History of stepped channels and spillways: a rediscovery of the "wheel"

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Abstract: Recently, spillways with a stepped profile have regained interest and favor among design engineers to pass flood waters over the dams. The stepped geometry enhances the energy dissipation above the spillway and reduces the size of a downstream stilling basin. In this paper, the author shows that the technique of stepped channels has been developed since Antiquity. Spillways and irrigation channels with stepped profiles were developed by several civilisations around the Mediterranean sea and in America. The main characteristics of the stepped spillways along the ages suggest a regular evolution rather than a revolution. Present stepped spillways are designed to pass similar discharges as 200 years ago.

Key words: stepped channels, spillway, irrigation system, history, design techniques, energy dissipation.

Résumé : Récemment, l'intérêt pour les évacuateurs de crues en marches d'escalier a augmenté considérablement, pour déverser les crues sur les barrages. Le présence de marches augmente le taux de dissipation d'énergie le long du coursier, et réduit la taille des bassin de dissipation d'énergie en aval. Dans cet article, l'auteur montre que la technique des canaux en marches d'escalier était connue depuis l'Antiquité. Des évacuateur de crues et des canaux d'irrigation, avec des marches d'escalier, ont été développés par plusieurs civilisations autour de la Méditérannée et aux Amériques. A travers les âges, les caractéristiques des évacuateurs de crues suggèrent une évolution de design plutôt qu'une révolution. Actuellement, les évacuateurs de crues en marches d'escalier sont conçus pour déverser des débits similaires à il y a 200 ans.

Mots clés : canaux en marches d'escalier, évacuateurs de crues, système d'irrigation, histoire, techniques de construction, dissipation d'énergie.

1. Introduction

The energy dissipation of spillway flows is usually achieved by (*i*) a standard stilling basin downstream of the spillway where a hydraulic jump is created to dissipate a large amount of flow energy, (*ii*) a high velocity water jet taking off from a flip bucket and impinging into a downstream plunge pool, or (*iii*) the construction of steps on the spillway to assist in energy dissipation (Fig. 1). Water flowing over a stepped channel can dissipate a major proportion of its energy. The steps increase significantly the rate of energy dissipation taking place along the spillway face, and eliminate or reduce greatly the need for a large energy dissipator at the toe of the spillway. Typical examples (Table 1) include the cascading spillway of La Grande 2 (James Bay project, Canada), the Clywedog dam spillway (United Kingdom), the New Victoria dam spillway (Australia), or the Upper Stillwater dam spillway (U.S.A.).

Recent investigations (Essery and Horner 1978; Rajaratnam 1990) showed two types of flow regimes: nappe flow and skimming flow. For flat slopes and small discharges, the water proceeds in a series of free-fall nappes from one step to another (i.e., nappe flow regime). The flow from each step hits the step below as a falling jet with the formation of a hydraulic jump on the step (Peyras et al. 1991; Chanson 1994). In the skimming flow regime, the water flows down the stepped face as a coherent stream skimming over the steps. The external edges of the steps form a pseudo-bottom over which the flow passes (Rajaratnam 1990, Chanson 1993). The transition from nappe flow to skimming flow occurs when the ratio of the critical depth over step height, d_c/h, becomes larger than 0.4 to 0.8 (Chanson 1994).

Some studies (e.g., Sorensen 1985) suggested that the use of stepped channels for energy dissipation purposes was a new concept, developed with the introduction of new construction materials (e.g., roller compacted concrete, gabions). The construction of stepped spillways is facilitated by the slipforming and placing methods of roller compacted concrete and with the construction techniques of gabion dams.

In fact, the design of stepped chutes has been used since Antiquity. Stepped channels were designed to contribute to the stability of a structure (e.g., overflow weir) and to dissipate flow energy. In the first part of the paper, several examples of ancient stepped spillways and irrigation channels with stepped profiles will be presented. It will be shown that the technique of stepped channels was developed independently by several ancient civilisations. Later, the author will review the hydraulic characteristics of stepped spillways through history.

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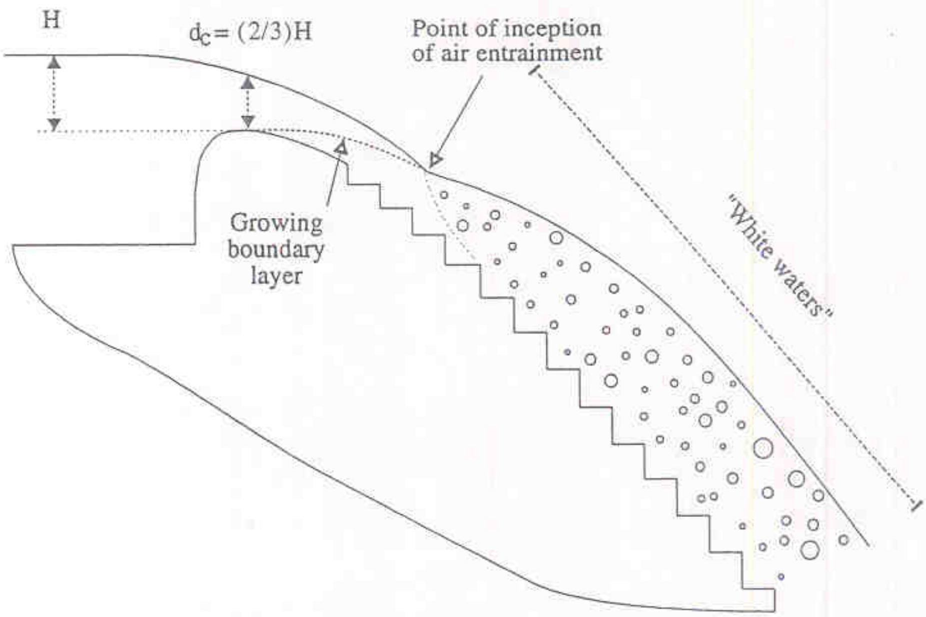
Fig. 1. Sketch of a stepped spillway.



2. History of stepped spillways

The world's oldest stepped spillways are probably those of the Khosr River dams, in Iraq (Fig. 2*a*). The Khosr River dams were built around B.C. 694 by the Assyrian King Sennacherib. They were designed to supply water to the Assyrian capital city Nineveh (near the actual Mosul). Remains of these dams are still in existence (Smith 1971). Both dams feature a stepped downstream face and were intended to discharge the river over their crests.

Much later, the Romans built stepped overflow dams in their empire; remains can still be found in Syria, Lybia, and Tunisia (Table 2). An example, the Kasserine dam, is shown in Fig. 3*a*. After the fall of the Roman empire, Moslem civil engineers gained experience from the Nabataeans,[1] the Romans, and the Sabaens.[2] Stepped spillways built by the Moslems can be found in Iraq and in Spain (e.g., Adheim dam, Mestella weir).

Following the reconquest of Spain, Spanish engineers benefited from the Roman and Moslem precedents and designed dams with overflow stepped spillways (e.g., Almansa dam, Alicante dam, Barrueco de Abajo dam). In 1791, they built the largest dam with a stepped spillway, the Puentes dam, but the dam was washed out in 1802 after a foundation failure. Before 1850, the dam expertise of Spanish engineers was most exceptional. Not surprisingly, after the conquest of America, the Spanish dam-building was exported to the "New Indies." In central Mexico, several stepped overflow dams were built by the Spanish during the 18th and 19th centuries (Fig. 3*b*).

The Spanish experience was known to French engineers by the middle of the 17th century. The feeder system of the Canal du Midi,[3] designed by Riquet and extended by Vauban, included several stepped channels and cascades (Rolt 1973). Stepped chutes were designed to dissipate the flow energy and to prevent scouring.

In the United Kingdom, several dams were built near furnaces and water mills. Some included stepped weirs and spillways. It is believed that English engineers gained experience from the Romans who built aqueducts and dams during their occupation.

It is worth mentioning the timber dams (and crib dams) with stepped overflow weirs. The northeast part of America benefited from the experience of northern European settlers and timber dams were reported as early as A.D. 1600. During the period 1800–1920, timber dams were popular in America, Australia, and New Zealand. Most timber dams were 3–6 m high, but some much bigger ones were built successfully to a height of 30 m. Timber overflow stepped weirs were able to sustain large flood discharges without major damage, e.g., the diversion dam on the Feather River (Fig. 3*f*).

3. Ancient irrigation canal systems

Drop structures and stepped profiles were used also in some early irrigation systems (Table 3, Fig. 2*b*). Most cases suggest that the hydraulic expertise was developed locally through evolution rather than technology transfer. In Saba (i.e., actual Yemen), the Sabaens used stepped channel profiles in the early Antiquity. In Peru, the Indians civilisations used stepped channels and drop structures prior to the Spanish conquest.

One of the most ingenious canal systems was the Quishuarpata canal. The canal included two steep chutes designed

[1] The Nabataeans were habitants from an ancient kingdom to the east and southeast of Palestine that includes the Neguev desert. The Nabataean kingdom lasted from around B.C. 312 to A.D. 106.

[2] The word Sabaen is the ancient name of the people of Yemen. The kingdom of Saba (or Sheba) is renown for the visit of the Queen of Saba to the King of Israel Salomon around B.C. 950.

[3] The Canal du Midi was built between 1666 and 1681 to provide an inland route between the Atlantic and the Mediterranean across southern France. The feeder system was later extended in 1686–1687.

Table 1. *Examples of recent stepped spillways.*

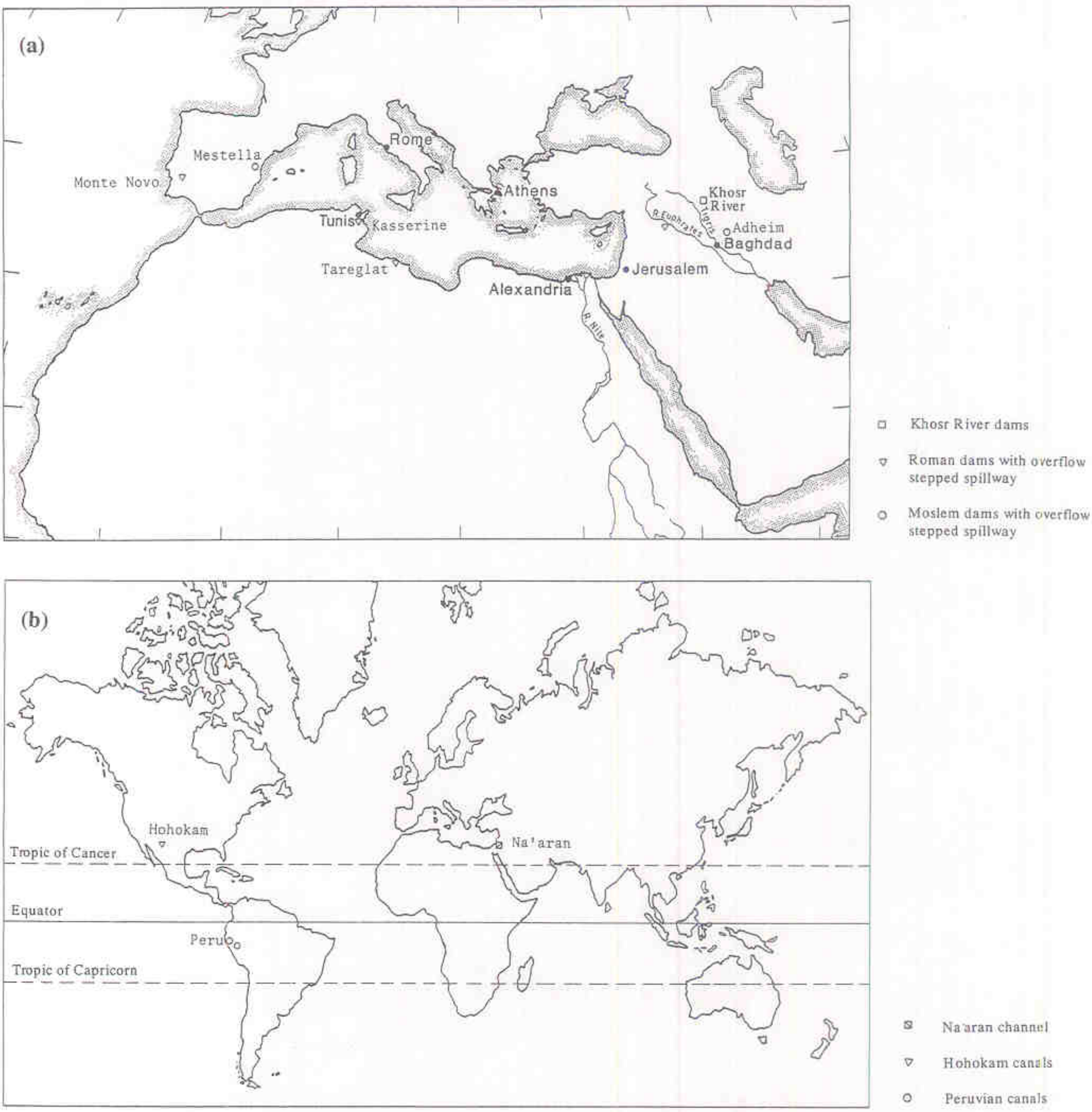
Name (1)	Reference* (2)	Slope α (°) (3)	Dam height H_{dam} (m) (4)	Maximum discharge q_w (m^2/s) (5)	Step height h (m) (6)	No. of steps (7)	Type of steps (8)	Remarks‡ (9)
Concrete dam spillway								
Clywedog dam, U.K., 1968	[EN]	60	72	2.8	0.76 (?)		Precast concrete beams	Buttress dam; spillway made of precast beams; W = 182.9 m
De Mist Kraal weir, South Africa, 1986	[HD]	59	30	30	1	19	Horizontal steps	RCC dam; W = 195 m
Zaaihoek dam, South Africa, 1986	[HD]	58.2	45	15.6	1	40	Horizontal steps	RCC dam; W = 160 m
Monksville, U.S.A., 1987	[SO]	52	36.6	9.3	0.61		Horizontal steps	RCC dam; W = 61 m
Olivettes dam, France, 1987	[BO, GO]	53.1	36	6.6	0.6	47	Horizontal steps	RCC dam; W = 40 m
Upper Stillwater, U.S.A., 1987	[HO]	72, 59	61	11.6	0.61		Horizontal steps	Overflow RCC dam; W = 183 m
M'Bali dam, RCA, 1990	[BI]	51.3	24.5	16	0.8	36	Horizontal steps	RCC dam; W = 60 m
New Victoria dam, Australia	[WA]	72, 51.3	52	5.4	0.6	85	Horizontal steps	Oveflow RCC dam; W = 130 m
Petit-Saut dam, Guyana, 1994	[DU, GO]	51.3	37	4	0.6		Horizontal steps	RCC dam
Unlined rock spillway								
Bellfield dam, Australia, 1966	[MI, T]		54.9	20.9	12.2	3	Unlined cascade; flat steps	Earth-cored rockfill-flanked dam; W = 23 m
Dartmouth dam, Australia, 1977	[T]		180	2700†	5	13	Unlined cascade in granite; flat steps	Earth and rockfill dam; channel width varies from 91.4 m at crest up to 350 m
La Grande 2 dam, Canada	[PO]	30	134	16 140†	17.8	1	Smooth profiled step; pool depth = 8.5 m	W = 122 m; 1st step: concrete lined
					9.1–12.2	11	Unlined horizontal steps	Unlined excavations; 2nd to 12th steps

*[BI], Bindo et al. 1993; [BO], Bouyge et al. 1988; [DU], Dussart et al. 1993; [EN], Engineering 1966; [GO], Goubet 1992; [HD], Hollingworth and Druyts 1986; [HO], Houston and Richardson 1988; [MI], Michels 1966; [PO], Post et al. 1987; [SO], Sorensen 1985; [T], Thomas 1976; [WA], Wark et al. 1991.

†Data refer to water discharge, Q_w, in m^3/s.

‡RCC, roller compacted concrete.

Fig. 2. Historical development of stepped channels in the world: (*a*) ancient stepped spillways; (*b*) ancient irrigation systems with stepped profiles.



both with small steps (h = 1 to 3 cm) along the chute course and large steps (i.e., drop structures) near the end. No stilling ponds were used. This canal system highlights the hydraulic expertise of ancient Peruvian engineers (pre-Inca and Inca). They designed canals able to sustain supercritical flows with steep slope gradients, drop structures, and hydraulic jumps at the downstream end of the canals.

4. Discussion

4.1. Spread of the spillway design technology

From Antiquity to the beginning of the 20th century, the Romans, Moslems, and Spanish contributed successively to the dissemination of the arts of dam-building. Dams and stepped overflow spillways were found early in the Middle East, then the practice spread through the Mediterranean in Roman times. The Muslim conquerors of the Hispanic peninsula brought their water traditions with them from the eastern and southern Mediterranean. Seven hundred years of Moorish control of Iberia left a strong influence of irrigation structures. Later, the Spanish conquerors of the New World transferred deliberately their technology in turn.

Spain occupied an exceptional place in the development of large dams. Most European countries and European settlements in America benefited from their expertise, including in the field of stepped spillway design. Clear evidences of the

Table 2. Historical stepped spillways (before A.D. 1850).

Name (1)	Year (2)	Reference* (3)	Dam height (m) (4)	Slope (deg.) (5)	Construction (6)	Comments (7)
Khosr River dams, Iraq	B.C. 694	[SM, FO, TH]	2.9		Masonry of limestone, sandstone mortared together	Built by the Assyrian King Sennacherib to supply water to his capital city Nineveh; discharge over the dam crest; lower dam
			>1.4	30		Upper dam; 5 steps
Kasserine dam, Tunisia	A.D. 100?	[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; 6 steps followed by an overfall; discharge over the dam crest; $W = 150$ m
Qasr Khubbaz, Syria	A.D. 100/200	[SM, ST]	6.1		Masonry dam with limestone slabs	Roman dam on the Euphrate river; reservoir capacity = 9000 m^3 of water
Tareglat dam, Lybia	A.D. 200/300	[VI]	>2		Masonry gravity dam reinforced by buttressing	Roman dam near Al Khums; soil-and-water retention dam; step height, $h = 0.6$ m
Monte Novo dam, Portugal	A.D. 300?	[QU, SC]	5.7		Curved gravity wall reinforced by two downstream buttresses; masonry construction	Roman or post-Roman dam 17 km east of Evora; supply water to a watermill; 6 steps
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 discharge = ~4000 m^3/s (?); $W = 73$ 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
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
Ashburnham Furnace dam, U.K.	1563?	[BI]	7		Stones with brick and brickwork repairs	Earth dam with gated masonry spillway; $W = 3.7$ m; 3 steps ($h \sim 1.5$ 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: $h = 2.7-5$ m, $l = 0.6-0.9$ m
St Ferreol 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
Barrarueco de Abajo, Spain	17??	[GD]	6.3	~25	Buttress dam; masonry construction	Overflow spillway; 5 steps inclined downward

Table 2 (*concluded*).

Name (1)	Year (2)	Reference* (3)	Dam height (m) (4)	Slope (deg.) (5)	Construction (6)	Comments (7)
Pabellon dam, Mexico	173?	[GP, HI, SM]	24		Buttress dam; rubble masonry set in mortar	Spanish construction; discharge over the crest; 3 steps
Presa de los Arcos, Mexico	178?	[HI, SM]	18		Buttress dam; rubble masonry set in mortar	Spanish dam across the Rio Morcinique; overflow spillway; 4 steps
Puentes dam, Spain	1791	[SM, WE]	50	51	Gravity dam; rubble masonry core set in mortar and faced with large cut stones; dam failure in 1802	Dam across the Rio Guadalentin; discharge over the crest; 4 steps followed by a uniform slope; step height, $h = 4.175$ m
Penarth weir, U.K.	1818	[BI]	2.4		Masonry crest	Stepped weir on the river Severn. 2 steps ($h \sim 1.2$ m); $W = 42$ m

*[BI], Binnie 1987; [FO], Forbes 1955; [GD], Garcia-Diego 1977; [GP], Gomez-Perez 1942; [HI], Hinds 1932, 1953; [QU], Quintela et al. 1987; [RO], Rolt 1973; [SC], Schnitter 1991; [SM], Smith 1971; [ST], Stein 1940; [TH], Thompson and Hutchinson 1929; [VI], Vita-Finzi 1961; [WE], Wegmann 1911.

Fig. 3*a*. Kasserine dam, Roman dam in Tunisia (A.D. 100) — details of the overflow spillway and the step geometry.

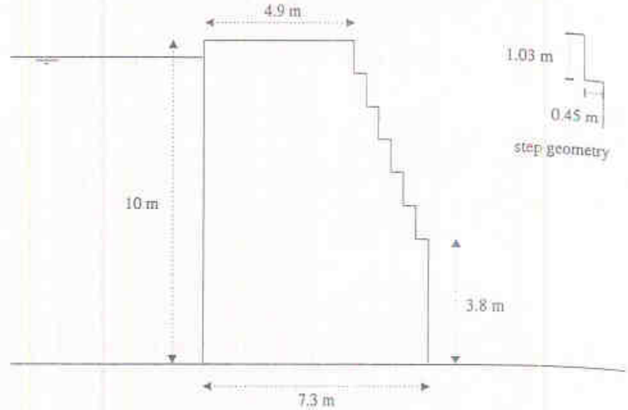
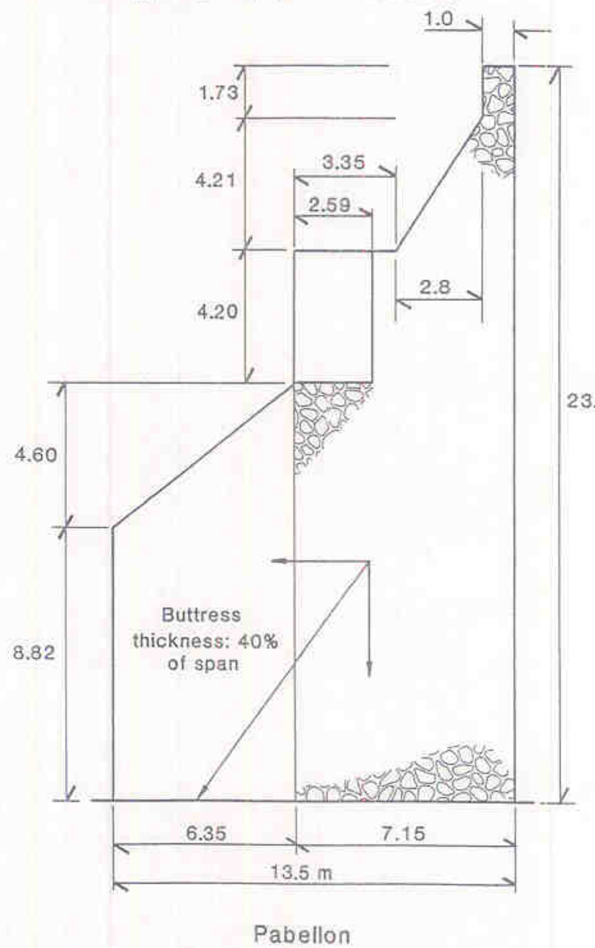


Fig. 3*b*. Pabellon dam, Spanish dam in Mexico (A.D. 1730?) — masonry dam reinforced by buttresses with overflow stepped spillway (after Hinds 1932).



Spanish influence were found certainly in France, Mexico, and United States (Table 4, Fig. 3).

It is worth noting that pre-European hydraulic expertise existed in northern, central and southern America. Irrigations channels with stepped profiles were used in America before the Spanish conquest (Table 3).

In most early dams (Table 2, Fig. 3), the waters were discharged over the dam crests. The stepped spillway geometry

Fig. 3c. Quinson dam, Verdon River, 1870 (France) (after Wegmann 1911).

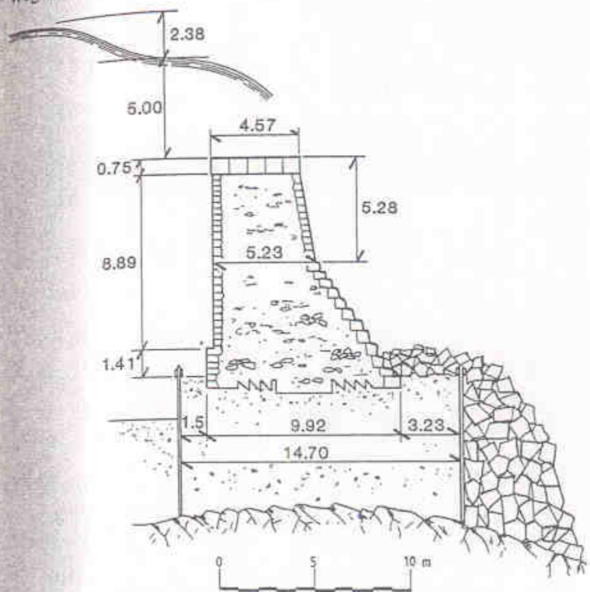
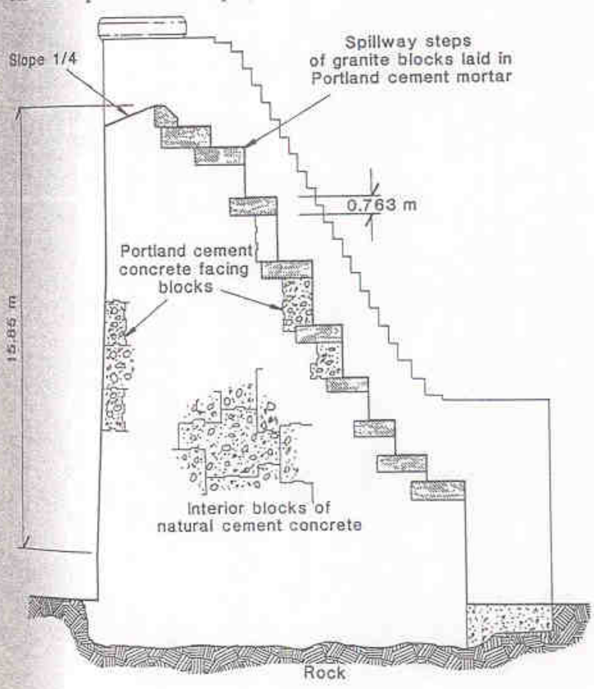


Fig. 3d. Pedlar River dam, Virginia, 1905 (U.S.A.), — spillway cross section (Schuyler 1909). (Note the granite blocks to protect the steps.)



was selected initially to contribute to the stability of the dam, for the simplicity of shape, or for a combination of the two. Later, design engineers realized the advantages of stepped channels for reducing the flow velocities (i.e., energy dissipation purposes) and to prevent scouring. By the fall of the 19th century, overflow stepped spillways were selected frequently to contribute to the dam stability and to enhance energy dissipation (Table 4). Most structures were masonry and concrete dams with a downstream stepped face reinforced by granite blocks. The spillway of the New Croton dam (1906) is probably the first stepped chute designed specifically to maximize energy dissipation.

Fig. 3e. Croton Falls dam, 1911 (U.S.A.) — spillway cross section (after Wegmann 1911). (Note the rounded steps.)

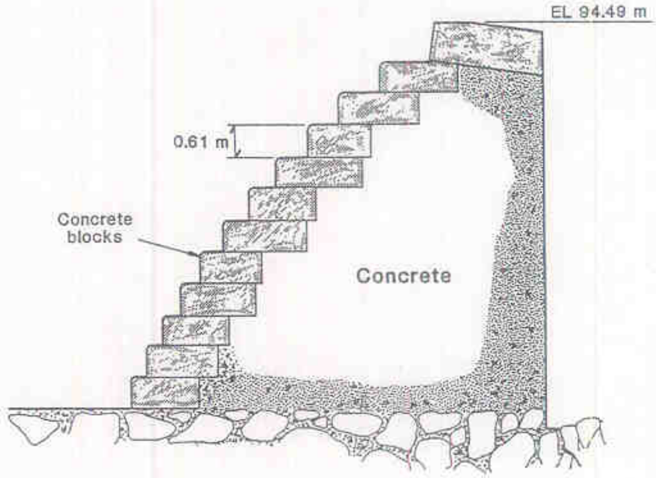
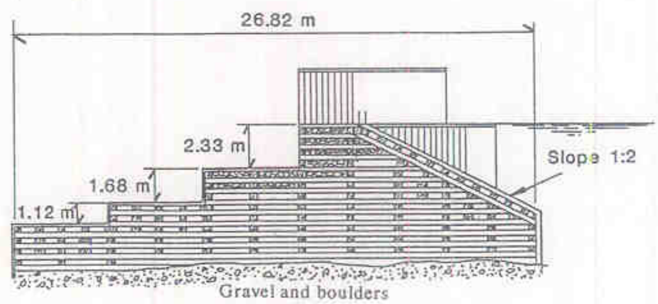


Fig. 3f. Feather River diversion weir, California, 1912 (U.S.A.).



In the first part of the 20th century, new progress in the energy dissipation characteristics of hydraulic jumps (e.g., Bakhmeteff and Matzke 1936) favoured the design of stilling basins downstream of chutes and spillways. Stilling basins allowed better energy dissipation and smaller structures, and they contributed to cheaper constructions.

Recently (in the 1970s), design engineers have regained interest for stepped spillways. This trend was initiated by the introduction of new construction materials, e.g., roller compacted concrete and strengthened-mesh gabions. Over the past decade, several dams have been built with overflow stepped spillway around the world (Table 1).

4.2. Design techniques

Since Antiquity, the design of stepped spillways and channels was recognized to reduce flow velocities and to prevent scouring. Some ancient engineers might have known the concepts of nappe and skimming flows. But there is evidence that, even at the beginning of the 20th century, hydraulic engineers had no quantitative information on the main flow properties (e.g., flow resistance and head loss). It is only recently that new progress on the hydraulics of stepped channels has been achieved, e.g., Essery and Horner (1978), Sorensen (1985), and Peyras et al. (1991).

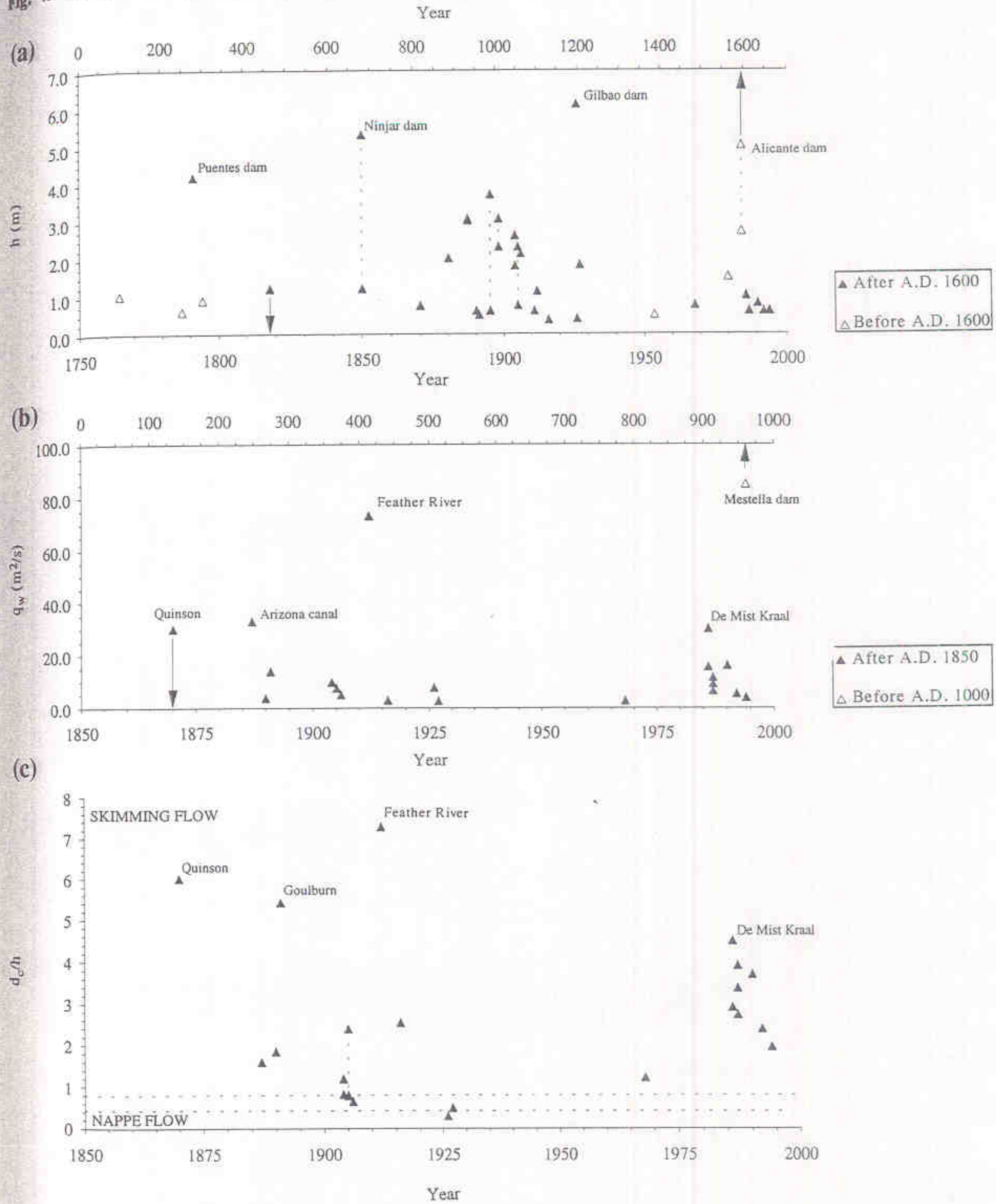
The author observes with interest a continuity in the design of stepped spillways. The characteristics of ancient stepped spillways are similar and comparable to the present

Table 3. Ancient irrigation systems with stepped profile (before A.D. 1850).

Name (1)	Year (2)	Reference* (3)	Discharge q_w (m^2/s) (4)	Slope α(°) (5)	Construction and hydraulic design (6)	Comments (7)
Wadi Beihan Valley, Yemen	B.C. 1000 to A.D. 200	[LE]				Himyarit irrigation system in Qataban
Hajar Bin Humeid			2.2–4.4	0.03–0.11	Paved channel	Main canal; maximum water depth = 1.5 m
			0.4–0.7	35–60	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
Na'aran Channel, Jericho, Israël	B.C. 103 to 76	[NE]			Field stones bonded by lime mortar; energy dissipation by drop structure	Part of the Wadi Qelt system built by the Hasmonean King Alexander Janneus; W = 0.6 m
Salado and Gila valleys, South Arizona, U.S.A.	B.C. 300 to A.D. 650	[HO, CR]			Earth and stone channels with plastered lining; stepped profile	Irrigations system built by the Hohokams; reused by the Mormons of Mesa City in late 19th century
Moche Valley, Peru	A.D. 200 to 1500	[FA1, FA2]				Irrigation systems built by the Mochica civilisation, later extended by the Chimus and the Incas; over 100 km of canals; W = 0.2 to 0.3 m; h < 2 m
Cerro Orejas			0.012		Terrace irrigation system with free-falling nappes	
Quishuarpata Canal, Peru	A.D. 1000? to 1532	[FA1]	0.5		Canal floor made of irregularly shaped granite blocks with granite faced walls	Artificial channel (6 km long) in the Hualancay river valley, near Cuzco; $W \leq$ 0.8 m; velocities up to 2.6 m/s; Froude numbers up to 2.7
Chute 1				23.3	Steep narrow steps; drop structures near the end	Pre-Inca design; 120 m long; h = 1–3 cm
Chute 2A				32.6	Steep narrow steps	Chutes 2A and 2B: 150 m long together; h = 1–3 cm
Chute 2B				31	Steep narrow steps; drop structures near the end	h = 1–3 cm
Cusichaca Valley, Peru	A.D. 1200 to 1532	[FA1]			Terrace irrigation system with free-falling nappes and granite linings	Inca irrigation system; h = 4 m
Inca Irrigation Systems, Peru	A.D. 1200 to 1532	[CO]		25–70†	Terrace irrigation systems	High altitude staircase farms (up to 3400 m altitude); h = 2.4–4.3 m
Ollantaytambo					Vertical channels and drop structures	

*[CO], Cook 1916; [CR], Crouch 1991; [FA1], Farrington 1980; [FA2], Farrington and Park 1978; [HO], Hodge (1893); [LE], LeBaron Bowen and Albright 1958; [NE], Netzer 1983.
†Mountain slope.

Fig. 4. Evolution of stepped spillway design: (a) step height, h; (b) maximum discharge capacity, q_w; (c) ratio d_c/h.



designs as shown in Fig. 4. Figure 4 presents the step height, h, the maximum discharge capacity, q_w, and the d_c/h ratio for a wide range of dams as a function of year of completion. The new spillway designs (Table 1) have a similar range of step height as the older constructions (Fig. 4a). Surprisingly, most recent stepped spillways are designed for a maximum discharge capacity no greater than ancient designs (Fig. 4b). New stepped spillway designs might be cheaper to build, but they do not provide larger discharge characteristics than ancient structures!

It is certain that small weirs and drop structures were designed for a nappe flow regime. But the author wishes to highlight that some ancient stepped spillways were designed for a skimming flow regime (i.e., d_c/h > 0.4 to 0.8).

5. Conclusion

Stepped spillways have been used for more than 2500 years. The Assyrian engineers were probably the first to design overflow dams with stepped spillways. Stepped spillways

Table 4. Stepped spillways built between 1850 and 1950.

Name (1)	Year (2)	Reference* (3)	Dam height (m) (4)	Slope (deg.) (5)	Construction (6)	Comments (7)
Nijar dam, Spain	1850	[SH, SM]	31		Curved gravity dam in masonry	Overflow dam; flat crest followed by 7 steep steps (h = 1.2–5.3 m)
Quinson dam (or Verdon dam), France	1870	[WE]	18	83, 51	Gravity dam; rubble with cut-stone facing	Overflow dam (W = 40 m); maximum discharge = 1,200 m^3/s; flat crest (4.6 m) followed by smooth slope (83°) and 10 steps (51°; h = 0.75 m)
Hijar dam, Spain	1880	[SH]	43	53?	Curved masonry dam	Step height, h = 2 m
Upper Barden reservoir, U.K.	1882	[BI]	42		Earth embankment with masonry spillways at each end	Maximum discharge = 43 m^3/s; flat steps at upstream end
Arizona canal dam, U.S.A.	1887	[EN1]	10		Timber cribs filled with loose rock and gravel; dam failure in 1905	Maximum discharge = 33 m^2/s; 3 horizontal steps
Tytam dam, Hong Kong	1887	[SH]	29	65	Gravity dam (40% stone, 60% concrete)	Broad crest (6.4 m) followed by 9 steps (h = 3.05 m)
Castlewood dam, U.S.A.	1890	[SH]	21	45	Rockfill dam with masonry walls; reinforced by an upstream earth embankment in 1900	Maximum discharge = 115 m^3/s; broad crest (2.5 m) followed by 16 steps (h = 0.61 m); W = 30.5 m
Goulburn weir, Australia	1891	[EV]	15	~30	Concrete gravity weir with horizontal steps made of granite blocks	Design discharge = 1970 m^3/s; record discharge 1982 m^3/s on 7 June 1917; W = 141 m; 12 steps (h = 0.5 m)
Titicus dam, U.S.A.	1895	[WE]	41	~63	Earth dam with masonry overflow spillway (masonry of rubble with cut stone laid in regular courses)	W = 61 m; 13 steps (h = 0.61–3.7 m)
Canyon Ferry dam, U.S.A.	1898	[WE]	8.8		Timber cribs filled with stones	W = 148 m; h = 2.3–3.05 m
Yuba River debris barrier, U.S.A.	1904	[EN2]	6.8	15.4	Debris dam: hydraulic fill anchored by rockfill, piling, and concrete facing	Maximum discharge = 9.8 m^2/s; W = 380 m; smooth profiled steps with concrete facing; h = 1.8–2.6 m
Pedlar River dam, U.S.A.	1905	[SH]	22.4	62	Concrete dam with spillway steps of granite blocks laid in cement mortar	Maximum discharge = 7.7 m^2/s; W = 45.7 m; 10 steps (h = 0.76–2.3 m); ventilated steps
New Croton dam, U.S.A.	1906	[W7, GO]	90.5	53	Masonry gravity dam; spillway damage in 1955	Maximum discharge = 1550 m^3/s; W = 305 m; h = 2.13 m
Croton Falls dam, U.S.A.	1911	[WE]	52.7		Cyclopean masonry dam with concrete block facing; horizontal steps made of granite	Overflow weir; W = 213 m; 12 steps with rounded step edges; h = 0.61 m, l = 0.305–0.91 m
Feather River diversion weir, U.S.A.	1912	[ET]	7.9	26.6	Crib weir with horizontal lumber steps	Maximum discharge = 73 m^2/s; W = 85.3 m

Table 4 *(concluded).*

Name (1)	Year (2)	Reference* (3)	Dam height (m) (4)	Slope (deg.) (5)	Construction (6)	Comments (7)
Lahontan dam, U.S.A.	1915	[RH]	49			Maximum discharge = 742 m^3/s
Warren dam, Australia	1916	[JO]	17.4	35	Concrete gravity dam; overtopped in 1917	Maximum spillway discharge = 100 m^3/s; W = 35 m; h = 0.37 m
Gilboa dam, U.S.A.	1926	[GM]	49		Masonry dam	Maximum discharge = 3130 m^3/s; inclined downwards steps (5.7°); h = 6.1 m; W = 403.6 m
St. Francis dam, U.S.A.	1926	[JA]	62.5		Concrete gravity dam; dam failure in 1928	Step height, h = 0.4 m; W = 67 m
Eildon Weir, Australia	1927	[KN]	42.7	56, 22	Rockfill dam with concrete spillway section	Maximum discharge = 566 m^3/s; step height, h = 1.83 m; 14 steps (56°); followed by a flat smooth slope and a 22° stepped channel; W = 208 m
Paderno power plant, Austria	19??	[SC]	18	17.7	Pooled steps	11 step cascade; step height, h = 1.6 m; pool height, d_1 = 1 m

*[BI], Binnie 1913; [EN1], Engineering News 1905*a*; [EN2], Engineering News 1905*b*; [ET], Etcheverry 1916; [EV], Evans 1984; [GM], Gausmann and Madden 1923; [GO], Goubet 1992; [JA], Jansen 1983; [JO], Johnson and Templar 1974; [KN], Knight 1938; [RH], Rhone 1990; [SC], Schoklitsch 1937; [SH], Schuyler 1909; [SM], Smith 1971; [W7], Wegmann 1907; [WE], Wegmann 1911.

were selected to contribute to the stability of the dam and for their simplicity of shape. Irrigation systems with stepped profiles were also developed in America and in the Middle East. Since the beginning of the 20th century, stepped chutes are designed specifically to dissipate flow energy. The steps increase significantly the rate of energy dissipation taking place on the spillway face and reduce the size of the required downstream energy dissipation basin. New construction materials (e.g., roller compacted concrete, gabions) have increased the interest for stepped chutes and spillways in the last decades.

Despite recent advances in technology, the characteristics (geometry and discharge) of stepped spillways show a continuity since the Antiquity up to now (Fig. 4). Despite the recent regain of interest for stepped spillways, the concept of "stepped chutes" is not a new technique (nor a revolution) but barely an evolution of design!

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List of symbols

d	flow depth (m)
d_c	critical depth (m); for a rectangular channel, $d_c = \sqrt[3]{q_w^2/g}$
Fr	Froude number, $\mathrm{Fr} = q_w/\sqrt{gd^3}$
g	gravity constant (m/s^2)
H_{dam}	dam height (m), i.e., dam crest head above downstream toe
h	height of steps (m)
l	horizontal length of steps (m)
Q_w	water discharge (m^3/s)
q_w	water discharge per unit width (m^2/s)
W	channel width (m)
α	channel slope