Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006.

Unravelling the physical template of a terminal flood plain–wetland sediment storage system

SCOTT RAYBURG, MARTIN THOMS & ERIN LENON

Water Research Laboratory, Institute of Applied Ecology, e-Water CRC,
University of Canberra, Australian Capital Territories 2601, Australia

scott.rayburg@canberra.edu.au

Abstract Flood plain–wetlands are hotspots of biological diversity and productivity, especially in semiarid environments and this is driven by water subsidies as well as the physical and chemical properties of flood plain–wetland soils. The purpose of this study is to examine surface soil characteristics in a complex, spatially diverse terminal flood plain–wetland to determine whether the surface soil characteristics follow a hydraulic gradient or reflect the more complex spatial mosaic. Surface soil samples (163) were collected from a regular grid with an average spacing of 1.8 km. Multivariate statistical analyses were performed to elicit spatial patterns in soil character and a series of surface maps of soil characteristics were derived to further explore spatial patterns within the flood plain-wetland complex. Results show surface soil characteristics to be spatially heterogeneous at multiple spatial scales and more complex than can be described by a series of hydraulic gradients.

Key words flood history; Narran Lakes; semiarid; soil texture; surface soil

INTRODUCTION

Flood plains, wetlands and lakes are common features along many river systems. In dryland environments, these features serve as oases of biological productivity and diversity (Morton, 1990) due, in large part, to their comparatively frequent inundation regimes and the richness of their soils. Understanding the links between inundation regime and soil richness provides insights into the consequences of climate change and/or water resource development in these areas.

The physical and chemical character of flood plain–wetland soils contributes to the distribution and abundance of flora and fauna within these systems. Habitat preferences of individual species are influenced by soil type (Capon, 2003) and post-inundation species distribution is influenced by spatial variations in the flood plain soil seed and egg banks (Boulton & Lloyd, 1992). Thus, knowledge of the distribution of soil types and their character can provide useful information as to the potential distributions of many plant and animal species as well as their likely biological responses to flooding or precipitation.

Flood plain–wetlands are depositional features that originate at, and interact with, a main river channel. Surface sediments within these features become finer with distance laterally from, and longitudinally down the main channel due to changes in the hydraulic characteristics of in-channel and overbank flows (Assleman & Middlekoop, 1995; Walling & He, 1998). For example, stream power is highest upstream and adjacent to the channel in overbank flows; therefore, larger particles are transported and deposited in these regions. Thus, lateral and downstream hydraulic gradients control the sediment size and, ultimately, the characteristics of flood plain–wetland soils. Although these relations have been observed in many flood plain–wetland systems, the presence of lateral and downstream hydraulic gradients in large flood plain–wetland complexes has not been established. The many possible flow paths within these systems may complicate the delivery of water and sediment thus making it difficult to predict the spatial pattern of surface soil characteristics in these systems.

The purpose of this study is to determine if the surface soil characteristics of an astomosing flood plain–wetlands exhibit variations typical of traditional flood plain-wetlands or whether they reflect the complex spatial mosaic of lakes, flood plains and channels found within the system. In addition, surface soil properties are related to topography, flood frequency and the distribution of perennial vegetation to identify possible structural controls on the character of sediment within the system.

METHODS

Study area

The Narran Lakes system is an ephemeral terminal flood plain–wetland complex located in the semiarid northwest of New South Wales, Australia. The Narran Lakes are fed by flows from the Narran River, the easternmost distributary of the Condamine-Balonne River, downstream of St George (Fig. 1(a)). Geomorphologically, the Narran Lakes are composed of several lakes (Narran Lake, Clear Lake, Back Lake, Long Arm), a complex river channel network and flood plains which form eight geomorphic regions: Narran Lake (NL), Northern Lake (N^{th}L), Red Soil (RS), Southern Flood Plain (SFp), Central Eastern Flood Plain (CEFp), Central Western Flood Plain (CWFp), North Eastern Flood Plain (NEFp) and North Western Flood Plain (NWFp) (Fig. 1(c)). The climate of the Narran Lakes is hot and dry with maximum summer temperatures near 50ºC and winter maximum temperatures around 20ºC. Average annual precipitation is about 480 mm year^{-1} in contrast to the average annual evaporation which is approximately 2000 mm year^{-1}. Evaporation exceeds precipitation in all months; thus, there is a large negative water balance (precipitation–evaporation) in the Narran lakes that persists throughout the year. Rainfall is highly variable from year to year and secular wet and dry periods are a feature of the region (Thoms & Parsons, 2003).

Soil surveys

Two soil surveys were incorporated in this study. The first consisted of samples taken from sites positioned on a regular grid with an average spacing of 1800 m between each sample point (Fig. 1(b)). For the second survey, soil samples were collected at locations where vegetation surveys had been carried out for another part of the larger Narran Lakes research project. In total, 163 soil samples were collected, 130 from the grid pattern and the remaining 33 from the vegetation sites (Fig. 1(b)). At each site, a 10-m quadrat was established and surface soil was collected at each corner and the centre of the quadrat.

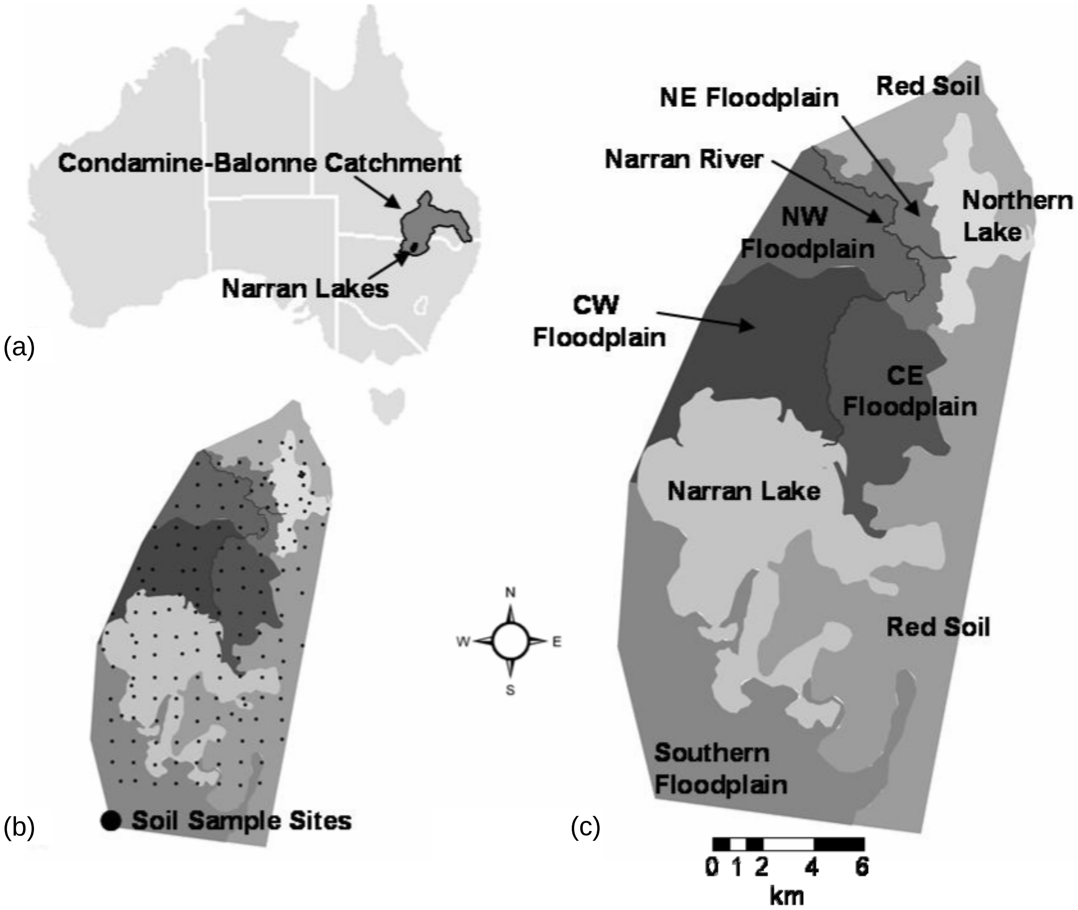

Fig. 1 Study site: (a) location of the Narran Lakes; (b) soil surface sample locations; (c) geomorphic regions.

Soil analysis

Soil texture was measured by determining the clay, silt and sand fraction of samples using an ASTM 152H soil hydrometer (ASTM, 1985). Soil colour was determined for both moist and dry samples using the Munsell Soil Colour Chart, and pH was measured with an INOCULO CSIRO soil pH test kit. Organic content was estimated as loss on ignition (LOI) at 550ºC for 2.5 h. Consistency limits of samples were investigated using the liquid and plastic limits, which were measured using the Casagrande Apparatus and glass plate as described by Sowers (1965).

Data analysis

For each of the soil variables identified above, the values were entered into a table in ArcGIS 8.2 along with their geographic position in the landscape. In addition, for each sample point, the elevation, height of the surrounding vegetation and the frequency of inundation (defined as the number of times inundated during the last 30 years by the largest annual flood) were determined. A radial basis function was then applied to each variable using the geostatistical analyst function in ArcGIS 8.2 to derive a soil surface map for each of the soil properties.

The soil character across the study area was further examined through a range of multivariate statistical analyses. A similarity matrix of Gower's similarity coefficients was first calculated using all soil variables and this matrix was used to test between-geomorphic region differences using the analysis of similarity (ANOSIM) routine in the PRIMER computer package (Clarke & Warwick, 1994). In addition, Semi-Strong-Hybrid Multidimensional Scaling (MDS; Belbin, 1993) was 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 different soil variables and the independent variables of site elevation, flood frequency and vegetation height and the position of samples in the 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.

RESULTS

Summary statistics and error assessments for the various soil variables are presented in Table 1. Results of ANOSIM are summarized in Table 2 and these show that there are clear differences between geomorphic regions (Global $R = 0.507$, $p < 0.001$). With regard to pair-wise comparisons, R statistics greater than 0.5 suggest that groups are clearly different (Clarke & Warwick, 1994). By this criterion, the soils associated with the eight geomorphic regions within the Narran Lakes system are clearly differentiated from the surrounding landscape—the red soil (RS) geomorphic region. Separations between the seven geomorphic regions within the Narran Lakes system are not clear. However, the soil character of the Northern Lakes samples ($N^{th}L$) is clearly separated from both the northeastern (NEFp) and northwestern flood plains (NWFp) whilst the southern flood plain (SFp) is clearly separated from the northeastern flood plain (NEFp). The separation of groups is represented graphically in the MDS plot shown in Fig. 2. The PCC results show only two soil variables, the percentage sand and liquid limit, which had R^2 values greater than 0.80 and their position is strongly associated with the different geomorphic regions in the study area (Fig. 1(c)). The percentage sand is closely associated with the red soils whilst liquid limit is associated with the

Table 1 Summary statistics and error assessments for each physical variable and soil characteristic.

Variable	Elev (m)	Veg (m)	FF (years)	pH	OM (%)	LL (%)	PL (%)	Sand (%)	Silt (%)	Clay (%)
Mean	121.10	0.65	6.60	8.26	8.85	26.08	21.88	34.07	26.20	39.74
CoV	0.025	2.24	1.28	0.13	0.46	0.34	0.38	0.64	0.49	0.54
Min	117.98	0.00	0.00	6.00	1.05	8.00	1.00	5.00	6.25	1.25
Max	134.84	9.50	27.00	10.00	19.61	44.18	43.87	80.00	80.00	85.00
Mean error	–0.12	0.03	0.14	0.02	0.04	0.16	0.20	–0.79	0.23	0.01
RMS	2.14	1.50	5.09	0.83	3.36	6.77	8.12	16.44	11.98	15.47

Elev, elevation; Veg, vegetation height; FF, number of years inundated during the last 40 years; OM, organic matter; LL, liquid limit; PL, plastic limit.

Table 2 ANOSIM comparing each geomorphic region.

Class	NL	N^th^L	RS	SFp	NEFp	NWFp	CEFp	CWFp
NL								
N^th^L	0.337[3]							
RS	0.877[1]	0.834[1]						
SFp	0.446[3]	0.009[4]	0.760[1]					
NEFp	0.147[4]	0.613[2]	0.839[1]	0.698[2]				
NWFp	0.273[3]	0.500[3]	0.696[2]	0.427[3]	0.180[4]			
CEFp	0.183[4]	0.068[4]	0.672[2]	0.222[4]	0.264[3]	0.085[4]		
CWFp	0.182[4]	0.114[4]	0.680[2]	0.162[4]	0.326[3]	0.097[4]	0.062[4]	

[1] strong separation; [2] some overlap but clearly different; [3] high degree of overlap but may be different; [4] not separable.

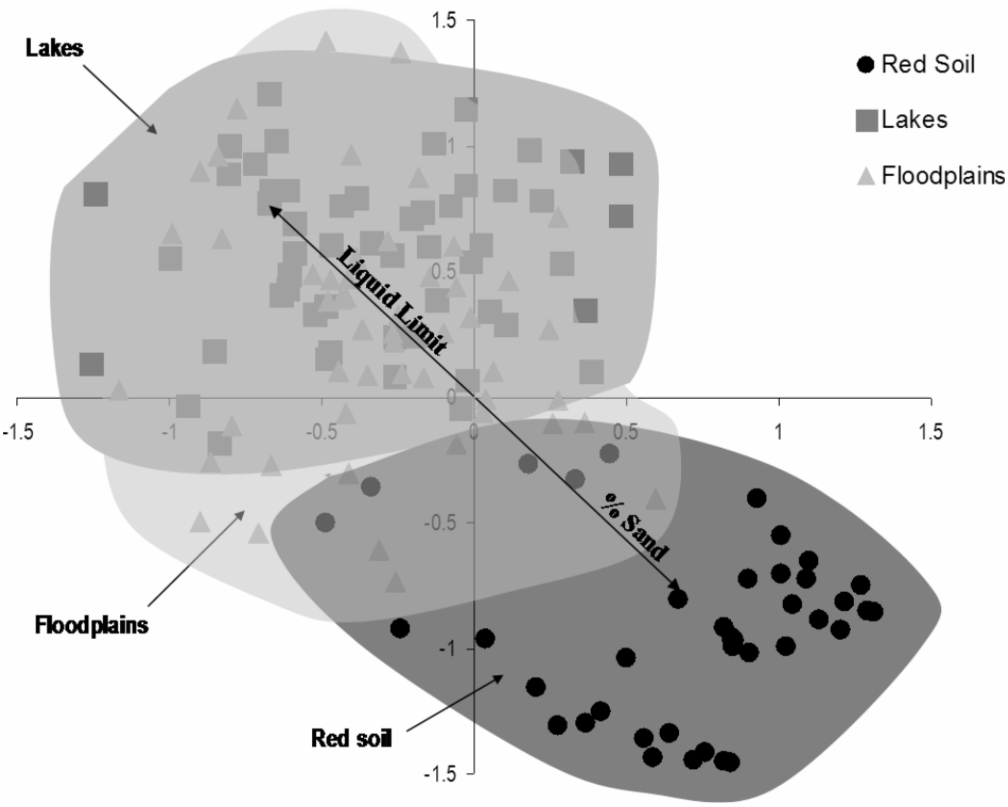

Fig. 2 SSH ordination in two dimensions of the soil samples collected from the study area. Soils have been plotted and labelled according to their contribution to their association with the red soil, lake or floodplain geomorphic regions. Significant PCC associations have also been plotted.

other geomorphic regions of the Narran Lakes. In terms of the independent variables of elevation, flood frequency and vegetation height the PCC analysis revealed that none had strong associations with any of the geomorphic regions; R^2 values were all less than 0.80.

Soil maps for each variable illustrate the complex nature of the soils in the Narran Lakes (Fig. 3). There appear to be both longitudinal and lateral patterns in many soil variables but there is also an obvious structural control related to the geomorphology

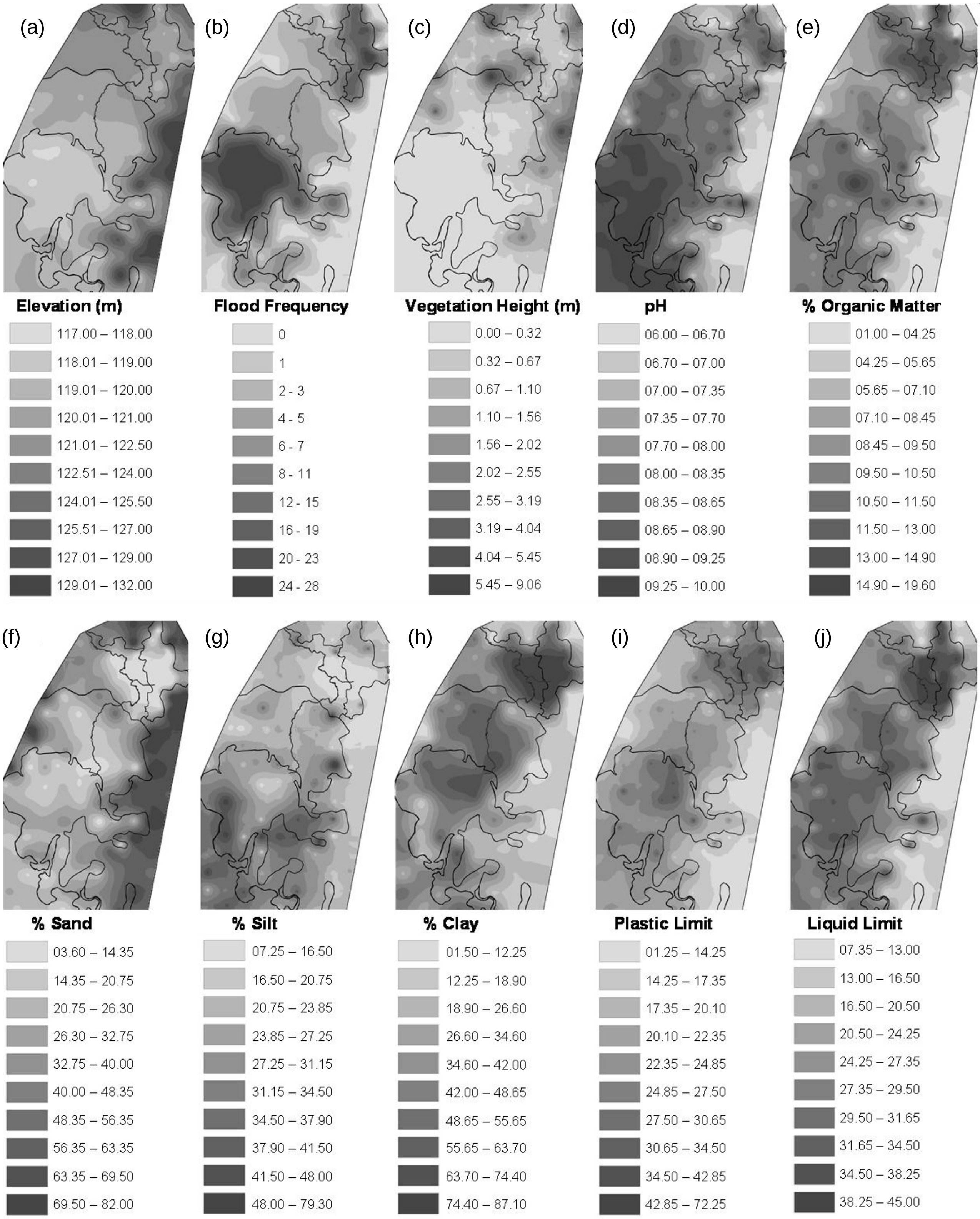

Fig. 3 Surface maps for each of the 10 physical and soil variables.

of the wetland. Lateral variations in soil character are most pronounced in the central flood plain regions and are particularly evident for soil texture and liquid and plastic limits. Longitudinal gradients in soil character are more subtle for most variables, with pH being the only notable exception.

The most apparent differences in the soil character of the pre-defined geomorphic regions occur between red soil and the lake and flood plain regions. The red soil region is characterized by low pH, organic matter, liquid and plastic limits and clay content while it has the highest sand content. Meanwhile the lake regions tend to be locations with high pH, organic matter, liquid and plastic limits and clay content while they have very low sand content. The flood plain regions, on the other hand, are more similar to the lake regions than they are to the red soil region but are characterized by more intermediate values for each soil variable, although locally high or low values do occur in particular locations.

In order to explore more fully the presence of lateral and longitudinal gradients in the system, each of the eight geomorphic regions and the system as a whole were assessed visually for the presence or absence of these gradients within them. The results for this assessment are presented in Table 3. These results show that there is a highly complex pattern, which is inconsistent from region to region and between different soil variables. There are no systematic lateral or longitudinal gradients present in any geomorphic region nor do any variables consistently display these gradients. In fact for the 63 possible soil property–geomorphic region combinations, 22% exhibited both longitudinal and lateral gradients, 30% had lateral gradients only, 3% displayed longitudinal gradients only and 56% showed neither lateral nor longitudinal gradients.

Table 3 Gradients of soil properties for each geomorphic region.

Class	pH	OM (%)	LL (%)	PL (%)	Sand (%)	Silt (%)	Clay (%)
NL	None	None	None	Lt, Lg	None	Lt, Lg	Lt
NthL	Lt	Lt	Lt	Lt, Lg	None	Lg	Lt, Lg
RS	None	None	None	Lg	None	None	None
SFp	Lt	None	None	None	None	None	None
NEFp	Lt	Lt	Long	None	None	None	Long
NWFp	Lt	Lt	Lt, Lg	Lt	Lt	Lt	Lt
CEFp	None	Lt	Lt, Lg	Lt, Lg	Lt	None	Lt, Lg
CWFp	None	Lt	Lt, Lg	Lt, Lg	Lt, Lg	None	Lt, Lg
Whole	Lg	Lt	Lt	Lt	None	None	Lt, Lg

Lt, lateral gradient is evident; Lg, longitudinal gradient is evident; None, no gradients or controls are evident.

DISCUSSION

Differences in surface sediment character between flood plain landforms have been demonstrated previously (Anderson *et al*., 1996). In particular, differences in sediment texture have been associated with variations in stream energy across flood plain surfaces (e.g. Marriott, 1996). Indeed, the model of James (1985) demonstrated decreases in flow turbulence with distance from the main river channel, resulting in near channel deposits being coarser than those in distal flood plain areas. At the time scale of a flood event, both Walling *et al*. (1997) and Thoms *et al*. (2000) have provided evidence that sediment textural and nutrient character differ between areas close to the river channel and those at more distal locations on the flood plain. Gradients in surface sediment character were not consistently recorded in this study. This may simply reflect variations in energy and sediment supply conditions at both the entire lakes scale and within individual geomorphic regions. In addition, the morphological complexity or heterogeneity of the Narran Lakes system may also influence the complex pattern of surface sediment character. Rates of accumulation and patterns of sediment character have been demonstrated to reflect surface topography and its roughness as well as flow conditions (Brunet *et al.*, 1994; Asselman & Middlekoop, 1995; Walling & He, 1998). Thus, the nature of sediment deposited in flood plain environments varies considerably in space and time (Asselman & Middelkoop, 1995; Walling & He, 1998).

Consistent spatial patterns in soil properties were not recognised at any scale considered in this study. At the system scale—the Narran Lakes—lateral gradients were most common and occurred for liquid and plastic limit, %organic matter and %clay. Longitudinal gradients were observed for pH and %clay, while %silt and %sand had neither lateral nor longitudinal gradients. Thus, we cannot describe the Narran Lakes system as one responding solely to lateral and longitudinal influences. A similarly complex structure is evident at the geomorphic region scale. At this smaller spatial scale, there are clear lateral and longitudinal gradients evident for some variables in some geomorphic regions, but there is no consistent lateral or longitudinal gradient present for any one geomorphic region or for any one variable. Importantly, there appears to be no obvious relationship across these two scales. For example, many geomorphic regions exhibit lateral but not longitudinal gradients for pH; however, at the system scale, only a longitudinal gradient was observed. Thus we have a system that is spatially diverse both at the system scale and the geomorphic region scale and there is little correlation between the presence or absence of gradients at these two scales.

Given the complex, spatially heterogeneous nature of the surface soils in the Narran Lakes system, it seems evident that there is a variety of factors influencing the distribution and characteristics of the soils found there. First, flow hydraulics has an obvious influence on surface soil properties. Although by no means ubiquitous at the system or geomorphic region scale, lateral and/or longitudinal gradients were found for about 44% of all cases. These gradients represent basic fluvial processes such as downstream fining and fining of overbank sediments with distance from the source channel. However, there is a complicating factor in that the magnitude and frequency of inundation in the Narran Lakes ecosytem is both temporally and spatially variable. That is, floods of similar magnitude do not necessarily occupy the same portions of the landscape as a result of the complex topography and multiple flow paths found in the Narran Lakes system. Thus, since each flood carries sediments of slightly different character and inundates different parts of the landscape, the soil response will be unique for each flood event. More specifically, variable sediment supply and energy conditions during high-flow events influence the accumulation and composition of sediment in flood plain areas. Hydraulic conditions, especially shear stress or unit stream power, vary across flood plains during over-bank flows, and marked variations can also occur along the river, between different reaches. These larger-scale differences along the river highlight the importance of geomorphological controls on the accumulation and dispersal of flood plain sediments. A further complicating factor is the impact of aeolian processes on the surface soil properties in the Narran Lakes system. Winds come predominantly from the southwest and west of the Narran lakes and there are a series of lunettes on the eastern side of the NthL region as a consequence. This obvious evidence of aeolian activity implies that the surface soil will also be subject to redistribution by wind.

Little is known about the functioning of large flood plain rivers as ecosystems and there is considerable debate about the roles of various landscape attributes, such as soil character. Australia's inland flood plain rivers have been described as "boom–bust" systems (Walker *et al*., 1997) with intense periods of high biological productivity during or immediately following infrequent and unreliable inundation. This ecological response and the relatively high biodiversity of these areas is, in part, a reflection of their physical complexity or heterogeneity. Environmental heterogeneity is a key driver of ecosystem health and resilience (Thoms *et al*., 2006) and one that must be inherently understood to advance sustainable conservation. Complex patterns of flood plain surface sediment character are an important attribute of the Narran Lakes flood plain–wetland complex and one that may be contributing to ecosystem integrity.

CONCLUSION

Surface soils in the Narran Lakes system display highly variable characteristics across a wide range of soil properties with respect to their spatial positioning within the landscape. These soils do not exhibit patterns consistent with existing studies of flood plain–wetland systems in that there are no consistent lateral or longitudinal patterns either at the system or geomorphic region scales. Further, the relationships between soil properties and elevation, flood frequency and vegetation height are inadequate to explain the spatial pattern in soil characteristics. Rather, there appears to be a complex interaction of process controls on the character of the surface soils. These controls include simple longitudinal and lateral sorting processes consistent with the hydraulics of river flow, a larger structural control exerted by the overall topography of the flood plain–wetland and the frequency of flooding that occurs there, and finally the redistribution of surface soil material by aeolian processes. Unravelling the complexity of environmental systems, such as flood plain wetlands, is important for understanding relationships between the heterogeneity and resilience of these ecosystems.

Acknowledgements The authors would like to thank the Murray Darling Basin Commission for providing the funding for this project. In addition, a number of people contributed a great deal of time to the data collection and analysis of the soil samples. In particular, we would like to thank Edwina Mesley and Nolani McColl for their invaluable contributions to this work.

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