147 m between dropshafts
Puit du Château		Dropshaft: h ~ 8 m				Rectangular or circular? 167 m between dropshafts
Brisecou Forest, Montjeu aqueduct	[CQ, PR]	Rectangular dropshaft: h = 4.4 m, b = 0.8 m, B = 3.0 m, L = 2.4 m, D = 1.57 m, P > 0.8 m	140		770	A series of 24 dropshafts (possible combination with steep chutes)
		9 dropshafts (h = 4.4 m)				15 to 30 m between dropshafts
		15 dropshafts (h = 4.4 m)				50 to 120 m between dropshafts
Cuicul aqueduct	[Al]					
Grand thermae distribution line		Circular (?) dropshafts: h ~ 1 to 0.4 m, b ≈ 0.45 m, ∅ = L = 0.80 m	3		85	Series of 4 dropshafts on an urban distribution line
Cologne aqueduct	[Gr]	Rectangular dropshaft: h = 0.35 m, b = 0.7 to 0.75 m, B = 0.9 m, L = 1.185 m, P = 0.2 m				Several dropshafts

d_c: critical flow depth; X: dropshaft cascade length; ΔH: total head loss. References: [Al] Allais 1933; [Ca] Carton 1899; [Co2] Conseil Général du Rhône 1991; [CQ] Coquet 1966; [Gr] Grewe 1986; [LP] Leveau and Paillet 1976; [PR] Pinette and Rebourg 1986; [Ve] Vertet 1983.

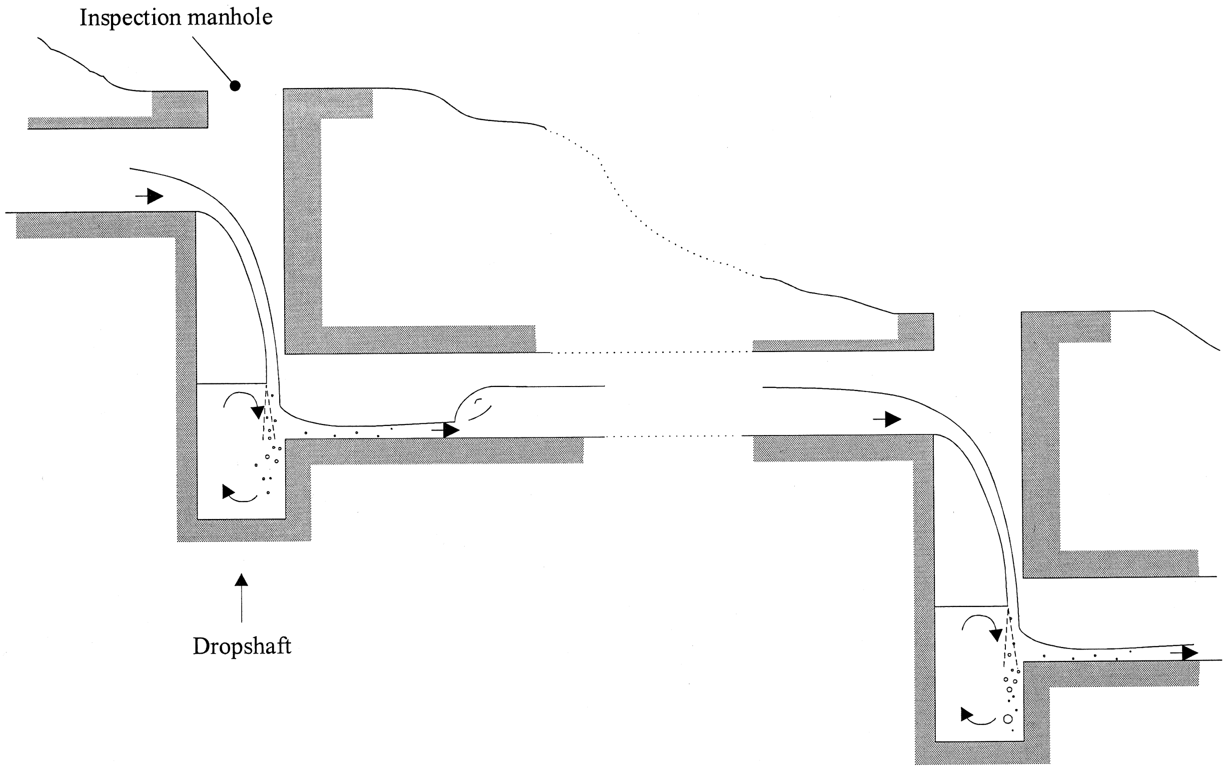


Fig. 10. Dropshaft cascade in Roman aqueduct

Cherchell, optimum performances (regime R1) were achieved for discharges less than 6,600 m^3/day.[36] This result challenges the accepted maximum discharge of 40,000 m^3/day.[37] For the Yzeron aqueduct, optimum operation (i.e., regime R1) occurred for flow rates up to 7,500 m^3/day in the Recret main section and 22,000 m^3/day in the Vaugneray branch. The Montjeu aqueduct's dropshafts at Brisecou Forest could operate safely with flow rates up to 40,400 m^3/day. It is reasonable to assume that the Recret branch operated with a discharge less than 7,500 m^3/day, a figure consistent with an overall discharge of 10,000 to 13,000 m^3/day in the Yzeron aqueduct, assuming a flow rate of 5,000 m^3/day at Vaugneray.[38] However, it was unlikely that either the Vaugneray branch or the Montjeu aqueduct operated at 22,000 and 40,400 m^3/day respectively. It is more likely that these two series of dropshafts were oversized designs and that optimum operation of the dropshaft was achieved in the setting outlined above as regime R1.[39]

CHUTE AND DROPSHAFT DESIGN

Although this study demonstrates the existence of steep sections along the aqueducts, certain questions remain. Were steep chutes and dropshafts intentional design features of Roman aqueducts? Did the aqueduct designer (*librator*) understand the basic concepts of chute and dropshaft hydraulics? Indeed, it is plausible that some steep chutes were introduced as a functional solution to connect aqueduct sections that had been built by different gangs.[40] The construction of stilling basin and dropshaft was not (and is still not today) a simple job: it required the advice of an experienced engineer.

---

[36] The Cherchell dropshafts were preceded by steep chutes, and the inflow conditions of the shaft were torrential (supercritical). Chanson (1998, 4–16) developed a complete analytical solution of the problem that gave a maximum flow rate of 6,600 m^3/day (for optimum performances).

[37] Leveau and Paillet 1976.

[38] For the Yzeron discharge, see Conseil Général du Rhône 1991. Estimate of the Vaugneray branch flow rate is based on the catchment in absence of further information.

[39] In mathematical terms, for aqueducts equipped with dropshafts operating with subcritical inflow, the flow rate must satisfy:

$$Q < 0.1292 \times \sqrt{g} \times b \times \frac{L^3}{h^{3/2}} \qquad \text{Regime R1}$$

where b is the dropshaft inflow width, L is the shaft length, and h is the invert drop (fig. 1) (Chanson 1998).

[40] For the techniques of construction and the problems associated with connecting different sections, see Fevrier 1979; Leveau 1979.

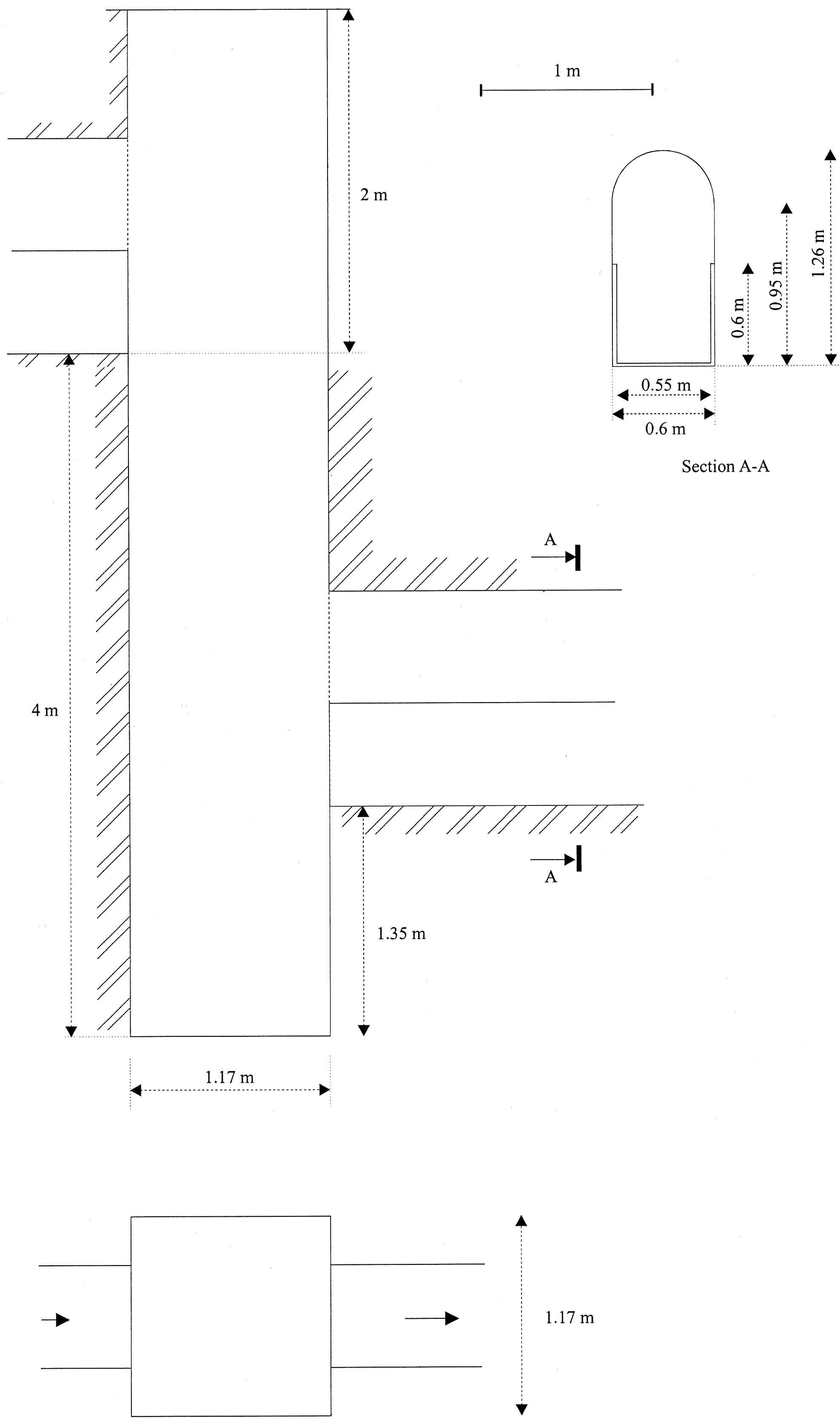


Fig. 11. Dimensioned drawings of dropshafts. Recret Puit-en-bas, Yzeron aqueduct.

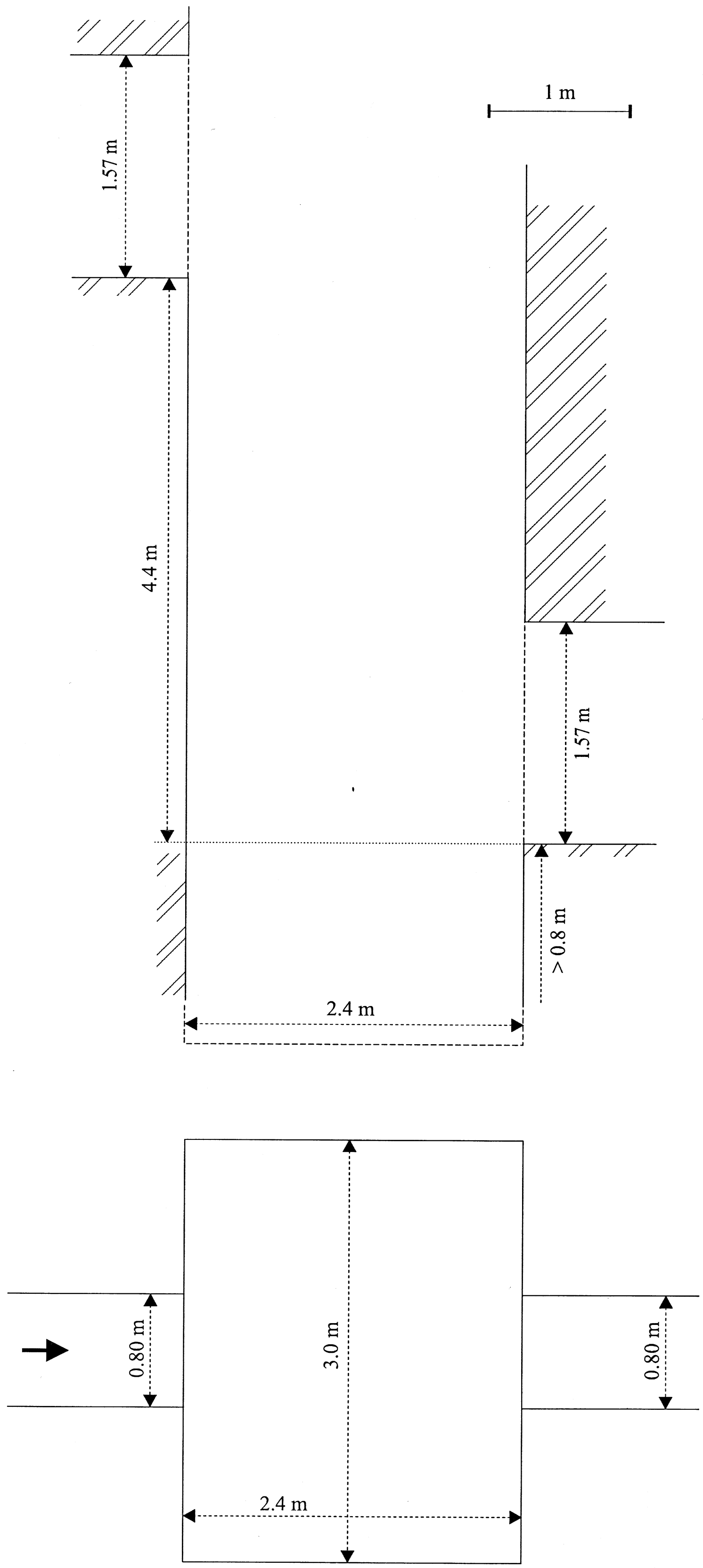


Fig. 12. Dimensioned drawings of dropshafts. Brisecou Forest, Montjeu aqueduct.

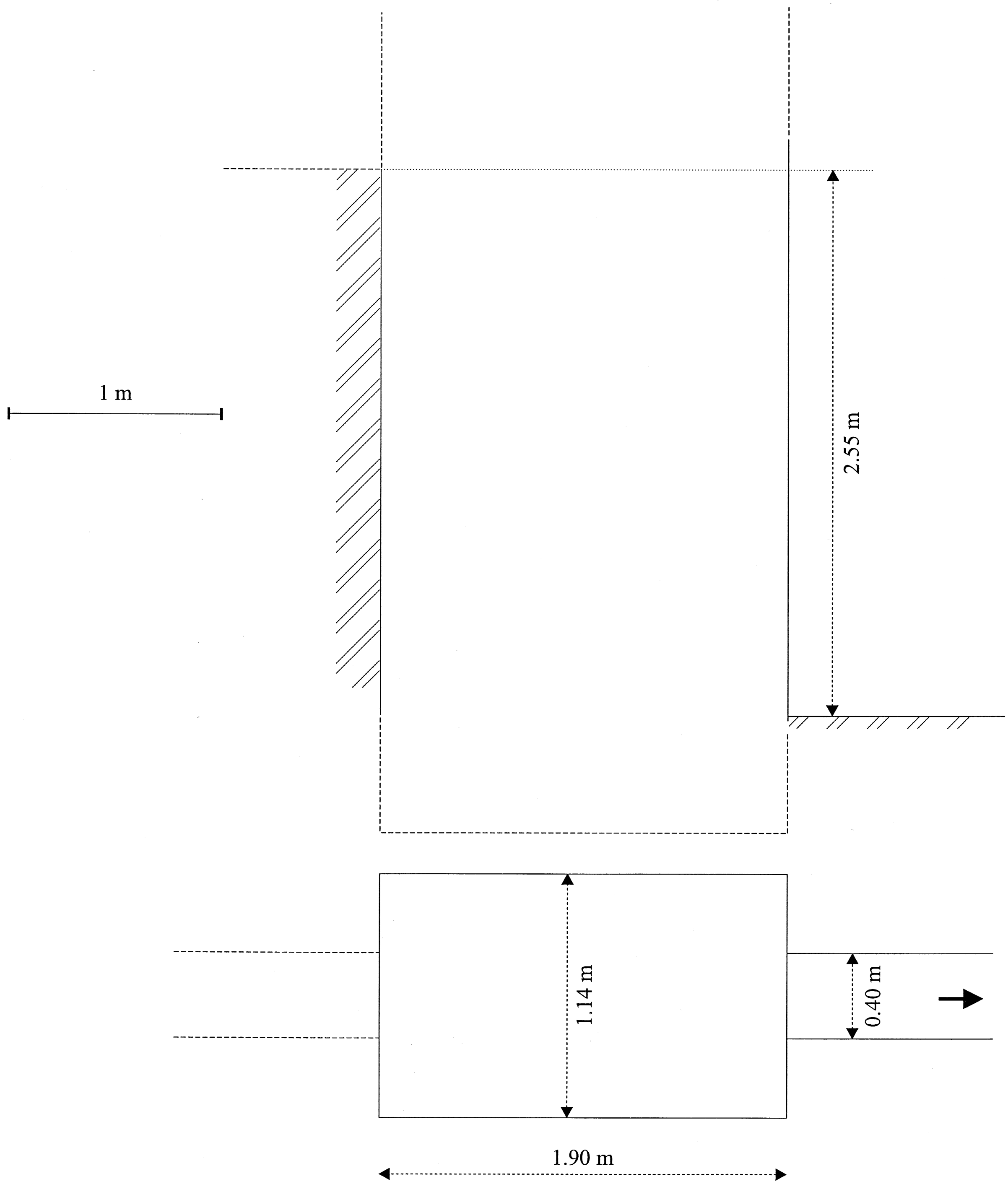


Fig. 13. Dimensioned drawings of dropshafts. Puit du Bourg, Vaugneray, Yzeron aqueduct (Vaugneray branch).

Well-documented evidence of aqueduct chutes and cascades clearly exists (tables 1–2, 5). These examples suggest that those who built them knew the problems they faced and intentionally designed the chutes and dropshafts accordingly. The series of steep chutes at Brévenne were imposed by the topography of the valley. They included vertical drops of up to 87 m (i.e., Chevinay/Plainet), which could not have been merely a simple construction problem. These chutes were part of the original design of the aqueducts. At Montjeu, Yzeron, and Cherchell (figs. 12, 13, 15), large series of dropshafts were installed: 24 dropshafts at Autun ($\Delta H = 140$ m), at least 15 dropshafts at Recret and more at Vaugneray, and 4 dropshafts at

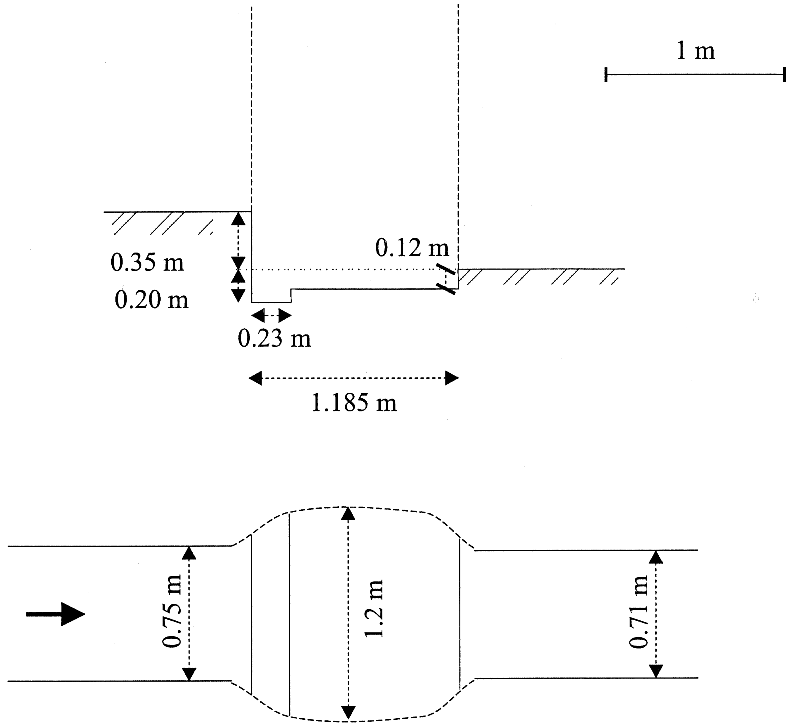


Fig. 14. Dimensioned drawings of dropshafts. Cologne aqueduct.

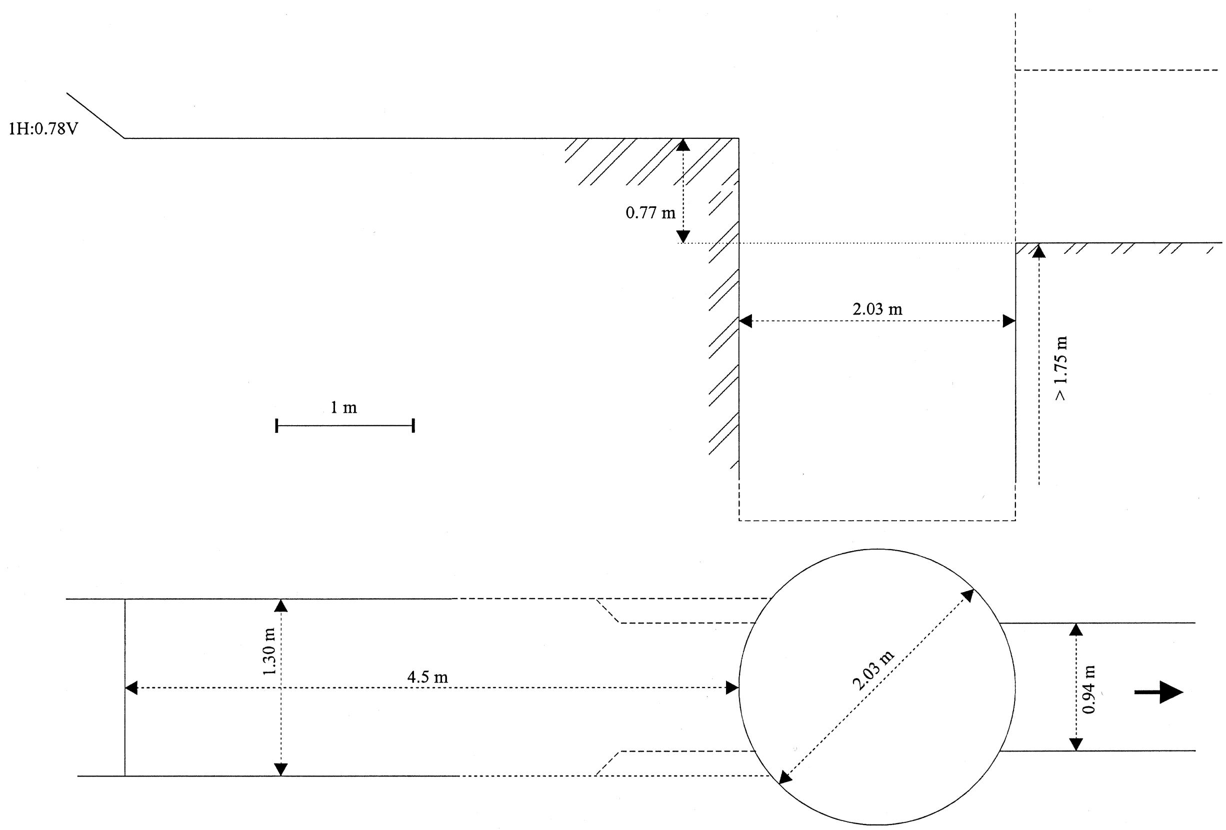


Fig. 15. Dimensioned drawings of dropshafts. Chabet Ilelouine (Cherchell aqueduct).

Fig. 16. Photograph of the Recret dropshaft model in operation. Regime R1, $Q = 0.00104$ m^3/s, $h/L = 1.68$, $D/L = 0.83$, $d_c/L = 0.0582$. Side view. Flow from left to right. High-speed photograph (~ 50 μs).

Fig. 17. Photograph of the Recret dropshaft model in operation. Regime R2, $Q = 0.00975$ m^3/s, $h/L = 1.68$, $D/L = 0.83$, $d_c/L = 0.259$. Side view, flow from left to right. High-speed photograph (~ 50 μs).

Chabet Ilelouine. Clearly these were engineering design features of the aqueducts![41] In both Roman and modern times, the hydraulic design of chutes and dropshafts has been a highly specialized task; the engineering design of the Roman aqueduct would have been reserved for only those Roman engineers with the highest skills. Nonetheless, there is no written documentation to support the theory that the engineers understood the basic concepts of continuity and energy as used in modern hydraulics. Even modern calculations of aqueduct hydraulics are embryonic.[42]

Table 7 summarizes those observations of very steep gradients that are well documented. Here we find evidence of very steep gradients in short stretches, up to 78 percent at Chabet Ilelouine, Cherchell. Steep chutes were found across a wide geographic range in Italy, France, Algeria, and Turkey, suggesting that the steep-gradient design was not unique to Rome but was also employed at aqueducts elsewhere in the empire. Second, the steepest longitudinal slopes (not counting stepped spillway chutes) were smooth and stepped chutes but not a series of dropshafts. Supercritical flow took place in steep channels. Most Roman

[41] At Cuicul (Djemila, Algeria), the location of the dropshaft cascade was most unusual: it was on a distribution branch in an urban environment rather than on the main line. The construction of the cascade was a major civil engineering work. Its underground location within the city might suggest that it was built prior to the surrounding buildings (e.g., *thermae*) and that careful urban planning was done at Cuicul. Alternatively, the city expansion might have taken place in stages and the cascade would have been out of town in an early stage.

[42] The present study suggests that the current "misunderstanding" of aqueduct hydraulics derives from the "ignorance" of most historians and archaeologists. The hydraulics calculations are easily feasible by undergraduate engineering students, provided that accurate information on the channel dimensions and flow rate are available (Chanson 1999; Henderson 1966).

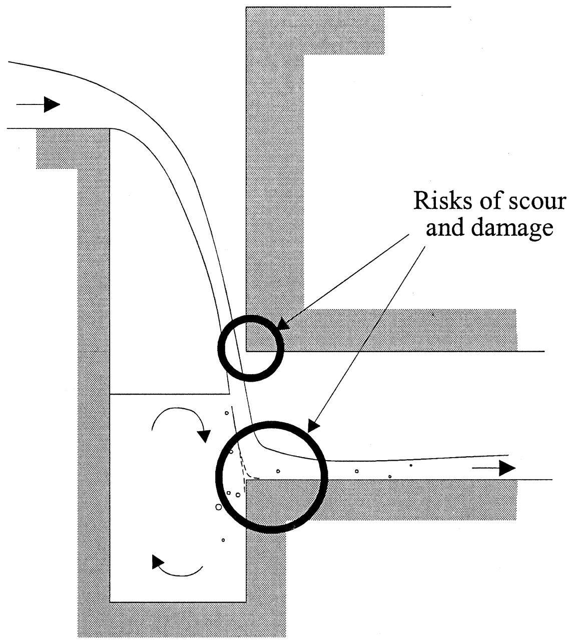


Fig. 18. Risks of scour and damage at a dropshaft operation with a flow regime R2

aqueducts had, overall, a mild slope that was associated with subcritical flows. The transition from the "steep" chute flow to the subcritical flow was characterized by a hydraulic jump. Hence, Roman engineers clearly had some experience of both supercritical flows and hydraulic jumps.

Third, and conversely, the data in table 7 highlights the fact that series of dropshafts were not used in the steepest topography, but rather for a range of longitudinal mean slopes up to 20 percent (table 7). This might suggest that dropshafts were not considered "safe" or "efficient" with very steep gradients. Construction problems may have affected the choice of dropshafts or steep chutes. Further, the dropshaft design might have been selected for purposes other than energy dissipation alone; for example, it might have been employed in some cases for re-aeration.

The Lyon aqueducts offer a useful example for a comparison between steep-chute and dropshaft cascade design. At Lyon, the Yzeron and Brévenne aqueducts were both designed with steep longitudinal gradient sections (fig. 19).[43] The older of the two, the Yzeron aqueduct, was equipped with a series of dropshafts (Recret, Vaugneray), while the aqueduct at Brévenne was equipped with steep "smooth" chutes (e.g., Courzieu II, Chevinay, Lentilly II). Why? At the Yzeron aqueduct, the overall drop of the two series of dropshafts was 38 m along 490 m at Recret, and 21.9 m along 375 m at Vaugneray, or 7.8 percent and 5.8 percent, respectively. In comparison, the overall gradient was about 4.8 to 5.4 percent at Beaulieu and about 15 percent in average at Montjeu (table 5).

These longitudinal gradients might seem small compared to the steep-chute gradients along the Brévenne aqueduct—22 percent at Courzieu II, 45 percent at Chevinay, and 8.2 percent at Lentilly II (table 1)—but the intervals between the steep chutes varied from about 7 to 16 km (fig. 19)! The overall drop in elevation from one chute intake to the next one was 65 m along 16.2 km at Courzieu II, 140 m along 11.2 km at Chevinay, and 80 m along 7 km at Lentilly II (0.4 percent, 1.25 percent, and 1.1 percent, respectively).

In summary, these figures suggest that the series of dropshafts of the Yzeron aqueduct were used for an overall gradient of 6 to 8 percent, while, at Brévenne, the longitudinal gradient of the aqueduct was only about 0.4 to 1.25 percent, including the steep chutes (fig. 19).

SUMMARY AND CONCLUSION

Roman aqueducts were equipped with short steep sections. For bed slopes ranging from 1 percent to 78 percent, three types of designs were used: the steep smooth chute followed occasionally by stilling basin(s) (fig. 9), the stepped cascade, and the series of dropshafts (fig. 10).

Steep chute flows were characterized by high velocity supercritical flows. Tailwater conditions were often subcritical, and hydraulic jump flow conditions occurred at, or downstream of, the transition to the flat conduit. A complete backwater analysis has shown the presence of unfavorable conditions associated with these channels, in particular undular flows and oscillating hydraulic jumps. I suggest that stilling basins were sometimes introduced to dissipate the energy of the waters and to prevent downstream propagation of surge waves and undulations (fig. 9). These basins were found at Alepotrypes, Courzieu II, Jouy, and Oudna. This implies that Roman hydraulic engineers observed flow instabilities along aqueducts and were capable of introducing devices to dampen the effects.

In a 1:4 scale laboratory model of a Recret shaft built specifically to investigate Roman dropshaft hydraulics, I observed three flow regimes. Optimum dropshaft operation occurred for the flow regime

[43] Burdy 1979, 64.

Table 6. Summary of Aqueduct Dropshaft Operation

(1) Aqueduct	(2) Flow Regime	(3) Flow Conditions	(4) Remarks
Cherchell			
Chabet Ilelouine	Regime R1	Q ≤ 6,600 m³/day	Supercritical inflow
	Regime R2	Q > 6,600 m³/day	
Yzeron			Subcritical inflows
Vaugneray	Regime R1	Q ≤ 22,000 m³/day	
	Regime R2	22,000 < Q ≤ 52,000 m³/day	
	Regime R3	Q > 52,000 m³/day	Assuming D = 1.26 m
Puit Gouttenoire	Regime R1	Q ≤ 7,500 m³/day	
	Regime R2	7,500 < Q ≤ 19,500 m³/day	
	Regime R3	Q > 19,500 m³/day	Assuming D = 1.26 m
Puit-en-bas	Regime R1	Q ≤ 7,500 m³/day	
	Regime R2	7,500 < Q ≤ 20,000 m³/day	
	Regime R3	Q > 20,000 m³/day	
Montjeu			Subcritical inflows
Brisecou Forest	Regime R1	Q ≤ 40,400 m³/day	
	Regime R2	40,400 < Q ≤ 74,700 m³/day	
	Regime R3	Q > 74,700 m³/day	

Table 7. Summary of Longitudinal Slopes of Steep Roman Chutes, Cascades, and Dropshaft Cascades

(1) Steep Section Type	(2) Bottom Slope tanθ (in %)	(3) Location
Aqueducts		
Steep chute	1.1	Anio Novus (Ponte dell'Inferno to Ponte Scalino tunnel)
Steep chute	1.3	Anio Novus (to Fienile tunnel)
Steep chute	1.6	Anio Novus (Ponte Scalino to Ponte Amato tunnel)
Steep chute	3.0	Corinth (Alepotrypes, upstream of stilling basin)
Dropshaft	4.1	Beaulieu (Puit d'Olivari)
Dropshaft (circ.)	4.8	Beaulieu (Puit du Château)
Dropshaft (circ.)	5.1	Cuicul (Series of 4 dropshafts along thermae, distribution line)
Dropshafts	5.2	Montjeu, Autun (series of 24 dropshafts)
Dropshafts (rect.)	5.8	Yzeron (Vaugneray, Puit du Bourg)
Steep chute	6.1	Anio Novus (Torrente Fiumicino)
Dropshafts (sq.)	7.8	Yzeron (Recret/Grézieu-la-Varenne cascade)
Steep chute	8.3	Brévenne (Lentilly II/Les Molières-Montcher)
Steep chute	10.7	Marcia (Gericomio)
Steep chute	15.7	Marcia (Gericomio)
Steep chute	16.4	Anio Vetus (Bridge at Mola di San Gregoria)
Drops or chutes?	19.0	Brévenne (Lentilly II - Le Guéret-La Rivoire)
Dropshafts (rect.)	19.6	Montjeu, Autun (9 dropshafts)
Drops or chutes?	20.0	Brévenne (St.-Pierre-La-Palud I)
Steep chute	20.6	Anio Vetus (Tivoli, Hadrian's Villa)
Steep chute	22	Brévenne (Courzieu II/La Verrière)
Steep chute	45	Brévenne (Chevinay/Plainet)
Steep chute	50	Claudia (below D. Cosimato cliff, upstream of bridge below Vicavaro)
Stepped chute	61	Andriake, Lycia
Steep chutes	78	Cherchell, Chabet Ilelouine
Dropshafts + chutes	38.4	Cherchell, Chabet Ilelouine (combination of dropshafts and chutes)
Spillways		
Stepped chute	122 to 164	Oued Guergour dam
Stepped chute	167	Oued Bou Mazouz dam
Stepped chute	229	Kasserine dam

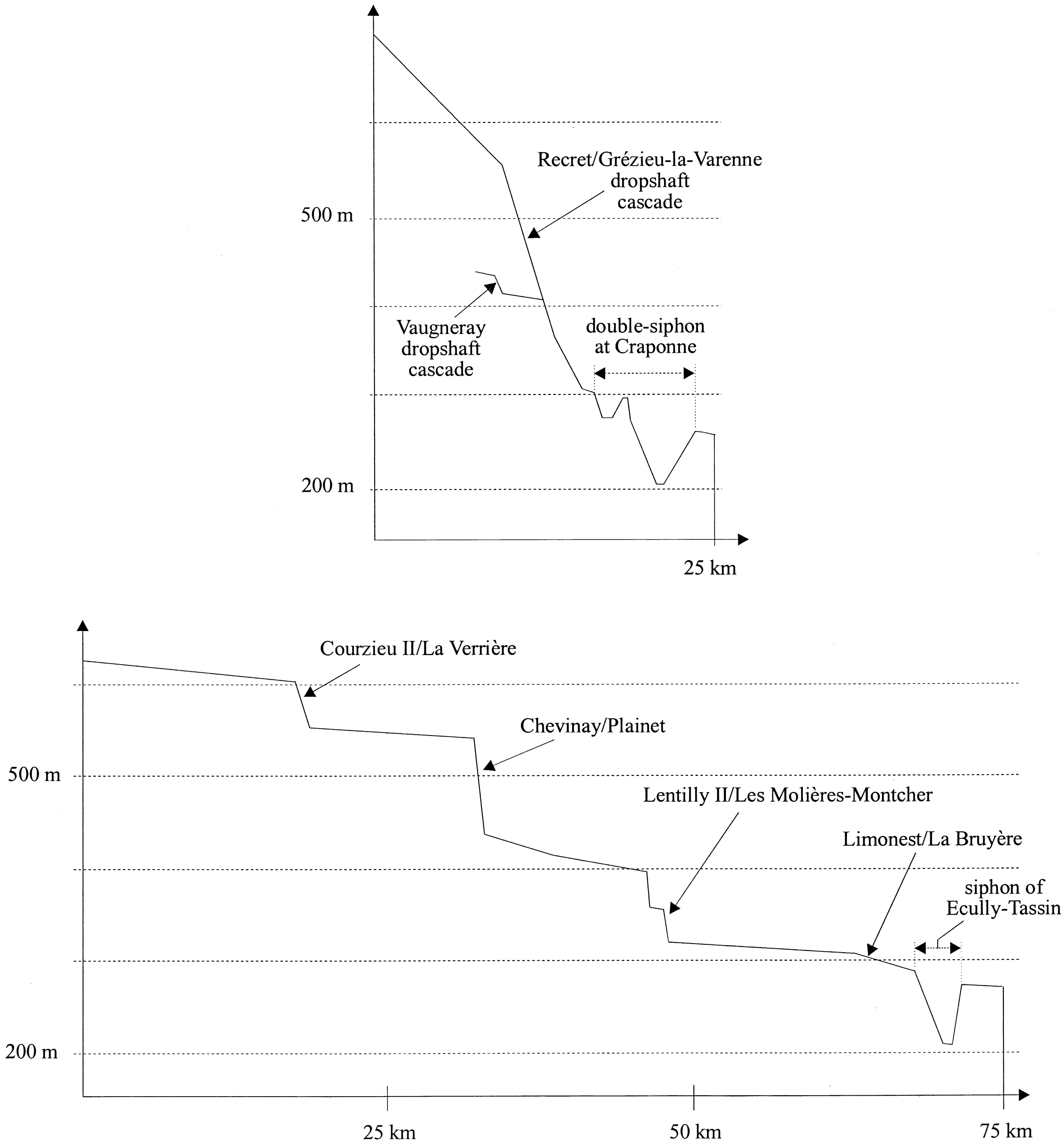


Fig. 19. Longitudinal profiles of the Yzeron (top) and Brévenne (bottom) aqueducts

R1, characterized by low flows and nappe impact into the shaft pool. In regime R1, the dropshaft design was most efficient in terms of energy dissipation and air bubble entrainment, particularly compared to modern designs. Calculations suggest that dropshaft operation at Cherchell took place for lower-than-accepted flow rates, while two series of dropshafts, at Montjeu and Vaugneray, were equipped with oversized shafts.

The designs of dropshaft cascade, as well as steep chute followed by dissipation basin, show that the Roman aqueduct engineers were able to design specific features to cope with steep sections. It remains unclear whether they had some understanding of the hydraulic principles, or worked by observations and trial and error.

Most aqueducts were enclosed (covered) along their entire length, limiting the possibility for gas transfer at the free surface. Thus, the downstream waters were low in dissolved oxygen content unless reoxygenation devices were installed. I suggest that dropshafts may have been introduced in place of steep chutes in order to reoxygenate the water as well as to dissipate the energy of the flow. Aeration technology is commonly used today to reoxygenate depleted waters and to enhance the water quality. I recommend that further archaeological work focus on the excavation and survey of chutes and dropshafts to confirm this hypothesis.

HYDRAULICS AND ENVIRONMENTAL ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING
THE UNIVERSITY OF QUEENSLAND
BRISBANE QLD 4072
AUSTRALIA
H.CHANSON@MAILBOX.UQ.EDU.AU

Appendix

HYDRAULICS OF OPEN CHANNEL FLOW: DEFINITIONS AND BASIC EQUATIONS

In open channel flows (e.g., fig. 1, a smooth chute), the *critical depth* d_c is the depth of flow producing maximum flow rate for a given specific energy. For a rectangular channel it equals: $\sqrt[3]{Q^2/gb^2}$ where Q is the discharge, g is the gravity acceleration, and b is the channel breadth. If the flow is critical, small changes in specific energy cause very large changes in depth. In practice, critical flows over a long reach of channel are unstable, characterized by large free-surface undulations. Such a flow pattern, called undular flow, is experienced with *near-critical* flows characterized by a Froude number greater than 0.3 but less than 3.0; where $Fr = V/\sqrt{gd}$, V is the flow velocity and d is the flow depth.[44]

Subcritical, or tranquil, flow occurs when the flow depth (d) is greater than the critical depth. As a channel becomes steeper, water tends to flow with greater velocity and shallower depth until, on steep sections, supercritical flow occurs and the rapid flow depth is less than the critical depth. Subcritical and supercritical flows are also called fluvial and torrential flows, respectively.

The transition back from supercritical to subcritical flow conditions creates a hydraulic jump, where the depth of flow suddenly increases. A hydraulic jump is undesirable because it leads to flow instability and possible surges, and thus has great erosive potential. Experimental observations highlighted different types of hydraulic jumps, depending upon the Froude number of the upstream flow. An undular hydraulic jump is observed at low Froude numbers (between 1 and 3). With increasing Froude numbers, other types of jumps include weak jump, oscillating jump (Froude number between 3.5 and 4.5), steady jump, and strong jump (Froude number is greater than or equal to 10) (see, e.g., fig. 4).[45]

HYDRAULIC CALCULATIONS OF STEEP CHUTES AND CASCADES

In long prismatic chutes, the flow conditions in steep chutes may be calculated assuming uniform equilibrium flow conditions (i.e., normal flow):

$$V_o = \sqrt{\frac{8g}{f}}\sqrt{\frac{(D_H)_o}{4}\sin\theta}$$

where V_o is the uniform equilibrium flow velocity, $(D_H)_o$ is the hydraulic diameter[46] at uniform equilibrium, f is the Darcy-Weisbach friction factor, and θ is the channel slope (fig. 1). The friction factor f is estimated from the Moody diagram for smooth chutes.[47] I computed f to be between 0.02 and 0.04 for Roman aqueducts with smooth mortar lining. For skimming flow over stepped cascades, f increases from 0.1 to 1 for bed slopes from 5 to 10 degrees, and f equals about 1 for steeper slopes.[48]

There is a fundamental difference between smooth and stepped chutes: the kinetic energy of the flow is significantly larger in smooth chute flow than for a stepped one, for identical flow rate and chute properties. As a result, larger energy dissipation must take place at the end of a smooth canal, and sometimes stilling structures must be introduced.

LIST OF SYMBOLS

A cross-section area (m^2)
B dropshaft width (m)
b open channel width (m)
D conduit height (m)
D_H hydraulic diameter (m), or equivalent pipe diameter, defined as:

$$D_H = 4\left(\frac{\text{cross-sectional area}}{\text{wetted perimeter}}\right) = \frac{4A}{P_w}$$

[44] For near-critical flows, see Chanson 1995b. In rectangular flat channels, the Froude number is unity at critical flow conditions: i.e., Fr = 1 for $d = d_c$ (critical flow depth).

[45] This classification is valid only for hydraulic jumps in rectangular horizontal channels (e.g., Henderson 1966; Chanson 1999).

[46] The hydraulic diameter is defined as four times the cross-section area (of the flow) divided by the wetter perimeter: $D_H = 4(A/P_w)$.

[47] Moody 1944.

[48] Chanson 1995a, 87–8.

d flow depth (m) measured perpendicular to the channel bed
d_b brink depth (m): i.e., depth at the edge of a drop
d_c critical flow depth (m); in a rectangular channel: $d_c = \sqrt[3]{q^2/g}$
d_o uniform equilibrium flow depth (m): i.e., normal depth
d_{tw} tailwater flow depth (m)
f Darcy friction factor (also called head loss coefficient)
Fr Froude number; for a rectangular channel: $Fr = V/\sqrt{gd} = Q/\sqrt{gd^3b^2}$
g gravity constant (m/s^2)
H total head (m)
h 1 – step height (m)
2 – invert drop (m) at a vertical dropshaft
L 1 – dropshaft length (m)
2 – length (m) of stilling basin
l step length (m)
P (shaft) pool height (m), measured from the shaft bottom to the downstream conduit invert
P_w wetted perimeter (m)
Q total volume discharge (m^3/s) of water
q discharge per meter width (m^2/s); for a rectangular channel: $q = Q/b$
V flow velocity (m/s); V_b brink flow velocity (m/s)
V_o uniform equilibrium flow velocity (m/s)
X chute/cascade length (m)
x horizontal Cartesian coordinate (m)
y vertical Cartesian coordinate (m)

Greek Symbols
ΔH head loss (m): i.e., change in total head
Δz change in bed (invert) elevation (m)
θ bed (invert) slope
$\varnothing$ diameter (m)

Subscript
c critical flow conditions
o uniform equilibrium flow conditions
$\varnothing$ tailwater flow conditions

Abbreviations
D/S (or d/s) downstream
U/S (or u/s) upstream

Works Cited

Allais, Y. 1933. "L'Alimentation en eau d'une ville romaine d'Afrique: Cuicul (Djemila)." *Cinquième congrès international d'archéologie, Alger, 14–16 avril 1930,* 93–117. Algiers: Société historique algérienne.

Apelt, C.J. 1984. "Goonyella Railway Duplication Drop Structures and Energy Dissipators at Culvert Outlets: Model Studies." *Report CH27/84,* Dept. of Civil Engineering, University of Queensland.

Ashby, T. 1935. *The Aqueducts of Ancient Rome.* Edited by I.A. Richmond. Oxford: Clarendon.

Blackman, D.R. 1978. "The Hydraulics of Aqueducts at Rome: A Study of the Four Great Aqueducts." *MMEL Report No. 35,* Dept. of Mechanical Engineering, Monash University, Australia.

———. 1979. "The Length of the Four Great Aqueducts of Rome." *BSR* 47:12–8.

Bradley, J.N., and A.J. Peterka. 1957a. "The Hydraulic Design of Stilling Basins: Hydraulic Jumps on a Horizontal Apron (Basin 1)." *Journal of the Hydraulic Division* 83/HY5:1401-1/1401-22.

———. 1957b. "The Hydraulic Design of Stilling Basins: Stilling Basin and Wave Suppressors for Canal Structures, Outlet Works, and Diversion Dams (Basin 4)." *Journal of the Hydraulic Division* 83/HY5:1404-1/1404-20.

Burdy, J. 1979. "Lyon: Lugudunum et ses quatre aqueducs." *Dossiers de l'archéologie, Séries les aqueducs romains* 38:62–73.

———. 1996. *Lyon: L'aqueduc romain du Gier.* Préinventaire des monuments et richesses artistiques 4. Lyon: Conseil Général du Rhône.

Carton, L.B.C. 1899. "Notices sur les fouilles exécutées à Dougga." *Bulletin trimestriel de géographie et d'archéologie de la S.G.A.P.O.* 13:157–9.

Chanson, H. 1995a. *Hydraulic Design of Stepped Cascades, Channels, Weirs, and Spillways.* Oxford: Pergamon.

———. 1995b. "Flow Characteristics of Undular Hydraulic Jumps: Comparison with Near-critical Flows." *Report CH45/95,* Dept. of Civil Engineering, University of Queensland.

———. 1997. "A Short History of Stepped Cascades in Australia." *ANCOLD Bulletin* 106:101–11.

———. 1998. *The Hydraulics of Roman Aqueducts: Steep Chutes, Cascades, and Dropshafts.* Brisbane: University of Queensland.

———. 1999. *The Hydraulics of Open Channel Flows: An Introduction.* London: John Wiley and Sons.

Chanson, H., and J.S. Montes. 1995. "Characteristics of Undular Hydraulic Jumps: Experimental Apparatus and Flow Patterns." *Journal of Hydraulic Engineering* 121:129–44 and 123:161–4.

Clamagirand, E., S. Rais, J. Chahed, R. Guefrej, and L. Smaoui. 1990. "L'Aqueduc de Carthage." *Journal La Houille Blanche* 6:423–31.

Conseil Général du Rhône. 1987. *L'Aqueduc romain du Mont d'Or.* Edited by H. Hours. Préinventaire des monuments et richesses artistiques 1. Lyon: Conseil Général du Rhône.

Conseil Général du Rhône. 1991. *L'Aqueduc romain de l'Yzeron.* Edited by H. Hours. Préinventaire des monuments et richesses artistiques 2. Lyon: Conseil Général du Rhône.

Conseil Général du Rhône. 1993. *L'Aqueduc romain de la Brévenne.* Edited by H. Hours. Préinventaire des monuments et richesses artistiques 3. Lyon: Conseil Général du Rhône.

Coquet, M. 1966. "Les aqueducs romains de Beaulieu et les puits de rupture de pente." *Cahiers ligures de préhistoire et d'archéologie* 15:283–95.

Darcy, H.P.G., and H. Bazin. 1865. *Recherches hydrauliques.* Paris: Imprimerie nationale.

Ervine, D.A., and A.A. Ahmed. 1982. "A Scaling Relationship for a Two-dimensional Vertical Dropshaft." In *Proceedings of the International Conference on Hydraulic Modelling of Civil Engineering Structures,* 195–214. Coventry: British Hydromechanics Research Association Fluid Engineering.

Fabre, G., J.L. Fiches, P. Leveau, and J.L. Paillet. 1992. *The Pont du Gard: Water and the Roman Town.* Paris: Presses du CNRS.

Fair, G.M., J.C. Geyer, and D.A. Okun. 1971. *Elements of Water Supply and Wastewater Disposal.* 2nd ed. New York: Wiley.

Fevrier, P.A. 1979. "L'Armée romaine et la construction des aqueducs." *Dossiers de l'archéologie, Séries les aqueducs romains* 38:88–93.

François, J., and N. Tabouillot. [1769] 1974. "Histoire de Metz par les religieux bénédictins de la congrégation de Saint-Vanne." *Imprimerie Claude-Sigisbert Lamort* 1:130–51. Reprint, Paris.

Gauckler, P. 1897. *Enquête sur les installations hydrauliques romaines en Tunisie* 1. Tunis: Imprimerie rapide.

———. 1902. *Enquête sur les installations hydrauliques romaines en Tunisie* 2. Tunis: Imprimerie rapide.

Gauckler, P.G. 1867. "Etudes théoriques et pratiques sur l'ecoulement et le mouvement des eaux." *Comptes rendues de l'académie des sciences* 64:818–22.

Grewe, K. 1986. *Atlas der römischen Wasserleitungen nach Köln.* Cologne: Rheinland-Verlag.

Hager, W.H. 1992. *Energy Dissipators and Hydraulic Jump.* Kluwer Academic Publications, Water Science and Technology Library 8. Dordrecht: Kluwer Academic.

Henderson, F.M. 1966. *Open Channel Flow.* New York: MacMillan College Division.

Hodge, A.T. 1992. *Roman Aqueducts and Water Supply.* London: Duckworth.

Knauss, J. 1995. "ΤΗΣ ΓΡΙΑΣ ΤΟ ΠΗΔΗΜΑ, der Altweibersprung: Die Rätselhafte Alte Talsperre in der Glosses-Schlucht bei Alyzeia in Akarnanien." *AA* 5:137–62.

Lefebvre, C. 1985. "L'Aqueduc romain de Gorze à Metz: Etat de recherche." *Cahiers lorrains* 1:21–51.

———, ed. 1996. *L'Aqueduc antique de Gorze à Metz.* Nancy: Serpenoise.

Leveau, P. 1979. "La construction des aqueducs." *Dossiers de l'archéologie, Séries les aqueducs romains* 38:8–19.

———. 1991. "Research on Roman Aqueducts in the Past Ten Years." In *Future Currents in Aqueduct Studies,* edited by T. Hodge, 149–62. Leeds: F. Cairns.

Leveau, P., and J.L. Paillet. 1976. *L'Alimentation en eau de Caesarea de Maurétanie et l'aqueduc de Cherchell.* Paris: Éditions l'Harmattan.

Lolos, Y.A. 1997. "The Hadrianic Aqueduct of Corinth (with an Appendix on the Roman Aqueducts in Greece)." *Hesperia* 66:271–314.

Montes, J.S., and H. Chanson. 1998. "Characteristics of Undular Hydraulic Jumps: Results and Calculations." *Journal of Hydraulic Engineering* 124:192–205.

Moody, L.F. 1944. "Friction Factors for Pipe Flow." *Transactions of the American Society of Mechanical Engineers* 66:671–84.

Novak, P., A.I.B. Moffat, C. Nalluri, et al. 1996. *Hydraulic Structures.* 2nd ed. London.

Ortloff, C.R., and D.P. Crouch. 1998. "Hydraulic Analysis of a Self-cleaning Drainage Outlet at the Hellenistic city of Priene." *Journal of Archaeological Science* 25:1211–20.

Pinette, M., and A. Rebourg. 1986. *Autun (Saône-et-Loire): Ville Gallo-Romaine.* Paris: Imprimerie nationale.

Rajaratnam, N., A. Mainali, and C.Y. Hsung. 1997. "Observations on Flow in Vertical Dropshafts in Urban Drainage Systems." *Journal of Environmental Engineering* 123:486–91.

Rakob, F. 1974. "Das Quellenheiligtum in Zaghouan und die Römische Wasserleitung nach Karthago." *MDI-RA* 81:41–89, pls. 21–76 and maps.

———. 1979. "L'Aqueduc de Carthage." *Dossiers de l'archéologie, Séries les aqueducs romains* 38:34–42.

U.S. Department of the Interior. 1960. *Design of Small Dams.* Denver: U.S. Government Printing Office.

Van Deman, E.B. 1934. *The Building of the Roman Aqueducts.* Washington, D.C.: Carnegie Institution.

Vertet, H. 1983. "Observations sur les aqueducs de Rusicade (Algérie)." In *Journées d'étude sur les aqueducs romains, Lyon, 26–28 mai 1977,* 349–69. Paris: Les Belles Lettres.