

Towards an objective approach for a regional - continental scale geomorphic river classification

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Abstract

River classification schemes are now widely used by a range of government agencies, managers and researchers to help reach an understanding of river form and process among the geomorphic complexity found in river channels, as a basis for understanding ecosystem patch dynamics and connections, and as means of organising and prioritising research and management activities. With some exceptions, existing schemas are generally qualitative, relying largely on expert judgement to delineate “homogeneous geomorphic reaches” for a specific river, from field, GIS, and/or remotely sensed data. In this paper, we demonstrate that continuous data for a number of morphological metrics can be derived relatively cheaply from available remotely sensed and GIS data, as a basis for a regional to continental geomorphic river classification. This approach is intended as a “proof of concept” for further development into a classification approach that can be applied across Northern Australia. Others have used many of the metrics used here in one form or another, however, they are rarely derived as continuous data throughout the drainage network. A test of the derived metrics against an existing classification within the Mitchell River in the Gulf of Carpentaria suggest that most existing reach classes can be discriminated within the derived metrics.

Keywords

Fluvial geomorphology, classification, GIS, DEM, Cape York

Introduction

The geomorphic and applied ecology literature is replete with examples of different river classification schemes, all of which have their own merits and limitations (e.g. Rosgen, 1994, 1996; Miller & Ritter, 1996; Kondolf, 1995). Most of these classifications are inherently subjective and highly influenced by the experience of the classifier, they are also influenced by the resolution of the data available to them and the discontinuous, and often arbitrary, spatial distribution of the field data. The reliance of most classification schemes on field data also limits the practical application of such approaches for regional or continental scale analysis, particularly to remote and inaccessible areas. At present a universally accepted geomorphic river classification scheme does not exist that can be applied at the continental scale, or indeed any scale (Naiman, 1992; Kondolf, 1995, Parsons *et al.*, 2004). Numerous attempts have been made at developing such schemes, with the Rosgen (1994) and the River Styles approach of Brierley and Fryirs (2005) being recent examples in a line extending back to Davis (1899). Naiman *et al.*, (1992) state that despite the lack of a universally accepted classification framework (and it should be noted that 15 years on, the situation remains the same) a consensus has been reached regarding the fundamental attributes of an enduring classification scheme. They state; “it should have the ability to encompass broad spatial and temporal scales, to integrate structural and functional characteristics under various in-stream disturbance regimes, to convey information about underlying mechanisms controlling in-stream features, and to accomplish this at low cost and at a high level of understanding among resource managers.” (Naiman *et al.*, 1992, p117). To this should also be added that the classification scheme should be as objective as possible and should be repeatable by different operators applying the classification system independently (Kondolf, 1995).

A common property of many river classification schemes is that they are dependent on high resolution field data, which are often collected at non randomly selected sites, frequently dictated by accessibility (see Parsons, *et al.*, 2004). Accessibility issues and spatial scale in the remote areas of Northern Australia severely limit the ability to use field sampling to detect major transitions.

Several researchers have utilised multivariate statistical techniques as a means of removing much of the subjectivity from classification (e.g. Mosley, 1987, Newson *et al.*, 1998, Thorp *et al.*, 2006) with varying degrees of success. Mosley (1987) was unable to distinguish meaningful classes from 190 river reaches in New Zealand, a result that may have been a function of the discontinuous nature of the data being used. The multivariate approaches reported by Newson *et al.*, 1998 and Thorp *et al.*, 2006, show more promise, providing the appropriate scale input data is available.

The metrics proposed are not intended to be the last word, rather they are metrics that have been derived from currently available data. For example, as a discharge proxy we are currently relying on catchment area (which we know is dubious at best in this region). However, the sparse gauging network in northern Australia, almost certainly precludes the derivation of meaningful proxy discharge data being derived across the whole landscape, and for this reason it is not included at this point in time. A rainfall/runoff model offers the best hope of deriving a more meaningful discharge proxy, and hence deriving stream power data, however this will be incorporated at a later date.

Methods

For the purposes of this pilot study we have selected the Mitchell River, which flows from the great divide (west of Cairns), across Cape York Peninsular into the Gulf of Carpentaria. The Mitchell river has a catchment area of $\sim 72,000\text{km}^2$ and a length of around 650km. A key reason for selecting this catchment is that a geomorphic classification has been previously undertaken for this river (Brennan & Gardiner, 2004) with the Geomorphic Assessment of Rivers (GAR) approach used by the Queensland Dept of Natural Resources and Water. This method is the Brierley and Fryirs (2005) River Styles method by another name. The existing classification provides us with the means of testing whether the seven derived metrics can be used to discriminate between the GAR classes in a statistically significant manner. The metrics chosen for this study are: catchment area, slope, valley width, channel width, channel confinement, sinuosity, and stream line elevation residuals. These metrics have been selected because, either separately or collectively, they are proxies for the distribution of energy within the channel network, or of the geologic controls on the catchment and its tectonic inheritance and are likely to underpin channel characteristics expressed at the reach scale. At the commencement of this project 90m SRTM (Shuttle Radar Topography Mission) elevation data was the best available for the study area, and is used to generate a number of the metrics described.

Stream line, area and slope

The stream line was manually digitised onto a Landsat image. A point was generated every 90 metres along the stream line (~ 6500 points) to create a set of stream sample points. A distance of 90m between sample points was chosen to correspond with the cell size of the SRTM elevation data. Downstream distance is calculated for each stream point, and the chosen metrics are derived at each of these points. Catchment area was derived with ArcHydro (CRWR, 2003), an ArcInfo extension, using the toolset therein and following standard methods of burning in stream lines and filling of sinks. Slope is calculated as the change in elevation divided by the distance between stream points. When calculated between each stream point (90m intervals) the slope data contains too much noise. Noise in the slope data is a combination of any error within the SRTM data, the radar's inability to penetrate the vegetation canopy, the DEM pixel size (90 X 90m), issues of georeferencing, and the minimum resolution of the z coordinate, which is 1m. Based on an assumption that there should be a low probability that the capture and processing of the SRTM data could produce values lower than the actual ground surface, we decided in this case to filter the elevation values and use only those points that are not higher than the elevation of an upstream point. Slope is derived only from the low point data set, and points on the stream sections between these points are assigned the slope interpolated between the low points.

Channel width, valley width, and confinement

Channel width and valley width are the hardest metrics to derive in a fully automated fashion, particularly given the resolution limitations of the available broadscale DEMs and imagery. In low relief landscapes, defining the effective valley floor width is much more difficult than it is in high relief landscapes. For this reason we have had to undertake some manual digitisation of margins, in lieu of developing image based methods of valley margin delineation. In the Mitchell River, macro channel margins (the outer bounds of the whole active channel zone) are distinct on Landsat imagery for almost all of the rivers length. Channel margins were manually digitised on the Landsat imagery. Mapping of valley margins was approached using

a combination of methods. The first step was to process the DEM using MrVBF (Multi-resolution Valley Bottom Flatness Index) (Gallant & Dowling, 2003). A standard threshold of 0.5, recommended by Gallant and Dowling (2003, p5) for the MrVBF index, was used to delineate valley bottoms. The MrVBF output were overlain on Landsat imagery and visually inspected. The output was unable to distinguish between valleys and ridges in the alluvial fan of the lower Mitchell, whereas it was found to produce a good approximation in the higher relief upper half of the catchment. The valley margins for the upper half of the Mitchell were digitised by joining the outer edge of the MrVBF valley bottom class surrounding the stream line, figure 1B. Where the derived valley and channel margin crossed, and in reality have probably converged, the valley margins were amended to match the channel margin.

In the low relief areas the valley margins were digitised using a 3D visualisation of the landscape, which involved draping Landsat imagery over the 90m DEM. This process was done using ArcScene, part of the ArcGIS software, which allows the user to greatly exaggerate the vertical scale and to rotate the representation of the landscape in 3 dimensions.

The stream points, channel margins, and valley margins were then used to derive channel and valley floor width values at each stream point. An algorithm was written (VBA) in ArcGIS to calculate the cross sectional distance of lines radiating at one degree intervals from a point and two bounding lines and then choose the shortest distance. All stream points were processed in this way for valley margins and channel margins, figure 1. This procedure explicitly does not capture any sort of distension of the valley margins, generally associated with tributary junctions, this can be seen in Figure 1B.

Degree of channel confinement was calculated as ratio of channel width to valley width at each stream point.

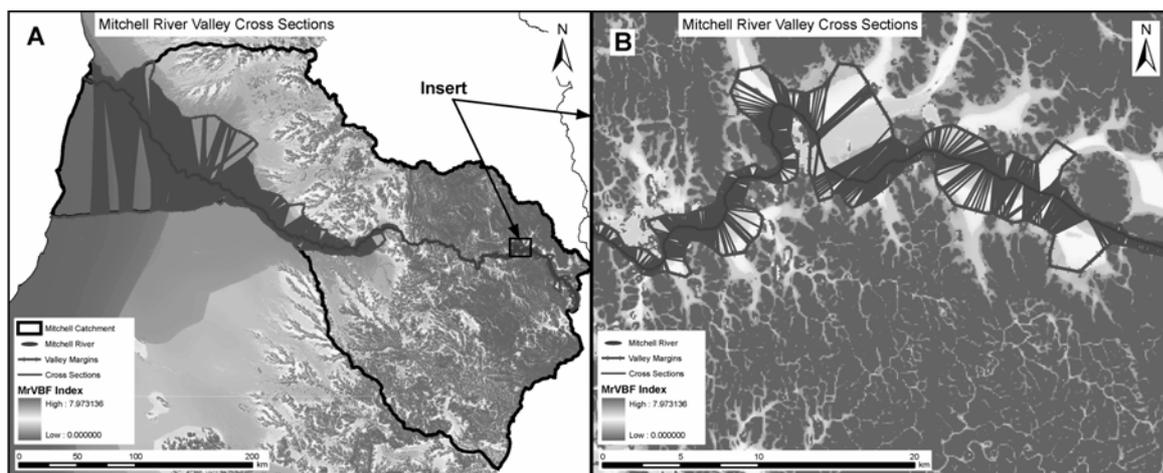


Figure 1. Mitchell River catchment showing MrVBF, the valley margins, and the valley cross sections in the upper and lower reaches of the catchment.

Sinuosity

When attempting to calculate sinuosity for a continuous data set, the long standing concept of sinuosity as the channel length / valley length immediately raised the question, over what length of valley should the sinuosity calculation be made? The standard approach is to have an a priori delineation of the valley segment start and end point. To address this issue, we tried several different multiples of valley width transposed to the valley centre line, with half of the length above the stream point and half below. Twice the valley width was settled on because it provides the best discrimination of reach classes down the river. Sinuosity was then calculated for each stream point.

Stream line elevation residuals

Stream line elevation residuals are the deviation of the elevation value at each stream point from a curve fitted to the longitudinal stream profile. Based on the idea that a hypothetical idealised river system with uniform environment drivers and uniform geology will have a longitudinal profile that can be described by a mathematical curve (i.e. some exponential decay or polynomial function), it is suggested here that the elevation residuals provide an insight in to the downstream changes of forcing factors that contribute to river morphology. In this case we have selected a 3rd order polynomial, and deviations from the curve are suggested to represent structural or lithological controls on the longitudinal profile.

Having generated the seven variables at 90m intervals, these continuous datasets were then split according to the independently derived GAR classes and descriptive and comparative statistics were calculated using the JMP statistical analysis software (JMP version 5.0.1.2).

Results

The graphs of each data set against distance downstream highlight the distinctive nature of most of these variables, with the possible exception of the catchment area and width trends. These two appear to be highly correlated in this system, and may well be redundant. Catchment area was included, however, as it is unlikely to be closely correlated with width in other drainage networks. Furthermore, it is currently the only usable discharge proxy that we have. Certain features, such as the dam and associated Lake Mitchell in the upper part of the catchment can be readily discerned as the “Dam Influence” GAR class from these plots, while others are less obvious. The catchment area acts as would be expected, increasing downstream with large steps where tributaries enter the trunk stream. The valley width graph expresses the trumpet like shape of the valley margins seen in figure 1A, with confined/partly confined valley settings through the Great Divide and the unconfined valley across the large alluvial fan that extends to the Gulf of Carpentaria. The channel width graph shows the narrow/wide channels of the confined/unconfined valley setting, the anthropogenic width of Lake Mitchell produces the large peak near the top of the catchment, and variations within the alluvial fan are most likely related to channel entrenchment associated with longer term evolution of the Mitchell. The confinement graph combines valley and channel width, the confined/partly confined river lengths are relatively distinct where confinement approaches or equals one. The elevation residuals are interesting in that they maybe capturing long term changes in flow and geological differences. The slope shows the general expected trend of high to low, but the noise in the underlying DEM data and the methods of filter the elevation along the stream line tried here are producing some spurious results. The sinuosity is as would be expected for the Mitchell which is not a very sinuous river, but the existence of an anomalously high peak mid catchment suggests the initial method of generating the channel and valley length tried here should be improved.

Figure 2 shows the seven measured variables graphed against downstream distance. Because it was not possible to develop a graphical coding system that would allow all classes to be distinguished in a small black and white image, the graphs are displayed with alternating black and grey corresponding to the relevant lengths of river as classified using GAR (Brennan and Gardiner, 2004). This highlights the downstream pattern of reach classes. The downstream sequence of GAR classes is listed and numbered in the legend and a selection of the numbers appear on the graphs between the dashed lines.

The data generated for the Mitchell for each of the seven variables was divided into the river lengths that correspond to the GAR classes and a one way analysis of variance (ANOVA) ($\alpha = 0.05$) and multiple comparison of group means using the Tukey-Kramer HSD (unequal sample sizes, $q^* = 3.16475$) test was done to test for significant difference between the GAR reaches for each variable. The data is spatially contiguous and therefore in most cases there exists some degree of auto-correlation. However, in terms of a one way ANOVA the residuals were not auto-correlated and thus satisfied the assumptions of ANOVA.

The Tukey-Kramer HSD analysis of variance between the GAR classes suggests that all but two of the ten classes defined by Brennan and Gardiner (2004) along the Mitchell main stem channel, can be discriminated with the seven derived metrics. Somewhat surprisingly the bedrock controlled classes are the two that do not appear to be discriminated. This may well be a function of unnecessary splitting in the GAR classes, which if they were combined with the headwater class (a somewhat arbitrary split at best), they could be discriminated on the basis of channel confinement.

Table 1 shows the Tukey-Kramer HSD levels represented as letters indicating membership in a particular group of means. Alphabetical order represents degree of group difference, “A” being greatest. The shaded cells of the table highlight the GAR groupings of each variable that are significantly different from all other GAR classes for that variable. GAR classes with the same letter are not significantly different from each other but are significantly different from other GAR classes with other letters unless there is more than one letter in which case there is an overlap indicating membership in more than one group.

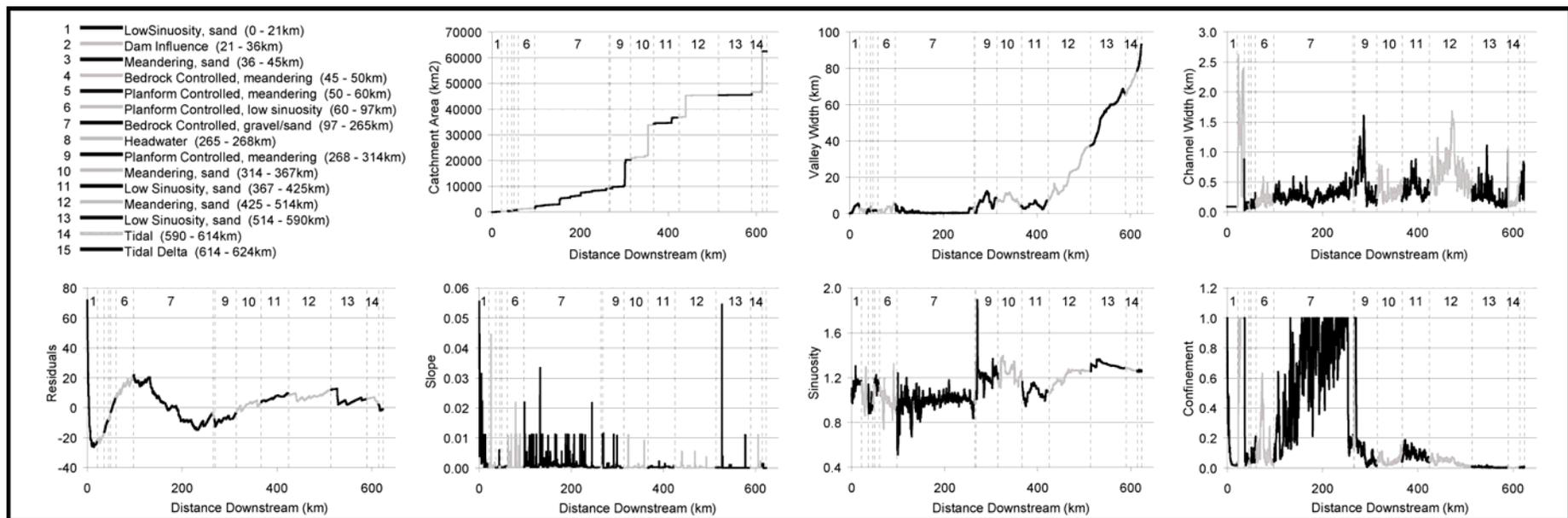


Figure 2. The seven measured variables graphed against downstream distance.

Table 1. Tukey-Kramer HSD analysis of variance of measured variables between the GAR classes.

GAR Class	Count	Geomorphic Parameter													
		Catchment Area (km ²)		Valley Width (m)		Channel Width (m)		Elevation Residuals		Slope		Sinuosity		Confinement	
		Mean (Std Error)	T HSD*	Mean (Std Error)	T HSD*	Mean (Std Error)	T HSD*	Mean (Std Error)	T HSD*	Mean (Std Error)	T HSD*	Mean (Std Error)	T HSD*	Mean (Std Error)	T HSD*
Bedrock Controlled, Gravel/Sand	1848	5642.2 (230.9)	F	803.4 (327.3)	F	294.67 (5.541)	D	0.915 (0.193)	D	0.001084 (0.00006)	A B	0.99304 (0.00261)	F	0.612456 (0.00439)	B
Bedrock Controlled, Sand	49	657.7 (1417.9)	G	2116.1 (2010.3)	E F	90.22 (34.028)	F	-5.366 (1.182)	F	0.000229 (0.00034)	B C D	1.02581 (0.01606)	E F	0.043008 (0.02699)	D E F
Dam Influence	136	245.4 (851.1)	G	1908.8 (1206.7)	E F	1433.54 (20.425)	A	-20.438 (0.710)	G	0.001033 (0.00021)	A B C D	1.04426 (0.00964)	E	0.803469 (0.0162)	A
Headwater	39	9072.5 (1589.4)	E F	1194.8 (2253.4)	E F	356.46 (38.142)	C D	-5.063 (1.325)	E F	0.002293 (0.00039)	A	1.12537 (0.018)	D	0.527095 (0.03025)	B
Low Sinuosity, Sand	1667	36040.6 (243.1)	C	29562 (344.7)	C	298.98 (5.834)	D	3.78 (0.203)	C	0.00101 (0.00006)	B	1.21789 (0.00275)	B	0.049682 (0.00463)	E
Meandering, Sand	1671	34400.7 (242.8)	D	15327.8 (344.2)	D	541.99 (5.827)	B	4.505 (0.202)	B C	0.000365 (0.00006)	D	1.21339 (0.00275)	B	0.046879 (0.00462)	E
Planform Controlled, Low Sinuosity	413	1274.5 (488.4)	G	2522.6 (692.4)	F	220.76 (11.721)	E	14.163 (0.407)	A	0.000833 (0.00012)	B C	1.01553 (0.00553)	E	0.148289 (0.0093)	C
Planform Controlled, Meandering	627	10493.6 (396.4)	E	5899.1 (562.0)	E	449.8 (9.513)	C	-5.896 (0.331)	F	0.000509 (0.0001)	C D	1.18558 (0.00449)	C	0.120573 (0.00754)	C D
Tidal	267	47345.3 (607.4)	B	71862.9 (861.2)	B	204.86 (14.578)	E F	5.624 (0.506)	B	0.000342 (0.00015)	C D	1.35701 (0.00688)	A	0.00284 (0.01156)	F
Tidal Delta	104	62488.8 (973.3)	A	84408.2 (1379.9)	A	447.11 (23.357)	C	-0.772 (0.811)	D E	0.000479 (0.00024)	B C D	1.3233 (0.01102)	A	0.005268 (0.01852)	E F

T HSD* Tukey-Kramer HSD levels not connected by same letter are significantly different ($q^* = 3.16475$, $\alpha = 0.05$)

Discussion and Conclusion

As highlighted by Kondolf (1995), demonstrating that arbitrarily derived classes are statistically different from one other, using categorical or continuous stream network and catchment metrics, is not the same thing as being able to derive the classes objectively from the same data. This is a different problem. Nevertheless, the fact that the classes can be discriminated using readily available, non-field derived, data is a promising first step towards a classification of rivers that is: a) transparent and objective; b) repeatable; c) cost effective; and d) numerically based rather than categorical. Continuous streamline data are problematic to analyse using multivariate statistics because of the inherent autocorrelation problems associated with data derived from a connected drainage network. Where most multivariate techniques require that the data is transformed or smoothed in some way to minimise these “problems”, in many respects these effects are a fundamental component of the data that needs to be incorporated into the analysis. One of the fundamental challenges in any classification is the delineation of meaningful boundaries, that are underpinned by real physical transitions or thresholds (Kondolf, 1995). Many people have tried, and failed, to derive objective classification schemes that reflect these boundary transition, and it is our belief that one of the reasons for this is that the spatial density of the input data is dictated by the logistical limitations of field sampling. At the resolution of the remote sensing data readily accessible now, it is becoming feasible to generate continuous data sets at an appropriate resolution to realistically encapsulate the drainage network parameters controlling reach-scale morphodynamics, and hence providing the scope to derive methods for an objective, numerically based, river classification scheme. This project is ongoing and will subsequently incorporate other attributes such as geology or drainage density. We have also recently acquired 30m SRTM DEM data which should improve our ability to interpret channel and floodplain features.

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