The sources and dispersal of sediment within a large flood plain complex

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Abstract Knowledge of sediment sources and their dispersal across the landscape is essential for understanding the dynamics of flood plain ecosystems. This is important for flood plain management because rates of upstream catchment erosion are predicted to increase considerably throughout much of inland Australia. In this study, the provenance and dispersal of sediment across a large lowland flood plain complex are investigated. A range of non-soluble geochemical elements were used in a Bayesian mixing model to determine the source and dispersal of very fine sand and clay sized particles across the lower Balonne flood plain in SE Australia. These two sediment fractions were chosen because they are the dominant material present within this flood plain complex. The relative contribution of the two main sediment sources differed for each of the sediment fractions. Clay sized particles were predominantly derived from the Maranoa catchment, whereas the very fine sand was derived from the Condamine catchment. In terms of the dispersal of these sediment fractions from the two main sources, very fine sands were dispersed relatively uniformly across the Lower Balonne flood plain, whereas the clay sized sediment was restricted to the main flow channels that dissect this flood plain. These spatial patterns are contrary to that expected in terms of the dispersal ability of sediment across flood plain surfaces and result from the complex hydrology of the flood plain surface along with the timing of flow events originating from the two tributaries.

Key words sediment dispersal; complex systems; Murray Darling Basin

INTRODUCTION

Efforts to understand, quantify and model the movement of sediment through fluvial systems have increased markedly over the last 50 years. This has been reflected in an expanding literature base describing approaches to the identification of source areas, pathways that link sediment sources and sinks, and general sediment-system behaviour. The edited volume on tracers in geomorphology by Foster (2000) and the collection of papers from the 2004 issue of the International Association of Hydrological Sciences (Golosov *et al.*, 2004) represent recent reviews that deal specially with the "state of play" in sediment dispersal within fluvial systems. The majority of papers in these two publications deal with advances in techniques and approaches for sediment fingerprinting with a trend towards multiple tracers (Collins *et al.*, 1998), reducing sampling uncertainty (Franks & Rowan, 2000) and the development of numerical mixing models. Illustrations of these advances are generally reported for small catchments. Only 11 of 88 papers in these two volumes focus on sediment processes in large fluvial systems; with large systems recently being defined by Miall (2006) as those with a catchment area greater than 50 000 km^2. This is contrary to the emerging trend in river science which seeks to understand large systems (Thoms *et al.*, 2007).

A positive relationship between scale and complexity is an accepted paradigm in the study of natural systems (Wiens, 1989). Larger systems can be characterised by an increase in the number of components; an increased number of different types of components; increased interconnections between components; the presence of both positive and negative feedback loops; and, a larger number of interactions between different levels of organisation within a system compared to smaller systems (Thoms *et al.*, 2007). Hence, large river systems can be assumed to be more complex than smaller river systems. Despite the curiosity about the unique physical, chemical and biological patterns and processes of large river systems, there has been frustration because they do not always conform to empirical models of function (Phillips, 1995), which are commonly derived from smaller systems. Examples include complex patterns of sediment textural and nutrient dispersal across large flood plain surfaces during inundation (Blair & McPherson, 1994; Asselman & Middelkoop, 1995; Thoms *et al.*, 2007) rather than predictable trends from proximal to distal flood plain regions; discontinuities in sediment budgets with significant imbalances between upstream sediment erosion and rates of accumulation in lowland sediment sinks (Phillips, 1995); and, variations in sources of sediment with respect to texture (Vital & Stattegger, 2000). Large rivers have, therefore, been described as being in a non-equilibrium state (Gupta, 2007) and as a result they have been less studied than more manageable smaller systems (Thoms *et al.*, 2007).

Large, lowland river systems are a significant feature of Australia's inland drainage basins. Characterised by low gradients and tortuous channels, they contain extensive flood plains which are important sinks for sediment eroded from upstream catchment areas. Knowledge of contemporary sediment sources and the dispersal of sediment across these large, river-flood plain systems is limited. This study investigates the source and dispersal of two different sediment fractions within the Lower Balonne, a large flood plain complex in SE Australia, using a composite geochemical procedure.

Study area

The Condamine-Balonne River drains 143 000 km^2 of the Great Dividing Range in SE Australia (Fig. 1). There are two principal subcatchments; the Maranoa in the western regions of the catchment, which has a catchment area of 20 000 km^2; and, the Condamine in the east with a catchment area of 87 300 km^2. The Maranoa and Condamine rivers join to form the Condamine Balonne River at St George and this river system eventually flows into the Barwon-Darling between the townships of Brewarrina and Bourke. The subcatchments have different geologies. The Maranoa is dominated by quartzose sandstone, whereas the Condamine contains greater proportions of Cainozoic siltstones, mudstones and significant areas of Tertiary basalts (Thoms *et al.*, 2007). The Lower Balonne flood plain is a dominant morphological feature of the Condamine-Balonne catchment (Fig. 1). This anastomosing section of the Condamine-Balonne River downstream of St George, known locally as the Lower Balonne flood plain, consists of five

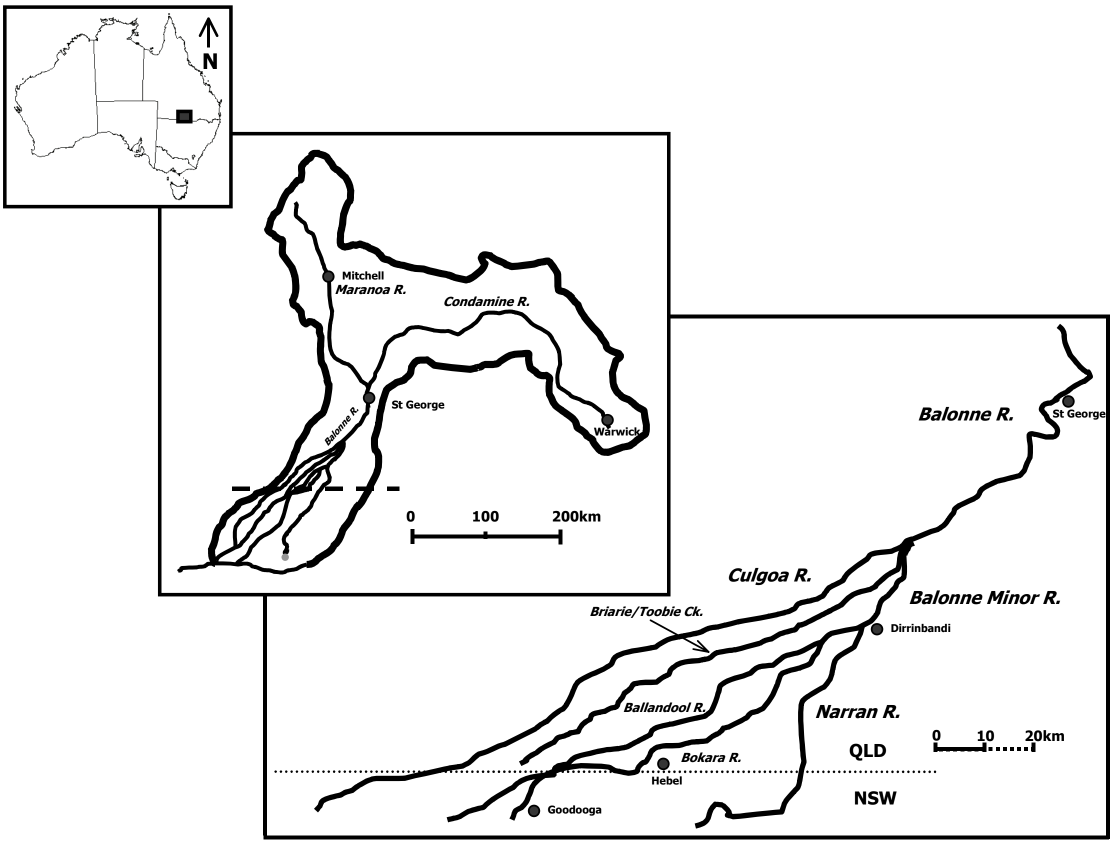

Fig. 1 The Lower Balonne flood plain in SE Australia.

anastomosing channels (the Culgoa, Ballandool, Bokhara and Narran rivers and the Briarie Creek) and an extensive flood plain surface covering 19 880 km^2. The Lower Balonne flood plain formed over a Tertiary, low-angle alluvial fan (Thoms, 2003) and the contemporary flood plain can be classified as a C2 flood plain (Nanson & Croke, 1992) associated with low stream energies, fine-grained sediments and display predominantly vertically accreted surfaces. The Culgoa and Narran rivers are the dominant flow channels, conveying 35% and 28%, respectively, of the long-term mean annual discharge at St George (Thoms, 2003). In contrast, the Ballandool River, Bokhara River and Briarie Creek only convey flows during higher discharge events. Hence, the temporal character of flow frequency, flow duration and flow magnitude differs between the inner Ballandool, Bokhara and Briarie channels and the outer Culgoa and Narran channels (Thoms, 2003). Channel gradients in the river-flood plain complex are low (0.0002–0.0003) and bankfull cross sectional areas tend to decline with distance downstream. Inundation of the flood plain surface is highly variable and depends on subtle changes in channel and flood plain morphology and discharge magnitude (Sims & Thoms, 2002). As a result, sediment deposition during overbank flows can vary between different geomorphic units located on the flood plain surface (Ogden *et al.*, 2007; Thoms *et al.*, 2007).

The catchment upstream of the Lower Balonne flood plain is dominated by agricultural land use and this is associated with extensive gullying and soil erosion. As a result, rates of fine sediment deposition are high in geomorphic units proximal to the river channel (up to 6.6 cm $year^{-1}$) compared to those in distal flood plain regions (up to 0.345 cm $year^{-1}$) (Thoms *et al.*, 2007) and to pre-European sedimentation rates (range 0.029 to 0.296 cm $year^{-1}$). The Lower Balonne region also contains many important flood plain wetlands, for which water and sediment management is a priority (Rayburg & Thoms, 2008, this volume).

METHODS

To establish the relative contribution of sediments derived from the two main subcatchment source areas to the Lower Balonne flood plain and to investigate the dispersal of these sediments across the flood plain, surface sediment samples (10–20 cm depth) were collected at regular intervals along the main channels of the Condamine ($n = 14$) and Maranoa rivers ($n = 9$) and from a regular sample grid across the flood plain ($n = 57$). Each sediment sample was comprised of three randomly collected sub-samples, the combined sample mass of which was greater than 10 kg.

Each sediment sample was air dried, split in half and used for either textural or geochemical analysis. The textural analysis samples were passed through a 2-mm sieve, pre-treated with hydrogen peroxide to remove organic material, and then dispersed with sodium hexametaphosphate before being sized with a Malvern Auto Sizer. Geochemical analyses provided 10 major elements and 39 trace elements and these were determined via an X-Ray Fluorescence spectrometer. On the basis of the textural analysis, geochemical analyses were conducted on two sediment size intervals. A preliminary analysis of the size distributions of the flood plain sediment revealed the 125–63 μm and <2 μm intervals were dominant in all samples, thus the sediment provenance exercise was determined on the very fine sand and clay sized size fractions.

A Bayesian Monte-Carlo mixing model was used to determine the likely source for each sediment sample collected from the Lower Balonne flood plain. Prior to this, all highly soluble elements were removed ($n = 37$) and the character of each potential source and the flood plain sediments (the sink) was examined via a range of multivariate statistical analyses. Initially, the Gower environmental difference measure (Belbin, 1993), which incorporates an implicit range-standardisation of variables, was used to derive a matrix of environmental distances between each source and the flood plain sink based on 12 low solubility elements. A two-way Analysis of Similarity (ANOSIM) was then used to test for differences between the two sources and the flood plain sediments based on the derived Gower matrix. In addition, Semi-Strong-Hybrid Multidimensional Scaling – MDS (Belbin, 1993) was then used to represent the similarity matrix graphically. A stress level of less than 0.2 indicated that the ordination solution was not random.

Relationships between the different geochemical elements and the position of the two potential sources and the flood plain sediments in multi-dimensional space were determined using Principal Axis Correlation (PCC; Belbin, 1993) and only those variables with an R^2 greater than 0.8 were considered for use in the Bayesian Monte-Carlo mixing model. An uncertainty analysis of the selected tracers was also undertaken using the approach outlined in Franks & Rowan (2000). Basically, the approach permits the objective derivation of confidence levels on different source areas. For a given set of geochemical tracers, the effects of uncertain sample means is propagated into the contribution of each source via Monte-Carlo sampling of the derived mean distributions. Values of the geochemical tracers from each source are selected from the derived ranges and the source contributions calculated through an optimisation procedure. This procedure is repeated until sufficient sampling of the tracer property distributions is achieved.

RESULTS

Surface sediments of the Lower Balonne flood plain contain particles that range in size from 2 mm to 0.001 μm, but in varying proportions. As a result, median grain sizes vary from 183 μm to 12 μm and can be classified as ranging from medium sand through to clay on the Wentworth scale. All the Lower Balonne flood plain sediments display a bimodal grain size distribution with a relatively coarse mode between 125 and 63 μm, and a finer mode <2 μm. The clay fraction (<2 μm) comprised 30% of the total distribution, whilst the very fine sand interval (125–63 μm) comprised 20%, on average. Significant quantities for these two modal intervals were present in the Maranoa and Condamine sediments; mean of 12.32% and 15.38% by weight, respectively, for the very fine sand interval and a mean of 1.23% and 3.21% by weight for the clay interval.

Results of the two-way ANOSIM indicate clear differences in the geochemical signature of the Maranoa and Condamine sediments (Global R = 0.781; $p < 0.001$). However, there is overlap between the flood plain sediments and those from the two subcatchments (Global R = 0.411; $p < 0.001$) as well as for the flood plain sediments and the Maranoa (Global R = 0.399; $p < 0.001$) and for the flood plain sediments and the Condamine. Global R-values >0.7 suggest that groups are clearly separated, whilst those within the range 0.5–0.69 suggest some overlap between groups, but are nonetheless clearly different and R-values <0.5 indicate a high degree of overlap between groups (Clarke & Warwick, 1994). Separation of the Maranoa, Condamine and Lower Balonne flood plain sediments is represented graphically in the MDS diagram presented in Fig. 2(a). The PCC results show only five geochemical elements (aluminium, cobalt, lead, strontium, titanium) had R^2 values >0.80 and their position in multivariate space was strongly associated with sediments from either the Maranoa or Condamine subcatchments (Fig. 2(b)). Concentrations of these five elements for surface sediments collected from the Maranoa and Condamine rivers as well as for the Lower Balonne flood plain are given in Table 1.

The optimization procedure to identify and reject non-informative trace elements revealed that all six geochemical elements had a significant contribution to deriving source area contributions for both the 125–63 μm and <2 μm size fractions in the Lower Balonne flood plain. Results of the mixing model demonstrate that an average 65 ± 9% of the clay-sized material on the Lower Balonne flood plain was derived from the Maranoa River. By comparison 93 ± 6% of the fine sands were derived from the Condamine River (Table 2).

Patterns of dispersal for the clay and fine sand intervals are presented in Fig. 3, with the ratio of Maranoa to Condamine derived sediment being presented in 20% intervals. A relatively uniform dispersal of Maranoa derived clay-sized material, contributing over 60% of this sediment fraction, is a feature of the Lower Balonne flood plain surface sediments. The only interruption to this pattern is the dominance of Maranoa derived clay along the Culgoa River where this source area contributes over 80% of this sediment fraction. There is also one small location on the western edge of the Culgoa River that contains between 20 and 40% of clay derived from the Maranoa. A similar relatively uniform dispersal pattern is noted for the fine sand fraction across the Lower Balonne flood plain. However, these sediments are dominated by Condamine-derived material. The majority of the Lower Balonne flood plain surface samples contained >80% of Condamine fine sands.

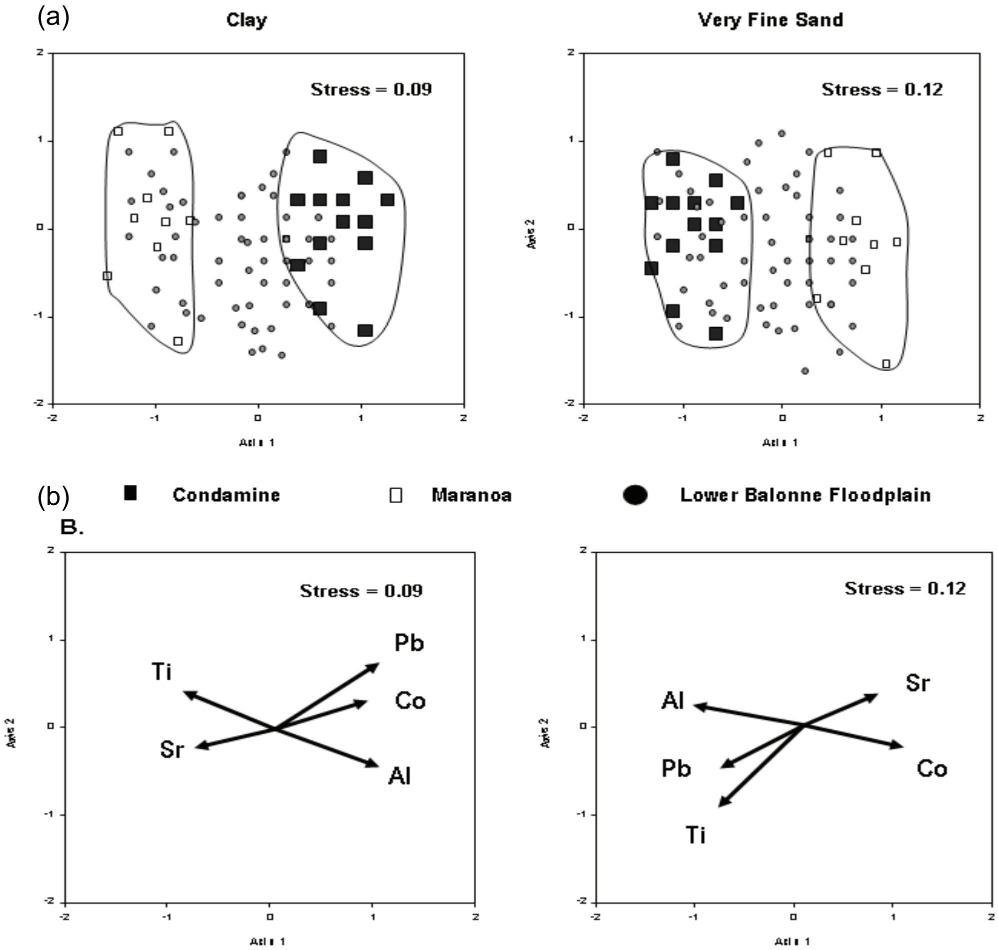

Fig. 2 Ordination and Principal Axis Correlation (PCC) of potential sediment sources and sinks in the Lower Balonne. (a) Ordination of sediment geochemical character, and (b) PCC of associated sediment geochemistry.

Table 1 Concentrations of geochemical elements in the Condamine Balonne catchment. Concentrations are in ppm.

	Condamine	Maranoa	Lower Balonne flood plain
Aluminium (Al)	2.3–9.8	6.8–15.1	2.6–13 4
Cobalt (Co)	92–211	158–311	85–238
Lead (Pb)	5–14	15–38	13–35
Strontium (Sr)	215–438	116–248	73–238
Titanium (Ti)	2.3–9.5	1–3.2	4.5–9.3

Table 2 Contributions of the very fine sand and clay sized sediment fractions from the Condamine and Maranoa sub–catchments to the Lower Balonne flood plain. Means and standard deviations are given.

Source Sub catchment	Sediment fraction: Very fine sand	 Clay
Condamine	93 ± 6	30 ± 10
Maranoa	5 ± 6	65 ± 9

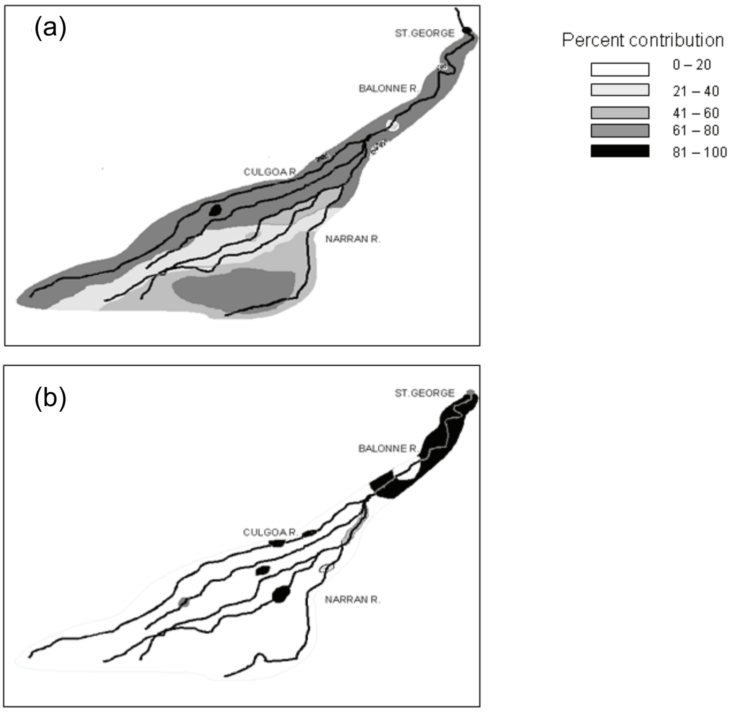

Fig. 3 Patterns of the relative contribution (%) of: (a) clay and (b) very fine sand derived from the Maranoa River across the Lower Balonne.

DISCUSSION

Surface sediments across the Lower Balonne flood plain are dominated by clay and very fine sand-sized material derived from the Condamine and Maranoa river subcatchments. The relative contribution of these two source areas differs for the two size fractions analysed. The Maranoa River is the dominant source of clay-sized sediment in the Lower Balonne flood plain, while the Condamine River is the dominant source for very-fine sands. This result is unexpected based on the geological character of the respective subcatchments. The Maranoa catchment is dominated by sandstone geologies, which are typically poor contributors of clay-sized sediment because of their moderate to high weathering resistance (Young & Nanson, 1983). These results are consistent with other studies of large river basins that have also found differential sediment sources with respect to particle size. Different source areas of clays and larger sand sized particles were noted by Vital *et al.* (1999) along the lower Amazon, with illite and montmorillonite dominated sediments originating from the Andes and those with notable heavy mineral signatures being predominantly from the Brazilian Shield. These differences were thought to occur because of variations in the erodibility of source rocks and conveyance losses of coarse particles during transport. The results from the Lower Balonne and the Amazon are also in agreement with those presented by Bottrill *et al.* (1999) for the River Severn Basin (UK). In this study, it was noted that the Avon River was the relatively more important source of <63 μm sediment because of the easily erodible Jurassic mudstones that dominate the geology of this subcatchment. By comparison, the River Vyrnwy was considered to be a more important source of <2 mm sediment than the fine fractions and this was attributed to the coarser composition of sediment that originates from this catchment and/or conveyance losses within the Upper Severn as result of deposition of coarser material in upstream flood plains. Whilst large amounts of sand-sized sediment are present within the river channel of the Maranoa, this may not be potentially available to the Lower Balonne flood plain because of low sediment delivery capacities. Stream powers required to transport sand-sized sediment, calculated for the Mitchell Gauging Station in the mid sections of the Maranoa River, have an average return interval of >20 years while those required to transport clay sized sediments is 2.3 years. By comparison, the Condamine River is a more dominant source of very-fine sands to the

Lower Balonne flood plain and this may result from more frequent higher stream powers of this river system. The average return interval for the initiation of motion of fine sands at Surat, just upstream of Condamine Maranoa confluence, is only 2.5 years.

The Lower Balonne flood plain is an extensive storage area of sediments derived from the upstream Condamine and Maranoa subcatchments. The dispersal of these sediments across this flood plain differs for clay and very fine sand-sized material. Clay displays a more complex dispersion pattern in comparison to the relatively uniform pattern of the very fine sands. The dominance of Maranoa-derived clay material in the upstream regions and along the channels of the Culgoa and Narran rivers is similar to the sediment dispersal pattern described by Blair & McPherson (1994) across low-angle alluvial fans. The apex and outer flow paths of these landforms are characterised by higher and more variable energy conditions and relatively poor fine sediment conveyance. The contemporary Lower Balonne flood plain has formed across a low-angle Cainozoic alluvial fan (Thoms, 2003) and the Culgoa and Narran rivers are the main flow paths conveying 35 and 28%, respectively, of the long term mean annual flows at St George. Flow variability in these two river channels is high in comparison to the other channels that dissect the contemporary flood plain (Thoms, 2003) and this may contribute to overall retention of clay sediments delivered from the Maranoa. The dispersal of very fine sands across the Lower Balonne flood plain originating from the Condamine subcatchment differs by comparison. The relatively uniform dispersal pattern of very fine sand reflects the fact that major inundation of this flood plain results mainly from floods generated in the Condamine subcatchment; a region that experiences a higher frequency of sediment competent flows, which are readily able to disperse coarser sediment across the Lower Balonne flood plain. A similar segregation of sediment sources with respect to flood frequency has been reported in other areas of the Lower Balonne. In their study of the Narran flood plain, Rayburg & Thoms (2008, this volume) found Maranoa-derived sediments to occur in those areas of the flood plain with relatively higher flood frequencies compared to those dominated by Condamine-derived sediments.

Large lowland-river flood plains are complex landscape features where the existence, development and arrangement of different patterns of sediment dispersal are a reflection of this complexity. We suggest that two modes of sediment supply and dispersal coexist in the Lower-Balonne flood plain. These two modes correspond to a lateral and longitudinal dimension and may relate to variations in energy and supply conditions at different scales. The Culgoa and Narran rivers are the dominant flow paths that experience a highly variable range of flow conditions (Thoms, 2003) and consequently have the ability to convey sediment of different sizes. Energy conditions are maintained along both rivers, but there are marked differences in stream power between floods of different magnitudes. Subsequently, patterns of clay dispersal in the Culgoa and Narran rivers manifest longitudinally and largely in channel during smaller floods. Coarser sands are dispersed across the flood plain during inundation at relatively higher flood magnitudes.

Sediment tracers offer the potential to understand the behaviour of fluvial ecosystems; they are an important tool in the geomorphologists “toolbox”. To increase their use and reliability, Foster (2000) raises the issue of establishing guidelines for their use and proposes a general methodology for the tracing of fine-sediment in rivers. The approach taken in this study differs somewhat from that proposed by Foster (2000) and offers several advantages. First, narrow particle size windows, identified in the textural distribution of the sedimentary deposit, were used instead of bulk sediment samples. In this case fine sediments were selected, thereby reducing the probability of changes in tracer properties between source and sink and the need for post processing of sediment distributions. Second, the natural geochemistry of the sediments was used as the tracer and only those elements with low solubilities were used, further reducing the chance of alteration between sediment sources and their place of deposition. Multivariate techniques were then used to identify those geochemical elements that had strong statistical association with the different source areas and those that contributed significantly to differences between the source areas. Multivariate analyses can elicit patterns and infer process in a quantitative rather than a qualitative manner (Thoms *et al.*, 2007) and represent an extremely powerful analysis and interpretation tool for sediment tracing studies. Third, once statistically relevant geochemical elements were identified, a simple and robust method for assessing uncertainty in the use of multi-parameter fingerprinting techniques was applied. When high density sampling cannot be undertaken, the approach outlined here, which was first suggested by Franks & Rowan (2000), can provide information about the natural variability and the "best" element characterisation of sink areas. Finally, a Bayesian Monte-Carlo mixing model was then applied to determine the contributions of different source areas to each sample in the flood plain deposit.

CONCLUSIONS

Are large flood plains complex systems (cf. Gupta, 2007) or is this just an excuse not to study them? Flood plains are nested hierarchical systems with graded organizational structures, whereby patterns and processes at any one level or scale are a composite of those at lower levels or scales. Order and complexity are both emergent properties of these systems. The decomposition of large systems into smaller units allows patterns and processes to be more fully understood. Initial studies of sedimentation across the Lower Balonne flood plain suggested a degree of complexity in sediment transfers; however, this study has demonstrated a two component sediment source-dispersal system. Sources and dispersal patterns differ for the two grain size fractions analysed. In addition, the study has clearly demonstrated a quantitative composite sediment tracing approach that has successfully determined the source and dispersal of sediment, thus adding to the understanding of the construction of large, lowland river flood plain systems.

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