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Flood plain nutrient dynamics: patterns, controls and the influence of changing hydrology

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Abstract Dissolved nutrients are mobilised from flood plain surfaces during periods of inundation. These dissolved materials are an essential resource for the functioning of flood plain–river ecosystems. However, little is known of the dynamics of nutrient release during periods of flood plain inundation or the factors controlling their release. Patterns of total organic carbon (TOC), total nitrogen (TN) and total phosphorus (TP) released from flood plain sediments were investigated in this study. In a series of experiments conducted over a 72-h period, sediments collected from various flood plain surfaces were wetted in order to assess possible controls, spatial patterns, and the influence of changing hydrology on the release of dissolved nutrients. Top-down constraints, including the reach location, degree of confinement and elevation above the river bed, all had a significant impact on release rates for TOC, as well as release rates and concentrations of TN. Sediment texture was significantly associated with TP concentrations only; although sediment texture was associated with TN and TOC release rates over time. These results indicate that larger scale constraints, such as position in the broader riverine landscape, influence spatial patterns of nutrient release rates over time more than smaller scale influences such as sediment texture. Using the release data for the various flood plain surfaces, combined with long-term flow data for several flow scenarios, simple budgets for dissolved nutrients were calculated for the study reach over the 1922–2000 period. A 43% reduction in the potential supply of dissolved nutrients was demonstrated with changes in river hydrology over this 78-year period associated with water resource developments.

Key words flood plain–river exchanges; complex systems; water resource development

INTRODUCTION

Knowledge of physical, chemical and biological processes is required at multiple scales for the conservation and management of flood plain–river ecosystems (Thoms, 2003). This is because patterns and processes within flood plain–river landscapes result from a combination of top-down constraints and bottom-up influences. Inundation of flood plains is important for the functioning and integrity of flood plain–river ecosystems because it facilitates exchanges of water, sediments, nutrients and biota between river channels and flood plains (Thoms, 2003). Whilst the importance of hydrological connections between rivers and flood plains has been acknowledged by many (Tockner *et al*., 2000; Amoros & Bornette, 2002; Thorp *et al.*, 2008) the majority of research has been conducted at single scales. At smaller scales for example, mechanisms controlling the release of dissolved nutrients from flood plain soils have been reported (cf. Baldwin & Mitchell, 2000) whilst at larger scales the implications of water developments on exchanges of dissolved material over tens of years have been reported (cf. Thoms, 2003). There is a strong trend to manage flood plain–rivers as ecosystems and this has been accompanied by a focus on the management of landscapes. Natural resource management agencies are incorporating larger-scale ideas such as ecosystem management, landscape heterogeneity, gap analysis and metapopulation conservation (Bissonette & Storch, 2003) and putting these concepts into practice.

Nutrients associated with the sediment stored within flood plains play an important role in regulating the productivity of both flood plains (Spink *et al.*, 1998) and the main river channel (Junk *et al.,* 1989). The distribution of nutrients on flood plain surfaces has been shown to be highly dependant on the character of surface sediments, with elevated concentrations of organic nitrogen, carbon and phosphorus being associated with fine textured sediments (Asselman & Middelkoop, 1995). Thus, the primary influence on their spatial distribution has been attributed to the textural character of the flood plain sediments (but see Thoms *et al.,* 2000, for an exception). However, larger scale factors such as landscape position, topography and flood plain vegetation have also been shown to influence the distribution of flood plain nutrients (Pinay *et al.*, 1995; Spink *et al.*, 1998). But there is a lack of studies that have considered these together.

Rivers around the world are under increasing pressure from human activities (Austin *et al.,* 2004). In Australia, large-scale water resource developments have occurred in most rivers in the Murray-Darling Basin since the 1960s (Thoms *et al*., 2004). In the Darling sub-catchment, for example, there are 12 large headwater dams, in excess of 5000 small weirs, and more than 300 water licenses. During 1997/98, 2074 GL were diverted from the Darling catchment; by comparison, the long-term annual mean flow is 2370 GL in the lower reaches of the Darling River at Wilcannia (Thoms & Sheldon, 2002). Large-scale developments have also occurred on the flood plains of many of these rivers with the construction of levees and water storages for the irrigation industry. In the Lower Balonne, for example, 179 750 hectares of flood plain, or approx. 10% of reactive flood plain surface, is isolated within levees. As a result, the magnitude, frequency and duration of hydrological connectivity between rivers and their flood plains has changed (Thoms, 2003). These changes have the potential to reduce the transfer of material from flood plain surfaces into river channels and impact on the productivity and integrity of the entire riverine ecosystem.

The aims of this study were to:

– Determine the patterns of dissolved nutrient release from the sediments on different flood plain surfaces.
– Investigate the influence of top-down geomorphic constraints (river valley, and flood plain elevation) and bottom-up influences of sediment texture on nutrient release.
– Calculate the impact water resource development has had on the potential exchange of dissolved nutrients between the flood plain and river channel over a 78 year period.

Study area and methods

The Barwon-Darling River drains 650 000 km^2 of the northwest portion of the Murray-Darling Basin in southeast Australia (Fig. 1). The catchment is characterised by extreme climatic variability and runoff with average annual rainfall and evaporation ranging from 200–1000 mm and 500–1800 mm, respectively (Thoms & Sheldon, 2000). The Barwon-Darling is a suspended load river with characteristic highly sinuous channels (sinuosities >2) and high bankfull width to depth ratios (>32). In its mid reaches, the river flows through a valley floor trough up to 40 km wide that contains extensive flood plain surfaces. It also has "complex" bankfull cross-sections (see

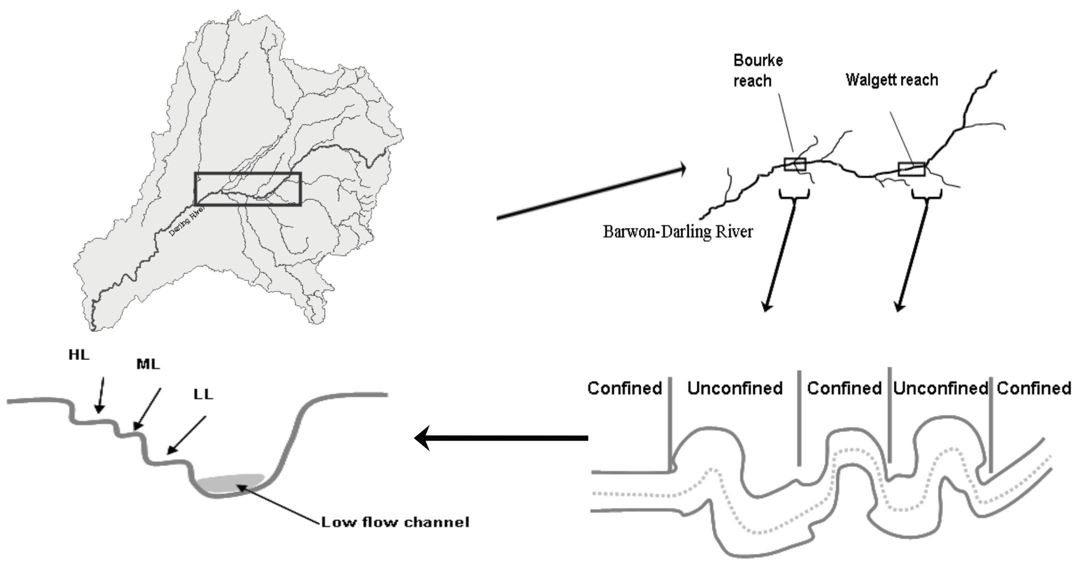

Fig. 1 Study location on the Barwon-Darling River in the Murray Darling Basin, Australia; with a breakdown to reach, channel and cross-sectional scale.

Woodyer, 1968; Thoms & Olley, 2004) because of the presence of inset flood plains or in-channel benches. These inset flood plains have been formed by the contemporary flow regime of the river (Thoms & Olley, 2004), and store large quantities of nutrients and organic material which become available to the river during inundation (Thoms & Sheldon, 1997). Recent research by Thoms & Sheldon (2006) has shown there to be at least seven different inset flood plain surfaces along the Barwon-Darling.

The study was conducted along two 15 km reaches of the river, one below the township of Walgett and the other above the township of Bourke (Fig 1). To assess the release of dissolved nutrients from various inset-flood plain surfaces, surface sediment from nine inset-flood plains along the Walgett reach and seven from the Bourke reach were collected. Two replicate surface samples were taken from each flood plain. The inset-flood plain surfaces were selected on the basis of their textural character and surface elevation (Southwell & Thoms, 2006) and included three elevation classes (low level, mid level and high level) and five sediment textural classes based on the full grain size distribution of surface sediments. Each flood plain textural class was determined using a multivariate procedure, as outlined in Southwell & Thoms (2006).

In the laboratory, 450 g of each sediment sample was air dried at room temperature then flooded with 1000 ml of distilled water. Approximately 100 ml of the overlying water were taken at 2, 6, 12, 24 and 72 hours from each flooded sample using syringes to minimise disturbance to the sediment. Each sample was replaced with 100 ml of distilled water. This release experiment was conducted under controlled temperature conditions (25°C) and in a darkened room in order to limit biological processes. Each sample of the collected water was analysed for Total organic carbon (TOC), Total nitrogen (TN) and Total Phosphorous (TP). TOC was analysed using a TOC1010 carbon analyser while TN and TP were oxidised using alkaline persulphate and recovered using microwave digestion, before being analysed using a Lachat flow injection analyser (Maher *et al.*, 2002). Experimental values were converted to an area release rate using the volume of supernatant. Linear mixed models using restricted maximum likelihood (REML) analysis were then performed to determine the influence of geomorphic constraints and sediment texture on TOC, TN and TP concentrations and their release over time.

To assess the influence of hydrological change on the potential amount of nutrients released from the various inset-flood plain surfaces, the number and surface area of all inset-flood plains along each reach was calculated and the commence to flow (point at which bench is inundated) of each flood plain surface was determined in the field (see Boys & Thoms, 2006). Periods of connection and disconnection for each flood plain surface were determined from a SPELL analysis (Gordon *et al*., 1992) of simulated daily discharge data obtained from the New South Wales Department of Environment and Conservation (NSW DECC) Integrated Quantity Quality Model (IQQM; Black *et al*., 1997). The rapid rate of water-resources development in the region, combined with the naturally variable flow, makes historical data inadequate for evaluating the impact of water-resources development on the hydrological regime of the Barwon Darling. The "natural" or "pre-development" flows were simulated from long-term mean climatic conditions, using a zero setting for flow regulating structures, abstractions of water and land-use development. The "current" flows were simulated using water and land-use conditions present in 2000 combined with long-term mean climatic conditions. Simulated "natural" flows were compared with simulated "current" flows for the period 1922–2000 for the Walgett and Bourke gauging stations.

To estimate the impact of water-resources development on the Barwon Darling River, a simple budget for each dissolved nutrient was derived for the simulated "natural" flow scenario and "current" scenario, as discussed above. Individual budgets were calculated in three steps. Step one incorporated data on the release of each dissolved nutrient from the wetted sediment collected from the various flood plain surfaces. Then, the potential supply of the dissolved nutrients from flood plain surfaces during inundation could be calculated. Step two used the simulated daily discharge data from the New South Wales Department of Land and Water Conversations IQQM. Both simulated "natural" and "current" flows at various flow stations along the study reaches were used for the period 1922–2000. From the daily flow data, the area of flood plain inundation in the flow scenarios was estimated. Step three estimated the daily dissolved nutrient released from the flood plain surfaces, and hence the potential supply of TOC, TN and TP from the collective of flood plain surfaces calculated.

RESULTS AND DISCUSSION

Surface sediment from the Barwon Darling flood plain released on average 20.4 mg L^{-1} of TOC (range: 4.3–52.9 mg L^{-1}), 0.4 mg L^{-1} of TN (range: 0.1–1.1 mg L^{-1}) and 2.1 mg L^{-1} of TP (range: 0.6–5.3 mg L^{-1}) after 72 h of wetting (Fig. 2). Concentrations and release rates of the three nutrients were significantly different over the five different time periods (Table 1). Release rates were greatest in the first 2 h for both TN and TP; however, a secondary spike in release was detected for TOC between 9 and 18 h after initial wetting (Fig. 2(a)). Average release rates appeared to stabilise 24-h following wetting for all dissolved nutrients and these were used to calculate reach-scale nutrient releases and the influence of changing hydrology.

REML analysis demonstrated the top-down constraints of valley location and elevation above the river bed to be significantly correlated with the release of dissolved nutrients from the wetted flood plain sediments. Significant interactions were recorded between valley location and time for both TOC and TN (Fig. 3, Table 1); of the TOC most likely a result of the secondary release spike observed 12 h after initial wetting of the sediment samples from the Walgett reach (Fig. 3). Flood plain sediments in the Walgett reach also released significantly more TN than those collected from the Bourke reach (Table 1). Sediments from the Bourke reach displayed a decrease in release rates of TN after 6 h of wetting (Fig. 3). The elevation of the flood plain surface was significantly

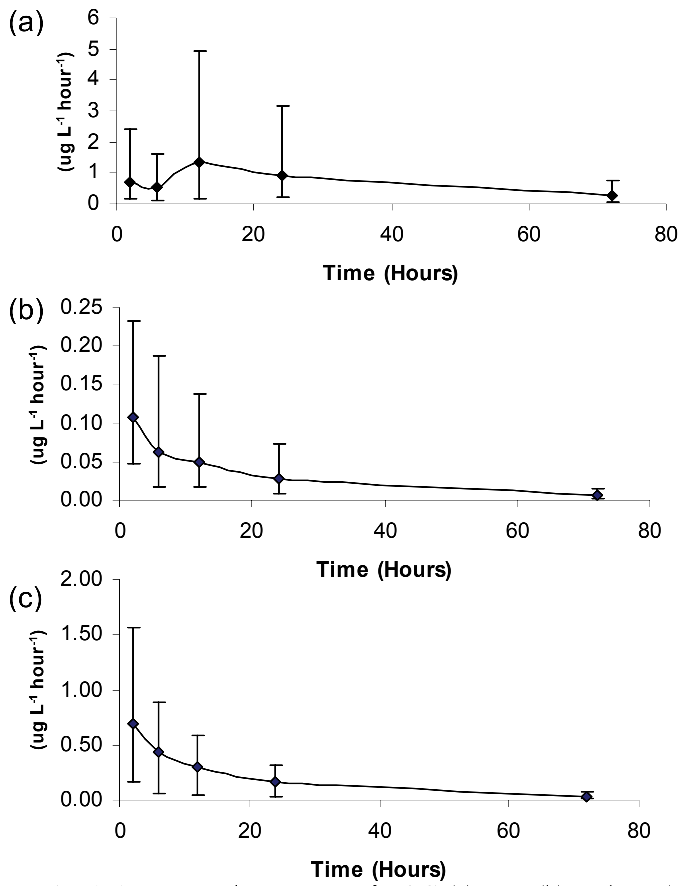

Fig. 2 Average release rates of TOC (a), TN (b) and TP (c) from inset flood plain surfaces on the Barwon-Darling River. Error bars represent minimum and maximum values.

Table 1 The influence of top-down and bottom-up influences on the release of dissolved nutrients (Total organic carbon – TOC, total nitrogen – TN and total phosphorus TP) from wetted flood plain surface sediment of the Barwon-Darling River. **significant at the 0.01 level; *significant at the 0.05 level; and NS, not significant.

Influence	TOC Release rate ($\log_{10}$)	TN Release rate ($\log_{10}$)	TP Release rate (4th root)
Time	** ($p < 0.01$)	** ($p < 0.01$)	** ($p < 0.01$)
Valley	N/S	N/S	N/S
Valley*time	** ($p < 0.01$)	** ($p < 0.05$)	N/S
Elevation	** ($p < 0.01$)	** ($p < 0.01$)	N/S
Elevation*time	** ($p < 0.001$)	** ($p < 0.01$)	N/S
Sediment	N/S	N/S	N/S
Sediment*time	** ($p < 0.01$)	** ($p < 0.05$)	** ($p < 0.05$)

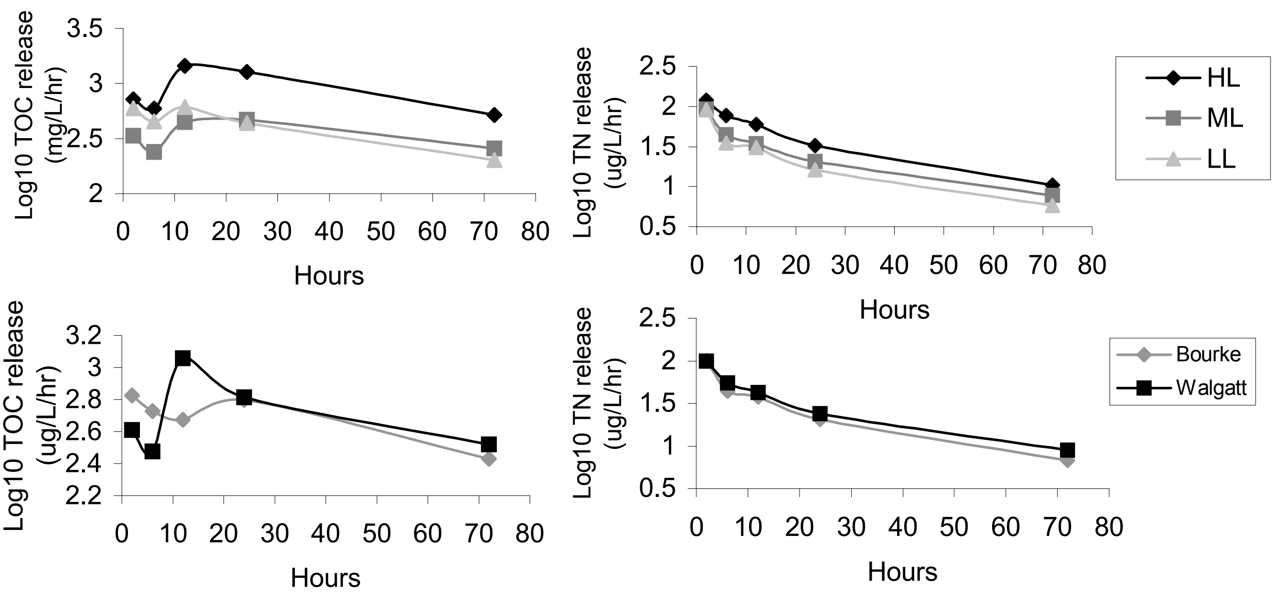

Fig. 3. Concentrations and release rates of TOC and TN over time grouped by valley location and elevation in channel along the Barwon-Darling River.

correlated with release patterns of TOC and TN. In all cases sediments from flood plain surfaces at higher elevations released significantly more TOC and TN than those from mid or lower level elevation (Table 1). These patterns are similar to those observed by Southwell & Thoms (2006) for quantities of organic matter and particulate nutrient concentrations found on these flood plain surfaces and are assumed to be associated with increasing distance from the active channel and proximity to riparian vegetation.

By comparison the REML analysis demonstrated there to be a significant association between the bottom-up influence of sediment texture and the concentrations and release rates of all three nutrients studied over time (Fig. 4, Table 1). Flood plain surfaces displaying a relatively coarse sediment texture had the lowest concentrations and release rates compared to relatively finer sediment textures (Fig. 4). These results are consistent with other studies (e.g. McComb & Qiu, 1998) which have indicated sediment texture to be strongly associated with the nutrient concentrations. Sediment texture has also been shown to influence microbial activity, which upon wetting mediates the release of nutrients into the water column (Pinay *et al*., 2000).

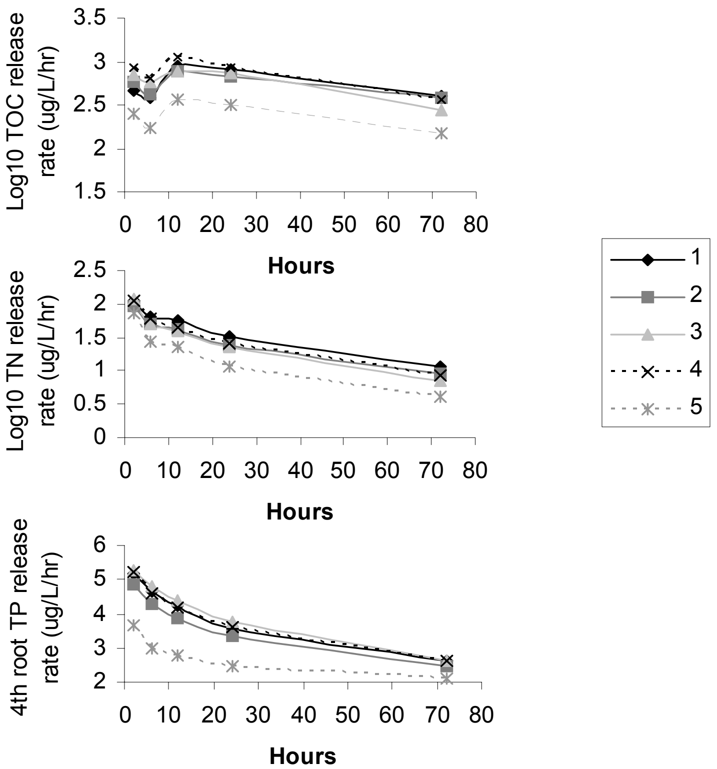

Fig. 4 Concentrations and release rates for TOC, TN and TP over time. Data are provided for each of the five flood plain sediment textural classes determined by Southwell & Thoms (2006), where textural group 1 are relatively finer sediments and textural group 5 are relatively coarser sediments.

Individual inset-flood plain surfaces (256) were recorded along both study reaches of the Barwon Darling and these had a combined surface area of 79 620 m^2. From these surfaces 302 kg of TOC, 9 kg of TN and 62 kg of TP would potentially be released under the total amounts of dissolved nutrients released under the "current" flow scenario (Table 2). Overall, those inset-flood plains along the Walgett reach would release 18% more TOC, 20% more TN and 10% more TP than those flood plain surfaces in the Bourke reach. In addition, higher elevation flood plains would release the most TOC (136 kg), whereas mid level flood plain surfaces would release the most TN (3.36 kg) and lower level flood plains would release the most TP (30.6 kg) (Table 2).

The greater loads of dissolved nutrients from the Walgett reach are the result of both higher nutrient release rates and the greater surface area of inset-flood plains within this reach. Spatial patterns in the potential supply of dissolved nutrients are patchy and do not follow longitudinal gradients. This patchiness along the Walgett reach is most likely the result of the combined controls of surface elevation and sediment texture which were significantly correlated with release rates of dissolved nutrients over time, and variations in the surface area of the inset-flood plains between the different elevation classes and reaches.

A reduction of 43% in the potential supply of dissolved nutrients has occurred with water resource development. Other studies investigating the influence of water resource development on the potential supply of nutrients from flood plain features within the Murray Darling Basin have also recorded reductions in nutrient loads of this magnitude (Thoms, 2003; Thoms *et al.*, 2005). Reductions to the potential supply of DOC from anabranch channels in the Macintyre River ranged from 12.5 to 98% as a result of water resource development (Thoms *et al.*, 2005). Moreover, Thoms (2003) showed greater reductions (22–48%) in the potential supply of DOC from flood plain surfaces that were relatively frequently inundated (average recurrence interval of <2 years) compared to those inundated by larger flood events (reductions of 3.98–5.78%, average recurrence interval of <5 years). The results of this study support the findings of Thoms (2003)

Table 2 Reach scale dissolved nutrient loads (in kilograms) for the 78 year period, from inset-flood plain surfaces along the Barwon-Darling River for the period 1922–2000; "nat" is potential loads under the natural flow scenario, "cur" is loads under the current flow scenario. The percentage column is the percentage reduction in loads from natural to current flow conditions. HL, higher elevation flood plain surfaces; ML, mid level flood plain surfaces; and, LL, lower level flood plain surfaces.

	Dissolved nutrient release								
	TOC			TN			TP		
	nat(kg)	cur(kg)	(%)	nat(kg)	cur(kg)	(%)	nat(kg)	cur(kg)	(%)
WALGETT									
HL	126.57	69.65	–45	3.26	1.79	–45	13.67	7.52	–45
ML	88.52	51.08	–42	3.20	1.84	–42	21.46	12.38	–42
LL	76.10	45.04	–41	2.72	1.61	–41	21.24	12.57	–41
total	291.19	165.77	–43	9.17	5.25	–43	56.37	32.48	–42
BOURKE	TOC			TN			TP		
	nat(kg)	cur(kg)	(%)	nat(kg)	cur(kg)	(%)	nat(kg)	cur(kg)	(%)
HL	113.04	66.43	–41	2.38	1.40	–41	5.31	3.12	–41
ML	55.36	31.48	–43	2.67	1.52	–43	14.43	8.21	–43
LL	67.24	38.18	–43	2.31	1.31	–43	31.91	18.11	–43
total	235.64	136.08	–42	7.35	4.22	–43	51.65	29.44	–43
COMBINED	TOC			TN			TP		
	nat(kg)	cur(kg)	(%)	nat(kg)	cur(kg)	(%)	nat(kg)	cur(kg)	(%)
HL	239.60	136.07	–43	5.63	3.19	–43	18.98	10.64	–44
ML	143.88	82.56	–43	5.86	3.36	–43	35.90	20.59	–43
LL	143.34	83.22	–42	5.03	2.92	–42	53.15	30.69	–42
total	526.82	301.85	–43	16.52	9.47	–43	108.02	61.92	–43

demonstrating relatively large reductions in the potential supply of dissolved nutrients from flood plain surfaces that are inundated relatively more frequently compared to those that are inundated infrequently.

The results of this study demonstrate that the potential supply of dissolved nutrients from inset flood plain surfaces to the Barwon-Darling River has been significantly reduced as a consequence of water resource development. This may be a conservative estimation given that reductions in hydrological variability have also been shown to reduce the geomorphic complexity of the river and the presence of inset-flood plains along the river channel margins (Thoms & Sheldon, 2006). The ecological consequences of these reductions remains relatively unknown; however, these reductions to the supply of allochthonous energy supplies to the river channel might place greater emphasis on autochthonous sources in the main channel ecosystem.

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