The Structure, Function and Management Implications of Fluvial Sedimentary Systems (Proceedings of an international symposium held at Alice Springs, Australia, September 2002). IAHS Publ. no. 276, 2002.

Connectivity and fragmentation of flood plain–river exchanges in a semiarid, anabranching river system

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Abstract The ecological integrity of flood plain–river systems is dependent upon hydrological connections between the main river channel and adjacent flood plain. These connections facilitate the exchange of carbon and nutrients and influence productivity. This paper considers carbon dynamics during phases of connection and disconnection in a large lowland river in southeast Australia. Data are presented on carbon stores in a number of anabranch channels during the disconnection phase, and the potential availability of dissolved organic carbon from these channels during the connection phase. Anabranch channels are an important physical patch type in this flood plain–river system, containing significant quantities of various carbon sources. During flooding these channels are potentially important sources of dissolved organic carbon for the main river channel. However, water resource development has reduced this potential supply of carbon by reducing hydrological connectivity between the anabranches and the main river channel. These changes have implications for the transfer of energy through the food web and hence also for the functioning of the ecosystem as a whole.

Key words connectivity; fragmentation; flood plain; anabranch channels; carbon; water resource development; Macintyre River

INTRODUCTION

Flood plain–river ecosystems are dynamic spatial mosaics in which water plays an important role in connecting landscape patches. The temporal character of flooding or hydrological connectivity influences the exchange of materials between the main river channel and flood plain patches (Spink *et al*., 1998). During inundation, dissolved organic carbon and nutrients are released from flood plain sediments and plant matter and may be transported into the river channel. Carbon is an important food source for riverine organisms, and forms the base of the food web in flood plain river ecosystems (Robertson *et al*., 1998). Hence its exchange between river and flood plain patches is important for the productivity of these systems.

Fragmentation is the reduction or elimination of connections between patches in a landscape (Kotliar & Wiens, 1990). Hydrological fragmentation in flood plain rivers is facilitated by the "flood pulse" (*sensu* Junk *et al*., 1989), creating heterogeneous patterns of wetting and drying on adjacent flood plain surfaces. Changes to wetting and drying regimes can interfere with the release, availability and exchange of carbon between river channels and the flood plain (Baldwin & Mitchell, 2000).

Anabranch channels are a common feature of Australian lowland rivers and are important patches in flood plain–river landscapes (Thoms & Sheldon, 2000a). They become connected to the main river channel during flood pulses, and gradually dry out and disconnect during flood recession and low flow periods. During periods of disconnection, anabranch channels accumulate leaf litter and other organic matter and may hold ephemeral billabongs (water holes) containing other potential carbon sources. Both particulate and dissolved forms of carbon may enter the main channel from anabranches during connection phases. This paper presents data on carbon pools present in anabranch channels of the Macintyre River, Australia, during the disconnection phase, and then examines the implications of changing hydrological connectivity for the potential availability of carbon from anabranch channels for the main river channel ecosystem.

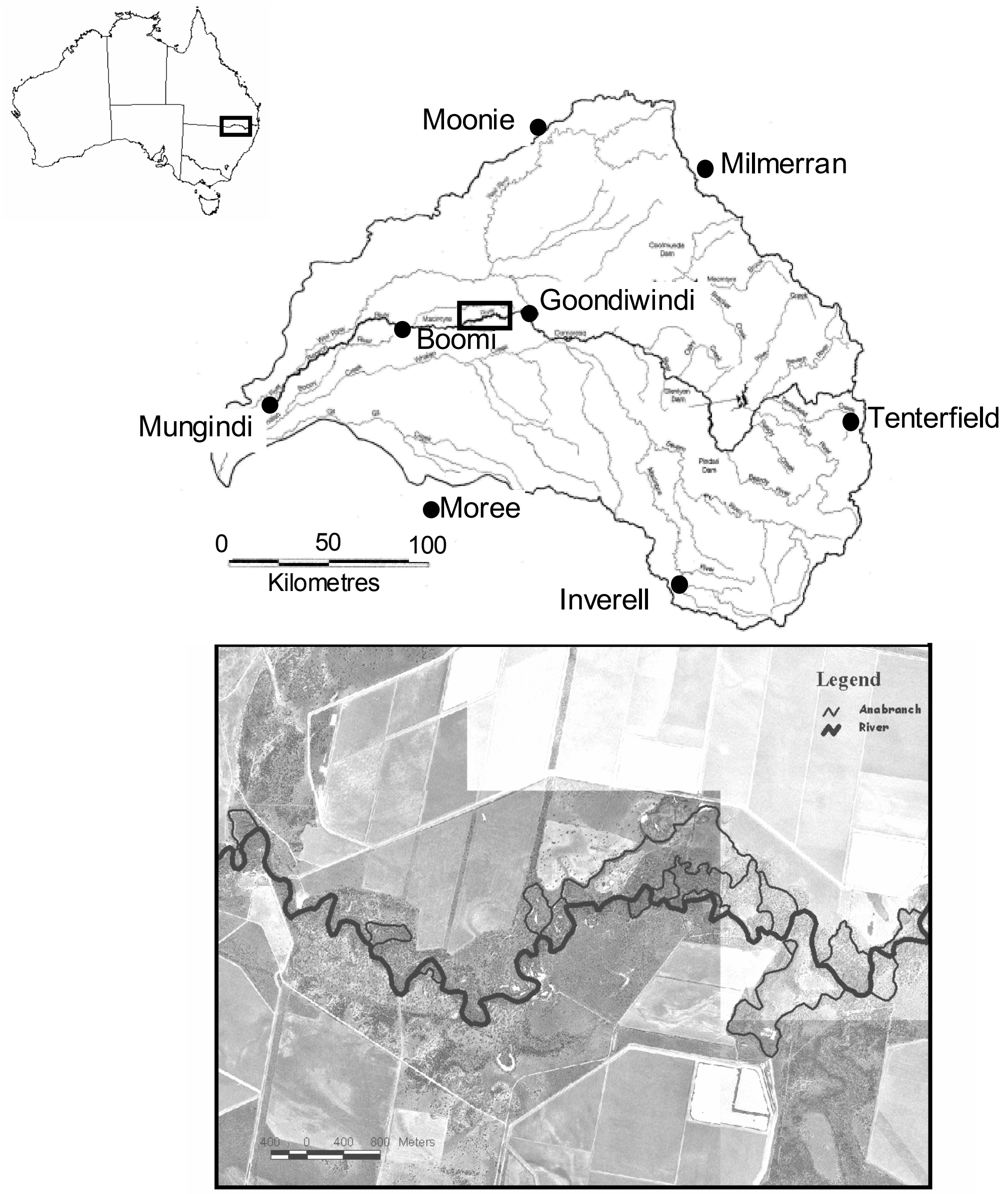

Fig. 1 The Macintyre River and its catchment, at the border of Queensland and New South Wales, Australia.

STUDY AREA

The Macintyre River is one of the principal streams in the Border Rivers catchment (48 000 km^2), forming the border of New South Wales and Queensland, Australia (Fig. 1). It is typical of the many lowland river systems in the Murray Darling basin, having a predominantly semiarid climate and variable flows. Annual discharges at Goondiwindi ranged from 61 000 to 4 488 000 Ml day^{-1} for the period 1900–1990. Three large headwater dams regulate flows in the Macintyre, and the flood plain is subject to extensive irrigated agriculture. Similar water resource development has reduced the magnitude and frequency of a range of discharges in the rivers of the Murray Darling basin (Thoms & Sheldon, 2000b).

This study focuses on a 15.8 km reach of the lower Macintyre River between Goondiwindi and Boomi (Fig. 1). Downstream of Goondiwindi, the Macintyre is a low gradient, highly sinuous "wash load" channel, with cohesive boundary sediments and an extensive flood plain (up to 20 km wide). The flood plain is heavily dissected by anabranch channels of various sizes. These ephemeral channels are disconnected from the main channel for most of the year (though many retain pools of water for several months) and commence to flow at various discharges.

METHODS

All channels in the study reach were mapped from aerial photographs and surveyed in the field for calculation of length, width and surface area. The commence to flow (CTF) discharge for individual anabranch channels was determined by surveying the main channel at the entry and exit points of each anabranch channel and calculating the corresponding discharge of the various sill heights via the Manning equation. To ensure that these discharges represented complete flow connection through each anabranch, an extra metre was added to each sill height and the discharges recalculated (Thoms *et al.*, 1996). Periods of connection and disconnection for the individual anabranch channels were determined from "SPELL" analysis (Gordon *et al.*, 1992) of simulated daily discharge data obtained from the New South Wales Department of Land and Water Conservation (NSW DLWC) Integrated Quantity Quality Model (IQQM; Black *et al.*, 1997). Simulated "natural" flows were compared with simulated "current" flows for the period 1900–1998 for the Goondiwindi gauging station. The "natural" flow is simulated with a zero setting for flow regulating structures, abstractions of water and catchment development, utilizing long-term climatic conditions. The "current" simulated flow used water and catchment development conditions present in 1997–1998 combined with long-term climatic conditions. The rapid rate of water resource development in the catchment and the natural variability of flows precluded the use of historical data.

Three anabranches, which were representative of those found in the study reach in terms of geomorphic character, were studied in detail during December 2000 and July 2001. Within each anabranch, transects were established at the entry, mid and exit points and at each transect three 0.5 m × 0.5 m quadrants were randomly located. The dry biomass of surface leaf litter and the total carbon content of surface sediment samples were measured via standard methods (APHA, 1998). Two replicate water column samples were taken from the top 0.3 m of the littoral zone in each anabranch billabong and from the main river channel downstream of the entry and exit point of each anabranch. Water samples were analysed for dissolved organic carbon (DOC) and phytoplankton (chlorophyll *a*; APHA, 1998). All samples were collected during the dry or disconnection phase, while anabranches and their billabongs were hydrologically isolated from the main river channel.

RESULTS

Fourteen anabranch channels were identified in the study reach, with a combined length of 20.5 km or 56% of the total channel length within the reach. Individual anabranch channels range in length from 0.4 to 3.9 km, corresponding to surface areas between 1 and 10 ha (Table 1). Individual anabranch channels are therefore smaller in size than the main river channel, which has a surface area of 61 ha within the reach, but combined they are an important patch type (surface area 51 ha).

The CTF discharges of the anabranch channels were calculated to range from 1195 to 47 367 Ml day^{-1}, and four groups of anabranches were recognized on the basis of these discharges (Table 1). Using the simulated natural daily flow data anabranch channels in the study area were calculated to have experienced between 107 and 468 wetting events for the period 1900–1998 (Table 2), depending upon the CTF discharge for each anabranch. Lower discharge anabranch channels (Group 1) experienced the greatest number of wetting events (*n* = 468), with a median duration of 6 days under

Table 1 Commence to flow discharge groupings and physical character of anabranch channels in the study area.

Anabranch group	CTF (Ml day^{-1})	Channel length (km)	Surface area (ha)
1	0–5000	10.18	25.28
2	5–10 000	6.76	16.78
3	10–20 000	0.83	2.05
4	20–50 000	2.73	6.78

Table 2 The wetting of anabranch groups under simulated natural (N) conditions and current (C) levels of water resource development and the percent difference (% Δ).

Group	Flow scenario	No. of events	Total days wet	Median days wet	Total days dry	Median days dry
1	N	468	3555	6	32 512	25
	C	407	2835	5	33 232	33
	% Δ	–13.3	–20.3	–16.7	2.3	29.4
2	N	322	1831	4	34 236	46
	C	287	1460	4	34 607	45
	% Δ	–10.9	–20.3	0.0	1.1	–2.2
3	N	192	850	4	35 217	72
	C	161	692	3	35 375	95
	% Δ	–16.1	–18.6	–25.0	0.4	31.0
4	N	81	249	3	35 818	193
	C	64	201	3	3866	226
	% Δ	–21.0	–19.3	0.0	0.1	17.1

natural flows. By comparison, higher discharge channels (Group 4), experienced 81 wetting events with a median duration of 3 days. The character of hydrological connectivity changed with water resource development. All anabranches experienced a reduction in the frequency and duration of wetting with water resource development but this differed between anabranch groups (Table 2). There was a 21% reduction in the number of times Group 4 anabranches experienced wetting compared to a 13% reduction for Group 1 anabranches.

Surface leaf litter was abundant in the three anabranch channels sampled (mean 687 g m^{-2}). Litter composition was highly variable, but overall the majority of the dry weight was attributable to "bark" (material other than leaves). Dry weights were spatially heterogeneous both within and between transects and anabranches (Table 3). Total mass is generally lower at the entry points and higher at the exits, and separation of the "leaves" and "bark" components clarifies this distinct pattern. The pattern of total carbon (TC) content in the surface sediments reflected that of ground surface litter, with lower levels near the entry of the anabranch channels increasing toward the exit point (Table 3).

Mean concentrations of dissolved organic carbon in the anabranch billabongs were approximately double those found in adjacent segments of the main river channel during all sampling periods (Table 4). For example, average DOC concentrations in anabranch billabongs during December 2000 were 9.58 ppm compared to 5.75 ppm in the main channel. Chlorophyll *a* analysis of water samples taken during July 2001 also revealed large populations of phytoplankton in the anabranch billabongs in comparison to the main channel (Table 4).

Table 3 Summary statistics for total mass of surface litter and total carbon (TC) content of the surface sediment within anabranch channels, December 2000.

	Anabranch channels:				Mean by transect:		
	Min	Max	Mean	SD	Entry	Mid	Exit
Total litter (g m^{-2})	25.3	3214.7	686.7	849.4	136.7	478.7	1444.6
"Bark" (g m^{-2})	5.67	2921.1	586.47	768.2	94.8	407.1	1244.4
"Leaves" (g m^{-2})	3.24	326.5	100.2	95.2	32.5	71.6	200.2
Sediment TC (%)	0.61	6.64	3.26	1.55	1.85	3.92	4.00

Table 4 Summary statistics for dissolved organic carbon (ppm) and chlorophyll *a* (mg m^{-3}, corrected for pheophytins) in anabranch billabongs and the main channel of the Macintyre River.

		Anabranch billabongs:				River channel:			
		Min	Max	Mean	SD	Min	Max	Mean	SD
DOC (ppm)	Dec.	7.12	14.91	9.58	2.37	4.91	8.62	5.75	0.81
	July	10.41	21.02	15.90	3.80	7.39	8.01	7.69	0.26
Chl *a* (mg m^{-3})	July	8.34	169.81	59.37	54.95	4.27	7.48	5.87	1.99

DISCUSSION

There are four defined phases of hydrological connectivity between the main channel and anabranch system during a flood pulse. These are the dry phase or period of disconnection between intervening flow events; the partial connection phase when flood waters begin to enter anabranch channels and wet the surface; complete flow of water through the channel; and the draining phase during the recession of the flow pulse. Carbon dynamics are likely to differ during each phase, and changes to the character of each in terms of its frequency and duration may result in changes in ecological functioning of the river system as a whole.

The disconnection phase dominates the Macintyre River ecosystem in terms of total time. Accumulation and concentration of carbon sources such as litter and detritus, algae, and dissolved organic carbon (DOC) occur within each anabranch during this phase. Stores of carbon present vary spatially regarding both quantity and quality. In terms of quantity, a general lack of carbon is evident near the entry points of anabranches in terms of both surface leaf litter and sediment (Table 3). The distribution of leaf litter in these channels is inherently controlled by vegetation distribution and type, but also appears to be heavily influenced by flow dynamics. This is reflected in the distribution pattern found in this study, and the fact that large woody debris dams and leaf packs appear to increase in frequency and size with distance down anabranches in the study area, being absent at entry points and accumulating at exit points. The character of an individual flow pulse is important in determining:

(a) whether litter is moved or buried within anabranches;
(b) the type and size of litter moved;
(c) the distance litter is moved; and
(d) where litter is deposited.

Flow dynamics are also of fundamental importance in determining patterns in sediment carbon content, which may be attributed to several related factors, including the biomass of the overlying litter, flushing and deposition of leaf litter and other organic matter during high flows, and sediment grain-size patterns within the anabranches. Flow pulses through anabranches deposit coarse sandy sediment at the entry point, and progressively finer silts and clays toward the exit, which have much higher affinity for carbon due to their greater surface area.

In terms of quality, the most labile sources of carbon (immediately available to the riverine food web) in the anabranches include the DOC and phytoplankton found within ephemeral billabongs. Comparison of the different “patches” or channels in the lower Macintyre system reveals that these sources of labile carbon are highly concentrated within anabranch billabongs when compared to the main river channel (Table 4). Thus anabranch billabongs are potentially important patch types in terms of providing “immediately available” food energy to the main river ecosystem during connection phases. Surface leaf litter is a more refractory, relatively longer-term source of carbon, particularly considering the dominance of “bark” material—it takes longer to break down, and can be buried and stored in sediments for significant lengths of time. Quantity and quality of leaf litter within anabranches would depend upon season and flood frequency. The natural flood season in the Macintyre system coincides with that for leaf-fall of the dominant Eucalyptus species. Freshly dropped litter is of much higher quality for consumption by riverine organisms than desiccated, degraded leaves. Thus frequent connection events may result in smaller quantities being transported to the river channel, however these quantities are likely to be of higher quality, and *vice versa*.

The availability of the various carbon sources within anabranch channels is dependent upon the character of hydrological connection. This character has changed in the lower Macintyre system because of water resource development. For example, water resource development has resulted in the increased duration of the disconnection phase in this system (Table 2). Hence, anabranch billabongs are more likely to dry out before re-connection occurs with the main river channel. Consequently, the relatively more labile food energy materials held and produced by billabongs will not be immediately available when connection takes place, perhaps forcing organisms of the main river channel ecosystem to rely on locally produced and/or more refractory sources.

Wetting of sediments and leaf litter in anabranch channels also releases quantities of DOC that can be readily assimilated into aquatic food webs (Baldwin & Mitchell, 2000). The high total carbon content of surface sediments, and the large loads of litter present in anabranches of the Macintyre system indicate that release of dissolved organic carbon may be an important carbon source during connection phases. McGinness & Thoms (in press) found that for surface sediments of the lower Balonne flood plain, Australia, the average DOC release upon wetting (in the laboratory) was equivalent to 2.28 kg (0.002 t) per hectare per day. Applying these results to the hydrological and geomorphological data generated in this study, the potential availability of dissolved organic carbon from the surface sediments of the various anabranch channels of the Macintyre River can be calculated for each of the natural and current flow scenarios. Approximately 283 t of DOC would have been made available from anabranch channels under "natural" conditions compared to 225 t under "current" conditions, for the period 1900–1998. Hydrological changes appeared to have a relatively greater impact on the Group 1 and 2 anabranches where there was an approximately 20% reduction in potential dissolved organic carbon supply (Table 5). These estimates reveal the potential impact of water resource development upon hydrological connections and the exchanges that they facilitate between patches in this flood plain–river landscape.

Table 5 The impact of hydrological change on potential DOC availability from anabranches in the study reach.

Anabranch group	Potential DOC release (t): Natural	Current	% Reduction
1	205	164	20
2	70	56	20
3	4	3	19
4	4	3	19

In this reach of the Macintyre River, anabranch channels are important patches in the landscape in that they contain large pools of carbon that are potentially available to the main river channel ecosystem during connection phases. There are complex spatial and temporal factors determining actual availability of anabranch carbon for the river when connection occurs. Changes in the character of hydrological connection may result in changes to the relative quantities of particular types of food energy available over time, with subsequent implications for the transfer of energy through the food web and hence also for the functioning of the ecosystem as a whole.

Acknowledgements This project is supported by funding from Land and Water Australia, the Australian Research Council, the Co-operative Research Centre for Freshwater Ecology, and the W. J. Weedon family.

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