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EXTREME RESERVOIR SEDIMENTATION IN AUSTRALIA: A REVIEW

Hubert CHANSON[1]

ABSTRACT

In the paper, the author reviews the problem of reservoir siltation in Australia. The issue was ignored too long and it is only recently that researchers and engineers have acknowledged the matter. First a review of fully-silted reservoirs is developed. The siltation records are compared with overseas sedimentation data and discussed. The study indicates that extreme siltation rates were observed in Australia. The magnitude of the data is similar to overseas extreme sedimentation records. The causes of reservoir failures are discussed.

Key Words: *Reservoir sedimentation*, *Australia Siltation records*, *Extreme siltation data*, *Reservoir failtures*

1 INTRODUCTION

Since the early European settlements in Australia, the coastal and continental development of the country has been coupled with the availability of water supply. Today Australia's economy is highly dependant upon its surface irrigation and more than 85% of water diversions are for agricultural purposes (irrigation and stock watering only). Any reduction in water storage caused by reservoir siltation, and the associated loss of fertile soil, is a critical parameter with economical and political impacts.

There are however conflicting informations on whether reservoir siltation has been significant in Australia. Indeed, for many years, reservoir sedimentation has not been an issue: "the (sediment) yield [...] is relatively low compared to others in the world" (OUTHET 1984, NSW Water Resources Commission); the classical text book *Open Channel Flow by F. M. HENDERSON*, University of Newcastle NSW, made no mention of reservoir siltation in Australia in the section "Sediment transport" (HENDERSON 1966). The issue of reservoir siltation in Australia was ignored and rejected until the late 1970s.

In the present paper, the author re-analyses existing data and new information on extreme reservoir siltation in Australia. He will show that several extreme siltation events took place and affected predominantly small to medium size reservoirs. It is the purpose of the study to present new comparative data, and to develop new compelling conclusions regarding reservoir sedimentation in Australia.

Hydrology of the Australian continent

Australia is a large continent (7 690 E + 3 km^2) of low relief (fig.1). Its most prominent topographic feature is the Great Dividing Range, a chain of low mountains and tablelands extending over 2 500 km along the Eastern and South-Eastern coastlines.

Although the average annual rainfall is about 420 mm, the spatial and temporal variability is high. The rainfall may vary from zero for several years during droughts to extreme hydrological

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Note. Discussion opens until Sep.30, 1999.

events (e. g. 515 mm in 6 hours at Dapto NSW, in 1984). The average runoff is only 13% of the rainfall, varying from 0 mm in most Western Australia to over 700 mm in some regions of Eastern Australia and Tasmania (Department of Natural Resources 1976). Indeed evaporation is high. Average annual standard pan evaporation exceeds 1 000 mm in nearly all parts of the continent, with extreme evaporation above 3 000 mm in Central Australia.

High evaporation coupled with the variability of surface runoff make conservation and development of surface water resources more expensive, less effective and more political than in many countries.

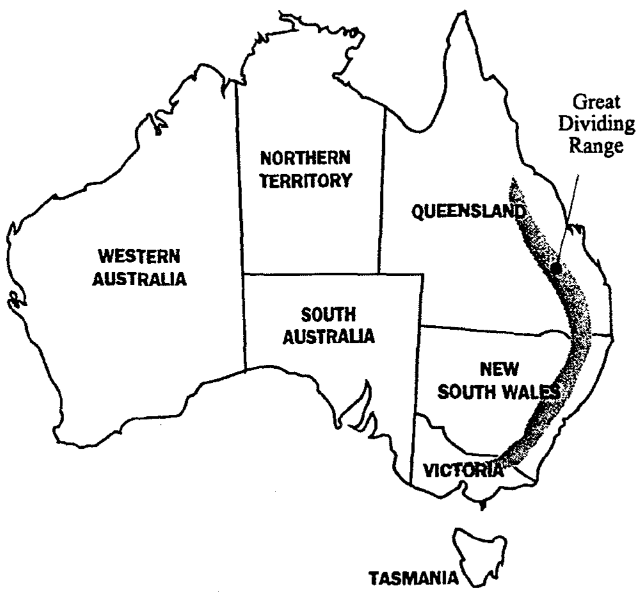

Fig. 1 Map of the Australian continent

2 EXTREME RESERVOIR SILTATION

The writer investigated several reservoir siltation cases. Between 1890 and 1960, more than twenty reservoirs (excluding farm dams) became fully-silted in Australia, most in New South Wales (Table 1). Fully-silted reservoirs includes town water supply reservoirs (e. g. Moore Creek dam), railway dams[2] (e. g. Gap weir) and mining reservoirs.

Table 1 Major reservoir siltation in Australia

Reservoir (1)	Location (2)	Completion date (3)	End of use (4)	Purpose (5)
Sheba dams	Nundle NSW	1888	--(*)	Mining. Two dams.
Corona	Broken Hill NSW	1890	1910 (*)	Irrigation.
Laanecoorie	Maryborough VIC	1891	Still in use	Irrigation.
Stephens Creek	Broken Hill NSW	1892	Still in use	Town water supply.
Junction Reefs	Lyndhurst NSW	1896	1930? (*)	Hydropower for mining activities.
Moore Creek	Tamworth NSW	1898	1924 (*)	Town water supply.
Gap	Werris Creek	1902	1924 (*)	Railway supply.
Pekina Creek	Orroroo SA	1907	1984	Irrigation and town water supply.
de Burgh dam	Barren Jack NSW	1908	--	Railway and town water supply.
Koorawatha	Cowra NSW	1911	-- (*)	Railway supply.
Pykes Creek	Ballan VIC	1911	Still in use	Irrigation and water supply.
Pekina Creek	Orroroo SA	1910s	1930s (*)	Town water supply.
Cunningham Creek	Harden NSW	1912	1929 (*)	Railway supply.
Illalong Creek	Binalong NSW	1914	1985? (*)	Railway supply.
Umberumberka	Broken Hill NSW	1915	Still in use	Town water supply.
Melton	Werribee VIC	1916	Still in use	Irrigation.
Korrumbyn Creek	Murwillumbah NSW	1918	1924? (*)	Town water supply.
Borenore Creek	Orange NSW	1928	Still in use	Railway supply. Town water supply today.
Quipolly	Werris Creek NSW	1932	1955 (*)	Railway supply.
Inverell	Inverell NSW	1939	1982 (*)	Town water supply.
Arrona Gorge dam	Leigh Creek Town SA	1950	--	Mining and town water supply.

Reference: Present study.
Note: (*): reservoir fully-silted today; (--): information not available.

[2] built to supply water to the steam engines for the railway. Steam engines were in use in Australia up to the 1970s.

2.1 Some Examples of Reservoir Siltation

The two Sheba dams

Completed in 1888 (first dam) and around 1890 (second one), the Sheba dams were designed to supply water to the gold mines of the Mount Sheba Company, near Nundle NSW located next to the edge of the Great Dividing Range. The upper dam is an earth embankment (7.6-m high, 91-m long) and the reservoir area is 5 acres. The lower dam is also an earthfill structure (6.1-m high, 64-m long) with a 4-acres reservoir area.

The dams are located at high altitude, nearly 1 100-m, on the Western side of the Great Dividing Range and water was collected on both the Western and Eastern slopes of the Range.

The dams are fully-silted and used for trout fishing and as touristic attraction. There are some safety concerns because the spillways are inadequate.

Pekina Creek dam

Built around 1905-1907, commissioned in 1911, the Pekina Creek dam is an earthfill structure, 24-m high after heightening in 1914. Located near Orroro SA, it was designed to supply irrigation and town water. The original reservoir capacity was 1.54 E+6 m^3 (after 1914 heightening) and the catchment area is 136 km^2. More than 50% of the reservoir was silted in 1944 and the sediment volume accounted for 60% of the initial capacity in 1971. The reservoir was disused in 1964 (McQUADE et al. 1981).

Koorawatha dam(s)

The Koorawatha dams, located near Koorawatha NSW, were railway dams, designed to supply water to the steam engines for the nearby railway line, opened in November 1886 and closed in 1980.

Two thin arch concrete dams were built successively at the same site. The first dam was 5 to 7 m high and it is located 5 to 10-m upstream of the present dam (fig. 2). The crest was still visible during dry periods up to the 1930s although, today, it is underneath the dry reservoir bed. Completed in 1911 (or 1913?), the second Koorawatha dam is a concrete single – radius arch (9-m high, 0.92-m thick at crest, 40-m arch radius). The upstream wall is vertical

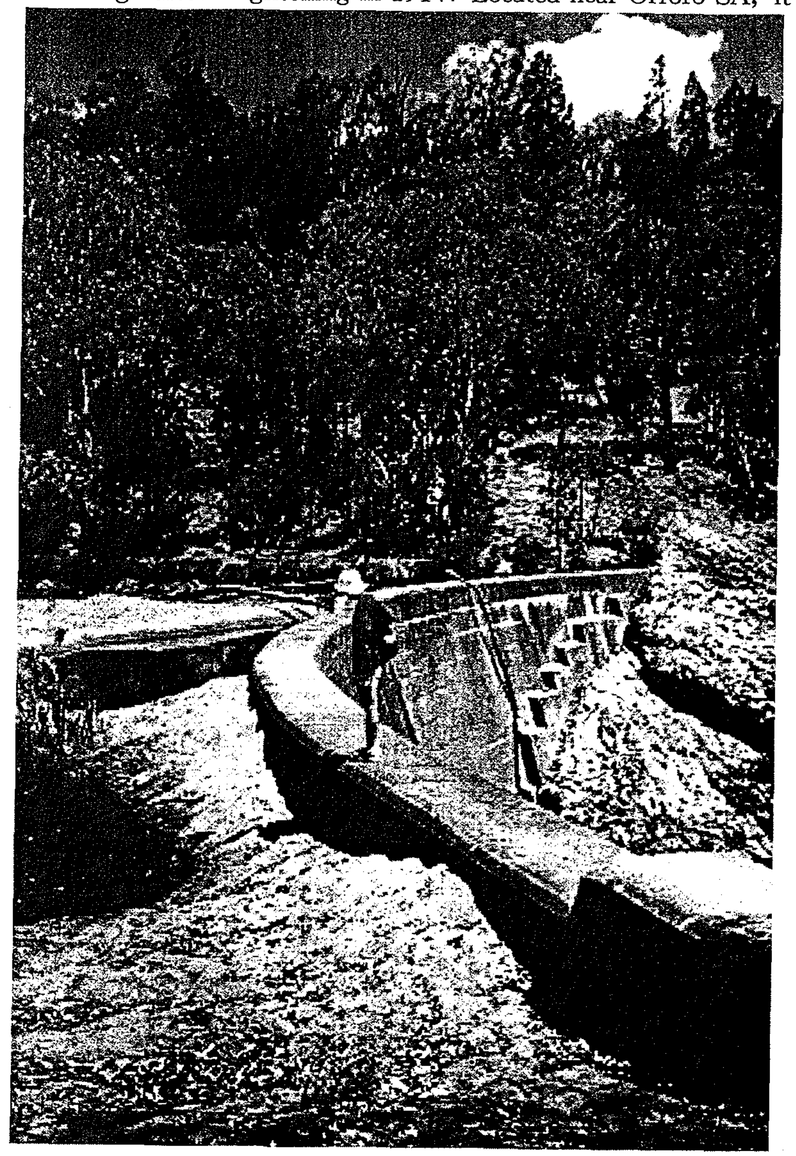

Fig. 2 Dry reservoir of Koorawatha weir, railway dam completed in 1911
View from the right bank in December 1997

and the downstream face is battered. The weir was equipped with an outlet system and an overfall spillway (24-m long, 0.3-m high). The reservoir is fully silted today, occupied by sand and gravels, suggesting sedimentation by bed-load (fig. 2).

Borenore Creek dam

Completed in 1928, the Borenore Creek dam was built to supply water to the Orange-Broken Hill railway line. The dam is a concrete single-radius arch wall (17-m high, 123-m long at crest, 1.12-m crest thickness) (fig. 3). The catchment area is 22 km^2 and the original storage capacity was 230 000 m^3. The dam was equipped with an outlet system and an overfall spillway. Interestingly a new outlet (pipe inlet) was installed, later, about half-height of the dam, as a result of the reservoir siltation which amounted for 150 000 m^3 in 1981 (fig. 3).

Fig.3 Borenore Creek dam completed in 1928
View from the left bank in December 1997. Note the old scour outlet system and the new water intake at half-height of the dam wall

After being used by the NSW Railway Department, the dam has been used as the town water supply for Molong. The reservoir is used only as an emergency reserve today.

Melton dam

Completed in 1916, the Melton dam is an earth and rockfill embankment and it was heightened in 1937 and 1967. The reservoir was built for irrigation purpose. The initial reservoir capacity of 21.0 Mm^3 was increased to 23.6 Mm^3 in 1937. The catchment area is 1 098 km^2.

During the 1930s and 1940s, the reservoir suffered heavy siltation caused by cattle and sheep grazing, gold and coal mining, and rabbit colonies in the catchment. In 1941, when the reservoir was nearly empty, a heavy rainstorm filled the reservoir in 36 hours and the spillway was heavily used. (The reservoir inflow was estimated at 1 444 m^3/s.) Massive siltation took place during the event and a 2.6-m thick silt deposit was left on the spillway intake after the flood. In 1945, the reservoir capacity was reduced down to 19.1 Mm^3. Erosion control works were carried out, including construction of check dams, furrowing works and elimination of vermin. In 1968, the reservoir siltation amounted for 6.6 Mm^3 of sediments.

Quipolly dam No.1

The old Quipolly dam or Quipolly dam No.1 was completed in 1932 to supply town water for

Werris Creek NSW, irrigation water and water for steam engines. The dam is a concrete single-arch (19-m high, 184-m long crest), the catchment area is 70 km^2 and the original storage capacity was 860 000 m^3.

The reservoir suffered heavy sedimentation between 1941 and 1943 (CHANSON and JAMES 1998). The reservoir was disused in 1955 and the reservoir is fully silted today. The reservoir acts now as a sediment trap for the new Quipolly dam (Quipolly dam No.2) located downstream.

3 DISCUSSION

3.1 Comparison between Australian and Overseas Siltation Rates

Comparative analysis with overseas experience suggests that reservoir sedimentation rates in Australia were high (Table 2). Table 2 compares most extreme (well-documented) siltation events in North-Africa, North-America, Asia, Europe and Australia. These and further data are summarised in figure 4, showing extreme siltation rates as a function of the duration of the study.

Table 2 Examples of extreme reservoir siltation rates in Australia and overseas

Reservoir (1)	Sedimentation rate (m^3/km^2/year) (2)	Study period (3)	Catchment area (km^2) (4)	Annual rainfall (mm) (5)
ASIA				
Wu-Sheh (Taiwan) (*S*)	10,838	1957-58	205	--
	9,959	1959-61	205	--
	7,274	1966-69	205	--
Shihmen (Taiwan) (*S*)	4,366	1958-64	763	> 2,000
Tsengwen (Taiwan) (*S*)	6,300	1973-83	460	3,000
Muchkundi (India)	1,165	1920-1930?	67	--
NORTH AFRICA				
El Ouldja (Algeria) (*W*)	7,960 (*F*)	1948-49	1.1	1,500
El Fodda (Algeria) (*W*)	5,625 (*F*)	1950-52	800	555
	3,060 (*F*)	1932-48	800	555
Hamiz (Algeria) (*W*)	1,300	1879-1951	139	--
El Gherza (Algeria)	615	1951-67	1,300	35
	577	1986-92	1,300	35
NORTH AMERICA				
Sweetwater (USA)	10,599	1894-95	482	240
White Rock (USA)	570	1923-28	295	870
Zuni (USA) (*)	546	1906-1927	1,290	250 to 400
Roosevelt (USA)	438	1906-25	14,900	--
EUROPE				
Saifnitz (Austria) (*)	6,820	1876	4	--
Monte Reale (Italy) (*)	1,927	1904-05	436	--
Wetzmann (Aust.) (*)	1,852	1883-84	324	--
Pont-du-Loup (France) (*)	1,818	1927-28	750	--
Pontebba (Austria)	1,556	1862-80	10	--
Lavagnina (Italy)	784	1884-1904	26	1,800
Roznov (Poland) (*S*)	398	1958-61	4,885	600
Cismon (Italy)	353	1909-19	496	1,500
Abbeystead (UK) (*)	308	1930-48	49	1,300 to 1,800
Porabka (Poland) (*S*)	288	1958-60	1,082	600
AUSTRALIA				
Quipolly (*)	1,143	1941-43	70	686
Pykes Creek	465	1911-45	125	--
Umberumberka	407	1961-64	420	220
Corona (*)	400	1890-1910	15	--
Eildon	381	1939-40	3,885	--
Moore Creek (*)	174	1911-24	51	674
Pekina Creek (*)	174	1911-44	136	340 to 450
Korrumbyn Creek (*)	1,400 (?)	1918-1924?	3	1,699

References: Present study, CHANSON and JAMES (1998), CHU (1991), CYBERSKI (1971), LAJCZAK (1994), ORTH (1934), ROWAN et al. (1995).
Notes:
(*S*) Summer rainfall climate; (*W*) Winter rainfall climate; (*F*) Important flushing; (*) fully-silted reservoir; (?) uncertain data; (--) Data not available.

Figure 4 suggests that most high (recorded) siltation rates are observed during short duration studies (1 to 10 years). There is however a lack of information on long-term siltation (over 70 years). Note further that the data indicate the net sedimentation rate, after flushing. In several cases where flushing was used, the real sediment inflow rate was much larger.

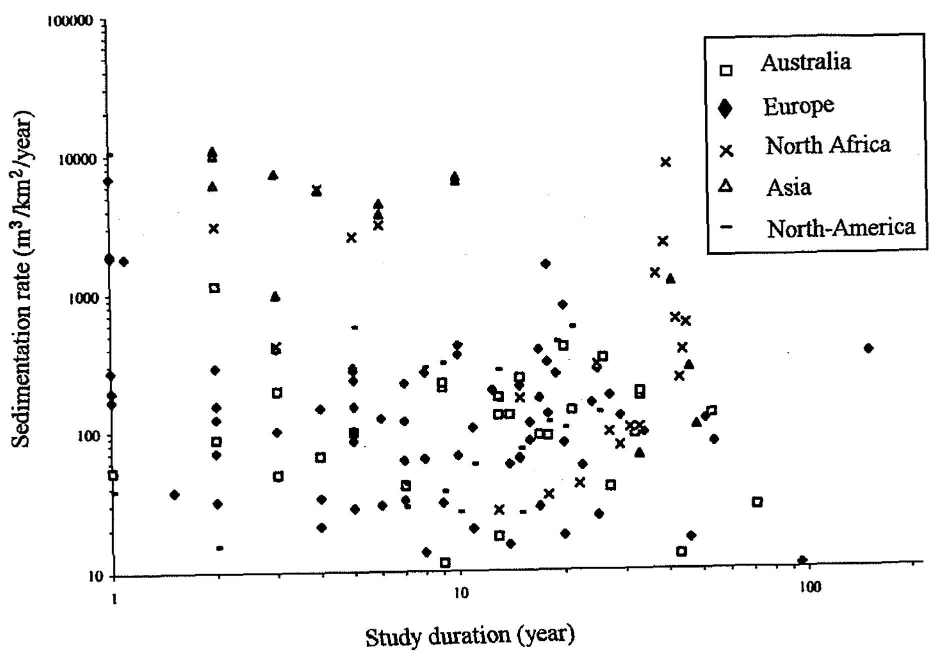

Fig.4 Extreme siltation rates ($m^3/km^2/year$) as a function of study duration (year)

Among the extreme events, the cases of the Shihmen reservoir, the El Ouldja dam and the Sweetwater reservoir are peculiar. The Shihmen dam (Taiwan R.O.C.) is a 133-m high dam built between 1958 and 1964. The maximum reservoir capacity was more than 60 000 000 m^3 and the catchment area is 763 km^2. Although the dam was inaugurated in 1964, the reservoir began filling in May 1963. In September 1963, 20 000 000 m^3 of silt accumulated during cyclonic floods (typhoon Gloria).

The El Ouldja dam was a debris dam built to protect the main Oued Djenden dam (Algeria). The siltation of the reservoir was studied in details between 1947 and 1950 (DUQUENNOIS 1951). The results highlighted siltation by bed-load material with sizes ranging from 1-mm to over 0.5-m and heavily-loaded turbidity currents of silt and clay (density between 1 100 and 1 300 kg/m^3).

Built between 1888 and 1887, the Sweetwater dam was designed to supply irrigation and town water to the San Diego area (USA). The catchment area is 482 km^2 and the original reservoir capacity was 20 E+6 m^3. Heavy siltation took place during the January 1895 flood and it was well-documented (SCHUYLER 1909).

In Australia, the sedimentation of Quipolly reservoir between 1941-1943 was an extraordinary event. Overall most sedimentation problems in Australia were experienced with small to medium size reservoir (catchment area less than 100 km^2 typically). In contrast large Australian reservoirs have not been sedimenting rapidly at the exception of Melton and Eildon reservoirs. Heavy siltation at Eildon was experienced in 1940 during torrential rainfalls, following bushfires which destroyed the forest over more than 50% of the catchment (JOSEPH 1953).

Today lower siltation rates are experienced in Australia, especially since the 1950s. It is believed that the reduction in sedimentation is related to the introduction of new farming techniques, new land conservations practices and an awareness of soil erosion problems. The same trend is experienced in the New South Wales, Victoria, South Australia and Queensland states (fig. 1).

3.2 Climatic Changes

Interestingly records suggest that the most extreme siltation periods in Australia took place during major floods following an El-Niño event and long droughts. Such extreme siltation events were experienced at the Junction Reefs reservoir (1902 floods after the Great Drought of 1900-1902), the Moore Creek reservoir (flood of February 1908), the Gap weir (floods of 1919), the Melton reservoir (flood of 1941), the Quipolly reservoir (floods of 1942-43).

Drought periods in Australia may be extremely severe. The most severe drought occurred between 1895 and 1903, 1902 being the severest year. During that period, sheep numbers declined by more than 50% and cattle by more than 40%. Recently, a decade of drought persisted between 1958 and 1968.

The world community has focused its attention on the early detection of drought (*El-NiÑo*) which is termed a "major catastrophe" in the television news. But the El-Niño phenomenon[3] takes place in average every 5 to 7 years. It is a recurrent climate pattern which is not properly managed by Local, National or International Institutions. No contingency for long-term policy has been made.

3.3 Sediment Flushing Devices

Surprisingly Australian reservoirs have been inadequately equipped with flushing devices (Table 3). Most Australian reservoirs were equipped with a single scour outlet ($\varnothing = 0.3$ to 0.5 m) inadequate to desilt a reservoir. Only few dams were equipped with two or more flushing systems: e.g., the Illalong Creek dam completed in 1914 and now fully-silted!

In comparison the Nabataeans[4], Romans and Spaniards equipped their reservoirs with large sediment flushing system. For example, the Roman engineers equipped the Monte-Novo dam (A.D. 300, Portugal) with two outlets of 1.2 and 1.4 m^2 cross-section area each. Such an expertise in sediment flushing, gained over the past 22 centuries, was obviously unknown to (or forgotten by) the Australian engineers.

4 SUMMARY AND CONCLUSION

The main findings of the study are: [1] reservoir sedimentation has been a serious problem in Australia, and [2] Australian engineers could draw upon local and overseas experience, and from past failures. Indeed several reservoirs (Table 1) became fully-silted because the designers did not take into account correctly the soil erosion and sediment transport processes, and no soil conservation practice was introduced.

Today the society expects the useful life of a reservoir to be more over 30 to 50 years. One lesson from past experience is the need to consider the dam, the reservoir and the catchment as a complete system which cannot be dissociated. Soil erosion and water runoff lead into the streams some sediment material that is trapped downstream by the dam wall. A total catchment management policy must be considered from the early stage of a reservoir design.

Fully-silted reservoirs stand as a source of embarrassment for the scientists and the public. Each reservoir failure must be a valuable teaching and pedagogic tool to heighten the awareness of students, professionals and local authorities and of the public. Society must learn from its mistakes, not to repeat them again!

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[3] also called El-Niño Southern Oscillation phenomenon (ENSO).

[4] habitants from an ancient kingdom to the East and South-East of Palestine that include the Neguev desert. The Nabataean kingdom lasted from around B.C. 312 to A.D. 106. The Nabataeans built a large number of soil-and-retention dams. Some are still in use today.

and Mr P. JAMES, Neutral Bay NSW for their assistance.

Table 3 Scour outlet systems

Dam (1)	Year of compl. (2)	H (m) (3)	Catch. area (km^2) (4)	Reserv. capac. (m^3) (5)	Bottom outlets (6)	Outlet area (m^2) (7)
NABATEAN DAM						
Sabra valley dam, Jordan	BC 100	4.6	--	3,600	1 outlet	0.49
ROMAN DAMS						
Kasserine dam	BC 100	10	--	--	Vaulted outlet tunnel	4
Örükayta dam, Corum, Turkey	AD 200	16	--	--	Vaulted bottom outlet	3
Cavdarhisar dam, Kütahya, Turkey	AD 200	7	--	--	Vaulted bottom outlet	11
Monte-Novo, Evora, Portugal	AD 300	5.7	2.9	--	2 outlets (1.2 & 1.4 m^2)	2.6
SPANISH DAMS						
Almansa dam, Spain	1384	15	--	2,800,000	2 water outlets + 1 scour outlet (1.95 m^2)	2.95
Alicante (Tibi) dam, Spain	1594	41	--	5,400,000	1 water outlet + 1 scour outlet (5 m^2)	6
Elche dam, Spain	1642-45	23.2	--	400,000	Vertical outlet + scour gallery	
Relleu dam, Spain	1650-1776?	28	--	600,000	Large scour gallery	
Puentes dam, Spain	1791	50	--	52,000,000	2 water outlets + scour gallery (51.1 m^2)	>52
AUSTRALIAN DAMS						
Moore Creek dam, Australia	1898	18.6	51	220,000	1 pipe outlet + 1 scour valve	~0.1
Gap weir, Australia	1902	6 to 10	160	--	No outlet.	0
Korrumbyn Creek dam, Australia	1919	14.1	3	27,300	1 pipe outlet + 1 scour valve	0.04
Old Quipolly dam, Australia	1932	19	70	860,000	1 pipe outlet + 1 scour valve	~0.2

References: Present study, SALADIN (1886), SCHNITTER (1971), SMITH (1971).
Notes: Year of compl.: year of completion; H: dam height; Catch. area: catchment area; Reserv. capac.: reservoir capacity.

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ABBREVIATIONS

NSW	New South Wales;
QLD	Queensland;
SA	South Australia;
VIC	Victoria;
WA	Western Australia.

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