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227

Flood-plain sedimentation in a dryland river: the River Murray, Australia

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Abstract Exchanges of water, sediment and associated nutrients between river channels and flood plains are important for the ecological functioning of large flood-plain river ecosystems. The deposition of sediment and associated nutrients was measured on four different flood-plain surfaces along a 15 km reach of the lower River Murray, southeastern Australia, during a controlled flood event. Discharge peaked at 80 000 megalitres per day (MLd), resulting in the entire flood plain being inundated for at least 114 days. During this period, 81 944 t of sediment or 13 % of the suspended load was retained within the study reach. Of this, 23 202.5 t was deposited on the various flood-plain surfaces. The sediments were mainly silty loams and contained large amounts of nutrients: the equivalent of 950 t of total organic carbon (TOC), 50 t of total Kjeldahl nitrogen and 2.3 t of total Kjeldahl phosphorus was deposited on the flood plain during this flood event. The spatial distribution of the deposited sediment and associated nutrients was found to be variable. The highest rates of sediment deposition were recorded nearest to the river channel, but the highest concentrations of nutrients were found in distal areas. Flood-plain topography, surface roughness and the timing of sediment input and associated nutrient input were considered to be the main factors influencing the highly variable spatial distribution of this exchange between the river channel and its flood plain.

INTRODUCTION

The lateral exchange of water, sediment and nutrients between river channels and their flood plains is an important ecosystem process. The flood pulse concept of Junk *et al.* (1989) highlights the importance of these transfers for ecosystem functioning and the integrity of flood-plain river systems. In particular, it suggests that the character of the flood event (pulse) controls the delivery of nutrients to and from the flood plain. However, the rate and pattern of sediment accumulation have also been demonstrated to reflect surface topography and its roughness as well as flow conditions (Asselman & Middelkoop, 1995; Brunet *et al.* 1994; Walling & He, 1998). As a result, sediment deposition in flood-plain environments varies considerably in space and time (Asselman & Middelkoop, 1995; Walling & He, 1998). However, general trends have been reported, such as the decrease in the size of deposited sediment across flood-plain surfaces (e.g. Marriott, 1992). While much is known of sediment accumulation in flood-plain areas, little is known of the fate of nutrients during overbank flows, by comparison.

Nutrients play an important role in regulating primary productivity in flood-plain systems (Brinson *et al.*, 1983; Spink *et al.*, 1998). Carbon and nutrients can be

transferred to flood plains in association with sediments during overbank flows (Pinay *et al.*, 1992). This can occur via adsorption onto sediment particles; hence their transfer is directly related to the proportion of fine sediment (silt–clay) deposition (Schwarz *et al.*, 1996; Walling *et al.*, 1997). Phosphorus is commonly associated with clay particles (Schwarz *et al.*, 1996). Carbon, nitrogen and phosphorus can also be bound to organic matter and thus the content of organic matter in flood waters will influence the exchange of these nutrients between a river channel and its flood plain (Pinay & DeCamps, 1988, Walling *et al.*, 1997). Studies by Pinay *et al.* (1992, 1995) and Brunet *et al.* (1997) have demonstrated the importance of erosion and deposition in the distribution of nutrients in overbank flows, while the Riverine Productivity Model (Thorp & Delong, 1994) emphasizes the importance of locally derived sources of organic matter. An understanding of the sources and fates of carbon and nutrients is essential for the sustainable management of healthy flood-plain river ecosystems.

Many Australian inland rivers are characterized by extensive flood plains and a network of channels that are connected only during episodic floods. Much of the general information demonstrating the linkages between river channels and their flood plain is derived from studies of relatively small temperate forest systems in North America and Europe. While many of the coastal systems in Australia appear to function in a similar manner (Lake, 1994), very little is known about the transfer of sediment, carbon and nutrients in larger Australian dryland systems (Robertson *et al.*, 1999). This paper investigates the transfer of sediment and associated nutrients from the river channel to the flood plain during a flood event on the River Murray, southeast Australia.

STUDY AREA

The River Murray (Fig. 1) is one of Australia's largest flood-plain river systems with a catchment area of 1.6×10^6 km^2 (Thoms & Sheldon, in press). Flows in the river are highly unpredictable and variable despite being regulated by a number of headwater dams and low-level weirs. The effects of water resource development on fluvial and other environmental processes have been reported elsewhere (e.g. Thoms & Walker, 1990; Walker & Thoms, 1993). Extensive flood-plain surfaces (up to 30–40 km wide) occur along the lowland reaches of the Murray. Active river channel adjustments since the Pleistocene (Schumm, 1968) and sporadic inundation patterns have produced a complex mosaic of physical habitat templets (see Townsend & Hildrew, 1994) that are biologically highly productive (Hillman, 1986). A typical section of flood plain along the lowland Murray consists of an array of billabongs (waterholes) of different sizes, cut-off and anabranch channels, levees and an assortment of undifferentiated surfaces at various elevations above the river channel.

During 1996 there was a drawdown of water levels in Hume Dam, the main regulating structure on the River Murray, resulting in extensive flood-plain inundation downstream. Local water authorities were forced to do this because of instability in the dam wall. Discharges peaked at approximately 120 000 MLd for 200 days immediately downstream. This "controlled flood event" provided an opportunity to monitor the exchange of water, sediments and nutrients between the
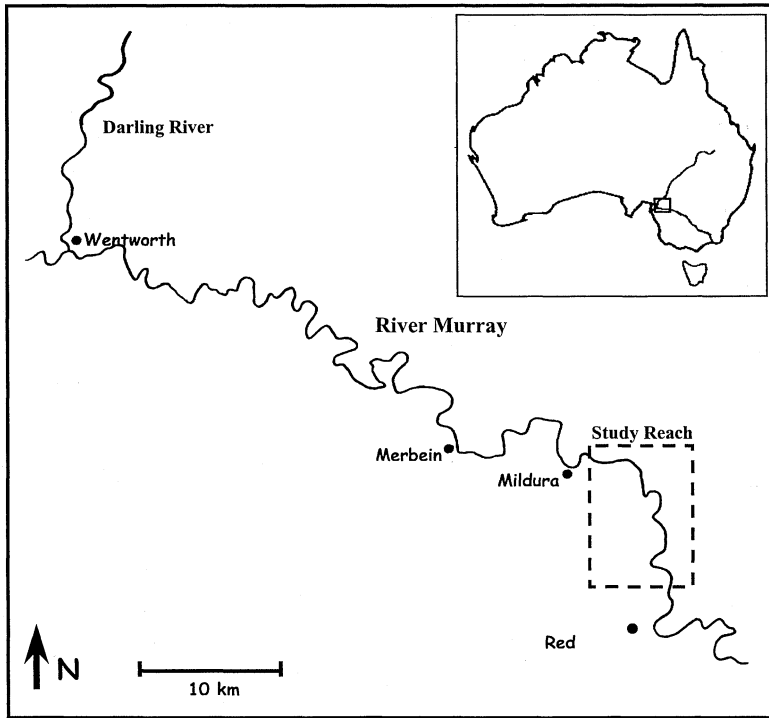
Fig. 1 The River Murray, southeast Australia, and the location of the study reach.

river channel and its flood plain at a site along a 15 km reach of the River Murray near the township of Mildura (Fig. 1). The site is part of a larger research programme investigating flood-plain processes. Local water authorities monitor discharge and suspended sediment concentrations on a daily basis both upstream and downstream of the study reach.

The lower Murray is characterized by a series of constrained and unconstrained flood-plain river zones (Thoms & Sheldon, in press). In constrained zones, flood-plain widths are typically 2–5 km; in the unconstrained zones they exceed 30 km. At this site, the river and flood plain are constrained within a relatively narrow "palaeo flood-plain river channel trough" 2–3 km wide. Overbank flows in this study reach are 20 000–26 000 MLd and the flood event peaked at 80 000 MLd immediately upstream, inundating most of the flood plain. The period of inundation varied between individual sections of the study reach. There are four main flood-plain surfaces in the reach (Table 1), each at a different elevation above the river bed; hence the inundation period ranged from 157 days for the flood-plain surface adjacent to the river (surface A) to 114 days for distal surfaces (surface D).

METHODS

Depth-integrated suspended sediment concentrations were monitored on a daily basis throughout the flood event at two sites, one upstream (Redcliffs) and one downstream

Table 1 Flood-plain character in study reach.

| | Flood-plain surface: | | | |
	A	B	C	D
Elevation above bankfull channel (m)	0–2	3–3.5	3.5–4.0	4.5
Distance from channel (m)	0–500	500–1000	1000–1500	>1500
Area (km²)	6.74	12.21	6.5	3.05
Dominant vegetation cover	Open shrub and red gum	Lignum	Native grass and shrubs	Native grass
Inundation period (days)	157	143	123	114

(Merbein) of the study reach, these sites being major gauging stations for the local water authority. Daily suspended sediment loads were calculated for each location during the period of overbank flows. Sediment deposition was measured as the amount of material accumulated on 1 m² artificial grass mats placed on the various flood-plain surfaces. These traps are similar to those employed by Lambert & Walling (1987) in a study of flood-plain sedimentation in the River Culm, UK. At 10 locations on each flood-plain surface three mats were randomly placed prior to the flood event and collected after flood waters had receded.

Sediments that had accumulated on the mats were air dried and then subjected to standard textural and chemical analyses. Initially a 5 g subsample was ultrasonically dispersed in a 5% sodium hexametaphosphate solution before being sized by a Malvern Autosizer, with a 63 mm lens. Results were expressed in phi (ϕ) units, where $\phi = -\log_2$ (mm). Each sediment sample was analysed three times to check instrument precision and to calibrate the instrument. US National Bureau Standards of known sphere size were run after every 25 samples. Concentrations of total organic carbon (TOC) were determined on 30 mg subsamples using a O-I-Analytical–Total Organic Carbon Analyser, and total nitrogen and total phosphorus concentrations were determined by Flow Injection Analysis after Kjeldahl digestion and dilution.

RESULTS

During the period of flood-plain inundation *c.* 81 944 t of sediment were deposited in the study reach, representing a 13% conveyance loss of the sediment input. This flood event experienced a minor peak approximately 65 days before the main flood peak on 19 November 1996. On these two occasions the sediment wave lagged the flood peak by 5 days and 16 days, respectively (Fig. 2).

Flood-plain deposition rates ranged from an average 0.001 kg m⁻² (±0.0003) on surface D to 1.94 kg m⁻² (±0.4) on surface A (Table 2). This amounted to 23 202.5 t of sediment being deposited on the entire flood-plain surface contributing 28% of the conveyance loss experienced within the study reach, or 3.8% of the total sediment input. Most of this sediment (56%) was deposited on flood-plain surfaces adjacent to the river (surface A). In general, the accumulation of sediment decreased significantly with distance from the river channel, but there was no discernible change in deposition along the study reach on any particular flood-plain surface (Analysis of variance, Anova: $p > 0.01$).
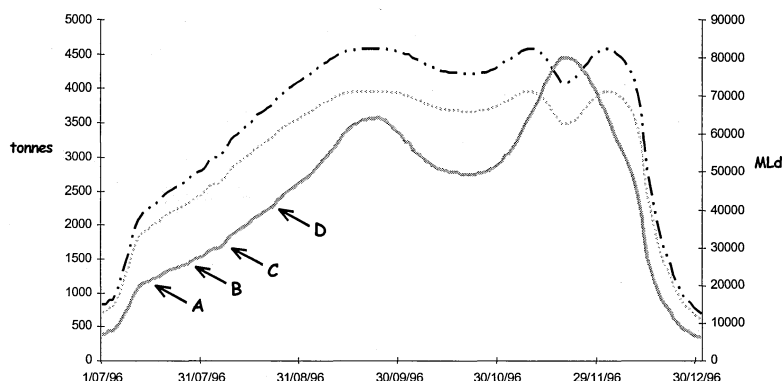
Fig. 2 Discharge and suspended sediment concentrations during a controlled flood event in the lower River Murray. Discharge (solid line) measured immediately upstream of the study reach; suspended sediment concentrations (dot and dashes) upstream and (dotted line) downstream of the study reach (Redcliffs). Arrows indicate the discharge at which each of flood-plain surfaces A–D was inundated.

Table 2 Mean sediment deposition on the flood plain along the study reach (standard deviations are in italics).

| | Flood-plain surface: | | | |
	A	B	C	D
Deposition rate (kg m^{-1})	1.94	0.76	0.18	0.001
	0.4	*0.12*	*0.07*	*0.03*
Total sediment deposited (t)	13 000	9 000	1 200	2.5

Sediments deposited onto the various flood-plain surfaces can be classified as silty loams (Brady, 1974). However, the relative contributions of sand (mean: 23.36%), silt (mean: 73.42%) and clay (mean: 3.21%) varied significantly (Anova: $p < 0.01$) between the different flood-plain surfaces. On average, the percent weight of sand was greater for surface B (34.7%), compared to the other surfaces (A: 20.77%; C: 13.92%; D: 75.83%). It was notable that there was a lack of clay-sized material on distal flood-plain surfaces whereas percent weights ranged from 2.96 to 5.81% for the other surfaces.

Associated nutrient concentrations also varied between the four flood-plain surfaces (Fig. 3). Consistently higher concentrations of nutrients were found on distal flood-plain surfaces. There was a ten-fold difference in the concentrations of TOC between flood-plain surface A (immediately adjacent to the river channel) and surface D (furthest from the channel), i.e. an average 32.2 mg g^{-1} (±7.4) for surface A compared to 354.0 mg g^{-1} (±120.3) for surface D. Concentrations of both total nitrogen (TN) and total phosphorus (TP) followed a trend similar to that of TOC (Fig. 3).

DISCUSSION

The retention capacity of the lower River Murray flood plain during this flood event was low in comparison to that recorded in other studies (Table 3). This is surprising.
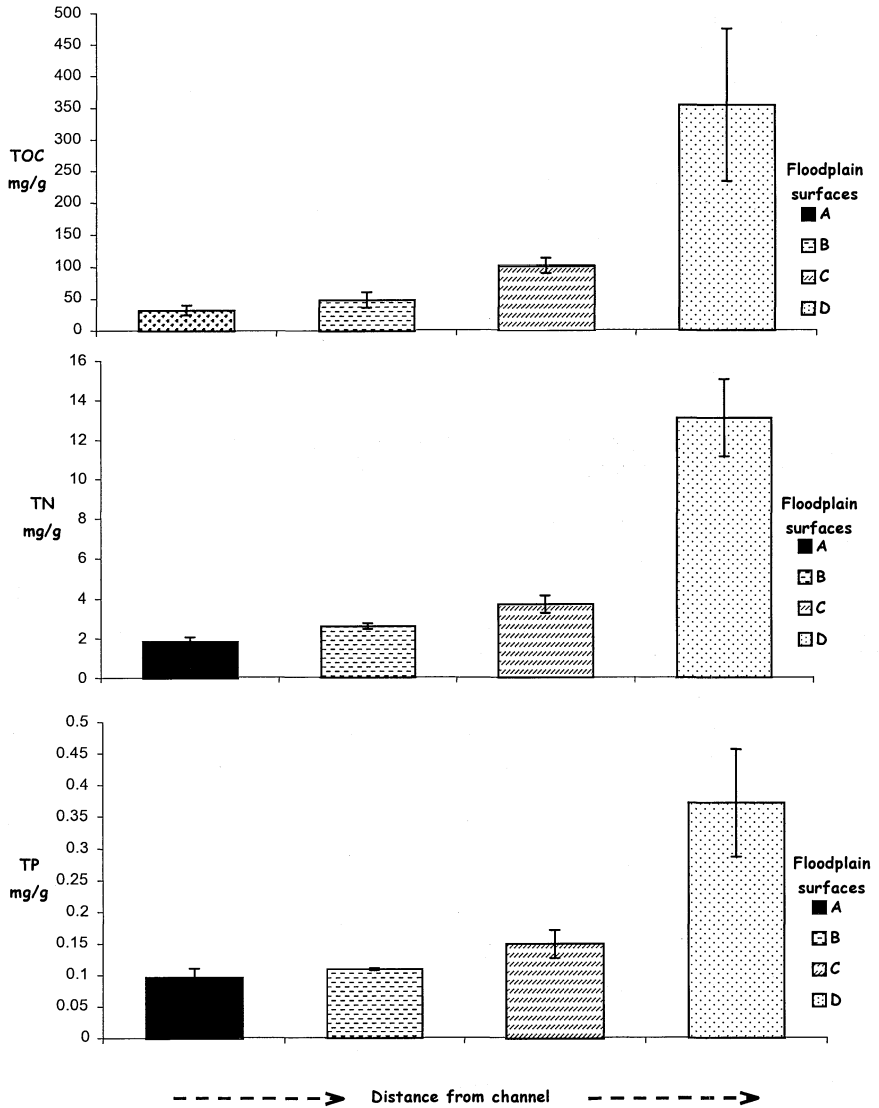
Fig. 3 Concentrations of total organic carbon (TOC), total nitrogen (TN) and total phosphorus (TP) in flood-plain deposited sediments.

Thoms (1995) recorded flood-plain sedimentation rates of 2.18 cm year^{-1}—equivalent to 39% of the long-term annual sediment load of the River Murray—in the Barmah Forest, approximately 450 km upstream of this site. Indeed, Thoms & Walker (1990) have demonstrated that sediment loads in the River Murray have increased by 200% as a result of catchment disturbance over the last 30–40 years. Further analysis of these data by Thoms (1995) also suggests that the potential supply of sediment to flood-plain areas in the Murray has increased by over 130% because of changes in the timing of inundation, an artefact of flow regulation.

Table 3 Flood-plain sediment conveyance losses.

River	Conveyance loss (%)	Source
Adour (France)	10–20	Brunet *et al.*, 1994
Amazon (Brazil)	Up to 50	Guyot *et al.*, 1994
White Clay (USA)	24	Johnston *et al.*, 1984
River Murray (southeast Australia)	22	Russell & Judd, 1959
Culm (UK)	28	Lambert & Walling, 1987
Rhine–Meuse (The Netherlands)	19	Middelkoop & Asselman, 1998
River Murray (mid reaches Australia)	39	Thoms, 1995
Hawkesbury (Australia)	9–27	Thoms *et al.*, 2000
? (USA)	10–20	Wolman & Leopold, 1957
Lower River Murray (Australia)	3.76	This study

Variable supply and energy conditions during high flow events will influence the accumulation of sediment in flood-plain areas. Hydraulic conditions, especially shear stress or unit stream power, vary across flood plains during overbank flows, and marked variations can also occur along the river, between different reaches. Miller (1995) and Thoms *et al.* (2000) have demonstrated that floods in narrow river-valley sections are more likely to experience higher maximum shear stresses on flood-plain surfaces than floods of comparable magnitude in broader river-valley sections. Data presented by Thoms *et al.* (1998) highlight marked hysteresis loops in stage–velocity relationships for overbank flows along the River Murray. Drainage of overbank flows from wide flood-plain river zones, and associated backwater effects, reduce the recession limb velocities resulting in a clockwise hysteresis of the stage–velocity relationship. In contrast, an anti-clockwise loop that occurs in the narrow flood-plain river zones where velocities are higher on the falling limb of the hydrograph results in 35–45% increases in unit stream power, limiting the deposition of finer sediments. These larger-scale differences along the river highlight the importance of geo-morphological controls on the accumulation and dispersal of flood-plain sediments.

The distribution of the deposited material was spatially variable across the flood plain with greater quantities being deposited on those surfaces within close proximity to the river channel. Other studies have also reported this (e.g. Asselman & Middelkoop, 1995; Walling *et al.*, 1996, 1997; Middelkoop & Asselman, 1998; Simm & Walling, 1998). Flood-plain topography, surface roughness, often related to vegetation, and the magnitude/frequency of the flood event are thought to have an important influence on flood-plain sedimentation processes.

Lateral variations in hydraulic conditions have also been reported to influence the texture of deposited material (Marriott, 1992; He & Walling, 1998). Although most of the sediments deposited in this study were characteristic of graded suspension (cf. Passega, 1977), there were notable differences in texture between the four surfaces. In particular, flood-plain surface B had coarser sediments with a greater sand content. This is contrary to the findings of Marriott (1992), Walling *et al.* (1997) and He & Walling (1998), who demonstrated a progressive decrease in the sand content and an increase in the clay content across flood plains. This varying texture is interesting given the influence of particle type on the transport of nutrients and carbon.

Large quantities (1002.3 t) of nutrients were deposited on the study flood plain during this flood; the equivalent of 950 t of TOC, 50 t of nitrogen and 2.3 t of phosphorus. Most of this (45.7%) was deposited on flood-plain surface B, i.e. not adjacent to the river channel, and on average 94.7% of this was carbon, 5.1% was nitrogen and the remainder phosphorus. Indeed, this study highlights the importance of floods as a cost-effective and natural fertilizing mechanism for flood-plain environments. Concentrations of carbon, nitrogen and phosphorus in the deposited sediment tended to increase across the flood plain in this study, but displayed no direct relationship to sediment texture. This is contrary to the findings of Asselman & Middelkoop (1995), who demonstrated an association between the distribution of some nutrients and sediment texture. In their study, increases in carbon and nitrogen concentrations were highly correlated with sediments that were dominated by clay-sized material; this explained the highly variable distribution of nutrients across the Meuse flood plain. Furthermore, it is well known that phosphorus is strongly associated with clay particles (Schwarz *et al.*, 1996) and this has been used to explain the spatial distribution of phosphorus deposition on flood-plain surfaces (Pinay & DeCamps, 1988). However, Brunet *et al.* (1997) and Walling *et al.* (1997) suggest concentrations of carbon and nitrogen are inversely proportional to rates of sedimentation. In both studies, low concentrations of nutrients were recorded in flood-plain areas adjacent to the river channels.

Phosphorus and nitrogen are also highly correlated with organic matter (Pinay *et al.*, 1995; Schwarz *et al.*, 1996; Walling *et al.*, 1997). Therefore the deposition of organic matter will influence the observed pattern in phosphorus and nitrogen concentrations across flood-plain surfaces. In this study, higher concentrations of TOC were found on the distal flood-plain surfaces. We suggest that this may be evidence of a "bath-tub ring effect". During overbank flows, debris consisting mainly of organic matter is deposited on the fringes of the flood plain when floodwaters recede. Therefore, the supply of this material will be an important factor influencing the spatial distribution of associated nutrients deposited onto flood-plain surfaces. Alternatively, Thorp & Delong (1994) stress the importance of fringing vegetation (local sources) as an input of organic matter and therefore as a control on other nutrients.

How larger flood-plain rivers function as ecosystems is poorly known and there is considerable debate about the source of nutrients. It has been argued (Walker *et al.*, 1995; Robertson *et al.*, 1999; Thoms & Sheldon, in press) that current ecosystem models for large flood-plain rivers, namely the River Continuum Concept (Vannote *et al.*, 1980), the Flood Pulse Concept (Junk *et al.*, 1989), and the Riverine Productivity Model (Thorp & Delong, 1994), are not adequate for dryland river flood-plain systems such as the River Murray. Flow and its interaction with flood-plain geomorphology may influence the flux of carbon and other nutrients between a river channel and its flood plain in these environments.

Dryland flood-plains are important ecotones that regulate interactions in lotic systems. Active management and restoration of these systems is a priority in many areas and has been the focus of recent research (e.g. Naiman & Decamps, 1990). However, management of these systems has tended to be concentrated in two main areas: the provision of flows of appropriate magnitude, frequency and duration to

sustain wetlands, and works to maintain the diversity of these systems. Inputs of sediment and associated nutrients are also important, but have received limited attention. Effective ecotone management requires an integrated approach in which land and water issues and sediment aspects are all considered. This requires a better understanding of the fate of sediment and associated nutrients and the influences controlling them.

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