MES AQUEDUCT

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INTRODUCTION

The hydraulic expertise of the Romans contributed significantly to the advance of science and engineering in Antiquity. Aqueducts were built primarily for public health and sanitary needs: i.e., public baths, thermes, toilets (HODGE 1992, FABRE et al. 1992,2000). Many were used for centuries; some are still in use, for example at Carthage (CLAMAGIRAND et al. 1990). Magnificent aqueduct remains at Rome, in France, Spain and North Africa for example, are still standing (e.g. ASHBY 1935, VAN DEMAN 1934, RAKOB 1974, Conseil Général du Rhône 1987, 1991, 1993, 1996) (Fig. 1). Aqueduct construction was an enormous task often performed by the army and the design was undertaken by experienced army hydraulicians. The construction cost was gigantic considering the small flow rates (less than 0.5 m^3/s) : it was around one to three millions sesterces per kilometre on average (e.g. FEVRIER 1979, LEVEAU 1991). [During the Augustan period (BC 33 to AD 14), one sesterce weighted about 1/336 of a pound of silver which would bring the cost of one kilometre of aqueduct to about US$ 23 to 69 millions, based on US$485.5 per ounce of silver on 25 November 1998 ! By comparison the pipeline for the Tarong power station (70-km long, 0.9 m^3/s) in Queensland costed AUD$ 0.2 millions per km (*Courier Mail* 3 Dec. 1994, p.13).]
Recent surveys have thrown new light on the longitudinal profiles of Roman aqueducts (GREWE 1986,1991, HODGE 1992, BURDY 2002). Most aqueducts consisted of very long flat sections with bed slopes around 1 to 3 metres per kilometre, and sometimes short steep portions in between (CHANSON 1998, 2000a). Despite arguments suggesting that Roman aqueducts operated with subcritical flows and that no energy dissipation device was required, hydraulic calculations of aqueduct hydraulics are embryonic. Modern engineering studies suggested that the current 'misunderstanding' of aqueduct hydraulics derives from the 'ignorance' of historians and archaeologists (BLACKMAN 1978,1979, CHANSON 1998,2000a). Most hydraulic calculations are feasible by undergraduate engineering students, provided that accurate information on the channel dimensions and flow rate are available (e.g. HENDERSON 1966, CHANSON 1999).

HYDROLOGY AND OPERATION OF ROMAN AQUEDUCTS

HYDROLOGY

The hydrology of a catchment is the relationship between rainfall, runoff and stream flows. A hydrological study is required for any water supply system, including an aqueduct. The hydrology of two catchments supplying ancient Roman aqueducts was recently studied : the source de l'Eure at Uzés, supplying the Nîmes aqueduct, and the source de Gorze, supplying the Gorze aqueduct (Metz). Both aqueducts were among the largest Roman aqueducts in Gaul and Germany, with those of Lyon and Cologne. Both were equipped with large-size channel (1.2 m wide at Nîmes, 0.85 to 1.1 m wide at Gorze). Each aqueduct were supplied by a natural spring, and the catchment area was about 45 to 60 km^2 (Table 1). Further both aqueducts included a large bridge-aqueduct : the Pont du Gard (360 m long, 48.3 m high), and the Pont sur la Moselle (1300 m long, 30 m high). Two further aqueducts (Mons at Fréjus, Mont d'Or at Lyon) are listed in Table 1.
Today both springs are in use. At Gorze, the average daily flow rate is 93 L/s. Modern data suggest that the aqueduct did not operate at full-capacity but for few months per year. During dry periods, the minimum daily flow rate was less than 10% of the maximum flow rate. At the Source de l'Eure (Uzès, Nîmes aqueduct), the average daily flow rate is 343 L/s. Modern data show however large discharge fluctuations. The minimum daily flow rate is about 125 L/s, while the maximum daily flow rate is around 1660 L/s. For the Mons aqueduct (Fréjus), the average daily flow rate of the Sources de la Siagnole are 1125 L/s. Again large fluctuations of flow rate are recorded, from no flow in dry periods to a maximum daily flow rate around 17,900 L/s !

REGULATION BASINS

A number of regulation basins were discovered along some aqueducts. At Nîmes and Gorze, two basins were found immediately upstream of the bridge-aqueducts (Table 1). At Nîmes, two further regulation basins were found (BOSSY et al. 2000). Most regulation basins consisted of a rectangular pool, a series of valves controlling the downstream aqueduct flow and an overflow system.

Why was the regulation of an aqueduct required ? First the flow rate had to be stopped for maintenance and cleanup. Water quality problems were known in cities (e.g. FRONTINUS, VITRIVIUS). One method consisted in the regular clean-up of the channel. Second regulation systems were possibly used to store water during night times. At Gorze and at Nîmes, the storage capacity in the aqueduct channel was about 20,000 and 55,000 m^3 respectively (Table 1). This technique would imply a good coordination of gangs of valve operators to open and close the gates twice a day : to open in the morning and to close the flow at night.

STEEP CHUTE DESIGNS

Roman aqueducts were designed with flat longitudinal slopes : i.e., 1 to 3 metres per kilometre on average typically ([1]). Some included however steep-gradient sections (CHANSON 2000a). Current knowledge and field observations suggest primarily three types of steep section design : (1) the steep 'smooth' invert chute followed sometimes by stilling basin(s), (2) the stepped channel and (3) the dropshaft cascade.

SMOOTH-INVERT CHUTES

A steep chute is characterised by supercritical flows and the kinetic energy of the flow is significantly larger than on a mild slope for the same flow rate. Energy dissipation must take place at the downstream end or in the downstream canal, and sometimes stilling structures must be introduced. The transition from high-velocity flow to a slower motion may take place as a hydraulic jump. In engineering practice, hydraulic designers want to avoid three types of jumps : undular, oscillating and strong hydraulic jumps. Strong hydraulic jumps are characterised by a high-potential for bed erosion and scouring while wave propagation can affect the operation of the conduit downstream of undular and oscillating jumps ([2]). The latter may induce vibrations on downstream gates and perturbation of discharge measurement devices.

A complete 'backwater' analysis was conducted for several well-documented steep chutes (BLACKMAN 1979, CHANSON 1998). The results highlighted the existence of hydraulic jumps in some aqueducts and the occurrence of unfavourable flow conditions. Oscillating hydraulic jumps occured at the Brévenne aqueduct (one chute) and undular flows took place at the Brévenne (one chutes), Gorze (bridge), Carthage, Anio Vetus (one bridge), Anio Novus (two bridges) aqueducts. These flow conditions were unsuitable for proper operation of the aqueduct unless structures were built to dampen the surge waves.

Although several researchers have argued about the existence of 'settling basins' along aqueducts to trap sediments (e.g. RAKOB 1974, BURDY 2002), it is believed that several basins were 'stilling basins' ([3]) built downstream of steep chutes (CHANSON 2000a). At Alepotrypes (Corinth), the

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[1]Sometimes even less, as for example, at the Nîmes aqueduct, 0.248 m/km in average and 0.37 m/km upstream of Pont-du-Gard.

[2]"*This type [of oscillating jump] has a pulsating action [...]. [It] is one of the most difficult [types of jump] to handle*" (BRADLEY and PETERKA 1957, pp. 1401-22). The same researchers 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 1957, p. 1404-2).

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

hydraulic power of the chute flow was nearly 9 kW and a downstream cistern acted as a dissipation basin. Three well-documented basin systems were built to damp waves: Sotizon downstream of the Courzieu II chute (Brévenne), Jouy-aux-Arches downstream of the Moselle bridge-canal (Gorze) and at least five circular basins at Oudna (Carthage) (CHANSON 2000a).

STEPPED CASCADES

Roman engineers used both single drops and stepped cascades along aqueducts (CHANSON 2000a,b). The stepped chute design was also common with dam spillways. For example, the oldest known stepped spillway was built around BC 1,300 in Greece and the Roman engineers built several significant stepped spillway systems (CHANSON 2001) ([4]). Roman engineers used single drops and stepped cascades (CHANSON 2000a,b). The Brévenne aqueduct included a number of steep chutes (e.g. CHANSON 2000a). One chute was definitely a stepped design : i.e., Chevinay. The steps were made of rockfill covered by stone slabs. The step dimensions were similar to modern precast concrete block systems developed by the Russians (CHANSON 2001). Another large cascade was found at Andriake in Turkey.

Different step geometries were used : flat horizontal step (e.g. Beaulieu), inclined downward flat step (e.g. Chevinay) and pooled step (e.g. Andriake). Such a wide range suggests that the Roman engineers had a strong experience, if not expertise, in stepped chute design. Pooled step and inclined downward step designs are not usual even by modern standards (e.g. PEYRAS et al. 1992, CHANSON 2001). What was the main purpose of the stepped cascade design ? At Chevinay, Beaulieu and Cherchell, the cascades were designed to dissipate the kinetic energy of the flow. At Andriake, the cascade is located at the downstream end of a series of arcades. Was the Andriake cascade built for energy dissipation purpose, to treat the water (re-aeration), for aquatic life (in the step pools) or a combination of the above ? The answer is as yet unknown.

A related design is of course the watermill cascade at Barbegal in the South of France. The available hydraulic power was large : i.e., about 25 to 50 kW ! There, a component of the dissipated energy was transferred to the water wheels.

DROPSHAFTS AND DROPSHAFT CASCADES

In Rome, vertical shafts were used also to interconnect aqueducts, particularly from newer higher channels to older canals. At Grotte Sconce ([5]), a branch of the Anio Novus aqueduct lead to a circular dropshaft and into the Claudia aqueduct, and a second rectangular dropshaft lead to the Marcia aqueduct ([6]), while, at San Cosimato Gorge, a side channel connected the Claudia to the Marcia aqueducts through a 9.2-m deep rectangular dropshaft ([7]). Other examples of 'interconnection shafts' at Rome included a square dropshaft from Claudia to Vetus at Voltata delle Corrozze ([8]) and a rectangular shaft from Anio Novus to Claudia near the Fosso Arcese bridge ([9]).

In some aqueducts, however, Roman engineers built series (or cascades) of dropshafts along the main branch, in France and North Africa predominantly (CHANSON 2002a). A dropshaft cascade is basically a subterranean chute : it consists of a series of dropshafts. The design of Roman dropshafts included an unusual feature, namely a deep wide shaft pool (Fig. 2). The pool of water acted as a cushion at the point of nappe impact preventing scour at the shaft bottom. The shaft pool facilitated further the entrainment of air bubbles by the plunging jet, maximising the bubble residence time and associated air-water gas transfer. The design contributed successfully to an enhancement of the

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[4]Roman dams equipped with drop spillways included Harbaka (AD 200-300?, Syria). Examples of stepped spillways included Kasserine dam (Tunisia AD 100?), Oued Guergour dam (Tunisia AD 100?), Qasr Khubbaz (Syria AD 100-200), and Tareglat dam (Libya AD 200-300).

[5]also spelled 'Grotte Sconcie'.

[6]ASHBY (1935), pp. 277-279 & Fig. 31; VAN DEMAN (1934), pp. 212-213 & 302-303.

[7]ASHBY (1935), pp. 101-102 & Fig. 7; VAN DEMAN (1934), pp. 76-77.

[8]VAN DEMAN 1934, p. 213.

[9]ASHBY 1935, p. 275.

dissolved oxygen (DO) content. The best documented dropshaft cascades are those of Brisecou (Montjeu), Recret (Yzeron), Cherchell and Valdepuentes. The latter aqueduct had two large cascades (Cerro de los Pinos, upstream of the Valdepuentes bridge and Madinat-al-Zhara), but dropshafts were also found in other places. Two dropshaft shapes were used : rectangular at Vaugneray, Recret and Montjeu (France), and circular at Cherchell (Algeria), Rusicade (Algeria) and Valdepuentes (Spain). The former shape was used at the older Yzeron aqueduct, possibly because of the ease of construction. The circular shape was used in newer aqueducts (e.g. Cuicul, Cherchell) suggesting that it was possibly a design evolution.

The dropshaft cascades were built for large drops in invert elevation : e.g., an overall drop of 200 m at Valdepuentes (Madinat-al-Zhara). The design had had an excellent reliability record and some cascades were used for centuries ([10]). It must be understood that the design was not obvious: a dropshaft cascade was a complex underground structure that included the construction of numerous shafts and interconnection channels in difficult topographic conditions. Two types of dropshaft cascades were built : i.e., flat invert slope in between shafts and steep slope. The former design was most common: e.g., at Autun, Recret and Cuicul. Steep inverts were built at Cherchell and Valdepuentes and the connection canals operated with supercritical flow conditions. At Valdepuentes, the invert slope was S_o = 5% between shafts; at Cherchell, a steep chute (S_o = 62%) was located upstream of each shaft. The Valdepuentes aqueduct was further equipped with three dropshafts with a 90º angle between the inflow and outflow conduits ([11]). This type of design was found only at Valdepuentes and Montjeu (France).

The dropshaft cascades might have been used for a rapid vertical drop in invert elevation, kinetic energy dissipation and flow aeration (CHANSON 2000a). In the first application, a dropshaft allows the connection between two flat conduits, located at different elevations, along a very short distance : i.e., the shaft length. The second application of dropshaft is the dissipation of the kinetic energy of the flow. Such a design is still used today: e.g. storm water systems in Tokyo, sewer system in Paris. A third application is the flow re-aeration of the flow resulting from the substantial air bubble entrainment taking place in the shaft pool.

CULVERT DESIGN

Although the world's oldest culvert is unknown, the Minoans and the Etruscans built ancient culverts in Crete and Northern Italy respectively (EVANS 1928, O'CONNOR 1993). Later the Romans built numerous culverts beneath their roads (BALLANCE 1951, O'CONNOR 1993). The culvert construction was favoured for small water crossings while a bridge construction was preferred for longer crossings. The common culvert shapes were the arched design and the rectangular (or box) culvert. The Romans built also culverts beneath aqueducts (CHANSON 2002b).

Along the Nîmes aqueduct, a large box culvert was recently excavated at Vallon No. 6, located 17 km downstream of Pont du Gard between the Combe de la Sartanette and Combe Joseph in the Bois de Remoulins (FABRE et al. 1992, 2000; CHANSON 2002b). The culvert was designed to allow stormwater passage beneath the aqueduct in a small valley, locally called *combe*. Note that catchment area was very small : i.e., 0.028 km^2. At Vallon No. 6, the culvert could pass an intense storm event corresponding to a maximum effective rainfall intensity of nearly 540 mm/hour which is consistent with observed maximum rainfall intensity of 800 to 900 mm/hour in the nearby Cévennes range ([12]). For comparison, the mean annual rainfall near Nîmes has been about 700-800 mm for the last fifty

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[10]For example, the dropshaft cascades of the Valdepuentes aqueduct were later re-used by the Muslims.

[11]Upstream of the Valdepuentes stream.

[12]Such hydrological events are called "évènements cévenols". An extreme hydrological event took place between Sunday 8 September and Monday 9 September 2002 in Southern France (Fig. 4). More than 37 people died. At Sommières, the water depth of the Virdoule river reached up to 7 metres, although the water depth is usually less than 1 m. Interestingly, the old house in the ancient town of Sommières had no ground floor because of known floods of the Virdoule river.

years. During the same period, recorded intense rainfalls included 430 mm in seven hours (61 mm/hour) on 3 October 1988 and 250 mm on the 12 October 1990 (FABRE et al. 2000, pp. 160-161).
The culvert was a multi-cell structure equipped with three rectangular cells with a total cross-section area in excess of 1.2 m^2. The cells were made of large limestone blocks placed on supporting pillars, or dividing walls, founded on worked bedrock. The upstream end of each dividing wall was cut in a chamfer to form cut-waters. Note that the Bornègre bridge on the Nîmes aqueduct, located between Uzès and Pont du Gard, was composed of three arches with two central piers equipped with upstream cut-waters. But the cut-waters of the culvert were better shaped. (The cut-waters of Bornègre bridge were more sturdy and less profiled that those of the multi-cell culvert : i.e., 60º convergence angle at Bornègre, 45º for the culvert.)
Historians and archaeologists have no doubt that the multi-cell culvert was built in the early stages of the aqueduct (i.e. 1st century A.D.). The excavation works showed no sign of refurbishment.
Culverts were seldom used beneath aqueducts and the Vallon No. 6 culvert downstream of Pont-du-Gard is an unique example. Its unusual features included a box culvert design of large dimensions, a multi-cell structure and a modern, sound design from a hydraulic perspective (CHANSON 2002b).

THE NÎMES AQUEDUCT

The Roman aqueduct supplying the city of Nîmes (*Colonia Augusta Nemausus*) is one of the best documented aqueducts (Fig. 3). Classical studies include ESPERANDIEU (1926), HAUCK and NOVAK (1987), SMITH (1992-93) and more importantly the multi-disciplinary works of FABRE et al. (1991,1992,2000). The notoriety of the aqueduct is connected with its crossing of the Gardon river: i.e., the Pont-du-Gard which is the most famous three-tier Roman bridge still standing (O'CONNOR 1993). Despite some discussion, it is believed that the aqueduct was in use from the 1st century A.D. up to the 4th or 5th century A.D. (FABRE et al. 2000).
The Nîmes aqueduct was 49,800 m long, starting at the Source de l'Eure at Uzès which drains a 45-50 km^2 catchment area. The total invert drop was only 14.65 m from the source to the *castellum dividorum* (repartition basin) at Nîmes, which gives the aqueduct one of the flattest gradient among Roman aqueducts (GREWE 1992, HODGE 1992, FABRE et al. 2000). The aqueduct channel was typically 1.2 m wide and the maximum flow rate was estimated to be about 0.405 m^3/s (35,000 m^3/day). FABRE et al. (1991) showed however an important variability of the spring output at Uzès. During a study period covering July 1967 to May 1968 and January 1976 to December 1978, the average streamflow was 0.343 m^3/s (29,600 m^3/day), while the minimum flow rate was 0.125 m^3/s (10,800 m^3/day) in September 1976 and the maximum discharge was 1.66 m^3/s (143,400 m^3/day) in October 1976.
By its dimensions and capacity, the Nîmes aqueduct was among the largest aqueducts built in Roman Gaul. The list includes the 86 km long Gier aqueduct (Lyon), the Gorze aqueduct (Metz) with its 1,300 m long bridge across the Moselle river, and the Mons aqueduct (Fréjus) with a maximum discharge capacity of 0.61 m^3/s (52,500 m^3/day). However the Nîmes aqueduct was smaller than the largest aqueducts at Rome : e.g., the Aqua Marcia, the Aqua Novus (HODGE 1992, FABRE et al. 1992).

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Gorze Aqueduct, Metz	{http://www.ac-nancy-metz.fr/ia57/jussy/netsco/English/accueil.htm}
Rome aqueducts	{http://www.donau.de/privhome/mrechenmacher/rom/karte1.htm}
Mons aqueduct, Fréjus	{http://www.chez.com/siagnole/}

Table 1 - Comparison between Roman aqueducts at Nîmes, Gorze (Metz), Mons (Fréjus) and Mont d'Or (Lyon)

	Gorze (Metz)	Nîmes	Mons (Fréjus)	Mont d'Or (Lyon)	Remarks
Hydrology Catchment area (km^2) :	58	45-50	130		
Spring(s) :	source des Bouillons (Gorze)	Eure (Uzés)	sources de la Siagnole (Mons)	(1) source du Thou (2) ruisseau d'Arches	
Hydrological study period:	1/1997 to 12/1998	7/1967 to 5/1968 & 1/1976 to 12/1978	1/1981 to 12/1993	late 20th century	
Average stream flow (m^3/day) :	8,050 (*)	29,600	97,200	(1) 400 (2) 1,000	Modern data based upon daily averages. (*) include overflows.
Standard deviation (m^3/day) :	2,950	--	--	--	Modern data
Maximum daily flow rate (m^3/day) :	10,980 (*)	143,400	1,550,000	(1) 1,500 (2) 3,000	Modern data based upon daily averages. (*) include overflows.
Minimum daily flow rate (m^3/day) :	1,100	10,800	0	(1) 100 (2) 150	Modern data
Hydraulic Aqueduct length (m) :	22,300	49,800	39,400	26,000	
Total drop in elevation (m):	14.19	17	481	372	

Internal canal width (m) :	1.1 2×0.85 (*)	1.2	0.60	0.5	Main canal. (*) bridge-aqueduct.
Estimated maximum discharge capacity (m^3/day):	15,000	35,000	52,500	10,000	Estimates (?).
Maximum water depth (m) :	0.92	1.0	potential pipe flow situations in some sections	0.65	Based upon the waterproofing of the canal.
Aqueduct storage volume (m^3) :	21,200	58,800	--	--	Excluding the bridge-aqueduct.
Bridge-aqueduct River :	Moselle	Gardon	--	--	
Bridge height (m) :	30	48.3	--	--	Pont sur la Moselle and Pont-du-Gard respectively.
Bridge length (m) :	1,300	360	--	--	
Bed slope along bridge-aqueduct ($S_o=\sin\theta$):	3.9 E-3	7 E-5	--	--	
Internal channel width (m):	2×0.85	1.2	--	--	
Upstream regulation basin - Volume (m^3) :	18.0	4.0	--	--	Bank full.
Downstream dissipation basin - Volume (m^3) :	4.24	N/A	--	--	Bank full.
Usage of the aqueduct Beginning :	AD 100/200	AD 40/80	BC 31/AD 70	BC 20	Estimates (?).
End :	AD 450/500	AD 350/500	AD 370/470	--	Estimates (?).

References : FABRE et al. (1991,1992,2000), VALENTI (1995a,b), LEFEBVRE (1996), BURDY (2002), CHANSON (2002c).

Fig. 1 - Photographs of Roman aqueducts

(A) Gier aqueduct, Lyon, France (86 km long) - Arcades de Chaponost, looking upstream from the Beaunant siphon head tank in June 1998

(B) Gier aqueduct, Lyon, France (86 km long) - Le Mornantay bridge (Mornant) in June 1998, looking upstream

(C) Brévenne aqueduct, Lyon, France (70 km long) - Biternay in Sept. 2000, inside the conduit, looking upstream

(D) Fréjus aqueduct (France)- Arches de Sainte Croix on 14 Sept. 2000, downstream of Chateau Aurélien (Parc Municipal)

(E) Fréjus aqueduct (France)- Arches de Sainte Croix, looking upstream on 14 Sept. 2000 - The open channel conduit was at the top of the arcades

Fig. 2 - Photograph of a full-size Roman dropshaft (2.1 m drop in invert elevation) - Experiments at the University of Queensland in 2002

Fig. 3 - Photographs of the Nîmes aqueduct
(A) Pont du Gard, Nîmes aqueduct, France in June 1998 - View from the right bank

(B) Pont de Bordnègre in Sept. 2000 - Inlet view, showing the bridge pier shaped to cut the waters

(C) Culvert beneath the aqueduct between Combe de Sartanette and Combe Saint Joseph, downstream of Pont du Gard in Sept. 2000 - Main culvert cell (0.8-m wide)

Fig. 4 – Flash flood in southern France on 9 September 2002

HYDRAULIC STUDY OF THE NÎMES AQUEDUCT

1. REGULATION SYSTEM

The regulation basin upstream of Pont-du-Gard has roughly a rectangular shape (1.9 m long, 2.1 m wide). The basin invert is 0.1 m below the main canal bed. Upstream and downstream of the basin, the canal is 1.2 m wide with a rectangular cross-section. The inside walls of both canals and basin are lined with mortar.

1.1 The basin outflow is controlled by a sluice gate installed in the outflow canal itself. For a flow rate of 20,000 m^3/day, the water depth in the canal, immediately upstream of the gate, is 0.55 m.
- Calculate the downstream water depth and the force acting on the gate. *Neglect tailwater effects.*
- Calculate the water depth in the regulation basin.

1.2 The regulation basin is also used as a settling basin to trap sediment matter. The basin can operate successfully as long as the shear velocity is less than 0.005 m/s. Calculate the corresponding maximum flow rate assuming a 1-m flow depth. (*A 1-m flow depth in the basin corresponds to bank full.*)

1.3 The Roman chief-engineer decides to undertake a hydraulic model study of the basin to test different gate configurations. Laboratory facilities limit the scale ratio to 4:1. The design flow in prototype is 30,000 m^3/day.
- Determine the maximum model discharge required.
- Determine the minimum prototype discharge for which negligible scale effects occurs in the model.
- Discuss your results.

2. FREE-SURFACE PROFILE CALCULATIONS

At the upstream end of the aqueduct, the waters from the Eure springs are collected in a large reservoir. The reservoir is controlled by a broad-crested weir (1.1 m wide, 2.1 m long with the crest located 1.4 m above the downstream canal invert) discharging into the main canal. The upstream 5 km of the canal are characterised by large variations in bed slope (Table 2.1).

Considering the real fluid flow in the upstream section of the aqueduct, Table 2.1 provides the geometric characteristics of the 5400-m upstream canal reach. For the design flow of 30,000 m^3/day, calculate the critical depth and normal depth in each sub-reach. Report the results in Table 2.2.

Compute the flow depth, flow velocity, Darcy coefficient, Froude number and friction slope at all the positions between the spring and Les Arabades. Plot the backwater curve (i.e. flow depth curve) on graph paper. *Flow resistance calculations must be performed using the Darcy-Weisbach friction factor.*

Table 2.1 - Nîmes canal geometry between Source de l'Eure and Les Arabades (Commune de St-Maximin)

Location (1)	Bed elevation (1) m	x (1) m	Roughness (2)	B (2) m	Remarks
Source de l'Eure (0)	73.60	0	Mortar	1.0	Immediately downstream of broad-crested weir.
2a	71.298	100	Mortar	1.1	
2b	71.220	181.61	Mortar	1.1	
2c	71.128	214.61	Mortar	1.1	
2d	71.054	245.80	Mortar	1.1	

Bassin du Val d'Eure (2A)	70.870	288.41	Mortar	1.1 / 1.2	Smooth change on canal width.
La Montagne (4)	70.810	793.14	Mortar	1.2	
Mas de Préville (7)	70.653	1168.75	Mortar	1.2	
Carrignargues amont (9)	70.110	2029.10	Mortar	1.2	
Les Arabades (19)	68.516	5436.25	Mortar	1.2	

Notes : (1) after FABRE et al. (2000); (2) new aqueduct dimension.

Table 2.2 - Summary table (normal depth and critical depth) for Q = 30,000 m^3/day

Sub-reach (1)	Bed slope (1)	d_c (1) m	d_o (2) m	B (2) m	Remarks
Source de l'Eure (0) to 2a				1.0	
				1.1	
2a to 2b				1.1	
2b to 2c				1.1	
2c to 2d				1.1	
2d to Bassin du Val d'Eure (2A)				1.1	
Bassin du Val d'Eure (2A) to La Montagne (4)				1.2	
La Montagne (4) to Mas de Préville (7)				1.2	
Mas de Préville (7) to Carrignargues amont (9)				1.2	
				1.2	
Carrignargues amont (9) to Les Arabades (19)				1.2	

Notes : (1) after FABRE et al. (2000); (2) new aqueduct dimension.

3. CULVERT DESIGN

Along the Nîmes aqueduct, a large box culvert is located at Vallon No. 6, located 17 km downstream of Pont du Gard. The culvert was designed to allow stormwater passage beneath the aqueduct in a small valley, locally called *combe*. Note that catchment area is very small : i.e., 0.028 km^2. The culvert is a multi-cell structure equipped with three rectangular cells. The cells are 0.5 m, 0.8 m, and 0.6 m wide. Each cell has an internal height of 0.65 m. The barrel length is 3.7 m and the invert slope is about 0.05. (The invert is worked bedrock : k_s ~ 10 mm.) The upstream end of each dividing wall is cut in a chamfer to form cut-waters.

Upstream and downstream of the culvert, the natural bed slope is steep (i.e. S_o ~ 0.16) and consists of gravels (k_s = 50 mm). The valley is narrow and may be approximated as a 3.2 m wide rectangular cross-section.

- For a catchment runoff of 1.5 m^3/s, calculate the normal depth in the valley.
- For the same runoff, calculate the change in upstream water level caused by the presence of the culvert.
- Did the culvert operate with inlet control or outlet control ?

Using the software Hydroculv™, calculate the change in upstream water level caused by the presence of the culvert for a runoff of 1.5 m^3/s. Compute the flow velocity inthe barrel.