The diversity of inundated areas in semiarid flood plain ecosystems

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Abstract Contemporary methods for managing flood plain ecosystems are biased towards temporal patterns of flow. Such approaches disregard the inherent spatial complexity associated with the flooding and drying of flood plain ecosystems and the influence this has on their productivity and biodiversity. This study investigates how the character of inundated patches changes through two flood events in the Narran Lakes ecosystem, Australia. A series of Landsat thematic mapper (TM) images were used to elicit patterns in inundated-patch character over time. Characteristics including patch number, size, shape and proximity to other patches were calculated for each image and subjected to multivariate statistical analyses. Strong positive relationships were observed between patch number; richness of patch area, shape and proximity and total surface area inundated. Hysteresis was also observed for the latter three relationships. This work highlights the importance of incorporating both spatial and temporal aspects of flood plain inundation in determining environmental water allocations for flood plain maintenance.

Key words environmental water allocations; flood plain wetlands; fragmentation; landscape diversity; satellite remote sensing

INTRODUCTION

Flood plains are ecotones that form a transition between aquatic and terrestrial environments. These ecosystems are dynamic spatial mosaics in which water plays an important role in connecting various patches on the flood plain surface (Thoms, 2003). Hydrological connections not only facilitate the exchange of carbon and nutrients between various parts of the flood plain–river ecosystem, but also create a dynamic mosaic of inundated patches during the expansion and contraction of flood waters. The biodiversity of flood plain ecosystems is relatively high compared to adjacent terrestrial environments, because their periodic inundation provides renewal of resources (Naiman *et al*., 2005) and they are inhabited by species from adjacent landscape systems as well as specialist "edge" species (Lynch & Whigham, 1984) that are sensitive to landscape change and disturbance.

Reductions in the size of inundated flood plain patches lead to increases in the ratio of edge-to-core habitat, thereby altering ecotone character. Flood plain diversity is maximized with an optimal mix of patch and edge habitat (Naiman *et al*., 1988). In this state, the physical template of flood plains will enhance exchanges of organic material, energy and organisms between patches without reducing biodiversity through excessive fragmentation or by the homogenization of habitat that accompanies high connectivity (Ward *et al*., 1999).

Allocating water to sustain natural ecosystems, restore rivers degraded by over-abstraction and protect biodiversity has become a key water resource management issue worldwide. Many approaches and techniques are available to assist in determining environmental water allocations. The majority focus on in-stream flow requirements and are not directly applicable to flood plains (Tharme, 2003). Those that are applicable only highlight the need for "flood plain maintenance flows" (e.g. Richter & Richter, 2000; Hughes & Rood, 2003) and that these flows should be commensurate with the natural frequency, magnitude and duration of inundation—as prescribed by the "natural flow paradigm" (Poff *et al*., 1997). Although prevalent in Australia and elsewhere, this approach is simplistic and may not achieve optimal environmental benefits, because it ignores the complex spatial aspect of flood plain inundation (Thoms, 2003). Managing flood plain flows to ensure landscape diversity or heterogeneity is an alternative approach and one that is an essential component in conserving system resilience (Pickett *et al*., 2003).

This study utilizes satellite imagery and a suite of spatial metrics to explore changes in the inundation character of a large Australian dryland flood plain ecosystem during two flood events. Data are used to examine patch heterogeneity (and potentially biodiversity) during the expansion and contraction of floodwaters across the Narran Lakes flood plain–wetland complex in Australia. Heterogeneity is measured in terms of the variability of, and relationships between, the total number of inundated patches, their size, shape and proximity to each other. The results of this study represent an important step in identifying how best to manage flood plain water allocations to provide enhanced patch diversity.

STUDY AREA

The Narran Lakes Ecosystem (29º49′S, 147º22′E) is a terminal flood plain–wetland complex in the Condamine–Balonne Catchment River, southeast Australia (Fig. 1(a)). The Narran Lakes ecosystem has four distinct water bodies: Clear Lake, Back Lake and Long Arm in the north and Narran Lake in the south, and a large flood plain area throughout (Fig. 1(b)). The local catchment area of the Narran Lakes ecosystem is relatively small (~46 km^2); consequently, the system does not fill as a result of local precipitation but from flows in the Narran River. Long-term mean annual flow (1960–2000) in the Narran River is 141 000 ML. However, flow is highly variable, with standard deviations (SD) for the same period exceeding 150 000 ML and the largest recorded flood exceeding 560 000 ML. High inter-annual flow variability in the Narran River (Thoms, 2003) results in a complex flood history with periodic wet/dry cycles within the Narran Lakes ecosystem. Preliminary analyses of satellite imagery suggest that, over the last 33 years, Clear Lake and Narran Lake have been inundated 23 and 16 times, respectively, while the intervening flood plain has only been inundated on six occasions. Extensive water resource development upstream has significantly changed the hydrology of the Narran River at a number of scales (Thoms, 2003) and is currently perceived as a major threat to the ecological integrity of the Narran Lakes ecosystem (Thoms & Parsons, 2003).

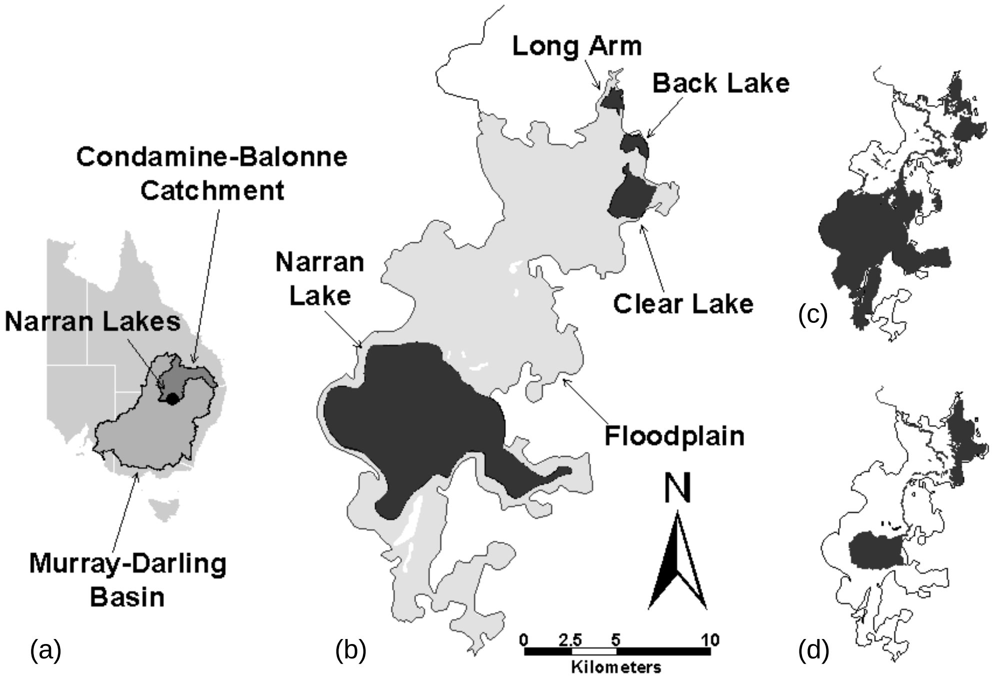

Fig. 1 Location of the Narran Lakes ecosystem: (a) regional location of the Narran Lakes; (b) the Narran Lakes ecosystem; (c) extent of the 1995–1997 flood sequence (August 1996); and (d) extent of the 2004 flood sequence (April 2004).

METHODS

Fourteen near cloud-free Landsat Thematic Mapper (TM5) scenes were obtained covering two flooding and drawdown sequences that took place from December 1995 to February 1997 and from February to December 2004. Total discharges of 496 000 and 26 000 ML were recorded for the 1995–1997 and 2004 floods, respectively. The maximum inundated areas of these floods have a 20 and 50% probability of occurrence, respectively, in any one year based on a log3 Pearson annual series. Antecedent conditions for each flood were relatively dry and consisted of a few pools of stagnant water in the channel entering the wetlands equating to areas of ~31 and ~25 ha, respectively. All images were geometrically corrected to Geodetic Datum of Australia 1994 (GDA94), Universal Transverse Mercator (UTM) zone 55S by cubic polynomial rectification. Image-to-image rectification was used with the base satellite image being rectified to a 250 K digital topographic map. A minimum of 20 ground control points (GCPs) were collected for each scene and all RMS errors were kept below one pixel (30 m). A Band 5 (1.55–1.75 μm) density slice was performed on all images, as this near infrared (NIR) band shows very high absorption of radiant flux for water and significant reflection for vegetation and bare soils. This analysis delineates a sharp boundary between land and water. In some cases, where the above method produced unsatisfactory results, an unsupervised ISODATA classification (maximum number of classes: 235; iterations: 24) was performed and classes were grouped into water and dry classes. The resultant rasters were converted to vector format for "cleaning" and editing (i.e. connection of channels where expert knowledge suggested connection would exist, removal of water tanks, clouds, errors and inundated areas unrelated to the Narran River inflow). Vectors were then converted to signed 32-bit integer grids for use in the spatial pattern analysis program FRAGSTATS Version 3.3 (McGarigal & Marks, 1995). A series of spatial metrics were obtained and analysed with FRAGSTATS using the 8-cell rule such that diagonally touching pixels were considered as one patch. Metrics analysed include number of patches, area, shape index and a proximity index. A full explanation of each metric is given in (McGarigal & Marks, 1995).

Four measures of diversity were calculated to provide a reflection of the overall distribution of the different inundated patch character—in this case: area, shape and proximity. The measures calculated were Margalef Richness Index (D_{Mg}), Shannon Evenness Index (D_{Se}), Shannon Weiner Diversity Index (D_{Sw}), and the Simpson Diversity Index (D_{Si}) (Zar, 1984). Combined, these indices provide a measure of abundance, richness and evenness components of diversity of individual inundated patches calculated from each image.

The character of flood plain inundation during the two flood events was examined via a range of multivariate statistical analyses. Initially, a similarity matrix of Gower's dissimilarity coefficients was calculated using the area of inundation, number of patches and the four diversity measures for each flood image. This matrix was used to test between flood differences using the analysis of similarity (ANOSIM) routine in the PRIMER computer package (Clarke & Warwick, 1994). Semi-Strong-Hybrid Multidimensional Scaling (MDS; Belbin, 1993) was used to represent the similarity matrix graphically. A stress level of less than 0.2 indicated that the ordination solution was not random (Clarke & Warwick, 1994). In order to reduce the possible influence of flood size, this statistical routine was undertaken with and without the total surface area inundated and patch number as variables. Relationships between the different inundated-patch variables and the position of each image in multi-dimensional space were determined using Principal Axis Correlation (PCC; Belbin, 1993) and only those variables with an R^2 greater than 0.8 were considered.

RESULTS

The area of inundated flood plain in the various satellite images ranged from 0.49 km^2 (December 2004) to 117.78 km^2 (August 1996). There were significant changes in the number of inundated patches from image to image and between the two floods. In addition, an anti-clockwise hysteresis pattern was observed during both floods (Fig. 2)—the number of inundated-patches being higher during drawdown than during inundation. Overall, only nine inundated-patches were recorded in the December 2004 image, whilst a maximum 165 inundated patches were recorded in the August 1996 images. A strong positive power relationship ($y = 0.8301x^{0.4943}$, $r^2 = 0.6265$, $P < 0.001$) between flood plain-inundated area and the number of inundated-patches was observed when data for the two flood events were combined (Fig. 2). The results of the ANOSIM indicate a significant difference between the two flood events in terms of the character of flood plain inundation (Global $R = 0.245$, $P < 0.001$). However, when total inundated area and patch number were removed as variables, there was no significant difference between the two floods (ANOSIM: Global $R = 0.823$, $P < 0.001$),

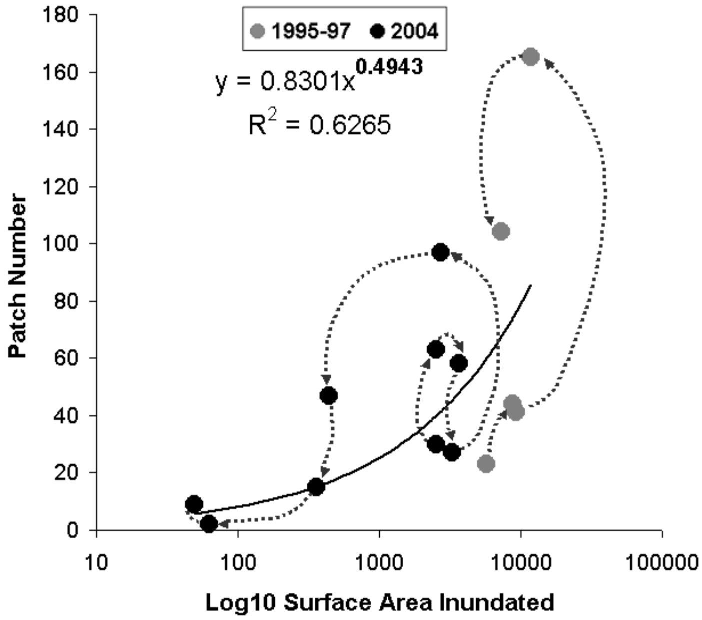

Fig. 2 Number of patches and inundated surface areas ($\log_{10}$ ha) for the 1995–1997 and 2004 flood sequences. The solid line is the line of best fit and the dashed lines trace the flood sequences for both flood events.

thereby minimizing the importance of size in discriminating between the two floods. The results of the PCC analysis indicate that only three inundated-patch variables, the Margalef Richness for size (R^2 = 0.811), shape (R^2 = 0.841) and proximity (R^2 = 0.823), were strongly associated ($R^2 > 0.8$) with the two flood events.

Summary data of the distribution of inundated-patch character in terms of the size, shape and proximity between inundated-patches are presented as box-and-whisker plots (Fig. 3). Median inundated-patch size did not vary greatly between individual images for both flood sequences (Fig. 3(a)), although there is an increase in the median size of inundated patches towards the end of each flood sequence, presumably as a result of smaller patches drying out leaving larger water bodies remaining. A similar pattern was recorded for the shape index (a size standardized shape regularity index) (Fig. 3(b)), with median patch shape ranging from 1.14 to 7.92 for the two flood events. However, median patch shape generally ranged between 1.14 and 1.97 for the two flood events, although the last two images of the 2004 event are an exception with median inundated-patch values increasing to 7.92. Median proximity values (Fig. 3(c)) fluctuated from less than 0.01 to over 5000, but there was a general decrease throughout the two flood events suggesting fragmentation prior to a sharp increase at the end of each flood.

Strong positive power relationships were observed between the surface area inundated and Margalef richness indices for inundated-patch size ($y = 0.2139x^{0.4002}$, $r^2 = 0.4636$, $P < 0.007$), shape ($y = 0.211x^{0.4712}$, $r^2 = 0.6095$, $P < 0.001$) and proximity ($y = 0.1315x^{0.2783}$, $r^2 = 0.4601$, $P < 0.003$) (Fig. 4) when data for both flood events were combined. However, these relationships were more complex during the individual floods. Clear clockwise and anti-clockwise hysteresis relationships were observed between surface area inundated and the various richness indices during individual flood events, the only exception being the relationship between surface area

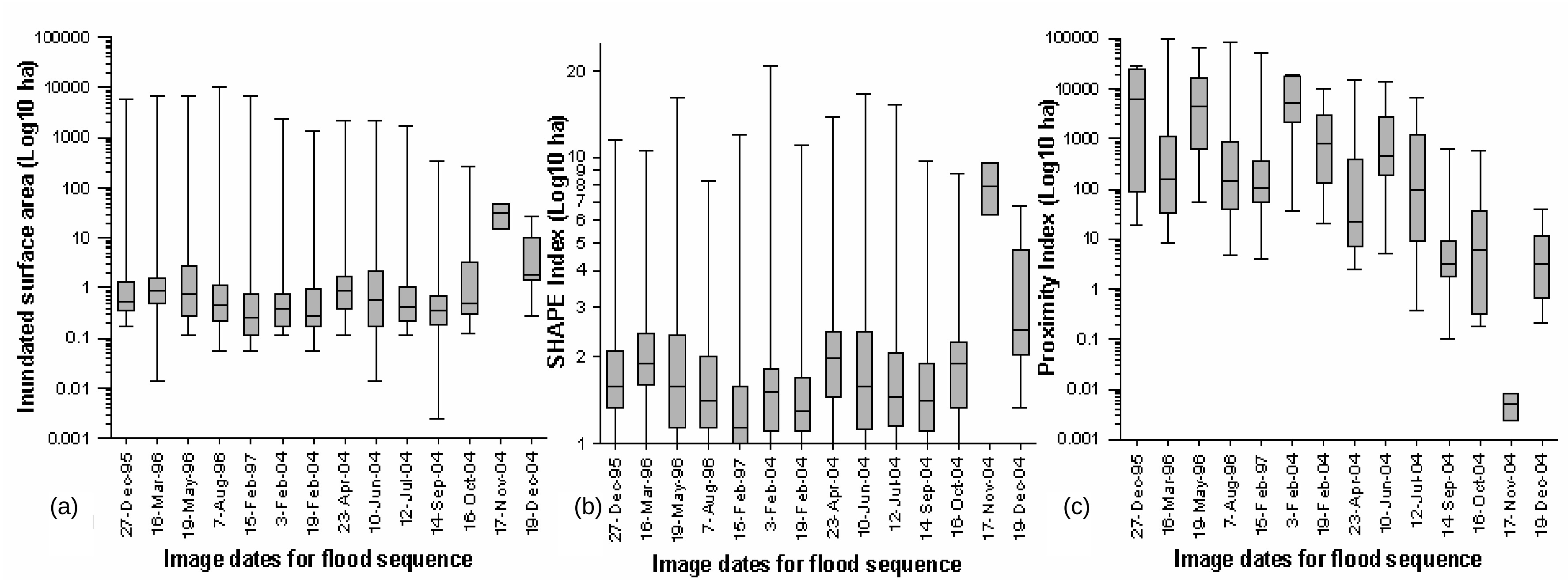

Fig. 3 Box-and-whisker plots for $\log_{10}$-transformed shape metrics for (a) patch sizes; (b) patch shapes; and (c) patch proximity for the 1995–1997 and 2004 Narran Lakes flood sequences.

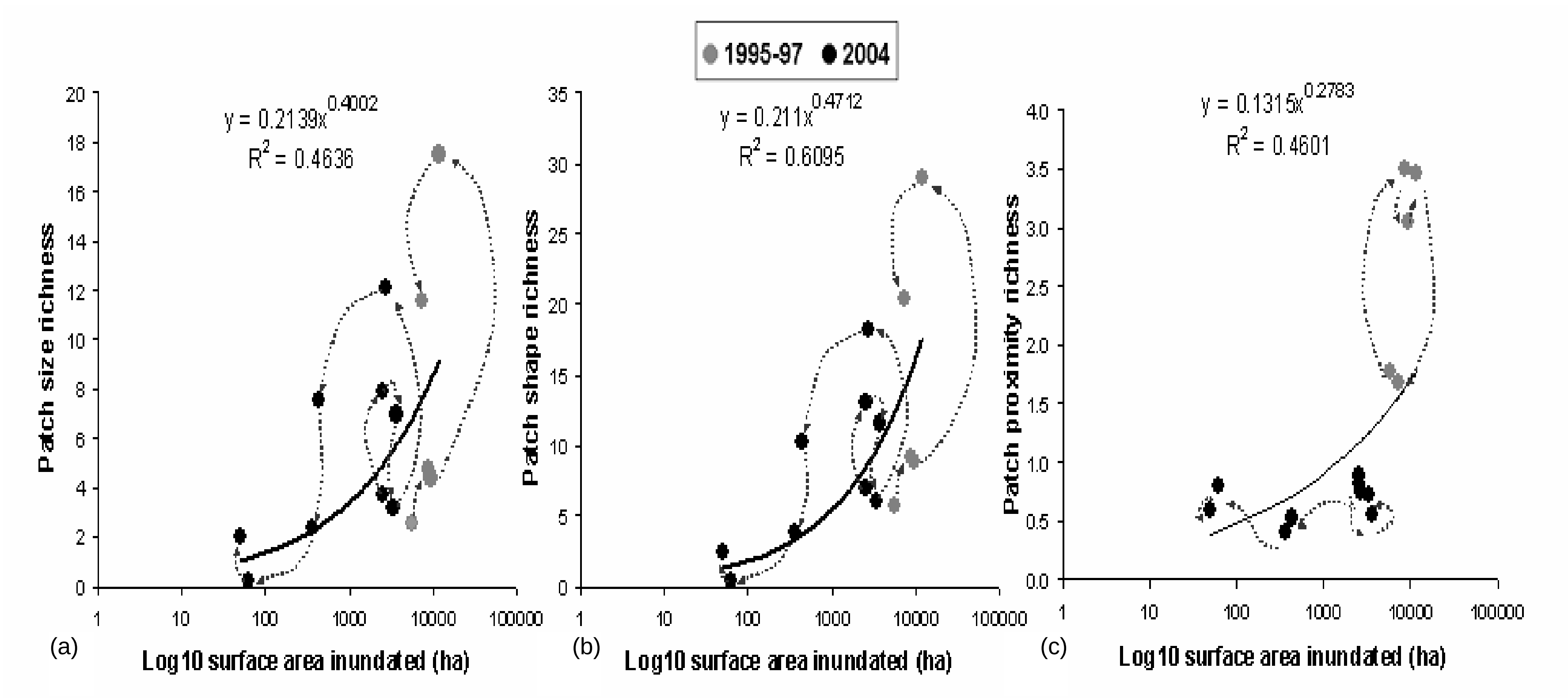

Fig. 4 Relationships for Margalef richness indices and inundated surface area for the 1995–1997 and 2004 flood sequences: (a) richness of patch sizes; (b) richness of patch shape; and (c) patch proximity. The solid lines are the line of best fit and the dashed lines trace the flood sequences for both flood events.

inundated and proximity for the 2004 flood. For patch area and shape, anti-clockwise hysteresis was observed indicating a greater diversity of inundated-patch sizes and shapes during the contraction of flood waters in comparison to the expansion of flood waters across the Narran Lakes flood plain. However, patch proximity for the 1995–1997 flood displayed a clockwise hysteresis indicating that the richness of proximities between patches is greater on the expansion of flood waters across the flood plain.

DISCUSSION

The expansion and contraction of flood waters across the Narran Lakes flood plain surface produced a dynamic mosaic of inundated patches. There was a complex response from the size of the inundated flood plain area, the number of inundated patches (Fig. 2) and the richness of their sizes, shapes and proximities to each other, during the two floods (Fig. 4). Flood size and the number of inundated patches appear to be the most important discriminators of inundated-patch character as indicated by the multivariate analyses. Once these variables were removed from the statistical analyses, no statistical difference between the two floods, in terms of the diversity of inundated-patch character, was observed. Overall, there was a high degree of overlap in the richness of inundated-patch character between the two floods, although maximum diversities for size and shape richness were recorded in August 1996, and for proximity in March 1996 (Fig. 4). The complex response to the expansion and contraction of flood waters is further illustrated by pronounced hysteresis in the relationship between surface area inundated and patch richness for size, shape and proximity. In addition, this pattern was not the same for each patch characteristic. Thus, the expansion and contraction phases of an inundation event are important drivers of flood plain inundated-patch diversity.

The interface between science and policy-management is turbulent (Cullen, 1990). Many knowledge gaps must be addressed to determine appropriate environmental water allocations for flood plain ecosystems, particularly given that techniques and procedures developed for in-stream environments are not directly applicable to flood plains. Boulton *et al.* (2000) suggests that, in the interim, specialist policies for flood plain systems must address the following:

– the importance of no flow (the drying phase), variable duration and timing;
– the need for integrated flow management on a whole-of-catchment scale;
– maintenance of flows to promote a diversity of habitat types on large time and spatial scales;
– explicit recognition that the public perceive no flow (the drying phase) as a problem; and
– educational programmes to remedy this concern.

This study has demonstrated how the spatial arrangement and character of inundated-patches across a large flood plain–wetland complex change over time. This is an important step in determining environmental water allocation for these systems. The ecosystems approach to determining environmental flow allocation advocates identifying flow bands that provide the greatest ecosystem response in terms of habitat created or ecological service provided (Thoms & Sheldon, 2002). Inundations of the Narran Lakes flood plain between 2500 and 12 000 ha are associated with the greatest range of inundated-patch character, in terms of the richness of inundated-patch size, shape and proximity. In other words, floods targeted to result in inundated surface areas within this range will result in relatively larger spatial variations in the arrangement and diversity of flood plain inundated-patches (Fig. 4). It is important to note that floods resulting in a greater total inundated surface area pass through this critical range on both flooding and drawdown. This has implications for managing the drawdown of large floods because the fragmentation resulting from allowing floods to dissipate naturally may result in a greater diversity in patch character. The relationship between discharge and the area of flood plain inundated have not yet been established for the Narran; however, once established, it will be possible to manage flows in the Narran River to maximize inundated-patch diversity, and therefore biotic diversity, for this flood plain.

Such an approach to setting environmental flows for flood plains develops the often neglected spatial aspect to the natural flow paradigm (Poff *et al.*, 1997) and provides an opportunity to maximize the benefit to the entire riverine ecosystem from an amount of water that may not allow restoration of key parts of the natural hydrograph. Thus flow management that targets both the temporal and spatial dimension of the flow regime, with flow allocations providing a dynamic mosaic of inundated-patches, may be key to maintaining the biodiversity of flood plain ecosystems.

CONCLUSION

The results of this study emphasize the need for considering spatial heterogeneity in the management of flood plain ecosystems, particularly in the allocation of environmental flows. Flood plain ecosystems are demonstrated to be extremely stochastic in inundated-patch character throughout individual flood sequences and it is the processes of expansion and fragmentation that drive this variation, as shown by multiple hysteretic relationships in inundated-patch character. Total inundated surface area and its positive correlated metric—patch number—emerged as the only characteristics significantly separating out the two floods investigated. Patch area, shape and proximity richness indices also demonstrated strong positive relationships with total inundated surface area. Using these correlations, an ecosystem approach is used to discern bands of inundated area associated with the greatest diversity in inundated-patch character as a means of theoretically maximizing biotic diversity. This can be extrapolated out to determine flood plain environmental water allocation if the relationship between discharge and inundated surface area is known. Managing flood plain environmental water allocation through the maintenance of dynamic patch mosaic is a novel approach, but seeks to address the gap in existing approaches to flood plain management.

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