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Gold Creek Dam and its Unusual Waste Waterway (1890-1997) : Design, Operation, Maintenance

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Abstract :

Completed in 1885, the Gold Creek dam is an earthen dam located on the outskirts of Brisbane, Australia. The spillway system was refurbished three times, each time to increase the maximum overflow capacity. In 1890, a concrete stepped waterway was built to replace the damaged unlined-rock channel. This staircase chute is an unique structure : it is the first large man-made waste waterway built in Queensland, it is the only stepped weir built in Queensland before 1900, and it is, so far as the writers are aware, the first concrete-stepped spillway built for a large dam.

The characteristics of the dam and its unusual stepped spillway are reviewed in a historical context. The design is compared with contemporary structures and present knowledge in stepped spillway design. The authors believe that the Queensland engineers gained expertise from overseas and within Australia for the stepped spillway design. However the selection of concrete for the step construction was made by the local engineers and the reasons behind the decision are not yet understood.

Keywords : spillway design, engineering heritage, concrete construction, stepped weir, spillway operation, spillway refurbishment, 19th century structure.

INTRODUCTION

During the 19th century, several large dams were built in Australia to supply cities with water. The Gold Creek dam was the 14th large dam completed in Australia (Australian National Committee on Large Dams 1990) on the western outskirts of Brisbane, Australia (fig. 1). It was also the second large dam[1] built in Queensland to supply water to the city of Brisbane. Because of the hydrology of the catchment area, the Gold Creek dam was re-equipped with a relatively large spillway in 1890.

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[1]The expression "large dam" is used as defined by the International Commission on Large Dams (1984).

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In this paper, the authors review the historical development of the dam and the waste waterway. The authors will show that the dam and its 1890 spillway were well-designed, and that the design was derived from Australian and overseas experience as well as local expertise. The original stepped spillway is still in use today, suggesting a sound design. Its history of design, operation and maintenance may provide useful information to dam and spillway operators.

DAM AND THE WASTE WATERWAY DESIGN

Gold Creek dam

The Gold Creek dam was designed by John B. Henderson (1836-1921) for the Brisbane Board of Waterworks, shortly after he was put in charge of all waterworks under construction in Queensland in 1879. The purpose of the dam was to increase the water supply for the city of Brisbane. The Gold Creek dam was the first dam designed by Henderson and its design appears very conservative.

The dam built between 1882 and 1885 is an earthfill embankment with a clay puddle[2] corewall. It was built under the general supervision of Henderson[3]. The site engineer was Alexander Stewart (1843-1900) who acted first as an assistant to Henderson and was later Engineer to the Brisbane Board of Waterworks from 1883 (Whitmore 1996). The fill material is unworked clay laid in 0.23-m (9 in) layers. The length of the dam is 187 m (624 ft) and the maximum height of the embankment is 26 m (86 ft). The reservoir storage capacity is about 1.8 10^{+6} m^3 and the catchment area is 10.5 10^{+6} m^2.

An overflow spillway is located on the left abutment on rock foundation (see next section). An outlet tower was built between 1883 and 1885 to draw water from the reservoir. The original structure, made of cast iron, failed in 1904, following improper operation while the reservoir was empty (Cossins 1996). The structure was replaced by the present concrete structure built in 1905. Figure 2 shows the dam, the cast-iron outlet tower and the stepped waste waterway shortly after its completion (original photograph taken around 1890).

Originally the Gold Creek reservoir supplied water directly to the city of Brisbane. In 1928 the reservoir was connected to the Enoggera reservoir via a tunnel beneath the ridge separating the Enoggera creek and Gold creek basins. The Gold Creek dam acted as an upper reservoir for the Enoggera reservoir as the Gold Creek reservoir is located close to and at a higher elevation than the Enoggera dam. Today the Gold Creek reservoir is no longer used for water supply, the pipeline having been decommissioned in 1991[4] and the reservoir is kept nearly full for recreational purposes.

In 1904, a slip occurred on the upstream slope of the embankment during the drainage of the reservoir and repairs were completed in March 1906 (Cossins 1996, Whitmore 1996). In 1966, water leaks from the downstream face were observed which might have been caused by a spring located below the dam foundation and observed by Stewart during the dam construction. These incidents were considered minor and the dam is still in good condition as shown on figures 3 and 4.

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[2]wet mixture of clay worked into a dense impervious core.

[3]HENDERSON was at the time Resident Engineer for Water Supply, Queensland Government.

[4]The tunnel was first decommissioned in 1977 but the water supply to Enoggera reservoir resumed from 1986 up to 1991.

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The waste waterway

History of the spillway (1885-1997)

The Gold Creek catchment area and the neighbouring Enoggera creek basin can be subjected to very intense rainfalls (e.g. 920-mm during a storm on 24 January 1974). Written records indicate however that, in the early stages of design, Henderson lamented at the paucity of data on the local rainfall patterns and collection of suitable data after the reservoir completion was requested.

Since the construction of the dam in 1882-1885, the spillway has been modified three times essentially, each time to increase the maximum discharge capacity (table 1). The original 1885 spillway was a crude channel cut in the left abutment. Presumably Henderson assumed that the spillway details could await further hydrological data.

In 1887, the spillway channel was widened by 15 m (50 ft) to increase its capacity (fig. 2a). The original right sidewall, made of brick, was repaired and extended a short distance in concrete.

In January 1887 and early in 1890, large overflows occurred and the unlined-rock spillway was badly damaged. As a result it was decided to build a masonry spillway. The drawings were signed by Stewart and the design was approved by Henderson[5]. The new spillway was a stepped chute made of concrete (fig. 2, 3 and 4) and the concrete aggregate was obtained from the original spillway rock material[6]. The final staircase structure had twelve steps, the bottom steps (i.e. 11th and 12th steps) being incomplete although Stewart's early drawings showed originally nineteen steps. The authors believed that the choice of the number of steps was dictated by the topography and construction matters rather than by hydrodynamic considerations.

In 1920, a low concrete wall was built across the spillway crest to increase the reservoir capacity. It was dismantled in 1932 (Whitmore 1996).

In 1975, the crest elevation of the spillway was lowered by 1.2-m (4 feet) to increase the maximum discharge capacity[7] but the steep channel was unmodified. Today the stepped chute is still in use (fig. 4).

Characteristics of the staircase waste waterway

In 1890 and 1975, the stepped spillway was designed with a broad flat crest followed by a stepped channel which had a 21-degree slope (fig. 2 and 3). At the end of the stepped chute, the residual energy of the flow is dissipated on natural bed rock, and the watercourse turns abruptly to the right (90 to 120-degree change of flow direction). The spill waters rejoin the natural bed of the creek downstream of the dam. The basic spillway characteristics are summarised in table 1 (Chanson and Whitmore 1996).

The maximum discharge capacity of the 1890 spillway was probably selected to pass the maximum observed overflow at the time (i.e. 170 m^3/s in January 1887). The 1890 overflow capacity (i.e. 200 m^3/s) would flow down the steps as a nappe flow regime : i.e., a succession of free-falling nappes.

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[5]Letter (17 April 1890) from HENDERSON to the Secretary of the Board of Waterworks, Brisbane.

[6]Hand labourers were recruited to break the rocks (COSSINS 1966).

[7]It is most likely that the decision to proceed was taken after the 1974 flood of the City of Brisbane.

Interestingly, the maximum discharge capacity of the 1975 spillway (i.e. 280 m^3/s) corresponds to a transition between nappe and skimming flow. Such conditions should be avoided because they are unstable and could lead to substantial damage (e.g. Arizona Canal dam, New Croton dam) (Chanson 1995a, pp. 187-205).

Another incongruity is the discrepancy between the discharge capability of the crest and the maximum capacity of the stepped channel. The 1975 crest design allows about 360 m^3/s of water to pass before the dam is overtopped. But, in the steep channel, the low height of the sidewalls limits the maximum overflow before sidewall overtopping to about 278 m^3/s (Chanson and Whitmore 1996). For larger discharges, overtopping of the right sidewall would occur, causing unacceptable scouring and erosion to the embankment dam toe.

Figure 4 presents photographs of the spillway in operation early May 1996. The photographs show the cascading waters at low overflow (i.e. nappe flow regime).

Dam construction and spillway location

Since the Antiquity, dam engineers learned the risks of dam erosion and destruction associated with large floods, and it was usual to design dams with a spillway system[8]. Flood waters were discharged above the dam (overflow weir), below the dam (tunnel outlet) or beside the dam (overflow channel or tunnel outlet).

The Gold Creek embankment was designed and built on the same lines as most English and Australian earth dams during the 19th century (see Humber 1876, Smith 1971, Schnitter 1994). Examples include the Lough Island Reavy dam, UK (1840), the Kentmere Head dam, UK (1848), the High Bullough dam, UK (1850), the Yan Yean dam, Australia (1857), the second Bilberry dam[9], UK (1858?), the Dale Dyke dam[10], UK (1863), the Enoggera dam, Australia (1864), the Expedition Pass dam, Australia (1869), the Malmsbury reservoir, Australia (1870), the Lower Barden dam, UK (1873). All these dams were earth structures with a clay puddle core.

Several old earthen structures had a similar spillway disposition as the Gold Creek dam (i.e. with lateral overflow chute) : e,g., the Bilberry reservoir (spillway built in 1867), the Dale Dyke reservoir, the Expedition Pass dam.

The discharge capacity of the Gold Creek dam spillway was relatively large at the time (see table 2) but it was not one of the largest structures. The Marib dam, first built around B.C. 750[11], was 14-m high in its later stages compared to 26-m for the Gold Creek dam and the spillway system could pass up to 510 m^3/s : i.e., about 2.6 times the capacity of Gold Creek dam spillway (built in 1890).

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[8]Ancient names for the spillway include : waste waterway, wastewater weir, idle-discharge outlet, byewash, bywash.

[9]also called Holme Styes dam (BINNIE 1981), Holmfirth dam and Huddersfield reservoir (SMITH 1971). The first Bilberry dam was built between 1839 and 1843. It was a 20.4-m high earth dam with puddle clay corewall. The embankment failed on 5 February 1852 and 81 people were killed. The second dam was designed by J.F. LA TROBE BATEMAN (1810-1889) in 1843 and construction started in 1854.

[10]also spelled Dale Dike (e.g. International Commission on Large Dams 1984). The earth dam, built in 1858, failed in 1864 and more than 250 people were killed in the incident. The failure was probably caused by piping and percolation along the tunnels within the embankment.

[11]The dam lasted up to A.D. 575. Its destruction was recorded in the Koran.

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When considering the Gold Creek dam in its historical context, some interesting questions arise : how did the design engineers gain expertise on stepped spillway design ? did they use any existing structure(s) as reference(s) ? why did the engineers choose to make the steps in un-reinforced concrete ?

TRANSFER OF STEPPED SPILLWAY TECHNOLOGY

Design of stepped waste waterways

The 1890 Gold creek dam spillway exhibits an interesting staircase geometry. The stepped chute contributes to the dissipation of the kinetic energy of the overflow. It is now recognised that a stepped spillway can be extremely efficient in dissipating up to 90% of the kinetic energy of the flow (Chanson 1995a, pp. 102-112).

Stepped spillways date back to the pre-Christian era, and in a review of their history, Chanson (1995a, pp. 23-43) reported that they were a common feature of the 19th century reservoir designs (table 2). In the USA, for example, nearly one third of the dams built during the 19th century had a stepped spillway. In France several masonry dams built between 1850 and 1900 had lateral stepped spillways (fig. 7, appendix 1), while Humber (1876) illustrated several English stepped spillways in his comprehensive treatise. In that context, it is believed that the Gold Creek dam waste waterway followed the design trends of the 19th century.

Further the authors believe that the design engineers of the Gold Creek dam spillway were aware of similar designs in England, in Victoria (Australia) and possibly in France.

Transfer of expertise in stepped spillway design

Influence from England

In some reports, Henderson quoted the book of Humber (1876) in which several stepped spillways are described : e.g., the Dale Dyke reservoir (plate 3, fig. 25), Halifax waterworks (plate 32, fig. 11 and 18), Manchester waterworks (plate 25, fig. 2 & plate 26, fig. 12 and 15), the Rotherham reservoir (plate 21, fig. 9). Further Humber stated explicitly : "The byewash will generally have to be made with a very steep mean gradient, and to avoid the excessive scour which could result if an uniform[12] 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 1976,p. 133) [footnote and underlining by the authors].

Experience in Victoria, Australia

Several stepped structures were built in Victoria (Australia) prior to the construction of the Gold Creek stepped spillway. Artificial cascades, drops, waterfalls and stepped channels were built as part of the Yan Yean scheme in 1883 to supply water to the city of Melbourne (Gibbs 1915). The Yan Yean project was supervised by Matthew B. Jackson, Chief Engineer for Waterworks, Melbourne City Council. Jackson (1825-?) was an experienced English engineer who was an expert witness at the Dale Dyke reservoir inquest in 1864 (Binnie 1981).

In Bendigo (Victoria), the Malmsbury Reservoir was completed in 1870. The 24 m high earth embankment is equipped with two lateral spillways. The right-bank spillway (also called Eastern spillway) is a masonry chute with a series of

[12]in the meaning of an uniform smooth channel bed (i.e. not stepped).

steps which are still in use today. In Victoria, also, the Goulburn weir was completed in 1891. The weir is an overflow stepped structure with 12 steps of 0.5-m height made of granite blocks and still used today. The authors believe that the Goulburn weir was probably designed prior to the Gold Creek stepped spillway.

There is evidence that the Brisbane engineers had good connections with Victorian engineers. Henderson was trained and worked in Victoria until 1878 when he moved to Queensland (Whitmore 1984). He worked with Joseph Brady (1828-1908) in Bendigo, Victoria. Brady surveyed and drafted the Yan Yean system in 1851, and he worked in Queensland between 1864 and 1869 where he designed in particular the Enoggera dam. It is certain that Henderson[13] was aware of the Malmsbury Reservoir spillway arrangement. Stewart was a North Welshman by birth. He studied at the University of Melbourne and then worked in Victoria for five years as a railway engineer before moving to Queensland (Whitmore 1996).

Influence of French expertise

Another influence might have been the French experience in stepped spillway design. Between 1850 and 1900 several masonry dams were constructed with a lateral stepped spillway : e.g., the Gouffre d'Enfer dam (fig. 6), the Ternay dam, the Pas du Riot dam (fig. 7), the La Rive dam and the La Tâche dam[14]. The first of these structures was designed by the French engineer Delocre (1828-1908) while the next three structures were built as replicas of the Gouffre d'Enfer dam (Wegmann 1911, Smith 1971). In his book, Humber (1876) mentioned the work of Delocre and the construction of the Gouffre d'Enfer dam built in 1858 (Humber, p. 123) (see App. 1). It is likely that Australian engineers knew these references.

In summary, the authors are convinced that the design engineers gained experience from stepped weir designs in England, in Victoria and possibly in France. The selection of a staircase spillway was a logical choice to maximise energy dissipation and to reduce scour along the spillway chute and at the foot of the byewash where the flow is turned through an angle of 90 to 120 degrees to the right.

1890 STEPPED SPILLWAY CONSTRUCTION MATERIALS

The unusual feature of the spillway at Gold Creek is that, in 1890, the floor was constructed of un-reinforced concrete without protection against erosion from the flowing water.

Although concrete was widely used by the Roman and Byzantine engineers, it was largely shunned as a building material until the 19th century when it was "re-introduced" as a construction material. In the 1850s, some houses were built of it in Australia and Australia's first concrete dam at Lower Stony Creek, near Geelong, Victoria, was completed in 1875 (Lewis 1988, Cowan 1995). Several other hydraulic structures were constructed in concrete in the 1880s (e.g. Beetaloo dam, South Australia in 1890, Goulburn weir, Victoria in 1891) but, at the time of building the Gold Creek dam spillway in 1890, concrete was still not seen as a basic construction material, least of all for flooring stepped wastewater spillways.

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[13]HENDERSON arrived in Bendigo in 1851 (MACKAY 1891).

[14]One author (CHANSON) visited the five French dams in December 1994.

For the construction of spillway steps, concrete was an unusual material to use in 1890 anywhere in the world. Traditionally, and indeed until well into the twentieth century, blocks of granite, ashlar, or other hard cut stone were used, particularly on the horizontal faces of the steps : e.g., Goulburn weir (Australia), Pas du Riot dam (France), Tytam dam (HK), Pedlar river dam (USA) (see Chanson 1995b). Even the stepped spillways associated with gravity dams built in concrete generally used cut stones to face the steps. Examples are the Tytam dam, the Goulburn weir, the Croton falls dam (USA).

Comments

The reason for the general reluctance to accept concrete as a suitable material for flooring stepped spillways was the fear that it would not withstand the various hydrodynamic loads to which it would be exposed without erosion, scouring or some form of deterioration. Moreover, it must be remembered that nineteenth century unreinforced concrete was weaker than today's concrete, the maximum allowable stress being less than 2 MPa[15]. The conventional cut stone protection was used in a similar manner to conventional concrete protection layer on the downstream face of today's Roller Compacted Concrete [16] weirs.

The authors believe Gold Creek to be the earliest stepped spillway floored entirely in concrete in Australia and probably one of the earliest in the world (if not the first) to use this construction material for such an application. It is still in reasonable good condition as shown by recent photographs and inspections of the dam. The original concrete stepped spillway is still in use. The shape of the steps is still intact and the spillway operates properly despite minor damage (e.g. fig. 5). The longevity of the spillway is a fine tribute to the quality of the design and construction. Note that the small amount of sediment material and debris carried during floods might have contributed to the effectiveness of the concrete stepped spillway.

INSIGHT INTO OPERATIONS AND REFURBISHMENT

Application to stepped spillway operation and design

The results of the study provide some insights into the design of old stepped spillways. The information may be valuable to professionals associated with the maintenance, operation and refurbishment of such a type of spillways. Indeed numerous old stepped chutes are still in use today. For example, the Pas-du-Riot dam, the Cantref reservoir, the Goulburn weir and the New Croton dam (masonry spillways), the La Tâche, Ternay and Gouffre-d'Enfer dams (unlined rock spillways), the Gold Creek dam (concrete spillway). These structures have behaved satisfactorily over more than a hundred years thanks to an adequate maintenance. Indeed the lack of maintenance can lead to partial or complete failure : e.g., the Arizona Canal dam in 1905, the Kobila dam in 1948. Carefully-maintained structures may last, however, over few centuries : e.g., the Kobila dam was used 362-years before failure, the Pabellon dam built in the 1730s was still in use in the 1950s, the Gold Creek dam.

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[15]SMITH (1971) indicated that the concrete of New South Wales dams built between 1890 and 1910 had a compressive strength no greater than 2.1 MPa.

[16]Roller Compacted Concrete (RCC) is a no-slump consistency concrete that is placed in horizontal lifts and compacted by vibratory rollers.

It is worth comparing the Gold Creek spillway characteristics with contemporary and modern spillway standards with respect to discharge intensity and step dimension. Figure 8 presents discharges per unit width and step heights of stepped spillways as functions of the year of completion. Recent RCC stepped spillways and unlined rock cascades (e.g. La Grande 2, Canada, Dartmouth, Australia) are included. Overall figure 8 indicates that 19th century stepped spillways were designed with similar step heights as today (fig. 8b) but the maximum discharge capacity was somewhat smaller (fig. 8a).

Stepped spillway refurbishments

In recent years, new hydrological data in Europe, America and Asia, and new risk assessment methods lead to an increase of the maximum discharge capacity of ancient spillways. Often the discharge capacity has been enhanced by a new spillway intake without spillway modification (e.g. Pas-du-Riot, Gold Creek, La Tâche dams) (table 3). In such cases the designers must check the new flow conditions on the spillway, the flow regime and the hydrodynamic forces to ensure that the original spillway can pass the new maximum discharge without damage. In particular it has been shown that the rate of energy dissipation on the stepped spillway decreases with increasing discharges (Chanson 1995a). The larger residual flow energy (with the new maximum discharge) might induce some damage downstream of the spillway.

The authors believe that the knowledge of the original design procedure can assist greatly the engineers during a refurbishment : e.g., by providing practical information on the design limitations and constraints.

SUMMARY AND CONCLUSION

The Gold Creek dam is an earth embankment built at the end of the 19th century. The general design of the earthen structure and the location of the spillway was similar to British and Australian dams built between 1850 and 1900. A number of these structures, including the Gold Creek dam, are still in use today. The stepped spillway of Gold Creek dam was built in 1890. It is an unique structure : i.e., it was the only stepped weir built in Queensland during the last century and the construction material (i.e. concrete) was most unusual.

The characteristics of the spillway and its modifications are detailed and compared with other 19th century structures (table 2). The geometry of the spillway was comparable to 19th century stepped weirs. The maximum discharge capacity was also alike. The authors noted with interest that today's maximum spillway capacity is limited by the height of the sidewall of the steep channel and not by the crest design.

It is believed that, in the 1880s, the Brisbane engineers gained expertise on stepped spillway design from experience in England, Victoria (Australia) and possibly France. The reason for the selection of concrete as construction material is still unclear and it had no precedent in Australia or elsewhere for a stepped spillway.

Photographs of the present structure show a structure in reasonably good condition.

Altogether the present investigation may assist professional engineers associated in the operation, maintenance and refurbishment of old stepped spillways. It provide new information on one sound design (Gold Creek dam spillway) and it develops a comparative analysis with similar existing structures (e.g. New Croton, Cantref, La Tâche reservoirs).

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LIST OF SYMBOLS

g	gravity constant : $g = 9.80$ m/s^2 in Brisbane, Australia;
h	step height (m);
l	step length (m);
Q	water discharge (m^3/s);
q	water discharge per unit width (m^2/s);
W	channel width (m);
α	channel slope;
σ_c	compressive strength (Pa) of concrete material at 90 days;

Abbreviations

ANCOLD	Australian National Committee on Large Dams;
ICOLD	International Commission on Large Dams;
RCC	Roller Compacted Concrete.

APPENDIX 1 - DELOCRE, HUMBER AND TRANSFER OF STEPPED SPILLWAY DESIGN

Delocre (1828-1908) was a professional engineer from the Administration des Ponts et Chaussées (France). He developed a method to design masonry gravity dams which was first applied to the Gouffre d'Enfer dam (Delocre

1866). His work adopted the idea and analysis of the French engineer M. de Sazilly (1812-1852). Their design method is considered as the basic analysis of the stability of gravity dams.

In his book, Humber (1876) was appreciative of the French savoir-faire : "The theory of masonry dams forms the subject of a very interesting and rather elaborate memoir by Delocre of the Administration des Ponts et Chaussées" (p. 123). The reputation of the Gouffre d'Enfer dam[17] was well known to him : "The dam of the Furens reservoir, as actually constructed, is shown on Fig. 86" (p. 125). Thus he was well aware of the expertise of French engineers and of their applications.

The writings of Humber suggest that the work of de Sazilly and Delocre and the design of the Gouffre d'Enfer dam were well known from British engineers. Further their analysis was later extended by W.J.M. Rankine (1820-1872) (Rankine 1872).

The Gouffre d'Enfer dam is located on the river Furan, upstream of the city of Saint-Etienne, France (fig. 6). It was designed by the engineers Delocre (1828-1908) and Graeff (1812-1884) for the flood protection of the city of Saint-Etienne and completed in 1866 (Smith 1971). Both the dam and its reservoir are still in use today but the reservoir level was permanently lowered in the 1990s to enhance the maximum spillway capacity and flood protection.

Three masonry dams were built subsequently as replicas of the Gouffre d'Enfer dam : the Ternay dam, completed in 1867, to supply water to the city of Annonay, France[18]; the La Rive dam (also called the Ban dam), completed in 1870, to supply water to the city of Saint-Chamond, France[19]; the Pas du Riot dam, completed in 1873, and located few kilometres upstream of the Gouffre d'Enfer dam, to supply water to the city of Saint-Etienne (fig. 7)[20].

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[17]It is sometimes called the Furan dam or Furens dam by some researchers (e.g. SMITH 1971).

[18]The Ternay dam is still in use but its stability was reinforced with a downstream rockfill embankment.

[19]The La Rive dam still stands but it is no longer in use. The structure is considered unsafe and a large tunnel outlet was drilled through the dam in 1994-1995 to prevent the rise of water level upstream of the masonry structure.

[20]The Pas du Riot dam is still in use in its original design. The spillway crest was lowered in 1990 to increase the maximum spillway capacity, the original stepped channel being still used.

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Table 1. Characteristics of the Gold Creek dam spillway from 1885 until now

Characteristic (1)	1885 spillway (2)	1887 spillway (3)	1890 spillway (4)	After 1975 (5)
Spillway crest				
Crest design :	Unlined rock (?)	Unlined rock (?)	Broad-crested weir (unlined rock and concrete floor, nearly-horizontal bed)	Broad-crested weir (unlined rock and concrete floor, nearly-horizontal bed)
Crest level :	3.048 m (10 ft) below dam crest	3.048 m below dam crest	3.048 m below dam crest	4.267 m (14 ft) below dam crest
Crest width :	40 m (130 ft)	55 m (180 ft) ([b])	55 m	52 m
Steep chute				
Transversal shape of the spillway :	Unlined rock	Unlined rock	quasi-circular flat arc	quasi-circular flat arc
Spillway geometry :	Unlined rock	Unlined rock	Stepped channel	Stepped channel
Channel width W :	40 m (130 ft)	55 m (180 ft)	55 m	55 m
Number of steps :	N/A	N/A	12 (all identical)	12 (1st small step and 11 identical steps)
Step construction	N/A	N/A	Concrete on rock foundation	Concrete on rock foundation
Step geometry :	N/A	N/A		
step height h :			1.5 m (5 ft)	1.5 m (0.4 m at 1st step)
step length l :			4 m (14 ft)	4 m (incl. at 1st step)
Channel slope :	(--)	(--)	21 deg.	21 deg.
Sidewall construction				
crest :	Brick	Brick	Brick	Brick and concrete
steep channel :			Rendered concrete	Rendered concrete
Sidewall height :				
crest :	1.5 m (5 ft)	1.5 m	1.5 m	2.7 m
steep channel :	(--)	(--)	1.4 m	1.4 m
Discharge				
Maximum spillway capacity Q :	(--)	(--)	200 m^3/s ([a])	278 m^3/s ([a])

Notes :

Most information is based upon the authors' observations and calculations.

N/A : not applicable.

(?) : uncertain.

(--) : information not available.

([a]) : maximum discharge capacity calculated by Chanson and Whitmore (1996)

([b]) : the widening was originally designed for 20 feet but it was decided to widen the channel by 50 feet

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Table 2. Gold Creek dam stepped spillway in a historical context

Name (1)	Year (2)	Dam height (m) (4)	Slope α (deg.) (5)	Construction (6)	Comments (7)
River Khosr dams, Iraq	B.C. 694	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. Called Ajilah dams.
		> 1.4	30		Upper dam. 5 steps.
Kasserine dam, Tunisia	A.D. 100?	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.
Khan dam, Uzbekistan	1000?	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?	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?	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.
Kobila dam, Slovenia	1586	10		Timber cribs filled with rocks. Destruction in 1948.	Overflow spillway. Crest length : 20 m.
St Ferréol dam, France	1671	32		Waterfalls, cascades, cataracts.	Earth dam with masonry spill weir followed by stepped cascades. Water supply for the Canal du Midi.
Kamenskii dam, Russia	1730?			Timber crib dam.	Overflow spillway designed by G.W. HENNIN. 5 steps. Design discharge ~ 5.2 m^2/s.
Pabellon dam, Mexico	1730?	24		Buttress dam. Rubble masonry set in mortar.	Spanish construction. Discharge over the crest. 3 steps.
Penarth weir, UK	1818	2.4		Masonry crest.	Stepped weir on the river Severn. 2 steps (h ~ 1.2 m). W = 42 m.
Ascutney Mill dam, USA	1834-35	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	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.
Gouffre d'Enfer dam, France (also called Furens or Furan dam)	1866	60		Curved gravity dam in masonry. Unlined rock spillway channel.	Lateral spillway followed by un-lined rock cascade. Refurbishment of spillway intake in 1990's. Cascade still in used today.
Bilberry dam, UK	1867	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.

Table 2. Continued

Name (1)	Year (2)	Dam height (m) (4)	Slope α (deg.) (5)	Construction (6)	Comments (7)
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 1990's. Still in use today.
Val House dam, UK	1868	17.4	30	Earth dam. Spillway : concrete floor and ashlar steps.	Lateral overflow spillway with stepped crest (60-m long, 3 steps, h = 1.5 m) followed by flat slope, then stepped channel (W = 12.2 m, 27 steps, h = 1.5 m). Maximum discharge : 160 m^3/s.
Ulley dam, UK	1870?	12.6	12.7	Earth embankment. Spillways : ashlar pitching set on concrete.	Two lateral overflow stepped spillways (W = 1.83 m, h = 0.69 m, l = 3.05 m).
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.
			16.8 (cascade)	Step made with crib and masonry (h = 0.74 m, l = 2.43 m)	Right bank (eastern) spillway : masonry chute with a masonry drop and a series of 6 steps at downstream end (W ~ 20 m). Discharge capacity : 310 m^3/s. Still in use today.
				Masonry smooth chute.	Left bank (western) spillway. Discharge capacity : 86 m^3/s.
Pas-du-Riot dam, France	1873	36		Curved gravity dam made of Cyclopean masonry.	Maximum discharge : 65 m^3/s. Lateral masonry 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	42		Earth embankment with masonry spillways at each end.	Maximum discharge : 43 m^3/s. Flat steps at upstream end.
Arizona canal dam, USA	1887	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	29	65	Gravity dam (40% stone, 60% concrete).	Broad crest (6.4 m) followed by 9 steps (h = 3.05 m).
Gold Creek dam	1890	26	21	Earthfill dam (built in 1885). Concrete spillway built in 1890 over the eroded unlined rock spillway.	Broad-crest followed by 12 steps (h = 1.5, l = 4 m). Maximum discharge : 200 m3/s. Crest level lowered by 1.4-m in 1975. Spillway still in use today.
Goulburn weir, Australia	1891	15	~ 30	Concrete gravity weir with horizontal steps made of granite blocks.	Design discharge : 1,970 m^3/s. Record discharge 1,982 m^3/s on 7 June 1917. W = 141 m. 12 steps (h = 0.5 m). Gate refurbishment in 1986. Still in use today.
La Tâche dam (also called Chartrain dam), France	1891	51	32.6	Curved gravity dam in masonry.	Unlined rock spillway, 10 steps (h = 2.4 to 5.4 m) followed by 9 masonry steps (h = 0.2 to 0.3 m). W = 2.2 m. Refurbishment of spillway intake in 1994.

Table 2. Continued

Name (1)	Year (2)	Dam height (m) (4)	Slope α (deg.) (5)	Construction (6)	Comments (7)
Cantref dam, Wales UK	1892	23.8	20 to 34	Earth dam with pudde 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.
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 today.
Urft dam, Germany	1905	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	90.5	53	Masonry gravity dam. 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	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 to 0.91 m.
Warren dam, Australia	1916	17.4	35	Concrete gravity dam. Overtopped in 1917. Spillway re-designed in 1926.	Maximum spillway discharge : 100 m^3/s. W = 35 m. h = 0.37 m.
Eildon Weir, Australia	1927	42.7	56 and 22	Rockfill dam with concrete spillway section. Spillway re-designed in 1936. New dam in 1955.	Maximum discharge : 566 m^3/s. Step height : h = 1.83 m. 14 steps (56 deg.) followed by a flat smooth slope and a 22-degree stepped channel. W = 208 m.

Reference : Chanson (1995b)

Notes :

h : step height

l : step length

W : channel width

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Table 3. Some examples of stepped spillway refurbishment associated with an increase of the maximum spillway discharge capacity

Dam (1)	Original maximum discharge capacity (2)	New maximum discharge capacity (3)	Remarks (4)
Gold Creek dam, 1890, Australia	200 m^3/s	280 m^3/s (1975)	h = 1.5 m. W = 55 m. Concrete steps.
Winterburn dam, 1893, UK	110 m^3/s	270 m^3/s (1995)	h = 2.26 m. Masonry construction.
L'Echapre dam, 1897, France	34 m^3/s	60 m^3/s (1989)	h = 3.2 to 4.1 m. W = 3 m. Unlined rock (gneiss).
Cantref dam, 1892, UK	157 m^3/s	157 m^3/s	Spillway refurbishment (between 1984 and 1989) by addition of a reinforced grass spillway in the middle of the dam (40 m^3/s) and two siphons (73 m^3/s) for PMF outflow of 255 m^3/s.

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(b) Sketch of the 1890 spillway (after the original photograph taken after spillway completion)

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Stepped spillway (view from downstream)

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Fig. 7. Photograph of the Pas du Riot dam (taken on 3 December 1994)

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(a) View of the downstream dam face from the left bank.

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Fig. 8. Comparative performances of stepped spillways built since 1830

(a) Discharge per unit width q (m^2/s)

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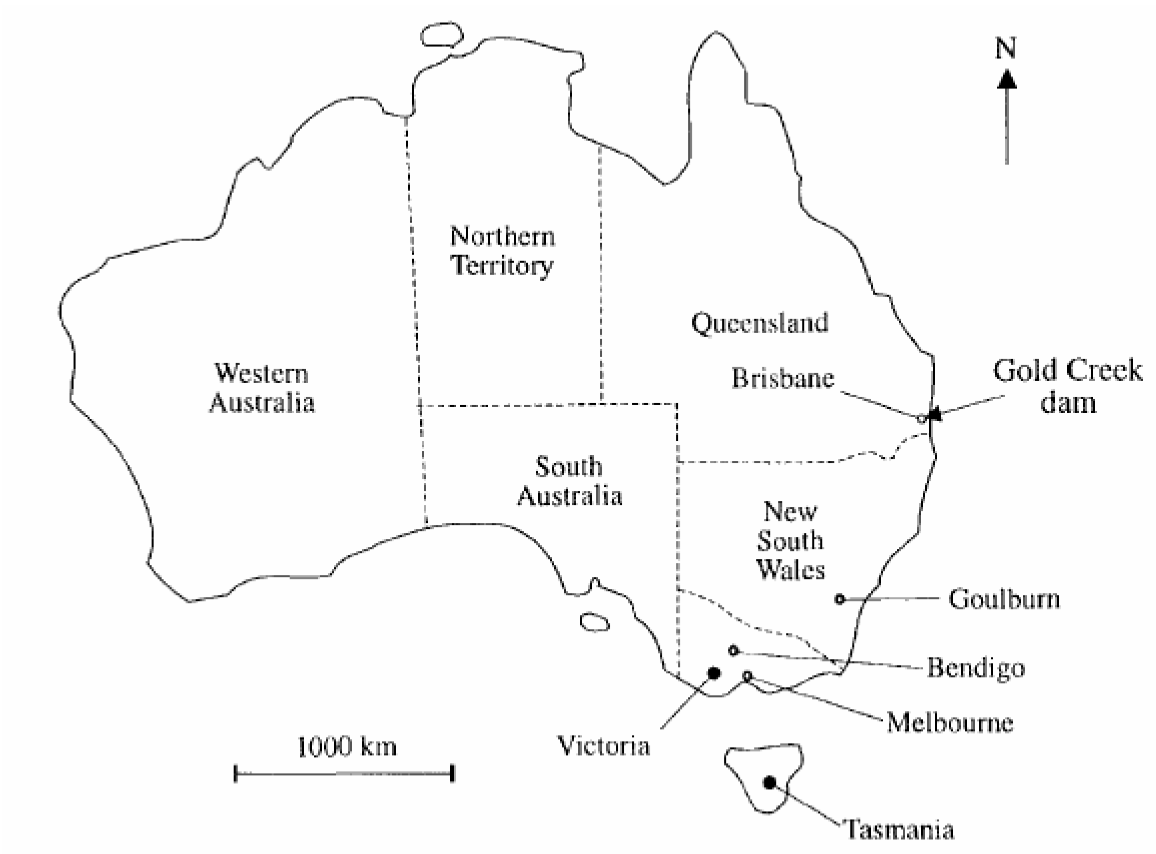

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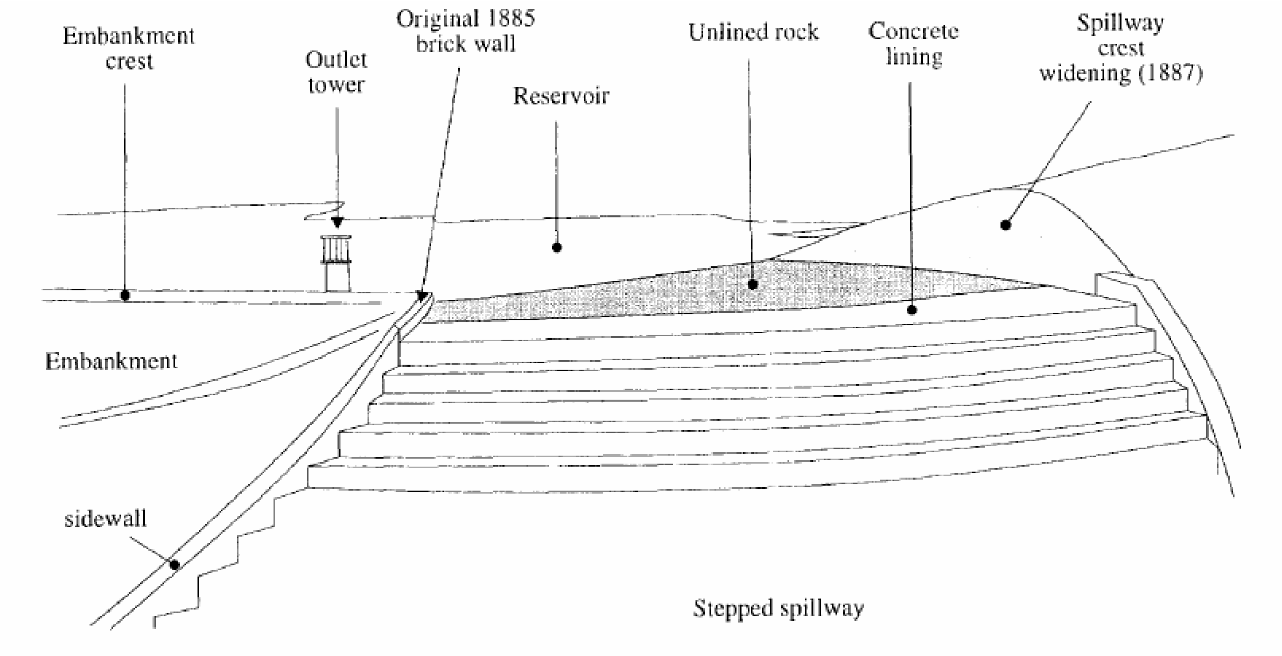

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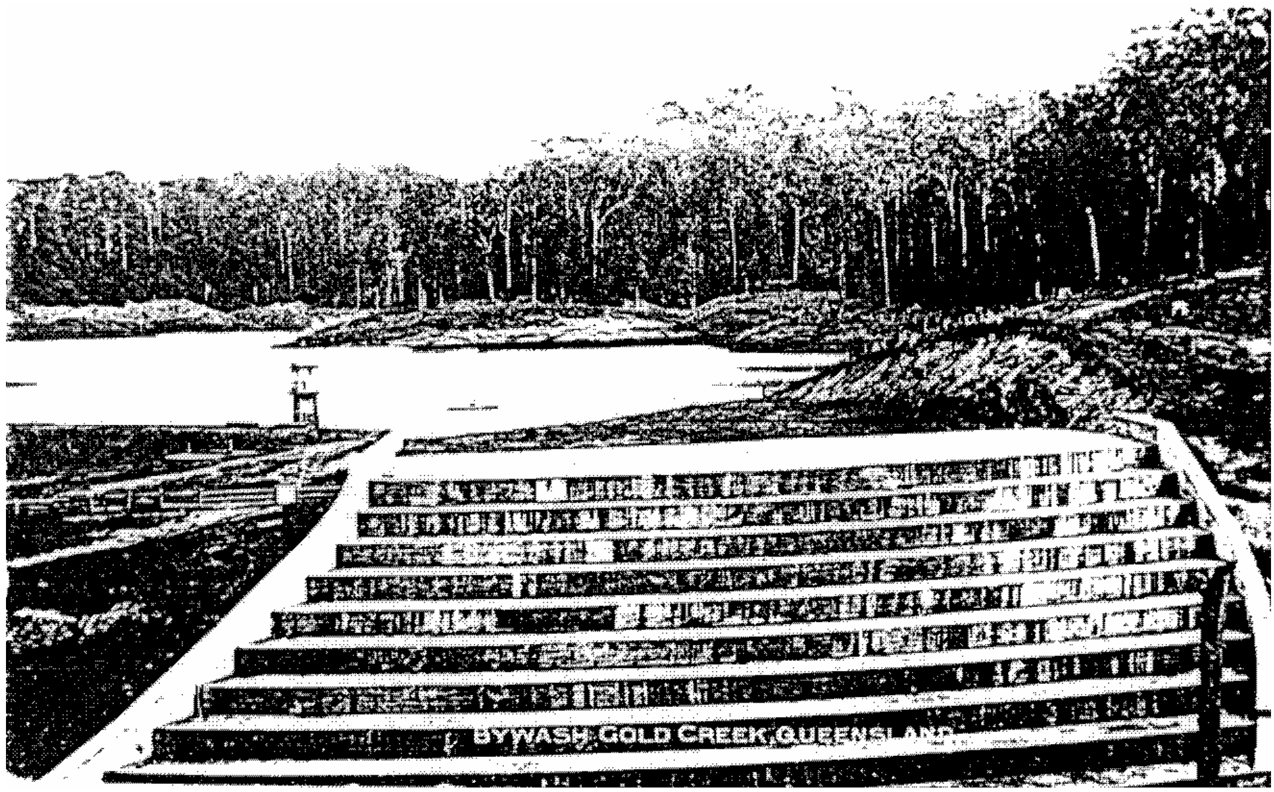

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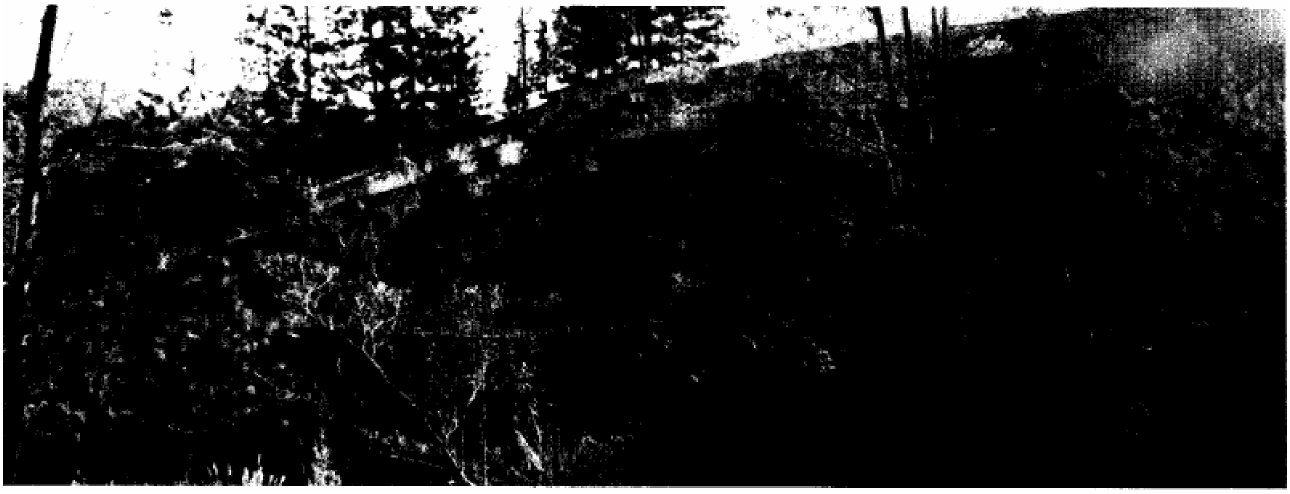

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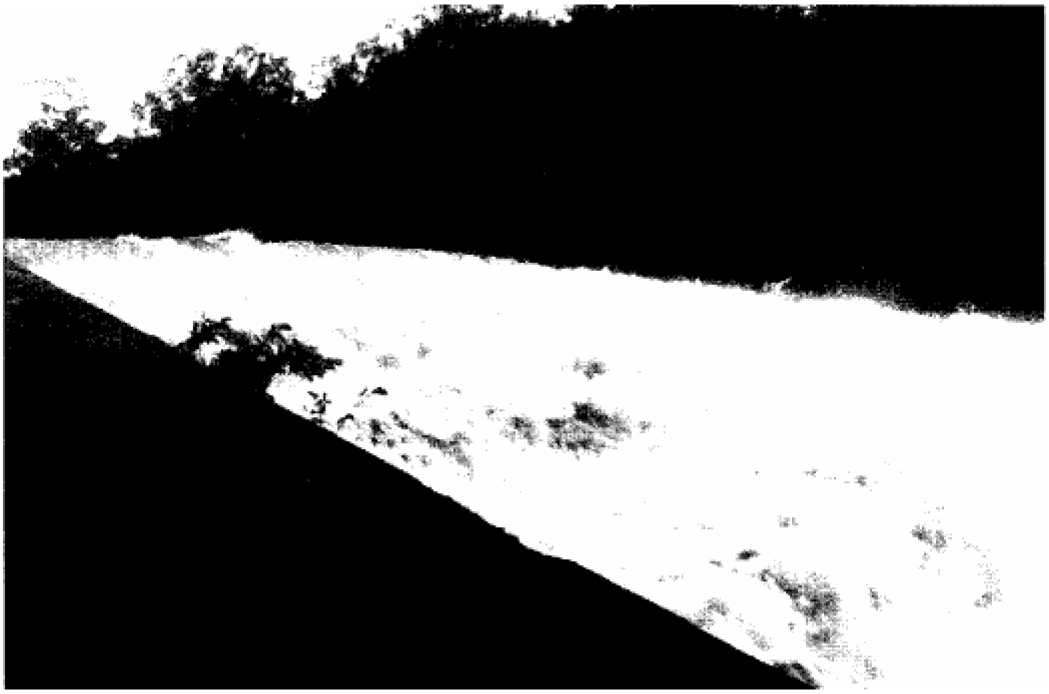

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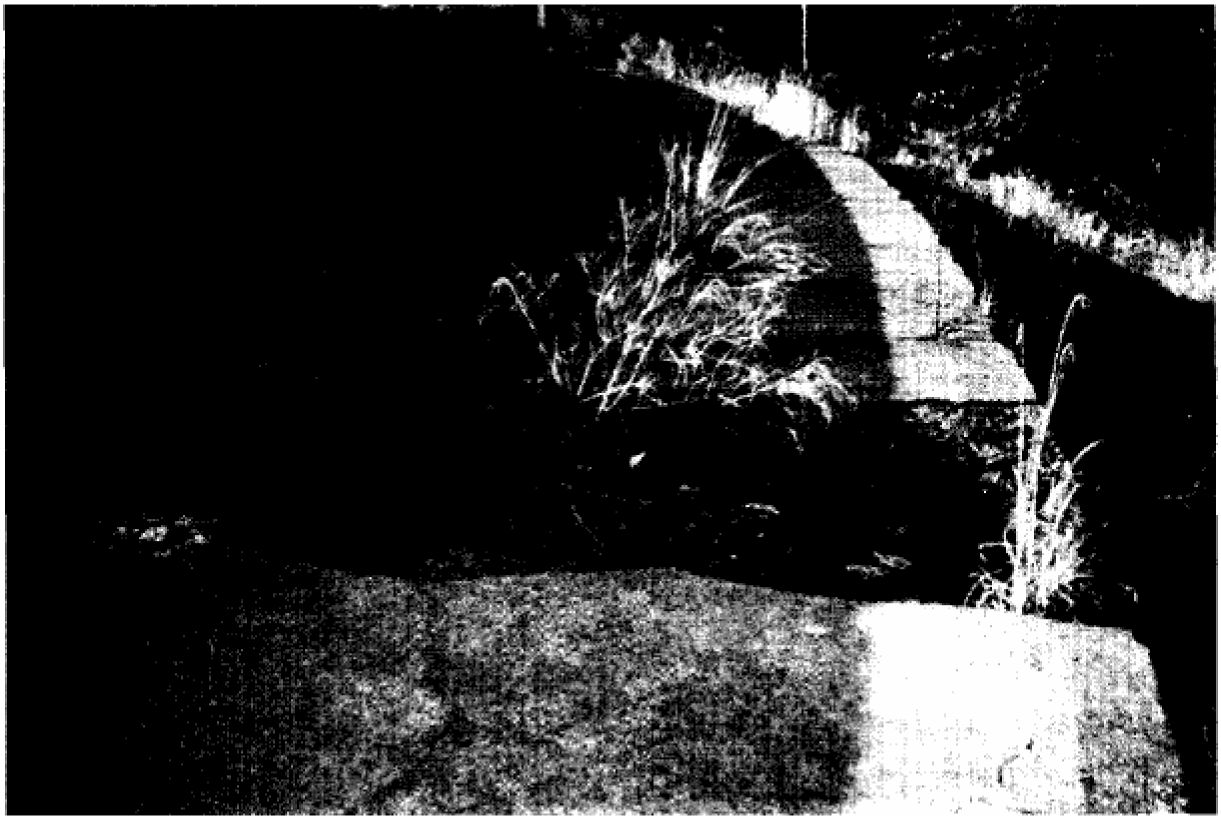

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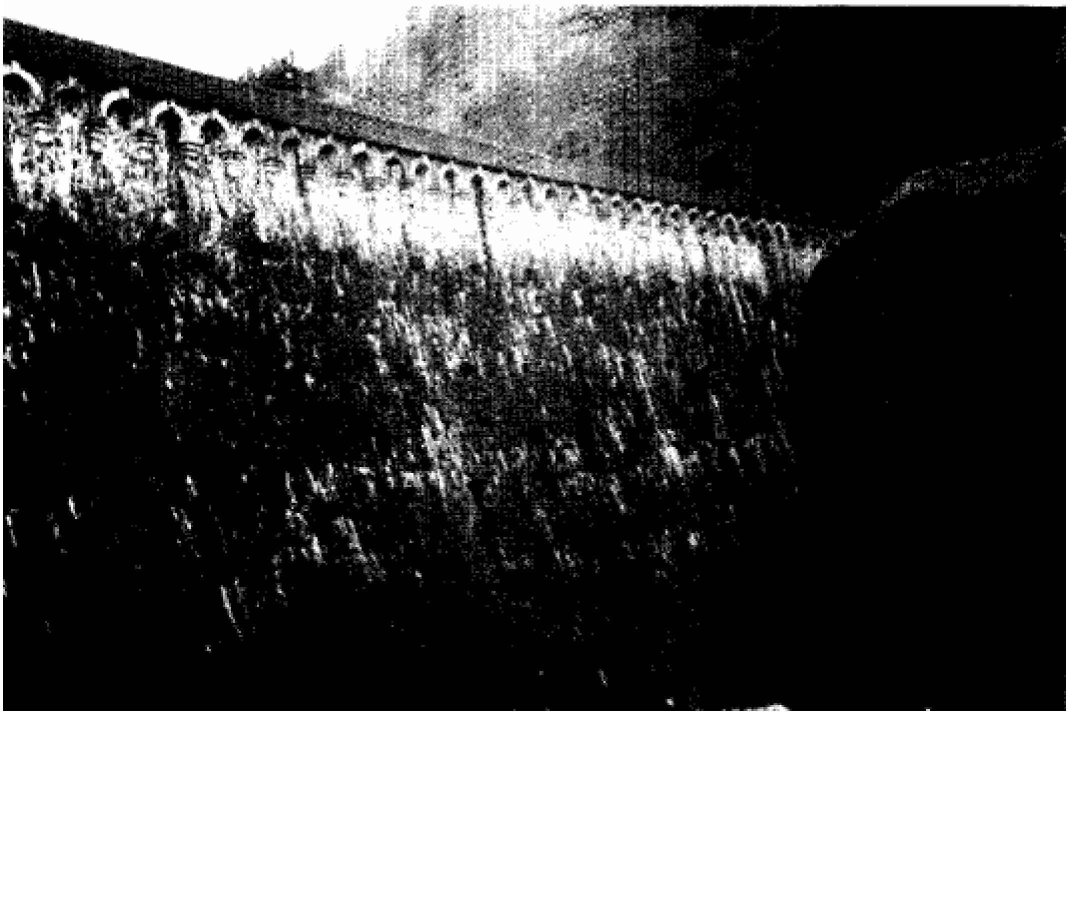

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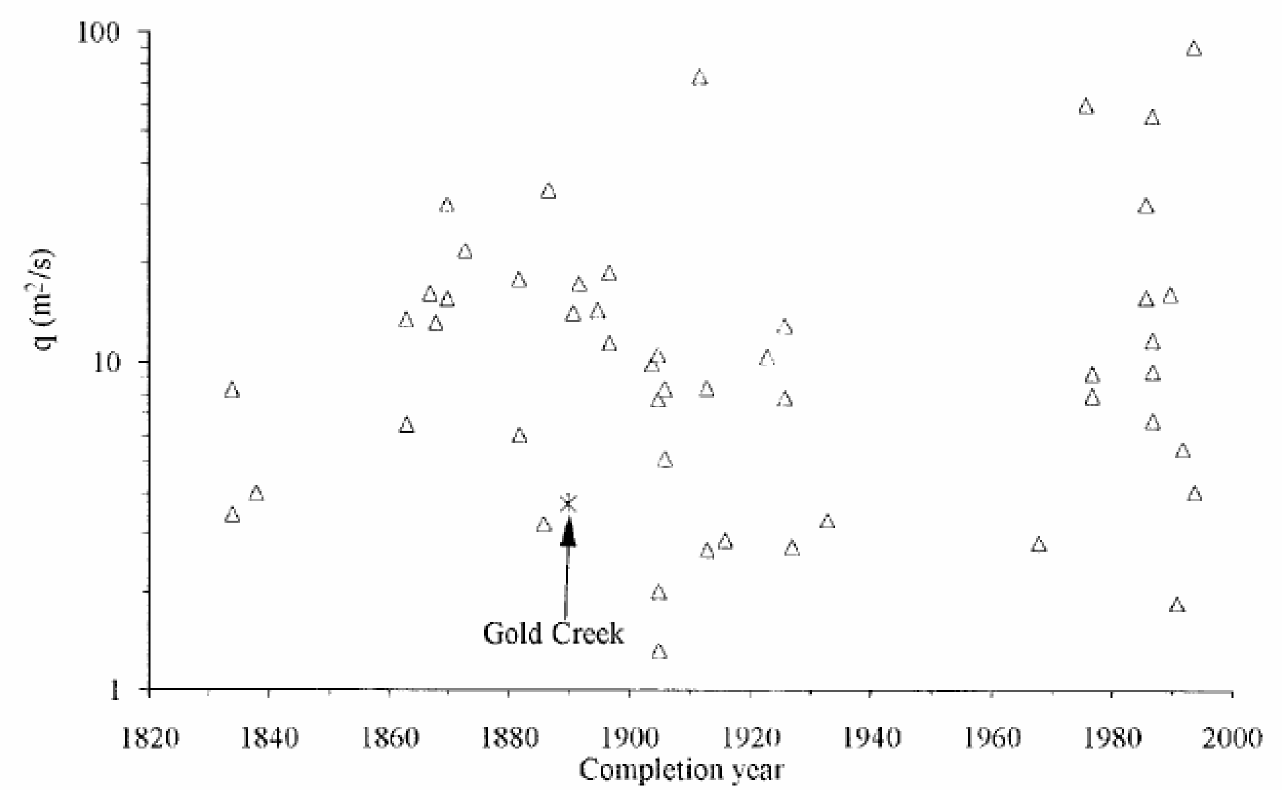

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