Rapid Reservoir Sedimentation of Four Historic Thin Arch Dams in Australia

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Abstract: Since the discovery of the Australian continent by Europeans, the development of the country has been closely linked with the development of water resources. At the end of the 19th century, several arch dams were built in New South Wales, four of which are described in this paper. The four dams (Moore Creek, Gap, Korrumbyn Creek, Quipolly) had similar features, i.e., water supply storage with thin concrete arch wall. Despite their technological sophistication at the time, they became fully silted very quickly, with each one being used for less than 25 years. Although their structural design was advanced, the design of the reservoir systems (dam, lake, and catchment) was a failure. The designers did not take into account correctly the soil erosion and sediment transport processes, and no soil conservation practice was considered. The experience gained from these failures may be of use today to prevent practicing engineers from making similar mistakes.

INTRODUCTION

Since the discovery of the Australian continent by Europeans, the water supply of the early settlements was always an important concern. The first inland expeditions usually followed the major rivers. The new settlers were attracted farther inland by the search for better pasture and, later, by the discovery of gold. The economic development of the colony, however, was significantly affected by the lack of regular water supply.

The early settlements took place in the southeast in what is now Victoria and New South Wales (Fig. 1), and numerous dams were built to provide regular water supply throughout the year. Nearly 90% of the 19th century reservoirs were built primarily for water supply (drinking water, stocking, and irrigation) but also for the mining industry (e.g., the two Sheba dams in 1888 and the Junction Reefs dam in 1897). Smaller dams were built for water supply for railway steam engines at the end of the 19th and beginning of the 20th centuries (e.g., Gap weir, 1902). By tradition most Australian large dams were earth embankments following the English experience. However several thin arch dams were built, in New South Wales primarily (e.g., Moore Creek dam in 1898 and Redbank Creek in 1899).

ARCH DAMS IN AUSTRALIA IN THE 19TH AND EARLY 20TH CENTURIES

One of the first significant dam structures built in Australia was the Parramatta dam, near Sydney. Built between 1851 and 1856, the 12.5-m high wall [before dam heightening of 3.35 m in 1898 (Wade 1909)] was contemporary with the Zola dam, in France. The dam was designed by P. Simpson (1789–1877), E. O. Moriarty (1824–1896), and W. Randle (Ash and Heinrichs 1996) with a cylinder shape. It is worth noting that Simpson was a former officer of the Royal Navy and Moriarty was a naval engineer. The authors believe that both engineers were familiar with the calculations of shells and ship hulls and, hence, with the thin cylinder formula (see Appendix I).

The Parramatta dam was the precursor of a series of thin arch dams built in New South Wales (NSW) by the state's Public Works Department under the successive supervision of C. W. Darley, L. A. B. Wade, and E. M. de Burgh between 1896 and 1920 (Wade 1909; de Burgh 1917). Altogether, more than 20 thin arch dams were built by the NSW Public Works Department and the arch dam design example was followed in other states (e.g., Barossa dam, 1902, South Australia; Sorell Creek dam, 1916, Tasmania) and by the NSW Railway Department. The design of the Australian thin arch dams was based on the thin cylinder formula (Wade 1909; de Burgh 1917) and it is probably a world first in the standardization of this design technique. At the time, the dams were recognized as advanced designs in Europe and the U.S. (Schuyler 1909; Wade 1909; Wegmann 1922; Smith 1971; Schnitter 1994). Wegmann [in the discussion of Wade (1909)] stated that, in his opinion, "the curved dams built . . . in New South Wales had been designed more logically" than any other arch dams or curved-gravity dams.

Contemporary arch dams include the Zola dam (France, 1854), the Abbeystead dam (U.K. 1881), Bear Valley dam (U.S., 1884), the Sweetwater dam (U.S., 1888), and the Upper Otay dam (U.S., 1900). All were single-arch designs similar to the Australian dams. The first double-curved arch dam was completed in 1903 (Ithaca dam, U.S.) and the first variable radius arch dam was built in 1914 (Salmon Creek, U.S.) (Wegmann 1922; Schnitter 1994).

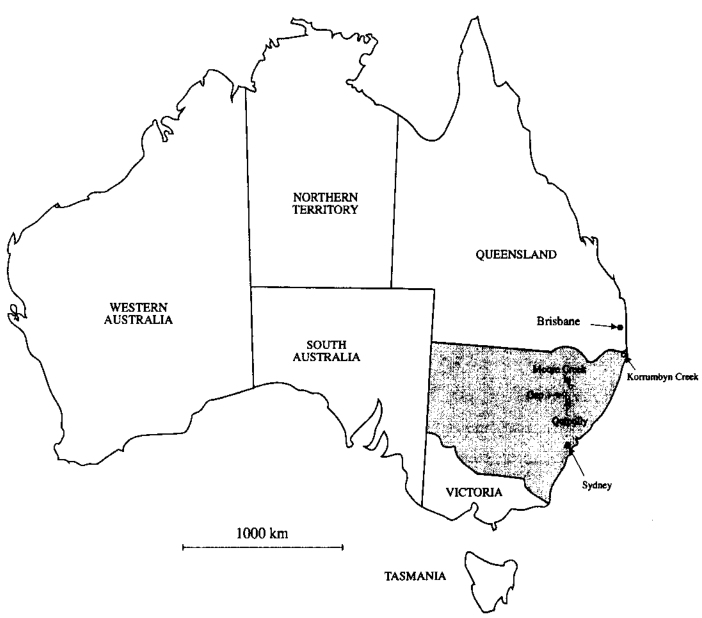

FIG. 1. Reservoir Locations

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RESERVOIR SEDIMENTATION

The primary characteristic of a water supply dam is its reservoir storage capacity, which is an economic and political asset. A reservoir interacts, however, with its catchment, often acting as a sediment trap, and the life expectancy of a reservoir is usually less than 100 years because of siltation. Reservoir sedimentation results from soil erosion, sediment transport, and sediment trapping by the reservoir. It is affected by the climate and hydrology of the catchment, the water and sediment chemistry, the vegetation cover, and land use, including man-made erosion.

Altogether, reservoir sedimentation is associated with a loss of reservoir capacity and often with loss of fertile soils.

Several Australian thin arch dams are still in use today, e.g., the Parramatta dam. However, some were used for less than 25 years despite their advanced structural design. The reservoirs silted up very rapidly and the dams became a source of embarrassment. In the present paper, the history of four reservoirs built between 1897 and 1932 that are fully silted today (Fig. 2–5) is described, and the causes of failure are analyzed.

HISTORY OF FOUR DAMS

Overview

The characteristics of the four reservoirs and dams are summarized in Tables 1 and 2. In Table 3, the chronology of main dates are summarized and compared with major climatic events that affected the Australian continent: El-Niño, La Nina, and drought. The El-Niño current and Southern Oscillation (ENSO), a global climatic change caused by warmer waters in the Pacific Ocean, alternates with colder conditions called La Nina. In eastern Australia, droughts are experienced habitually during an El-Niño, whereas floods are often observed during a La Nina.

Three dams were designed by the NSW Public Works Department; the fourth dam (Gap weir) was built by the state's Railway Department. Three reservoirs are located within inland catchments forming the Murray-Darling basin. The fourth reservoir (i.e., Korrumbyn Creek) is within the Tweed River catchment, which drains to the Pacific Ocean (Fig. 1).

Moore Creek Dam

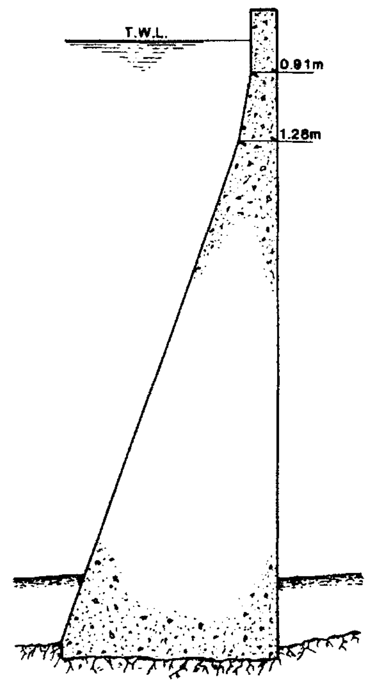
The Moore Creek dam was completed in 1898 to supply water to the town of Tamworth, NSW. The 18.6-m-high dam was designed with advanced structural features, i.e., a thin single-arch wall (7.7 m thick at base, 0.89 m thick at spillway crest, 0.87 m thick at dam crest) made of portland cement concrete (Table 2). The arch wall had a vertical downstream face and a battered upstream face (Fig. 2). The thin arch extended with a left-bank gravity cross section with downstream inclined face. The dam was equipped with an overall spillway and two bottom outlets (a scour valve, i.e., a bottom outlet structure used to release silty waters and reduce the sedimentation rate, and a pipe outlet).

Between 1898 and 1911, the reservoir was filled with 85,000 m^3 of sediment. Observations recorded at the time suggested that most siltation took place during the floods of February 1908 and January 1910. In 1924 the reservoir ceased completely to supply water because it was fully silted. The dam is still standing today and listed in the world register published by the International Commission in Large Dams (1984).

Gap Weir

Completed in 1902, the Gap weir is located near the Gap railway station, 5 km from the railway junction of Werris

(a)



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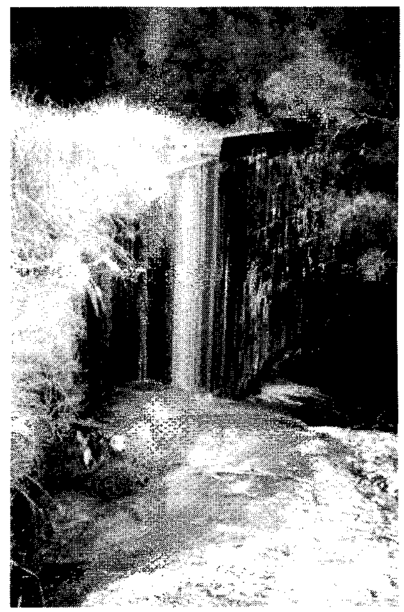


(c)

FIG. 2. Moore Creek Dam (1898): (a) Cross Section of Dam Arch; (b) View from Right Bank of Downstream Vertical Wall (1997 Photograph); (c) View from Downstream Showing Overfall Spillway Section, with Scour at Bottom of Wall behind Leftmost Tree (1997 Photograph)

TABLE 1. Characteristics of Reservoirs

Reservoir (1)	Location (2)	Stream (3)	Volume* of reservoir (m^3) (4)	Catchment area (km^2) (5)	Use (6)	Remarks (7)
Moore Creek dam, 1898	20 km north of Tamworth, NSW	Moore Creek	220 × E + 3	51	Water supply for the town of Tamworth	Complete reservoir siltation by 1924 (and probably earlier); bed-load siltation primarily
Gap weir, 1902	5 km west of Werris Creek, NSW	Werris Creek	—	160	Water supply for railway purposes	Sedimentation by suspension load; fully silted in 1924
Korrumbyn Creek dam, 1917–1918	Mount Warning National Park, 20 km west of Murwillumbah	South Korrumbyn Creek	27.28 × E + 3	3	Water supply for the town of Murwillumbah	Rapid bed-load sedimentation associated with jammed scour valve
Quipolly dam, 1932	20 km southeast of Werris Creek, NSW	Quipolly Creek	860 × E + 3	70	Water supply of the town of Werris Creek	Sedimentation volume larger than half of the initial storage by 1952; disused since 1955

*Original capacity.

TABLE 2. Technical Characteristics of Dams

Dam (1)	Maximum height[a] (m) (2)	Crest length (m) (3)	Construction (4)	Spillway and dam outlets (5)
Moore Creek, 1898	18.6	155	Thin arch dam (single arch: R = 75 m) with vertical downstream wall and battered upstream wall, extending with a left-bank gravity section; portland cement concrete construction; wall thickness = 0.87 m at crest, 7.7 m at base	Overfall spillway: $Q \sim 250$ m^3/s; two bottom outlets: scour valve and pipe outlet
Gap, 1902	6–10[b]	45–50[b]	Thin arch dam (single arch) with vertical upstream wall and battered downstream wall; concrete construction; wall thickness, 0.94 m at crest	Overfall spillway: $Q \sim 35$–40 m^3/s; No bottom outlet
Korrumbyn Creek 1917–1918	14.1	—	Thin arch dam (single arch: R = 61 m, $\theta \sim 47°$) with vertical upstream face and battered downstream face, with left-bank tangent of gravity cross-section; portland cement concrete construction; wall thickness = 1.1 m at crest, 5.2 m at base	Overflow spillway: $Q \sim 125$ m^3/s; bottom outlets: one scour valve and one pipe outlet (12 L/s)
Quipolly, 1932	19	184	Thin arch dam (single arch: R = 61 m, θ = 93°) with vertical upstream wall and battered downstream face extending with a short right-bank gravity section; concrete construction; wall thickness = 1.08 m at crest, 6.99 m at base	Overflow spillway: $Q \sim 240$ m^3/s; bottom outlets: one scour valve and one pipe outlet

Note: Q denotes maximum overflow capacity without dam overtopping; R is the curvature radius of the cylinder; and θ is the opening angle (i.e., central angle).
[a]Height above lowest foundation.
[b]Estimated from site inspection.

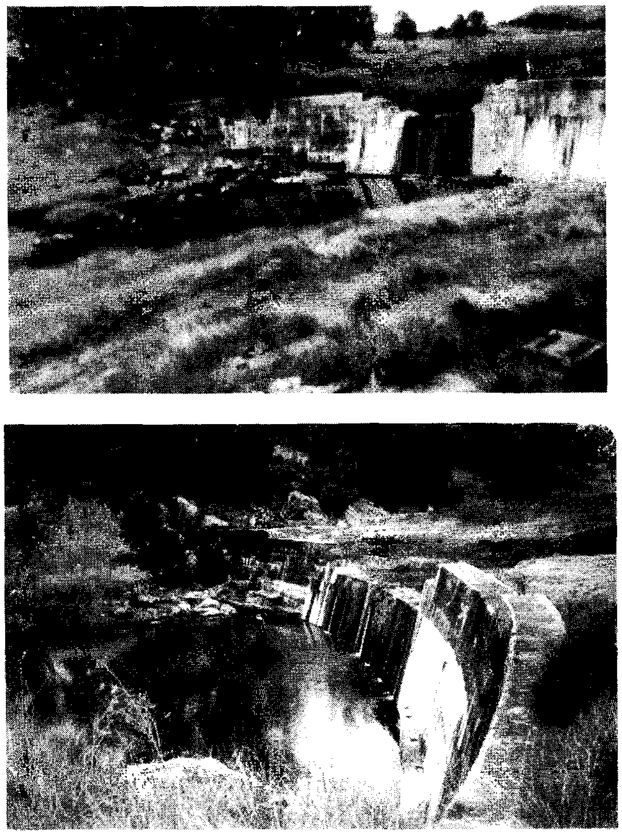
Creek (Fig. 3). It was built to supply water to the steam engines.

The dam wall is a single-arch concrete structure with upstream vertical face and inclined (battered) downstream face (~73° angle with horizontal). The original spillway was an overfall spillway extending over most of the weir crest followed by a relatively deep plunge pool, but no scour outlet was built (although a drawing prior to construction showed one).

The reservoir became fully silted by 1924. It was abandoned and replaced by available water supply from Quipolly Creek and later from the Quipolly dam. (The change to engine motors occurred in the 1970s and did not affect the decision.) After 1924, the dam wall was blasted twice to facilitate the passage of flood flow and to limit upstream flooding. Interestingly, the reservoir is located downstream of a long flat floodplain (slope < 0.2, streamwise length > 6 km). The river, cutting through into the reservoir sediment, highlights the silty material caught by the weir, suggesting a siltation process by suspended load.

Korrumbyn Creek Dam

The Korrumbyn Creek dam is located on the Korrumbyn Creek, a tributary of the Tweed River. The dam was completed in late 1918 to supply water to the town of Murwillumbah, NSW. The 14.1-m-high dam (Fig. 4) is a single arch wall (61 m radius in plan) with a left-bank tangent of gravity cross section. [De Burgh (1917) indicated a 12.4 m maximum dam height. However, the first author saw the drawings prior to and



(a)

(b)

FIG. 3. Gap Weir (1902): (a) View from Downstream (1960s Photograph); (b) View from Left Bank, with Creek Flowing from Right to Left (1997 Photograph)

after construction and noted several significant changes in design, including the dam height.] It was equipped with two bottom outlets (a pipe outlet and a scour valve) and an overfall spillway. The catchment area is only about 3 km^2, for an original volume of 27,280 m^3.

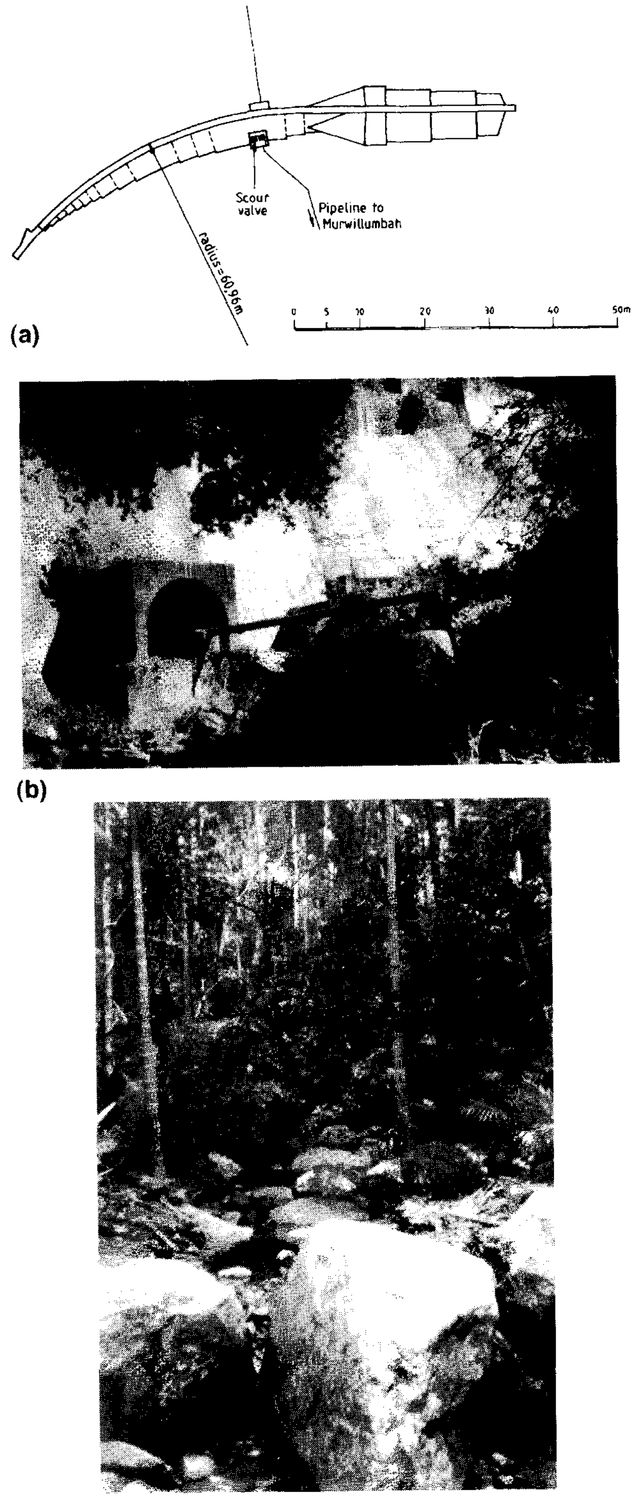
The dam was rapidly abandoned because a log jammed the scour pipe entrance during a flood. It could not be removed and the reservoir silted up very quickly by bed load. Further, during dry periods, the water level would drop and the water would turn green and become foul as it warmed up, making it unfit for use. The dam still stands today, the reservoir being occupied by an overgrown tropical forest (Fig. 4).

Quipolly Dam

The Quipolly dam, also known, according to the world register published by the International Commission on Large Dams (1984), as old Quipolly dam and Coeypolly Creek dam No. 1, was completed in 1932 to supply drinking water, irrigation, and water for railway steam engines to the town of Werris Creek, NSW. The dam wall is a concrete single arch (1.08 m thickness at crest) (Fig. 5). The design of the dam arch is elegant in comparison with Moore Creek dam and Korrumbyn Creek weir, both designed with a (thicker) gravity section. The reservoir was equipped with two bottom outlets and an overfall spillway.

Between 1932 and 1941, 130,000 m^3 of sediment accumulated (15% of initial reservoir capacity). In 1943 the siltation volume amounted to 290,000 m^3 (34% of initial capacity). By 1952, more than half of the initial storage had been lost. The reservoir was abandoned in 1955 upon the completion of a new dam (Quipolly dam No. 2), built 3 km downstream, and the reservoir is fully silted today. Although the dam is "officially" useless, it acts in fact, as a sediment trap to prevent or reduce the sedimentation of the new Quipolly dam.

Note the large spillway capacity (150-m-long crest, $Q \sim$ 240 m^3/s). This suggests that the design engineers were well aware of large flood events. By comparison, the second Quipolly dam was equipped with a 380 m^3/s spillway capacity. It is worth noting that the maximum spillway capacity of Moore Creek dam (i.e., 250 m^3/s) was comparable, but the catchment area was smaller (i.e., 51 km^2, see Tables 1 and 2).

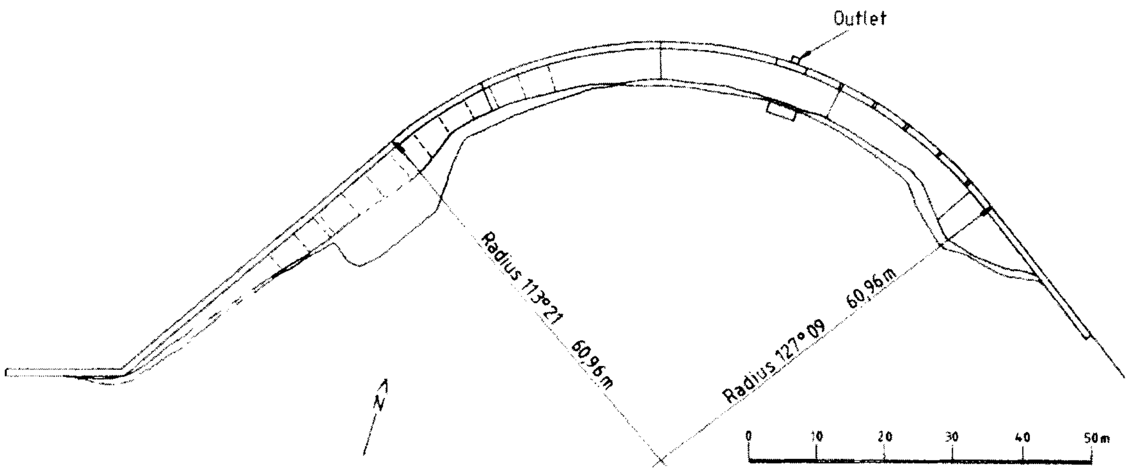


(a)

(b)

(c)

FIG. 4. Korrumbyn Creek Dam (1918): (a) Plan View, from Original Drawing after Construction; (b) View from Downstream Showing Bottom Outlet System on Left and Pipe to Murwillumbah (1997 Photograph); (c) View Looking Upstream of Korrumbyn Creek 1.5 km Upstream of Dam Wall Showing Coarse Sediment Material (1997 Photograph)



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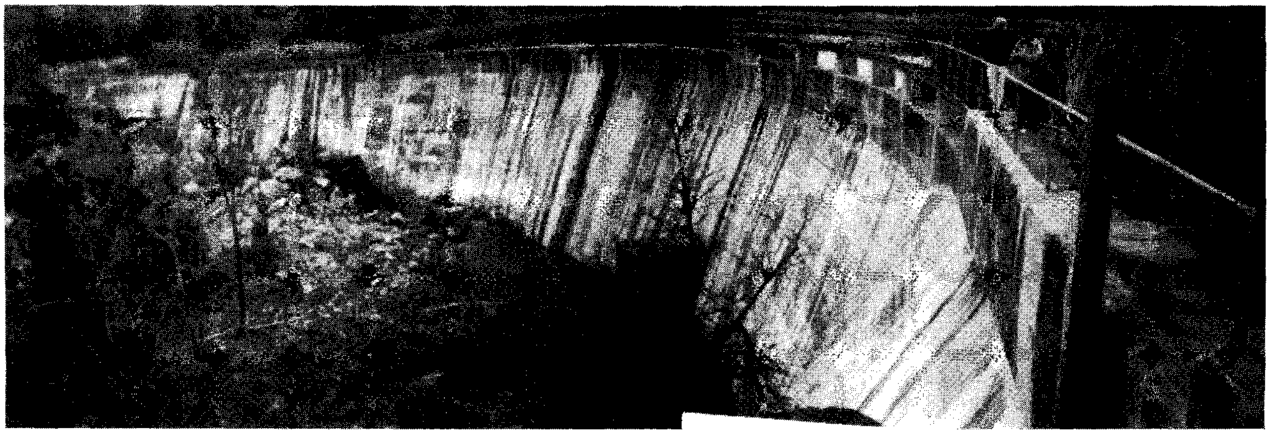

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FIG. 5. Quipolly Dam (1932): (a) Elevation in Plan, from Original Drawing; (b) View from Left Bank Showing Outlet System at Bottom of Downstream Wall (1997 Photograph)

CAUSES OF FAILURE

At the time of their construction the four dams embodied advanced structural features: thin arch walls, very unusual designs, and concrete construction, despite the problems in cement supply and difficulties in bringing it on-site. Their stories highlight errors in the design of the reservoirs, their interactions with the catchment, and the lack of consideration of siltation resulting from sediment transport processes.

The Gap weir was built without a bottom outlet; thus it could not be scoured. Note, further, that the spillway capacity (35–40 m^3/s) was small compared with the Moore Creek and Korrumbyn Creek dams, both of which have a smaller catchment.

The Korrumbyn Creek dam had an insufficient catchment area (3 km^2). Although the mean annual flow rate could "theoretically" fulfill the water needs of Murwillumbah, it was known that the stream discharge was very irregular. In 1916, the average weekly flow rate ranged from 0.75 L/s (Jan. 2–8, 1916) to 886 L/s (April 8–15, 1916), and the spillway was sized for a 125,000 L/s flood. All told, the reservoir never properly supplied Murwillumbah with water. Furthermore, the catchment is very steep: the stream bed slope is larger than 7.6° (0.133V/1H) in the first 2 km upstream of the dam! This caused significant sediment load in the creek. Today the riverbed still exhibits a wide range of sediment materials [Fig. 4(c)], and bed-load siltation could be predicted with contemporary experience (in the opinion of the authors, after inspection of the riverbed).

The catchment of Moore Creek dam is characterized by a thin layer of fertile soil. At the end of the 19th century, the forest was cleared for grazing. Further it seems that a substantial increase in sheep livestock number occurred at the same time. Both the clearing of the catchment and the increase of stocking rate increased the erodibility of the soils and contributed to the rapid sedimentation of the reservoir.

The siltation of Quipolly reservoir also is probably related to improper land management of the catchment.

DISCUSSION

Because of sedimentation, the four reservoirs each had a useful life of less than 25 years. Why? Several factors contributed to the sedimentation: a subtropical climate characterized by intense summer rainfall; streams with significant sediment loads; poor land management practices (by current standards), which devastated the native pasture and enhanced soil erosion (e.g., Moore Creek); design mistakes (e.g., Gap); and improper selection of site (Korrumbyn Creek). Additional considerations must also be taken into account, and these are discussed below.

Climatic Effect

Northern NSW is characterized by a subtropical climate with a dry season (winter) and a wet season (summer). This annual cycle is, however, subjected to interannual climatic events: the El-Niño and La Nina. Usually the El-Niños coincide with drought periods in Australia and India (Diaz and Markgraf 1992) while La Ninas are associated with flooding in Australia. This pattern was clearly established between 1878 and 1888 by Sir Charles Todd, South Australia government

TABLE 3. Chronology of Reservoir Sedimentation

Date (1)	El-Niño (2)	Australian drought (3)	La Niña (4)	Moore Creek (5)	Gap (6)	Korrumbyn Creek (7)	Quipolly (8)
		1884–1886					
	1887–1889	1888					
	1891*						
	1897	1896					
1898				Completion			
	1899–1900*	1899					
1902	1902	1902			Completion		
			1903–1904				
	1904–1905	1905					
			1906–1907				
	1907	1907					
1908			1908–1909	Flood and heavy siltation			
1910				Flood and heavy siltation			
	1911–1922	1912					
	1914–1915	1914					
			1916–1917				
1918	1918–1919	1918				Completion	
1919					Flood and heavy siltation		
			1920–1921				
	1923	1923					
1924				Fully silted	Fully silted	Disused?	
			1924–1925				
	1925–1926*	1925					
			1928–1929				
	1930–1931	1930					
			1931–1932				
1932	1932*	1932					Completion
			1938–1939				
	1939						
	1940–1941*	1940					
1942–1943			1942–1943				Flood and heavy siltation
	1943	1943					
			1949–50				
	1951	1951					
1952							Sedimentation = 50%
	1953	1953					
1955							Disused

Note: See Diaz and Markgraf (1992).
*Corresponds to "strong" or "very strong" El-Niños [(Diaz and Markgraf 1992) pages 129–131].

observer, and was well documented by H. C. Russell, NSW government observer [(Grove 1995) page 17]. The main information is summarized in Table 3, where Australian droughts and El-Niño and La Nina events are listed in chronological order, together with important dates in the history of the four reservoirs. The information on floods and siltation is based on local observations of floods and spillway use and on surveys of the reservoirs in the following dry periods.

In terms of soil erosion and sediment load, the most extreme hydrological events are exceptional floods following a long drought period (associated with an El-Niño). Dry conditions retard the growth of vegetation cover and the following wet conditions erode the bare unprotected soil. Further, soil management and conservation practices are not often applied by farmers and graziers during long droughts. Overgrazing of pastures followed by failure of pasture regeneration drastically increases the erodibility of the unvegetated ground. The following torrential rains easily wash away the soils, and as a result the streams carry a large sediment load that winds up in dam reservoirs.

Table 3 gives examples of such extreme events: the flood of February 1908 at Moore Creek (column 5), the floods of 1919 at Gap weir (column 6), and the floods of 1942–1943 at Quipolly (column 8). Each flood event followed a long drought period, and heavy siltation was recorded in each case.

Sediment Transport Processes and Design

Basically, the stories of the four reservoirs reflect a lack of understanding of sediment transport processes and soil conservation practices. Each dam must be considered as an engineering failure. The reservoirs failed because the designers did not understand the basic concepts of sediment transport and reservoir sedimentation. First let us remember that the knowledge of sediment process and movable-boundary hydraulics was "embryonic" in the 1900s. The fundamental concepts of sediment transport were developed in the late 19th century and first half of the 20th century by, among others, du Boys (1879), Schoklitsch (1914, 1930), Einstein (1942, 1951), and Meyer-Peter (1949, 1951).

However, it is surprising to note that the designers of Korrumbyn Creek dam and Quipolly dam did not learn from the experience of Moore Creek dam and Gap weir. By 1912 the sedimentation of Moore Creek dam was well advanced and documented. This information was available prior to the construction of Korrumbyn Creek dam. Similarly the experience

TABLE 4. Thin Cylinder Formula Calculations Applied to Arch Dams

Dam (1)	R (m) (2)	e (crest) (m) (3)	e (base) (m) (4)	Maximum height (m) (5)	Concrete strength (MPa) (6)	Tensile stress[a] per Eq. (1) (MPa) (7)	Tensile stress[b] per Eq. (1) (MPa) (8)
Moore Creek	75	0.87	7.7	18.6	2.15	1.8	3.6
Gap	–	0.94	~3.5	6–10	—	—	—
Korrumbyn Creek	61	1.1	5.2	14.1	1.61	1.62	3.3
Quipolly	61	1.08	7.0	19	—	1.62	3.3

Note: See Wade (1909) and de Burgh (1917).
[a]Assuming hydrostatic pressure on the upstream face.
[b]Assuming a 2.650 kg/m^3 sediment density and a 0.38 soil porosity.

of Gap weir (located less than 20 km from Quipolly dam) should have influenced the design of Quipolly dam, e.g., with the choice of a larger scour outlet. It appears also that the land management practices applied to Quipolly catchment in the period 1930–1950 were identical to those of Moore Creek catchment in 1900–1910 (James 1997).

Moore Creek, Korrumbyn Creek, and Quipolly reservoirs were designed and built by the same organization (i.e., NSW Public Works Department). It is surprising that the experience of reservoir siltation was not shared among colleagues and used to improve the design technique.

Opinion

The authors feel that each failure should be a learning experience, illustrating poor understanding of movable-boundary hydraulics. The mistakes could have been prevented with today's knowledge. In one case (Gap weir), the addition of a scour valve would have been sufficient. In another (Korrumbyn Creek), the site was unsuitable because of the heavy bed load carried by the stream. At Moore Creek, a soil conservation policy should have been introduced in the catchment, as at Quipolly reservoir.

Three reservoirs now serve no purpose and they are regarded by the public as engineering failures. Only one dam (Quipolly) may be considered as still partially useful, i.e., sediment trap for Quipolly dam No. 2.

CONCLUSION

During the European settlement of Australia in the 19th and 20th centuries, a series of thin arch dams was built in southeastern Australia for water supply purposes. Among these, four dams were silted very rapidly and were abandoned in less than 25 years.

After a brief history of each reservoir, the authors have discussed the main causes of reservoir siltation: extreme climatic conditions and streams with heavy sediment load, but also improper soil conservation practices and design mistakes.

Although the dams had advanced structural features, their stories reflect a lack of understanding of sediment transport processes by the designers. The authors hope that these four examples will serve as pedagogic examples by professionals and students to improve future hydraulic designs.

APPENDIX I. THIN CYLINDER FORMULA

For a circular pipe of radius R and thickness e, the tensile stress, σ_c, in the pipe wall equals

$$\sigma_c = \frac{RP}{e} \qquad (1)$$

where P is the water pressure.

This equation may be applied to thin arch dams. Results are summarized in Table 4 and the calculations are compared with the concrete strengths stated by Wade (1909) and de Burgh (1917). Note that the concrete strengths (column 6 of the table) were very close (too close?) to the required tensile strengths with hydrostatic pressure loads (column 7). Discussions of Wade's paper suggested that "the factor of safety . . . was too low." More recently Schnitter (1994) mentioned also the "narrow safety of margin."

First, experience shows that the dams are still standing today and inspections have shown that the walls are in good condition. Further, the dam walls are subjected nowadays to pressure loads (on the upstream face) substantially larger than the hydrostatic pressure because of the reservoir siltation (column 8 of the table). It is thought that the concrete strengths (column 6) underestimate the actual material properties.

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APPENDIX III. NOTATION

The following symbols are used in this paper:

e = wall thickness (m);
P = pressure (Pa);
Q = water discharge (m^3/s);
R = arch radius (m);
θ = opening angle (i.e., central angle); and
σ_c = tensile stress (Pa) in wall.