

Contribution of diffuse sources to the sediment and phosphorus budgets in Ben Chifley Catchment, Australia

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Received: 13 September 2008 / Accepted: 11 May 2009 / Published online: 29 May 2009
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Abstract Relative contribution of different diffuse sources to the sediment and phosphorous (P) budgets in the Ben Chifley Reservoir was estimated using a multivariate mixing model and geochemical indices and tracers. The influence of the underlying geology on land use characteristics and the dynamics of sediment and P in the catchment were discussed. Sediments currently in transport to the reservoir are derived mainly from areas underlain by Quaternary alluvium, accounting for 33% of the reservoir sediment budget. A major portion of the sediments from the Quaternary alluvium originates from pasture land which also contributes about 60% of sediment-bound P in the reservoir, followed by cropland (30%) and forest area (10%). Phosphorus-based fertiliser contributes more than 50% of the soil P in pasture and cropland and more than 60% in forest plantation area. The remaining P reaching the reservoir originates from natural soils (native sources). Phosphate from both fertiliser and native sources are transported to the water courses and ultimately the reservoir as a consequence of gully, stream bank and surface erosion. Erosion control, trapping of fertiliser runoff, establishing riparian vegetation and reducing application of P-based fertiliser by increasing native pasture cultivation in the risk areas should be considered as management options for controlling the impact of P and sediment in the reservoir.

Keywords Catchment management · Eutrophication · Sediment, nutrients, reservoir · Water quality

Introduction

Developing sound management strategies to control eutrophication (water enrichment with phosphorous and nitrogen) and associated algal blooms in lakes and reservoirs should be based on a good understanding of sources and sinks of nutrients, particularly P, in the catchments. Sediments and P entering water courses are derived from point and diffuse sources. Point sources, typically discharged from a pipe or channel, are commonly associated with industrial and urban activities and include industrial effluent, sewage effluent, landfill leachates, and leakage from filling stations, cattle- and sheep-dip sites. Whereas diffuse contaminants enter water bodies through multiple pathways and sources including agricultural runoff, fertilisers, soil erosion, decomposition of organic matter, ground water seepage and atmosphere (Campbell and Edwards 2001).

A complex interaction of processes and factors are responsible for delivering sediment and nutrients to the downstream reservoirs. Catchments' geology, soil, land use and other anthropogenic activities are critical in determining availability and transformation of P and sediments. A large portion of P reaching freshwater courses is transported in association with fine sediment as particulate P (PP). Although PP as compared to dissolved P is less harmful to aquatic environment, after settling at the bottom sediments some of the PP may be released to the overlying water as dissolved P (Svendsen et al. 1995). Radionuclides, stable isotopes, heavy minerals and geochemical fingerprinting techniques have been successfully applied to

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identify sources and dynamic of sediments and associated nutrients (Caitcheon et al. 1994; Martinotti et al. 1997; Olley and Caitcheon 2000).

The Ben Chifley Reservoir, the main water supply of Bathurst in New South Wales, Australia, has been experiencing cyanobacterial blooms since 1991 with populations reaching up to 450,000 cells/mL. This toxic blue-green algal blooms are dominated by *Anabaena* and *Microcystis* genera (Rahman et al. 2005). The bloom is adversely affecting the town water supply, aquatic ecosystem and recreational amenity of the reservoir. The reservoir is P limited in terms of cyanobacteria bloom with an N:P molar ratio greater than 20 (Rahman et al. 2005).

This article aims to quantify the relative contribution of different diffuse sources to the sediment and P budget in the Ben Chifley Reservoir and to enhance our understanding of the underlying geology and land use on their dynamics in rural catchments.

Materials and methods

Study site

The Ben Chifley catchment is located southeast of Bathurst, an inland country town in the Central West region of New South Wales (NSW), Australia. It covers about 985 km² and is drained by the Campbells River and its tributaries (Fig. 1). The catchment is characterised by a

mixture of sedimentary, igneous and metamorphic rocks and deposits (Fig. 2). For the purpose of this study, the geological formations in the catchment were grouped into four Landscape Genesis (LG) units on the basis of similarity in lithological characteristics, genesis, soil type, land use, land capability, soil erosion and slope (Al Bakri 2001, 2002). The LG units and associated land use pattern are presented in Table 1. Eighteen different soil types are known in the catchment. Red podzols, yellow podzols and red earths, being the most common soils, covering about 60% of the catchment (DLWC 1997b). Land clearing for agricultural purposes was started around 1850. Pasture, softwood plantation and native timber occupy more than 99% of the catchment area, whereas cropland and horticultural land represent less than 1% of the catchment (Taylor 1994). The Forest area represents 12.7% (116 km²) of the catchment consisting of 110 km² of pine plantation and 6 km² of native eucalypt forest. The land use in the catchment includes sheep and cattle grazing on native and improved pasture and cultivation of winter crops (e.g., wheat and oats) and vegetables (DLWC 1997a).

Sample collection

Soil samples from the catchment were collected on the basis of spatial distribution of the LG units (geology), soil type and land use pattern (Fig. 2). Fifty-four soil samples were collected from 27 sites during January 2001. At each site, two samples were taken from two depths, top soil

Fig. 1 Location of Ben Chifley Catchment

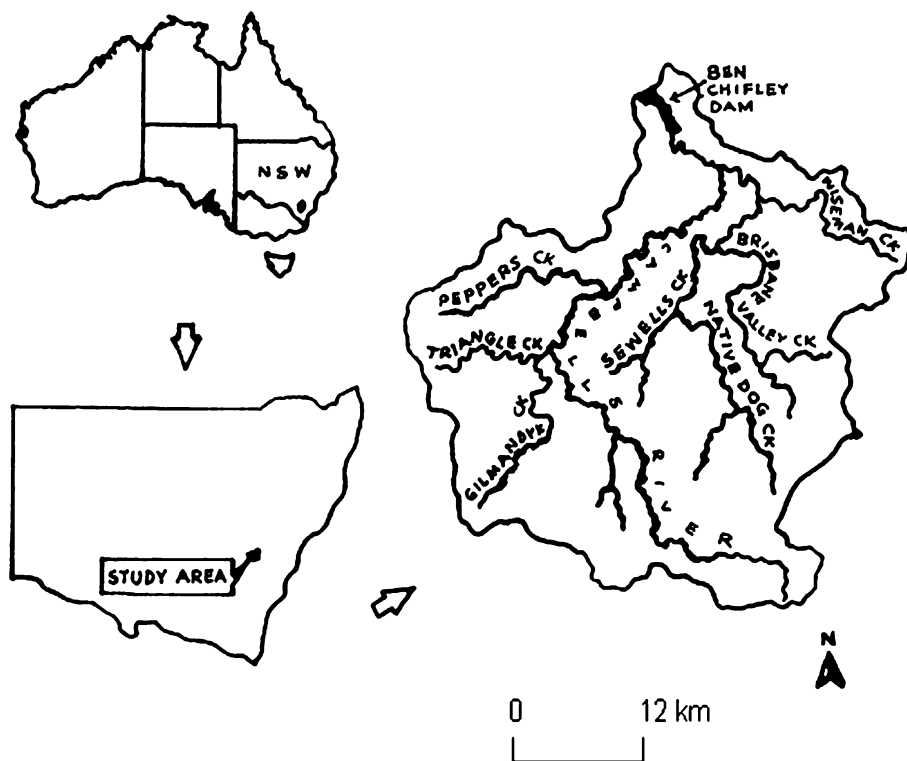
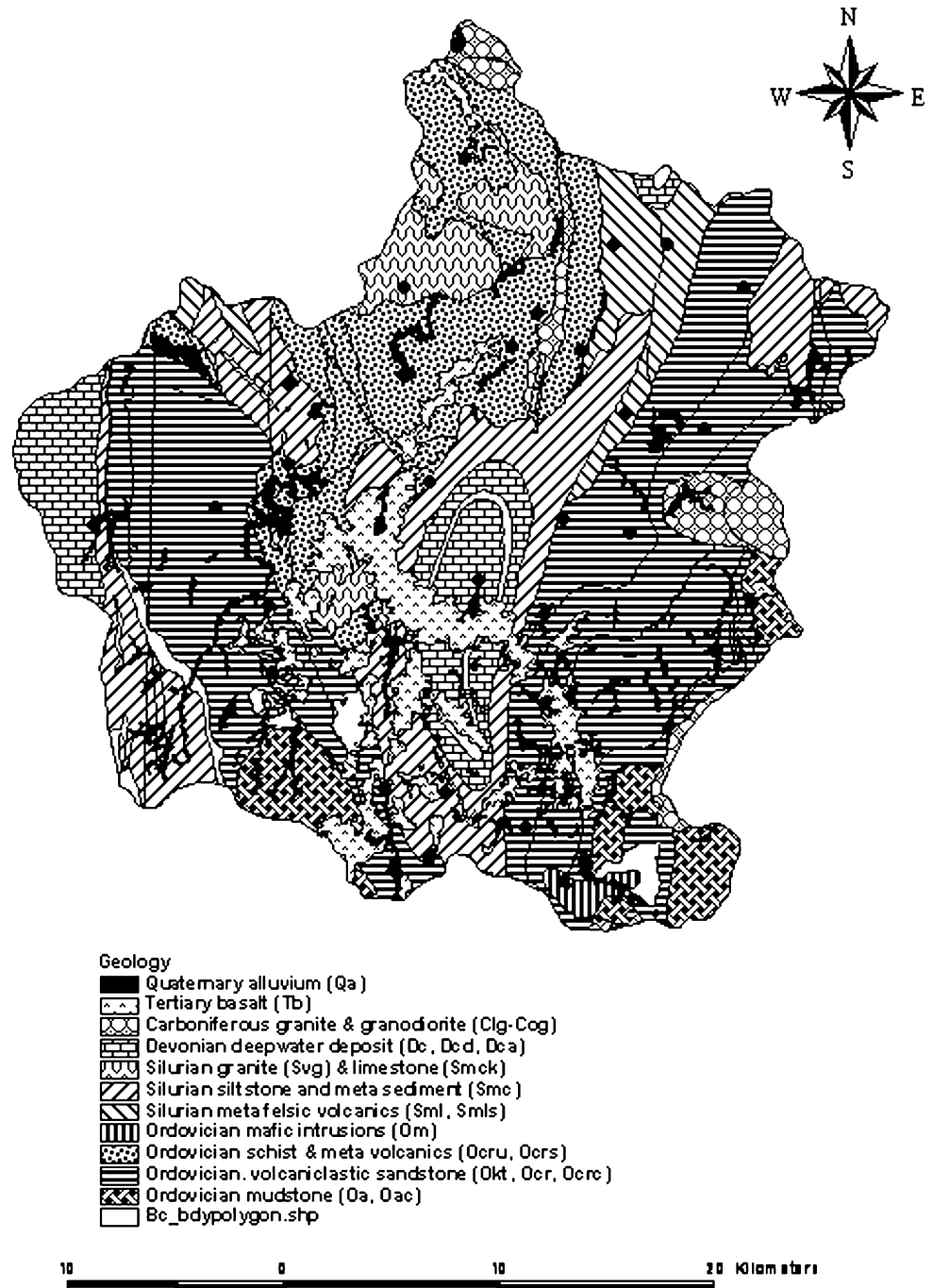


Fig. 2 Geological map and location of soil sampling sites (black circle) in the Ben Chifley Catchment



(0–15 cm) and sub-soil (15–30 cm). Three replicated sediment cores were also collected from each of three sites in the reservoir. All samples were cleaned by removing grass and other plant debris before being air dried at room temperature.

Geochemical analysis

Soil samples of grain size finer than 63 μm were used in the analysis of major elements using Phillips PW1404 X-ray fluorescence (XRF) spectrometer and inductively coupled

plasma-mass spectrometry (ICP-MS). Geochemical data were used to determine the chemical index of alteration (CIA) and immobile element ratios. These indices and ratios were used to identify sources and delivery of sediment from the catchment to the reservoir. The CIA of the soil samples is calculated from the following equation (1):

$$CIA = \frac{(Al_2O_3)}{(Al_2O_3 + CaO^* + Na_2O + K_2O)} \tag{1}$$

where the concentrations are in molecular proportions and CaO* represents Ca in the silicate fraction only (Olley and

Table 1 Landscape Genesis (LG) units and associated land use type in the Ben Chifley Catchment

LG units	Rocks/deposits	Area (km ²) (% of the catchment)	Land use (% total catchment area)		
			Pasture	Forest (softwood plantation and native timber)	Cropland and horticulture
Alluvium	Quaternary alluvium	38 (3.9%)	96	3	1
Basaltic	Tertiary basalt	548 (55.6%)	79	5	16
	Ordovician mafic				
	Ordovician volcaniclastic sandstone				
	Ordovician schist metavolcanics				
Granite	Carboniferous granite and grandiorite	126 (12.8%)	61	37	2
	Silurian granite				
	Silurian metafelsic volcanics				
Sedimentary and metasediment	Ordovician mudstone	273 (27.7%)	90	9	1
	Devonian deepwater deposits				
	Silurian siltstone and metasediments				

Caitcheon 2000). The index value indicates the extent of weathering that aluminosilicate minerals have undergone (McLennan 1993). Unweathered aluminosilicate minerals have CIA values of about 0.5, whereas clay minerals typically have values of 0.75–1.0 (Olley and Caitcheon 2000). Sources of sediment could also be identified by comparing the immobile elements such as titanium (Ti), zircon (Zr), iron (Fe) and aluminium (Al) ratios of the source (catchment soil) and sink (reservoir sediment) (Caitcheon et al. 1995).

Source identification of sediments and P

A tracing investigation was conducted to determine the relative contribution of the main potential diffuse sources to the sediment and P budgets of the reservoir. This investigation focussed on four LG units (Quaternary alluvium, basalt including metamafic, granite including metafelsic and sedimentary including metasediment) and three land use categories (pasture, cropland and native and pine forests). Geochemical elements used in the tracing investigation were selected on the basis of the criteria C1 and C2:

- C1 the median concentrations of the element in reservoir sediment (sink) are between the median concentrations of that element in potential source groups
- C2 the concentrations of the element in potential source groups are significantly different with 95% confidence

Non-parametric Kruskal–Wallis *H* test was employed to test which elements exhibited significant difference between the individual source types (Collins et al. 1996). In all, 13 elements were found to meet both the criteria and comprised of major elements (CaO, Na₂O, SiO₂ and Ta),

trace elements (Ag, As, Cr, MnO, Nb, Sb, TiO₂ and V) and a rare earth element (Lu).

A multivariate mixing model based on Collins et al. (1996) and Walling et al. (1999) was employed to estimate the relative contribution from the potential sources of sediments to the reservoir. In this method, the proportion *P* contributed by the *m* individual source component *s* are established by minimising the sum of the squares of the residuals (*R_{es}*) for the *n* tracer properties involved, where:

$$R_{es} = \sum_{i=1}^n \left(\frac{C_{ssi} - \left(\sum_{s=1}^m C_{si} P_s \right)}{C_{ssi}} \right)^2 \quad (2)$$

C_{ssi} represents the concentration of tracer property *i* in the reservoir sediment sample, *C_{si}* is the median concentration of tracer property *i* source component *s* and *P_s* is the relative contribution from source component *s*. All tracer property concentrations were scaled to 0–1 to ensure that equal weight is given to the individual fingerprinting properties used in the mixing model and thus contributing to the overall sum of squares of the residuals (Collins et al. 1996; Walling et al. 1999).

An index value was estimated from the ratio of percent contribution of P and sediments to the percent area covered by individual source components. This index value was used to compare the potential productivity of different source components in the catchment.

Contribution of chemical fertiliser to soil P

The contribution of fertiliser to soil P in the catchment was assessed following the methods used by Martin and McCulloch (1999). This method uses the weight ratio of neodymium (Nd) to P as an indicator of fertiliser addition to

the catchment soils. Nd is a rare earth element which is almost exclusively derived from terrestrial sources. Concentrations of Nd and P of catchment soils, sediments and most commonly used fertiliser in the catchment were analysed by using ICP-MS and XRF, respectively. These data were then used into the following equations to estimate the contribution of fertiliser P to the catchment and sediments:

$$\text{Nd}/\text{P}_{\text{sed}} = \text{Nd}/\text{P}_{\text{fert}} \times X + \text{Nd}/\text{P}_{\text{native}} \times Y \quad (3)$$

$$X + Y = 1 \quad (4)$$

where, “sed” stands for the reservoir sediment, “fert” for fertiliser and native ratio value of Nd/P, respectively. The variables X and Y are the unknown contribution amounts ($\times 100$) from fertiliser and native sources (Wallbrink et al. 2003). Equation 2 is applied to calculate the sum of the squares of the residuals (R_{es}) for Nd/P value of both the fertiliser and native soil. The value of X and Y which gives the minimum R_{es} is considered as the percent contribution of native and fertiliser source (Wallbrink et al. 2003).

Results

Geochemistry: elemental composition

Major element concentrations in the catchment soils and reservoir sediments are summarised in Table 2. In general, SiO_2 , Al_2O_3 and Fe_2O_3 account for approximately 94% of the major element composition in both soil and sediment samples. A negative correlation is observed between SiO_2 and Al_2O_3 (Fig. 3), indicating two-component mixing model of quartz and clay minerals (Argast and Donnelly 1987). Like catchment soils, the reservoir sediments shows a positive relationship between P_2O_5 and Fe_2O_3 (Fig. 4). This kind of relationship supports the association of P with clay and Fe (Norrish and Rosser 1983).

The CIA value of the surface soil ranges between 0.56 and 0.87 with an average value of 0.70 ± 0.07 . About 78% of the surface soil samples collected from the catchment have relatively low CIA value ranged from 0.58 to 0.73 with an average of 0.67 ± 0.05 indicating that these soils are not fully weathered and they still contain a significant amount of residual feldspar (Olley and Caitcheon 2000). A few surface samples that were collected from the upper part of the catchment showed higher CIA values ranging from 0.75 to 0.87 (average 0.81 ± 0.06) indicating extensive weathering. The sub-surface soil samples have CIA values ranged from 0.50 to 0.89 with an average value of 0.65 ± 0.09 . The average CIA value of the reservoir sediments is 0.66 ± 0.02 which is consistent with the soils derived from alluvium, basalt and sedimentary rocks (Table 2). This consistency also provides a basis of the likely sources of the reservoir sediment.

The average particulate phosphorus concentrations (wt % P_2O_5 in $<63\text{-}\mu\text{m}$ soil fraction) in both surface and sub-surface soils associated with alluvium and basaltic rocks are comparatively higher than the soils from granitic and sedimentary origin (Table 2). The average concentration of P_2O_5 in the reservoir sediments (0.17 ± 0.02) is very close to the average concentration measured in alluvial and basaltic soils. The average concentration of P_2O_5 in alluvial soils is 0.17% in both surface and sub-surface samples. Basalt and metamafic soils have average P_2O_5 concentrations ranged from 0.16% in surface to 0.18% in sub-surface samples.

Potential sources of sediment

Quaternary alluvium LG unit

Quaternary alluvium consists of sand, silt and clay and offers a good potential for agriculture. About 4% of the catchment area belongs to this LG unit. It has been reported that the alluvial deposits and soils have been derived mainly from granite and felsic volcanic rocks and are prone to serious gully and stream bank erosion due to high sodium content (Al Bakri 2002). The land use pattern underlain by this LG unit includes 96% pasture, 3% forest and 1% croplands (Table 1). Quaternary alluvium contributes 33% of the sediments in the reservoir (Table 3). A major portion of the sediments from the Quaternary alluvium is originated from pasture land (23%) followed by forest (7%) and cropland (3%) (Table 3).

Basaltic LG unit

Basaltic geology covers about 56% of the catchment area and consists of Tertiary basalt, Ordovician mafic intrusion, volcanoclastic sandstone, and metavolcanics (Table 1). Tertiary basalt only covers 7% of the catchment area. This LG unit supports intense agricultural activity and displays very little surface or gully erosion. As the rocks in this area consist entirely of unstable minerals such as calcium plagioclase and ferromagnesian, deep, fertile, well structured and highly productive soil are normally produced (Al Bakri 2002). The land use in the basaltic LG unit is dominated by pasture land (79%) followed by cropland (16%) and forest (5%). Basaltic area contributes about 22% of the total reservoir's sediment including 10% from pasture land and 12% from cropland and forest areas (Table 3).

Granitic LG unit

Granitic LG unit consists of Carboniferous granite and granodiorite, Silurian granite and Silurian metafelsic volcanics. It occupies approximately 12.5% of the catchment

Table 2 Element concentrations in the soil and reservoir sediment samples (<63 µm) collected from the main LG units

LG units	<i>n</i>	Depth (cm)	Ag (ppm)	Al ₂ O ₃ (wt%)	As (ppm)	CaO (wt%)	Cr (ppm)	Fe ₂ O ₃ (wt%)	K ₂ O (wt%)
Quaternary alluvium	2	0–15	0.08 ± 0.01	11.1 ± 1.03	12.3 ± 6.6	1.84 ± 0.44	140 ± 102	6.25 ± 0.46	1.44 ± 0.12
	2	15–30	0.07 ± 0.02	11.5 ± 0.95	11.8 ± 7.1	1.89 ± 0.48	143 ± 107	6.57 ± 0.38	1.44 ± 0.04
Basalt including metamafic	14	0–15	0.06 ± 0.02	8.54 ± 1.85	11.8 ± 4.4	0.87 ± 0.57	134 ± 96	4.18 ± 0.96	1.13 ± 0.27
	14	15–30	0.05 ± 0.02	9.36 ± 1.99	13.8 ± 5.9	0.86 ± 0.55	145 ± 101	4.76 ± 1.15	1.15 ± 0.26
Granite including metafelsic	4	0–15	0.06 ± 0.01	10.3 ± 0.72	11.2 ± 5.2	1.02 ± 0.95	79 ± 72	3.37 ± 1.28	1.60 ± 0.50
	4	15–30	0.06 ± 0.02	10.4 ± 1.10	9.8 ± 4.3	1.06 ± 0.85	77 ± 72	3.31 ± 1.35	1.69 ± 0.49
Sedimentary and metasediment	7	0–15	0.06 ± 0.01	7.91 ± 1.12	6.9 ± 2.9	1.02 ± 0.62	181 ± 138	3.73 ± 1.40	1.17 ± 0.31
	7	15–30	0.05 ± 0.02	8.71 ± 1.50	7.8 ± 3.1	1.04 ± 0.67	188 ± 125	4.07 ± 1.26	1.23 ± 0.34
Reservoir sediment	9	0–30	0.06 ± 0.02	13.4 ± 1.95	10.3 ± 1.7	1.15 ± 0.04	160 ± 14	6.16 ± 1.24	1.77 ± 0.29
Kruskal–Wallis <i>H</i>			10.4	NA	8.39	9.55	14.3	NA	NA
<i>P</i> value			0.01	NA	0.04	0.02	<0.01	NA	NA
LG units	<i>n</i>	Depth (cm)	Lu (ppm)	MgO (wt%)	MnO (wt%)	Na ₂ O (wt%)	Nb (ppm)	Nd (ppm)	P ₂ O ₅ (wt%)
Quaternary alluvium	2	0–15	0.42 ± 0.04	1.48 ± 0.69	0.15 ± 0.03	0.91 ± 0.04	17.9 ± 0.64	22.1 ± 3.27	0.17 ± 0.14
	2	15–30	0.44 ± 0.04	1.56 ± 0.69	0.16 ± 0.03	0.93 ± 0.15	18.3 ± 10.4	22.1 ± 4.97	0.17 ± 0.13
Basalt including metamafic	14	0–15	0.43 ± 0.07	1.12 ± 0.62	0.10 ± 0.04	0.86 ± 0.45	12.0 ± 2.36	22.4 ± 3.77	0.16 ± 0.04
	14	15–30	0.44 ± 0.09	1.24 ± 0.69	0.10 ± 0.04	0.90 ± 0.67	12.0 ± 4.13	22.8 ± 3.75	0.18 ± 0.05
Granite including metafelsic	4	0–15	0.58 ± 0.11	0.96 ± 0.62	0.06 ± 0.04	1.70 ± 0.16	11.8 ± 0.76	24.6 ± 9.69	0.08 ± 0.02
	4	15–30	0.60 ± 0.15	0.94 ± 0.62	0.05 ± 0.03	1.47 ± 0.91	11.2 ± 1.13	25.6 ± 8.25	0.06 ± 0.03
Sedimentary and metasediment	7	0–15	0.52 ± 0.06	1.38 ± 0.92	0.09 ± 0.02	0.63 ± 0.39	15.8 ± 2.52	21.8 ± 2.42	0.10 ± 0.03
	7	15–30	0.48 ± 0.09	1.52 ± 1.05	0.70 ± 0.50	0.10 ± 0.02	16.4 ± 10.3	23.2 ± 3.52	0.09 ± 0.04
Reservoir sediment	9	0–30	0.51 ± 0.04	1.96 ± 0.34	0.13 ± 0.06	1.26 ± 0.16	13.5 ± 0.15	28.8 ± 1.17	0.17 ± 0.02
Kruskal–Wallis <i>H</i>			10.4	NA	8.72	9.78	13.2	NA	NA
<i>P</i> value			0.02	NA	0.03	0.02	0.004	NA	NA
LG units	<i>n</i>	Depth (cm)	Sb (ppm)	Ta (ppm)	TiO ₂ (wt%)	V (ppm)	Zr (ppm)	CIA	Ti/Zr
Quaternary alluvium	2	0–15	1.55 ± 0.49	1.35 ± 0.21	1.03 ± 0.07	183 ± 6	340 ± 86	0.67 ± 0.06	0.24 ± 0.08
	2	15–30	1.30 ± 0.28	1.20 ± 0.14	1.03 ± 0.04	185 ± 16	320 ± 79	0.59 ± 0.07	0.25 ± 0.07
Basalt including metamafic	14	0–15	1.18 ± 0.53	0.91 ± 0.29	0.71 ± 0.14	116 ± 17	388 ± 110	0.71 ± 0.07	0.14 ± 0.03
	14	15–30	1.19 ± 0.85	0.90 ± 0.32	0.73 ± 0.13	126 ± 19	375 ± 113	0.67 ± 0.09	0.15 ± 0.04
Granite including metafelsic	4	0–15	1.80 ± 0.36	1.05 ± 0.21	0.60 ± 0.12	83 ± 18	371 ± 65	0.64 ± 0.08	0.13 ± 0.05
	4	15–30	1.23 ± 0.87	0.93 ± 0.09	0.59 ± 0.16	84 ± 18	396 ± 134	0.61 ± 0.09	0.12 ± 0.05
Sedimentary and metasediment	7	0–15	0.80 ± 0.23	1.19 ± 0.23	0.82 ± 0.11	98 ± 29	448 ± 165	0.71 ± 0.07	0.14 ± 0.04
	7	15–30	0.76 ± 0.21	1.20 ± 0.20	0.84 ± 0.32	107 ± 29	443 ± 210	0.65 ± 0.10	0.15 ± 0.04
Reservoir sediment	9	0–30	1.00 ± 0.10	1.03 ± 0.06	0.74 ± 0.04	150 ± 28	177 ± 33	0.66 ± 0.01	0.32 ± 0.07
Kruskal–Wallis <i>H</i>			10.2	8.17	11.4	11.5	NA		
<i>P</i> value			0.02	0.04	0.01	0.01	NA		

area. Due to the presence of high Na-plagioclase in granitic rocks, this area is dominated by dispersed clay and poorly structured soils that are prone to severe gully and stream bank erosion. As a result this, LG unit displays the least productive agricultural land and most degraded soils system in the catchment (Al Bakri 2002). The land use pattern is dominated by pasture and forestry. It is estimated that 22% of the reservoir's sediments originates from this unit contributed 12% from the forest area and 10% from the pasture area (Table 3).

Sedimentary and metasediments LG unit

This unit is comprised of Ordovician mudstone, Devonian deepwater deposit and Silurian siltstone and metasediment which cover 4.7, 7.2 and 15.1% (total of 27%) of the catchment area, respectively. Ordovician mudstone is dominated by argillaceous rocks consisting of silt and clay derived from mafic igneous material. Devonian and Silurian deposits consist of fine grained sediments rich in Na-plagioclase. This in turn led to the development of soils

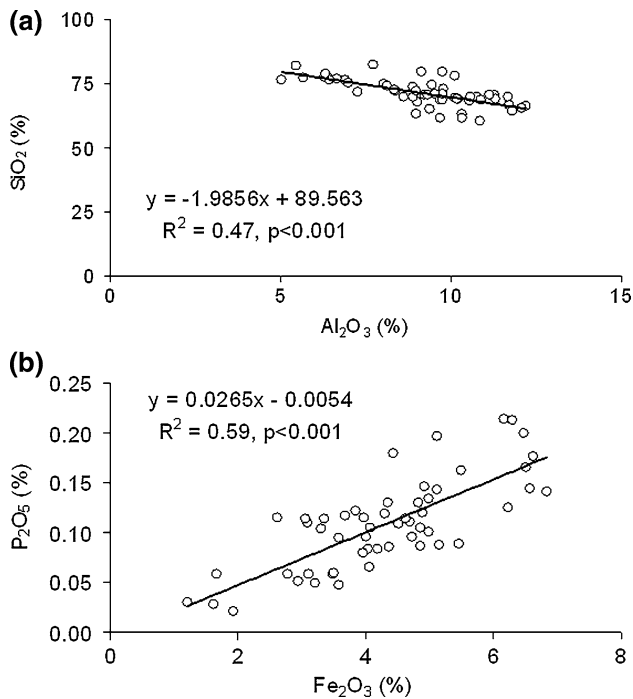


Fig. 3 Relationship between SiO₂ and Al₂O₃ (a), and between Fe₂O₃ and P₂O₅ (b) in catchment soils

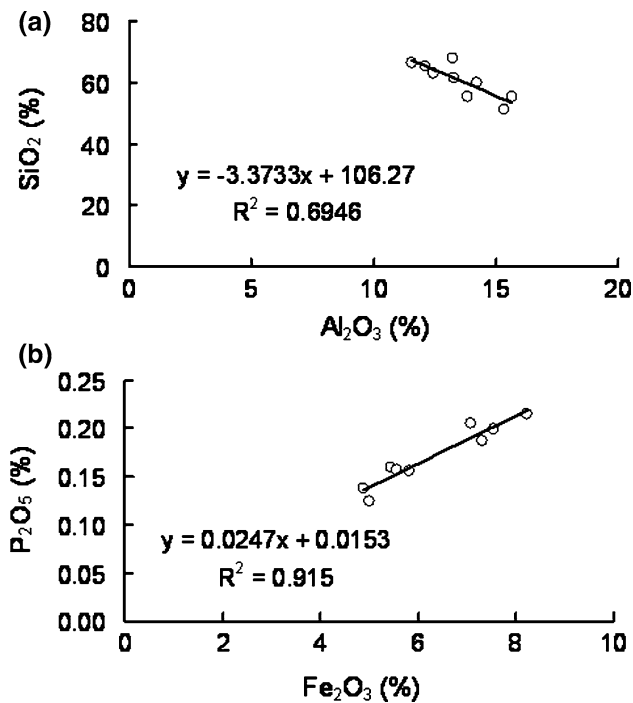


Fig. 4 Relationship between SiO₂ and Al₂O₃ (a) and between Fe₂O₃ and P₂O₅ (b) in reservoir sediment

that are prone to erosion (Beckman 1983; Al Bakri 2001). Pasture is the dominant land use covering 90% of this LG unit, whereas the timber and croplands occupy 9 and 1% of the landscape, respectively. The contribution to the

Table 3 Relative contribution of the sediments in the Ben Chifley Reservoir from potential sources

LG units	Land use	Sediment	
		% Contribution	Yield index ^a
Quaternary alluvium	Pasture	23	
	Forest	3	
	Cropland	7	
		33.0	8.5
Basaltic and metamafic	Pasture	10	
	Forest	6	
	Cropland	6	
		22.0	0.4
Granitic and metafelsic	Pasture	7	
	Forest	12	
	Cropland	3	
		22.0	1.7
Sedimentary and metasediment	Pasture	9	
	Forest	9	
	Cropland	5	
		23.0	0.8

Data reported as mean ± standard deviation. Kruskal–Wallis test was performed for surface (0–15 cm) samples only

^a Yield index is estimated from the ratio of % contribution to % area of individual LG unit

reservoir sediments is estimated to be 23% of which 9% from each of pasture and forests and 5% from cropland 5% (Table 3).

Potential sources of phosphorus

Soil samples that had P₂O₅ (wt%) concentration within the concentration range of the reservoir’s sediments (0.16–0.20) were used in the mixing models to estimate their relative contribution to sediment-bound P in the reservoir. Those samples were grouped on the basis of geology and land use categories. The mixing model reveals that PP in the reservoir sediment is mainly derived from Quaternary alluvium soil accounting for 40% of the total sediment P. This is followed by basaltic soil (30%), sedimentary soil (20%) and granite soil (10%). In terms of land use, about 60% of P in the reservoir’s sediments originates from pasture land followed by 30% from the cropland and 10% from the forest land (Table 4).

Phosphorus in the soils of rural catchments is commonly originated from weathering of minerals and rocks, crop/plant residues, commercial fertilisers and other agricultural sources (Campbell and Edwards 2001). To assess fertiliser’s contribution to P in the reservoir, the Nd/P ratio of soil samples was used against a baseline value (Wallbrink

Table 4 Relative contribution of particulate phosphorus (PP) in reservoir sediments from potential sources

	LG units			
	Quaternary alluvium	Basalt and metamafic	Granite and metafelsic	Sedimentary and metasediment
% Contribution	40	30	10	20
Yield index ^a	10.3	0.5	0.8	0.7
	Land use category			
	Pasture	Forest	Cropland	
% Contribution	60	10	30	
Yield index ^a	0.7	0.7	6.0	

^a Yield index is estimated from the ratio of % contribution to % area under individual LG unit and land use category

et al. 2001, 2003). The Nd/P ratio of two native forest soils collected at a depth below 30 cm was considered as the baseline or native value. Samples having lower ratio than the native value are considered enriched with phosphorus derived from fertiliser. On the other hand, samples with Nd/P ratios greater than or equal to the baseline value indicate that they have an indistinguishable fertiliser source (Wallbrink et al. 2001, 2003). Most of the 54 surface and sub-surface soils have Nd/P values well below the baseline value of 0.12 (Fig. 5). This indicates that the application of phosphate fertiliser is probably the main source of soil phosphorus in the catchment. Those samples that had Nd/P ratio below the baseline value were chosen for a preliminary quantification of fertiliser contribution to soil and sediment P. The fertilisers themselves have very high P and relatively low Nd concentrations. The Nd/P ratio of fertilisers Monosodium phosphate (MSP) and Double superphosphate (DSP) is 12.4×10^{-5} and 7.9×10^{-5} , respectively and are distinguishable from the catchment soils (Table 5). To adopt a conservative approach in estimating fertiliser contribution to P in soil, the higher Nd/P value (12.4×10^{-5}) for fertiliser and the average Nd/P ratio (11.8×10^{-2}) for native soil was used in the mixing models (Eqs. 3, 4). From the preliminary calculation, it has been estimated that more than 50% of the soil P in pasture and cropland area originates from phosphorus-based fertiliser and more than 60% of soil P in forest plantation area originates from fertiliser (Table 5).

The soil of the Ben Chifley catchment is nutrient deficient particularly in terms of phosphorus, sulphur and potassium (DLWC 1997b). Therefore, improved pasture, crop cultivation and pine plantation in these soils require nutrient supplement through the application of chemical fertiliser and animal manures. Phosphate fertiliser at the rate of 120 kg ha^{-1} is widely applied in this catchment (Rahman 2005). This rate is two times higher than the rate of fertiliser application in the adjacent Orange water supply catchment (Al Bakri and Chowdhury 1997) which is

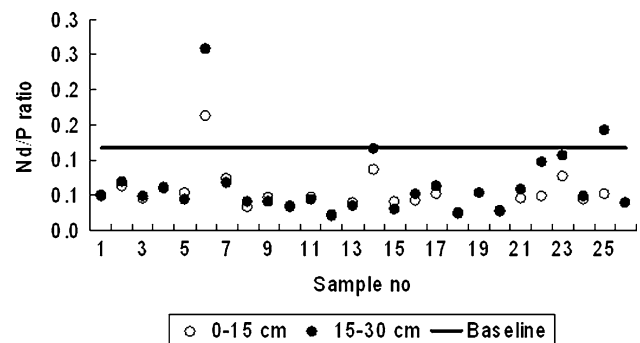


Fig. 5 The Nd/P ratio in catchment soils as compared with that of baseline value. (horizontal line represents the baseline value, 0.12)

dominated by Tertiary and Ordovician basaltic rocks. Tertiary basalts are rich in the phosphate mineral apatite which leads to high P_2O_5 concentration in soil (Caitcheon et al. 1995).

Discussion

Catchment soils and the reservoir sediments are rich in Si, Fe and Al in the following order: $\text{SiO}_2 > \text{Al}_2\text{O}_3 > \text{Fe}_2\text{O}_3$. Catchment soils shows a negative correlation between SiO_2 and Al_2O_3 contents indicating a two-component mixing system of quartz and clay minerals (Argast and Donnelly 1987). This is consistent with the geology of the area which is dominated by granitic and felsic volcanic rocks (quartz rich parent material) and mafic volcanic and fine sedimentary rocks (rich in clay minerals) (Al Bakri 2002). The positive correlation between P_2O_5 and Fe_2O_3 supports the clay/Fe/P association (Norrish and Rosser 1983) which is also common in the case of the reservoir sediments.

The CIA value of the reservoir sediment (0.66) is consistent with that of catchment soils except for the soils of Tertiary basalt origin with a CIA value of 0.87, signifying a higher degree of weathering. This indicates that sediments

Table 5 Concentration of Nd, P and calculated fertiliser contribution to P in catchment soils

Land use	Concentration			Nd/P (ratio)	Contribution of P from fertiliser (%)
	Nd (ppm)	P (P ₂ O ₅ wt%)	P (ppm)		
Native forest	33.5	0.07	286	0.11	Baseline
Forest (pine plantation)	22.3	0.13	564	0.04	65 ± 4
Pasture	21.9	0.11	496	0.04	56 ± 4
Cropland	23.6	0.11	515	0.05	58 ± 2
Phosphate based fertiliser commonly used in the catchment					
Monosodium phosphate (MSP)	18.6	34.5	825 × 10 ²	12.4 × 10 ⁻⁵	
Double super phosphate (DSP)	6.54	18.9	151 × 10 ²	7.9 × 10 ⁻⁵	

currently in transport to the Ben Chifley Reservoir do not originate from the Tertiary basaltic but they are derived from the areas of the catchment that have low CIA values particularly from the quaternary alluvium and granite sites which have median CIA values of 0.62 and 0.64, respectively. The low CIA value indicates that the catchment soils still contain a significant amount of residual feldspar (Olley and Caitcheon 2000). The granitic soils are relatively rich in sodium level and tend to be more erodible than those derived from basaltic rocks. As the basaltic rocks are dominated by calcium plagioclase with insignificant amounts of Na-plagioclase, soils derived from such rock type rarely contain dispersive clays and tend to be less erodible than granitic soils (Al Bakri 2001). The mixing model estimates that the pasture based area underlain by Quaternary alluvium is the dominant source area of the sediments reaching the reservoir. The median concentration of P in the reservoir sediments is within the range of the concentrations observed in the catchments' soils underlain by Quaternary alluvium, basalt and sedimentary geology. On the basis of the catchment geology, the contemporary sources of sediment-bound P in the reservoir are Quaternary alluvium (40%) followed by basalt (30%), sedimentary (20%) and granite (10%). Contribution by unit area (yield), the Quaternary alluvium has the highest potential in producing sediment and particulate phosphorus with the yield index of 8.5 and 10.3, respectively. In terms of land use, about 60% of the particulate P in the reservoir sediments originates from the pasture land. Cropland contributes about 30% particulate P. However, using the yield potential, it is estimated that cropland contributes more than ten times that contributed by pasture area. Winter crops of wheat, oats and vegetables are grown on the banks of the narrow flood plain areas along the lower reaches of the Campbells River mostly underlain by basalt LG unit. To determine the relative contribution of native sources (soils) and fertilisers to particulate P in the reservoir, the Nd/P ratio of the catchment soils was assessed

against the Nd/P ratio of two native forest soils. This comparison reveals that phosphorus-based fertilisers accounts for more than 50% of phosphorus reaching the reservoir. This finding is consistent with the fact that improved pasture, crop cultivation and other agricultural activities in the catchment receive higher rates of phosphate fertiliser applications than nearby agricultural areas such as Orange catchment due to nutrient deficient catchment soils. (Al Bakri 2002).

Conclusions

The study reveals that more than 50% of the PP in the reservoir sediments is ultimately derived from P-based fertilisers applied in the catchment. On the other hand, native sources (natural soils) contribute the remaining fraction of the PP content. However, P derived from both fertilisers and native sources has delivered to water courses as sediment-bound P as a consequence of stream bank, gully and surface erosion associated with agricultural practices in the catchment. The Quaternary alluvium LG unit is the most significant area in terms of contributing sediment and PP to the reservoir. On the basis of yield per unit area, the alluvium deposits contributes 5–21 times more P and sediments than the other LG units. This is followed by the contribution of granitic LG unit. The major land use category belongs to these two LG units is improved pasture which receives high amount of phosphate fertiliser at the rate of 120 kg/ha. Soils in both these areas suffer from serious gully and stream bank erosion as the parent materials are inherently high in Na content producing dispersing and highly erodible soils. Therefore, erosion management, trapping of fertiliser runoff, establishing riparian vegetation buffer zone and reducing fertiliser application in those risk areas should be considered as management options for controlling erosion and subsequent sediment and P impact on the reservoir.

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