Trans. Newcomen Soc., **72** (2000–2001), 295–318

Historical Development of Stepped Cascades for the Dissipation of Hydraulic Energy

by

Hubert CHANSON ME, ENSHM, Grenoble, INSTN, PhD(Cant.), DEng(Qld)

INTRODUCTION

Recent advances in technology have permitted the construction of large dams, reservoirs and channels. These progresses have necessitated the development of new design and construction techniques, particularly with the provision of adequate flood release facilities and safe dissipation of the kinetic energy of the flow. The latter is usually achieved by a high velocity water jet taking off from a flip bucket (or from the dam crest) and impinging into a downstream plunge pool acting as a water cushion (e.g. Chastang Dam, France), a standard stilling basin downstream of the spillway where a hydraulic jump is created to dissipate a large amount of flow energy (e.g. U.S. Bureau of Reclamation designs), or the construction of steps on the spillway to assist in energy dissipation (e.g. Gold Creek dam, Australia).

The stepped cascade design is recognised for its energy dissipation and flow aeration performances. Some studies (e.g. SORENSEN 1985) suggested that the design of stepped channels as energy dissipators was a new technique developed with the recent introduction of new construction materials (e.g. RCC, strengthened gabions). This statement is simply untrue. The stepped cascade design has been used for more than 3,500 years, although an earlier study suggested that the oldest stepped spillway was built during the 7th century B.C. (CHANSON 1995a). In Antiquity, the stepped chute design was used for three purposes: stepped spillways, stepped waterways (storm waters, irrigation channels), and in town water supply systems (e.g. Roman aqueducts). There is a major difference between a spillway and a waterway. The former is characterised by a steep slope and high-velocity flows, and the kinetic energy of the flow must be dissipated to prevent damage or possible failure of the dam. The latter (the waterway) is usually a flatter channel with lower flow velocities and in which energy dissipation is required to prevent scour and erosion of the invert and of the banks. Irrigation channels, storm waterways and sediment control structures are encompassed in the definition.

The oldest stepped chutes were built in Greece and Crete. The expertise on stepped spillway design was spread around the Mediterranean area by the Romans, Muslims and Spaniards successively. Although the early stepped cascades were built in cut-stone masonry or timber, a wider range of construction materials was introduced during the 19th century. In the first half of the 20th century, the stepped cascade design became out of fashion, partly because of the maintenance costs. Nonetheless the long-lasting operation of several famous stepped cascades has demonstrated the soundness of the design as well as the expertise of the designers. Note that, during the 16th to 18th centuries, a number of 'Grandes Cascades' were built for aesthetic purposes. Their development is discussed elsewhere (CHANSON 1998).

This paper describes the history of stepped spillways, the use of stepped cascades in the Roman aqueducts. It will be shown that the technique of stepped channels was developed independently by several ancient civilisations.

HISTORICAL STEPPED CHUTE

Ancient stepped spillways

The world's oldest stepped spillway is presumably the overflow stepped weir in Akarnania, Greece, built around 1,300 B.C. (Fig. 1). The weir is an earthfill embankment, 10.5 m high with a 25 m long crest (KNAUSS 1995). The downstream slope is stepped (14 steps) with masonry rubble set in mortar. The mean slope is about 45 degrees, varying from 39° down to 73° and the step height ranges from 0.6 to 0.9-m (KNAUSS 1995). The dam is still standing (Fig. 1).

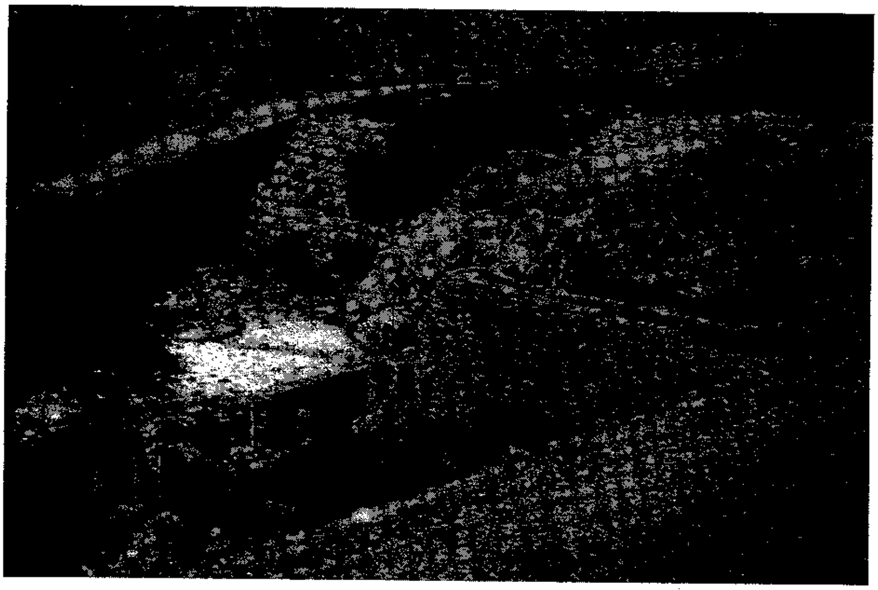


Fig. 1. Old stepped weir (dam) in Akarnania, Greece B.C. 1,3000 (Courtesy of Professor KNAUSS) Three-quarter view with watermill in foreground and new road ramp over the weir in background.

Other ancient stepped structures include two overflow stepped dams in Assyria (Table 1). The Romans built a number of stepped overflow dams in their empire. Remains are found still in Syria, Libya and Tunisia (Table 1). An impressive structure was the Kasserine Dam where the overflow spillway extended on the 150 m long crest. Smaller structures were Tareglat (Libya), Qasr Khubbaz (Syria) and Oued Gergour (Tunisia). Moslem civil engineers built dams with stepped overflow in Iraq—Adheim Dam, Iran—Khajou Bridge Weir, Saudi Arabia—Darwaish Dam, and Spain—Mestella Weir (e.g. Fig. 2). The Adheim Dam was a particularly modern design with a vertical upstream face and steep downstream slope (51°) similar to modern gravity dams. Although three sluices were included, the writer's opinion is that flood overflow over the downstream stepped face was likely. Spanish engineers used Roman and Moslem structures, but they also designed new weirs and dams with stepped spillways e.g. at Almansa, Alicante and Barrarueco de Abajo. Their dam expertise was introduced in the "New Indies" after the conquest of America. In Central Mexico several stepped overflow dams were built during the 18th and 19th centuries. Some were still in use at the beginning of the 20th century (e.g. GOMEZ-PEREZ 1942, Ministerio de Obras Públicas, Transportes y Medio Ambiante 1993, pp.256–257, CHANSON 1995b, p.27–28 and 31–33). An interesting example is the Pabellon Dam, also called San Blas Dam, in Aguascalientes (Mexico).[1] Built in stone masonry, its principal function was irrigation water supply and water power.[2] The reservoir is still in use today and GOMEZ-PEREZ (1942) showed the spillway in operation in the 1950s.

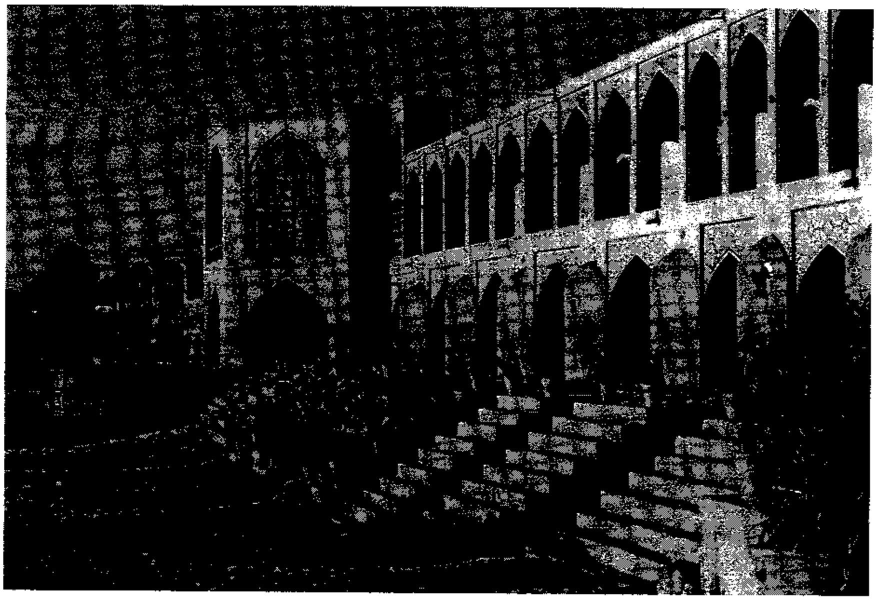


Fig. 2. Khajou Bridge-Weir, Isfahan (Iran, 1660): view of the downstream stepped chutes (Courtesy of Mr. A. R. YAZDANY)—Note low-flow channels, the stepped chutes being used only for large flood flows. The Khajou Bridge-Weir is also called Pul-i-Khadju, Khadjoo, Khwaju, Hasanabad or Khvaju.

At the end of the 18th century and early 19th century, a number of masonry dams were equipped with stepped spillways in France, England, Spain, Central America and USA. Timber and timber crib dams with stepped overflows were built in central Europe and Russia (Table 1). GORDIENKO (1994) reported a 12 m high rockfill dam with a timber crib overflow spillway built around 1700 A.D. in Russia (Fig. 3). The North-Eastern part of America benefited from the experience of Northern European settlers. During the period 1800–1920, timber dams were popular in America, Australia and New Zealand. Most timber dams were less than 10 m high but some much bigger ones were built successfully.

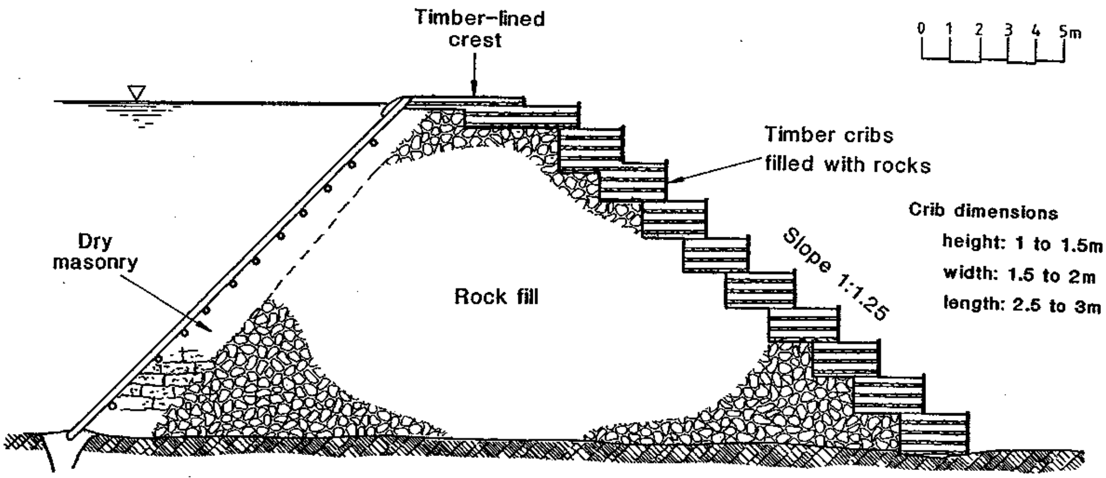


Fig. 3. Russian dam at the time of Peter the Great, around 1700, (after GORDIENKO 1944).

Ancient waterway systems

Drop structures and stepped chutes were used in early irrigation and storm waterway systems (Table 2). The oldest structure was probably a series of stepped culverts under a viaduct near Knossos in Crete (Fig. 4). The stepped culverts were designed to carry safely the floodwater down the right slope of the Vlychia valley beneath a road viaduct leading to the Knossos palace; the bridge was at least 10 m high and 5.5 m wide (EVANS 1928). Three stepped waterways were excavated although more possibly existed. The steps were made of "*squared ashlar masonry*" with hard clay mortar (EVANS 1928). It is believed that the viaduct and stepped culverts were built during the Minoan period around B.C. 1,500. They were contemporary to the Akarnania stepped weir in Greece.

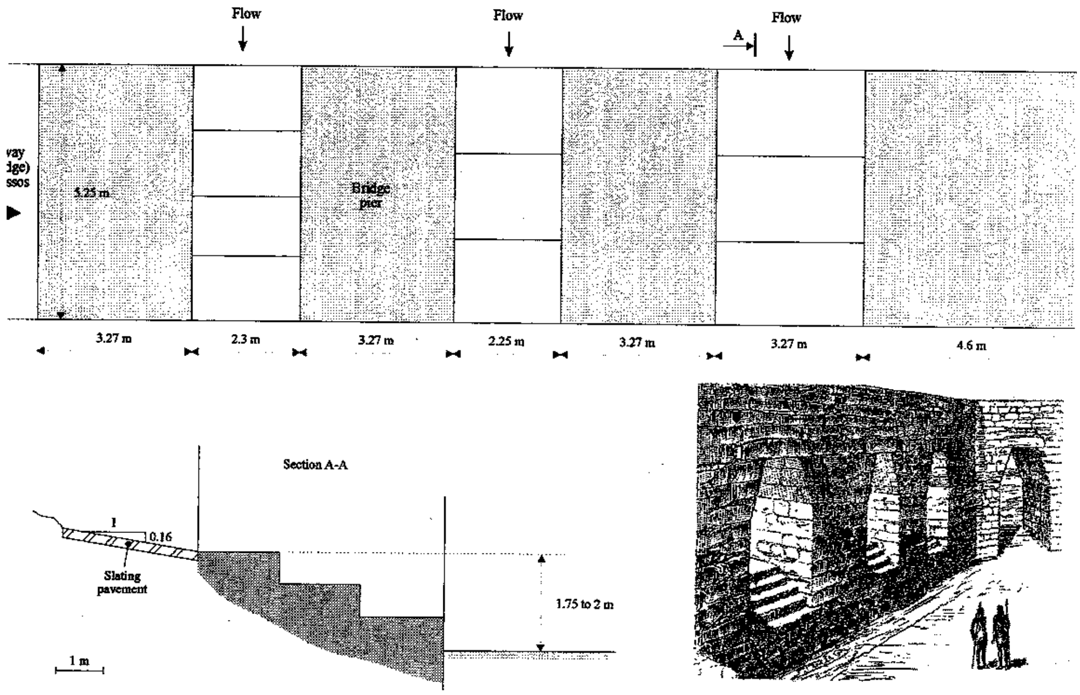


Fig. 4. Stepped culverts underneath the road to Knossos in the Vlychia valley (after EVANS 1928)
Insert: sketch by EVANS (1928)

In Baluchistan, check dams for sediment retention and cultivation of flood plains were built around 2,500 to 1,800 B.C.: i.e. the Garbabands (RAIKES 1964–65). One type of construction consisted of upstream and downstream stepped faces with an intermediate earth and rubble filling. Although not well-documented, this type of stepped weir might have influenced later dam construction in Iran.

Evidence of stepped canals were found in the Middle East and in the Americas (Table 2). One ingenious system was the Quishuarpata Canal, Peru. The canal included two 100 m long chutes designed with small steps (h = 1 to 3 cm) along the chute course, large steps near the downstream end and no stilling structures. These canals operated with supercritical flows on the steep chutes and hydraulic jumps at the downstream end of the canals. The design technique highlights the hydraulic expertise of ancient Peruvian engineers (pre-Inca and Inca). A related case is the ancient terrace irrigation systems. In terrace irrigation, the water falls from one terrace onto the next one and the flow energy must be dissipated at the end of each fall.

Stepped cascades in Roman aqueducts

The Roman aqueducts were long canals supplying townships in water for public heath purposes (public baths, latrines). They were designed with flat longitudinal slope (1 to 3 m/km in average) to operate as free-surface flows (e.g. HODGE 1992). Short sections however had a steep-gradient, up to 78% (CHANSON 2000a). Current knowledge and field observations suggest primarily three types of design; steep smooth-invert chutes, stepped channels and dropshaft cascades. The two latter designs are of interest (Fig. 5 and 6).

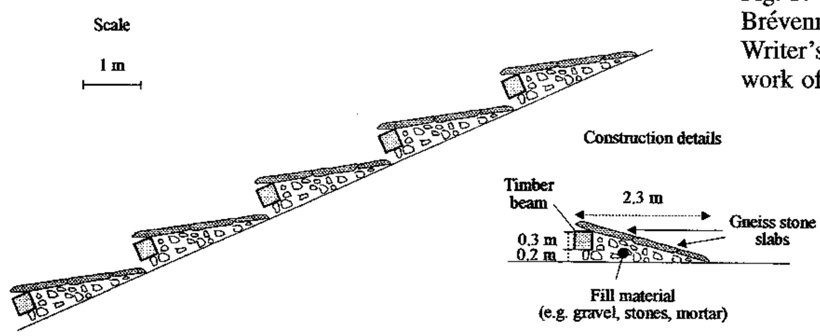
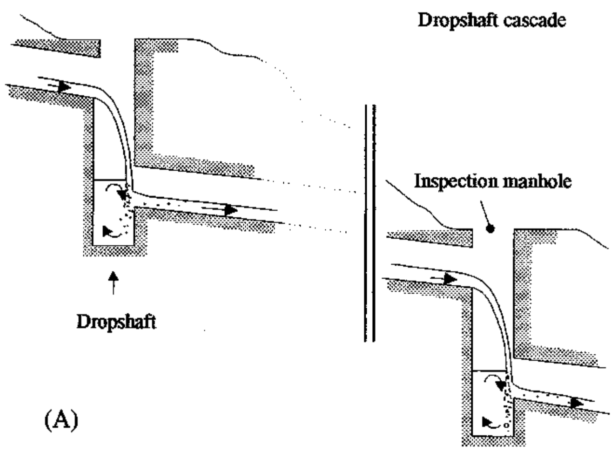
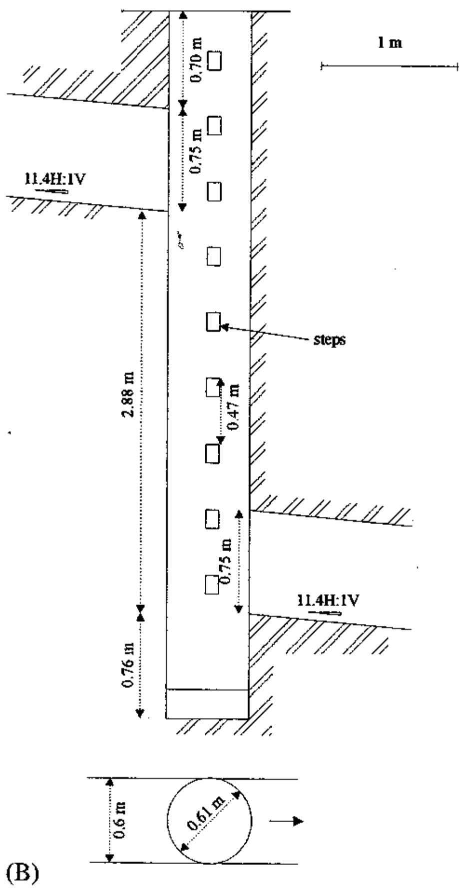


Fig. 5. The stepped chute at Chevinay, Brévenne Aqueduct (Lyon)
Writer's proposal based upon the work of P. LEVEAU et J. FAGE.

Fig. 6. Dropshaft cascades in Roman aqueducts
(A) General sketch (Valdepuentes, Cordoba, Spain)
(B) Cerro de los Pinos cascade, Valdepuentes Aqueduct (Cordoba)—Dropshaft No. 11.





Valdepuentes Aqueduct
(Aqua Vetus, Cordoba)
Pozzo resalto No. 11
upstream of Valdepuentes Bridge
Fuentes de la Teja-Madinat al Zahra

(B)

Stepped cascades

Roman engineers used both single drops and stepped cascades (Table 3). The Brévenne Aqueduct included a number of steep chutes (e.g. CHANSON 2000a). One chute was definitely a stepped design, at Chevinay (Fig. 5). The steps were made of rockfill covered by stone slabs. The step dimensions are similar to modern precast concrete block systems developed by the Russians (e.g. CHANSON 1995b, pp. 177–181). 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 (Fig. 5). 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. 1991, CHANSON 1995b).

What was the main purpose of the stepped cascade design? At 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 the watermill cascade at Barbegal in the South of France (Table 3). The available hydraulic power was large, about 30 to 50 kW. There, a component of the dissipated energy was transferred to the water wheels.

Dropshaft cascades

A dropshaft cascade is basically a subterranean chute; it consists of a series of dropshafts (Table 4, Fig. 6). The design of Roman dropshafts included an unusual feature, namely a deep wide shaft pool (CHANSON 2000a). The best documented dropshaft cascades are those of Brisecou (Montjeu), Recret (Yzeron), Cherchell and Valdepuentes.[3] 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.

A series of dropshafts or dropshaft cascades were built for large drops in invert elevation e.g. an overall drop of 200 m at Valdepuentes (Madinat-al-Zhara, Table 4). The design had had an excellent reliability record and some cascades were used for centuries.[4] It must be understood that the design was not obvious: a dropshaft cascade was a complex hydraulic structure that included the construction of numerous shafts and interconnection channels in difficult topographic conditions. Two types of dropshaft cascades were built, 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 (Fig. 6) where 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 90° angle between the inflow and outflow conduits. This type of design was unique (CHANSON 2001).

DISCUSSION

Dissemination of the stepped-chute expertise

From Antiquity up to the beginning of the 20th century, the Romans, Moslems and Spanish contributed successively to the dissemination of the art of dam-building. Their contribution in maintaining and developing the expertise in stepped channel design was most important. Dams with stepped overflow spillways were built very early in the Mediterranean area (Table 1). The construction technique spread around the Mediterranean Sea in Roman times (CHANSON 1995a). During their expansion period, the Moslems learned from the Sabaens, Nabataeans and Romans. They brought their water traditions to the Hispanic peninsula. After the reconquest of Spain, the Catholic Spanish used a number of Roman and Moslem structures, and they developed their own expertise. Later they deliberately transferred their technology into the Americas. Most European countries and European settlements in America benefited from the Spanish expertise in dam and stepped spillway design. Clear evidence of the Spanish influence were found certainly in France, Mexico and United States.

With most ancient stepped waterway systems (Table 2), it is believed that the hydraulic expertise was developed locally. In Yemen and Israel, the inhabitants benefited from some local 'savoir-faire', the Sabaen and Nabataean expertise respectively. In Peru, the Indians civilisations used stepped channels and drop structures prior to the Spanish conquest e.g. the Chimus and Incas. Note the different evolution processes i.e. a dissemination of design expertise for spillways and cascades versus local evolution for irrigation structures. The experience of Roman dropshaft cascades was unique (Table 4). The design technique was forgotten and the expertise was lost until recently.

Construction methods

Although the early stepped cascades were built in cut-stone masonry or timber, a wider range of construction materials was introduced during the 19th century. It included composite materials (e.g. Malmsbury 1870) and non-reinforced concrete e.g. Gold Creek 1890 (Table 1). During the 19th century, the overflow stepped spillway design was frequently selected with nearly one third of the dams built in USA being equipped with a stepped cascade (e.g SCHUYLER 1909, WEGMANN 1922). The development was marked by two milestones; the Gold Creek Dam cascade (1890, Australia) and the New Croton Dam (1906, USA). Completed in 1885, the Gold Creek Dam was initially equipped with an unlined cascade spillway. After heavy scour during flood spills, a concrete stepped cascade ($h = 1.5$ m, $l = 4$ m) was built in 1890 (Fig. 7). It is believed that the Gold Creek cascade was the world's first concrete stepped spillway and the ancestor of modern RCC stepped spillways (CHANSON and WHITMORE 1998). Completed in 1906, the New Croton dam spillway is probably the first stepped chute designed specifically to maximise energy dissipation (WEGMANN 1907). It is still in use despite a major accident in 1955 (MARSCH 1957, CHANSON 1995b).

Design concepts

Since Antiquity, the design of stepped chutes was recognised to reduce flow velocities. During the Renaissance period, Spanish and Italian hydraulic engineers (e.g. Juanelo TURRIANO, LEONARDO DA VINCI) developed these principles to stepped weirs. LEONARDO DA VINCI expressed the basic ideas: the flow, "*the more rapid it is, the more it wears away its channel*"; if a waterfall "*is made in deep and wide steps, after the manner of stairs, the waters (...) can no longer descend with a blow of too great a force*". He illustrated his conclusion with a staircase waterfall (Table 2) "*down which the water falls so as not to wear away anything*" (RICHTER

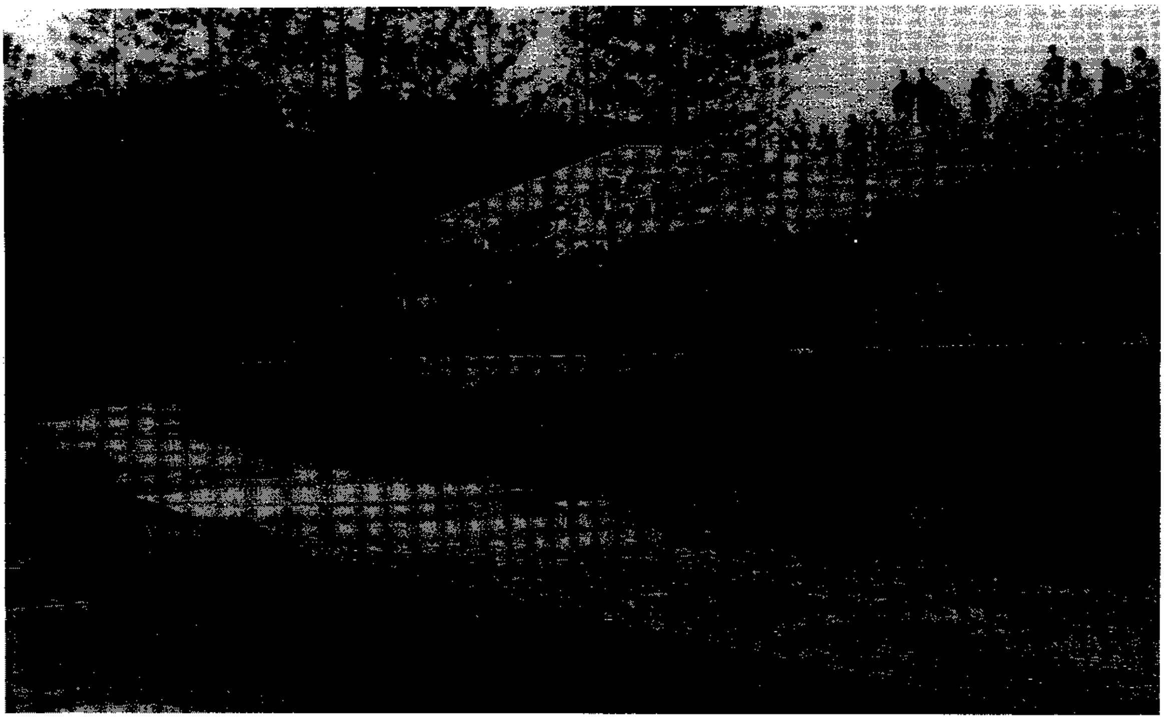


Fig. 7. Gold Creek Dam spillway, Brisbane, Australia, 1890
The world's first concrete stepped spillway during a field trip in August 1998.

1939). TURRIANO was involved in the design of the Alicante dam that included a stepped spillway equipped with 7 steps (SMITH 1971, SCHNITTER 1994). The codex attributed (falsely or not) to Juanelo TURRIANO included some sketches of stepped overflow weirs and of an architectural weir similar to the modern Pulteney weir in Bath,[5] (e.g. GARCIA-DIEGO 1976). The stepped spillway design was well known during the 19th century. In his textbook, HUMBER stated : "*The byewash,[6] will generally have to be made with a very steep mean gradient, and to avoid the excessive scour which could result if an uniform,[7] channel were constructed, it is in most cases advisable to carry the byewash down by a series of steps, by which the velocity will be reduced. This is very well illustrated in the case of the Rotherham Works*" (HUMBER 1876, p. 133). For the Malmsbury dam cascade, SANKEY (1871) recommended a wide spillway crest followed by a reduction in channel width associated with the introduction of a series of steps. Downstream of the channel contraction, "*the floor dropped by a series of steps for 60 feet and apron beyond* [...] *so constructed* [...] *as to ensure the velocity of the current being arrested and the quiet discharge of the flood into the Coliban*" river (SANKEY 1871, p.28).

For a given chute geometry (width, step height, step length), small flows behave as a succession of free-falling jets and nappe impact (i.e. nappe flow regime) while larger flows skim over the pseudo-bottom formed by the step edges i.e. skimming flow regime (e.g. CHANSON 1995b). There are fundamental differences between the hydraulics of nappe and skimming flows, and a good observer, like LEONARDO DA VINCI, can easily distinguish between the two regimes. It seems likely that some ancient engineers recognised the basic flow patterns (e.g. nappe or skimming flow). There is however no evidence of hydraulic design guidelines (e.g. flow resistance, head loss) even at the beginning of the 20th century. It is only very recently that new progress on the hydraulics of stepped channels has been achieved. This is possibly a reason why the interest for stepped cascades dropped during the first part of the 20th century : "*cascades were formerly used a great deal.* [... but they] *have seldom lived up to their expectations, and have seldom justified their high cost.* [...] *Considerably cheaper means of dissipating energy are known today*" (SCHOKLITSCH 1937, p. 913). New progress in the energy dissipation characteristics of hydraulic jumps favoured the design of hydraulic jump stilling basins downstream of the spillway chutes (e.g. BAKHMETEFF and MATZKE 1936). Stilling basins allowed larger energy dissipation and smaller structures. Altogether the concept of downstream stilling basins contributed to cheaper construction costs.

Modern applications

In the 1970s, design engineers regained interest for stepped spillways (Fig. 8). The trend was initiated by the introduction of new construction materials e.g. roller compacted concrete (RCC) and gabions with polymer coated wire. Over the past two decades, several dams have been built with overflow stepped spillway world-wide e.g. CHANSON 1995b (Fig. 8A). New design techniques were also introduced e.g. embankment overtopping protection with pre-cast concrete blocks and cast-in-situ concrete (Fig. 8B).

A major issue associated with the design of modern stepped spillways has been the ignorance of past experience and local expertise (CHANSON 1995b, 2000b). By the 1970s, most expertise in stepped spillway design was lost. Well-known hydraulic textbooks did not even mention the stepped chute design (e.g. CHOW 1959, US Department of the Interior 1965, HENDERSON 1966). Leading professionals ignored local experience. For example, the late Professor SORENSEN (1985) forgot the North-American stepped spillways, like the New Croton Dam near Cornell University in New York. In the UK, ESSERY and HORNER (1978) were unaware of the Cantref and Beacons dam spillways. Many stepped spillway structures have been used successfully for more than a century e.g. the Khaju Bridge Weir (Iran, 1650), the Pabellon Dam (Mexico, 1730), the Pas-du-Riot Dam (France 1873), the Gold Creek Dam (Australia, 1890), the Cantref Dam (Wales 1892), and the Llwyn-on Dam (Wales 1926) all of which are still in use. The long-lasting operation of numerous stepped cascades demonstrate the soundness of the design as well as the expertise of their designers.

Today most engineers, young and senior, have never been exposed to the complexity of the stepped spillway design because the design expertise was lost until recently.[8] As a result, possibly, contemporary stepped spillways are designed for a maximum discharge per unit width no greater than ancient designs (Fig. 9). It is worth mentioning several 19th-century dams with stepped spillways which were recently refurbished e.g. Gold Creek, La Tâche, Pas-du-Riot, and Ternay dams (CHANSON and WHITMORE 1998). In each case, the spillway intake was modified to increase the maximum discharge capacity, but the stepped chute remained unchanged, suggesting a strong confidence in the ancient stepped channel designs.

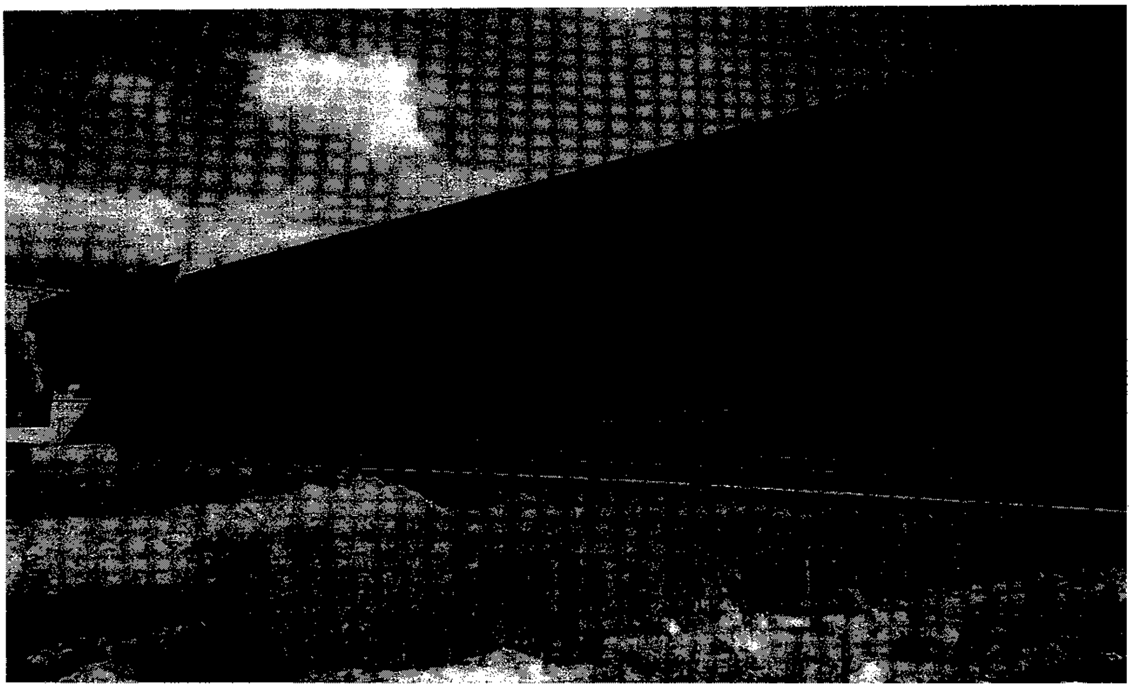


Fig. 8A. Modern applications of stepped spillways
Riou Dam, France 1990; a roller compacted concrete dam with stepped spillways
(Photographed in June 1998)

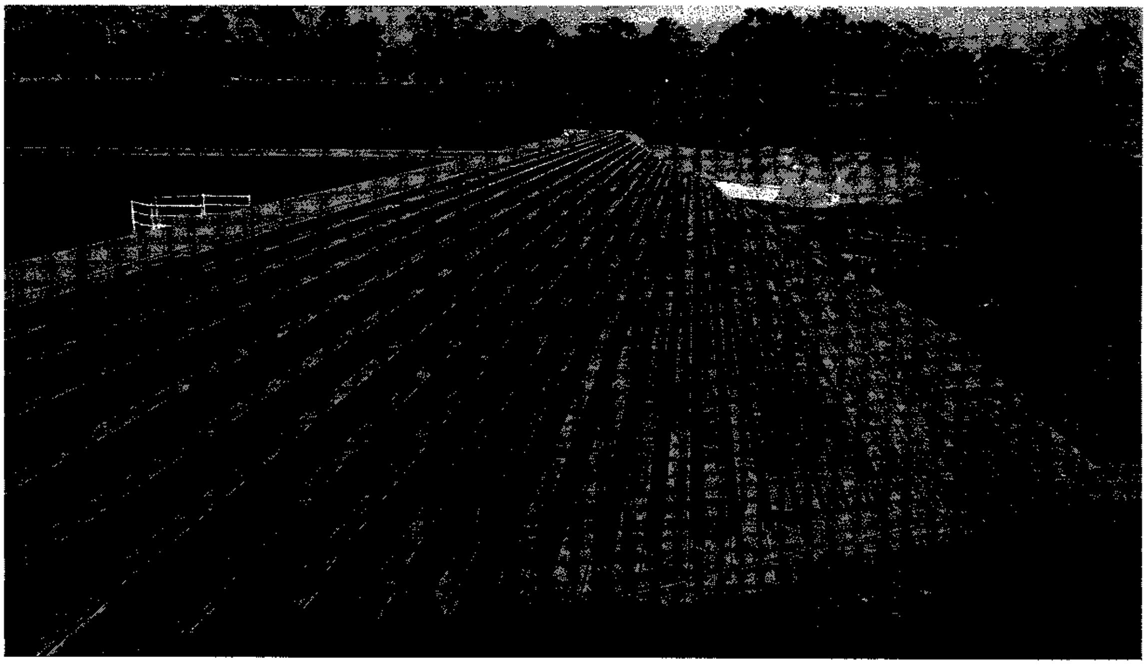


Fig. 8B. Melton Dam, Australia 1916: concrete overtopping protection built in 1987
(Photographed in June 2000)

SUMMARY AND CONCLUSION

Stepped weirs and channels have been used for more than 3,500 years, since the early structures in Greece and Crete. In Antiquity, the stepped chute design was used for dam spillways, waterways, and in town water supply channels. Most early structures were built in the Mediterranean area. Despite recent advances in technology, the design characteristics of stepped spillways show some continuity from Antiquity up to now. Notwithstanding the recent revival of interest in stepped spillways, the concept of the stepped chute is not a new technique but simply an evolution of design. The successful operation of a number of stepped chutes for decades and even centuries has demonstrated the soundness of the design. The experience of the stepped chute design is an illustration a loss of hydraulic expertise by professional engineers during the 20th century. It is hoped that a lesson will be learned and that the profession will not re-invent the wheel every sixty years.

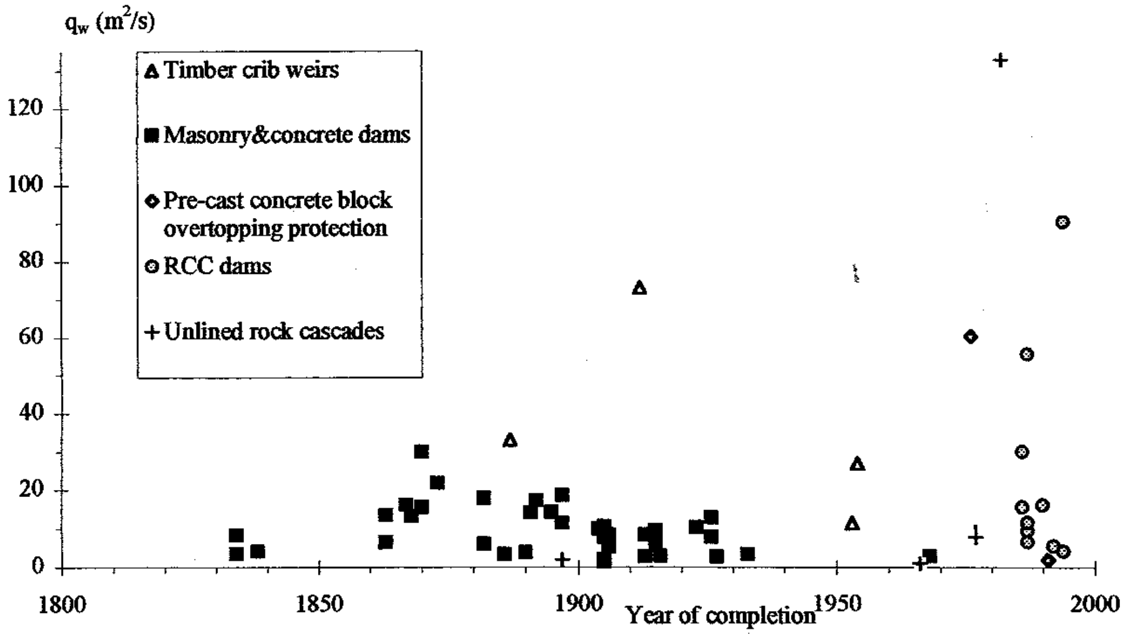


Fig. 9. Maximum discharge capacity of stepped spillways (Period 1800–2000).

TABLE 1

Some historical stepped spillways

Name (1)	Year (2)	Ref. (3)	Dam height (m) (4)	Chute slope α (deg.) (5)	Construction (6)	Comments (7)
Akarnania weir, Greece	B.C. 1300	[KN, MU]	10.5	39 to 73	Earthfill overflow weir with downstream stepped face : rubble masonry set in mortar.	Water supply. Equipped with a water mill. Used by the Byzantines. h = 0.6 to 0.9 m.
River Khosr dams, Iraq	B.C. 694	[SM, FO, TH]	2.9		Masonry of limestone, sand-stone mortared together.	Built by the Assyrian King SENNACHERIB to supply water to his capital city Nineveh. Discharge over the dam crest. Lower dam. Also called Ajilah dams.
			> 1.4	30		Upper dam. 5 steps.
Kasserine Dam, Tunisia	A.D. 100?	[SAL, SM]	10	57	Cut and fitted masonry blocks with mortared joints used to face a rubble and earth core.	Roman dam 220 km SW of Tunis, Tunisia. 4.9 m broad crest, followed by 6 steps and a final drop. Discharge over the dam crest. W = 150 m.
Oued Guergour Dam, Tunisia	A.D. 100?	[SAL]	3.6		Rubble masonry dam.	Roman dam between Kasserine and Haïdra. 3 steps (h = 0.55 to 2 m).
Qasr Khubbaz, Syria	A.D. 100/200	[SM, ST]	6.1		Masonry dam with limestone slabs.	Roman dam on the Euphrates river. Reservoir capacity : 9,000 m^3 of water.
Darwaish Dam, Saudi Arabia	A.D. 700?	[FA]	10	71	Both outer walls made of dry masonry with earth or rubble core in between.	Moslem dam near Taif. 5 steps (h ~ 1.6 m).
Tha'laba Dam, Saudi Arabia	A.D. 700?	[FA]	9	80	Both outer walls made of dry masonry with earth or rubble core in between.	Moslem dam near Taif. Horizontal crest (7.3 m long) followed by 5 flat steps (h ~ 1.8 m).
Robella Dam, Spain	A.D. 900?	[SC]	3.5		Rubble masonry. Shaped crest followed by 5 steps.	Moslem stepped weir. 5 steps (h = 0.37 to 0.7 m).
Mestella Dam, Spain	A.D. 960	[SM]	2.1	27	Rubble masonry and mortar core faced with large masonry blocks and mortared joints.	Stepped weir built by the Moslems. Maximum dis-charge : around 4,000 m^3/s (?). W = 73 m. 5 steps (h = 0.35 and 1 m).

Name (1)	Year (2)	Ref. (3)	Dam height (m) (4)	Chute slope α (deg.) (5)	Construction (6)	Comments (7)
Khan Dam, Uzbekistan	1000?	[SC]	15.2	81	Gravity dam. Granite ashlar masonry.	Moslem dam (Ghaznavid dynasty) 100 km North of Samarkand. 2.3 m wide crest followed by 7 steps (h = 1.5 to 3.3 m).
Adheim Dam, Iraq	1300?	[SM]	15.2	51	Gravity dam. Cut masonry blocks connected with lead dowels poured into grooves.	Built by the Moslems during the Sassanian period. 7.5 m wide crest followed by steps.
Almansa Dam, Spain	1384?	[SM, WE]	15	40	Curved gravity dam. Rubble masonry with a facing of large masonry blocks.	Discharge over the dam crest. Broad crest followed by 14 steps and an overfall.
Torogh Dam, Iran	1450?	[HA]	20		Gravity dam. Masonry.	Mongolian dam near Mashhad. Stepped rocklined spillway.
Ashburnham Furnace Dam, UK	1563?	[BI]	7		Earth dam with gated masonry spillway. Stones with brick and brickwork repairs.	W = 3.7 m. 3 steps (h ~ 1.5 m).
Kobila Dam, Slovenia	1586	[BR]	10		Timber cribs filled with rocks. Destruction in 1948.	Overflow spillway. Crest length : 20 m.
Alicante Dam, Spain	1594	[SM]	41	79	Curved gravity dam. Rubble masonry set in mortar, faced with masonry blocks.	Overflow spillway (W = 80 m). 7 steps : h = 2.7 to 5 m, l = 0.6 to 0.9 m. Also called Tibi dam.
Fariman Dam, Iran	1600?	[FA]	21		Gravity dam with a central buttress. Masonry.	Safavid dynasty. 2 steps (h ~ 6.5 & 14.7 m. Dam heightening in 1930s by 1.5 m.
Khajou Bridge-Weir, Iran	1660?		3		Masonry bridge-weir equipped with low-flow deep channels and stepped overflows.	Built by Shah Abbas II. 132 m long weir. 10 steps. Still in use today.
St Ferréol Dam, France	1671	[RO]	32		Waterfalls, cascades, cataracts.	Earth dam with masonry spill weir followed by stepped cascades. Water supply for the Canal du Midi.
Russian Dam	1700?	[GO]	12	39	Rockfill dam with timber crib spillway.	Flat crest (3.9 m) followed by 2 first small steps (h = 0.3 & 0.76 m) and 9 steps (h ~ 1.3 m). Design discharge : 0.53 m^3/s.

Name (1)	Year (2)	Ref. (3)	Dam height (m) (4)	Chute slope α (deg.) (5)	Construction (6)	Comments (7)
Kamenskii Dam, Russia	1730?	[DA]			Timber crib dam filled with clay.	Designed by G.W. HENNIN. Overflow spillway (W = 23.5 m) with 5 steps. Design discharge ~ 5.2 m^2/s.
Pabellon Dam, Mexico	1730?	[GP, HI, SM]	24		Buttress dam. Rubble masonry set in mortar.	Spanish construction. Discharge over the crest. 3 steps. Still in use today. Also called San Blas dam.
Presa de los Arcos, Mexico	1780?	[HI, SM]	18		Buttress dam. Rubble masonry set in mortar.	Spanish dam across the Rio Morcinique. Overflow spillway. 4 steps.
Penarth Weir, UK	1818	[BI]	2.4		Masonry crest. Horizontal steps with sloping faces.	Stepped weir on the river Severn below Newtown. 2 steps (h ~ 1.2 m). W = 42.5 m.
Ascutney Mill dam, USA	1834–35	[BA]	12.8		Arched gravity dam made of cut granite with rubble filled core. Downstream stepped buttressing wall.	Overflow stepped spillway (W = 30.48 m) across the Connecticut river. Smooth concrete crest followed by stone stepped profile. Water supply to watermills and later hydropower (1898). Still in use today
Dale Dyke Dam, UK	1863	[HU]	29		Earth dam (failure in 1864).	Lateral spillway (W = 7.3 down to 3.5 m). Maximum discharge : 47 m^3/s. 5 steps (h = 0.4 to 0.74 m) followed smooth channel.
Bilberry Dam, UK	1867	[BIB]	16.1		Earth dam with puddle clay corewall (1854–1856?). Lateral overflow spillway with stepped channel.	Maximum discharge : 49 m^3/s. Lateral stepped channel (W = 3.048 m). Reservoir still in use today.
Ternay Dam, France	1867		41		Curved gravity dam in masonry. Unlined rock spillway.	30 steps (h ~ 0.3 to 0.8 m). Refurbishment of spillway intake in 1990s. Still in use today.
Malmsbury Reservoir, Australia	1870		24		Earth embankment with masonry spillways at each end.	Right bank spillway : masonry chute with a series of 8 steps (W ~ 20 m). Still in use today.

Name (1)	Year (2)	Ref. (3)	Dam height (m) (4)	Chute slope α (deg.) (5)	Construction (6)	Comments (7)
Pas-du-Riot Dam, France	1873		36		Curved gravity dam made of Cyclopean masonry. Masonry spillway.	Maximum discharge : 65 m^3/s. Lateral spillway : 7 steps (h ~ 2.5 to 3 m). Trapezoidal section (base width ~ 3 m). Nappe flow regime. Still in use today.
Upper Barden Reservoir, UK	1882	[BIA]	42		Earth embankment with masonry spillways at each end.	Maximum discharge : 43 m^3/s. Flat steps at upstream end.
Le Pont Dam, France	1882		27		Curved gravity dam (granite rubble masonry) with 7 buttresses. Pooled masonry steps with rounded crest.	Design by H. BAZIN. Maximum discharge capacity : 195 m^3/s (Maximum flood : 139 m^3/s in 1910). Steps : h = 2.8 to 6.97 m, 13-deg. mean slope. W = 29.5 m down to 10 m. Pool bed in unlined rock.
Bridgeport Dam, USA	1886	[SH, WE]	13		Gravity dam made of rubble masonry laid in mortar. Downstream stepped face. Upstream earth embankment built afterwards to reduce dam leakage.	Overflow spillway (W = 24.8 m, h = 0.29 to 0.95 m). Maximum discharge capacity : 78 m^3/s.
Tytam Dam (or Tai Tam Dam), Hong Kong	1887	[SH]	29	65	Gravity dam (40% stone, 60% concrete). Downstream stepped face covered by ashlar blocks.	Broad crest (6.4 m) followed by 9 steps (h = 3.05 m).
Gold Creek Dam, Australia	1890		26	21	Earthfill dam with puddle clay corewall (1885). Concrete stepped spillway (1890) over eroded unlined rock spillway.	Broad-crest (W = 55 m) followed by 12 steps (h = 1.5 m, l = 4 m). Maximum spillway capacity : 200 m^3/s. Crest level lowered by 1.2 m in 1975 and by another 0.4 m in 1998. Still in use today.
Cantref Dam, Wales UK	1892		23.8	20 to 34	Earth dam with puddle clay corewall. Masonry stepped spillway.	Maximum discharge capacity : 157 m^3/s. h = 0.3048 m. W = 9.14 m. Still in use today. Increase of spillway capacity in the 1980s by addition of two siphon spillways and a reinforced earth spillway.
Titicus Dam, USA	1895	[WE]	41	~ 63	Earth dam with masonry overflow spillway (masonry of rubble with cut stone laid in regular courses).	Maximum spillway capacity : 472 m^3/s. W = 61 m. 13 steps (h = 0.61 to 3.7 m).

Name (1)	Year (2)	Ref. (3)	Dam height (m) (4)	Chute slope α (deg.) (5)	Construction (6)	Comments (7)
Beacons Dam, UK	1897		16.5		Earth dam with puddle clay corewall. Masonry stepped spillway.	Maximum discharge capacity : 113 m^3/s. h = 0.3048 m. W = 9.14 m. Replaced by a smooth chute in the 1980s.
Upper Coliban Reservoir, Australia	1903		30		Earth dam with lateral spillway.	Spillway chute includes a drop (6.7 m) and 2 series of steps (h = 1.2 m, W ~ 32 m). Refurbishment of spillway intake in 1993. Still in use.
Urft Dam, Germany	1905	[KE, SH]	58		Curved gravity dam (slate masonry) with upstream earth embankment.	Maximum discharge : 200 m^3/s. W = 100 m. Steps cut in natural rock covered by concrete (h = 1.52 m).
New Croton Dam, USA	1906	[W7]	90.5	53	Masonry gravity dam. Spillway built in block stone masonry. Spillway damage in 1955.	Maximum discharge : 1,550 m^3/s. W = 305 m. h = 2.13 m. Still in use today.
Croton Falls Dam, USA	1911	[WE]	52.7		Cyclopean masonry dam with reinforced concrete block facing. Horizontal steps made of granite.	Overflow weir : W = 213 m. 12 steps with rounded step edges : h = 0.61 m, l = 0.305 to 0.91 m.
Klingenberg Dam, Germany	1913?	[ENG]	13.25		Curved gravity dam.	Maximum discharge : 100 m^3/s. W = 37.4 down to 12 m. 12 steps (h = 0.6 to 2.2 m).
Lahontan Dam, USA	1915	[RH, DG]	49	22.9 (right) 26.6 (left)		Maximum discharge : 850 m^3/s. Spillway refurbishment in 1940. Two stepped spillways (h = 3.05 & 3.35 m).
Hetch-Hetchy Dam, USA	1923	[KE]	69.4 ([a])	57 ([a])	Gravity dam (granite masonry). Dam heightening in 1937–38.	Now called O'Shaughnessy dam. Uncontrolled siphon-spillway followed by stepped chute ([b]). Maximum spillway discharge : 566 m^3/s. W = 55 m. h = 2 m.
Llwyn-on Dam, UK	1926		22.1		Earth dam with puddle clay corewall. Masonry stepped spillway.	Maximum discharge capacity : 235 m^3/s. h = 0.3048 m. W = 18.29 m. Still in use today.
Mühleberg Weir, Austria	1930?	[SCH]	20		2 flat steps followed by baffle blocks.	Step heights : h = 8.16 and 8.9 m.

Name (1)	Year (2)	Ref. (3)	Dam height (m) (4)	Chute slope α (deg.) (5)	Construction (6)	Comments (7)
Ryburn Dam, UK	1933	[WO]	26.9	60	Concrete overflow dam with d/s stepped face (concrete steps).	Maximum discharge : ~ 120 m^3/s. Steps : h = 1.86 m, l = 1.07 m.. W = 36.6 m.

Notes : h : step height; l : step length; W : chute width; ([a]) : original dam; ([b]) : stepped geometry selected to improve the new concrete bond during the dam heightening.

References : [BA] BATTISON (1975); [BI] BINNIE (1987); [BIA] BINNIE (1913); [BIB] BINNIE (1981); [BR] BREZNIK (1984); [DA] DANILEVSLKII (1940); [DG] DOUMA and GOODPASTURE (1940); [ENG] ENGELS (1914); [FA] : FAHLBUSCH (1987); [FO] FORBES (1955); [GO] : GORDIENKO (1944); [GP] GOMEZ-PEREZ (1942); [HA] : HARTUNG and KUROS (1987); [HI] HINDS (1932,1953); [HU] HUMBER (1876); [KE] KELEN (1933); [KN] KNAUSS (1995); [MU] MURRAY (1984); [RO] ROLT (1973); [RH] RHONE (1990); [SAL] SALADIN (1886); [SC] SCHNITTER (1994); [SCH] SCHOKLITSCH (1937); [SH] SCHUYLER (1909); [SM] SMITH (1971); [ST] STEIN (1940); [TH] THOMPSON and HUTCHINSON (1929); [W7] WEGMANN (1907); [WE] WEGMANN (1911); [WO] WOOD (1933).

TABLE 2

Ancient waterway systems with stepped cascades

Name (1)	Year (2)	Ref. (3)	Disch q_w (m^2/s) (4)	Slope α (deg.) (5)	Construction and hydraulic design (6)	Comments (7)
Knossos, Crete	B.C. 1,500 (?)	[EV]		11	Stepped culverts. Ashlar masonry with clay mortar. 3 steps (h = 0.67 m). 4 steps (h = 0.5 m).	Storm waterway under road viaduct to palace. ΔH = 1.75 to 2 m. W = 2.25 to 3.1 m.
Wadi Beihan valley, Yemen	B.C. 1000 to	[LE]				Himyarit irrigation system in Qataban.
Hajar Bin Humeid	A.D. 200		2.2 to 4.4	0.03 to 0.11	Paved channel.	Main canal. Maximum water depth : 1.5 m.
			0.4 to 0.7	35 to 60	Stepped intake and drop structures at downstream end.	Secondary canals. W = 0.5 to 5 m. Maximum flow depth < 0.5 m. h = 0.15 to 0.3 m.

Name (1)	Year (2)	Ref. (3)	Disch q_w (m^2/s) (4)	Slope α (deg.) (5)	Construction and hydraulic design (6)	Comments (7)
Na'aran channel, Jericho, Israel	B.C. 103 to 76	[NE]			Field stones bonded by lime mortar. Energy dissipation by drop structures.	Part of the Wadi Qelt irrigation system built by the Hasmonean King Alexander Janneus. W = 0.6 m.
Moche valley, Peru	A.D. 200–1500	[FA1, FA2]				Irrigation systems built by the Mochica civilisation, later extended by the Chimus and the Incas. Over 100 km of canals.
Cerro Orejas			0.012		Terrace irrigation system with free-falling nappes.	W = 0.2 to 0.3 m. h < 2 m.
Quishuarpata canal, Peru	A.D. 1000? to 1532	[FA1]	0.5		Canal floor made of irregularly shaped granite blocks with granite faced walls.	Artificial irrigation channel (6 km long) in the Hualancay river valley, near Cuzco. W ≤ 0.8 m.
Chute 1				23.3	Steep narrow steps. Drop structures near the end.	Pre-Inca design. 120 m long. h = 1 to 3 cm.
Chute 2A				32.6	Steep narrow steps.	Chutes 2A and 2B : 150 m long together. h = 1 to 3 cm.
Chute 2B				31	Steep narrow steps. Drop structures near the end.	h = 1 to 3 cm.
Vigevano, near La Sforzesca, Italy	A.D. 1500?	[RI]		26.6	Staircase waterfall (130 steps).	Irrigation channel described by LEONARDO DA VINCI. h = 0.152 m.

Notes : h : step height or drop height; q_w : discharge per unit width; W : chute width; ΔH ; total head loss; ([a]) : mountain slope.

References : [EV] EVANS (1928); [FA1] FARRINGTON (1980); [FA2] FARRINGTON and PARK (1978); [LE] LeBARON BOWEN and ALBRIGHT (1958); [NE] NETZER (1983); [RI] RICHTER (1939).

TABLE 3

Stepped cascades and drops in Roman aqueducts

Steep Section (1)	ΔH (2)	L (3)	S_0= sinθ (4)	Q_{max} (m^3/s) (5)	Remarks (6)
Stepped cascades					
Chabet Illelouine, Cherchell aqueduct (Alg.)	19	–	–	0.076	Downstream of Oued Bellah.
Beaulieu aqueduct	37	–	–	–	Petite cascade. Horizontal and inclined stepped faces : h ~ 0.5 m.
Chevinay, Brévenne aqueduct (Lyon, Fra.)	87	200	0.40	0.116	Steps inclined downwards : h = 0.92 m, δ = - 11°.
Andriake, Lycia	11	18	0.52	–	Series of 5 pooled steps. W = 1.78 m, h = 2.82 m, d_t = 0.78 m.
Drops					
Claudia aqueduct	–	–	–	2.2	Single drop : h = 1.1 m. Near bridge below Vicavaro.
Water mill					
Barbegal	20	60	–	0.26	2 rows of 8 mill wheels each.

Notes : h : step height; L : chute length; Q_{max} : maximum discharge estimate; S_o : bed slope; W : channel width; ΔH : total head loss; δ : angle between the step and horizontal (i.e. δ < 0 inclined downward).

References : CHANSON (2000a), Present study.

TABLE 4

Dropshaft cascades in Roman aqueducts

Steep Section (1)	ΔH (2)	L (3)	S_0= sinθ (4)	Q_{max} (m^3/s) (5)	Remarks (6)
Vaugneray, Yzeron Aqueduct (Lyon, Fra.)	22	375	0.058	0.058	Vaugneray branch of Yzeron aqueduct. About 8 rectangular dropshafts (1.9 × 1.1 m^2, h~2.5 m). W=0.4 m.
Recret/Grézieu-la-Varenne, Yzeron Aqueduct (Lyon, Fra.)	38	490	–	0.150	About 15 rectangular dropshafts (1.2 × 1.2 m^2, h~2.5 m). W=0.55 m.
Chabet Illelouine, Cherchell Aqueduct (Alg.)	12.3	32	0.36	0.076	4 series of steep chutes (W=0.94 m) followed by circular dropshaft (Ø=2.4 m, h=0.8 m).

Steep Section (1)	ΔH (2)	L (3)	$S_0=\sin\theta$ (4)	Q_{max} (m^3/s) (5)	Remarks (6)
Moulin Romain, Gunugu Aqueduct (Tun.)	20	–	–	–	4 to 5 circular dropshafts (∅=0.8m, h=3.5 to 4 m). W=0.86 m.
Beaulieu Aqueduct (Aix-en-Pr., Fra.)	37	–	–	–	Combination of steep chutes and dropshafts.
Brisecou Forest, Montjeu Aqueduct (Autun, Fra.)	140	770	0.13	–	A series of 24 rectangular dropshafts (32.4 m^2, h=4.4 m).
Grand thermes, Cuicul Aqueduct (Tun.)	3	85	0.034	–	Series of 4 circular dropshafts (∅=0.8 m, h=0.4 to 1 m)) on urban distribution line (W = 0.45 m).
Mechernich-Lessenich, Köln Aqueduct (Germ.)	84	–	0.045	0.23	One rectangular dropshaft (1.2 × 0.9 m^2) installed on a steep section.
Cerro de los Pinos, Valdepuentes Aqueduct (Cordoba, Spa.)	120	400	0.29	0.255	Upstream of Valdepuentes bridge. Series of 34 circular dropshafts (∅=0.55 to 0.6 m, h~3 m). Three unusual 90-degree bend shafts: *spiramina*.
Madinat-al-Zhara, Valdepuentes Aqueduct (Cordoba, Spa.)	200	–	–	0.255	Series of 7 circular dropshafts.

Notes : h : drop in invert elevation; W : channel width; ΔH : total head loss.
References : CHANSON (2000a), VILLANUEVA (1993).

ACKNOWLEDGEMENTS

The writer thanks the following people in providing relevant information: Mr. E. A. BATTISON, Windsor, Vermont USA; Mr. L. Stuart DAVIES, Welsh Water, United Kingdom; Direction Départementale de l'Equipement, Côte d'Or; Ms CHOU Y. H., Brisbane, Australia; Mr. J. FAGE, Lyon, France; Madame GAUMONT, Montsauche-les-Settons, France; Pr. J. KNAUSS, Münich University of Technology, Germany; Dr. P. LEVEAU, Aix-en-Provence, France; Professor C. O'CONNOR, Brisbane, Australia; Mr. P. PULICANI, Direction Départementale de l'Equipement Côte d'Or, France; Mr. P. ROYET, CEMAGREF, Aix-en-Provence, France; Mr. Rod SMYTH, Coliban Water, Australia; Mr. Brit STOREY, US Bureau of Reclamation, USA; Mr. Richard TUMMAN, Brookfield, Australia; La Ville de Saint-Etienne (M. BONNEFOY, Direction Générale), France; Dr. A. V. VILLANUEVA, University of Cordoba, Spain; Professor R. L. WHITMORE, Brisbane, Australia; Mr. R. WINGATE, US Bureau of Reclamation, USA; Mr. A. R. YAZDANY, Iran.

NOTES

1. The dam is located in the Hacienda of San Blas, near the town of Pabellon de Hidalgo, about 35 km from Aguascalientes City.
2. A water mill was built downstream of and on the left of the dam wall. It is no longer in use.

3. The writer argues, however, that previous studies of the Montjeu aqueduct, Autun were inaccurate (CHANSON 200c). Most works relied upon the the original work of ROIDOT-DELEAGE (1879?) published posthumously. Field obsrvations conducted in September 2000 demonstrated some of his drawings were not exact (CHANSON 200c p.1–1).
4. For example, the dropshaft cascades of the Valdepuentes aqueduct were later re-used by the Muslims.
5. Completed in 1971, the 4 m high concrete weir has a horseshoe shape in plan and includes 3 steps. It was built as part of Bath flood control scheme (GREENHALGH 1974).
6. A channel to carry waste waters i.e. spillway.
7. In the meaning of a uniform smooth channel bed (i.e. not stepped).
8. The writer has lectured on stepped spillway hydraulics at postgraduate and undergraduate levels since 1992 in Australia and overseas (CHANSON 1999, pp. 313–363). It is believed that his texts (CHANSON 1995b, 1999) are the first modern hydraulic engineering textbooks reintroducing the hydraulic design of stepped spillways.

REFERENCES

BAKHMETEFF, B. A., and MATZKE, A. E. (1936). "The Hydraulic Jump in Terms of Dynamic Similarity." *Transactions,* ASCE, Vol. 101, pp.630–647. Discussion : Vol. 101, pp.648–680.

BATTISON, E. A. (1975). "Ascutney Gravity-Arch Mill Dam - Windsor, Vermont 1834." *IA Jl of the Soc. of Industrial Archeology,* Summer, Vol. 1, No. 1, pp.53–58.

BINNIE, A. R. (1913). "Rainfall Reservoirs and Water Supply." *Constable & Co*, London, UK, 157 pages.

BINNIE, G. M. (1981). "Early Victorian Water Engineers." *Thomas Telford,* London, UK, 310 pages.

BINNIE, G. M. (1987). "Early Dam Builders in Britain." *Thomas Telford,* London, UK, 181 pages.

BREZNIK, M. (1984). "The Safety and Endurance of the Old Dams of Idrija." *Proc. Intl Conf. on Safety of Dams*, Portugal, Balkema Publ., Rotterdam, The Netherlands, pp.133–139.

CHANSON, H. (1995a). "History of Stepped Channels and Spillways : a Rediscovery of the 'Wheel'." *Can Jl of Civ. Eng.*, Vol. 22, No. 2, April, pp.247–259.

CHANSON, H. (1995b). "Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways." *Pergamon*, Oxford, UK, Jan., 292 pages.

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

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

CHANSON, H. (2000b). "Forum Article. Hydraulics of Stepped Spillways: Current Status", *Jl of Hyd. Engrg.*, ASCE, Vol. 126, No. 9.

CHANSON, H., and WHITMORE, R.L. (1998). "Gold Creek Dam and its Unusual Waste Waterway (1890–1997) : Design, Operation, Maintenance." *Can. Jl of Civil Eng.*, Vol. 25, No. 4, Aug., pp.755–768 & Front Cover.

CHOW, V. T. (1959). "Open Channel Hydraulics." *McGraw-Hill*, New York, USA.

DANILEVSLKII, V. V. (1940). "History of Hydroengineering in Russia before the Nineteenth Century." *Gosudarstvennoe Energeticheskoe Izdatel'stvo,* Leningrad, USSR (in

Russian) (English translation : *Israel Program for Scientific Translation*, IPST No. 1896, Jerusalem, Israel, 1968, 190 pages).

DOUMA, J.H., and GOODPASTURE, R.A. (1940). "Hydraulic Model Studies for Reconstruction of the Lahontan Dam Spillway." *Hydraulic Laboratory Report No. HYD–71*, US Bureau of Reclamation, Dept. of the Interior, Denver, 13 Jan., 2 pages & 8 figures.

ENGELS, H. (1914). "Handbuch des Wasserbaues." ('Handbook of Hydraulic Structures.') *Wilhelm Engelmann*, Leipzig, Germany, 2 volumes (in German).

ESSERY, I. T. S., and HORNER, M. W. (1978). "The Hydraulic Design of Stepped Spillways." *CIRIA Report No. 33*, 2nd edition, Jan., London, UK.

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.

FAHLBUSCH, H. (1987). "Alte Talsperren im Gebiet des Königreichs Saudi Arabien." ('Ancient Dams in the region of the Saudi Arabia Kingdom.') *Historische Talsperren*, Vol. 1, K. Wittwert, Stuttgart, Germany, pp.199–220 (in German).

FARRINGTON, I. S. (1980). "The Archaeology of Irrigation Canals with Special Reference to Peru." *World Archaeology*, Vol. 11, No. 3, pp.287–305.

FARRINGTON, I. S., and PARK, C. C. (1978). "Hydraulic Engineering and Irrigation Agriculture in the Moche Valley, Peru : c. A.D. 1250–1532." *Jl of Archaeological Science*, Vol. 5, pp.255–268.

FORBES, R. J. (1955). "Studies in Ancient Technology." *Leiden*, E.J. Brill, 9 Vol..

GOMEZ-PEREZ, F. (1942). "Mexican Irrigation in the Sixteenth Century." *Civil Engineering*, ASCE, Vol. 12, No. 1, pp.24–27.

GORDIENKO, P. I. (1944). "Rockfill Overflow Dams." *Gidrotekhnicheskoe Stroitel'stvo*, No. 3 (in Russian).

GREENHALGH, F. (1974). "Bath Flood Protection Scheme." *Wessex Water Authority*, Bath, UK, 43 pages.

HARTUNG, F., and KUROS, G. R. (1987). "Historische Talsperren im Iran." ('Historical Dams in Iran.') *Historische Talsperren*, Vol. 1, K. Wittwert, Stuttgart, Germany, pp.221–274 (in German).

HENDERSON, F. M. (1966). "Open Channel Flow." *MacMillan Company*, New York, USA.

HINDS, J. (1932). "200-Year-Old Masonry Dams in Use in Mexico." *Engineering News-Record*, Vol. 109, Sept. 1, pp.251–253.

HINDS, J. (1953). "Continuous Development of Dams since 1850." *Transactions*, ASCE, Vol. CT, pp.489–520.

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

HODGE, F. W. (1893). "Prehistoric Irrigation in Arizona." *The American Anthropologist*, Vol. VI, pp.323–330.

HUMBER, W. (1876). "Comprehensive Treatise on the Water Supply of Cities and Towns with Numerous Specifications of Existing Waterworks." *Crosby Lockwood*, London, UK.

KELEN, N. (1933). 'Gewichtsstaumauern und Massive Wehre." ('Gravity Dams and Large Weirs.') *Verlag von Julius Springer*, Berlin, Germany (in German).

KNAUSS, J. (1995). "ΤΗΣ ΓΡΙΑΣ ΤΟ ΠΗΔΗΜΑ, der Altweibersprung. Die Rätselhafte Alte Talsperre in der Glosses-Schlucht bei Alyzeia in Akarnanien." *Archäologischer Anzeiger*, Heft 5, pp.138–162 (in German).

LeBARON BOWEN Jr., R. and ALBRIGHT, F. P. (1958). "Archaelogical Discoveries in South Arabia." *The John Hopkins Press*, Baltimore, USA.

MARSH, F. B. (1957). "Danger of Fixed Flashboards shown by Flood at Croton Dam." *Civil Engineering*, ASCE, Vol. 64, pp.408–409.

Ministerio de Obras Públicas, Transportes y Medio Ambiante (1993). "Obras Hidráulicas en América Colonial." *CEHOPU, CEDEX & Tabapress*, Madrid, Spain (in Spanish).

MURRAY, W. M. (1984). "The Ancient dam of the Mytikas Valley." *American Jl of Archaeology*, Vol. 88,pp.195–203 & Plates 32–33.

NETZER, E. (1983). "Water Channels and a Royal Estate from the Late Hellenistic Period in the Western Plains of Jericho." *Symp. on Historical Water Development Projects in the Eastern Mediterranian*, Jerusalem, Israël (Mitteilungen, Institut für Wasserbau der Technischen Universität Braunschweig, Germany, No. 82, 1984).

PEYRAS, L., ROYET, P., and DEGOUTTE, G. (1991). "Ecoulement et Dissipation sur les Déversoirs en Gradins de Gabions." ('Flows and Dissipation of Energy on Gabion Weirs.') *Jl La Houille Blanche*, No. 1, pp.37–47 (in French).

RAIKES, R.L. (1964–1965). "The Ancient Garbalands of Baluchistan." *East and West*, pp.26–35.

RHONE, T. J. (1990). "Development opf Hydraulic Structures." *50th Anniversary of the Hydraulics Division 1938–1988*, ASCE, A.M. ALSAFFAR Ed., New York, USA, pp.132–147.

RICHTER, J. P. (1939). "The Literary Works of LEONARDO DA VINCI." *Oxford University Press*, London, UK, 2 volumes.

ROLT, L. T. C. (1973). "From Sea to Sea—The Canal du Midi." *Allen Lane*, London, UK, 198 pages.

SALADIN, H. (1886). "Rapport sur la Mission Faite en Tunisie de Novembre 1882 à Avril 1883." *Archives des Missions Scientifiques et Littéraires*, Ministère de l'Instruction Publique, France, Serties 2, Vol. 13, pp.1–225 (in French).

SANKEY, R. E. (1871). "Report on the Coliban and Geelong Water Schemes of Water Supply." *Report*, presented to both Houses of Parliament, Victoria (Australia), 11 November.

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

SCHOKLITSCH, A. (1937). "Hydraulic structures." *ASME*, New York, USA, 2 volumes.

SCHUYLER, J. D. (1909). "Reservoirs for Irrigation, Water-Power and Domestic Water Supply." *John Wiley & sons*, 2nd edition, New York, USA.

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

Soil and Water (1992). *Soil and Water Newsletter*, Council of Agriculture, Executive Yuan, Taiwan, No. 13, Sept..

SORENSEN, R. M. (1985). "Stepped Spillway Hydraulic Model Investigation." *Jl of Hyd. Engrg.*, ASCE, Vol. 111, No. 12, pp.1461–1472. Discussion : Vol. 113, No. 8, pp.1095–1097.

STEIN, A. (1940). "Surveys on the Roman Frontier in Iraq and Trans-Jordan." *The Geographical Journal*, Vol. XCV, pp.428–438.

THOMPSON, R. C., and HUTCHINSON, R. W. (1929). "The Excavations of the Temple of Nabû at Nineveh." *Archaeologia (London)*, Vol. 79, pp.103–148.

US Department of the Interior (1965). "Design of Small Dams." *Bureau of Reclamation*, Denver CO, USA, 1st edition, 3rd printing.

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).

WEGMANN, E. (1907). "The Design of the New Croton Dam." *Transactions*, ASCE, Vol. LXVIII, No. 1047, pp.398–457.

WEGMANN, E. (1911). "The Design and Construction of Dams." *John Wiley & Sons*, New York, USA, 6th edition.

WEGMANN, E. (1922). "The Design and Construction of Dams." *John Wiley & Sons*, New York, USA, 7th edition.

WOOD, J. N. (1933). "Features of Construction of the Ryburn Dam." *Trans. Instn. Water Engrs*, UK, Vol. 38, pp.28–67.