ACTA GEOLOGICA HISPANICA, v. 35 (2000), nº 3-4, p. 329-338

Sedimentation in a semi-arid zone reservoir in Australia determined by ^{137}Cs

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ABSTRACT

Sediment has accumulated behind a masonry dam built in the 1880s in the Barrier Range, north-west of Broken Hill, New South Wales, Australia. The contributing catchment has an area of 12.5 ha, and is used for rangeland grazing for sheep and goats. It is estimated from surveys and measurements of heavy metals and caesium-137 that over 1000 tonnes of sediment have accumulated in the reservoir since its inception. Approximately one-third of the sediment has been delivered since the mid-1950s.

Sediment accumulation is equivalent to a catchment erosion rate of 0.78 t ha^{-1} y^{-1} prior to the mid-1950s, whereas from the mid-1950s to the present it is 0.59 t ha^{-1} y^{-1}. This indicates that the trap efficiency of the reservoir has decreased and/or the sediment supply has become relatively exhausted and/or there has been a progressive increase in vegetation cover related to reduced grazing pressures. The estimated rates of erosion are considerably lower than for other sites in semi-arid New South Wales probably because sediment has been transported in overflows of the dam wall.

Key words: Sedimentation. Semi-arid zone. Australia. Caesium-137.

INTRODUCTION

Study of fluvial sedimentation using the environmental radioisotope caesium-137 (^{137}Cs) method in the Australian arid and semi-arid zones has been confined to the Stephens Creek reservoir which supplies the mining city of Broken Hill in western New South Wales (Figure 1). Campbell and Ross (1980) carried out a preliminary study of ^{137}Cs as an indicator of sedimentation rates at three sites on the reservoir floor. They found significant concentrations of ^{137}Cs (<22 Bq kg^{-1}) and were able to partition core samples into periods before and after maximum fallout (1964). The study reported in this paper further examines the use of the ^{137}Cs method for reservoir research in an environment collecting coarser sediments than the Stephens Creek reservoir. From measurements of sedimentation rates, inferences may be drawn about rates of sediment delivery and soil erosion within a drainage basin which has been used for grazing for a period of over 100 years. These results can be compared with measured sedimentation rates for another, larger, reservoir which was constructed nearby between 1913 and 1915 (Wasson and Galloway, 1986), as well as other measurements from within the semi-arid zone of New South Wales.

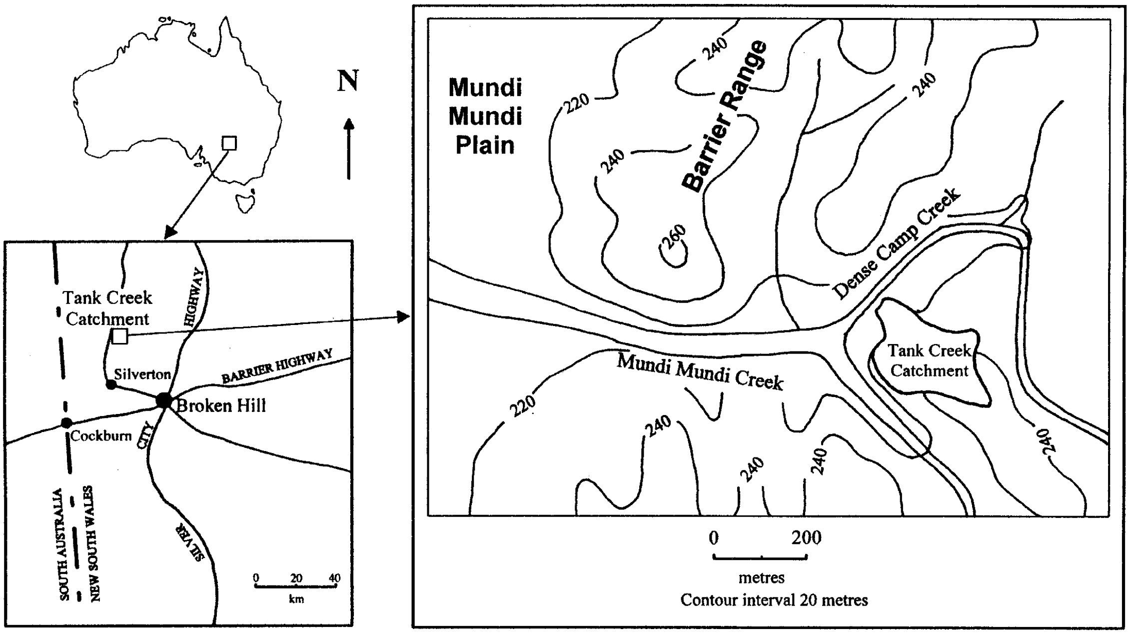


Figure 1. Study site location.

THE STUDY SITE

The study reservoir collects water from a catchment of 12.5 ha, named Tank Creek, on the western foothills of the Barrier Range north-west of Broken Hill (Figures 1 and 2). The drainage basin is approximately 220 m above sea level with a mean annual, but highly variable, rainfall of 206 mm. The basin is underlain by steeply dipping Early to Middle Proterozoic metasediments of the Willyama Supergroup (Stevens et al., 1994). Slopes within the basin are mantled with stones, and there are rock outcrops. The relative relief of the basin is 46 m, with a relief ratio of 0.079. Soils have been classified as lithosols, and in places there are red texture-contrast soils on the lower slopes (Walker, 1991). Vegetation is sparse, but there are scattered Acacia trees, shrubs, forbs and grasses.

The reservoir is impounded by a masonry wall 1.5 m high across Tank Creek, a tributary of Dense Camp Creek, in turn a tributary of Mundi Mundi Creek, which drains westwards from the Barrier Range (Figure 1). The masonry wall at its northern end has been extended by the addition of 3.5 m of iron plate and stone, making the total wall length 19 m. On reaching the wall, water is diverted into a masonry tank (9.8 x 7.7 m internal surface area, 2.5 m deep) let into the adjacent left-bank flood plain (Figure 2). The date of construction of the wall and the tank is unknown, but it is thought to date from the period 1880-1890 when buildings at the Mundi Mundi Head Station were being established (Schmidt, 1998). The reservoir was one of several water-harvesting sites

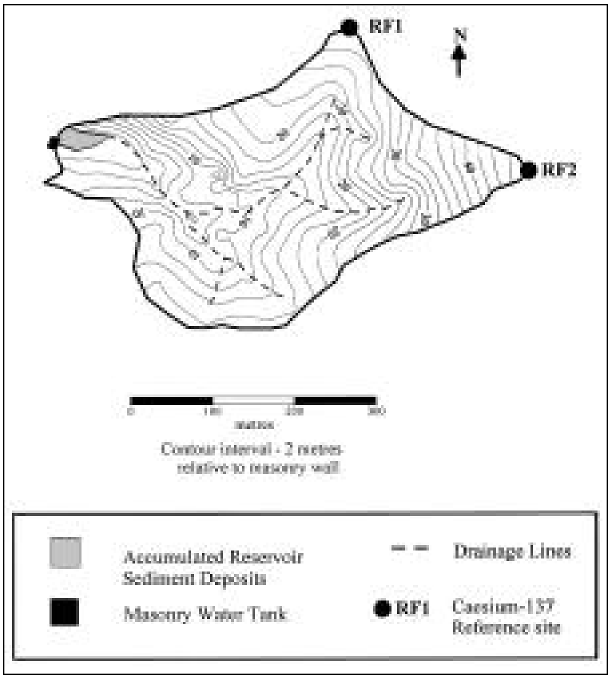


Figure 2. Tank Creek catchment.

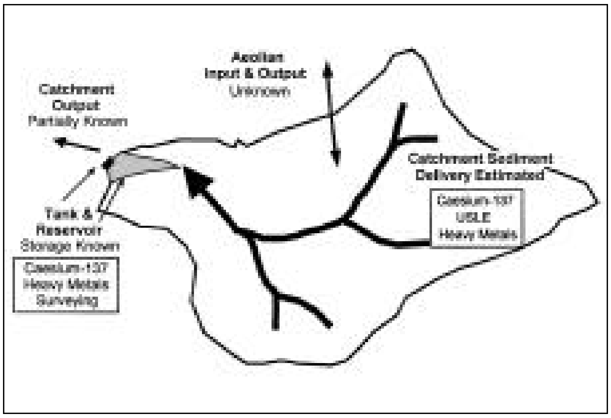


Figure 3. The sediment dynamics of Tank Creek catchment.

established at Mundi Mundi. The buildings were abandoned in the early 1930s, but the land continued to be used for the grazing of sheep and goats.

Figure 3 illustrates the possible sediment dynamics of Tank Creek and reservoir system. Since the installation of the water-harvesting works, sediments have accumulated behind the impounding masonry wall and in the masonry tank. Water and sediment overflows from these structures have occurred, with some sediments being deposited within the channel and on the flood plain in the 40 m reach of Tank Creek above its confluence with Dense Camp Creek. Also, there will have been some inputs and erosional losses by wind action.

METHODS

Eight pits and 42 auger holes have been used to determine the depth of reservoir and tank sedimentation (Figure 4). Sediment samples were collected at 20 mm depth intervals in Pits 17, 18 and 19 in the main reservoir and Pit 20 in the tank. In Pits 21, 22, 23 and 24, sediment samples were collected according to the visible stratigraphy. The surface topography of the reservoir was surveyed so that the depth and volume of accumulated sediment could be determined.

Two reference sites for ^{137}Cs atmospheric input were sampled on the drainage basin divide (RF1 and RF2; Figure 2). Each site was sampled by a scraper plate within

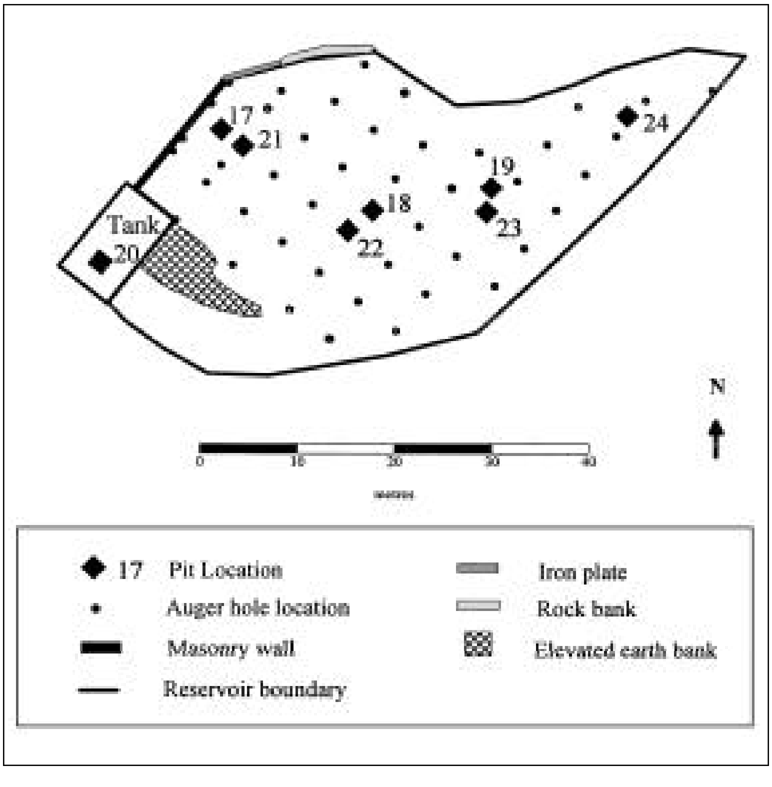


Figure 4. Tank Creek reservoir showing sampling pits and auger hole locations.

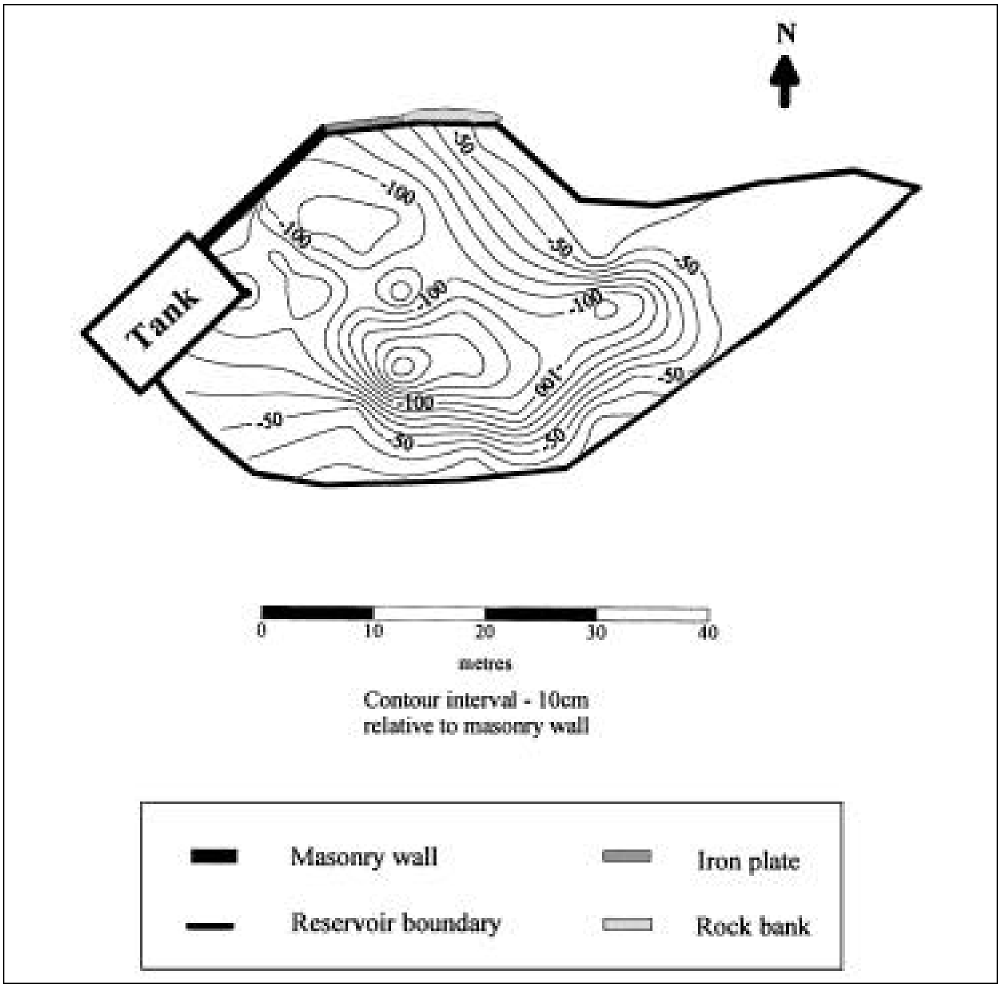


Figure 5. The original reservoir topography.

a 195 x 500 mm steel frame at 20 mm depth-intervals (Campbell et al., 1988).

Sediment samples were dried at 400ºC, crushed and sieved. Organic content was determined by loss on ignition at 4250ºC (Smith and Atkinson, 1975 : 174-175). The hydrometer method (Smith and Atkinson, 1975: 121-122) and sieving were undertaken to determine particle size distribution. Gamma spectroscopy was used to determine ^{137}Cs concentrations of sediment <2 mm, and atomic absorption spectrophotometry was used to measure lead concentrations for pit correlation and dating. Lead smelters operated at Daydream Mine and Broken Hill from 1885-1886 and 1886-1898 respectively. Both are within 40 km of the study site and both are south-east of the site in a prevailing up-wind direction.

RESULTS

The reservoir has a surface area of 1000 m^2 and the tank, 75 m^2. Reservoir-floor topography shows the presence of a former pool on the outside of a channel bend which is defended by a rock outcrop to the north, 15 m in height (Figures 2 and 5). The total volume of accumulated sediment in the reservoir and tank is 797 m^3, equivalent to approximately 1070 t.

In two upstream pits (18 and 19), there are thick deposits of gravel (> 2 mm) which represent episodes of coarse bed load transport down Tank Creek (Figure 6a). Pits 17, near the wall, and 20, in the tank, have much finer sediments (Figure 6b), but laminations are still visible. Often, laminations are paired, fine over coarse, with over 100 of such 'couplets' visible in Pit 17 and approxi-

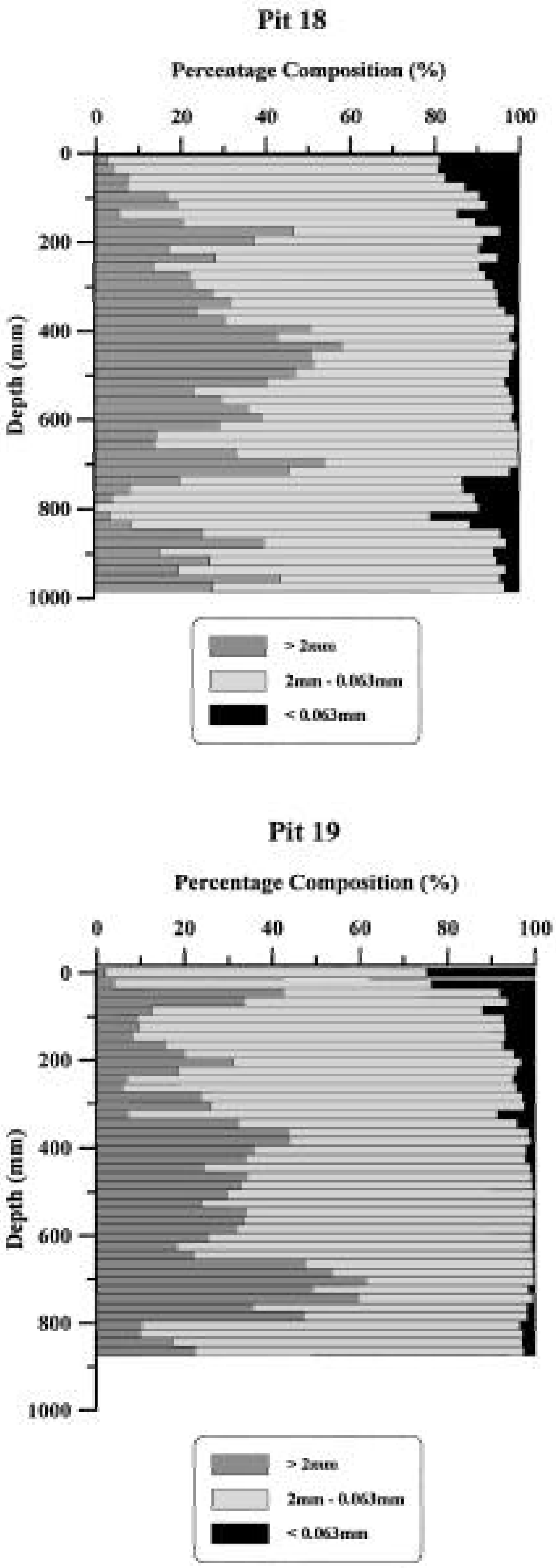


Figure 6a. Sieving particle profiles for Pit 18 and 19.

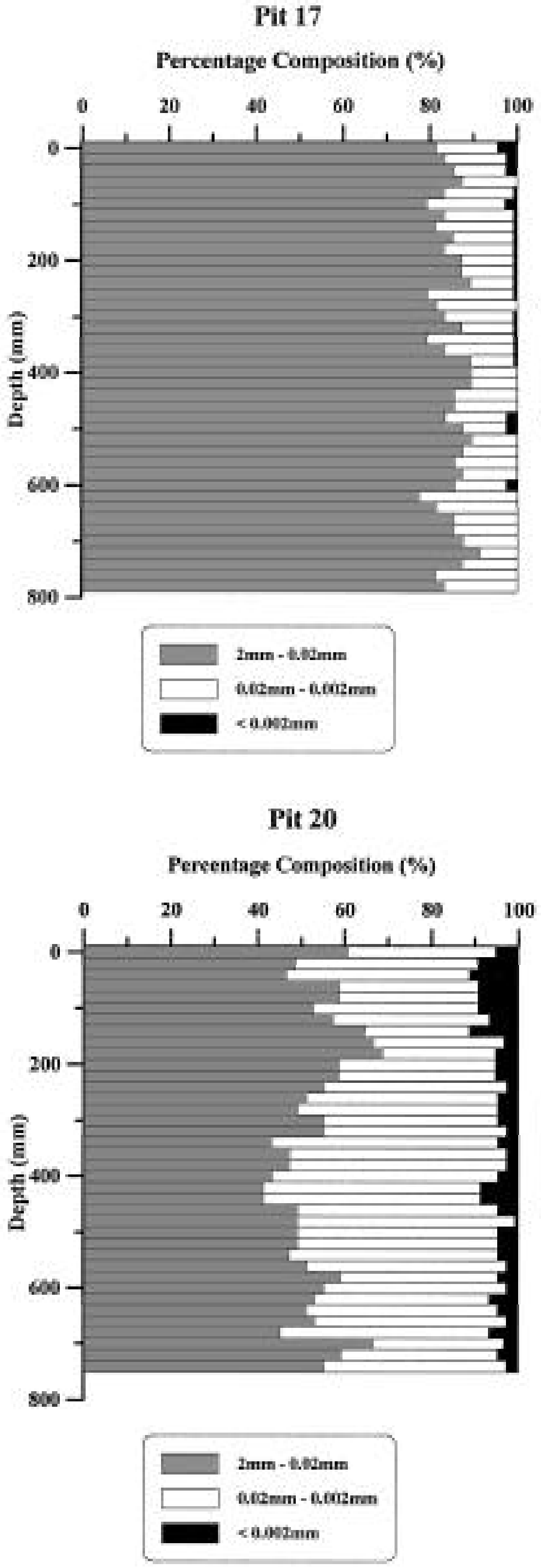
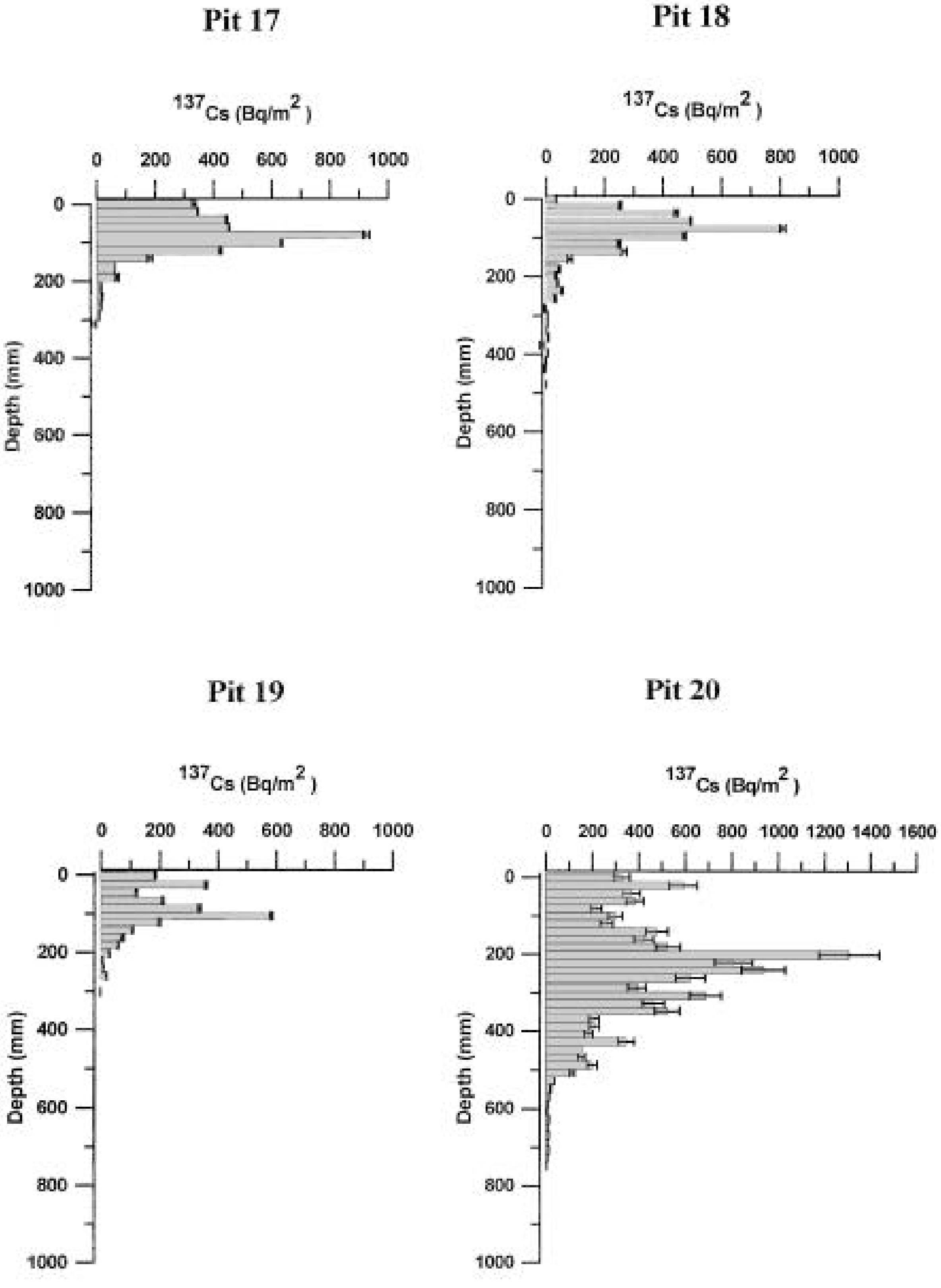


Figure 6b. Hydrometer particle size profiles for Pit 17 and 20.



Pit 17

Pit 18

Pit 19

Pit 20

Figure 7. Caesium-137 profiles for Pits 17, 18, 19 and 20.

mately 60 in Pits 18 and 19. In Pit 18, there is a marked change in texture above 350 mm from the surface, with sediments becoming finer and structures more massive (Figure 6a).

Caesium-137 distribution in Pits 17, 18 and 19 (Figure 7) shows the presence of the isotope in the uppermost 280 mm of Pit 17, 260 mm of Pit 18 and the top 220 mm of Pit 19. There are variations in the amount of ^{137}Cs present per layer, and there appears to be a definite break in the profile below which no ^{137}Cs is present. In Pit 18, the total ^{137}Cs profile is contained within the finer sediments with the more massive structure (Figure 7). Within the tank (Pit 20, Figure 7), ^{137}Cs is present throughout, although there is great variability with depth. Generally, from the surface to 210 mm, ^{137}Cs values increase. From the peak ^{137}Cs value (1308 Bq m^{-2}), at 210 mm depth downwards, there is a decline. From 588 mm to the base of Pit 20, ^{137}Cs content is generally below 10 Bq m^{-2}.

The ^{137}Cs results for the two reference sites are shown in Table 1. The distribution of ^{137}Cs is limited to the upper 6 cm of reference site 1 and upper 8 cm of reference site 2. The bulk of ^{137}Cs is contained in the uppermost 2 cm of both profiles and accounts for 88.6% (reference site 1) and 75.3% (reference site 2) of the total ^{137}Cs content.

Lead profiles for Pits 17, 18, 19 and 20 are shown in Figure 8. The depth-distribution of lead shows a general tendency to increase with depth. In Pit 20 (the tank), which has the finest sediments, there is a peak in lead concentration at 700 mm depth, which is matched by a broad peak at 780-830 mm in Pit 18.

Table 1. Total content of ^{137}Cs in reference site depth profiles.

Depth (cm)	**Reference site 1** ^{137}Cs (Bq m^{-2})	**Reference site 2** ^{137}Cs (Bq m^{-2})
0 - 2	118.7 ± 8.3	184.8 ± 8.3
2 - 4	8.6 ± 5.7	40.0 ± 8.0
4 - 6	6.7 ± 3.6	8.9 ± 6.1
6 - 8	ND	11.8 ± 4.2
8 - 10	ND	ND
10 - 12	ND	ND
Total ^{137}Cs	134.0 ± 10.6	245.5 ± 13.7

ND: ^{137}Cs not detected in sample

Organic content within the four reservoir profiles are presented in Figure 9. Pit 18 and 19 show very little variation in organic content following the initial elevated levels at the surface. Pit 17 and 20 show similar depth profiles to those of Pits 18 and 19, however, organic content tends to fluctuate slightly more with depth.

DISCUSSION

Results for the two reference sites (Table 1) vary significantly from each other, although the higher figure (245.5 Bq m^{-2}) more closely corresponds to a value predicted from mean annual rainfall. Elliott et al. (1997) for New South Wales, and McFarlane et al. (2000) for the southern part of Western Australia, showed the following relationships between mean annual precipitation and ^{137}Cs reference values for sites located between 29ºS and 36ºS in New South Wales and south of 32ºS in Western Australia.

NSW $Y = 20.3 + 0.072X$ (n = 20; r = +0.89) (1)
WA $Y = 0.074 * X + 10.7$ (n = 20; r = +0.89) (2)

Y is the ^{137}Cs reference value (mBq cm^{-2}) and X is mean annual precipitation (mm). Tank Creek is located at 31.7ºS and has a mean annual rainfall of 206 mm

Following decay to 1990, Equation (1) predicts a ^{137}Cs reference value of 284.6 Bq m^{-2}, while equation (2) predicts a ^{137}Cs reference value of 259.4 Bq m^{-2}, which compares favourably with the 245.5 Bq m^{-2} obtained at Tank Creek.

Total ^{137}Cs within the pit profiles greatly exceeds the ^{137}Cs reference value (Table 2), confirming that they are sedimentation sites by both the presence of excess ^{137}Cs and the deep profiles. Greatest ^{137}Cs excess is in the tank (Pit 20) probably because finer sediments have been deposited there (Table 2).

Sediments containing ^{137}Cs are more recent than the mid-1950s, indicating that approximately 35% of the depth-profile of Pit 17, 27% of Pit 18 and 25% of Pit 19 have been laid down since that date. All profiles show similar variability in ^{137}Cs with depth in Pits 17 - 19 (Figure 7).

The peak in lead concentration at 700 mm depth (Figure 8) on finer sediments of the tank (Pit 20) strongly suggests a specific influx of atmospheric lead because

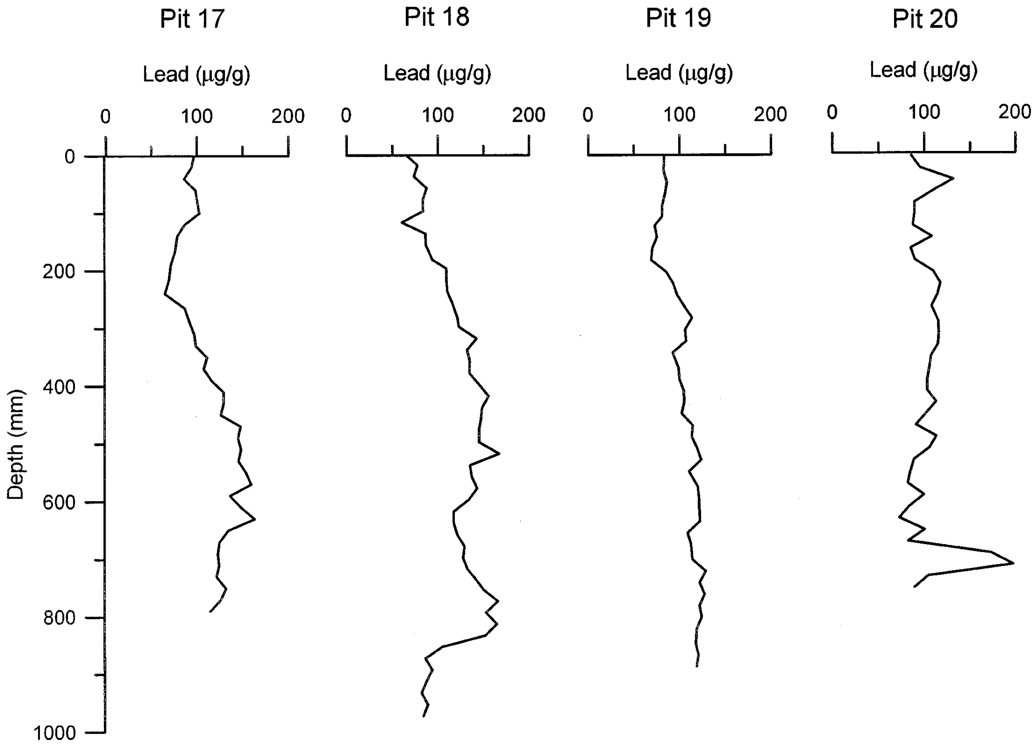


Figure 8. Lead profiles for the Tank Creek reservoir deposits.

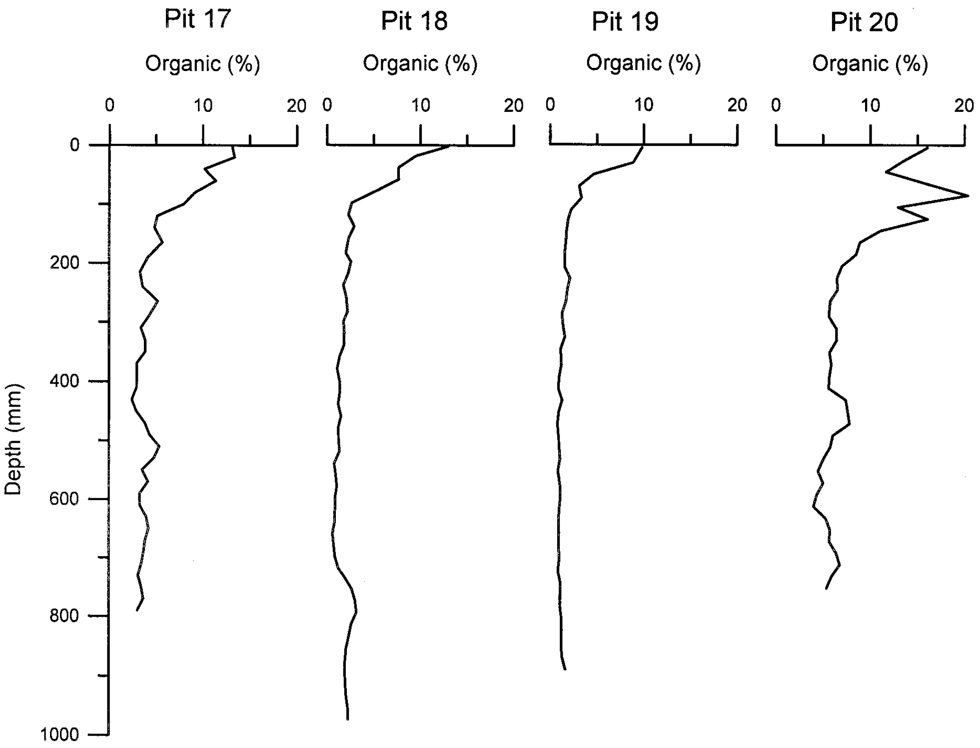


Figure 9. Organic content profiles for the Tank Creek reservoir deposits.

Table 2. Total content of ^{137}Cs at pit sites compared with reference value.

	Total ^{137}Cs (Bq m^{-2})	Magnitude greater than reference value[a]
Pit 17	3927.3	16.0
Pit 18	3 294.0	13.4
Pit 19	2 256.7	9.2
Pit 20	11 125.7	45.3

[a]Reference value 245.5 Bq m^{-2}

there are no geologic deposits of that mineral in the drainage basin. It is likely that lead-enriched sediments near the bottom of the profile in Pit 20 date from 1885-1898 when the smelters were operating. The presence of ^{137}Cs throughout 80% of the Pit 20 profile indicates a hiatus, suggesting that some sediment has been removed from the tank. While there is no corroborative evidence, it is possible that the water tank has been cleaned of sediment, but the bottom-most sediments (containing lead) were left undisturbed for fear of rupturing the floor.

Organic content in all four pits appears to be related to particle size (Figure 6a, 6b & 9). In Pits 18 and 19, a strong correlation exists between the silt and clay fraction (<0.063 mm) and organic content, with r = +0.75 (Pit 18) and r = +0.95 (Pit 19). Sediments in Pits 17 and 20 are generally much finer and significant relationships between the clay fraction (<0.002 mm) and organic content were identified (Pit 17: r = +0.62, Pit 20: r = +0.66). The link between organic content and particle size may be attributed to two factors. Firstly, following a flood event, small, short-lived grasses germinate in the finer reservoir and tank sediments. Secondly, the finer sediments are able to lock and hold a greater proportion of the organic matter in the sediment matrix.

The reservoir and tank were constructed in approximately 1880, so that 1070 t of sediment has accumulated in 115 years. Of this, approximately 336 t of sediment is labelled with ^{137}Cs, suggesting a post 1955 sediment accumulation rate of 0.59 t ha^{-1} y^{-1}. This contrasts with a pre 1955 sediment accumulation rate of 0.78 t ha^{-1} y^{-1}. Both rates may be considered minimum erosion rates for the catchment, because water and sediments have overflowed the reservoir wall and tank. The disparity between sediment accumulation rates for each time period may be attributed to a number of factors, including the decreasing trap efficiency of the reservoir, improved management practices by landholders, or it may reflect a regional shift in soil erosion rates for south-eastern Australia as noted by Wasson and Galloway (1986) and Srikanthan and Wasson (1993).

Rates of catchment erosion derived from measurements of reservoir sedimentation must take account of reservoir trap efficiency, which, in the case of Tank Creek, is unknown. However, considerable recent sedimentation downstream of the tank and wall has been observed, which probably accounts for the relatively low rates of erosion estimated by this study (Table 3). Although the rates shown in Table 3 for western New South Wales have been derived by different methods for different types of

Table 3. Rates of soil erosion / catchment sediment yield in semi-arid New South Wales

Site	Rainfall (mm y^{-1})	Erosion rate (t ha^{-1} y^{-1})	Method	Authors
Umberumberka	206	5.2 (1915 - 1941)	Reservoir	A
Reservoir		2.0 (1941 - 1982)	Surveys	
Fowlers Gap	234	30.6 - 209[a]	Erosion pins (10 years)	B
Cobar	337	Nil (site 1) 7.3 (site 2)	^{137}Cs regression model	C
Tank Creek	206 0.59 (1955-98)	0.78 (c. 1880-1955) Survey	Reservoir	This study

[a] Scalded (bare) surface; Authors: A, Wasson and Galloway, 1986; B, Fanning, 1994; C, Elliott et al., 1997

land cover, the Tank Creek estimates appear low. Further work to determine erosion rates within the drainage basin using heavy metals, ^{137}Cs and erosion models will help assess the information derived from the reservoir sedimentation survey on Tank Creek.

ACKNOWLEDGEMENTS

The research potential of the Mundi Mundi Head Station (Leehee) site was recognised by Associate Professor J. B. Laronne, Ben Gurion University of the Negev, Beer Sheva, Israel, and we thank him for his continued interest in the project. Access to the site was granted by Mr and Mrs S. Schmidt (Eldee) and Mr P.E . Bloore (Belmont), and we are most grateful to Stephen and Naomi Schmidt for their hospitality and support. Field and laboratory assistance from Chris Dever, Peter Shimeld, Louise Ormerod and Peter Loughran, all of the Department of Geography and Environmental Science, The University of Newcastle, is gratefully acknowledged. An Australian Research Council Small Grant was provided by The University of Newcastle.

This is publication Number 42 of the Geomorphology and Quaternary Science Research Unit, Department of Geography and Environmental Science, University of Newcastle.

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