Identifying relationships between flood history, flood frequency and the provenance of surface sediments in a semi-arid terminal wetland

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Abstract In semi-arid environments, dryland wetlands serve as key loci for biological diversity and productivity. This stems from their relative abundance of water and the comparative richness of their soils which are reinvigorated by the delivery of sediment and nutrients during relatively infrequent flood events. Therefore, to fully understand the nature of these environments, it is important to understand the links between the delivery of water and sediment (particularly with respect to varying sediment sources) to semi-arid wetlands and the physical and chemical properties of the surface sediments deposited within them. The purpose of this study was to: (1) determine the provenance (e.g. locally derived or fluvial sources) of surface sediments within a semi-arid wetland, the Narran Lakes Ecosystem in central eastern Australia; (2) determine how sediment provenance relates to flood frequency and flood history; and (3) identify variations in the physical and chemical properties of sediments with different sources. The study employs a set of 163 samples, collected along an irregular grid spaced at ~1.8 km, which were analysed to determine the physical and chemical properties of the surface sediments. The ratio of titanium to aluminium (Ti/Al) was used to differentiate between fluvial sub-catchment and locally derived sediment sources. The sourced sediments were then compared to flood frequency maps in the wetland and related to the flood history of the two principal source sub-catchments to see if sediment sourcing could be reliably linked with long term flood inundation patterns. The results of this study indicate that there are distinct and strong associations between the source of the sediments in a particular location of the wetland and the frequency of flooding that occurs there. These associations can be more completely understood by examining the flood history of the source sub-catchments. In addition, the sediments derived from each fluvial source and from locally derived hillslopes have distinct differences in their physical and chemical properties. Thus, the nature of the sediments and the resultant ecology of the Narran Lakes Ecosystem may be influenced by differential sediment sources.

Key words sediment sourcing; Narran Lakes Ecosystem; Murray Darling Basin; Ti/Al ratio; fingerprinting

INTRODUCTION

In semi-arid environments, lakes, flood plains and wetlands are oases of biological productivity and diversity (Morton, 1990). This is a consequence of their comparatively frequent inundation and the concomitant delivery of nutrient laden sediments during flood events. To understand the physical drivers of flood plain–wetland ecological responses, therefore, the nature and character of water and sediment delivery to the flood plain–wetland system needs to be investigated. Although many studies have focused on the magnitude and frequency of flooding in these systems, investigations into the nature, timing and sourcing of sediment delivery in semi-arid flood-plain wetlands are much less common. Notable exceptions include recent work by Ogden *et al*. (2007) and Thoms *et al*. (2007) in the lower Balonne catchment in Australia. These studies largely focus on sediment nutrient patterns in semi-arid flood plains and/or spatial and temporal patterns of sedimentation across different geomorphic units and at different spatial scales. A key omission in this work is the consideration of where sediments originate within the landscape.

The concept of sediment fingerprinting provides a mechanism by which sediments can be traced to their source area (be that a sub-catchment or geomorphic unit) (Walling, 2005). Typically, one or more physical or chemical properties is used to fingerprint source areas and then these physical and chemical signatures are tied to either transported suspended sediments during flooding (e.g. Collins *et al*., 1998; Owens *et al*., 2000) or to overbank sediment deposits (e.g. Bottrill *et al*., 2000; Olley & Caitcheon, 2000). Sediment fingerprinting has been most commonly employed in humid environments and with transported sediments. In semi-arid environments, where the delivery of both water and sediment are essential to both short- and long-term ecosystem health, it is imperative to link investigations of sediment sourcing with hydrological conditions in source and depositional areas. The establishment of these links will improve the management of semi-arid flood-plain wetlands by providing a complete picture of the spatial and temporal variability of source areas contributions of both water and sediment to the system.

The aim of this paper is to investigate links between flood frequency, flood history and the provenance of sediments in a semi-arid terminal wetland system. Specific objectives include: (1) identifying the sources of sediments in the Narran Lakes Ecosystem; (2) determining how sediments from different sources are distributed with respect to flood frequency in the Narran Lakes Ecosystem; (3) elucidating the links between flood history and the sedimentation patterns found in the Narran Lakes Ecosystem; and (4) to identify differences in sediment character in the post depositional material from each sediment source.

SITE DESCRIPTION

The Narran Lakes Ecosystem is a terminal flood-plain complex of the Narran River, a major distributary channel located in the lowland section of the Condamine-Balonne catchment (Fig. 1). Like many Australian inland rivers the Condamine-Balonne is an allogenic river originating in a well-watered area but flowing for most of its length across a dry landscape (Thoms & Sheldon, 2000). Maximum summer temperatures often exceed 50ºC while winter maxima are around 20ºC. Rainfall is highly variable both within and between years but there is a pronounced wet/dry periodicity, which is a common feature of dryland regions in Australia (Gentilli, 1986). Mean annual evaporation ranges from 230 mm in the headwaters to over 2000 mm in the lower catchment. Thus large portions of the lower flood-plain region of the Condamine-Balonne catchment have a large negative water balance. Flows in the Condamine-Balonne are also highly variable, with annual flows at St George, in the lower catchment, ranging between 23 960 ML and 7 385 000 ML (1975–2000). Downstream of St George, the Condamine-Balonne River divides into five separate channels (Fig. 2). The Culgoa and Narran rivers (which feed the Narran Lakes Ecosystem) are the main channels, conveying 35% and 28%, respectively, of the long-term mean annual flow at St George.

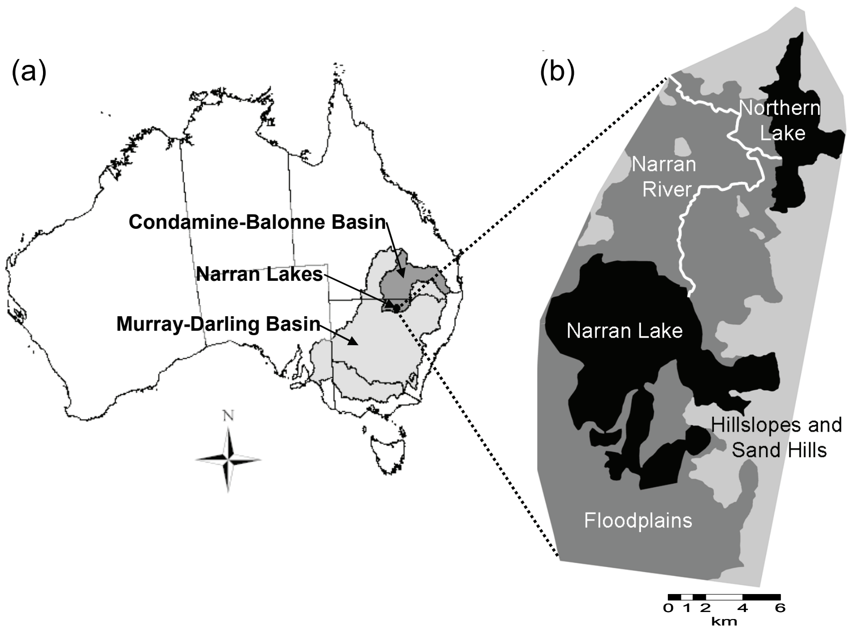

Fig. 1 Site map for the Condamine-Balonne Catchment: (a) location of the Condamine-Balonne Catchment and the Narran Lakes Ecosystem within Australia; (b) the detail of the Narran Lakes Ecosystem illustrating the lakes, flood plains and surrounding hills.

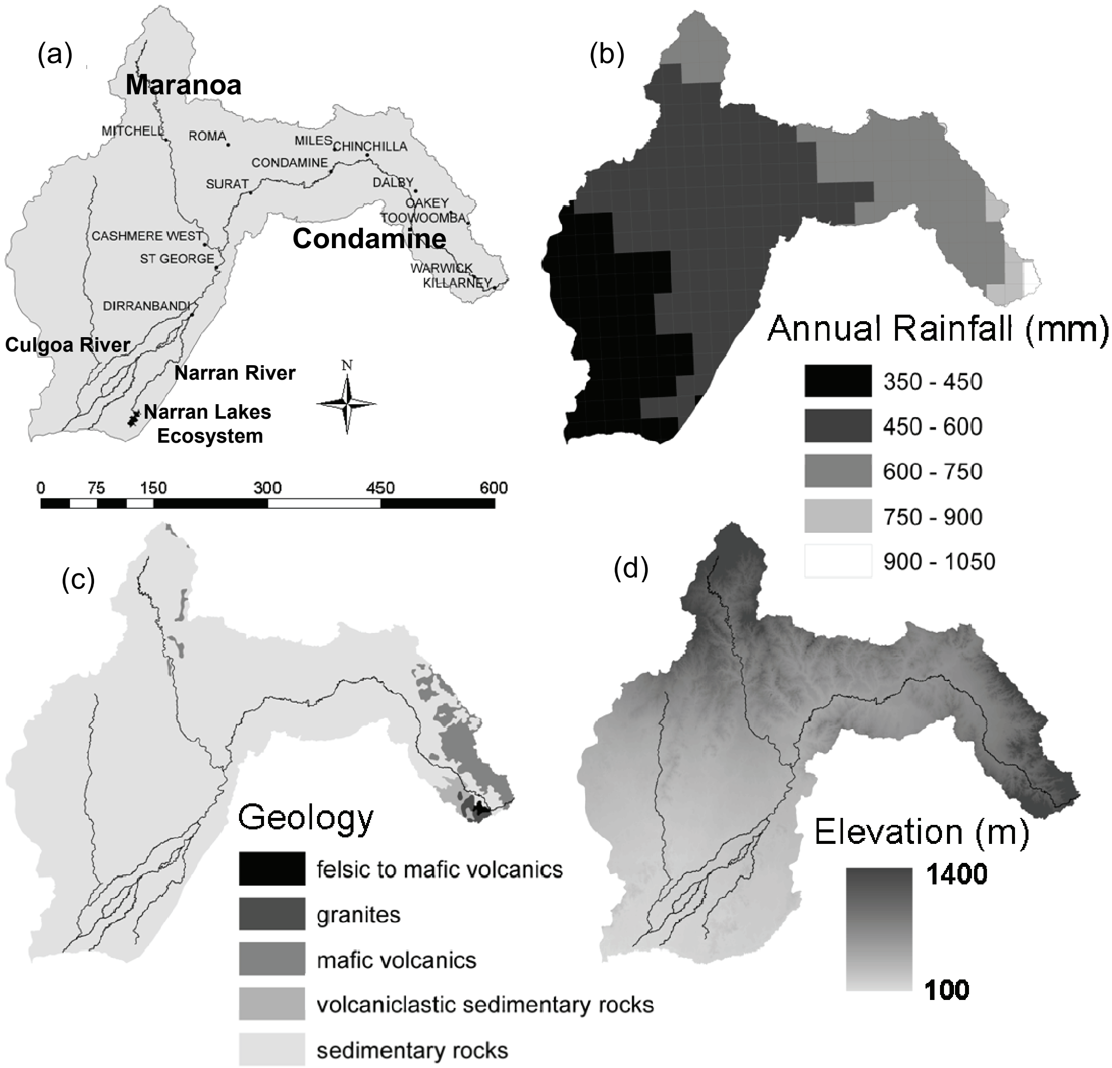

Fig. 2 Characteristics of the Condamine-Balonne Catchment: (a) locations of major towns and gauging stations; (b) mean annual rainfall; (c) geology; (d) digital elevation model.

METHODS

A total of 163 sediment samples were collected from a randomly generated pattern with an average spacing of 1800 m between each point. At each sample site, a 10 m quadrat was established and surface sediments were collected at each corner and in the centre of the quadrat. For each sample, a number of physical and chemical sediment properties were determined, including: the percent sand, silt and clay; pH; organic matter content; and a series of geochemical properties (aluminium, barium, calcium, cobalt, copper, iron, lead, magnesium, manganese, phosphorous, potassium, sodium, strontium, titanium, and zinc). Soil texture was determined using an ASTM 152H soil hydrometer (ASTM, 1985) and pH was measured with an INOCULO CSIRO soil pH test kit. Organic content was estimated as loss on ignition (LOI) at 550°C for 2.5 h. Geochemical properties were determined using a variety of techniques depending on the chemical property in question.

Sediment sources were determined using the Ti/Al ratio as described by Brennan (2001) for the Condamine-Balonne catchment. Flood frequencies were determined for the Narran Lakes Ecosystem based on a series of satellite images covering the maximum extent of every flood between 1981 and 2004. Flood histories were derived for three river gauges: Cashmere in the Maranoa sub-catchment, Surat in the Condamine sub-catchment, and Wilby Wilby on the Narran River.

RESULTS AND DISCUSSION

Sediment sources and sub-catchment characteristics

The Maranoa and Condamine sub-catchments of the Condamine-Balonne Catchment each have distinct physical characteristics which result in variations in the timing and magnitude of flooding, and sediment transport and the geochemical signature of their sediments. Figure 2 illustrates some of the key attributes of each sub-catchment and the larger Condamine-Balonne Catchment. The Maranoa sub-catchment comprises an area of 19 650 km^2 and lies in the drier western part of the Condamine-Balonne Catchment. It has a relatively steep headwater area (where average annual rainfall reaches 600–750 mm/year) and is underlain almost exclusively by relatively weak sedimentary rocks. The Condamine sub-catchment has an area if 47 251 km^2 and lies in the wetter eastern part of the Condamine-Balonne Catchment. It originates in a steep, well watered headwater area where average annual rainfall ranges from 600 to more than 1000 mm/year. The Condamine sub-catchment is more geologically complex than the Maranoa sub-catchment, with a mixture of sedimentary rocks in the mid and lower reaches, and granites, and felsic and mafic volcanics in the headwater regions.

The differences in headwater geology in the two sub-catchments result in distinct geochemical signatures for their sediments sources. Investigating sediment properties in each sub-catchment (i.e. sediments found before the tributaries join at St George) Brennan (2001) found that the Ti/Al ratio was a good discriminator of their sediment sources. In particular, the Condamine sub-catchment had sediments with Ti/Al ratios ranging from 0.049 to 0.100 (resulting from the relatively high quantities of Titanium in the volcanic rocks) while the Maranoa sub-catchment had Ti/Al ratios that ranged from 0.039 to 0.051.

If the Ti/Al ratio is to be used as a tracer for sediments deposited in the Narran Lakes Ecosystem it is important to understand the nature of flow and sediment transport from each sub-catchment. Figure 3 illustrates the flows from the Maranoa and Condamine sub-catchments over the period of record (1969–present). The gauging station nearest to St George was used in both cases (Cashmere for the Maranoa and Surat from the Condamine; see Fig. 2) to minimise the impacts of flow extractions or additional flow inputs. The Condamine sub-catchment contributes a much larger proportion of flows (88%) downstream of St George than does the Maranoa (which contributes only 12% of the flow entering the Narran Lakes). Thus, most of the *water* delivered to the Narran Lakes Ecosystem over the last 40 years has been from the Condamine sub-catchment. Although no similar data exist for the suspended sediments from each sub-catchment (i.e. there is no long term sediment

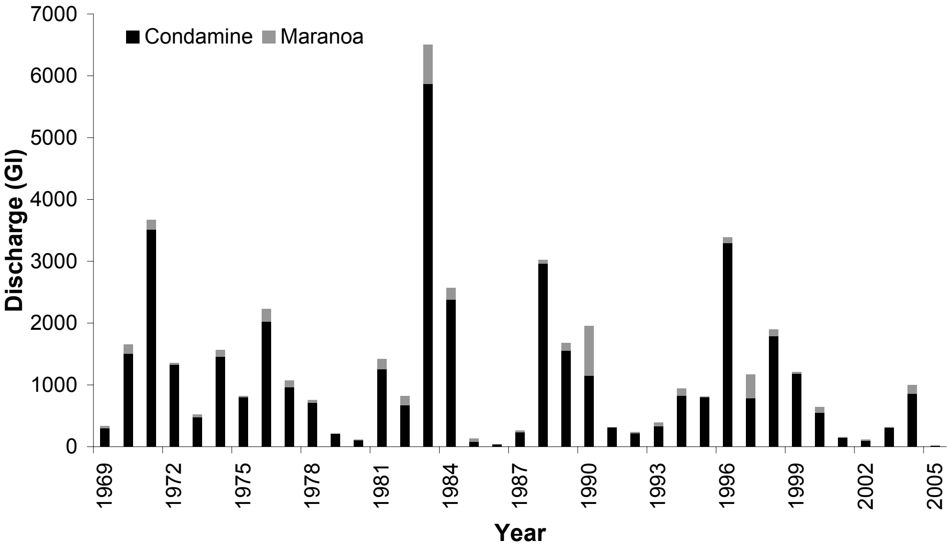

Fig. 3 Relative contribution of the Maranoa and Condamine sub-catchments to flows downstream (at St George).

Table 1 Suspended sediment observations for the Condamine and Maranoa sub-catchments.

Date	Discharge (ML)	TSS Load (tonnes)	TSS Concentration (mg/L)
Condamine			
December 2004	70 465	101 801	1 445
June 2005	3 748	7 105	1 896
December 2005	159 954	166 341	1 060
Maranoa			
February 1997	192 944	180 169	934
February 2001	4 468	7 203	1 612

Note: TSS = Total suspended solids

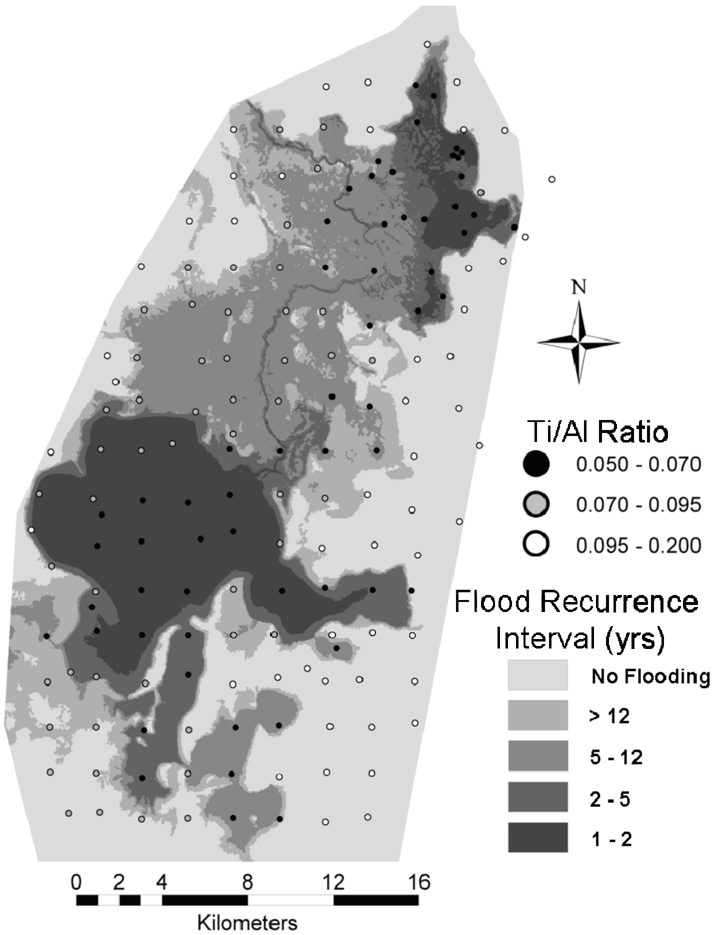

Fig. 4 The spatial distribution of Ti/Al ratios in the Narran Lakes Ecosystem with respect to local flood frequency.

recording station in either sub-catchment) a few suspended sediment measurements have been taken during flooding events. Table 1 summarises the recorded sediment data for each sub-catchment. Although the data are limited, it is apparent that there is no significant difference in the sediment load or concentration derived from either sub-catchment (i.e. for comparable discharges, both loads and concentrations are similar from both sub-catchments). Therefore, it should be possible to eliminate variations in sediment delivery from each sub-catchment as a contributing factor to the nature of the sediments in the Narran Lakes Ecosystem. Rather, differences in the magnitude and frequency of flooding (and the sediments that are carried from each catchment during these floods) should determine the spatial patterns of sediment sources found in the Narran Lakes Ecosystem.

Sediment sources and flood frequency

To determine the sources of the sediments in the Narran Lakes Ecosystem, Ti/Al ratios were plotted for 163 surface sediment samples collected from the site. These were then plotted against a map showing the frequency of flooding in the Narran Lakes Ecosystem (Fig. 4). The first and most obvious observation that can be made from these data is that there are three (rather than two) sources of sediment within the Narran Lakes Ecosystem. In areas prone to flooding, Ti/Al ratios fall within the range of observations made by Brennan (2001) in the Condamine and Maranoa sub-catchments (i.e. between 0.050 and 0.100). However, there were also sediments with very large Ti/Al ratios (up to 0.200). These were invariably found in areas that do not flood (i.e. areas higher in elevation than the 100-year flood plain). These sediments are therefore attributed to a local source, namely the rocks that form the hills immediately surrounding the Narran Lakes Ecosystem.

The remaining sediments all have Ti/Al ratios within the range of observations from the two sub-catchments (as defined by Brennan, 2001) and are therefore attributed a fluvial origin. These were sub-divided into two categories based on the Ti/Al ratio present in each sub-catchment: (1) sediments with little or no Maranoa influence (Ti/Al between 0.070 and 0.095); and (2) sediments with moderate to large contributions derived from the Maranoa (Ti/Al between 0.050 and 0.070). Thus, a total of three sediment source classes were identified: sediments sourced from the local hillslopes; sediments sourced from the Condamine sub-catchment; and sediments sourced from both the Maranoa and Condamine sub-catchments.

The distribution of these sediment sources with respect to the frequency of flooding within the Narran Lakes Ecosystem is quite marked (Fig. 4). As previously mentioned, the sediments sourced from the local hillslopes invariably occur in regions that never flood. This is unsurprising since it is highly unlikely that sediments delivered from the upstream sub-catchments could make their way to the adjacent hillslopes. Although some aeolian redistribution is possible, these sediments would be as likely to be carried outside the Narran Lakes Ecosystem entirely as to the adjacent hillslopes. Therefore, most of the sediments found on the hillslopes are derived from the underlying geology with only minor aeolian inputs from the Condamine and Maranoa sub-catchments. The sediments sourced exclusively from the Condamine sub-catchment (i.e. sediments with Ti/Al between 0.070 and 0.095) are found largely in areas that flood only infrequently (i.e. no more than once in 5 years and especially common in areas that flood less frequently than once in 20 years). Meanwhile, sediments that are sourced from both the Maranoa and Condamine sub-catchments are predominantly found in areas that flood very frequently (less than 5 years, and especially common in areas that flood once every 1–2 years).

Thus, the Narran Lakes exhibit a distinct and clear segregation of sediment sources with respect to flood frequency. Maranoa sediments occur only in areas that flood frequently whereas Condamine sediments occur across all flood frequency zones but are found exclusively in infrequently flooded areas. Locally derived sediments are found in areas that never receive flood waters. To more fully explore the nature of these relationships and to explain and understand why the sediments are so clearly segregated based on flood frequency, it is necessary to consider the links between flood history and flood frequency in the Condamine and Maranoa sub-catchments.

Sediment sources and flood history

Flooding in the Condamine and Maranoa sub-catchments was compared to the flows in the Narran River over the period of record (1969–present) to determine how flood history might impact on the distribution of sediments from different sources in the Narran lakes Ecosystem (Fig. 5(a)). Although this is a relatively short flood record, there were several very large flood events during this period and a number of small and intermediate events. The results of this comparison show that: (1) during large floods in the Narran Lakes Ecosystem the proportion of water (and hence sediment) sourced from the Maranoa is relatively small (considerably below the long term average of 12%); and (2) during small floods in the Narran River the proportion of water and sediment sourced from the Maranoa sub-catchment tends to be intermediate to high (near or above the long-term average of 12% and up to 41%). To further investigate this relationship, the flows in the Narran River were plotted against the proportion of flow (at St George) sourced from the Maranoa sub-catchment (Fig. 5(b)). Again, this plot illustrates the preference for large floods (those greater than 300 GL which have a recurrence interval greater than 7.5 years) to be dominated by water and sediment sourced from the Condamine while smaller floods (those less than 300 GL with recurrence intervals of less than 7.5 years) seem to regularly include medium to large contributions from the Maranoa. Indeed, the long term average (over the period of record) for the proportion of flow sourced from the Maranoa for small and medium sized floods (12%) and for large floods (6%) confirms this finding.

The findings from the flood history component of this study confirm those identified through the consideration of flood frequency. The flood history results show that Maranoa sediments were largely confined to frequently flooded areas. The frequently flooded portions of the Narran Lakes Ecosystem are those which floods of any magnitude will likely inundate (i.e. small, medium and large floods). Thus, included in these areas are the full range of Maranoa inputs and the overall contribution of Maranoa sediment to these areas is likely to be roughly 12% (which is the long-term average of flow that originates in the Maranoa). Condamine sediments, on the other hand, are largely found in infrequently flooded areas (i.e. those reached by only the rarest flood events). The flood history data indicate that, during large events, flows (and hence sediment) are largely sourced from the Condamine with only minimal (6% or less) inputs coming form the Maranoa. Thus, it is unsurprising that these sediments should more closely reflect pure Condamine sediments with higher

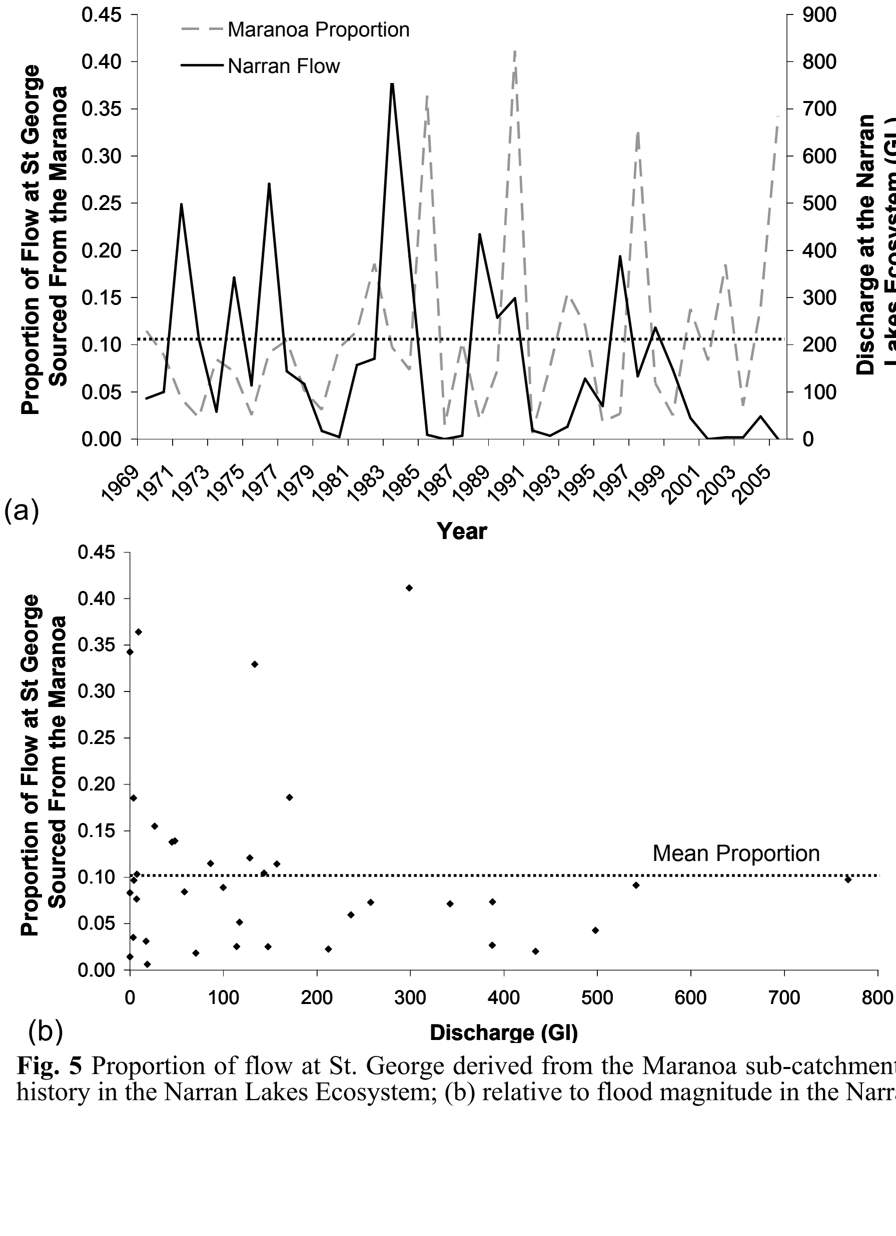

Fig. 5 Proportion of flow at St. George derived from the Maranoa sub-catchment: (a) relative to flood history in the Narran Lakes Ecosystem; (b) relative to flood magnitude in the Narran Lakes Ecosystem.

Ti/Al ratios than those found in the more frequently flooded areas where a larger proportion of the sediment is sourced from the Maranoa (with very low Ti/Al ratios).

Physical and chemical properties of sediments from each source

There are clear differences between the physical and chemical properties of the soils derived from each sediment source (Table 2). These can be characterized by seven distinct types of relationships: (1) variables for which there is no difference irrespective of sediment source (Cu and Co); (2) variables for which Maranoa sediments record the highest values, Condamine sediments have intermediate values and hillslope sediments have the lowest values (%Organics, Al, Ca, Fe, K, Mg, Sr and Zn); (3) variables for which Condamine and Maranoa sediments are similar and have high values while hillslope sediments are different and record lower values (%clay, %silt and Ba); (4) variables for which Condamine and Maranoa sediments are similar and have low values while hillslope sediments are different and record higher values (%sand, pH and Ti); (5) variables for which all sediments are different and Maranoa sediments record the highest values, hillslope sediments have intermediate values and Condamine sediments have the lowest values (P); (6) variables for which only Maranoa sediments are different and these record higher values than the other sediment sources (N); and (7) variables for which only Maranoa sediments are different and these record lower values than the other sediment sources (Mn). These results show that each sediment source results in a unique combination of physical and chemical properties. Hillslope soils are coarse, have high pH, Mn, Ti and P and low levels of organic matter and all other geochemical properties. Meanwhile, Condamine dominated and Maranoa-Condamine mixture sediments can be differentiated on the basis of geochemical properties for which most have higher values in the mixed sediments than in the Condamine sediments.

Table 2 Physical and chemical properties of the sediments from the three principal sediment sources in the Narran Lakes Ecosystem.

Variable	Condamine and Maranoa derived sediments	Condamine derived sediments	Local hillslope derived sediments
Sand (%)	16.50	16.89	53.83
Silt (%)	64.16	65.14	34.25
Clay (%)	19.33	17.97	11.93
pH	8.76	8.81	6.96
Organic (%)	11.42	9.92	4.54
Al (%)	8.06	6.68	4.89
Ba (ppm)	308.62	324.81	244.12
Ca (%)	1.12	0.77	0.20
Co (ppm)	11.60	12.09	10.49
Cu (ppm)	29.16	25.24	24.02
Fe (%)	4.09	3.39	2.43
K (%)	1.48	1.24	0.88
Mg (%)	0.93	0.69	0.23
Mn (ppm)	390.02	464.94	479.45
Na (%)	0.20	0.25	0.17
N (ppm)	1313.79	1061.48	1080.98
P (ppm)	657.76	487.04	521.37
Pb (ppm)	11.72	12.24	11.57
Sr (ppm)	157.62	128.13	65.92
Ti (%)	0.50	0.53	0.58
Zn (ppm)	78.10	63.02	41.47

CONCLUSION

The sediments in the Narran Lakes Ecosystem can be segregated into their respective sources using a simple ratio of Ti/Al. Using this ratio, sediments sourced from local hillslopes have the highest Ti/Al ratios (>0.095), sediments sourced exclusively from the Condamine sub-catchment have intermediate Ti/Al ratios (0.070–0.095) and sediments of mixed Maranoa and Condamine origin have relatively low Ti/Al ratios (<0.070). The distinctive Ti/Al signatures of the sediments have clear associations with flood frequency in the Narran Lakes Ecosystem with locally sourced sediments occurring outside the active flood plain, Condamine sediments occurring in rarely flooded areas and mixed sediments occurring in frequently flooded areas. These associations are supported through a consideration of flood history which shows that, when Narran River flows are large, Maranoa flows are only a small proportion of the total flow at St George and when Narran River flows are small or intermediate in size, Maranoa flows comprise a larger proportion of the flow upstream at St George. Thus, large flows in the Narran River (which reach the infrequently flooded portions of the Narran lakes Ecosystem) contain water and sediment almost exclusively derived from the Condamine and hence explain the presence of Condamine sediments in rarely flooded areas.

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