EXTREME RESERVOIR SEDIMENTATION IN AUSTRALIA: A REVIEW

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ABSTRACT

This paper reviews the problem of reservoir siltation in Australia. The issue has been ignored for too long and it was only recently that researchers and engineers 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 have been observed in Australia. The magnitude of the data is similar to overseas extreme sedimentation records. The causes of reservoir failures are discussed.

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 dependent upon its surface irrigation and more than 85 per cent 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 economic and political impacts.

There are, however, conflicting data on whether reservoir siltation has been significant in Australia. Indeed, for many years, reservoir sedimentation has not been an issue: the classic text book, *Open Channel Flow* by F. M. Henderson (1966) of the University of Newcastle, New South Wales, made no mention of reservoir siltation in Australia in the section on sediment transport. 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 shows that several extreme siltation events have taken place and affected predominantly small to medium-sized reservoirs. It is the purpose of this 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. 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. Rainfall may vary from zero for several years during droughts to extreme hydrologicalevents (for example, 515 mm in six hours at Dapto, New South Wales, in 1984). The average run-off is only 13 per cent of the rainfall, varying from 0 mm in most of 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 run-off make conservation and development of surface water resources more expensive, less effective and more political than in many countries.

EXTREME RESERVOIR SILTATION

The author investigated several reservoir siltation cases. Between 1890 and 1960, more than 20 reservoirs (excluding farm dams) became fully silted in Australia, the majority of which were in New

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South Wales (table 1). Fully-silted reservoirs include town water supply reservoirs (for example, Moore Creek dam), railway dams[1] (for example, the Gap weir) and mining reservoirs.

Table 1. Major reservoir siltation in Australia

Reservoir	Location	Completion date	End of use	Purpose
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.

– information unavailable; * reservoir now fully silted.

Some examples of reservoir siltation

(a) *The two Sheba dams*

The first dam was completed in 1888 and the second around 1890. The Sheba dams were designed to supply water to the gold mines of the Mount Sheba Company, near Nundle, New South Wales, located on 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 totals five acres. The lower dam is also an earthfill structure (6.1 m high, 64 m long) with a four-acre reservoir area.

The dams are located at high altitude, at nearly 1,100 m on the western side of the Great Dividing Range, and water was collected from both the western and eastern slopes of the range. The dams are fully silted and are now used for trout fishing and as a tourist attraction. There are some safety concerns because the spillways are inadequate.

(b) *Pekina Creek dam*

Built around 1905-1907 and commissioned in 1911, the Pekina Creek dam is an earthfill structure. In 1914 its height was increased to 24 m. Located near Orroro, South Australia, it was designed to supply needs for irrigation and the town inhabitants. The original reservoir capacity was 1.54 E+6 ma (after heightening) and the catchment area covered 136 km^2. More than 50 per cent of the reservoir was silted up in 1944 and the sediment volume accounted for 60 per cent of the initial capacity in 1971. Use of the reservoir was discontinued in 1964 (McQuade and others, 1981).

(c) *Koorawatha dams*

The two Koorawatha dams, located near Koorawatha, New South Wales, were railway dams. They were designed to supply water to the steam engines on the nearby railway line. The first dam opened in November 1886 and closed in 1980.

[1] Built to supply water for steam engines on the railway. Steam engines were in use in Australia until the 1970s.

Two thin arch concrete dams were built successively at the same site. The first dam was 5 to 7 m high and was located 5 to 10 m upstream of the present dam. The crest was still visible during dry periods up to the 1930s; today, it is underneath the dry reservoir bed. Completed sometime between 1911 and 1913, the second Koorawatha dam comprised a concrete single-radius arch (9 m high, 0.92 m thick at the crest, with a 40-m arch radius). The upstream wall is vertical and the downstream face is battered. The weir is equipped with an outlet system and an overfall spillway (24 m long, 0.3 m high). The reservoir is fully silted today with sand and gravel, suggesting sedimentation by bedload.

(d) *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 the crest, with a 1.12-m crest thickness). 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 halfway up the height of the dam as a result of reservoir siltation that amounted to 150,000 m^3 in 1981. After being used by the New South Wales Railway Department, the dam became the supply source for the town of Molong. The reservoir is used only as an emergency reserve today.

(e) *Melton dam*

Completed in 1916, the Melton dam is an earth and rockfill embankment that was heightened in 1937 and 1967. The initial capacity of the reservoir, which was built for irrigation purposes, totalled 21 million m^3 and was increased to 23.6 million m^3 in 1937. The catchment area is 1,098 km^2.

During the 1930s and 1940s, the reservoir suffered heavy siltation resulting from cattle and sheep grazing, gold and coal mining, and rabbit colonies that abounded in the catchment area. 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 rainstorm and a 2.6-m thick silt deposit was left on the spillway intake after the flood.

By 1945, the reservoir capacity had been reduced to 19.1 million m^3. Erosion control works were carried out, including the construction of check dams, furrowing works and elimination of vermin. In 1968, the reservoir siltation amounted to 6.6 million m^3.

(f) *Quipolly dam No. 1*

The old Quipolly dam or Quipolly dam No.1 was completed in 1932 to supply water to the town of Werris Creek, New South Wales, as well as irrigation water and water for steam engines. The dam is a concrete single arch (19 m high and a crest of 184 m in length), with a catchment area of 70 km^2 and an original storage capacity of 860,000 m^3.

Heavy sedimentation occurred between 1941 and 1943 (Chanson and James, 1998) and use of the reservoir was discontinued in 1955. The reservoir, which is completely silted up, now acts as a sediment trap for the new Quipolly dam (Quipolly dam No. 2) located downstream.

DISCUSSION

Comparison between Australian and overseas siltation rates

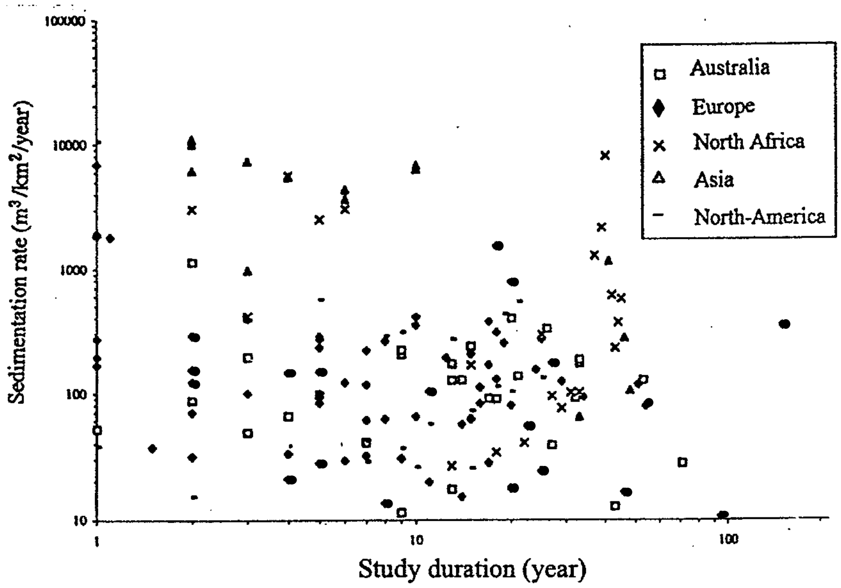
Comparative analysis with overseas experience suggests that reservoir sedimentation rates in Australia are high; table 2 compares most extreme (well-documented) siltation events in North Africa, North America, Asia, Europe and Australia. These and other data are summarized in the figure, showing extreme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

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

Reservoir	Sedimentation rate ($m^3/km^2/year$)	Study period	Catchment area (km^2)	Annual rainfall (mm)
ASIA				
Wu-Sheh (Taiwan Province of China) *S*	10,838	1957-58	205	--
	9,959	1959-61	205	--
	7,274	1966-69	205	--
Shihmen (Taiwan Province of China) *S*	4,366	1958-64	763	> 2,000
Tsengwen (Taiwan Province of China) *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 (Austria) *	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

Sources: Chanson and James, 1998; Chu, 1991; Cyberski, 1971; Lajczak, 1994; Orth, 1934; Rowan and others, 1995; and the present study.

S: summer rainfall climate; *W*: winter rainfall climate; *F*: important flushing; *: fully silted reservoir; ?: uncertain data; -- : data not available.



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

The above figure suggests that the higher (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). It should also be noted 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.

Among the extreme events, the cases of the Shihmen reservoir, the El Ouldja dam and the Sweetwater reservoir are peculiar. The Shihmen dam (Taiwan Province of China) is a 133-m high dam built between 1958 and 1964. The maximum reservoir capacity was more than 60 million m^3, with a catchment area is 763 km^2. Although the dam was inaugurated in 1964, the reservoir began filling in May 1963. By September 1963, 20 million m^3 of silt had 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 detail between 1947 and 1950 (Duquennois, 1951). The results highlighted the siltation by bedload material with particle 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 of the United States. The catchment area is 482 km^2 and the original reservoir capacity was 20 E + 6 m^3. Heavy siltation that occurred during the January 1895 flood was well documented (Schuyler, 1909).

In Australia, the sedimentation of the Quipòlly reservoir between 1941 and 1943 was an extraordinary event. Overall, most sedimentation problems in Australia have been experienced with small to medium-sized reservoirs (typically, with catchment areas of less than 100 km^2). In contrast, large Australian reservoirs have not been sedimenting rapidly, with the exception of the Melton and Eildon reservoirs. Heavy siltation at Eildon was experienced in 1940 during torrential rainfall that followed bushfires. The fires destroyed the forest cover on more than 50 per cent of the catchment (Joseph, 1953).

More recently, especially since the 1950s, lower siltation rates have been experienced in Australia. It is believed that the reduction in sedimentation is related to the introduction of new farming techniques, new land conservation practices and an awareness of soil erosion problems. The same trend is being experienced in the States of New South Wales, Victoria, South Australia and Queensland.

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 in 1919), the Melton reservoir (flooding in 1941) and the Quipolly reservoir (floods in 1942 and 1943). Drought periods in Australia can be extremely severe. The most serious drought occurred between 1895 and 1903, with 1902 being the severest year. During that period, sheep numbers declined by more than 50 per cent and cattle by more than 40 per cent. More 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 has been termed a "major catastrophe" by the media. But the El Niño phenomenon[2] takes place, on average, every five to seven 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.

Sediment flushing devices

Surprisingly, Australian reservoirs have been inadequately equipped with flushing devices (table 3). Most Australian reservoirs were originally equipped with a single scour outlet (Ø = 0.3 to 0.5 m) that was inadequate for desilting a reservoir. Only a few dams were equipped with two or more flushing systems. One example is the Illalong Creek dam, which was completed in 1914 and is now fully silted.

[2] Also called the El Niño Southern Oscillation phenomenon (ENSO).

Table 3. Scour outlet systems

Dam	Year of completion	Height of dam (m)	Catchment (km^2)	Reserve capacity (m^3)	Bottom outlets	Outlet area (m^2)
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

Sources: Saladin, 1886; Schnitter, 1994; Smith, 1971; and the present study.

In comparison, the Nabataeans,[3] Romans and Spaniards equipped their reservoirs with large sediment flushing systems. For example, Roman engineers equipped the Monte-Novo dam (300 A.D.) in Portugal with two outlets of 1.2 and 1.4 m^2 cross-section areas each. Such expertise in sediment flushing, gained over the past 22 centuries, was obviously unknown to, or forgotten by, Australian engineers.

SUMMARY AND CONCLUSION

The main findings of the study are that:

(a) Reservoir sedimentation has been a serious problem in Australia;

(b) Australian engineers could draw upon local and overseas experience, including past failures. Indeed, several reservoirs (table 1) became fully silted because the designers did not correctly take into account the soil erosion and sediment transport processes, and no soil conservation practices were introduced.

Today, society expects the useful life of a reservoir to be 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 that cannot be dissociated. Soil erosion and water run-off result in some sediment material being trapped

[3] Inhabitants of an ancient kingdom to the east and south-east of Palestine that included the Negev desert. The Nabataean kingdom lasted from around 312 B.C. to 106 A.D. The Nabataeans built a large number of soil-and-retention dams, some of which are still in use today.

downstream by the dam wall. Therefore, 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 scientists and the public. Each reservoir failure must serve as a valuable teaching and pedagogic tool in order to heighten the awareness of students, professionals, local authorities and the public. Society must learn from its mistakes and avoid repeating them.

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