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Variety is the spice of river life: recognizing hydraulic diversity as a tool for managing flows in regulated rivers

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Abstract Biodiversity in river ecosystems is supported by physical diversity in the river environment. Physical diversity is, in part, defined by hydraulic characteristics such as water depth, flow velocity, and turbulence. Establishing the relationship between discharge and hydraulic character is an important step in the process of managing flow to maintain and enhance physical and biological diversity within these systems. This paper considers the relationship between discharge and hydraulic character in the regulated lowland section of the River Murray, Australia. Spatial variation in hydraulic conditions was determined by mapping hydraulic character at three flow discharges: 2000, 3000 and 9000 ML day^{-1} in three reaches of the River Murray. These data were used to define patches of distinct hydraulic conditions, primarily using depth-averaged flow velocity. The physical character and spatial arrangement of these patches varied according to reach and discharge. This study shows that spatial flow variability can be used as a management tool to maximize habitat diversity in regulated rivers.

Key words ADP; flow; River Murray; patches; riverine ecosystem; spatial-temporal variability

INTRODUCTION

The allocation of water for environmental purposes is a major challenge for environmental managers worldwide. Changes to the natural flow regime; in terms of the magnitude and frequency of flows that result from flow regulation and water abstractions alter the natural hydraulic conditions of a river. This ultimately contributes to the modification and reduction in existing habitat heterogeneity and overall diversity of river ecosystems (Poff *et al.*, 1997; Parsons *et al.*, 2003). Many flow management strategies are built upon the natural flow paradigm (Tharme, 2003) with the idea that flows should be managed to mimic, as far as practical, the natural flow regime. However, it is often difficult to achieve regimes that mimic, in any real way, the natural flow regime, especially in large lowland rivers where a large proportion of annual flow is allocated for human demands. In recognition of this there is a perceived need to establish what the key elements of the hydrograph are for river ecosystems and target species in order to maximize the ecological return for water allocated to the environment. Given the importance of temporal and spatial variability in physical habitat, an obvious approach to the question of how to maximize ecological benefit is to focus on the spatial and temporal patterns of hydraulic conditions created by different flows and flow regimes.

Temporal and spatial variation in flow is important for the creation and maintenance of heterogeneous habitat patches at channel, reach and network scales, and the arrangement of these patches is critical in sustaining river ecosystems (Tockner *et al.*, 2000; Poole, 2002). Flow variation is important at all scales (Biggs *et al.*, 2005). However, mesoscale flow variability has been largely ignored in lowland systems. This is partly because spatial and temporal variation in hydraulic conditions is less obvious in lowland streams than in upland streams, but also because logistical difficulties have prevented measurement of hydraulic conditions at the spatial scale and precision required to characterize mesoscale hydraulic variation in lowland streams. However, the development of Acoustic Doppler methods means that the rapid and accurate measurement of flow velocities in three dimensions at fine spatial scales is now possible, thus enabling the nature of hydraulic variation in lowland rivers to be investigated.

This study uses an Acoustic Doppler Profiler (ADP) to examine the distribution of patches of distinct hydraulic character in a lowland river under varying discharge conditions. It is hoped that this study will demonstrate that this approach can be used to predict how different flow scenarios will affect spatial and temporal patterns in hydraulic condition (and hence physical habitat), and thus provide a valuable river management tool.

METHODS

Study area

The study was conducted in the Lock 11 weir pool at Mildura on the lower River Murray in SE Australia, immediately upstream of its confluence with the Darling River (Fig. 1). Flow in the lower Murray is regulated by a series of headwater dams

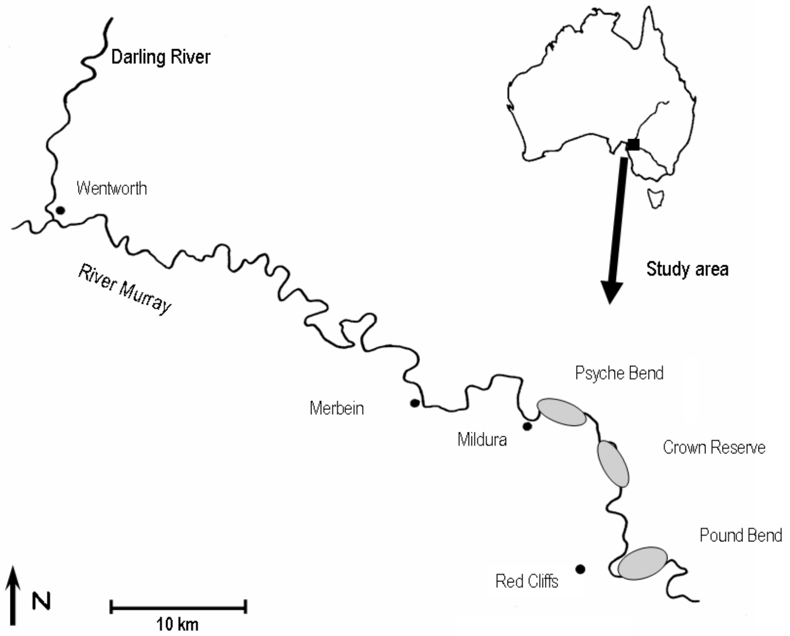

Fig. 1 The Lower River Murray showing the location of the study reaches.

and low level weirs situated on upper River Murray and its tributaries (Thoms & Walker, 1993). These regulatory structures serve principally to deliver water for irrigated agriculture. Although natural patterns of higher winter flows and lower summer flows have been maintained, upstream flow regulation and water abstractions has resulted in a ~50% reduction in annual average discharge and a suppression of peak flows throughout the lower Murray (Maheshwari *et al.*, 1995).

Flow velocity was measured at three reaches. Psyche Bed (Site 3), a 1.1 km reach is located immediately upstream of the Lock 11 weir pool (Fig. 1). Crown Reserve (Site 6), a 1.04 km reach is 32 river-km upstream of Psyche Bend, but also contained within the Lock 11 weir pool (Fig. 1). Pound Bend (Site 11), is a 1.8 km free-flowing site some 130 river-km further upstream of Crown Reserve (Fig. 1).

Study design

Flow surveys were carried out at each reach during three different discharges: 3000 ML day^{-1}, 9000 ML day^{-1} and 2000 ML day^{-1} during April 2004, July 2004 and May 2005, respectively. Flow velocities were measured using boat-mounted Acoustic Doppler profiler (ADP). Depth-velocity profiles were recorded at intervals along the perimeter of the channel and along transects across the channel every 5–10 m. The position of each profile was recorded simultaneously with a differential GPS. Between 439 and 1219 profiles were recorded for each reach and measurement run, equating to a profile every 115 to 533 m^2 of reach area.

Data analysis

Individual velocity profiles were summarized as depth-averaged velocities in cm s^{-1} using the Sontek River Surveyor program. For each reach and measurement run, the depth-averaged velocities were interpolated to raster grids in ArcGIS 8.2 using an Inverse Distance Weighting transformation. Grids were then reclassified into classes or hydraulic patches based on boundaries determined from the break points in the cumulative frequency curve of all depth-averaged velocities. These grids, which represent a “landscape” or “reach-scape”, were used to derive 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 hydraulic patches belonging to each of the *a priori* determined classes for each reach-scape.

The character of different reach-scapes was examined via a range of multivariate statistical analyses. Initially, the Gower environmental difference measure (Belbin, 1993), which incorporates an implicit range-standardization of variables, was used to derive a matrix of environmental distances between reach-scapes based on all the reach-scape metrics. A two-way Analysis of Similarity (ANOSIM) was then used to test for differences between sites and flows 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. A stress level of less than 0.2

indicated that the ordination solution was not random. Relationships between the different hydraulic patch variables and the position of each reach-scape in multidimensional space were determined using Principal Axis Correlation, PCC (Belbin, 1993) and only those variables with an R^2 greater than 0.8 were considered.

Reach-scape diversity, in terms of hydraulic patch character, was also determined according to the rank dissimilarity used to compute the comparative Index of Multivariate Dispersion (IMD) as described by Warwick & Clarke (1993). This measure was developed to determine if community structure has increased variability under certain conditions (Warwick & Clarke, 1993). Thus, this multivariate measure of rank dissimilarity was adopted for the present study to determine if patterns or relationships existed between flow and site and the diversity of reach-scapes.

RESULTS

Depth-averaged velocities (DAV) recorded across all sites and flows ranged from 0.05 m s^{-1} to 1.96 m s^{-1}. The median DAV was 0.33 m s^{-1}, while 10th and 90th percentiles fell at 0.24 m s^{-1} and 0.54 m s^{-1}, respectively. A total of seven DAV classes—hydraulic patches—were determined from the cumulative frequency curve (Fig. 2). The hydraulic patch boundaries and percent of total profiles belonging to each hydraulic patch are presented in Table 1; the spatial distributions of each class are mapped for each reach-scape in Fig. 3.

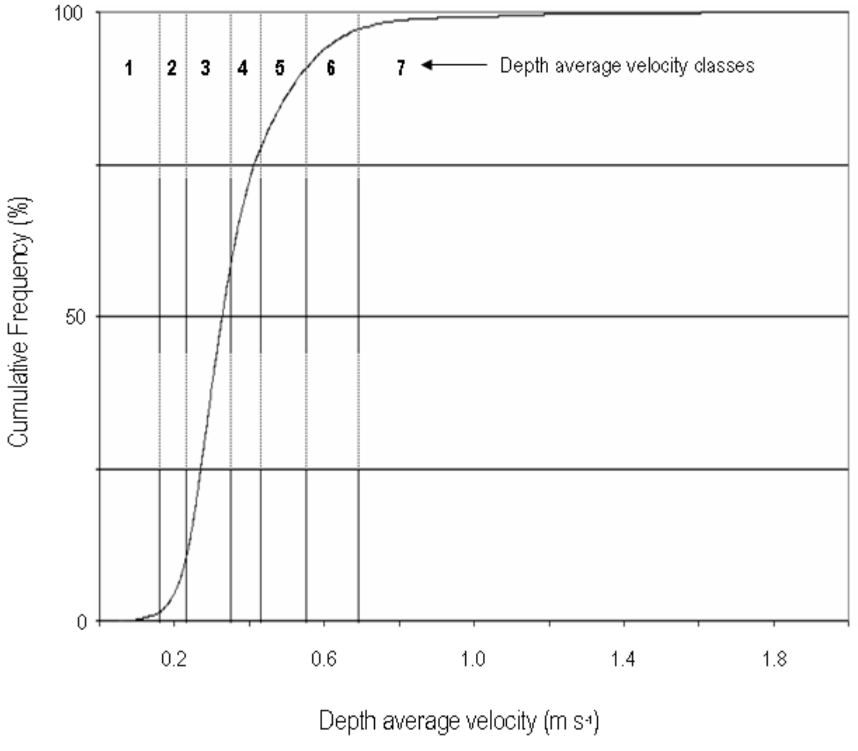

Fig. 2 Cumulative frequency curve of depth averaged velocities for profiles from all reaches and all discharges. Vertical lines correspond to breaks in slope delineating the different depth-averaged velocity classes.

Table 1 The character of hydraulic patches recognized in the study area.

Velocity class	Depth average velocity ($m\ s^{-1}$)	Profiles in each class (%)
1	<0.16	1.26
2	0.16–0.23	7.51
3	0.23–0.35	47.94
4	0.35–0.43	20.16
5	0.43–0.55	13.58
6	0.55–0.69	6.73
7	>0.69	2.82

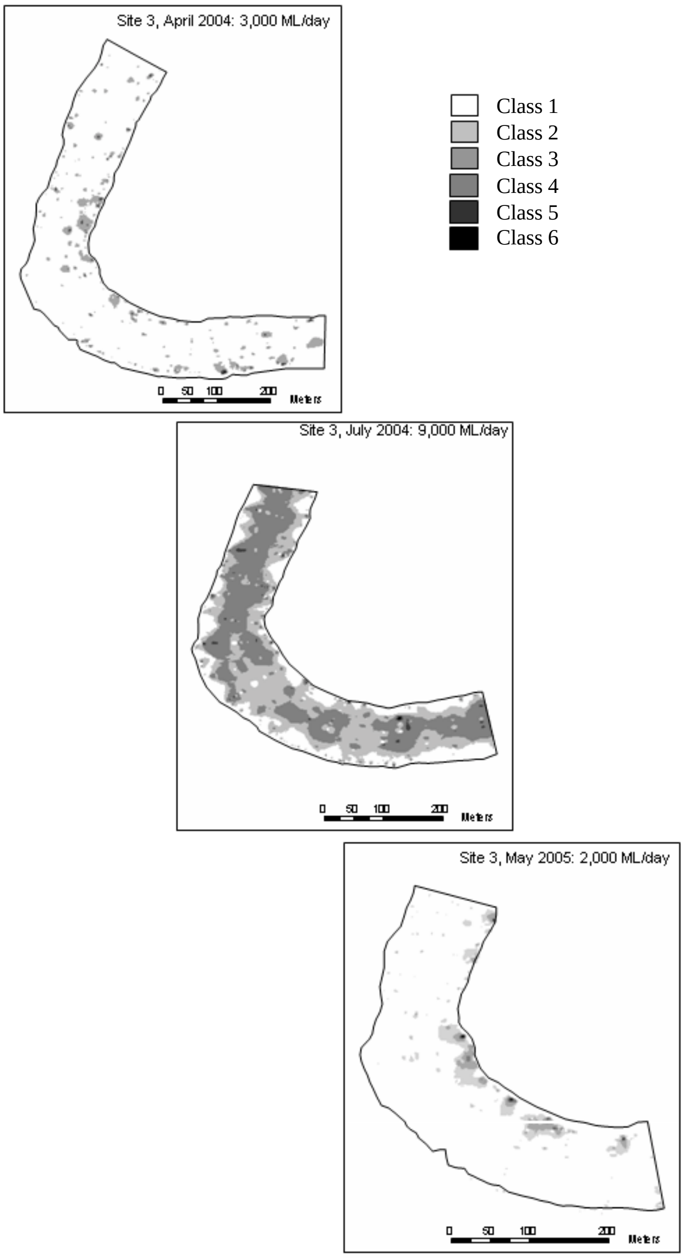

Fig. 3 Reach-scapes for Psyche Bend associated with different discharges, depicting the arrangement of each of the seven hydraulic character classes (patches) in each reach-scape.

Table 2 Summary patch metrics for each reach-scape.

Patch variable	Flow (ML day^{-1})								
	2000	3000	9000	2000	3000	9000	2000	3000	9000
	Site								
	Psyche Bend			Crown Reserve			Pound Bend		
Reach area (ha)	7.70	13.96	10.55	7.97	11.27	10.55	7.97	23.37	22.38
No of patches	174	221	240	359	302	240	359	712	383
Patch Density (N°/ha)	2257	1582	2275	4504	2679	2275	4504	3046	1711
Landscape shape index	4.76	5.87	10.3	15.92	11.12	10.29	15.91	19.98	15.44
Mean patch area (ha)	0.04	0.06	0.04	0.02	0.03	0.04	0.02	0.03	0.05
Mean patch shape	1.22	1.18	1.26	1.45	1.22	1.26	1.45	1.39	1.43
Mean patch fractal dimension	1.12	1.09	1.08	1.14	1.08	1.08	1.14	1.10	1.11
Mean proximity (m)	7	4	5	7	6	5	7	7	7
Simpson diversity index	0.16	0.14	0.66	0.77	0.55	0.66	0.77	0.79	0.75
Simpson evenness	0.19	0.18	.083	0.89	0.66	0.82	0.89	0.92	0.87

The abundance of hydraulic patches varied between reach-scapes; ranging from 174 individual patches at Psyche Bend during May 2005 to 712 at Pound Bend in July 2004. This reflects, in part, minor variations in the size of each site surveyed but nonetheless also reflects reach-scape differences between sites and response to flow changes (Fig. 3). Summary statistics for the various metrics used to describe the hydraulic patch character (Table 2) suggest reach-scape differences. Results of the two-way ANOSIM indicate clear site and flow differences between reach-scapes, although differences were stronger for site influences; Global $R = 0.756$, $p < 0.001$ and Global $R = 0.511$, $p < 0.001$ for site and flow respectively. Global R-values greater than 0.7 suggest that groups are clearly different whilst those within the range 0.5–0.69 suggest some overlap between groups but clearly different and R-values less than 0.5 indicate a high degree of overlap (Clarke & Warwick, 1994). Separation of reach-scapes is represented graphically in the ordination (Fig. 4) with reach-scapes being coded by site and flow. The PCC results show only four hydraulic-patch variables, patch shape, diversity, fractal number and the Landscape Shape Index had R^2 values greater than 0.80 and their position in multivariate space was strongly associated with reach-scape in terms of site and flow influences.

The diversity of hydraulic patches within each reach-scape was generally higher for the different flows compared to the response of individual sites to the different flows. IMD values for flow changes are 1.067 (2000 ML day^{-1}), 0.867 (3000 ML day^{-1}) and 1.067 (9000 ML day^{-1}) in comparison to values of 0.80, 0.933 and 1.267 for Psyche Bend, Crown Reserve and Pound Bend, respectively.

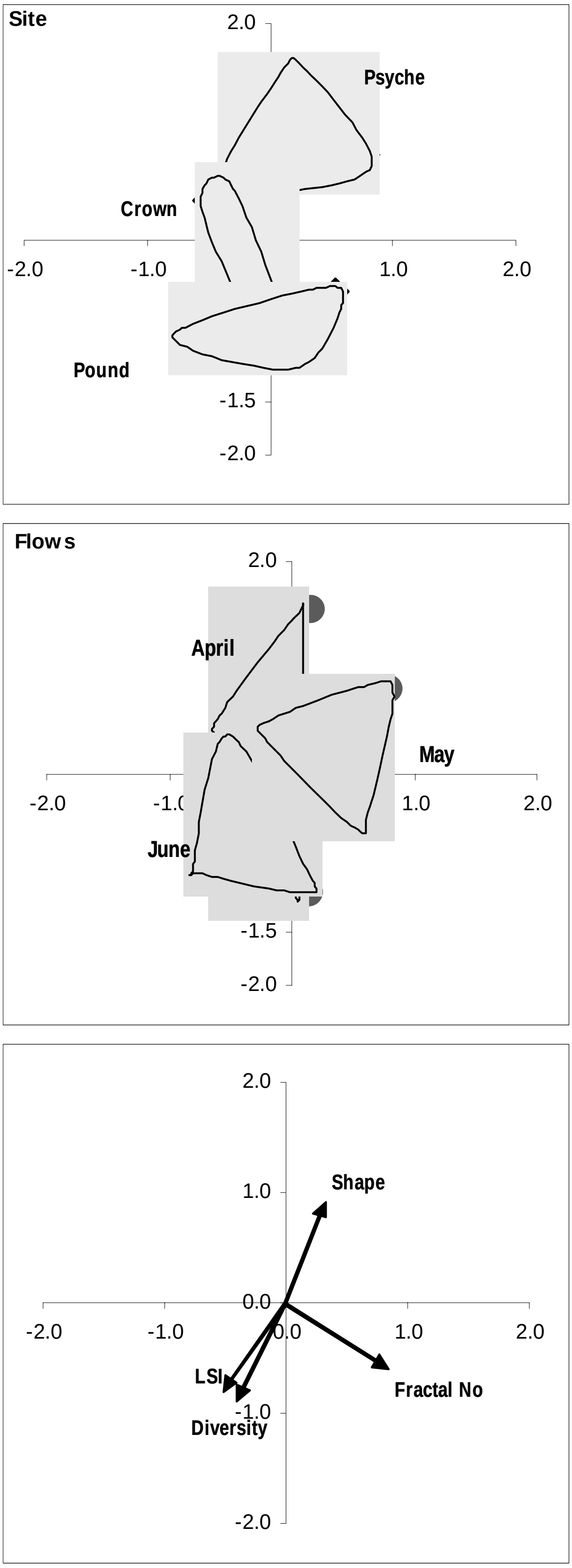

Fig. 4 Graphical summaries of the multi-variate analyses. Ordinations are given for reach-scapes coded by site and flow and the resultant PCC is also given. The stress level for both ordinations were less than 0.2.

DISCUSSION

Differences in the hydraulic patch character of reach-scapes located within the Lock 11 weir pool of the lower River Murray were greater between sites than between flows (Fig. 4). The two-way ANOSIM showed stronger between site separations of reach-scapes compared to flows. Indeed, the reach-scape of each site responded in a different manner, in terms of the character and spatial arrangement of hydraulic patches, to the three different flows. Variation between the Pound Bend reach-scapes, a free-flowing section of the weir pool, was greater in comparison to that of Psyche Bend and Crown Reserve with IMDs of 1.267, 0.80 and 0.923, respectively. This systematic change in reach-scape variability with distance from the weir suggests a collective complex response of the weir pool to changes in flow. Walker & Thoms (1993) recorded similar variations in water level fluctuations along two weir pools in South Australia further downstream on the Murray. Water level fluctuations were greater immediately downstream of each weir and virtually nonexistent immediately upstream of each weir. Thus, spatial variations in reach-scape character and behaviour are a feature of these weir pools and recognising this environmental heterogeneity may be an important management tool in rivers that are heavily regulated by flow structures.

No systematic difference in the “spread” of reach-scapes across flows was observed. The level of between reach-scape differences is relatively similar at each of the three-recorded discharges. Reach-scape variability’s, as indicated by IMD were 1.067, 1.067 and 0.867 for flows of 2000 ML day^{-1}, 3000 ML day^{-1} and 9000 ML day^{-1}, respectively. These preliminary data do suggest significant reductions of within weir pool reach-scape variability may occur with discharges between 3000 and 9000 ML day^{-1}. In other words, the difference between the reach-scapes of weir pools and those of free-flowing sections is reduced at higher discharges. These results support those recorded by Dyer & Thoms (2006) in the upper reaches of the Murrumbidgee River, a tributary of the River Murray, where although the relative proportions, distribution and diversity of hydraulic patches changed with flow, changes did not follow any predictable relationship; however, distinct thresholds were identified for changes in the composition of reach hydraulic character.

The results of this preliminary study demonstrate that the arrangement and distribution of hydraulic patches differ along a weir pool and do so in response to flow changes. Thus, there is a spatial dimension embedded within the temporal signature of flows in the lower river Murray. Hydraulic character is considered to be a key component of aquatic habitats (Statzner & Higler, 1986; Jowett, 1997) and communities of benthic organisms are often defined by patches of differing hydraulic character (Lancaster & Hildrew, 1993). Flow changes will produce spatial variations in the arrangement of aquatic habitats and will influence the distribution of aquatic communities. Efforts to examine habitat heterogeneity in lowland rivers have tended to focus on snags, macrophytes and edge habitat (Sheldon & Walker, 1998; Crook & Robertson, 1999), ignoring the open water sections or “matrix” (*sensu* Forman, 1995) of these river systems that are assumed to be not important. Whilst acknowledging these obvious edge patches are important, it is possible that these more subtly delineated patches of hydraulic condition could account for unexplained variations in the structure and ecosystem functions of lowland rivers. It is therefore possible to consider environmental flow management in lowland rivers in light of the spatial character of the hydraulic patches and manage for increased reach-scape diversity, and thus biotic, diversity.

Such an approach to setting environmental flows 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 riverine environment from an amount of water that does not allow restoration of key parts of the natural hydrograph. In many regulated rivers often there is not sufficient water allocated to the environment to enable restoration of the full temporal flow signature. We contend that by focusing on the spatial dimension of flow variability it is possible to introduce hydraulic variability and diversity that is of benefit to the ecosystem functioning of the river system using a limited amount of water. This form of flow management targets both the temporal and spatial dimension of the flow regime with releases targeted to provide a dynamic mosaic of hydraulic patches, which may be key to maintaining the biodiversity of the reach.

Advances in instrument technology increase our ability to collect data in more arduous environments. The use of the Acoustic Doppler Profiler in this study has facilitated an increase in the knowledge of the hydraulic character of a large lowland river system; and especially of the spatial attributes of hydraulic character over several different flows. Despite the limited number of reach-scapes used in this study, the data gathered deal with more proximate drivers—hydraulic conditions directly influence organisms, whereas discharge is, of itself, meaningless to organisms. Environmental flow management in larger lowland rivers must expand its focus on habitat-based studies to include the entire ‘matrix’ and consider the spatial and temporal dynamics of reach-scapes.

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