Which confluences should we use to differentiate stream segments for management? A geomorphic assessment

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Abstract

One of the most common actions in river research and rehabilitation is to divide stream networks into more manageable spatial scales; such as zones, segments, and reaches. The segment is a popular unit for stream management, being the scale over which geomorphic characteristics considered to be relatively consistent and comparable. Stream confluences are the typical criteria for differentiating these segments, as the input of discharge at a confluence is assumed to impart a predictable and significant step-change in morphology. This research examines this assumption. We explore the nature, magnitude and significance of morphologic adjustment at a set of confluences in Victoria, Australia. Symmetry ratio (relative size of merging streams) is shown to be a key indicator for predicting the magnitude and significance of adjustment at any given confluence over the scale of the study region. We recommend using symmetry ratio and an improved understanding of confluence dynamics to assist in defining geomorphic thresholds and spatial-scale boundaries within stream systems. This has direct implications for how stream networks are described for both research and management.

Keywords

Tributary junction, channel geometry, variability, ecosystem structure, physical habitat

Introduction

Geomorphic scale hierarchies are frequently used to facilitate the catchment scale integration of research from disciplines such as geomorphology, ecology and hydrology. A suite of these frameworks has evolved over the last 20 years (Table 1), each incorporating a discrete array of spatial (and temporal) scales. Despite wide spread adoption of these frameworks, the definition of scale boundaries remains largely subjective. ‘Segment’ boundaries (Table 1, shaded cells) are typically stream confluences, which are generally assumed to be points of significant geomorphic change in catchments. Incorporating a quantitative understanding of morphologic adjustment at confluences will greatly improve the practicability of these scale frameworks.

Table 1: Comparison of geomorphic scale hierarchies.

Extent	*Frissell et al, 1986*	*Rowntree, 1996*	*Newson & Newson, 2002*	*Thomson et al, 2001*	*Thoms & Parsons, 2002*
$10^3 – 10^5$ m	Stream System	Catchment	Catchment	Catchment	Basin
		Zones	Subcatchment	Landscape Unit	River system
$10^2 – 10^3$ m	Segment System	Segment	Segment		Functional process zone
$10^1 – 10^2$ m	Reach System	Reach	Reach	River Style	Reach
			Site		
$10^0 – 10^1$ m	Pool/riffle System	Morphological Unit	Morphological Unit	Geomorphic Unit	Functional channel set
$10^{-1} – 10^0$m		Biotope	Transect	Hydraulic Unit	Functional unit
			Biotope		
10^{-2} - 10^{-1}m	Micro-habitat		Patch		Meso-habitat

Quantitative predictions of channel adjustment at confluences has proven difficult in the past (Miller, 1958; Richards, 1980; Gippel, 1985; Roy and Woldenberg, 1986; Rhoads, 1987; Roy and Roy, 1988), and until now has been considered largely un-achievable due low resolution of data (Benda *et al.*, 2004b) and the complexity of riverine environments (Rhoads, 1987). From data available at the time, Rhoads (1987) proposed that only confluences with a symmetry ratio (ratio of the bankfull areas of merging streams) > 0.7 could be expected to demonstrate predictable downstream channel adjustment. We test this threshold, using detailed surveys to adequately characterise the channel and account for localized variability which has complicated previous efforts (Gippel, 1985). Specifically, we examine the relationship between symmetry ratio and the *magnitude* and *significance* of morphologic adjustment at confluences. Results are incorporated into a refined geomorphic scale hierarchy with new quantitative criteria for segment boundaries.

Methods

Field sites

Confluences of varying symmetry ratio (estimated) and catchment area were selected from the Goulburn River and Ovens River catchments in Victoria, Australia (see Figure 1). All sites (Table 2) are unregulated, wadeable, gravel bed streams with occasional bedrock outcrops, and similar adjacent landuse.

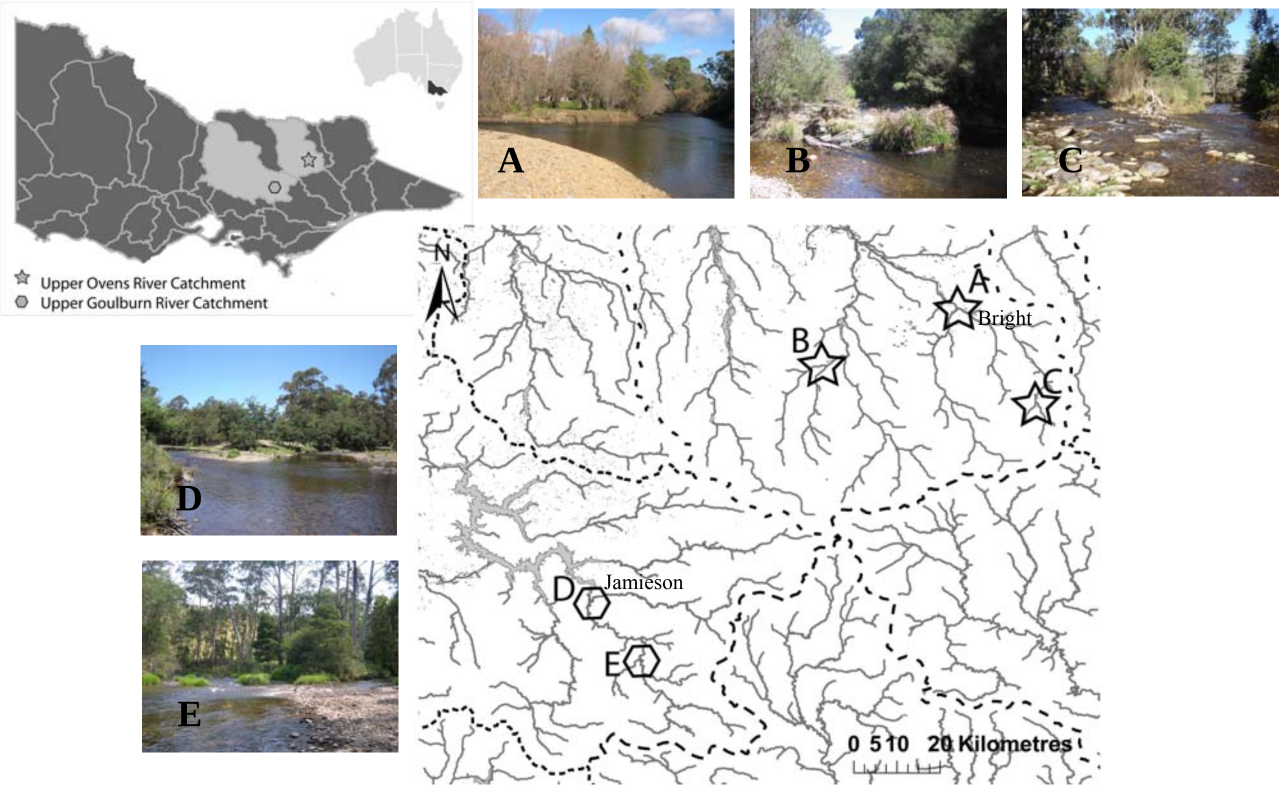

Figure 1. Field sites near the towns of Jamieson and Bright – catchment borders are denoted by dashed lines, see Table 2 for site details

Table 2. Site details.

	Confluence	**Catchment area CA (km^2)**	**Strahler order**	**Shreve order**	**Mean Annual Flow MAF(ML)**	**Slope**	**Valley confinement VBF**	**Symmetry ratio by CA**
A	Buckland River Ovens River	489 539	4 4	50 63	225484 264564	0.0071 0.0053	4.01	0.91
B	Rose River Dandongadale River	188 184	3 3	28 23	71922 75091	0.0200 0.0200	4.67	0.98
C	Ovens River West Ovens River East	46 73	2 3	5 7	24889 45971	0.0176 0.0240	2.85	0.71
D	Jamieson River Goulburn River	386 716	3 4	37 88	210663 422899	0.0004 0.0006	3.00	0.54
E	Gaffney's Creek Goulburn River	88 417	3 4	9 50	58795 271832	0.0070 0.0030	3.68	0.21

Data collection and analysis

At each site a channel survey was conducted (approximately 1000 x-y-z data points), extending over 250m from the confluence (to encompass at least 2 pool-riffle sequences) over all three reaches, see Figure 2. At least 10 random cross-sections were included per reach to ensure channel variability was adequately characterised; using the method devised by Stewardson and Howes (2002). An adapted Wolman (1954) count (100 semi-random points of b-axis) was conducted over each reach for a rapid assessment of substrate.

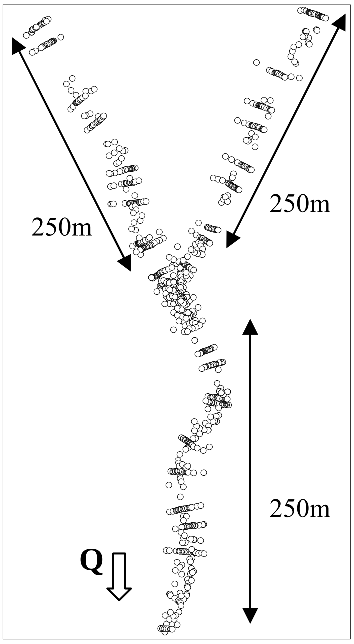

Figure 2.
Survey points at site C
(Q indicates flow direction)

For each confluence, bankfull hydraulic parameters were calculated for all cross-sections (10 cross-sections per reach, 3 reaches per confluence), and mean values determined for each reach, along with substrate size. The measured symmetry ratio, *s*, was calculated according to Equation (i), and percentage change in channel area (for assessing magnitude of channel change) *c*, was calculated according to Equation (ii);

$$s = \frac{A_2}{A_1} \quad \text{(i)} \qquad c = \frac{(A_2 + A_1) - A_3}{(A_2 + A_1)} \times 100 \quad \text{(ii)}$$

Where A_2 is the mean bankfull area of the smaller incoming tributary, A_1 the larger tributary, and A_3 the combined channel downstream.

To determine the statistical significance of changes to the in-stream environment, an analysis of variance (ANOVA) was conducted on data sets from each confluence (bankfull parameters and substrate size).

Results

Mean bankfull parameters (wetted perimeter = P, area = A, hydraulic radius = R, average depth = D, surface width = W) for each reach at each site (A – E) are presented in Table 3, plus mean substrate (b-axis) size, and also capacity change, *c*, (%) and symmetry ratio, *s*, (calculated from bankfull area).

Table 3. Mean values of parameters (calculated from the ten cross-sections per reach) plus % capacity change and symmetry ratio for each confluence - sites A – C in Table (i) and sites D – E in Table (ii)

(i)	A			B			C		
	Trib1 Ovens	Trib2 Buckland	Combined Downstream	Trib1 Dandongadale	Trib2 Rose	Combined Downstream	Trib1 OvensEast	Trib2 OvensWest	Combined Downstream
P (m)	25.95	24.31	51.57	9.45	9.28	15.16	19.97	12.96	21.05
A (m^2)	22.51	21.96	43.77	6.62	5.76	10.88	13.58	9.60	19.84
R (m)	0.91	0.91	0.85	0.71	0.62	0.72	0.69	0.75	0.97
D (m)	0.93	0.92	0.86	0.77	0.65	0.75	0.71	0.79	1.00
W (m)	25.32	23.89	51.01	8.86	8.85	14.60	19.53	12.36	20.39
baxis(cm)	10.22	11.08	9.76	11.80	16.48	8.45	14.46	9.82	11.29
Capacity change (*c*)			**-2%**			**-12%**			**-14%**
Symmetry ratio (*s*)			**0.97**			**0.87**			**0.71**

(ii)	D			E		
	Trib1 Goulburn	Trib2 Jamieson	Combined Downstream	Trib1 Goulburn	Trib2 Gaffney's	Combined Downstream
P (m)	26.05	24.98	44.93	27.97	10.22	34.74
A (m^2)	31.06	25.87	48.89	11.13	6.05	14.18
R (m)	1.20	1.04	1.09	0.41	0.59	0.42
D (m)	1.23	1.07	1.11	0.41	0.62	0.42
W (m)	25.36	24.26	44.38	27.83	9.87	34.66
baxis (cm)	10.85	10.60	13.84	7.16	9.70	9.99
Capacity change (*c*)			**-14%**			**-18%**
Symmetry ratio (*s*)			**0.83**			**0.54**

Key results to note from Table 3 include:

- Higher symmetry ratios correspond with smaller reductions in channel area (i.e. greater continuity) – this relationship is graphed in Figure 3.
- Width increase (and subsequently wetted perimeter) is essentially additive at all confluences (site C is the only exception)
- Depth (and subsequently hydraulic radius) does not increase as expected below the confluence, either staying about the same or even marginally decreasing (with the exception of site C)

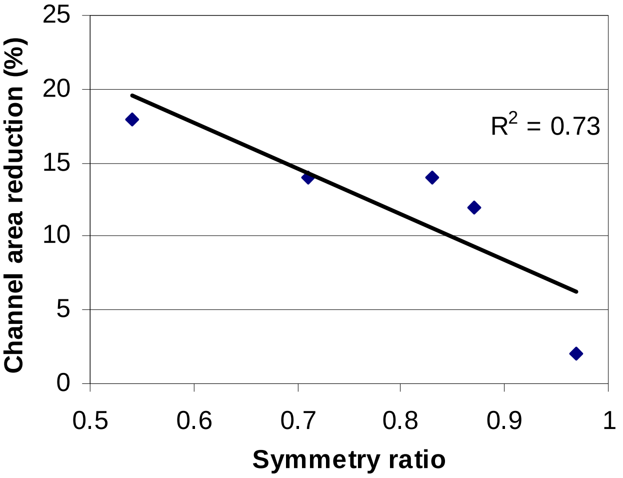

Figure 3. Relationship between measured symmetry ratio (A_2/A_1) and % reduction in channel area downstream

Results from ANOVA analysis on data sets of bankfull hydraulic parameters and substrate size are presented in Table 3. All data sets conformed to normal distributions with no significant trends. Evidence to reject the null hypothesis at a 0.05 level of significance is used as the criteria for defining 'significant change'.

Table 4. ANOVA results (using data sets from each of the three reaches per site) – bold (<0.05) shaded squares indicate statistically significant changes between the pairs of reaches; sites A – C in Table (i) and sites D – E in Table (ii) (DS denotes the down-stream reach, and the larger tributary is listed in the first column of each site).

(i)	**A**			**B**			**C**		
	Ovens & DS	Buckland & DS	Ovens & Buckland	Dand & DS	Rose & DS	Dand & Rose	Ovens East & DS	Ovens West & DS	OvensEast & OvensWest
P	**0.00**	**0.00**	0.68	**0.00**	**0.00**	0.95	0.73	**0.00**	**0.00**
A	**0.00**	**0.00**	0.68	**0.00**	**0.00**	0.17	**0.00**	**0.00**	**0.00**
R	0.66	0.66	1.00	0.99	0.10	0.13	**0.00**	**0.00**	0.59
D	0.57	0.66	1.00	0.92	0.20	0.10	**0.00**	**0.01**	0.42
W	**0.00**	**0.00**	0.75	**0.00**	**0.00**	1.00	0.82	**0.00**	**0.00**
baxis	0.89	0.38	0.65	**0.05**	**0.00**	**0.00**	**0.02**	0.44	**0.00**

(ii)	**D**			**E**		
	Goulburn & DS	Jamieson & DS	Goulburn & Jamieson	Goulburn & DS	Gaffney's & DS	Goulburn & Gaffney's
P	**0.00**	**0.00**	0.61	**0.01**	**0.00**	**0.00**
A	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
R	**0.03**	0.33	**0.00**	0.94	**0.00**	**0.00**
D	**0.01**	0.62	**0.00**	0.94	**0.00**	**0.00**
W	**0.00**	**0.00**	0.62	**0.01**	**0.00**	**0.00**
baxis	**0.02**	**0.01**	0.972	**0.01**	0.95	**0.02**

Key results to note from Table 4 include:

- All confluences have a significant adjustment in bankfull area (capacity) downstream, even those with a symmetry ratio below the proposed threshold of 0.7 (Rhoads, 1987).
- Sites A & B & E have significant changes in width and wetted perimeter, but not depth or hydraulic radius (between main tributary & downstream; first column of Table 4) – site C is the opposite to this, and Site D has significant changes in all parameters.
- Significant changes in substrate size do not appear to be related to confluence symmetry ratio

Discussion

Our results indicate that symmetry ratio can confidently be used for predicting the magnitude of channel adjustment at stream confluences, within the extent of our study region (<500km^2). The higher the symmetry ratio of a confluence, the more continuity in the magnitude of change (the closer we get to $A_1+A_2=A_3$). It is possible that this relationship might be more complicated over larger catchment areas. For example, a symmetrical confluence in an upland area, with tributaries geographically close, may be more likely to experience homogeneous precipitation events across both sub-catchments. In this case channel forming flows would arrive near-simultaneously at the confluence, with the downstream channel being adjusted to accommodate this ($A_1+A_2=A_3$). Consider another symmetrical confluence further down the catchment, draining larger sub-catchments but still of equal areas. There now may be increased chance of a lag time between precipitation events over the sub-catchments. In this case the channel forming flows may be less likely to arrive simultaneously at the confluence, and the downstream channel need only be adjusted to a lesser capacity than if the confluence experienced synchronous peaks. Alternatively, storm cell size could increase with catchment area such that sub-catchments of the joining streams experience homogeneous precipitation events the majority of the time, in which case the symmetry ratio relationship presented in this paper would be expected to hold over all catchment areas. A conceptual study of this problem, *symmetry vs. synchronicity*, is currently being undertaken to gain an understanding of the hydrology driving the magnitude and significance of morphologic adjustment at confluences.

We have also shown that the nature of adjustment is not always the same. All confluences except Site C demonstrated a dominance of widening over deepening in the combined bankfull channel downstream. This may be an anomaly, or it may be associated with Site C having the lowest valley confinement and least bedrock (outcropping) that may be restricting channel deepening at the other sites. For all sites, the adjustment in channel area was considered statistically significant, coupled with a significant adjustment in either widening or deepening downstream. This suggests that a symmetry ratio of 0.5 (or maybe even lower pending further research) could be used with reasonable confidence as a quantitative predictor to define confluences of geomorphic significance. However, this does not appear to hold for substrate size. Although the majority of our study sites did have a significant adjustment in substrate size between the larger upstream tributary and the downstream reach, the nature of the change was not predictable, sometimes increasing and sometimes decreasing with no particular correlation to symmetry ratio or substrate size from the incoming tributary. This may be attributed to the possible inaccuracy of the rapid assessment procedure used (adapted Wolman count). However, our results do support those of Rice (1998, 1999), who advocates that sedimentological networks and hydrologic networks do not necessarily correspond and discrete sedimentary links should not be assumed to coincide with stream confluences.

We recommend that a refined symmetry ratio of 0.5, reduced from 0.7 (Rhoads, 1987), be incorporated into geomorphic scale hierarchies, to help differentiate between confluences of definite *geomorphic significance* (symmetry ratio ≥ 0.5) in terms of a step-change in channel morphology, versus those of only *hydrological significance*. The former to be used for refining criteria used for defining physically homogeneous ‘sectors’ within catchments for river research and management, the latter to denote ‘segments’. In Table 5 we provide a refined version of the geomorphic scale hierarchy, incorporating results from this research and also other qualitative understanding of confluence features (Benda *et al*, 2004a; 2004b).

Table 5. Refined version of upper levels in a basic geomorphic scale hierarchy framework.

Extent	Scale	Description
$10^3 – 10^4$ m	*Catchment*	Area lying within topological boundaries (high points)
$10^2 – 10^3$ m	*Zone*	Upland – Midland – Lowland (Erosion, transfer & deposition zones)
$10^2 – 10^3$ m	*Sector*	Bound by obvious geologic features/substrate changes (geologic intrusions, confinement etc.) AND/OR confluences of geomorphic significance – Symmetry ratio >=0.5 and evidence of morphological features (bars etc. Benda *et al* 2004a, 2004b).
$10^2 – 10^3$ m	*Segment*	Bound by smaller confluences (symmetry ratio <0.5 & absence of morphological features) imparting no significant geomorphic adjustment to the channel, yet still constituting a hydrological input to the in-stream environment.
$10^{-1} – 10^2$ m	Other finer scales include: Patch, Flow-type, Geomorphic Unit, and Reach (smallest to largest)	

Conclusion

We have shown symmetry ratio to be a good predictor of the magnitude of morphologic adjustment at stream confluences over the extent of the region studied (<500km^2), and that a symmetry ratio of 0.5 could be used in conjunction with qualitative observations to assist in defining confluences of geomorphic significance. Further research should be conducted to refine these ideas, to assist in providing more rigour and reduced subjectivity in the definition of 'segments' for management. Testing the conceptual thresholds implied by geomorphic scale hierarchies, at all scales, should be pursued, otherwise our research and management will be limited by scales that we perceive to be significant, rather than by what we measure to be so. This research is part of a broader investigation into morphologic adjustment at stream confluences, and implications for river research and management.

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