Int. J. Engng Ed. Vol. 14, No. 4, p. 265–275, 1998
Printed in Great Britain.

0949-149X/91 $3.00+0.00
© 1998 TEMPUS Publications.

Teaching Case Studies in Reservoir Siltation and Catchment Erosion*

H. CHANSON
Senior Lecturer in Fluid mechanics, Hydraulics and Environmental Engineering, Department of Civil Engineering, The University of Queensland, Brisbane QLD 4072, Australia
E-mail: h.chanson:mailbox.uq.edu.au

PATRICK JAMES
Environmental Consultant, Patrick James & Associates, 5/2 Hardie Street, Neutral Bay NSW 2089, Australia

Waters flowing in streams and rivers have the ability to scour channel beds, to carry particles (heavier than water) and to deposit materials. This phenomenon of sediment transport can affect substantially the design of reservoirs. The paper describes four case studies of siltation which rendered useless water storage structures in less than 25 years. Although each dam had advanced structural features, the hydrology of the catchment and sediment transport processes were not properly taken into account. The study highlights practical situations in which a reservoir must be analysed as a complete system, taking into account structural features, hydraulics, hydrology, sediment transport, catchment erosion and catchment management. The case studies may be used as teaching examples to increase student interest on the significance of sediment transport problems and to emphasise the design procedure to professionals. They may serve also to alert the community at large to basic errors caused by improper soil conservation policy and the inability to predict sediment/load process.

SUMMARY OF EDUCATIONAL ASPECTS OF THIS PAPER

1. The case studies are used as supporting material in the undergraduate teaching of open channel hydraulics and design of hydraulic structures.
2. The study highlights practical situations where the designers failed to consider the reservoir and its catchment as a complete system, consisting of: structural features, hydraulics, hydrology, sediment transport, catchment erosion and catchment management policy.
3. Past experience and failures should be used as valuable pedagogic tools by both professionals and engineering students.

INTRODUCTION

WATERS FLOWING in streams and rivers have the ability to scour channel beds, to carry particles heavier than water and to deposit materials. This phenomenon (i.e. sediment transport) is of great economical importance and numerous failures have resulted from the inability of engineers to predict sediment motion: e.g., bridge collapse (pier foundation erosion), formation of sand bars in estuaries and navigable rivers, destruction of banks and levees.

Classical (clear-water) hydraulics is sometimes referred to as 'fixed boundary hydraulics' and the basic principles of hydraulics can be taught in a simple scientific manner (e.g. [1 pp. 1–173]). Professionals and engineering students can apply these principles to most man-made channels (e.g. concrete-lined channels, rock tunnels, rockfill-protected channels) and to some extent to grassed waterways. Fixed boundary hydraulics cannot predict the morphology changes of natural streams because of the numerous interactions with the catchment, its hydrology and the sediment transport processes: i.e., the stream boundaries are movable ('movable boundary hydraulics'). It is now recognised that movable boundary hydraulics is characterised by strong interactive processes between rainfall intensity and duration, water runoff, soil erosion resistance, topography of the stream and catchment, and stream discharge.

In the paper, the authors describe four engineering failures which may offer undergraduate students with valuable insights into reservoir siltation and engineering responsibilities. After a short description of each case, they illustrate that, despite advanced structural features, each reservoir was improperly designed. Each failure is explained in simple engineering terms. The conclusions may be used as teaching examples for engineering students and professionals to highlight the complexity of reservoir design, and the interactions between sediment transport and catchment erosion.

* Accepted 15 November 1997.

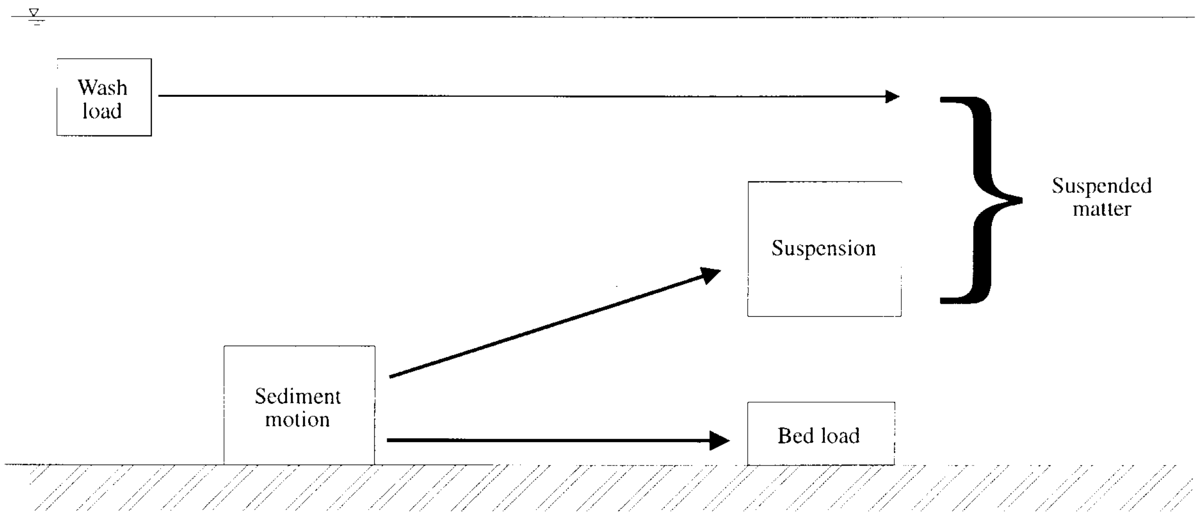


Fig. 1. Sediment transport classification.

Basic definitions

- Sediment transport is the general term used for the transport of material (e.g. silt, sand, gravel, boulder) in rivers and streams.
- The transported material is called the 'sediment load'.
- Distinction is made between the 'bed load' and the 'suspended load', the bed load characterises grains rolling along the bed while suspended load refers to grains maintained in suspension by turbulence.
- The total sediment discharge in a stream is the total volume of sediment particles in motion per unit time. It includes the sediment transport by bed load motion and by suspension as well as the 'wash load' (Fig. 1).

THE TALE OF FOUR RESERVOIRS

Presentation

Since the discovery of the Australian continent by Europeans, the water supply of the colony was always an important concern. Large water reservoirs were built first in the South-East, in the states of New South Wales and Victoria. By tradition most Australian dams were earth embankments following the British experience. Interestingly the NSW Public Works Department built a series of thin arch dams (Fig. 2) which was the first attempt in the world to standardise this design technique. At the time, the dams were recognised as advanced designs in Europe and in USA ([2, 3, also 4, 5]).

Despite their advanced structural design, several thin arch dams were used for less than 25 years. The reservoirs silted up very (too) rapidly and the dams have become a source of embarrassment. The basic characteristics of four reservoirs are summarised in Tables 1 and 2. In Table 3, the causes of failures are summarised. The dam walls are still standing today, fully-silted (Figs 3 to 6).

Moore creek dam

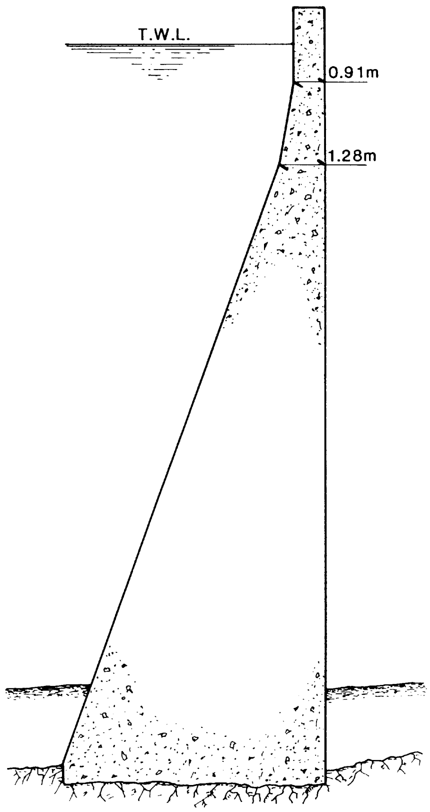
The Moore Creek Dam was originally called the Tamworth Dam and completed in 1898. It is a 18.6-m high dam which incorporated significant advances in structural design: i.e. thin single-arch (7.7-m thick at base for 0.87-m thick at dam crest), made of Portland cement concrete. The arch wall has an unusual downstream vertical face and a inclined upstream face (Figs 2 and 3). The single arch extends with a left-bank gravity cross-section. The dam was equipped with a large overfall spillway ($Q \sim 100\,m^3/s$), a scour valve and a pipe outlet.

Rapid siltation of the reservoir was observed: $85\,000\,m^3$ of sediment had accumulated by 1911 (39% of original capacity). Records indicated that most siltation took place during two major floods with dam overtopping in February 1908 and January 1910. By 1924 the reservoir was fully-silted and disused.

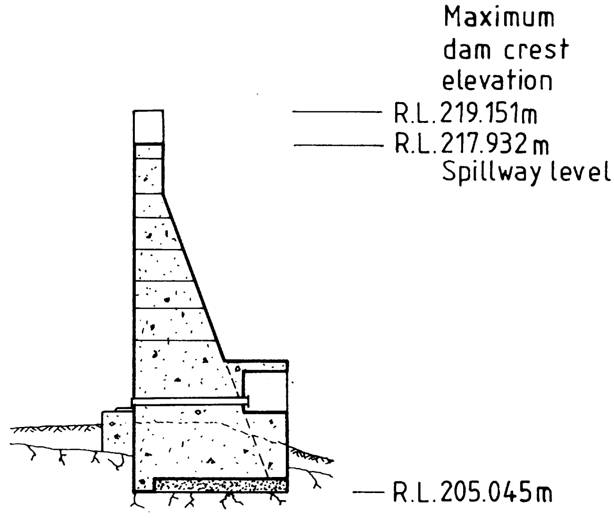
Gap weir

The Gap weir was built by the NSW Railways Department as supply water for railway steam engines. Completed in 1902, the dam wall is a single-arch concrete structure with upstream vertical and inclined downstream faces (Fig. 4). It was equipped with an overfall spillway ($Q \sim 35$ to $40\,m^3/s$) followed by a deep plunge pool, but no scour outlet was built although a drawing prior to construction showed one.

The reservoir was fully-silted by 1924. It was abandoned and replaced by available water from Quipolly Creek and later from the Quipolly dam (completed in 1932). (The change in train engines occurred in the 1960s and did not affect the decision.) The dam wall was breached twice with explosives to reduce upstream flooding. The river, cutting through the reservoir sediment, has exposed the silty material trapped by the weir, indicating a siltation process by suspended-load predominantly. The dam is located downstream of

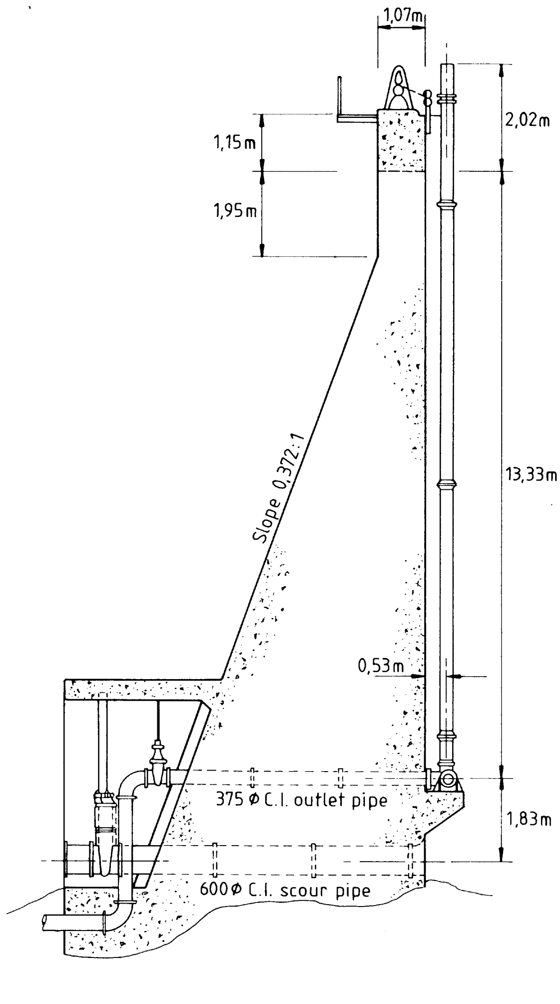


MOORE CREEK DAM



KORRUMBYN CREEK DAM

Fig. 2. Cross-sections of thin arch walls. (A) Moore Creek. (B) Korrumbyn Creek. (C) Quipolly.



QUIPOLLY DAM

Table 1. Characteristics of reservoirs and catchments

Reservoir, completion date	Vol. of reservoir m^3 [1]	Catchm. area km^2	Original purpose	History	Present use	Remarks
Moore Creek Dam, 1898	220× E + 3	51	Water supply for the town of Tamworth.	Heavy siltation during 1908 and 1910 floods. Complete reservoir siltation by 1924. Bed-load siltation primarily.	NONE. Fully-silted reservoir, occupied by a young forest (later than 1973).	Was considered as a source of sand extraction (for concrete). Access by 4WD vehicle and on foot.
Gap Weir, 1902	–	160	Water supply for steam engines at the Gap railway station, near the rail junction of Werris Creek	Heavy siltation during 1919 floods. Fully silted by 1924. Sedimentation by suspension load.	NONE.	The wall was blown away twice with explosives to reduce upstream backwater effects. Visible from the road.
Korrumbyn Creek Dam, 1918	27.28× E + 3	3	Water supply for the town of Murwillumbah.	Rapid bed-load sedimentation associated with jammed scour valve. Poor water quality	NONE. Reservoir occupied by an overgrown tropical rain forest.	Reservoir included in a national park. Dam access impracticable.[2]
Quipolly Dam, 1932	860× E + 3	70	Water supply of the town of Werris Creek.	Heavy siltation during 1942-43 floods. Siltation volume >50% by 1952. Disused since 1955.	SEDIMENT TRAP Protecting Quipolly dam No. 2, located 3-km downstream (completed in 1955).	Accessible and visible from the road.

Note: [1] original capacity; [2] although the dam abutment is less than 5-m from the road, the dam wall is not visible from the road; Accessible on foot by following the creek from downstream.

a 6-km long flat plain (slope < 0.2) along which the bed-load would deposit before reaching the reservoir.

Korrumbyn creek dam

The Korrumbyn Creek Dam was completed in 1918 for water supply purposes. It is located less than 50 km from the Pacific coast. The wall is a 14.1 m high single arch (1.1 m thick at crest, 61 m radius in plan) with a left-bank extension of gravity cross-section (Fig. 5). The dam was equipped with two bottom outlets (pipe outlet and scour valve) and an overfall spillway ($Q \sim 125\,m^3/s$).

The reservoir was rapidly abandoned because the scour pipe was jammed by a log which could not be removed. Prior to the incident, water supply from the reservoir was inadequate. The reservoir water level used to drop during dry periods, and the water would turn green and become unfit for use. Altogether the reservoir silted up very quickly by bed-load transport and was disused in less than 20 years. Note that, although the original volume of the reservoir was 27 280 m^3, the catchment area is only about 3 km^2 (Table 1)!

Quipolly dam

The Quipolly Dam (also known as old Quipolly Dam or Coeypolly Creek Dam No. 1) was completed in 1932. The dam wall (Fig. 6) is a slender arch in comparison with Moore Creek Dam and Korrumbyn Creek Weir, both designed with a (thicker) gravity section. It is a concrete single-arch (1.08 m thickness at crest). The dam was equipped with two bottom outlets and an overfall spillway ($Q \sim 240\,m^3/s$).

15% of the initial reservoir capacity was silted between 1932 and 1941. In 1943 the siltation volume amounted to 34% of the initial capacity. By 1952, more than half of the initial storage had disappeared. The reservoir was abandoned in 1955 at the completion of the Quipolly Dam No. 2, located 3 km downstream. The (old) Quipolly Reservoir is fully silted nowadays. Although the Quipolly Reservoir is 'officially' disused, it has become a sediment trap preventing efficiently the sedimentation of the Quipolly Reservoir No. 2.

CAUSES OF FAILURES: AN ANALYSIS

The four dams were built with advanced structural features, at their time: thin arch walls made of concrete. However each reservoir must be considered as an engineering failure (Table 3). Their rapid siltation rate and their short lifetime (less than 25 years) indicate a lack of understanding of the interactions between the reservoir, the catchment and the siltation process resulting from sediment/load inflow. The designers did not understand the basic concepts of sediment transport and catchment management.

Table 2. Technical characteristics of single arch dam walls

Dam	Maxi. height m[1]	Crest length m	Construction	Spillway	Bottom outlets
Moore Creek, 1898	18.6	155	Thin concrete arch (R = 75 m). Wall thickness: 0.87 m at crest, 7.7 m at base.	Overfall $Q \sim 100\,m^3/s$	2 outlets: scour valve and pipe outlet.
Gap Weir, 1902	6 to 10[2]	45 to 50[2]	Thin concrete arch. Wall thickness: 0.94 m at crest.	Overflow $Q \sim 35$ à $40\,m^3/s$	No bottom outlet.
Korrumbyn Creek, 1917–1918	14.1	–	Thin concrete arch (R = 61 m, $\theta \sim 47°$). Wall thickness: 1.1 m at crest, 5.2 m at base.	Overfall $Q \sim 125\,m^3/s$	Outlet system: one scour valve and one pipe outlet (12 L/s).
Quipolly, 1932	19	184	Thin concrete arch (R = 61 m, $\theta = 93°$). Wall thickness: 1.08 m at crest, 6.99 m at base.	Overfall $Q \sim 240\,m^3/s$	Outlet system: one scour valve and one pipe outlet.

Notes: [1] height above lowest foundation; [2] estimated from site inspection; Q: maximum overflow capacity without dam overtopping; R: curvature radius of the cylinder; θ: opening angle (i.e. central angle).

The siltation of Moore Creek Reservoir was caused by rapid catchment erosion. At the end of the 19th century, the natural vegetation occupying the catchment was cleared for farming and stocking. It appears, further, that a significant increase in sheep livestock took place around 1890–1910. Both the clearing of the catchment and an increase of sheep cattle diminished the soil resistance against erosion during heavy rainfalls, hence contributing to the rapid sedimentation of the reservoir.

The Gap Weir was built without scour outlet and sediment could not be removed. Additionally the spillway capacity was very small compared to the other dams which have all smaller catchments (Tables 1 and 2).

The Korrumbyn Creek Dam had an insufficient catchment area ($3\,km^2$). The stream discharge was very irregular and the reservoir could not fulfil the water needs. Further the catchment is very steep (bed slope $>7.6°$) and the channel bed contains a wide range of sediment materials. A rapid reservoir siltation by bed-load could be predicted with today's experience (in the opinion of the first author, after an inspection of the river bed along several kilometres, upstream and downstream of the dam).

The siltation of Quipolly Reservoir is probably related to soil erosion of the catchment, in connection with improper catchment management. Note that the reservoir is the only one of the four which retains some usefulness today: i.e., a sediment trap for Quipolly Dam No. 2.

Summary

Despite some advanced features in terms of structural design, the four reservoirs failed because the designers did not understand the basic concepts of sediment transport (Table 3). Two reservoir siltations (Moore Creek, Quipolly) resulted from major catchment erosion and absence of total catchment management policy. One reservoir (Korrumbyn Creek) should have not been built: the site was improper (heavy bed-load) and the water demand could not be met (very small catchment area). The siltation of Gap Weir was caused by a design mistake: i.e., absence of scour valve.

Table 3. Causes of reservoir failures and possible remedies

Reservoir	Cause of failure	Remedy	Comments
Moore Creek Dam, 1898	Siltation by bed-load primarily, resulting from overgrazing of catchment (sheep stocks).	1—Soil conservation practices in catchment 2—Larger scour outlet (?)	
Gap Weir, 1902	Siltation by suspended load. Lack of bottom outlet to scour reservoir.	1—Scour valve	Very small overfall spillway capacity.
Korrumbyn Creek Dam, 1917–1918	Log jammed in scour valve, rapid bed-load siltation and 'green-blue' algae in water.	1—Selection of another site	Improper site. Very (too) small catchment.
Quipolly Dam, 1932	Siltation, resulting from overgrazing of catchment.	1—Soil conservation practices in catchment 2—Larger scour outlet	

Fig. 3. Moore Creek Reservoir nowadays. Photographs taken on 14 June 1997 (by H. Chanson). (A) Downstream wall. The scour valve is visible just left of the tree. (B) Crest view, looking toward the right bank.

LESSONS FROM FAILURES

Learning from practical cases is an essential factor in engineering education. Engineering practice is often a combination of theory and practical constraints (i.e. limits to the theory). One of the skills of the engineering educator is to be able to demonstrate the interaction between engineering theory and practical limits. To this end, case studies of failures may be used to inspire students with the relevance and excitement of engineering design. They are also pedagogic examples to alert students with the issues of responsibility, accountability and ethics in engineering. Often failures are

Fig. 4. The Gap Weir and its silted reservoir from a photograph taken on 13 June 1997 (by H. Chanson). The black line is the original spillway crest.

Fig. 5. Photograph of the Korrumbyn Creek Dam wall and the surrounding tropical rain forest. Photograph taken on 25 April 1997 (by H. Chanson).

the result of simple errors and insufficient common sense. Failure analysis is a vital means to reinforce engineering theory and to combine it with engineering practice.

The failures described in the paper illustrate the complexity of movable boundary hydraulics and catchment erosion. Four reservoirs were used for less than 25 years. Why? What could we learn from experience?

Additional parameters affected the sedimentation history of the reservoirs. The hydrology of each catchment is characterised by intense rainfall

Fig. 6. Photograph of the Quipolly Dam, from the right bank. Photograph taken on 13 June 1997 (by H. Chanson).

during the wet seasons. Streams often carry an important sediment load. The soils have a thin fertile cover and intensive farming can devastate the natural vegetation and enhance soil erosion.

Hydrology of the catchments: global climatic effect

Northern New South Wales is characterised by a sub-tropical climate with a dry season and a wet summer season. This annual cycle is however affected by inter-annual climatic events (El-Niño) associated with long period of droughts [6]. This long-term pattern was clearly established between 1878 and 1888 by Sir Charles Todd, South Australia Government Observer, and well documented by H. C. Russell, NSW Government Observer ([7], p. 17). It was known in South-East Australia at the time of construction of the reservoirs.

In terms of soil erosion and sediment load, the most extreme hydrological events are extreme floods following a long drought period (associated with an El-Niño). Dry conditions retard the growth of vegetation cover. Further overgrazing of pastures (during droughts) followed by failure of pasture regeneration increases drastically the erosion susceptibility of the unvegetated ground. The following torrential rains wash away the soils and large sediment loads are carried away into the reservoirs. Three (of the four reservoirs) experienced such extreme hydrological events associated with heavy siltation: the Moore Creek Reservoir (flood of February 1908), the Gap Weir (floods of 1919), and the Quipolly Reservoir (floods of 1942–43).

Interestingly three dams (Moore Creek, Korrumbyn Creek, Quipolly) were equipped with relatively large spillway capacity (100, 125 and 140 m^3/s respectively), with allowance for dam overtopping, for relatively small catchment areas (51, 3 and 70 km^2 respectively). (For comparison, the Quipolly Dam No. 2 was equipped with a 380-m^2/s spillway capacity.) This suggests that the designers were aware of large flood records. Records indicate further that the reservoirs were built to fulfil water needs during the dry years.

Although design engineers were aware of the extreme hydrology of the catchments, it appears that they ignored (or neglected) the catchment erosion and sediment-load motion taking place during extreme floods.

Sediment transport and design experience

Basically the stories of the four reservoirs reflect a lack of understanding of sediment transport processes. Should we blame the design engineers? What could we learn from their mistakes?

True, the knowledge of sediment motion 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 20th century: e.g., [8–14]. However the authors are very surprised 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: the information was available prior to the construction of Korrumbyn Creek Dam.

Similarly the experiences of Moore Creek and Gap Weir should have influenced the design of Quipolly Dam. The Moore Creek and Gap dams are located about 55 and 20 km respectively from Quipolly reservoir. Their experience should have affected the reservoir design: e.g., by introducing a total catchment management policy to minimise soil erosion and by including a larger scour outlet for sediment flushing. Practically the scour valve at Quipolly was not much larger than at Moore Creek, and the land management practices applied to Quipolly catchment in the period 1930–1950 were identical to those of Moore Creek catchment in 1900–1910 [15]!

Sedimentation rates

It is interesting to compare the sedimentation rate of the reservoirs with other structures. Figure 7 presents the siltation rate of Moore Creek and Quipolly reservoirs (in m^3 per km^2 of catchment and per year) as a function of the study period (i.e. period between consecutive observations). (Note that $1\ m^3/km^2/year = 0.55$ tonnes/km^2/year,

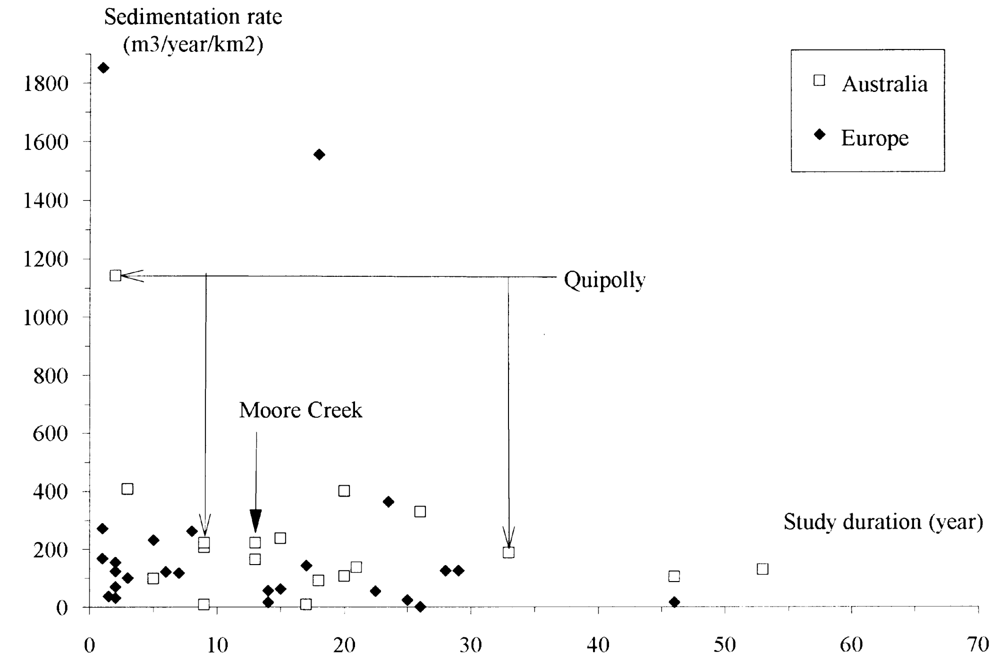


Fig. 7. Sedimentation rates in m^3 per km^2 of catchment and per year: extreme sedimentation cases in Australia and in Central Europe [17, 18].

assuming sandy sediment material.) The data are compared with large sedimentation rates observed in Australia (e.g. Corona, Stephens Creek and Umberumberka near Broken Hill NSW) and in Central Europe. In Fig. 7, each siltation rate could be considered as very significant.

The results (Fig. 7) indicate that the siltation rates at Moore Creek and Quipolly were important and similar to other extreme situations. However most reservoirs included in the study plot (Fig. 7) were not fully-silted in less than 25 years!

ENGINEERING FAILURES AS TEACHING TOOLS

Impact of the reservoirs on the community nowadays

In their time the four dams were perceived as technological progress. The Moore Creek Dam, in particular, was well publicised both locally and internationally: in the press, with visits by experts, by reference in reputed textbooks (e.g. [16]). Currently the reservoirs are basically forgotten by the public and considered as a source of embarrassment by the engineers.

In Murwillumbah few people know of the Korrumbyn Creek Dam, even among residents living near the reservoir. (The first author contacted over 20 people living less than 10 km from the dam site. Only two people knew the location of the dam.) Further the relevant local authorities (i.e. Tweed Shire Council, NSW National Parks and Wildlife Service) have no longer technical information on the dam. Access to the dam is extremely difficult as if nobody wanted to remember the site.

The same observation applies to the Gap Weir, except for an easier access. In addition the authors have not found (as of today) one drawing of the dam as executed. Even the exact wall height is unknown.

Moore Creek Dam has a different status. Because it was well publicised, residents of the catchment know the dam location although access is via private properties. Local authority engineers (i.e. Tamworth City Council, Parry Shire Council) do not hold technical drawings and local residents consider the dam as a 'typical engineering failure'.

Today the four dams have no use but the Quipolly Dam. Interestingly the NSW Dam Safety Committee organises regular safety inspections of three dams: Moore Creek, Korrumbyn Creek and Quipolly.

Application: teaching tools for students

In the authors' opinion, the four reservoirs should serve as valuable pedagogic and teaching support nowadays. They may be used to heighten the awareness of engineering students, professional engineers and the public of problems associated with sediment transport processes and their interactions on the design of hydraulic structures. Both engineers and engineering students should learn from past mistakes.

In practice, the first author has introduced the story of the four reservoirs as part of the undergraduate teaching for an introduction to catchment hydraulics, sediment transport and design of hydraulic structures. The authors feel that each case should be a learning experience illustrating poor understanding of movable-boundary hydraulics and soil conservation practice. The mistakes of these reservoirs 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 is unsuitable because of the heavy bed load carried by the stream. At Moore Creek and Quipolly reservoirs, a soil management policy should have been introduced.

Further the experience of Moore Creek (1898 to say 1914) was not applied in the construction of Korrumbyn Creek Dam (1917 to 1924). The experience of both these projects was not applied to Quipolly Reservoir, yet all three were designed and their construction supervised by the same organisation (i.e. the NSW Public Works Department). Why was the experience of reservoir siltation gained over a 20-year period not shared between colleagues and used to improve the design technique.

Are too many engineers focused on future projects and unwilling to apply hindsight to learn from experiences and failures? Is it a characteristics of professional engineers not to admit mistakes? Whatever the reason it is unfortunate because both engineering students and professional engineers can learn valuable lessons from failures: technical lessons, management policy and communication skills.

Design of reservoirs: developing an expertise?

The authors note that the four dams were built with identical features. No evolution in design took place between Moore Creek (1898) and Quipolly (1932) dams. The dams were a single-arch (vertical cylinder) design, first applied some 40 years before to the Parramatta Dam (completed in 1856, near Sydney). The design technique was improved between 1856 and 1890: Moore Creek dam is taller and thinner than Parramatta Dam.

Between 1890 and 1920, progresses in arch-dam design were made in America. New methods of arch-dam analysis were introduced: e.g., theory of elastic arches, distribution of the loads, double-curved dome-like arch, arch with variable radius of curvature. None of these progresses was introduced in Australia where dam designs stagnated with the single-radius cylinder design.

The lack of evolution in design suggests that the designers made no serious attempt to improve their design technique. Australian engineers were (apparently) cut off from engineering advances in America and Europe. The authors wonder whether a similar attitude was taken with regards to progresses in sediment transport process during the first half of the 20th century.

Lessons from failures: benefits to teachers

Engineering applications and normal engineering practice are often a combination of theory plus practical constraints. One of the skills of an engineering educator is to be able to demonstrate the interface between engineering theory and practical limits. To this end the use of case studies is an ideal tool. Of particular relevance are the results of basic mistakes. Failure analysis is a valid and vital means of reinforcing engineering theory and combining it with practice.

The failure described here are the results of trivial oversights: e.g., streams too steep, unprotected catchments, no provision for adequate scour outlets and mistakes not corrected in subsequent designs. To know that a small error can result in a large failure may motivate students not to repeat the same mistakes.

CONCLUSION

The authors have documented several case studies illustrating reservoirs failures caused by siltation and catchment erosion. The failure cases are used to introduce students to the complexity of reservoir management and sedimentation. The main lesson is the importance of designing a reservoir as a complete system, including hydrology, soil conservation practice, sediment transport principles and hence the siltation process.

Four advanced-design concrete dams have been examined. They were built, silted very rapidly and disused in less than 25 years. The main causes of reservoir siltation are: extreme climatic conditions and heavy sediment load of the streams, but also improper soil conservation practices and design mistakes.

Although the dams had advanced structural features, the story of each reservoir reflects a misunderstanding of the sediment transport processes by the designers. It is noted also that the engineers did not learn from past mistakes. The authors hope that the four examples can be used by professionals and students, as pedagogic examples, to improve future hydraulic designs by designing reservoirs as complete systems.

Acknowledgements—The authors wish to thank the following people for their assistance and help: Mr N. Bedford, Tamworth NSW, Ms Chou Y. H., Brisbane QLD, Mr and Mrs D. Davidson, Murwillumbah NSW, Dr M. R. Gourlay, Brisbane QLD, Mr P. Heinrichs, Sydney NSW; Ms C. Litchfield, Brisbane QLD, Mr G. Ryan, Tamworth NSW.

REFERENCES

1. F. M. Henderson, *Open Channel Flow*, MacMillan Company, New York, USA (1966).
2. J. D. Schuyler, *Reservoirs for Irrigation, Water-Power and Domestic Water Supply*, John Wiley & Sons, 2nd edition, New York, USA (1909).
3. L. A. B. Wade, Concrete and masonry dam construction in New South Wales, *Min. of Proc. of Instn. of Civil Engineers*, London, **178**, No. 9, Paper 3791 (1909), pp. 1–26; discussion, pp. 27–110.
4. N. Smith, *A History of Dams*, The Chaucer Press, Peter Davies, London, UK (1971).
5. N. J. Schnitter, *A History of Dams: the Useful Pyramids*, Balkema Publ., Rotterdam, The Netherlands (1994).
6. H. F. Diaz and V. Markgraf, *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillations*, Cambridge University Press, UK (1992).
7. R. H. Grove, The East India Company, the Australians and the El-Niño: colonial scientists and analysis of the mechanisms of global climatic change and teleconnections between 1770 and 1930, Working Paper No. 182, *Working Papers in Economic History*, Australian Nat. Univ., Canberra, Australia, (March 1995).
8. P. F. D. du Boys, Etude du Régime et de l'Action exercée par les Eaux sur un Lit à Fond de Graviers indéfiniment affouillable (Study of flow regime and force exerted on a gravel bed of infinite depth), *Ann. Ponts et Chaussées*, Paris, France, série 5, **19**, (in French) (1879) pp. 141–195.
9. A. Schoklitsch, *Über Schleppkraft un Geschiebebewegung*, Engelmann, Leipzige, Germany (in German) (1914).
10. A. Schoklitsch, *Handbuch des Wasserbaues*, (Handbook of Hydraulic Structures), Springer, Vienna, Austria (1930).
11. H. A. Einstein, Formulas for the transportation of bed-load, *Transactions*, ASCE, **107**, (1942) pp. 561–573.
12. H. A. Einstein, The bed-load function for sediment transportation in open channel flows. *US Dept. of Agriculture Techn. Bulletin No. 1026*, Soil Conservation Service, Washington DC, USA (1950).
13. E. Meyer-Peter, Quelques Problèmes concernant le Charriage des Matières Solides (Some problems related to bed load transport), *Soc. Hydrotechnique de France*, No. 2 (in French) (1949).
14. E. Meyer-Peter, Transport des matières Solides en Général et problème Spéciaux, *Bull. Génie Civil d'Hydraulique Fluviale*, Tome 5 (in French) (1951).
15. P. James, Catchment erosion and sediment filled dams, *ANCOLD Bulletin*, No. 106, (Aug. 1997) pp. 112–123.
16. E. Wegmann, *The Design and Construction of Dams*, John Wiley & Sons, New York, USA, 7th edition (1922).
17. J. Cyberski, Accumulation of debris in water storage reservoirs of Central Europe, *Proc. Int. Symp. on Man-Made Lakes, Their Problems and Environmental Effects*, ICSU, Knoxville TN, USA (1971); (also in *Man-Made Lakes: Their Problems and Environmental Effects*, Ackermann, W. C., White, G. E., Worthington, E. B., and Loreena-Ivens, J. editors, AGU Publ., Washington, USA, (1973), pp. 359–363).
18. A. Lajczak, The rates of silting and the useful lifetime of dam reservoirs in the Polish Carpathians, *Zeitschrift für Geomorphologie*, **38**, No. 2, (1994), pp. 129–150.

Hubert Chanson is a Senior Lecturer in Fluid Mechanics, Hydraulics and Environmental Engineering at the Department of Civil Engineering, The University of Queensland. His research interests include experimental investigations of multiphase flows and particularly air/water mixtures, design of hydraulic and coastal structures, and modelling of water quality in rivers, estuaries and the ocean. He wrote two books: *Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways*, Pergamon (1995) and *Air Bubble Entrainment in Free-surface Turbulent Shear Flows*, Academic Press (1997) and over seventy international refereed journal papers. He has been active also as consultant for both governmental agencies and private organisations.

Patrick James is the principal of Patrick James & Associates, an independent environmental and resource development consultancy established in 1982. He qualified in metallurgy (RMIT) and has worked in England, the Netherlands and Australia on high temperature material R&D. Since 1978 he has worked in resource development, in particular in the extractive (quarrying) industry. He has a BSc in physical geography and resource and environmental management from Macquarie University. He is a foundation Member of the Environment Institute of Australia and a Fellow of the Institute of Quarrying.