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Hydraulic Engineering into the 21st Century: a Rediscovery of the Wheel ? (1) A Review

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Abstract
Hydraulics is the branch of civil engineering related to the science of water in motion, and the interactions between the fluid and the surrounding environment. It is shown that hydraulic engineers were at the forefront of science for centuries. The end of the 20th century marked a change of perception in our society for hydraulic engineering. Is there a need for further hydraulic engineering ? Yes, definitely. This is illustrated with an example (culvert design) and complemented by a second paper (CHANSON 2003). Some reflexions on the role of water engineering are presented. It is suggested that hydraulic engineers and academics must be pro-active to develop further scholarship and quality expertise as a part of a long-term strategy.
Keywords: *hydraulic engineering, challenges, culvert, politics, teaching, education*

1- Introduction

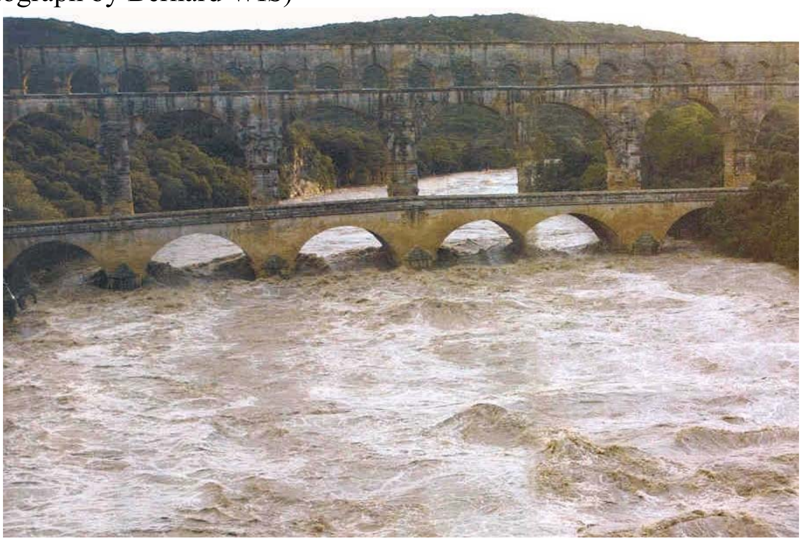
What is Hydraulic engineering ?

The beginnings of Civil engineering as a separate discipline may be linked to the foundation of the 'Corps des Ponts et Chaussées' (Bridge and Highway Corps) in France in 1716 and the establishment of the 'École Nationale des Ponts et Chaussées' (National School of Bridges and Highways) in 1747. Among the directors were the famous hydraulicians A. CHEZY (1717-1798) and G. de PRONY (1755-1839). Other famous professors included B.F. de BELIDOR (1693-1761), J.B.C. BELANGER (1789-1874), J.A.C. BRESSE (1822-1883), G.G. CORIOLIS (1792-1843) and L.M.H. NAVIER (1785-1835). Hydraulics is the branch of civil engineering "that deals with practical applications of liquid in motion" : e.g., the transmission of energy or the effects of flowing waters (Merriam-Webster's Collegiate Dictionary). Hydraulic engineering deals with practical applications of fluids, primarily liquids, in motion and it is related to fluid mechanics which in large part provides its theoretical foundation.

In its broad sense, hydraulic engineering relates predominantly to the science of water in motion, and the interactions between the flowing fluid (water) and the surrounding environment. It encompasses a broad range of applications. Although some involve man-made systems (e.g. aircrafts, submarines), many deal with the complexities of Nature. Those latter applications include rainfall runoff, river engineering, sediment transport, groundwater movement, lake, ocean and reservoir dynamics, waves, surface flows, and the alteration of natural flows by man including pollution. Hydraulics is clearly a field for people who care for Mother Nature and know how to apply the laws of fluid mechanics for the benefits of our Society while preserving Nature (LIGGETT and ETTEMA 2001). Hydraulic engineering deals with two- and three-phase flows, yet includes also interactions with aquatic life (the fourth dimension !).

Fig. 1-1 : Ancient hydraulic works
(A) Nabataean dam on the Mamshit stream (also called Mampsis or Kunub) on 10 May 2001 (Courtesy of Dennis MURPHY) - Dam wall built around the end of 1st century BC - Downstream slope of the dam wall

(B) Pont du Gard, Nîmes aqueduct, France during a flash flood in September 2002, looking upstream (Photograph by Bernard WIS)



Past, present, and future

Hydraulic engineers were at the forefront of science for centuries (Fig. 1-1). For example, although the origins of seepage water was long the subject of speculations ([1]), the arts of tapping groundwater developed early in the Antiquity. The construction of

[1]For example, "Meteorologica" by ARISTOTLE

qanats, which were hand-dug underground water collection tunnels, in Armenia and Persia is considered as one great hydrologic achievement of the ancient world. *Roman aqueducts* were magnificent waterworks and demonstrated the "savoir-faire" of Roman engineers. The 132 km long Carthage aqueduct was considered one of the marvels of the world by the Muslim poet EL KAIROUANI. Many aqueducts were used, repaired and maintained for centuries and some are still used in parts (e.g. Carthage). A major navigation canal system was the *Grand canal* fed by the Tianping diversion weir in China. Completed in BC 219, the 3.9 m high 470 m long weir diverted the Xiang river into the South and North canals, allowing navigation between Guangzhou (formerly Canton), Shanghai and Beijing.

(C) Vallon No. 6 culvert (Nîmes aqueduct) during 1980s excavations (after FABRE et al. 1992) - Note the inlet and the three cells beneath the aqueduct - The aqueduct flowed from left to right

(D) Storm waterway at Miya-jima (Japan) below Senjò-kaku wooden hall on 19 Nov. 2001 - The steep stepped chute ($\theta > 45^{\circ}$, $h \sim 0.4$ m) was built during the 12th century AD

Hydraulic engineers have had an important role to contribute although the technical challenges are gigantic, often involving multiphase flows and interactions between fluids and biological life. The extreme complexity of hydraulic engineering is closely linked with the geometric scale of water systems, the broad range of relevant time scales, the variability of river flows from zero during droughts to gigantic floods, the complexity of basic fluid mechanics with governing equations characterised by non-linearity, natural fluid instabilities, interactions between water, solid, air and biological life, and Man's total dependence on water. The end of the 20th century marked a change of perception in our society, especially in developed countries (ODGAARD 2001). Environmental issues, sustainability and environmental management have become "fashionable" topics. What do they mean ? Is there a need for further hydraulic engineering ? How can you manage something without expert knowledge ? Will environmental managers save the planet from floods and droughts ?

In the following paragraphs, an example of recent development in hydraulic engineering is illustrated : i.e., the design of culverts. Further developments in hydraulic engineering are developed in a second paper (CHANSON 2003). Later some reflexions on the role of water engineering are presented.

2- A Typical Example: the Hydraulics of Culverts

2.1 Presentation

Culverts are among the most common hydraulic and civil engineering structures. A culvert is a covered channel of relatively short length designed to pass water through an embankment. Its purpose is to carry safely flood waters, drainage flows and natural streams below the earthfill structure. Culverts have been used for more than 3000 years. Although the world's oldest culvert is unknown, the Minoans and the Etruscans built culverts in Crete and Northern Italy respectively (EVANS 1928, O'CONNOR 1993). Later the Romans built numerous culverts beneath roads and aqueducts (BALLANCE 1951, O'CONNOR 1993, CHANSON 2002). The culvert construction was favoured for small water crossings while bridge construction was preferred for longer crossings. Table 2-1 lists well-documented Roman culverts built beneath aqueducts. Figure 1-1C shows a multicell culvert beneath the Nîmes aqueduct. This advanced design was capable of discharging rainfall runoff in excess of 10 times the maximum aqueduct flow rate (CHANSON 2002).

2.2 Hydraulic design of standard culverts

Modern designs of culverts do not differ much from Etruscan and Roman culverts (e.g. Fig. 2-1). The primary design constraint is minimum construction costs, but additional constraints might include maximum acceptable upstream flood level and scour protection at outlet. The discharge capacity of the barrel is primarily related to the flow pattern : free-surface barrel flow or drowned barrel. When free-surface flow takes place in the barrel, the discharge is fixed by the entry conditions. Whereas with drowned culverts, the discharge is determined by the culvert resistance. The design process for standard culverts can be divided into two parts. First a system analysis must be carried out to determine the objectives of the culvert, the design data, the constraints. In a second stage, the barrel size is selected by a test-and-trial procedure, in which both inlet-control and outlet-control calculations are performed. At the end the *optimum size* is the smallest barrel size allowing for inlet operation (e.g. CHANSON 1999, pp. 365-382).

Standard culverts are characterised by significant afflux at design flow conditions. The afflux is the rise in upstream water level caused by the hydraulic structure. It is a measure of upstream flooding. Numerous solutions were devised to reduce the afflux for a given design flow rate by rounding the inlet edges, using throated entrances and warped wing walls, introducing a bellmouth intake: e.g., California Division of Highways (1956), NEILL (1962), Federal Highway Administration (1985), HAMILL (1999). These solutions are expensive and often marginal.

Table 2-1 : *Stormwater drainage systems (culvert & small bridges) beneath Roman aqueducts*

Location (1)	Type ([a]) (2)	Barrel/throat characteristics (3)	Remarks (4)
Small Bridges			
Small bridge near Vollem, Cologne aqueduct	Arched bridge ([a])	Single-rib segmental arch supported by large stone block walls: 1.1-m wide, 1.1 maximum height. Cross-section area : ~ 1 m^2.	Meternich-Vollem, upstream end of aqueduct.
Pont Bornègre, Nîmes aqueduct	Arched bridge	Three segmental arches (ashlar masonry). Total span ~ 17 m.	Located 9 km u/s of Pont du Gard. Catchment area ~ 0.7 km^2. Max. flood flow: 5 m^3/s.
Pont-Amont at Roc-Plan, Nîmes aqueduct	Arched bridge	3 arches (3.4 m high, 2.8 m wide, 5.4 m long) with 4 buttresses.	37.8 km upstream of Nîmes.
Pont de la Baume-Sartanette, Nîmes aqueduct	Arched bridge	One arch (course rubble). Span : 4.08 m (2.23m after refurbishment)	Located 1.4 km d/s of Pont du Gard. Catchment area: 0.3 km^2.
Combe Joseph, Nîmes aqueduct	Arched bridge	One arch (rubble masonry). Span : 4.05 m.	Located 2,473 m d/s of Pont du Gard. Catchment area: 0.14 km^2.
Pont de la Combe Pradier, Nîmes aqu.	Arched bridge	Single arch (original design). Aqueduct invert elevation: 64.691 m NGF.	30.3 km upstream of Nîmes.
Culverts			
Vallon No. 6 culvert, between Combe de la Sartanette and Combe Joseph, Nîmes aqueduct	Multi-cell box culvert	3 rectangular cells : 0.5×0.65 m^2, 0.8× 0.65 m^2, 0.6×0.65 m^2. Cross-section area : > 1.24 m^2. Barrel construction : large limestone blocks. Cutwater design of dividing wall upstream end.	31.9 km upstream of Nîmes. Downstream of Pont du Gard. Catchment area: 0.028 km^2. Max. discharge capacity: 4.2 m^3/s. See Fig. 1-1C.
Pont-Aval at Roc-Plan, Nîmes aqueduct	Arched culvert ([a])	3 biased cells (1.7 m high, 1.15 m wide, 5.4 m long). Aqueduct invert elevation: 66.381 m NGF.	38 km u/s of Nîmes. Barrel partly cleared in Oct. 1988 during violent storm which damaged Nîmes.
Culvert of the Vallon de Coste-Belle, Nîmes aqu.	Box culvert	4 rectangular cells (5.5 m long). Total opening width: 1.1 m. Construction : Stone slabs.	36.9 km u/s of Nîmes, between Pont Bornègre and Pont du Gard.
Culvert, Combe Pradier, Nîmes aqueduct ([b])	Box culvert	Single rectangular cell. Aqueduct invert elevation: 64.691 m NGF.	Stage 2 after filling of the arch for reinforcement. 30.3 km u/s of Nîmes.
Culvert of Les Escaunes, Nîmes aqueduct	--	Aqueduct invert elevation: 64.1 m NGF.	22 km u/s Nîmes. Between La Perotte tunnel and Les Cantarelles tunnel.
Culvert near Burg Dalbenden, Cologne aqueduct	Arched culvert	1 cell (single rib segmental arch): 0.9-m wide, 0.7-m maximum height. Cross-section area : ~ 0.6 m^2.	Kall-Urft, upstream end of aqueduct.
Series of culverts, Brévenne aqueduct	--	Locations : Chevinay across Le Plainet stream; at Sourcieux; ...	
Series of culverts, Gier aqueduct	--	Locations : primarily in the upstream section.	

Notes: ([a]) : terminology after O'CONNOR (1993); ([b]) : after second refurbishment (Stage 2); (--):

no information. References: BURDY (1993), CHANSON (2002a), FABRE et al. (2000), GREWE (1986).

Fig. 2-1 : Standard culvert outlet below Algester Rd, Algester QLD (Australia) in Aug. 1999

2.3 Minimum Energy Loss culvert design

During the late 1950s and early 1960s, a new culvert design was developed in Queensland (Australia) under the leadership of late Professor Gordon R. McKAY (1913-1989): the Minimum Energy Loss (MEL) culvert ([2]). A MEL culvert is a structure designed with the concept of minimum head loss and nearly-constant total head along the waterway. The flow in the approach channel is contracted through a streamlined inlet into the barrel where the channel width is minimum, and then is expanded in a streamlined outlet before being finally released into the downstream natural channel. Both inlet and outlet must be streamlined to avoid significant form losses and the flow is critical from the inlet lip to the outlet lip. The barrel invert is usually lowered to increase the discharge capacity (Fig. 2-2). The resulting MEL design is often capable to operate with zero afflux at design flow. Professor C.J. APELT presented an authoritative review (APELT 1983) and a well-documented audio-visual documentary (APELT 1994). The writer highlighted the wide range of design options (CHANSON 2000,2001).

Since 1960, about 150 structures were built in Eastern Australia. While a number of small-size culverts were built in Victoria, major structures were designed and built in Queensland where torrential rains during the wet season place a heavy demand on culverts and little head loss is permissible. The first MEL structure was the Redcliffe storm waterway system (also called Humpybong Creek drainage outfall) completed in 1960. It consisted of a MEL weir acting as culvert drop inlet followed by a 137-m long MEL culvert discharging into the Pacific Ocean. The weir was designed to prevent salt intrusion in Humpybong Creek without afflux, while the culvert discharged flood water underneath a shopping centre parking. The structure passed floods greater than the design flow in several instances without flooding (McKAY 1970) and it is still used. The largest MEL waterway is the Nudgee Road MEL waterway near the Brisbane airport with a design discharge capacity of 800 m^3/s and built between 1968 and 1970. The grass-lined structure is still in use and passed successfully flood flows in excess of design flow.

[2]Minimum Energy Loss culverts are also called Energy, Constant Energy, Minimum Energy, Constant Specific Energy culverts ... (e.g. APELT 1983).

Several MEL culverts were built in southern Brisbane during the construction of the South-East Freeway in 1970-1971. The design discharge capacities ranged from 200 to 250 m^3/s. The culverts operate typically several days per year (Fig. 2-2B). McKAY (1971) indicated further MEL culverts built in Northern Territory near Alice Springs in 1970. COTTMAN and McKAY (1990) described the Newington bridge MEL water completed in 1975 (Q_{des} = 142 m^3/s). In 1975 and 1988, the structure passed 122 and 150 m^3/s respectively without any damage.

MEL culverts received some strong interests in Canada, USA and UK : e.g., LOWE (1970), LOVELESS (1984), Federal Highway Administration (1985, p. 114).

Fig. 2-2 : Minimum Energy Loss waterway in Brisbane (Q_{des} = 220m^3/s, B_{max} = 33m, B_{min} = 11m)
(A) Waterway outlet looking upstream on 13 May 2002 - Note the busway and motorway bridges above the channel and students surveying the waterway

(B) MEL waterway in operation on 31 Dec. 2001 for about 80 m^3/s looking upstream

Prototype experience

Several structures were observed operating at design flows and for floods larger than design. Inspections during and after flood events demonstrated a sound operation associated with little maintenance. While McKAY (1971) gave general MEL culvert guidelines, Professor Colin APELT stressed that a successful design must follow closely two basic design concepts: streamlining of the flow and near-critical flow conditions APELT (1983). Flow separation must be avoided at all cost. In one structure, separation was observed in the inlet associated with flow recirculation in the barrel (Cornwall St, Brisbane). MEL culverts are usually designed for Fr = 0.6 to 0.8 and supercritical flow conditions must be avoided. This is particularly important in the outlet where separation must be avoided as well.

The successful operation of large MEL culverts for over 40 years has highlighted further practical considerations. MEL culverts must be equipped with adequate drainage to prevent water ponding in the barrel invert. Drainage channels must be preferred to drainage pipes. For example, the MEL waterway shown in Figure 2-2 is equipped with a well-designed drainage system. One issue is the loss of expertise in MEL culvert design. In Brisbane, two culvert structures were adversely affected by the construction of a new busway 25 years later ([3]). As a result, one major arterial will be overtopped during a design flood (Marshall Rd, Brisbane).

3. Challenges ahead : Teaching hydraulic engineering

Water plays a major role in human perception of the environment because it is an indispensable element. The technical challenges are formidable : sustained research and teaching efforts are essential. Scientific progresses have been hampered by a lack of concerted support from a generation of "environmental planners" and politicians. During the last three decades, universities in developed countries have rationalised their engineering curricula. This has been associated with the development of computer-based courses, project-based subjects, and flexible delivery material, often at the expenses of lecture quality, practical studies and field works. The education of hydraulic engineers is a major challenge. Basic fluid mechanics is introduced in engineering and applied mathematics degrees. Some hydraulics subjects might be offered in postgraduate courses, but hydraulic engineering involves the interactions between water, soil, air and aquatic life. Such topics are not taught in undergraduate nor postgraduate curricula in most universities. The writer has lectured basic hydraulics, sediment processes, hydraulic design and air-water flows at both undergraduate and postgraduate levels since 1991 (CHANSON 1999,2001). He believes that many researchers, professionals and government administrators do not fully appreciate the complexity of hydraulic engineering nor the needs for further education of quality.

Figures 2-2C and 3-1 illustrate hands-on teaching of hydraulics. Figure 3-1A shows Open Channel Flow students (3rd Year) inspecting the Gold Creek dam spillway. Key features include a 55-m wide, 60-m long broad crest, a stepped chute and the absence of downstream stilling basin. Figure 3-1B shows Hydraulic Design students (4th Year) in front of the fully-silted Korrumbyn Creek dam. The dam and reservoir were accessed after a half-hour bushwalk guided by the rangers in the dense sub-tropical rainforest of Mt Warning National Park (NSW). Figure 2-2C presents Civil Design students (4th Year) surveying a MEL culvert. Altogether 8 culverts and flood plains were surveyed and analysed, and results were presented in a series of reports and oral presentations assessed by student peers and lecturers. Overall, anonymous student feedback demonstrated that students considered field works as an essential component of the hydraulic engineering courses and an important aspect of the civil engineering curriculum. Field works were

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[3]This new busway is visible in Figure 2-2, above the MEL waterway outlet, but this structure was not affected.

well-suited for group works, allowing students to gain better in-depth understanding of professional teamwork and designs. Although the students believed that field studies did not replace traditional lectures, most felt that the field experience helped them to think more critically in hydraulic engineering. Anonymous results indicated further that field studies were not self-learning. Students needed expert guidance and knowledge to comprehend all aspects of a prototype design.

Fig. 3-1 : Undergraduate student field works at the University of Queensland
(Left) Open channel flow class (84 students) in Gold Creek dam stepped spillway
(Right) Hydraulic design class (24 students) in front of the fully-silted Korrumbyn Creek dam

4. Political role(s) of water systems

The sustainable development of Earth water systems is the key of long-term peace and stability. The control of water systems is closely linked with political stability. The 21st century is facing high risks of armed conflicts centred around water systems, and freshwater system issues will be the focal point of future armed conflicts. For example, the Tigris and Euphrates river catchments with potential conflicts between Turkey, Iraq and Syria. This situation is not new but the risks are far greater in the 21st century.

Armed conflicts around freshwater systems have been plenty. In the Bible, a wind-setup effect allowed Moses and the Hebrews to cross shallow water lakes and marshes during their exodus. Droughts were artificially introduced : e.g., during the siege of the ancient city of Khara Khoto ('Black City') in AD 1372, the Chinese army diverted the Ezen river ([4]) supplying water to the city ([5]). Man-made flooding ([6]) of an army or a city was carried out by the Assyrians (Babylon, Iraq BC 689), the Spartans (Mantinea, Greece BC 385-84), the Chinese (Huai river, AD 514-15), the Russian army (Dnieprostroy dam, 1941). A related case was the air raid on the Möhne dam conducted by the British, in 1943, during the dam buster campaign (Fig. 4-1). Dyke destruction and associated flooding played also a role in several wars. For example, the war between the cities of Lagash and Umma (Assyria) around BC 2,500 was fought for the control of irrigation systems and dykes; the Dutch broke dykes near Amsterdam to stop the French army in

[4]also called Hei He river ('Black River') by the Chinese.
[5]Located in the Gobi desert, Khara Khoto was ruled by the Mongol king Khara Bator (WEBSTER 2002).
[6] by building an upstream dam and destroying it.

1672; in 1938, the Chinese army destroyed dykes along the Huang Ho River (Yellow River) to slow down the Japanese army.

Fig. 4-1 : Möhne dam shortly after the R.A.F. raid on 16-17 May 1943 - Almost 1,300 people died in the floods following the dam buster campaign, mostly inmates of a Prisoner of War (POW) camp just below the dam.

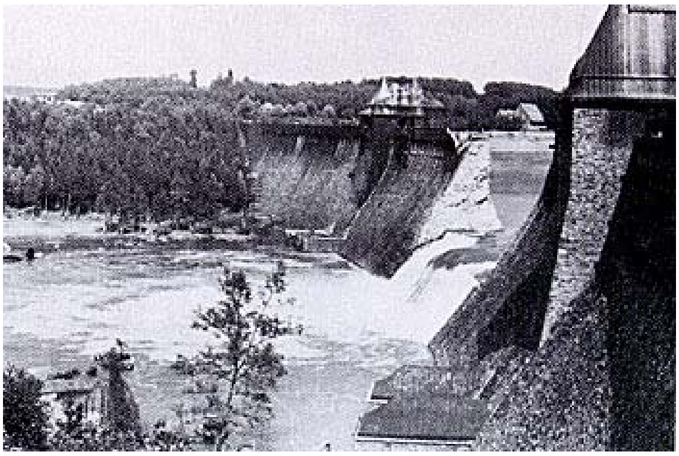

Fig. 4-2 : Former military ships on 12 September 1996 at Vozrozhdenie Island, Big Aral Sea (Courtesy of TETHYS-JRAK expedition, photograph by Roman Jashenko)

Recently some attention was focused on river management of large water systems : e.g., the Mekong river and the discord between China, Thailand, Laos, Cambodia and Vietnam. However lesser known water conflicts are likely to generate armed conflicts. The scope of the relevant issues is broad and complex, and includes water pollution, water supply, flooding, drought. An example is the disaster of the Aral Sea (e.g. WALTHAM and SHOLJI 2001). Since 1987, the Aral Sea is divided by a permanently-dry isthmus between the northern small Aral Sea and the southern big Aral Sea. Figure 4-2 illustrates grounded freighters as the result of the sea shrinkage ([7]).

[7]The Vozrozhdenie Island, in the west part of the big Aral Sea, is a huge dump of chemical weapons from the former Soviet Union. Today it is almost connected to the mainland.

5. Conclusion

Water plays a major role on our Planet because it is an indispensable element. The technical challenges associated with water engineering are formidable. Sustained teaching and research efforts are essential. Hydraulic engineers were at the forefront of science for centuries. Famous examples include the qanats and the Grand canal in China. The end of the 20th century marked however a change perception of hydraulic engineering with a shift in focus toward environmental issues, sustainability and management. Such trends, led by government institutions, industries and university administrations, have placed more focus on political issues at the expenses of quality expertise and engineering innovation.

Further advances in hydraulic engineering are a basic necessity to provide Humanity with water during this 21st century. The writer has shown innovative developments in hydraulic engineering of basic structures (culverts) which must be associated with active research and dynamic teaching. The writer believes that hydraulic engineers and academics must be pro-active and dynamic to develop further scholarship and quality expertise as a part of a long-term strategy. It is the writer's belief that the development of our planet cannot succeed without further Research and Higher Education initiatives (incl. funding) in Hydraulic Engineering.

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7. References

APELT, C.J. (1983). "Hydraulics of Minimum Energy Culverts and Bridge Waterways." *Australian Civil Engrg Trans.*, I.E.Aust., Vol. CE25, No. 2, pp. 89-95.

APELT, C.J. (1994). "The Minimum Energy Loss Culvert." Videocassette VHS colour, Dept. of Civil Eng., University of Queensland, Australia, 18 minutes.

BALLANCE, M.H. (1951). "The Roman Bridges of the Via Flaminia." *Papers of the British School at Rome*, Vol. 19, pp. 78-117 & plates xiv to xix.

BURDY, J. (1993). "Préinventaire des Monuments et Richesses Artistiques. III L'Aqueduc Romain de la Brévenne." *Bosc Frères Publ.*, Lyon, France, 230 pages & 1 Map (in French).

California Division of Highways (1956). "California culvert practice : reprint of a series of technical abstracts from California highways and public works." *Division of Highways*, Dept. of Public Works, State of California, 2nd edition, 119 pages & 1 map.

CHANSON, H. (1999). "The Hydraulics of Open Channel Flows : An Introduction." *Butterworth-Heinemann*, Oxford, UK, 512 pages.

CHANSON, H. (2000). "Introducing Originality and Innovation in Engineering Teaching: the Hydraulic Design of Culverts." *European Journal of Engineering Education*, Vol. 25, No. 4, pp. 377-391.

CHANSON, H. (2001). "Teaching Hydraulic Design in an Australian Undergraduate Civil Engineering Curriculum." *Jl of Hyd. Engrg.*, ASCE, Vol. 127, No. 12, pp. 1002-1008.

CHANSON, H. (2002). "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. (2003). "Hydraulic Engineering into the 21st Century: the Rediscovery of the Wheel ? (2) New Challenges." *Proc. 6th Intl Conf. on Civil Eng.*, Isfahan, Iran, May 5-7, Keynote lecture, 2nd part, 12 pages.

COTTMAN, N.H., and McKAY, G.R. (1990). "Bridges and Culverts Reduced in Size and Cost by Use of Critical Flow Conditions." *Proc. Instn. Civ. Engrs.*, London, Part 1, Vol. 88, pp. 421-437. Discussion : 1992, Vol. 90, pp. 643-645.

EVANS, A.H. (1928). "The Palace of Minos : a comparative account of the successive stages of the early Cretan civilization as illustrated by the discoveries at Knossos." *Macmillan*, London, UK, Vol. II, Part 1, 390 pages & 19 plates.

FABRE, G., FICHES, J.L., LEVEAU, P., and PAILLET, J.L. (1992). "The Pont du Gard. Water and the Roman Town." *Presses du CNRS*, Caisse Nationale des Monuments Historiques et des Sites, Collection Patrimoine au Présent, Paris, France, 127 pages.

FABRE, G., FICHES, J.L., and PAILLET, J.L. (2000). "L'Aqueduc de Nîmes et le Pont du Gard. Archéologie, Géosystème, Histoire." *CNRS Editions*, CRA Monographies Hors Série, Paris, France, 483 pages & 16 plates (in French).

Federal Highway Administration (1985). "Hydraulic design of Highway Culverts." *Hydraulic Design Series No. 5*, Report No. FHWA-IP-85-15, US Federal Highway Admin., 253 pages.

GREWE, K. (1986). "Atlas der Römischen Wasserleitungen nach Köln." ('Atlas of the Roman Hydraulic Works near Köln.') *Rheinland Verlag*, Köln, Germany, 289 pages (in German).

HAMILL, L. (1999). "Bridge Hydraulics." *E&FN Spon*, London, UK, 367 pages.

LIGGETT, J.A., and ETTEMA, R. (2001). "Civil-engineering education: Alternative paths." *Jl of Hyd. Engrg.*, ASCE, Vol. 127, No. 12, pp. 1041-1051.

LOVELESS, J.H. (1984). "A Comparison of the Performance of Standard and Novel Culvert Designs including the Effects of Sedimentation." *Proc. 1st Intl Conf. Hydraulic Design in Water Resources Engineering: Channels and Channel Control Structures*, K.V.H. SMITH Ed., Southampton, UK, Springer Verlag Publ., Vol. 1, pp. 183-193.

LOWE, S.A. (1970). "Comparison of Energy Culverts to Standard Three Cell Box Culverts." Masters thesis, University of Manitoba, Canada.

McKAY, G.R. (1970). "Pavement Drainage." *Proc. 5th Aust. Road Res. Board Conf.*, Vol. 5, Part 4, pp. 305-326.

McKAY, G.R. (1971). "Design of Minimum Energy Culverts." *Research Report*, Dept of Civil Eng., Univ. of Queensland, Brisbane, Australia, 29 pages & 7 plates.

NEILL, C.R. (1962). "Hydraulic Tests on Pipe Culverts." *Alberta Highway Research Report 62.1*, Research Council of Alberta, Edmonton, 52 pages.

O'CONNOR, C. (1993). "Roman Bridges." *Cambridge University Press*, UK, 235 pages.

ODGAARD, A.J. (2001). "Trends and Current Developments in Hydraulic Engineering." *Workshop on Integrated Water Resources Management*, National Chiao Tung University, Hsinchu, Taiwan, October 15-16, Keynote Lecture.

WALTHAM, T., and SHOLJI, I. (2001). "The Demise of the Aral Sea - An Environmental Disaster." *Geology Today*, Vol. 17, No. 6, pp. 218-224.

WEBSTER, D. (2002)."China's Unknown Gobu: Alashan." *National Geographic*, Vol. 201, No. 1, p. 48.