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Floodplain–river ecosystems: lateral connections and the implications of human interference

Martin C. Thoms*

Co-operative Research Centre for Freshwater Ecology, University of Canberra, Canberra, ACT 2601, Australia

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Abstract

Floodplains are ecotones that form a transition between aquatic and terrestrial environments. These important ecosystems can be described as dynamic spatial mosaics in which water plays an important role in connecting various patches on the floodplain surface. Hydrological connections facilitate the exchange of carbon and nutrients between the river channel and the floodplain and therefore influence the productivity of the entire river system. This paper examines the influence of hydrological connections on the potential exchange of dissolved organic carbon between a large Australian floodplain to a river channel, and the effects of land and water developments on these exchanges. The paper proposes that an understanding of floodplain ecosystems requires an interdisciplinary approach—a recognition of the importance of the three disciplines hydrology, geomorphology and ecology. Large-scale water-resources and floodplain development has significantly altered the spatial and temporal patterns of hydrological characteristics in the Lower Balonne floodplain, Australia. The magnitude, frequency and duration of flooding events have all been reduced. The construction of levees and water storages has also reduced the reactive floodplain surface area. The presented data show the impacts of these changes on the potential supply of dissolved organic carbon from the floodplain surface during periods of inundation. Annual reductions of up to 1293 tonnes of dissolved organic carbon supply were noted and reductions were especially significant for floods with an average recurrence interval of 2 years or less. Some small flood events no longer facilitate the potential supply of dissolved organic carbon from the floodplain to the river channel because of water-resources and floodplain developments.

Keywords: Connectivity; Floodplain ecosystems; Dissolved organic carbon

1. Introduction

Floodplain–river ecosystems are dynamic spatial mosaics in which water plays an important role in connecting various landscape patches. Lateral connections between the main river channel and floodplain—two important macro-scale patches in these systems—are considered to be essential for the functioning and integrity of floodplain–river ecosystems (Amoros and Bornette, 2002). For example, flooding often results in the elevation of floodplain soil nutrient concentrations (Ogden and Thoms, 2002) with commensurate increases in plant growth (VanOorschot et al., 1998). While much is known about the transfer of sediment, nutrients and biota from river channels to

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* Fax: +61-261-201-2328.
E-mail address: martin_thoms@enterprise.canberra.edu.au (M.C. Thoms).

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floodplains (e.g. Asselman and Middelkoop, 1995; Walling and He, 1998; Thoms et al., 2000), relatively little is known about the transfer from floodplains to river channels during periods of hydrological connectivity. Baldwin and Mitchell (2000) have reported that inundation of floodplains facilitates the release of dissolved organic carbon and nutrients from surface sediments, making them potentially available, along with plant matter, to be transported back into the river channel during flood recession. Carbon, in particular, is an important energy source for aquatic organisms, forming the base of food webs in floodplain–river ecosystems. In a preliminary study of flow-driven exchanges of organic carbon between billabongs (floodplain waterholes) and the main channel of the Murrumbidgee River, Australia, during a single flood event, Robertson et al. (in press) demonstrate that export of dissolved organic carbon from these floodplain patches was sufficient to support in-channel respiration for approximately 20 days. Therefore, exchanges of materials between different floodplain patches and the main river channel can also influence the overall productivity of fluvial ecosystems.

Fragmentation is the reduction or elimination of connections between patches in a landscape (Kotliar and Wiens, 1990). Hydrological fragmentation in floodplain–rivers is facilitated by the ‘flood pulse’ (sensu Junk et al., 1989) creating variable patterns of wetting and drying on adjacent floodplain surfaces. However, changes to the wetting and drying regimes of floodplains through land and water-resources development interfere with the release, availability and exchange of carbon between floodplains and river channels. Human activities change the lateral connectivity of floodplain–river systems in two ways: by altering the natural hydrological pattern of floodplain inundation, and through land use changes brought about by the construction of levees, dykes and other engineering structures on the floodplain itself which reduce reactive floodplain surface areas.

Extensive floodplain surfaces and a network of channels that are connected only during episodic floods are characteristic of Australian inland rivers (Thoms and Sheldon, 2000). Much of the general information demonstrating the linkages between river channels and their floodplains 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 lateral transfer of material in larger Australian dryland systems (Robertson et al., 1999). These systems have been described as natural boom and bust ecosystems (Walker et al., 1997) with intense periods of high biological productivity during or immediately following infrequent and unreliable inundation. There has been a recent trend of increasing large-scale water-resource developments in these regions to capture water during major flood periods and little is known of their influence on these floodplain–river ecosystems. It has been hypothesized that large-scale water extractions during booms may lead to permanent busts (Walker et al., 1997; Thoms and Cullen, 1998; Boulton et al., 2000). Hydrological modifications do fragment floodplain–river ecosystems by changing the periodicity of lateral connections (Dynesius and Nilsson, 1994) and this may interfere with exchanges of sediment, carbon and nutrients between different patches in the floodplain–river landscape thereby altering the overall productivity of these ecosystems. The enhanced natural variability of dryland ecosystem processes (Graf, 1988; Davies et al., 1994) requires management approaches for these systems must differ from those in temperate and humid regions if the ecosystems are to maintain their ecological integrity (Thoms and Cullen, 1998; Boulton et al., 2000).

This paper examines the influence of land and water developments on hydrological connections in a large Australian floodplain–river ecosystem and considers the consequence of these changes on the potential exchange of dissolved organic carbon from the floodplain surface to the river channel. It also proposes that an understanding of floodplain ecosystems requires an interdisciplinary approach—recognizing the importance of the disciplines of geomorphology and ecology.

2. Study area

The Condamine–Balonne River drains the highlands of eastern Australia in southern Queensland (Fig. 1). Like many Australian inland rivers the Condamine–Balonne is an allogenic river originating in a well-watered area but flowing for most of its length across a dry landscape (Thoms and Sheldon, 2000).

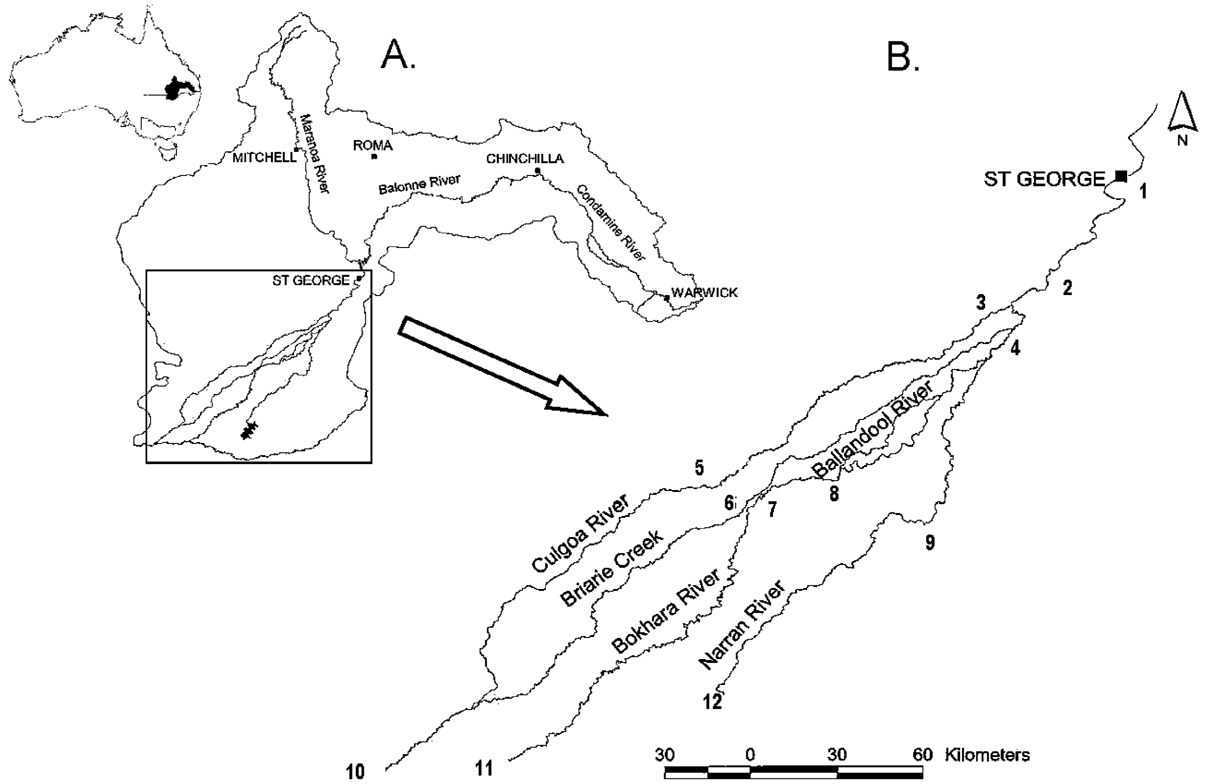

Fig. 1. (A) The Condamine Balonne Catchment. (B) The Lower Balonne Floodplain. Numbers are the location of the various flow stations (see text for explanation).

Rainfall within the catchment is variable and droughts and floods occur periodically throughout the region. The long-term median annual rainfall ($n = 73$ years) decreases from east (1105 mm at Toowoomba) to west (517 mm at St George) across the catchment. Most rainfall occurs in the summer months (November–April) and is associated with tropical monsoonal activity. Mean annual evaporation ranges from 230 mm in the headwaters to 1890 mm in the lower catchment. Flows in the Condamine–Balonne are also highly variable, with annual flows at St George, in the lower catchment, ranging between 23,960 and 7385,000 megalitres (Ml) (1975–2000) with an annual median of 728,175 Ml. Flood events generally occur between November and April; hence the annual flow pattern is summer-dominated.

Of the five geomorphological river zones identified in the Condamine–Balonne catchment the anabranch zone in the lower reaches of the river system is the longest (Thoms and Sheldon, 2002). The Lower Balonne Region (Fig. 1) is an extensive floodplain that contains a complex suite of geomorphic features, including levees, scrolls, swales, distributary channels, in-channel benches, palaeochannels, cutoffs and flat floodplain surfaces. The contemporary river–floodplain complex in the Lower Balonne Region covers an area of 19,800 km^2 and has developed upon the surface of a tertiary-aged low-angle alluvial fan (Foster et al., 2002).

Downstream of St George, the Condamine–Balonne River divides into five separate channels (Fig. 1). The Culgoa and Narran Rivers are the main channels, conveying 35% and 28%, respectively, of the long-term mean annual flow at St George. The Ballandool River, Bokhara River and Briarie Creek only flow during higher discharge periods. All five rivers have low channel gradients (0.0002 to 0.0003), are tortuous in planform (sinuosities exceed 2.2; cf. Schumm, 1977) and transport predominantly fine sediments. Bankfull cross-sectional areas of most of the channels (the Briarie is the exception) decrease with distance downstream, so there are regular overbank flows.

Discharges of the five main channels in the Lower Balonne differ substantially (Table 1). A large proportion of average flows occur in very wet years and during major floods. Variability in flow is also high: coefficients of variation (CVs) for annual flows range from 103 to 200 (Table 1), and median annual flows can be less than 30% of mean annual flow. Flows (both annual volumes and flood peaks) generally decrease downstream towards the end of the system because of a lack of tributary contributions and larger evaporation, a characteristic feature of Australian inland river systems (Thoms and Sheldon, 2000). There have been changes in the hydrological regime of the Lower Balonne over the last 100 years, with the period prior to the 1900s and since the mid-1940s being wetter, on average. This has been associated with greater runoff and flood activity than for the period 1900 to 1945 (Riley, 1988). These changes reflect the shift in the geographical pattern of correlation between precipitation and the SOI for the years before the 1950s compared with the years since the 1950s (Simpson et al., 1993).

The spatial pattern of inundation across the Lower Balonne Floodplain is complex (Fig. 2). Using a series of 13 Landsat TM images acquired at various discharges, Sims and Thoms (2002) have modeled floodplain inundation. Floodplain inundation appears to be highly correlated with flows at St George. From this model it appears that inundation of the Lower Balonne Floodplain occurs in three phases. Flows in excess of 26,450 Ml/day at St George (equivalent to an average recurrence interval (ARI) of 1.5 years based on an annual flood series) result in the initial wetting of the floodplain surface. The floodwaters are confined essentially to the central region of the floodplain until flows exceed 60,000 Ml/day (ARI of 2.5 years). At this discharge, significantly larger areas of floodplain become inundated and floodwaters begin to re-enter the Culgoa River approximately 30 km downstream of the bifurcation of the Condamine–Balonne River. Most of the floodplain is inundated once flows exceed 160,512 Ml/day (ARI of 10.5 years). Overall, the western and central regions of the Lower Balonne Floodplain are flooded more frequently than the eastern regions (Fig. 2). There are several small regions of the floodplain that remain dry even during a flood event with an ARI of 10.5 years. Floods wet the Lower Balonne Floodplain from inside to out and this pattern of inundation is closely associated with the spatial pattern of floodplain vegetation communities and their response to watering (Sims and Thoms, 2002).

Most water-resources development in the Condamine–Balonne Catchment has occurred since the

Table 1
Summary statistics of the historical daily flow record (Ml/day) for six stations in the Lower Balonne Region

	Balonne @ St George	Culgoa @ Whyenbah	Narran @ Hebel	Briarie @ Hebel	Bokhara @ Hebel	Ballandool @ Hebel
Period of record	1965–1999	1965–1999	1965–1999	1965–1999	1965–1999	1965–1999
Basic statistics						
Mean	3357.5	1272.6	566.5	216.6	186.2	173.8
Median	1995	817.2	326	19.14	82.1	50.4
Median as % of mean	59%	64%	57.5%	8.8%	44%	29%
Minimum	65.6	25	0	0	0	0
Maximum	20,233	6192	3392	2142	1195	1602
Measure of the distribution						
Skew	0.952	2	2.35	3.3	2.5	3.5
Measures of variability						
Interquartile						
CV	128	103	130	200	135	181

Ml/day = megalitre per day.

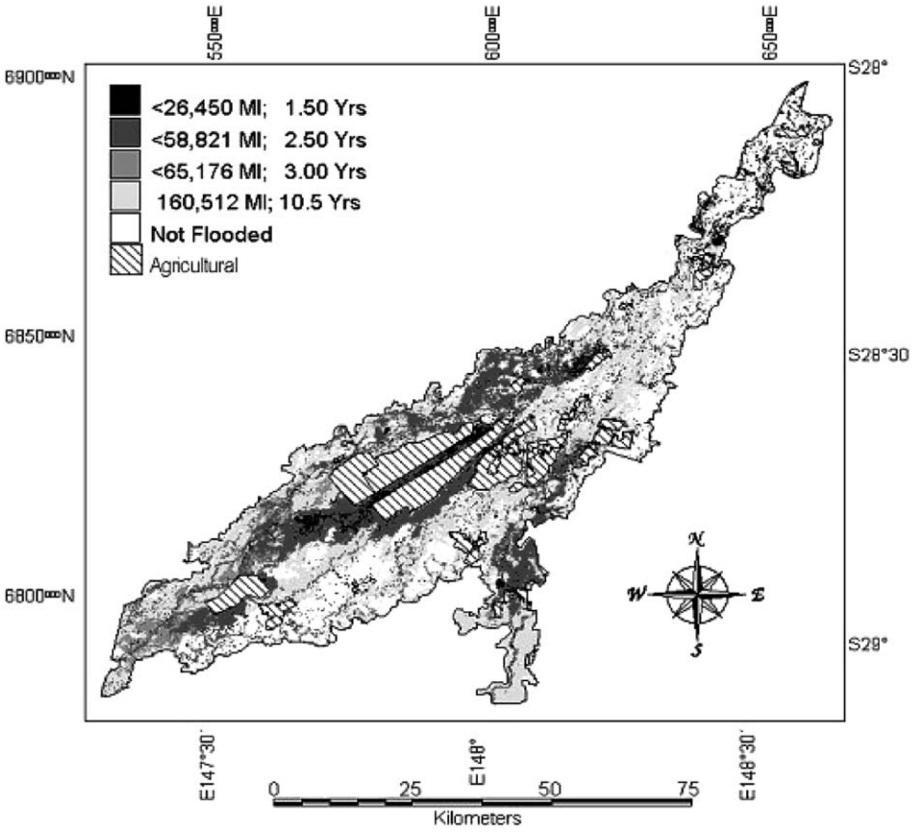

Fig. 2. Floodplain inundation of the Lower Balonne. Hatching shows area of floodplain development.

advent of irrigated agriculture in the 1960s. There are three main irrigation developments within the Condamine–Balonne catchment, of which the St George Irrigation Area located on the Lower Balonne Floodplain is the largest. There are also four significant public water storages in the catchment, which service irrigation, agricultural and domestic supply. Leslie Dam (106,250 Ml) is located in the upper part of the catchment on Sandy Creek; Chinchilla Weir (9800 Ml) is in the middle zone of the river; Beardmore Dam (81,800 Ml) and Jack Taylor Weir (10,100 Ml) are in the anabranch zone of the river. Overall, 30% of the main stem of the Condamine–Balonne River is influenced by river regulation (Thoms and Parsons, in press). There are also numerous private off-stream water storages on the Lower Balonne Floodplain that have a combined storage volume in excess of 500,000 Ml.

3. Data and methods

The rapid rate of water-resources development in the region, combined with the naturally variable flow in the rivers, makes historical data inadequate for evaluating the impact of water-resources development on the hydrological regime of the Lower Balonne Floodplain. Thus, simulated daily discharge data from the Queensland Department of Natural Resources and Mines Integrated Quantity Quality Model (IQQM) were used for evaluating hydrological change. Simulated 'natural' flows were compared with simulated 'current' flows for the period 1922–2000 for 12 stations located throughout the Lower Balonne Floodplain region (Fig. 1). A full description of the model and its reliability is given in Black et al. (1997). The 'natural' or 'pre-development' flows are simulated with a zero setting for flow regulating structures, abstractions of water and land use development, and use long-term mean climatic conditions. The 'current' flows are simulated using water and land use conditions present in 1999–2000 combined with long-term mean climatic conditions.

Hydrological data for the study area were analyzed in three ways. First, a multivariate analysis of a set of 340 flow variables was calculated for each station in the 'natural' and 'current' scenarios, to reveal changes in the spatial and temporal pattern of hydrological character for the entire region. Second, selected flood discharges were also compared for the two flow scenarios. Annual series flood frequency analyses were performed on both simulated data sets for each station, using a Log Pearson 3 distribution (Pilgram, 1987). Third, a flow-spell analysis (Gordon et al., 1992) was undertaken on both data sets to determine changes in numbers of flow-spells (the number of times a flow exceeded a threshold volume) and their durations.

For the multivariate analysis, 340 flow variables were calculated for each flow scenario and station. They fell into seven types and various categories, including magnitude, frequency, duration, timing and rate-of-change aspects of overbank flows. Each of the categories was assigned to the regime, history or pulse scale according to the time period over which they influence hydrological character. Hydrological processes vary on time scales of hours, days, seasons, years and longer (Poff, 1997) and this variation can be resolved into three time-frames to describe the hydrological character of a river: namely, its flow regime, flow history and flood pulse. Flow regime represents the long-term statistical generalization of flow behaviour and incorporates macro-scale influences that occur over hundreds of years. Flow history represents the sequence of floods or droughts and incorporates meso-scale influences between 1 and 100 years. Flood pulse represents a flood event and incorporates micro-scale influences that generally last for less than 1 year. Previous studies on hydrological changes in dryland rivers by Thoms and Sheldon (2000) have demonstrated that water-resources development can have a marked but variable impact at all three scales—highlighting the time aspect of flow changes.

Many of the stations in the natural and current water-resource development data sets had missing data, arising from 'zero-divide' errors in the calculation of some flow variables. Multivariate statistical techniques generally require a complete data set that is free of missing values. Therefore any flow variable that had a missing-data value for one or more of the 12 stations was deleted from the data set. Flow variables that were invariant (that is, they contained the same value across all 12 stations) were also removed from the data set. The final data set for multivariate analysis contained 221 flow variables for both current and natural flow data.

All multivariate analyses were performed using the PATN analysis package (Belbin, 1993). The 12 stations in the natural and current water-resource development scenarios were classified separately, using the flexible-Unweighted Pair-Groups using Arithmetic Averages (UPGMA) fusion strategy recommended by Belbin and McDonald (1993). The Gower association measure was used in all classifications, because this measure is range-standardized and is recommended for nonbiological data (Belbin, 1993). Groups of stations with similar hydrological character were selected by viewing a dendrogram representation of the classification. Dendrogram groups were arrayed onto a map to find the positions of stations with similar hydrological character. These groups of stations with similar hydrological character equate to hydrological zones in the Lower Balonne River.

Stations in each scenario were ordinated using Semi-Strong-Hybrid Multidimensional Scaling, and a Monte Carlo permutation test (Belbin, 1993) then tested whether the ordination solution (as determined by the stress level) occurred by chance alone. Stations were arrayed in ordination space according to the dendrogram groups identified in the classification analysis, which, in turn, equate to hydrological zones. Each ordination was performed in three dimensions and, as such, there are three possible axis comparisons (dimensions 1v2, 1v3 and 2v3). Bi-plots of each combination were constructed and the axes representing the best separation of dendrogram groups in ordination space were selected for presentation.

The relationship between flow variables and groups of stations in ordination space was determined using Principal Axis Correlation (PCC; Belbin, 1993), which generates a correlation value (R^2) for each attribute, with high values being indicative of a strong association between a flow variable and the position of stations in ordination space. A Monte Carlo permutation test then tested the significance of the correlation values. Only the significant variables with an R^2 above the 80th percentile (when the R^2 values of all 221 variables were considered) were included as vectors on the ordination plot. Association between each vector and a group of stations was assigned visually, and vectors were subsequently tallied according to the regime, history and pulse scales.

An assessment of land use change on the Lower Balonne Floodplain was undertaken via a comparison of 10 Landsat TM images acquired between 1998 and 2000. Geometric rectification of each image was performed by registering a base image (19 January 1993) to a map grid and co-registering each subsequent date of imagery to the base image using 40 ground control points. This resulted in a co-registration error of less than 1 pixel between each full image scene. Radiometric correction of the imagery was performed by applying sun angle correction and dark pixel subtraction algorithms (Lillesand and Kiefer, 1994) to the base image. A pseudo-invariant calibration was also used (Schott et al., 1988) to equalise pixel brightness in other dates of imagery to the base image. These images allowed the detection of artificial levees and water storage areas on the floodplain and the calculation of their respective surface areas.

To estimate the impact of water-resources and floodplain development on the Lower Balonne Floodplain ecosystem, a simple dissolved organic carbon budget was derived for the ‘natural’ flow scenario, with no water-resources and floodplain development, and the ‘current’ scenario calculated with those conditions prevailing in 2000, as discussed above. Individual dissolved organic carbon budgets were calculated in three steps. Step one incorporated the experimental data of McGinness and Thoms (2002) on the release of dissolved organic carbon from wetted floodplain surface sediment for various floodplain morphological units. The surface area of each morphological unit present on the Lower Balonne Floodplain was obtained from Thoms et al. (2003). Combined, the potential supply of dissolved organic carbon from the entire floodplain during inundation was calculated. In step two, the areas of floodplain inundated, on a daily basis, for two flow scenarios (‘natural’ and ‘current’) were estimated using the model of floodplain inundation as derived by Sims and Thoms (2002) and the daily-simulated discharge data from the Queensland Department of Natural Resources Integrated Quantity Quality Model (IQQM). Both simulated ‘natural’ and ‘current’ flows at St George were used for the period 1986–1995, a period of rapid development. Step three estimated the daily dissolved organic carbon released from the wetted floodplain surface by combining the actual release of dissolved organic carbon (as derived in step one) with the area of floodplain inundated (step two), thereby providing the potential supply of dissolved organic carbon from the Lower Balonne Floodplain under ‘natural’ and ‘current’ conditions.

4. Results and discussion

4.1. Hydrological change

Classification of the ‘natural’ flow scenario reveals three groups with a similar hydrological character. These three groups have a clear spatial arrangement in the Lower Balonne Floodplain (Fig. 3) and this may reflect spatial differences in flooding character or alternatively modeling artifacts. The spatial arrangement of the three groups relate to the Culgoa River, Narran River and the Ballandool–Bokhara–Briarie systems combined. The ‘current’ flow scenario classification reveals a distinct spatial pattern of hydrological character (Fig. 3B) that is different from the ‘natural’ flow scenario. Only two groups could be identified, the Culgoa River and a combined group of the Ballandool–Bokhara–Briarie and Narran. Ordination of the 12 stations for the two flow scenarios confirmed the classification groupings by revealing the same patterns. The same three groups of stations emerged in the natural-flow scenario analysis and the same two in the current-flow scenario. The homogenization of station groupings associated with the current-flow scenario suggests that the hydrological character found in rivers on the Lower Balonne Floodplain is becoming less spatially diverse with water-resources development.

Only 65 flow variables had an R^2 value above the 80th percentile in both ordinations, and these were analyzed further using Principal Axis Correlation. Analysis of the two flow scenarios showed that different scales of hydrological variables were associated with each ordination group (Table 2). In the natural-flow scenario, all three scales of variables—regime,

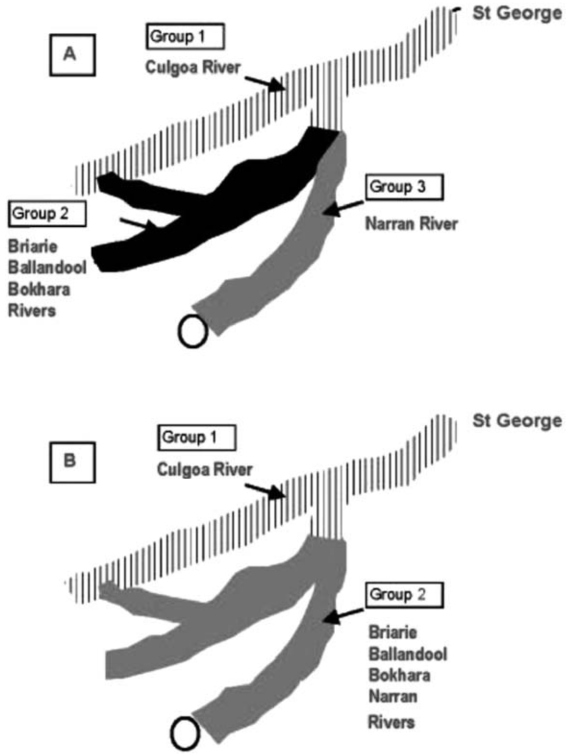

Fig. 3. A pictorial diagram of the Lower Balonne Floodplain showing the spatial arrangement of dendrogram groups for the (A) natural and (B) current flow scenarios in the Lower Balonne. The different river groups represent those flow stations that were grouped together statistically in the multivariate analysis.

history and pulse—were associated with Groups 1 and 2, the Culgoa and Narran flow stations, but only history- and pulse-scale variables were associated with Group 3, a combined set of stations from the Briarie, Bokhara and Ballandool Rivers (Table 2). The proportion of history-scale variables was high for Group 1 and 2 but variables were evenly distributed between history and pulse variables for Group 3. For the current-flow scenario, regime-, history- and pulse-scale variables were associated with each of the two groups (Table 2). However, history-scale variables were more prominent with Groups 1 and 2 (the Culgoa and a collection of stations from the Narran, Briarie, Bokhara and Ballandool Rivers). Thus, there appears to be a different distribution of flows through time between the natural- and current-flow scenarios. Regime-scale variables increase in prominence for the majority of stations throughout the Lower Balonne Floodplain with water-resources development.

Comparison of the different flow scenarios also suggests that water-resources development has had different effects on different flow groups (Table 3). For the current-flow scenario there is a loss of 29.53% of median annual volumes of water entering the Lower Balonne Floodplain (as measured by flows at St George). Moreover, the impact of water-resources development differs for floods of different magnitudes (Table 3). At St George, flows with an ARI of 1.5 years are affected most, being reduced by 47.59% while flood events with an ARI of up to 10 years have been reduced by 9.22%. Spell Analysis further demonstrates the implications of water-resources development on floodplain hydrology albeit at a finer scale (Fig. 4). For the period 1922–2000 the Lower Balonne Floodplain has been inundated on fewer occasions and all the floods have lasted less time. For example, reductions of up to 40% were recorded

Table 2
Tally of regime-, history- and pulse-scale variables associated with the position of stations in ordination space

	Hydrological scale		
	Regime	History	Pulse
Natural flow scenario			
Group 1 (Stations 1, 2, 3, 4, 5, 10)	20	60	20
Group 2 (Stations 9, 12)	10	70	20
Group 3 (Stations 6, 7, 8, 11)		50	50
Current flow scenario			
Group 1 (Stations 1, 2, 3, 4, 5, 10)	30	60	10
Group 2 (Stations 6, 7, 8, 9, 11, 12)	50	40	10

Values are expressed as a percentage of the total number of variables (65—see text for explanation) associated with each group. The location of each station is given in Fig. 1.

Table 3
Hydrological change in the Condamine–Balonne system at St George

	Natural	Current	% Change
Median annual flow (Ml)	976,997	688,457	– 29.53%
Flood discharges			
1.5 ARI (Ml/day)	31,813	16,672	– 47.59%
2 ARI (Ml/day)	56,287	43,879	– 22.04%
5 ARI (Ml/day)	123,663	18,268	– 4.63%
10 ARI (Ml/day)	183,788	166,832	– 9.22%

Simulated flow data (IQQM) are given for the 1922–2000 period. Ml = megalitre, Ml/day = megalitres per day, ARI = average recurrence interval.

in the number of inundation events at St George (Fig. 4). Overall, median reductions in the number of times a flow event occurred ranged from 11% at St George to 34% on the Ballandool River. Changes in the duration of individual inundation events were also recorded and these ranged from 10% to 60% with median reductions for individual stations between 13% and 44%.

In summary, water-resources development in the Condamine–Balonne catchment has altered the hydrological character of the Lower Balonne Floodplain. Sites in the study area now have hydrological characters that are similar instead of different, and at all sites the floods are fewer and smaller now. Walker et al. (1995) have described flow as the maestro that orchestrates the pattern and process in river ecosystems. In this study, there has been a complete change in the hydrology at a range of scales. As a consequence the wetting and drying regime of the floodplain surface has changed.

4.2. Changes in floodplain land use

Development on the Lower Balonne Floodplain has occurred with the construction of levees and water storages. Although there had been minor developments before the late 1980s, there has been rapid expansion of irrigated crops and water storage on the floodplain since that time (Table 4). While the areas involved occupy only 9.5% of the total surface area of the Lower Balonne Floodplain they are an important loss of reactive floodplain surface area.

The present-day floodplain surface consists of morphological features commonly found on floodplains formed by vertical and lateral accretion as well as on those that experience channel avulsions (Foster et al., 2002; McGinness and Thoms, 2002). These groups of morphological features have distinctive textural and geochemical differences. McGinness and Thoms (2002) found significant differences in the average total organic carbon content of the topsoil collected from 11 different morphological features identified on the floodplain. Irrespective of location on the floodplain they found that channel islands, channel banks and levees contained between 70% and 123% more total organic carbon than palaeo-channels, flood runners and flat floodplain surfaces. Furthermore laboratory experiments, which simulated inundation of the

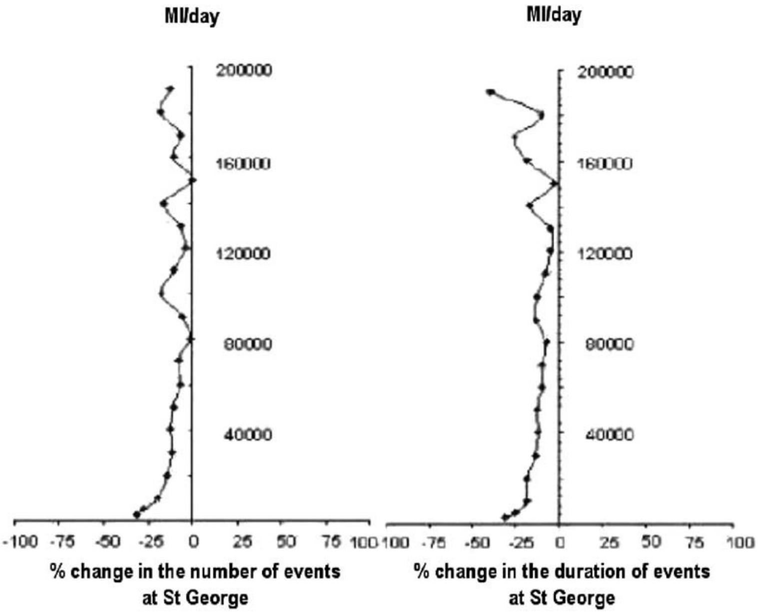

Fig. 4. Change in flow-spell character between the natural-flow and current-flow scenarios for St George.

Table 4
Floodplain development in the Lower Balonne system downstream of St George

	1988	2000
Cropped area (ha)	4300	80,000
Water storage surface area (ha)	1825	99,750
Capacity of water storages	54,750	1,160,000
Total area (ha)	6125	179,750

floodplain sediments, demonstrated that 97% of the total organic carbon released upon wetting of these various topsoils was in the dissolved form and could be consumed by micro-organisms (McGinness and Thoms, 2002). Concentrations of dissolved organic carbon released from the surface sediments ranged from 10 to 45.70 ppm after 24 h, and averaged 6.60 ppm. Significant differences in the release of dissolved organic carbon were also noted between the different morphological units. Dissolved organic carbon release in samples was on average 112% greater from surface sediment in mid channel bars, levees, channel banks and ridge swale systems than from in-channel benches, flood runners, oxbows, palaeo-channels, distributary channels and flat floodplains. This suggests that some floodplain areas are more productive in terms of potential dissolved organic carbon supply than others.

The geomorphology of the Lower Balonne Floodplain has been described in detail by Foster et al. (2002), McGinness and Thoms (2002), Sims and Thoms (2002) and Thoms et al. (2003). These studies note an array of different morphological units. At the scale of the entire floodplain there appears to be a greater diversity of morphological units in the upstream reaches of the floodplain than in the downstream reaches. The distribution is a reflection of the geomorphological history of the Lower Balonne floodplain (Thoms et al., 2003). Using the Shannon diversity index, Thoms et al. (2003) note that the diversity of morphological units between St George and 30 km downstream of the bifurcation of the Condamine–Balonne River was four times that of the remaining floodplain. Flat floodplain, distributary channels and flood runners dominated the lower reaches of the Lower Balonne Floodplain. Those are the morphological units that release relatively little dissolved organic carbon upon wetting. All morphological units were present in the upstream reaches. At this scale it appears that upstream floodplain reaches may be larger potential suppliers of dissolved organic carbon, per unit area, than the downstream floodplain reaches upon inundation. Therefore the loss of floodplain surfaces, through development, may be relatively more important in the upstream floodplain reaches.

Most of the irrigation developments on the Lower Balonne Floodplain have occurred in the upstream floodplain reaches between St George and 30 km downstream of the Culgoa–Narran bifurcation (Fig. 2). This has two important consequences for the Lower Balonne Floodplain. First, as just discussed, there may have been a proportionately large loss of highly reactive floodplain surfaces, in terms of the release of dissolved organic carbon from the surface sediments, because of developments in this area. The construction of levee banks and water storages has resulted in a 23% loss of reactive floodplain surface in the upper reaches of the Lower Balonne Floodplain. Second, developments on the floodplain have influenced the distribution of floodwaters across the floodplain during periods of overbank flow, especially in the area downstream of the Culgoa–Narran bifurcation. Before floodplain development, inundation of the floodplain began once flows reached 26,450 Ml/day at St George, and water moved into a network of small ephemeral channels across the floodplain surface, starting immediately downstream of the first channel bifurcation. Large-scale overland flow does not now occur across the Lower Balonne Floodplain. The construction of levee banks and water storages has concentrated floodwaters into several large floodplain channels, 30 km in length and 2 km wide (Fig. 2), thereby restricting the dispersal of floodwaters and sediment through the floodplain channel network.

4.3. Ecological implications

The modeled data suggest that development reduced the quantities of dissolved organic carbon released from the Lower Balonne Floodplain by nearly 8000 tonnes during 1986–1995. Approximately 33,300 tonnes of dissolved organic carbon would have been made available under ‘natural’ conditions, compared to 25,629 tonnes under ‘current’ conditions, during that period. Annual reductions in dissolved organic carbon released range from 21 to 1293 tonnes for those years, or 8–79% (Fig. 5).

Water-resources development and floodplain development have had different impacts on the potential supply of dissolved organic carbon from the Lower Balonne Floodplain. Large floods potentially supply more dissolved organic carbon available than small floods because they inundate more of the floodplain surface. For example, under the natural-flow scenario a flood with an ARI of 10 years would initiate the potential release of 520 tonnes of dissolved organic carbon on average, compared to 90 tonnes from a small flood (ARI of 1.5 years) (Fig. 6). However, small flood events especially those with an ARI of < 2 years have been reduced by 22–48% compared to reductions of 3.98–5.78% for floods with an ARI of >5 years. Hence, the estimated reduction in potential dissolved organic carbon release from the floodplain surface varies for floods of different magnitudes. Fig. 6 shows the estimated quantities of dissolved organic carbon released in floods of different magnitudes under both ‘natural’ and ‘current’ flow scenarios, plus under the influence of floodplain development. A change in the hydrological regime alone reduces the potential supply of dissolved organic carbon from the floodplain surface by 7.6–50%, while floodplain development may reduce this potential supply by a further 23–50%. The combined impact of water-resources and floodplain developments completely eliminates the role of floods with an ARI < 2 years in dissolved organic carbon release from the original floodplain surface. So, under ‘current’ hydrological and floodplain-development conditions the potential supply of dissolved organic carbon from the Lower

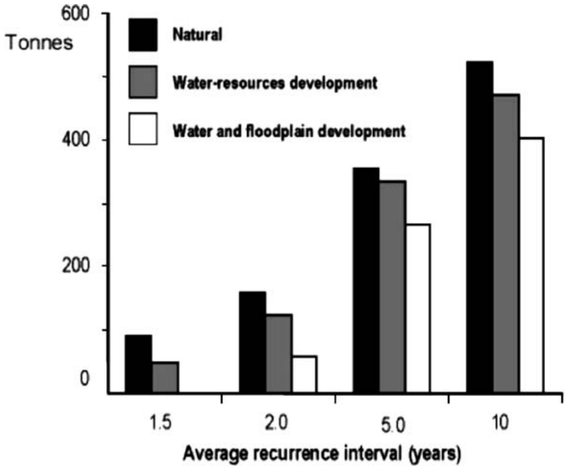

Fig. 6. The influence of water-resources and floodplain development on the potential supply of dissolved organic carbon from the Lower Balonne Floodplain during floods of different magnitudes.

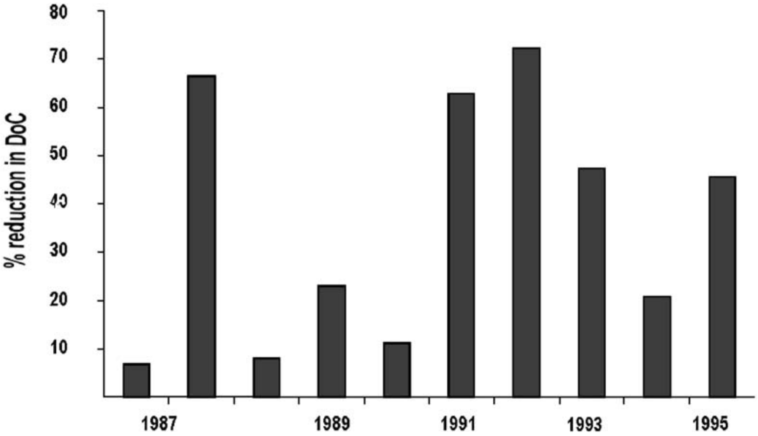

Fig. 5. Annual reductions in the potential supply of dissolved organic carbon from the Lower Balonne Floodplain. Reductions were calculated from a comparison of the dissolved organic carbon loads simulated for ‘natural’ and ‘current’ conditions. A full description of the methods is given in the text.

Balonne Floodplain appears to be reduced by 23–100% depending on the size of flood.

4.4. Floodplain–river ecosystems

An interdisciplinary landscape approach is required for the study of floodplains (Thoms and Parsons, 2002; Ward et al., 2002), to improve our understanding of these complex ecosystems and our chances of successfully restoring them. The landscape approach should incorporate the disciplines of geomorphology, hydrology, chemistry and ecology. Although different disciplines are often brought together to solve environmental problems in river systems, their integration is fraught with challenges that may make the combination ineffective. Pickett et al. (1994) identify three consequences of combining disciplines:

(a) gaps in understanding appear at the interface between disciplines;
(b) disciplines focus on specific scales or levels of organization; and,
(c) as subdisciplines become rich in detail they develop their own view points, assumptions, definitions, lexicons and methods.

These consequences often prevent a single applied understanding of the river ecosystem.

The present study has demonstrated the consequences of changing the hydrology and the area of reactive floodplain surface, on an ecological process—the potential supply of dissolved organic carbon. It has hence shown the potential value of an interdisciplinary approach for floodplain ecosystems.

Conceptual river system models, such as the Flood Pulse Concept of Junk et al. (1989) and the Riverine Productivity Model of Thorp and Delong (1994), recognize the importance of lateral connections for biogeochemical cycles, the structure of biotic communities and the overall ecological integrity of floodplain–river ecosystems. However, studies have tended to focus on the response of floodplains to changes in the frequency, magnitude and duration of the flow regime (e.g. Amoros and Bornette, 2002) and transfers of materials from the river channel to the floodplain. Very few studies note the importance of the availability and condition of the actual floodplain surface and transfers from the floodplain to the river channel, even though the spatial heterogeneity of floodplain habitats has been recognized as being important for floodplain functioning (Tockner et al., 2000).

Floodplains are typically characterized as complex landscape features (Nanson and Croke, 1992). The existence, development and arrangement of features on the surface of a floodplain are imprints of past and current fluvial processes. Recognition of this complexity will be important for the sustainable conservation of floodplain ecosystems and will require knowledge of basic geomorphological processes and how these may influence ecological functions at a range of scales (Bornette et al., 1998).

The results of this study suggest that floodplain surfaces can have a significant influence on the potential supply of dissolved organic carbon. In the case of the Lower Balonne Floodplain, development on the floodplain has added to the effect of water-resources development in reducing the potential supply of dissolved organic carbon, especially for floods with an ARI of <2 years (Fig. 6). Floodplain development not only isolates large tracts of reactive floodplain surface through the construction of levees but also changes the character of the floodplain surface. Vegetation clearance and similar activities can alter the natural roughness of the floodplain surface, thereby influencing access to and retention of organic carbon. The influence of changes to the floodplain surface appears to decrease in larger floods.

The ecological relevance of hydrological connections can be expressed by more than just the magnitude, frequency and duration of wetting. At a floodplain scale, distinct zones of varying hydrological character are evident in the Lower Balonne. These zones are evident in both the natural and the current water-resources development scenarios (Fig. 3). Zonation in hydrological character has not previously been demonstrated within river systems. It suggests that different parts of a river system have distinct hydrological characters.

Zonation along river systems has often been demonstrated for geomorphological character (Leopold and Wolman, 1957; Schumm, 1988; Davies et al., 2000) and ecological character (Illies and Botosaneanu, 1963; Vannote et al., 1980), but this study demonstrates that the same principle operates for hydrology. Moreover, the pattern of spatial zonation differs between scenarios and this suggests that the hydrological character is becoming homogenized in the study area, in response to the pressure of water extraction that occurs directly from the channel or harvesting that occurs on the floodplain during flood events.

Impacts of water-resources development on the magnitude and frequency of flood events and low flows have been demonstrated in other Australian dryland rivers (Kingsford and Thomas, 1995; Kingsford, 2000; Thoms and Sheldon, 2000). However, those studies used standard hydrological analyses to evaluate the effects of water-resources development. The present study uses an approach that incorporates more hydrological attributes than previous studies. It has demonstrated that changed hydrological character from site to site in the floodplain is reduced under the current water-resources development scenario, and that the time patterns of hydrological character also differ between the two flow scenarios (Fig. 3).

5. Conclusions

Floodplains are important ecotones—transition areas—that regulate interactions in flowing freshwater systems. Active management and restoration of these systems have a high priority in many areas and have been the focus of recent research (Naiman and Decamps, 1990). However, restoration management has tended to concentrate on 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. Whilst development has changed the functioning of the Lower Balonne Floodplain (Ogden et al., 2002) restoration can be attempted. The science of environmental flow allocations is concerned primarily with maintaining appropriate hydrological regimes that facilitate natural biological, physical and chemical processes. Applying the science of environmental flow allocations here would restore flooding of larger areas of floodplain, for longer periods, and with strategic timing. However, appropriate land management is also an option. The identification of key floodplain areas that release or have higher fluxes of carbon and other nutrients is a key. Once identified, these areas could be given a higher conservation status, and development could be restricted there. Effective floodplain–ecotone management needs an integrated approach in which land and water issues are all considered.

Little is known about the functioning of large floodplain–rivers as ecosystems and there is considerable debate about the roles of various landscape patches and periods of hydrological connectivity. It has been argued (Walker et al., 1995; Robertson et al., 1999; Thoms and Sheldon, 2000) that current ecosystem models for river systems, namely, the River Continuum Concept (Vannote et al., 1980), the Flood Pulse Concept (Junk et al., 1989) and the Riverine Productivity Model (Thorp and Delong, 1994), are not adequate for floodplain–river ecosystems. An interdisciplinary approach has the potential to bring about fresh solutions to the study and management of floodplain–river ecosystems, because the hydrology, geomorphology and ecology of river systems interact at many geographic and time scales.

In the context of floodplain ecosystems, hydrological factors will have a variable influence on geomorphological and biological factors, and vice versa. Hydrological attributes may have an important role in certain areas of a floodplain but have a reduced influence in other areas. For effective management of floodplain–river ecosystems, it is essential that the key interactions, both spatial and through time, be identified. At present many management strategies do not adequately recognize the part(s) of floodplain–river systems that can or need to be managed, and often fail to provide scientific knowledge at the appropriate scale. The interface between science—in this case hydrology, geomorphology and freshwater ecology—and policy management is turbulent but potentially exciting. Communication of scientific knowledge to the water industry can only improve with the development of an interdisciplinary approach that guides the study of floodplain–river ecosystems.

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