(Proc. of JS.1 at the Joint IAHS & IAH Convention, Hyderabad, India, September 2009). IAHS Publ. 328, 2009.

The character and behaviour of flood plain vegetation landscapes

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Abstract Flood plains are an important component of the riverine landscape providing a range of ecosystem goods and services. In dryland environments, flood plains are a refuge for a wide variety of plant and animal species. Flood plain features often appear to display relatively coarse gradients of structure with distance from the main river channel in response to decreasing flow efficiencies and increasing elevation. However, when viewed at smaller scales, flood plains are heterogeneous landforms representing a mosaic of patches embedded within the large flood plain ecotone. This may occur because smaller scale variations in topography may disrupt longitudinal and lateral patterns. Flood plains are dynamic ecosystems and an obvious example of this is changing vegetation patterns overtime, which create a dynamic heterogeneous vegetation environment in flood plains. Complex patterns of change in flood plain landforms and associated vegetation influence the productivity and biodiversity of these systems. Consequently, understanding the character of flood plain vegetation landscapes and the changing nature of vegetation patches over time may be an important tool for managing these ecosystems. This study investigates how the flood plain vegetation-patch character of the lower Murrumbidgee River, Australia, changes over time. A series of vegetation community maps of the flood plain, spanning a period of 40 years, were used to determine the landscape patch character of this fragmented landscape. Patch characteristics such as size, patch number, length and shape complexity were calculated for each vegetation state and subjected to a range of uni- and multivariate statistical analyses to elucidate patterns in the flood plain landscape over time. The influence of changing hydrology on this important flood plain ecosystem is discussed.

Key words flood plain vegetation landscapes; fragmentation; ecotones; patch mosaics

INTRODUCTION

Flood plains are commonly viewed as ecotones or Aquatic Terrestrial Transitional Zones (ATTZs) that form at the boundary of river systems and their wider catchment. A comprehensive literature exists describing the lateral distribution of vegetation across flood plains and the influence of hydrology, landforms, sediment character and life history factors (see Naiman *et al*., 2005, for a review). Many studies have shown plants to be distributed laterally across flood plains and this distribution is often related to well-defined valley and fluvial landforms resulting from distinct hydrogemorphic processes (Hupp & Osterkmap, 1996). Different fluvial landforms occur at higher elevations above the main channel and these are associated with decreasing flow durations and wetting frequencies. This physiographic approach to the understanding of plant distributions across flood plains has provided strong and often linear predictive understandings and models for the spatial configuration of vegetation communities within riverine landscapes.

Since landscape ecology was taken into the water less than a decade ago (Wiens, 2002) much has been learned about rivers as landscapes. Riverine landscapes are dynamic, shifting mosaics of physical and biological patches of different size, shape, juxtaposition, configuration and composition (Whited *et al*., 2007; Thorp *et al*., 2008). Water is a key driver of riverine patch mosaics, and flows of different magnitude, duration and frequency act to re-configure the physical patch mosaic and influence the distribution, composition and abundance of organisms within the river template (Palmer *et al*., 2000; Fausch *et al*., 2002; Parsons *et al*., 2005; Tockner *et al*., 2006). Implicit in our understanding of rivers as landscapes is that regardless of how they are viewed, the spatial heterogeneity and temporal variability of patches within riverine landscapes determines biological and physical diversity, maintains the resilience and integrity of ecological systems, and provides economically valuable ecosystem goods and services (Pickett & Rogers, 1997; Walker & Salt, 2006).

Flood plains are resilient ecosystems (Thoms, 2003), but are amongst some of the most threatened landscapes in the world (Tockner *et al*., 2008). Alteration of flow regimes by dams, and increased water extraction for human, agricultural and industrial use has often left little environmental water available to sustain the natural dynamics of flood plain landscapes. Many flood plains are now so isolated from main river channels that connection occurs only during very large flood events. Flood plain development has also had major impacts on flood plain landscapes, changing the structure and function of patches. Climate change is also likely to result in further alteration to flood plain landscapes, even in unregulated rivers, as precipitation patterns change, extreme droughts and floods become more common and agricultural production and land-settlement patterns re-organize (Thoms, 2003). Despite the substantial environmental, social and economic benefits provided by flood plains, most large-river flood plains have undergone landscape change and lost some or all aspects of their landscape character, thereby reducing their capacity to provide such benefits.

The majority of our understanding on flood plain vegetation comes from studies focused at smaller scales within a relatively narrow riparian corridor. The entire flood plain extent, which may stretch for kilometres either side of the riparian corridor, is often not considered. However, the advent of advanced GIS technologies has provided the tools to begin to understand aspects of vegetation at larger scales – scales of the entire flood plain landscape. GIS and remote sensing has been used extensively in terrestrial landscapes to examine structural and functional aspects of vegetation, such as growth and productivity (Hill *et al*., 2004; Wang *et al*., 2004), and has helped to understand the effects of climate variability, land management and conservation in vegetated landscapes (Li *et al*., 2004; Barbosa *et al*., 2006; Piao *et al*., 2006; Wiegand *et al*., 2008). The use of these technologies in flood plain landscapes would provide information about the dynamics of flood plain vegetation at a large scale, with commensurate benefits for water resource management (Zoffoli *et al*., 2008). This study examines the structure and dynamics of flood plain vegetation function at a large, whole-of flood plain scale in response to water resource development.

STUDY AREA

The Murrumbidgee River is one of the principal river systems in the Murray Darling Basin in southeast Australia (Fig. 1). It has a catchment area of approx. 84 000 km^2 and has its headwaters

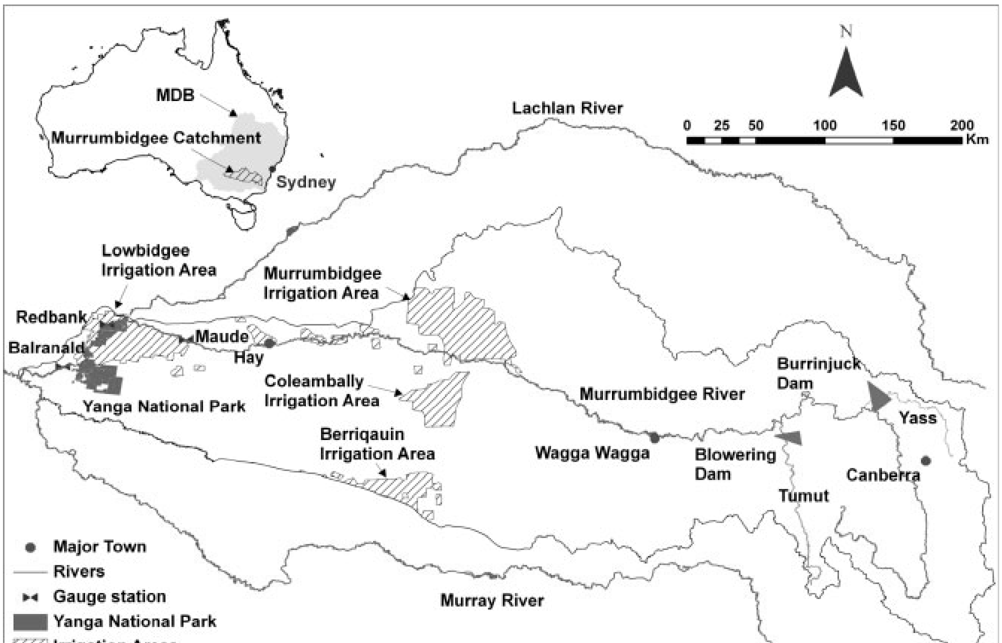

Fig. 1 The Murrumbidgee catchment showing the location of the Yanga flood plain (dark grey area). The inset map shows the location of Murrumbidgee Catchment within the Murray-Darling River basin in Australia (adapted from Wen *et al.* 2009).

in the Snowy Mountains (1600 m ASL). The Murrumbidgee River flows in a westerly direction before joining the River Murray approximately 1200 km downstream at Boundary Bend (60 m a.s.l.). It is a typical lowland Australian river system (Thoms & Sheldon, 2000a); having a semi-arid climate and a highly variable flow regime. Long term average annual rainfall (1920–2005) varies between 1500 mm in the headwater regions of the catchment to less than 400 mm in the western lowland plains. By comparison, long term average annual evaporation ranges from 648 mm to 1800 mm and for most of the catchment evaporation exceeds rainfall. Under "average" climatic conditions only 24% of rainfall is converted to runoff from the catchment area above Wagga Wagga, while downstream the rainfall runoff coefficient is less than 2% (Khan *et al.* 2004). Annual discharges range from 251 000 ML to 6 610 000 ML, for 1937–2005 at Maude Weir, located in the lower reaches of the catchment (Fig. 2).

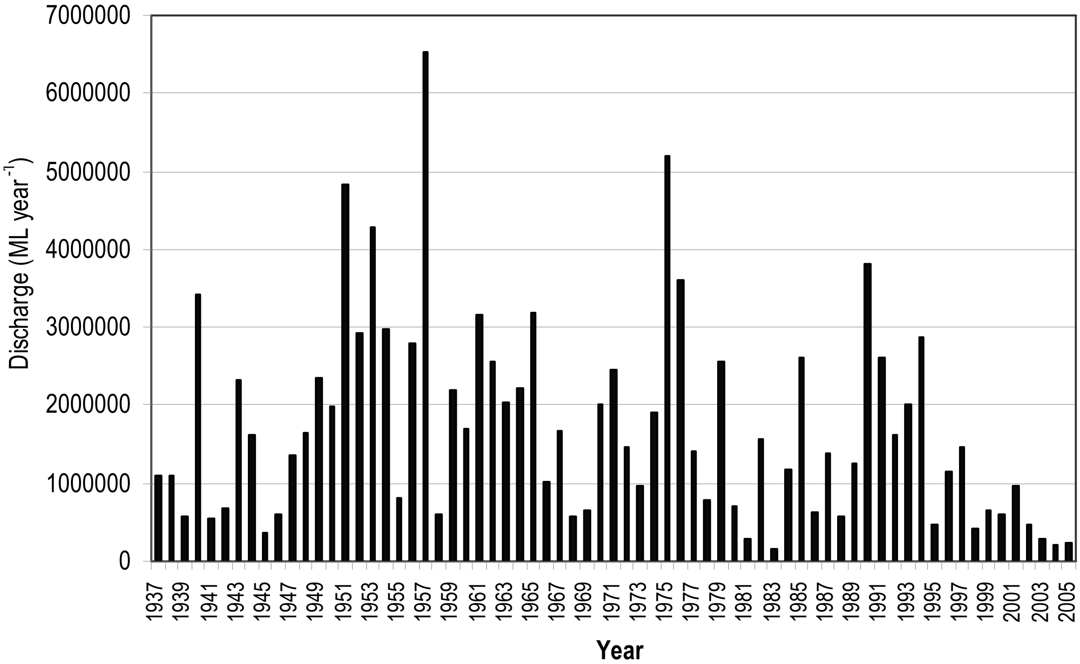

Fig. 2 Observed annual discharges for the Murrumbidgee River at Maude Weir (1937–2005).

The Murrumbidgee River is a highly regulated system with 14 large dams and eight low level weirs on its main channel or tributary systems. The largest regulating structures are Burrinjuck and Blowering Dams with reservoir capacities of 1.026 million ML and 1.628 million ML, respectively. As a result the flow regime of the lower Murrumbidgee River has been significantly altered with changes in the magnitude and frequency of a range of discharges being similar to that recorded in other river systems of the Murray Darling Basin (Thoms & Sheldon, 2000b). Prior to flow regulation, overbank flows occurred approximately once in every three years and major flood plain inundation occurred once in every 10 years in the Lower Murrumbidgee River (Maher, 1990).

This study focuses on the lower reaches of the Murrumbidgee River between the townships of Balranald and Hay (Fig. 1). Here the Murrumbidgee River is a low gradient, highly sinuous "wash load" channel, with cohesive boundary sediments and an extensive flood plain (up to 20 km wide). The study was conducted in the flood plain area of Yanga National Park (Fig. 1). Prior to being gazetted as a National Park in 2005 this area was part of the Lowbidgee Flood Control and Irrigation Scheme that was predominately used for natural pasture agriculture. The frequent flooding and the natural drying-wetting regime of the area supported a complex flood plain vegetation community including Lignum (*Muelenbeckia florulenta*) swamps, River Red Gum (*E. camaldulensis*) forests and Black Box (*E. largiforens*) woodlands. Numerous billabongs and open water lakes, all of which provide important habitat for water birds, fish and a range of reptiles and mammals (Maher, 1990), are present on the flood plain surface. *E. camaldulensis*, an iconic Australian flood plain vegetation species, cover more than 20 000 ha of the flood plain in Yanga National Park. Reductions in the magnitude, frequency and duration of flood plain inundation, a consequence of water resource development, are thought to have had a significant impact on the flood plain landscape of the region.

METHODS

To assess the influence of hydrological change on the Yanga flood plain, periods of inundation were determined from a SPELL analysis (Gordon *et al*., 1992) of simulated daily discharge data obtained from the New South Wales Department of Water and Energy (NSW DWE) 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 lower Murrumbidgee River. 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. "Current" flows were simulated using water and land-use conditions present in 2000 combined with long-term mean climatic conditions. These simulated flow scenarios were compared for the period 1937–2005 for the Maude gauging station, which is just upstream of the Yanga flood plain.

A set of digitised aerial photos scanned at 1200 dpi were obtained of the study area for the years 1965, 1973, 1997 and 2005. These photographs were ortho-rectified to produce images that were used for mapping of flood plain vegetation. An Aerial Triangulated (AT) block model was established for each photographic set in the SOCET photogrammetric software and an AT solution was produced using a series of ground control points located from SPOT 2.5 metre imagery allowing points to be tied between overlapping photos and a surface DEM. The AT model mathematically determines the position and orientation of each photograph and the residual errors. Aerial photos were examined stereoscopically to map the distribution of different vegetation communities across the flood plain. A digital mosaic ortho-rectified photograph was produced for each year and vegetation communities mapped in MapInfo GIS using the ortho-photo mosaic as a base. Vegetation boundaries were drawn as lines in MapInfo, which were converted to topologically clean GIS data sets. A GIS polygon layer was constructed in ArcGIS for each set of line-work and labels. Topology was established by snapping and intersecting lines, removing overshoots (dangles) and sliver polygons. A series of tests were run to identify issues such as identified irregularities in polygon labelling (Wen, 2009).

Maps constructed for the different years represent a "vegetation landscape" of the flood plain vegetation communities and these were used to derive a number of metrics using the spatial pattern analysis program FRAGSTATS Version 3.3 (McGarigal & Marks, 1995). These metrics describe the abundance, shape, size, spatial arrangement and diversity of the different flood plain vegetation communities present in the 1965, 1973, 1997 and 2005 photographs. The character of the four vegetation landscapes was examined via a range of multivariate statistical analyses. Initially, the Gower environmental difference measure (Belbin, 1993), which incorporates an implicit range-standardisation of variables, was used to derive a matrix of environmental distances for the vegetation landscapes based on all the vegetation landscape metrics. An Analysis of Similarity (ANOSIM) was then used to test for differences between the four vegetation landscapes based on the derived Gower matrix. In addition, Semi-Strong-Hybrid Multidimensional Scaling–MDS (Belbin, 1993) was then used to represent the similarity matrix graphically, with a stress level of less than 0.2 indicating the ordination solution not to be random. Relationships between the different vegetation landscape patch variables and the position of each vegetation landscape in multi-dimensional space was then explored using a Principal Axis Correlation–PCC (Belbin, 1993) with only those variables with an R^2 greater than 0.8 being considered.

RESULTS

The magnitude and frequency of daily flows in the lower Murrumbidgee River have changed substantially in association with water resource development. The daily current flow duration curve (1937–2005) displays a marked downward shift in comparison to the natural flow duration curve. As a consequence all flows occur less. For example, flows that would have occurred 10, 50 and 90% of the time, under the natural scenario, have reduced from 22 000, 4300 and 500 ML day^{-1} to 12 000, 1000 and 280 ML day^{-1}, respectively, under the current flow scenario. The Yanga flood plain in the lower Murrumbidgee River experiences inundation when daily discharges at the Maude Weir gauging station exceeds 20 000 ML day^{-1} and a comparison of the simulated "natural" and "current" flow regimes reveal a 71% reduction in the number of overbank events under the current flow scenario for the period 1965–2005 (Table 1). The duration of flood plain inundation is also markedly different between the natural and current flow scenarios. For the 41-year period, the flood plain would have been inundated for 1966 days under the natural flow scenario compared to 648 days for the current scenario; representing a 67% reduction in the duration of flood plain inundation. Changes in the wetting and drying regime of the Yanga flood plain appear to be relatively greater for the period 1998–2005 in comparison to the periods between 1965–1973 and 1974–1997, with these periods corresponding to the dates of aerial photography used to construct the flood plain vegetation community maps. During this latter period (1998–2005) no flood plain inundation occurred under the current flow regime, while 12 events would have been expected naturally with a total duration of 162 days.

Table 1 Changes in flood plain inundation of the Yanga flood plain based on simulated flow data at Maude Weir.

Period	Total Years	Number of overbank events		Duration of inundation (days)		Dry period (days)	
		Current flow scenario	Natural flow scenario	Current flow scenario	Natural flow scenario	Current flow scenario	Natural flow scenario
1965–1973	9	8	20	261	334	3026	2953
1974–1997	24	21	69	387	1470	8379	7296
1998–2005	8	0	12	0	162	2922	2760
TOTAL	41	29	101	648	1966	14327	13009

A total of 18 different vegetation landscape communities were identified across the Yanga flood plain (Table 2). River Red Gum forest that had a shrubby understory comprised predominantly of Lignum and some River Cooba was the dominant vegetation community, in terms of surface area, observed in all four aerial photographs. This vegetation community covered 11 943 ha or 24% of the flood plain surface in the Yanga National Park, on average. This was followed by the Black Box with a chenopod groundcover vegetation community (6282 ha or 12.6% of the surface area), the scald areas with blue bush (5877 ha, 11.8%) and the River Red Gum forest with a Spike-rush ground cover community (5264 ha, 10.6%). Cleared land accounted for a relatively small percentage of the total flood plain area (3276 ha, 6.6%) while the vegetation communities of *Acacia melvillei* woodland, Red mallee (*E. oleosa*) woodland, Prickly wattle (*Acacia victoriae*) woodland, Saltbush (*Atriplex nummularia*) shrubland and Spike-rush dominated sedgelands (*Eleocharis* sp.) were all relatively rare, in terms of their surface area contribution, with each contributing to less than 1% of the total flood plain area.

The spatial distribution of the flood plain vegetation communities as displayed in the 1965, 1973, 1997 and 2005 aerial photographs is presented in Fig. 3. Overall, the 18 vegetation communities are not uniformly distributed across the Yanga flood plain, and this spatial configuration is consistent between each of the four photographs. Dillon bush shrubland and scald grassland communities appear to be relatively more dominant in the northern sections of the flood

Table 2 Basic landscape characteristics for the 18 vegetation communities within the Yanga flood plain.

Vegetation type	1965		1973		1997		2005	
	NP	TA (ha)	NP	TA (ha)	NP	TA (ha)	NP	TA (ha)
River Red Gum (RRG) tall gallery forest (adjacent to rivers)	40	992	25	898	64	905	58	933
RRG forest with spike-rush ground cover	10	5792	10	6063	10	4581	10	4621
RRG forest with grass/chenopod shrub ground cover	18	2217	18	1219	42	4452	36	3501
RRG forest with shrubby (lignum/river cooba) understorey	8	12029	12	12477	13	11339	8	11925
Black Box (BB) with lignum/nitre goosefoot understorey	27	5275	22	3346	29	2983	28	2984
Black Box with grass/chenopod shrub groundcover	23	5308	25	7032	29	6224	31	6565
Spike-rush dominated sedgelands (*Eleocharis* sp.)	7	154	3	86	6	77	11	150
Lignum dominated shrubland	12	1558	9	1875	31	1609	28	1241
Nitre goosefoot/cottonbush dominated shrubland	9	763	10	1717	3	40	9	672
Dillon bush dominated shrubland	43	3552	33	2841	56	4164	43	4395
Scald areas with scattered blue bush/dillon bush/grassland	38	6804	36	6792	40	5368	37	4545
Belah/rosewood dominated woodland	6	932	6	890	15	986	12	918
Acacia melvillei woodland	3	492	3	471	1	259	4	370
Red mallee (*Eucalyptus oleosa*) woodland	2	42	2	40	2	40	2	40
Prickly wattle (*Acacia victoriae*) woodland	–	–	–	–	1	14	1	14
Saltbush (*Atriplex nummularia*) shrubland	3	38	3	37	2	32	4	31
Cleared land	2	1789	3	1908	15	4582	18	4826
Lake and other water body	5	1975	6	2020	7	2058	4	1980
TOTAL	256	49712	226	49712	366	49712	344	49712

NP – number of patches; TA (ha), total area in hectare.

plain (Fig. 3). In this area various River Red Gum with different understorey plant communities are present, although these vegetation communities are not as prominent as in other sections of the Yanga flood plain. In the mid sections of the flood plain different River Red Gum plant understorey communities dominate the entire flood plain landscape. In particular, River Red Gum galley forests dominate a narrow riparian area adjacent to the main channel of the Murrumbidgee River, whereas River Red Gum forests with either Spike rush or Chenopod shrub land or Lignum understorey combinations, dominate the remainder of the flood plain (Fig. 3). In the southern sections, Belah/Rosewood dominated woodland, Dillon bush shrublands, scald grasslands, cleared land and Black Box with various understorey combinations dominate.

The area and abundance of vegetation community patches varied between the four vegetation landscapes. Overall, eight of the vegetation communities increased in area, five decreased and the remaining five vegetation communities stayed the same between 1965 and 2005. In terms of the total number of vegetation community patches, 88 new patches were created during this period representing a 34% increase (Fig. 4). Associated with this change were increases in patch density and a slight decrease in the largest patch index. The most notable change occurred between 1973 and 1997, where an additional 140 new vegetation patches were recorded, comprising 39 new River Red Gum gallery forest patches, 24 River Red Gum with chenopod understorey patches, 22 Lignum patches and 23 Dillon bush patches. Changes in the combined area and number of patches for each vegetation community are summarised in Table 2. Results of the two-way ANOSIM on

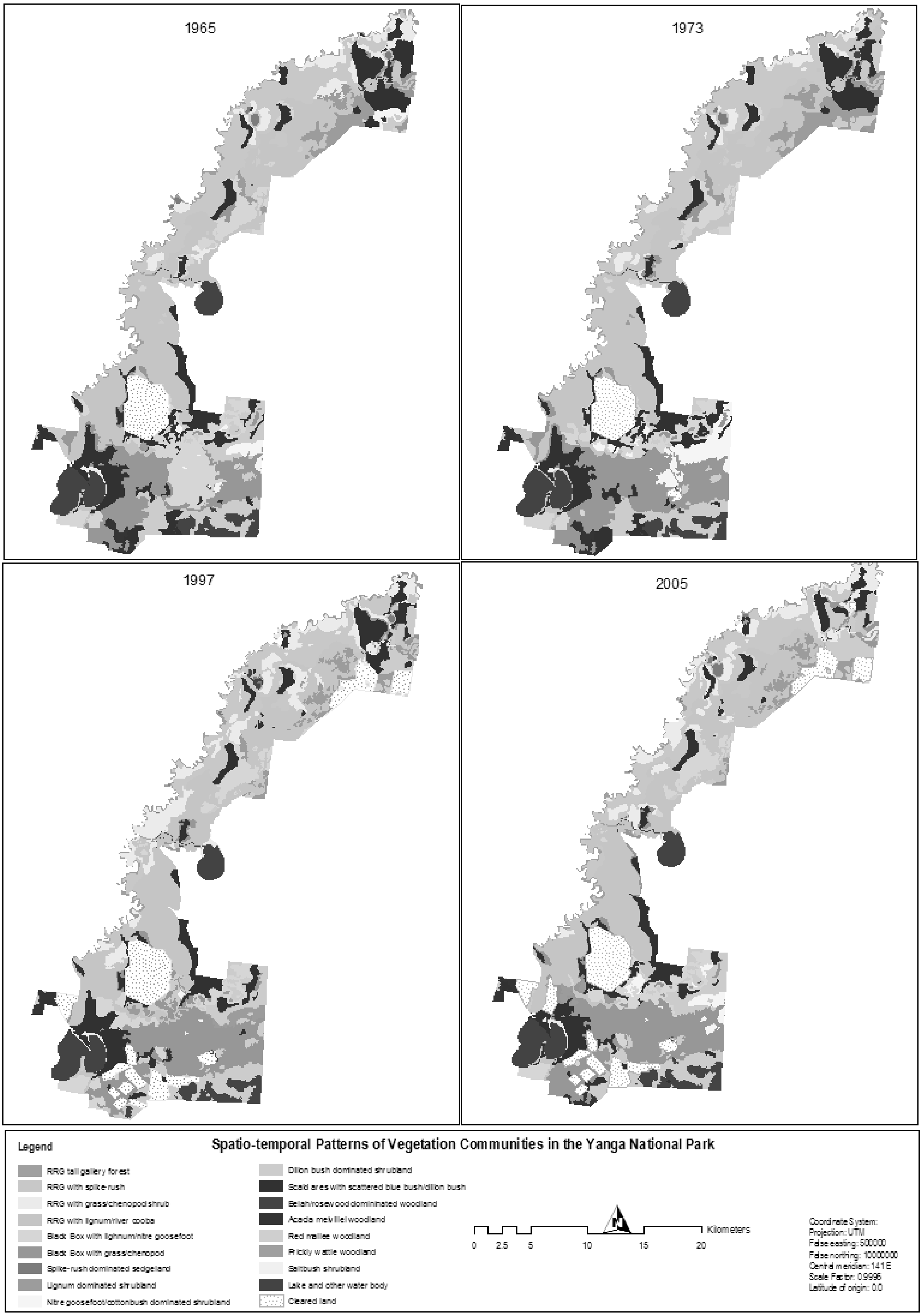

Fig. 3 The distribution of the 18 vegetation communities identified in Yanga flood plain during the years 1965, 1973, 1997 and 2005.

individual patches indicate differences between some vegetation community groups and no differences in the overall patch character between the four years (Global $R = 0.653$, $p < 0.001$ and Global $R = 0.211$, $p < 0.001$ for vegetation community groups and year, respectively). Six vegetation community groups did change consistently between the different years; these being River Red Gum with a chenopod under storey, Black Box with a lignum under storey and a chenopod under storey, Dillon bush land, scalded grasslands and the Belah woodlands. The PCC results show only two patch variables; patch area and fractal number had R^2 values greater than 0.80 and their position in multivariate space was strongly associated with different vegetation landscapes in terms of vegetation community group and year influences.

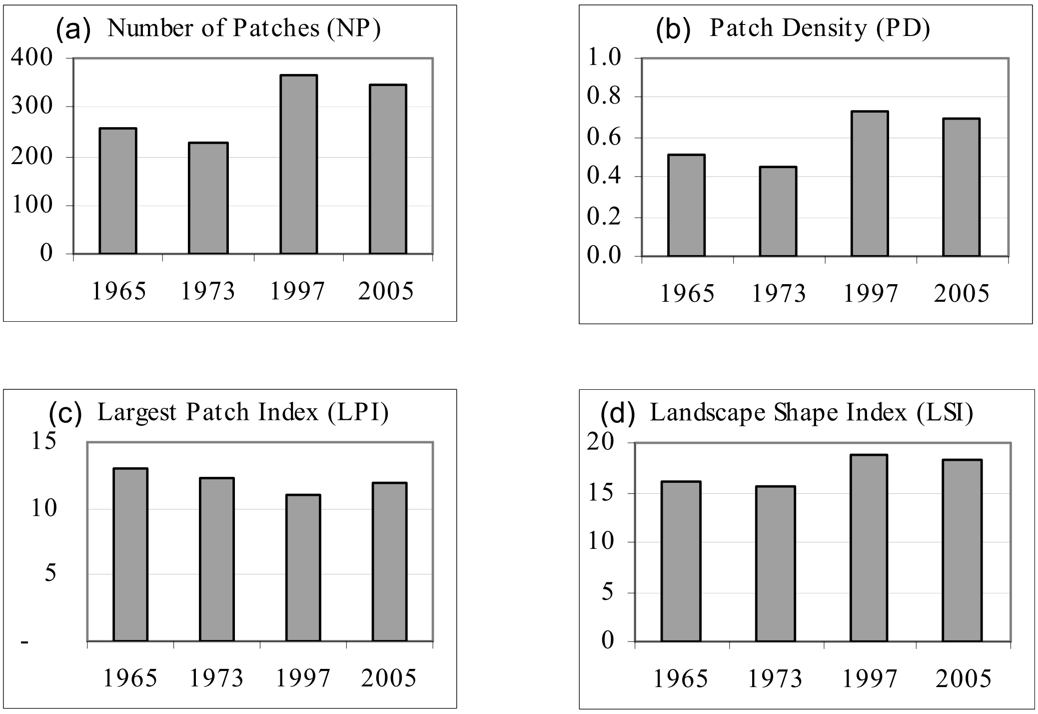

Fig. 4 The change in character of the vegetation landscape of the Yanga flood plain: (a) number of patches (NP); (b) patch density (PD); (c) largest patch index (LPI); (d) landscape shape index (LSI).

DISCUSSION

Flood plain landscapes are natural fragmented ecosystems because of periodic hydrological connections. The integrity of these ecosystems is thought to be dependent, in part, upon exchanges of energy and matter between patches, such as the main river channel, adjacent flood plain surface and other morphological features, during periods of connection. Water resource developments and associated regulation of flows and infrastructure change the natural character of fragmentation in flood plain landscapes, and have important consequences for their overall productivity. The four states of the vegetation community structures in the Yanga flood plain show no consistent predictable pattern of vegetation community across the landscape (see Fig. 3). This suggests that the vegetation landscape of the Yanga flood plain does not resemble that of a typical Ecotone or ATTZ (Aquatic Terrestrial Transition Zone). Rather, this flood plain vegetation landscape resembles a mosaic of vegetation community patches which change over time.

A patch can be defined as a surface area that differs from its surroundings in nature or appearance (Turner, 1989) and that may be represented by the different morphological features or, in this study, different vegetation community structures. We have shown these vegetation landscape patches to differ in terms of their size, shape and proximity to each other, this being a product of current and past hydrological activity. Hydrological connectivity between the river channel and various flood plain patches is thought to be an important factor stimulating flood plain–river ecosystems (Tockner *et al.*, 2000). Flooding not only facilitates exchanges of sediments, nutrients and biota between river channels and flood plain patches, but also supplies water that is essential for the structure and functioning of vegetation communities within these landscapes (Amoros & Bornette, 2002). Fragmentation is a term used for the increase or elimination of patches and or connections between patches in a landscape (Kotliar & Wiens, 1990). Fragmentation of flood plain–river ecosystems is exacerbated by human activities in two ways. First, the construction of levees, dykes and other engineering structures, commonly used as flood control measures, isolates flood plain patches not only from the river channel, but also from other flood plain patches. Second, water resources development changes the period of hydrological connection. The impact of water resource development on river systems is well documented (e.g. Petts, 1984) and hydrological change can occur at different scales (cf. Thoms & Sheldon, 2000b).

This study has shown the influence of water resources development on the fragmentation of vegetation patches in Yanga flood plain over time. An analysis of the natural and current flow scenario flood spells confirm a marked reduction in overbank flow events to the Yanga flood plain between 1965 and 2005, which is attributed to the water resources development in the upper catchment. Associated with this was an increase in patch density and slight decrease in largest patch index of the vegetation landscape, suggesting an overall fragmentation of this vegetation landscape overtime. Changes in vegetation community patch structure were recorded across the entire landscape throughout the study period. The River Red Gum forest and Black Box forest are regarded as drought tolerant vegetation species. Although, the total area of both in River Red Gum forest and Black Box woodlands remains unchanged during the period, there was a marked change in their associated understorey vegetation with change in hydrological condition. The change in the understorey vegetation indicates that these communities are more sensitive to hydrological change than that of the River Red Gum and Black Box trees.

In terms of vegetation patch characteristics, the most notable change occurred between 1973 and 1997. During this period several new patches of Red River Gum gallery forest patches emerged, but the total area of this vegetation community remained the same. This indicates fragmentation of the River Red Gum forest patches occurred during the period. Other notable changes occurred in the flood plain shrublands communities. Many of the scrublands patches increased in number, but this was associated with a decrease in their total area, except for the Dillion bush dominated shrublands, which gained both in number as well as total area. Overall, the relatively stable area of River Red Gum forest and Black Box woodlands reveals no long-term response (in terms of extent) of the dominant vegetation communities to a change in flood plain hydrology. In comparison, their associated understorey and other vegetation communities including grass shrublands appear to be more sensitive to changes in hydrological condition.

Resilience is the amount of change a system can undergo (its capacity to absorb disturbance) and remain within the same regime that essentially retains the same function, structure and feedbacks (Walker & Salt, 2006). Of the nine fundamental principles of resilience thinking in river ecosystems, the identification of slow and fast variables are important in driving regime shifts between alternate stable states. The results of this study of the vegetation landscape of Yanga flood plain suggest River Red Gum and Black Box may be slow variable indicators while understorey vegetation communities represent fast variables. Future monitoring of the influence of changing hydrology on this flood plain vegetation should have different strategies for the different vegetation responses.

CONCLUDING REMARKS

Many of the world's large flood plain-rivers have been altered by human activity, and water resources development is considered to be a primary cause of decline in the biodiversity and ecological integrity of these systems (Tockner *et al.*, 2006). The management and rehabilitation of these altered ecosystems requires knowledge about the effects of activities such as water resources development on both the spatial and temporal dimensions of fragmentation. The present study has applied an interdisciplinary approach, linking hydrology and landscape-ecology, within a framework to investigate the consequences of a changed hydrology and vegetation landscape character. Three of the six central themes that unify landscape ecology (Wiens, 2002) were used in this study: (1) landscapes comprise a mosaic of patches; (2) patches may differ in size, shape and proximity to each; (3) scale is important. The four snapshots of vegetation community structures investigated in this study reveals that the Yanga flood plain does not resemble a typical Ecotone or ATTZ (Aquatic Terrestrial Transition Zone), rather it resembles a mosaic of patches of vegetation communities.

Acknowledgements This study was supported by the Department of Environment and Climate Change (DECC), NSW and the Murrumbidgee Catchment Management Authority, Australia. Dr Li Wen and Dr Neil Saintilan of DECC were thanked for helped with data provision, particularly the vegetation community maps. Dr Michael Reid and Dr Melissa Parson and other colleagues at RLRL are gratefully acknowledged for the fruitful discussions during the course of study.

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