HYDRAULIC ENGINEERING AND ROMAN AQUEDUCTS: MODERN PERSPECTIVES

Hubert Chanson
Professor in Hydraulic Engineering and Environmental Fluid Mechanics, The University of Queensland, School of Civil Engineering, Brisbane QLD 4072, Australia - Email: h.chanson@uq.edu.au, URL: http://www.uq.edu.au/~e2hchans

1. INTRODUCTION

The Roman engineering heritage encompasses a number of magnificent structures including bridges, roads, dams and aqueducts, with many still standing (Fig. 1 to 4). Among these, the aqueducts constitute a fine example of water resource engineering and many aqueduct sections are still in use, in Tunisia, Spain and France for example. Surprisingly, relatively little is known on their engineering design nor the hydraulic knowledge of Roman engineers (Hodge 1992, Fabre et al. 2000). Some scholars suggested that the basic principles of fluid mechanics were unknown from the Romans (Garbrecht 1987, Hodge 1992,2002), but recent arguments showed the contrary (Chanson 2000,2002,2010).

Herein the hydraulic design of several Roman aqueducts is re-analysed using modern hydraulic engineering knowledge. The operation of the aqueduct system is discussed and it is shown that the aqueducts were equipped with a number of hydraulic structures for flow control and energy dissipation. The design of these devices implied a solid expertise in open channel hydraulics and pipe flows. In turn, the Roman hydraulic engineers had some advanced technical expertise.

(A, Left) Cornalvo dam, Spain with the intake tower in 2007 (Courtesy of Franz Jacobsen)
(B, Right) Esparragalejo, dam Spain (Courtesy of Geoff Sims)

(C) Ancient Roman bridge across Wadi al Murr near Mosul, Irak, in the 1920s (Credits Max von Oppenheim)
Fig. 1. Roman hydraulic structures

(A) Pont du Gard, Nîmes aqueduct, France on 6 June 1998, viewed from upstream, right bank

(B) Gorze aqueduct bridge across the Moselle River (France) on 3 May 20008 (Courtesy of Guy Bergé)

Fig. 2. Roman aqueduct bridges

2. ROMAN AQUEDUCT: DESIGN AND CONSTRUCTION

The aqueducts were some long subterranean channels following the topographic contours lines. The very-large majority of the aqueduct was built at or just below the natural ground level. The channel invert and sidewalls were lined with mortar up to 0.5 to 1 m above the invert (Fabre et al. 2000, Burdy 2002). During operations, the waters were flowing as open channel flow and the water depths ranged typically from less than 0.05 m to 1 m (Chanson 2002). The conduit was covered to reduce the contamination of the water by dirt and impurities. The roof internal height was usually between 1.1 and 2.1 m allowing regular access for maintenance. The role of repair and maintenance crews was critical for a proper operation of the aqueduct system as well as the quality of the waters.

The construction of aqueducts was a gigantic task often conducted under the supervision of military engineers. The construction was a public entreprise financed by the Emperor, the community, private citizens or a combination of these (Leveau 2004). The Nîmes aqueduct (Fig. 2A) was financed by both the Emperor and the city. The construction costs were huge considering the modest flow rates: about 2 to 2.5 millions sesterces per km for the aqueducts of Rome and a water discharge less than 0.4 m3/s (Février 1979, Leveau 1991,2006). Based upon the silver contents of sesterce during the Augustan period, the cost would be today 1.9 to 2.4 millions AU$ per km assuming US$0.71 per g of silver! For comparison, the Tarong water pipeline construction in Australia costed US$100,000 per km in 1994, and the pipeline delivered 0.9 m3/s.

The construction of the aqueduct system was a gigantic project and the design required a range of engineering skills including hydrology, surveying, civil and hydraulic engineering, and construction management (Février 1979, Mays 2010). The construction site involved hundreds of workers and it took several years to complete the aqueduct: from 3 years for the Anio Vetus in Rome to 15 years for the Nîmes aqueduct, and possibly more for some. The engineers used three types of conduits: open channels, lead pipes and earthenware pipes (Leveau 2006). The canals were built in masonry and sometimes cut in the rock and the flow motion was driven by gravity. The lead pipes were used for pressurised sections including the inverted siphons (e.g. Aspendos, Lyon).


(A) Arcades at Oued Miliane (Courtesy of Michel Royon)


(B) Water cisterns of La Malga (Courtesy of Michel Royon)

Fig. 3. Carthage aqueduct, Tunisia


(A) Arcades near Via Batteli

(B) Details of specus

Fig. 4. *Caldaccoli aqueduct in Pisa, Italy on 29 July 2008*

The Roman aqueducts were built for the public health and sanitary requirements of the cities. These needs encompassed the public fountains, public baths, and toilets (Hodge 1992, Fabre et al. 2000, Mays 2010) (Fig. 5). The aqueducts were built after the town establishment, and did not constitute the original drinking water supply. The aqueduct water delivery was used further in the sewer system and assisted with the fight against fires (e.g. in Rome). Some aqueducts were built for irrigation purposes and to feed the industries (e.g. mines, flour mills). A number of aqueducts were built for the drainage of swampy areas such as the Fucine Lake in Italy. Altogether it was argued that an aqueduct was a show of power and wealth of the Roman civilisation (Fevrier 1979, Leveau 1979).

(A) Roman bath (Thermae) in Pisa, Italy on 29 July 2008

(B) Toilets (Latrines) in the Roman Forum (Roman Agora), Thessaloniki, Greece on 25 August 2003

Fig. 5. Roman baths and latrines

3. ROMAN AQUEDUCT: HYDRAULICS AND OPERATION

A number of aqueducts were fed by natural springs. Some springs are still in use today: e.g., those of the Gorze, Mons and Nîmes aqueducts (Chanson 2002,2008). Their operation provides some interesting data. Recent hydrological records suggest that a water supply system cannot operate at large flow rates for more than a couple of months per year at best. During the dry seasons, the aqueduct discharge was limited by the spring output, and recent hydrological data yielded a ratio of maximum to minimum daily flow rates between 10 to more than 1,000 (Chanson 2008). For example, the spring of La Siagnole at Mons yielded between zero and 17.9 m^3/s for the period 1981-1993; the daily discharge was less than 0.07 m^3/s for 1/4th of the study period, typically during the summer; within a given month, the daily discharge varied within one to three orders of magnitude (Valenti 1985). While the ancient flow rates are unknown, it is thought that a similar discharge variability occurred during the Roman period.

In response to the discharge variability, the Roman engineers devised a number of remedial measures. These included the construction of reservoirs and cisterns at the aqueduct downstream end: e.g., at Cuicul (Algeria), Autun (France), Rome and Carthage (Fig. 3B). As an illustration, the cistern capacity was in excess of 3×10^6 m^3 at Dougga (Tunisia) (De Vos Raaijmakers et al. 2013). Another method consisted in the dynamic regulation of the aqueduct itself. Vitrivius recommended the installation of regulation devices (Hodge 1992), and a number of recent studies presented several in-stream regulation systems (Fabre et al. 2000, Bossy et al. 2000, Chanson 2002). The regulation of the aqueduct was a basic requirement to prevent overflows and spillages during the wet seasons, to provide an optimum operation with minimum energy losses and maximum flow rates during the dry periods, to regulate the water outflow and for maintenance. A dynamic regulation allowed a regulated water supply in response the city needs during the day time and some water storage in the channel sections during the night periods (Bossy et al. 2000, Chanson 2002,2008). For a relatively large aqueduct (e.g. Gorze, Nîmes), the aqueduct conduit could store about 20,000 m^3 to 50,000 m^3 of water, corresponding to 1 to 3 weeks of water supply depending upon the population and the water restrictions.

The successful operation of the aqueducts required some solid expertise in open channel hydraulics and hydraulic structure designs. For example, some advanced stormwater systems were designed and built to protect the aqueduct from runoff water, including multi-cell culverts and bridges (Chanson 2002b,2008). For example, the floods of the Gardon River, flowing beneath the Pont du Gard (Fig. 2A), are renown; these spectacular floods are locally called 'gardonnades'. Between 1463 and 2003, 123 major floods were recorded: i.e., a major flood every 4 to 5 years. The maximum instantaneous discharge is 3,100 m^3/s for a 1-in-20 years flood. Three floods in excess of 5,000 m^3/s were documented between 1900 and 2010 (Dezileau et al. 2014). These data may be compared to an average annual discharge of 33 m^3/s.

Along the aqueducts, a number of regulation basins were built and they included some control gates and overflow devices. The control gates would be undershoot sluices while the overflows would be controlled by overshoot gates.

The operation of vertical sluice gates along the Gorze and Nîmes aqueducts were estimated (Chanson 2002). A proper operation required some gate openings less than 0.07 to 0.1 m at Gorze and less than 0.1 to 0.12 m at Nîmes. In other water systems, some overflow weirs were used to regulate the flow. The successful operation of regulation devices required further some sound prediction of the free-surface profile along the aqueduct channel to ascertain: the optimum location of the devices, and their optimum characteristics. Did the Roman engineers use some small size (laboratory) models? Today any such water supply system would be modelled physically or numerically during the design stages.

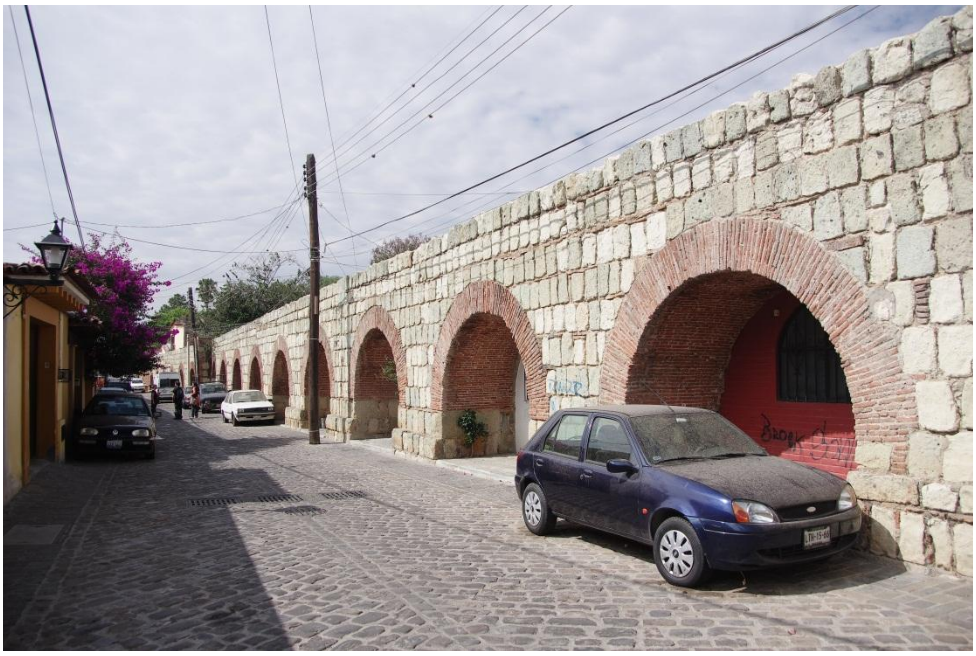

(A) Operation for Q = 0.016 m^3/s (B) Operation for Q = 0.067 m^3/s

Fig. 6. *Roman drophshaft in operation*

The aqueducts were equipped with a few steeper sections as well as some overflow devices that required the introduction of energy dissipation systems. The dissipation of the kinetic energy was critical for a proper downstream operation, to prevent scour of the channel bed and damage to the aqueduct structure itself. Some recent studies showed at least three designs: that is, a steep smooth chute followed by a hydraulic jump, a stepped cascade, and a dropshaft system (Chanson 2000,2002c). Figure 6 shows the full-scale model of a drophaft installed on the Yzeron aqueduct (Lyon). Figure 6 illustrates its operation for two different flow rates (Chanson 2007). One major dissipation structure was located along the Valdepuentes aqueduct at Cordoba (Spain) with a series of three dropshaft cascades yielding a total drop of more than 350 m. The operation of these energy dissipation structures was complex, including by modern standards, and required some advanced hydraulic expertise.

4. DISCUSSION

From Antiquity up to modern times, the Romans, Moslems and Spaniards contributed to the dissemination of hydraulic engineering and hydraulic structure design. Hydraulic structures and canals were built very early in the Mediterranean area. The construction technique spread around the Mediterranean Sea in Roman times. During their expansion, the Moslems gained expertise from the Sabaens, Nabataeans and Romans among a few civilisations (Viollet 2007). The Moslems brought their water traditions to Spain. After the reconquest, the Spaniards re-used a number of Roman and Moslem structures, and they expanded the hydraulic engineering expertise, which was in turn transferred to the Americas (Smith 1971). Clear evidences of the Spanish influence were found in Mexico and United States. Figure 7 shows the remains of a Spanish aqueduct completed during the 18th century and used up to the mid 20th century.



(A, Left) Arcades, Calle de Manuel Garcia Vigil

(B) Aqueduct bridge

Fig. 7. Spanish aqueduct in Oaxaca, Mexico completed in 1751 (Photographs on 13 Mar. 2015)

With most ancient canal systems, it is believed that the hydraulic knowledge developed locally. In Irak, Yemen Israel, large waterways systems were built. In Peru, the Indians civilisations (e.g. Chimus, Incas) constructed significant water supply canal systems prior to the Spanish conquest. On another hand, the experience of Roman dropshaft and dropshaft cascades was unique (Chanson 2000,2002c). In fact, the design expertise was forgotten and lost until recent times.

5. CONCLUSION

The Roman aqueducts operated successfully for centuries and their design constituted some major achievement including by modern standards. Although the aqueducts were long subterranean channels following the hillslope contour lines, they were equipped with a number of hydraulic structures including regulation devices, stormwater systems and energy dissipators. These successful design and operation of these devices required some advanced knowledge in fluid mechanics and hydraulic engineering. Indeed the complexity of basic fluid mechanics is linked with the non-linearity of the governing equations. The Roman aqueducts represent a superb illustration of successful civil engineering designs, covering hydrology, hydraulics, structural engineering, surveying and project management.

This contribution yields many questions. Who were the Roman engineers? How did they design the aqueduct system? How did the engineers predict the free-surface profiles and determine the needs for regulation devices and energy dissipators? Was physical modelling or prototype tests conducted? The author believes that the Roman engineering expertise was limited to a handful of engineers; these were the precursors of the French Ingénieurs du Corps des Ponts, British Royal Engineers, and US Army Corps engineers.

ACKNOWLEDGEMENTS

The writer acknowledges the exchanges with many people, incl. Dr. D. Blackman, Mrs. Chardon-Picault, Dr. P. Leveau, Mr. J.C. Litaudon, Mr. Strasberg, late Mr. V. Valenti, Dr A.V. Villanueva.

REFERENCES

Bossy, G., Fabre, G., Glard, Y., and Joseph, C. (2000). "Sur le Fonctionnement d'un Ouvrage de Grande Hydraulique Antique, l'Aqueduc de Nîmes et le Pont du Gard (Languedoc, France)." ('On the Operation of a Major Water Supply System in the Antiquity: the Nîmes Aqueduct and Pont du Gard (Languedoc, France).') *Comptes Rendus de l'Académie des Sciences de Paris, Sciences de la Terre et des Planètes*, Vol. 330, pp. 769-775.

Burdy, J. (2002). "Les Aqueducs Romains de Lyon." ('The Roman Aqueducts of Lyon.') *Presses Universitaires de Lyon*, Lyon, France, 204 pages.

Chanson, H. (2000). "Hydraulics of Roman Aqueducts: Steep Chutes, Cascades and Dropshafts." *American Jl of Archaeology*, Vol. 104, No. 1, Jan., pp. 47-72.

Chanson, H. (2002). "Certains Aspects de la Conception hydrauliques des Aqueducs Romains." ('Some Aspect on the Hydraulic Design of Roman Aqueducts.') *Jl La Houille Blanche*, No. 6/7, pp. 43-57.

Chanson, H. (2002b). "Hydraulics of a Large Culvert beneath the Roman Aqueduct of Nîmes." *Jl of Irrigation and Drainage Engrg.*, ASCE, Vol. 128, No. 5, pp. 326-330.

Chanson, H. (2002c). "An Experimental Study of Roman Dropshaft Hydraulics." *Journal of Hydraulic Research*, IAHR, Vol. 40, No. 1, pp. 3-12.

Chanson, H. (2007). "Air Entrainment Processes in Rectangular Dropshafts at Large Flows." Journal of Hydraulic Research, IAHR, Vol. 45, No. 1, pp. 42-53.

Chanson, H. (2008). "The Hydraulics of Roman Aqueducts: What do we know? Why should we learn ?" Proc. World Environmental and Water Resources Congress 2008 Ahupua'a, ASCE-EWRI Education, Research and History Symposium, Hawaii, USA, Invited Plenary, 13-16 May, R.W. Badcock Jr and R. Walton Editors., Paper 166, 16 pages (CD-ROM).

Chanson, H. (2010). "Hydraulic Engineering in Roman Times: from Hydraulic Structures to Water Conveyance." *Proc. International Symposium on Water and City in Kanazawa - Tradition, Culture and Climate*, Kanazawa, Japan, 14-15 Oct., Edited by Steering Committee of International Symposium on Water and City in Kanazawa, Invited plenary lecture, pp. 43-51. (Japanese translation: pp. 123-131) Discussion: Panel Discussion Transcription - International Symposium on Water and City in Kanazawa - Tradition, Culture and Climate, Kanazawa, Japan, 15 Oct. 2010: pp. 6-7, 15, 18-19 & 25, Edited by Steering Committee of International Symposium on Water and City in Kanazawa, published in Feb. 2011.

De Vos Raaijmakers, M., Attoui, R., and Battisti, A. (2013). "Rus Africum Tome II. Le paysage rural antique autour de Dougga: l'aqueduc Aïn Hammam-Thugga, cartographie et relevés." *Edipuglia*, Bari, Italy, 301 pages & 3 plates (DOI: 10.4475/728) (in French).

Dezileau, L., Terrier, B., Berger, J.F., Blanchemanche, P., Latapie, A., Freydier, R., Paquier, A.,Lang, M., and Delgado, J.L. (2014). "Reconstitution des crues extrêmes du Gardon à partir d'une analyse paléohydrologique." La Houille Blanche, No. 4, pp. 44-52 (DOI: 10.1051/lhb/2014037).

Fabre, G., Fiches, J.L., and Paillet, J.L. (2000). "L'Aqueduc de Nîmes et le Pont du Gard. Archéologie, Géosystème, Histoire." ('The Nîmes Aqueduct and Pont du Gard. Archaeology, Geosystem, History.') *CNRS Editions*, CRA Monographies Hors Série, Paris, France, 483 pages & 16 plates.

Février, P.A. (1979). "L'Armée Romaine et la Construction des Aqueducs." ('The Roman Army and the Aqueduct Contruction.') *Dossiers de l'Archéologie*, Séries Les Aqueducs Romains, Vol. 38, Oct./Nov., pp. 88-93.

Garbrecht, G. (1987). "Hydraulics and Hydraulic Research: a Historical Review." *Balkema Publ.*, Rotterdam, The Netherlands.

Hodge, A.T. (1992). "Roman Aqueducts & Water Supply." *Duckworth*, London, UK, 504 pages.

Hodge, A.T. (2002). "Roman Aqueducts & Water Supply." *Duckworth*, London, UK, 2nd edition, 504 pages.

Leveau, P. (1979). "La Construction des Aqueducs." ('The Construction of Aqueducts.') *Dossiers de l'Archéologie*, Séries Les Aqueducs Romains, Vol. 38, Oct.-Nov., pp. 8-19.

Leveau, P. (1991). "Research on Roman Aqueducts in the Past Ten Years." *Future Currents in Aqueduct Studies*, Leeds, UK, T. Hodge ed., pp. 149-162.

Leveau, P. (2004). "L'archéologie des Aqueducs Romains ou les Aqueducs Romains entre Projet et Usage." ('The Archaeology of Roman Aqueducts or Roman Aqueducts between Project and Usage.') in *Elementos de Ingenierai Romana, Libro de ponencias, Congreso Europeo Las Obras Publicas Romanas*, Tarragona, Nov., 13 pages.

Leveau, P. (2006). "Conduire l'Eau et la Contrôler: l'Archéologie des Aqueducs Romains." ('Carrying Water and Controlling it: the Archaeology of Roman Aqueducts.') *Colloque International de la Société Française d'Archéologie Classique, Archéologie et Histoire des Techniques du Monde Romain*, Paris, 18 Nov., 22 pages.

Levi, E. (1995). "The Science of Water. The Foundation of Modern Hydraulics." *ASCE Press*, New York, USA, 649 pages.

Mays, L.W. (2010). "A Brief History of Roman Water Technology." in "Ancient Water Technologies." *Springer*, Dordrecht, Germany, L.W. Mays Editor, pp. 115-137.

Smith, N. (1971). "A History of Dams." *The Chaucer Press*, Peter Davies, London, UK.

Valenti, V. (1995). "Aqueduc Romain de Mons à Fréjus. 1. Etude Descriptive et Technique. Son Tracé, son Profil, son Assise, sa Source ..." ('Roman Aqueduct of Mons at Fréjus. 1. Description and Technical Analysis. Its Plan, Profile, Footings, Source...') *Research Report*, Fréjus, France, 97 pages.

Viollet, P.L. (2007). "Water Engineering in Ancient Civilizations. 5,000 Years of History." *CRC Press*, 322 pages.

Bibliography

Allais, Y. (1933). "L'Alimentation en Eau d'une Ville Romaine d'Afrique : Cuicul (Djemila)." ('The water Supply of a Roman City in Africa: Cuicul (Djemila).') *5th Congrès International d'Archéologie*, Alger, pp. 93-117 (in French).

Ashby, T. (1935). "The Aqueducts of Ancient Rome." *Clarendon Press*, Oxford, UK, edited by I.A. Richmond, 342 pages.

Blackman, D.R. (1975). "On Measurements of Aqueducts : a Compilation of Quantitative Data on the Aqueducts of Ancient Rome." *MMEL Report No. 27*, Dept. of Mechanical Engineering, Monash University, Australia, 4 pages & 4 tables.

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, 61 pages.

Blackman, D.R. (1978). "The Volume of Water Delivered by the Four Great Aqueducts of Rome." *Papers of the British School at Rome*, Vol. 46, pp. 52-72.

Blackman, D.R. (1979). "The Length of the Four Great Aqueducts of Rome." *Papers of the British School at Rome*, Vol. 47, pp. 12-18.

Chanson, H. (1995). "History of Stepped Channels and Spillways : a Rediscovery of the 'Wheel'." *Canadian Journal of Civil Engineering*, Vol. 22, No. 2, April, pp. 247-259.

Chanson, H. (1998). "Le Développement Historique des Cascades et Fontaines en Gradins." ('Historical Development of Stepped Cascades and Fountains.') *Jl La Houille Blanche*, No. 7/8, pp. 76-84 (in French).

Chanson, H. (2000). "A Hydraulic Study of Roman Aqueduct and Water Supply." *Aust. Jl of Water Resources*, I.E.Aust., Vol. 4, No. 2, pp. 111-120. Discussion: Vol. 5, No. 2, pp. 217-220

Chanson, H. (2000-2001). "Historical Development of Stepped Cascades for the Dissipation of Hydraulic Energy." *Transactions of the Newcomen Society*, Vol. 71, No. 2, pp. 295-318.

Chanson, H., and James, D.P. (2002). "Historical Development of Arch Dams : from Cut-Stone Arches to Modern Concrete Designs." *Australian Civil Engineering Transactions*, IEAust, Vol. CE43, pp. 39-56 & front cover.

Gerrmain de Montauzan, C. (1907). "Rapport sur une Mission Scientifique en Italie et en Tunisie." *Nouvelles Archives des Missions Scientifiques*, Tome XV, Page II:71-123 (in French).

Germainde Montauzan, C. (1908). "Aqueducs Antiques de Lyon. Etude Comparee d'Archaeologie Romaine." *Ernest Leroux*, Paris, France (in French).

Grewe,K. (1986). "Atlas der RömischenWasserleitungen nach Köln." ('Atlas of the Roman Hydraulic Works near Köln.') *Rheinland Verlag*, Pulheim, Germany (in German).

Leveau, P. (1996). "The Barbegal Water Mill in its Environment: Archaeology and the Economic and Social History of Antiquity." *Journal of Roman Archaeology*, Vol. 9, pp. 137-153.

Leveau, P. (2002). "Environnements Fluviaux et Sociétés: Nouvelle Approches de l'Hydraulique Romaine dans le Sud de la Gaule." ('Fluvial Environments and Societies: New Approaches to the Study of Roman Hydraulic Systems in Southern Gaul.') *Jl La Houille Blanche*, No. 4/5, pp. 56-60 (in French).

Leveau, P. (2007). "Les Moulins de Barbegal 1986-2006." in "*Force Hydraulique et Machineries à Eau dans l'Antiquité Romaine*", J.P. Brun and J.L. Fiches Editors, Napoli, Italy, pp. 185-199.

Leveau, P., and Paillet, J.L. (1976). "L'Alimentation en Eau de Caesarea de Maurétanie et l'Aqueduc de Cherchell." ('The Water Supply of Caesarea of Mauretanie and the Cherchell Aqueduct.') *Librairie Edition L'Harmattan*, Paris, France, 183 pages & 10 plates (in French).

Leveau, P. (2013). "L'aqueduc d'Arles dans le territoire de la cité: topographie et hydrologie." ('The Arles aqueduct in the city shire: topography and hydrology.') *Agri centuriati*, Vol. 9, pp. 81-104 (in French).

Lopez-Cuervo, S. (1985). "Medina Az-Zahra Ingeniera y Formas." *Publicaciones del Ministerio de Obras Publicas y Urbanismo*, Madrid, Spain169 pages (in Spanish).

Rakob, F. (1974). "Das Quellenheigtum in Zaghouan und die RömischeWasserleitung nach Karthago." *Mitt. des Deutschen Archaeologischen Instituts Roemische Abteilung*, Vol. 81, pp. 41-89, Plates 21-76 & Maps (in German).

Schnitter, N.J. (1967). "A Short History of Dam Engineering." *Water Power*, Vol. 19, Apr., pp. 142-148.

Schnitter, N.J. (1976). "The Evolution of the Arch Dam." *Intl Water Power & Dam Construction*, Vol. 28, Oct., pp. 34-40 & Nov., pp. 19-21.

Schnitter, N. (1979). "Les Barrages Romains." ('The Roman Dams.') *Dossiers de l'Archéologie*, Séries Les Aqueducs Romains, Vol. 38, Oct.-Nov., pp. 20-25 (in French).

Schnitter, N.J. (1991). "Roman Dams and Weirs in the Iberian Peninsula." *8th Intl Symp. on History of Hydraulics*, Merida, Spain (Mitteilungen, Inst. für Wasserbau der Technische Univ. Braunschweig, Germany, Vol. 117, 1992, pp. 161-177).

Schnitter, N.J. (1994). "A History of Dams : the Useful Pyramids." *Balkema Publ.*, Rotterdam, The Netherlands.

Smith, N.A.F. (1992-93). "The Pont du Gard and the Aqueduct of Nîmes." *Trans. Newcomen Soc.*, Vol. 64, pp. 53-76. Discussion : Vol. 64, pp. 76-80.

Smith, N.A.F. (2007). "The hydraulics of Ancient Pipes and Pipelines." *Trans. Newcomen Soc.*, Vol. 77, No. 1, pp. 1-49.

Van Deman, E.B. (1934). "The building of the Roman aqueducts." *Carnegie Institution of Washington*, Publication No. 423, Washington DC, USA.

Villanueva, A.V. (1993). "El Abastecimiento de Agua a la Cordoba Romana. I : El Acueducto de Valdepuentes." ('The Water Supply of the Roman Cordoba. I : Aqueduct of Valdepuentes.') *Monografias No. 197*, Universidad de Cordoba, Servicio de Publicaciones, Cordoba, Spain, 172 pages (in Spanish).

Villanueva, A.V. (1996). "El Abastecimiento de Agua a la Cordoba Romana. II : Acueductos, Ciclo de Distribución y Urbanismo." ('The Water Supply of the Roman Cordoba. II : Aqueduct, Distribution System and Urbanism.') *Monografias No. 251*, Universidad de Cordoba, Servicio de Publicaciones, Cordoba, Spain, 222 pages (in Spanish).

Viollet, P.L. (2000). "L'Hydraulique dans les Civilisations Anciennes. 5000 ans d'Histoire" *Presses de l'Ecole Nationale des Ponts et Chaussées*, Paris, France, 374 pages (in French).