Predicting River Channel Type from Flow and Sediment Regime Attributes

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Abstract: Different river channel types provide different instream habitats, and river channel types are largely determined by catchment-scale flow and sediment regime attributes. River channel types in this sense include a variety of natural types (e.g. cobble riffle-pool, gravel riffle-pool, sand meandering) as well as impacted channel types (e.g. sand slug). An ability to predict channel type across a range of natural and impacted classes would enable stream managers to establish habitat reference conditions for impacted streams. In addition, linking channel type to the sediment and flow regimes, identifies the changes within catchments that are impinging on river habitat condition, and identifies areas where improved catchment management have the greatest potential to improve in river habitat condition. An approach along these lines is being developed in the upper Murrumbidgee catchment in New South Wales, Australia. Channels are classified from field observations and measurements of channel planform, major bedforms, water surface slope and bed surface sediment texture. Models to predict natural channel type and the occurrence of sand slugs on the basis of stream power and sediment supply have been developed. Stream power through the river network is estimated using channel slopes from a digital elevation model and hydrologic regionalisations based on observed and modelled flow series. Sediment supply to the river network is modelled using an empirical model of hillslope erosion and a decision-tree model of gully erosion. We demonstrate the ability of the model to predict the occurrence of natural channel types and sand slugs across the upper Murrumbidgee. Future work will focus on improving these models through better estimation of sediment transport capacity and natural sediment supply, and through the consideration of spatial variation in riparian vegetation and the extent of large woody debris.

KEYWORDS: river channels; sediment transport; river habitat; sand slugs

1. INTRODUCTION

River channels vary widely in form and process and so vary in the character of habitat that they provide to aquatic plants and animals. River channel types are primarily determined by their flow and sediment regimes and their geomorphic setting. Most existing classifications of river channel types [e.g. Alabyan and Chalov, 1998; Rosgen, 1994; Kellerhals et al., 1976] however, are based largely on river form variables and the link to river process variables is usually weak. Such classifications do not provide a strong basis on which to predict river channel types from information on sediment and flow regimes. Nor do they provide a basis for predicting how a given channel type will respond to changes in the sediment and flow regime.

Changes to sediment and flows regimes occur as a result of catchment disturbance (for example, land clearing and mining) and dam construction with subsequent flow regulation and diversion [e.g. Van Steeter and Pitlick, 1998; Young et al., 2001]. These changes are one of the major causes of river degradation, yet the process understanding of the catchment-river linkages is poor. This lack of understanding is a major obstacle to river restoration, and has lead to a tendency for river restoration project to focus at the reach scale on the symptoms of river degradation, rather than at the catchment scale on the cause of river degradation.

1.1 Study Outline

In this paper we describe a classification of river channel types, and demonstrate an ability to predict channel types from modelled values of catchment sediment supply and river sediment transport capacity. We use field measurements of median grain size, and field assessments of channel planform and major bedforms as a basis for classifying channel types. We have adopted (with minor modifications) the suite of channel types defined by Montgomery and Buffington [1997] and recognize the following channel types: bedrock, cascade, coarse plane-bed, step-pool, cobble riffle-pool, gravel riffle pool, gravel meandering, sand meandering, sand slug, incised channel, organic creek. The criteria used to distinguish these channel types from field measurements and observations are summarized in Figure 1.

The predictive model of channel type is then developed using modelled estimates of sediment supply and estimates of sediment transport capacity (based on measured channel slope and modelled discharge) as explanatory variables.

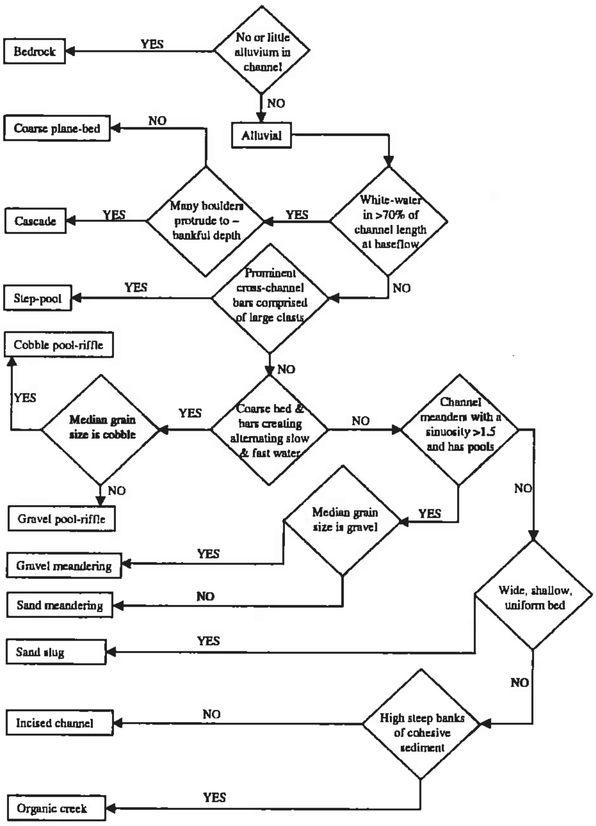

Figure 1. Flow chart for classification of channel type from field measurements and observations.

2. METHODS

2.1 Field Methods

The study was conducted in the upper Murrumbidgee – the approximately 30,000 km^2 upstream of Wagga Wagga. The upper Murrumbidgee catchment includes rivers with disturbed catchments and rivers with relatively pristine catchments. For the field program, a total of 36 sites were used. Using a network generated from a 25 m grid cell DEM for the upper Murrumbidgee River (for which streams were assumed to be initiated at a 50 km^2 threshold), we randomly selected 20 sites on rivers with disturbed catchments, and 8 sites on each of two rivers with pristine catchments. Random selections were rejected if they were too remote (>1 km through thick bush), contiguous with previously selected reaches, or from a slope class already selected, thus ensuring that the full range of channel slopes was sampled. Multiple site selection was prevented on tributaries less than 50 km in length.

At the sites, reaches were defined to comprise at least two pool-bar sequences. Exceptions were made for exceedingly long white-water reaches, and for meandering reaches where 1-2 meander wavelengths were sampled. As many as 8 riffles or steps were sampled within a single reach where they were small and closely spaced.

In the field, water surface elevations and distances were measured using a laser theodolite from which channel and riffle slopes and riffle-pool spacings were calculated. Bankfull channel widths were also measured. Bed particles were sampled according to reach planform: in straight channels sediments were taken from one to eight (usually two or three) contiguous riffles. Particles were sampled using the method of Wolman [1954] at random points along regular transects down the riffle. At least 100 particles were measured in each reach, with the number per riffle approximately proportional to the riffle length. Assuming a standard deviation of 0.3, this estimates the median particle size to ± 15% at a 95% confidence level [Hey and Thorne, 1983]. Where a mix of sand and gravel was encountered, the coarsest particle was selected and measured. The number of occurrences of bedrock and root mat were also recorded. In sinuous channel sediments were taken from point bars and inflection point deposits. Although the point bar sediments are finer, the difference is small relative to the range of sediment sizes encountered in this study, so both types of sample were included in the analyses.

For each site, observations of the degree of channel confinement were recorded, photographs taken and sketch maps drawn.

For the statistical analyses of channel type, an additional eight reaches were selected, for which no field measurements were made, but which could be confidently identified as sand slugs from aerial photographs and informal field inspections. This gave a total of 44 reaches for the analyses.

2.2 Flow and Sediment Regime Modelling

Specific sediment transport capacity (ω) was estimated using the formulation of Yang [1972]:

$$\omega = kw^{-1.4}Q^{1.4}S^{1.3} \tag{1}$$

where Q is the daily flow, S is the channel slope, and k is a constant that includes parameters describing hydraulic roughness and bed sediments. In these analyses we assume that variation in k across the river network is small in comparison to variation in Q and S and so can reasonably be treated as a constant.

In this study mean annual values of ω are used. To capture the important affects of daily flow variability on mean annual ω, mean annual values of the sum of daily discharges each raised to the 1.4 power (denoted $\Sigma Q1.4$) were used for Q in Equation 1 (see Equation 2).

$$\Sigma Q1.4 = \frac{365}{n}\sum_{i=1}^{n} Q_i^{1.4} \tag{2}$$

where Q_i are the daily discharges.

Because daily flow data were not available for each site, the hydrologic regionalisation developed by Young [2001] was used to estimate $\Sigma Q1.4$ for each site (Equation 3) on the basis of drainage area (A) and mean annual rainfall spatially averaged across the drainage area (Rf).

$$\Sigma Q1.4 = 10^{-7.790} A^{1.323} Rf^{\,3.391} \tag{3}$$

Values of A were estimated from the 25 m DEM, and values of Rf were derived using the 25 m DEM and a 5 km by 5 km gridded rainfall surface produced by the Queensland Department of Natural Resources and Mines [http://www.dnr.qld.gov.au/silo].

Equation 3 provides estimates of the natural values of $\Sigma Q1.4$. Ten of the study reaches (including four of the unsurveyed sand slug reaches) are on regulated rivers where flows are substantially modified from natural, and hence the current value of $\Sigma Q1.4$ cannot be determined from Equation 3. For these sites historic regulated flow records from the nearest gauge station were used to calculate a value of $\Sigma Q1.4$ for current conditions using Equation 2.

For the current conditions, the coarse sediment supply (SS) to each reach was estimated using the SedNet model [Prosser et al., 2001]. SedNet uses the gully network density predictions of Hughes et al. [2001] to estimate gully-derived sediment loads and estimates bank erosion using as an empirical function of bankfull discharge and the proportion of stream bank occupied by riparian vegetation [Prosser et al., 2001]. Only spatially coarse data (100 m resolution) were available across the entire catchment to indicate the presence of riparian vegetation. SedNet assumes 50% of the sediment loads generated by gully and stream bank erosion are coarse sediment that move as bedload. SedNet also assumes that this sediment is in the size range 2-4 mm, and that for material coarser than this, there has been no significant increase in supply. SedNet routes coarse sediment through the drainage network depositing coarse sediment in reaches where the supply exceeds the transport capacity.

SedNet assumes that there is no supply of coarse sediment to the river network under natural conditions. While this provides a reasonable reference condition for comparing the spatial pattern of sediment load increases due to catchment disturbance, it is clearly not useful for exploring the role of natural coarse sediment supply in determining channel type. In drainage basins with relatively uniform geology, hydrology and vegetation, sediment supply to a reach can be expressed as a power function of the drainage area [Montgomery et al., 1996], with an exponent less than 1. The magnitude of the exponent indicates the efficiency of sediment delivery from the basin, with steep basins with narrow valleys that do not store much sediment having exponents close to 1, and flatter basins with wider valleys that store significant sediment volumes having exponents much less than 1. In these initial analyses we assumed an exponent of 0.5.

The natural and current values of ω and SS were used in GENSTAT [GENSTAT 5 Committee, 1998] to build logistic regression models to predict natural and current channel type. A square root transform of ω was used to prevent the GENSTAT logistic regression routine attempting to determine the logarithm of zero. For the preliminary prediction of natural channel type, we consider only the following classes: (i) coarse-bed, high energy (CBHE) channels (bedrock, cascade, coarse plane-bed, step-pool), pool-riffle (P-R) channels, and fine-bed, low energy (FBLE) channels (meandering, fine plane bed, organic creek). For the prediction of natural channel type, the sand slugs were omitted, leaving 36 sites. For the preliminary prediction of current channel type we sought only to predict the occurrence of sand slugs. For this model the full 45 sites were used. For both models, P=0.05 was used to test the significance of explanatory variables.

The logistic regression models were then applied to the 541 reaches in the upper Murrumbidgee to predict the distribution of the natural channel types, and the current occurrence of sand slugs.

3. RESULTS

Both $\omega^{0.5}$ and SS were significant explanatory variables for natural channel type. The total deviance (a measure of sample variation) in the data was 65.0, and the logistic regression model accounted for a deviance of 29.6, with a residual deviance of 35.4. The observed and predicted natural channel types (Table 1) show a good performance for coarse-bed high energy (CBHE) and pool-riffle (P-R) channels, but a poorer performance for the fine-bed low energy (FBLE) channels. The poorer performance for FBLE channels is likely to be partly a result of difficulty in correctly classifying the field sites based on field observations. Several sites were clearly impacted by elevated sand supply but not to the extent of classifying them as sand slugs. For these sites, it is sometimes difficult to distinguish between FBLE channels and sand-impacted P-R channels.

Table 1. numbers of observed and predicted natural channel types.

Observed type	Predicted type		
	CBHE	P-R	FBLE
CBHE	5	2	0
P-R	1	20	2
FBLE	0	3	3

The logistic regression model of natural channel type predicts that five of the observed sand slugs would naturally have been FBLE channels, and three would naturally have been P-R channels.

Both ω and SS were significant explanatory variables for predicting the occurrence of sand slugs. The total deviance in the data was 45.0, and the logistic regression accounted for a deviance of 25.6 with a residual deviance of 19.4. The predictions of sand slug occurrence show a reasonable match to the observations (Table 2), with 4 incorrect predictions across the 45 sites.

Table 2. numbers of observed and predicted occurrences of sand slugs.

Observed type	Predicted type	
	Sand slug	No sand slug
Sand slug	7	2
No sand slug	2	34

The predicted occurrence of natural channel types across the upper Murrumbidgee (Figure 2) highlights the small number of CBHE reaches and the preponderance of P-R reaches. By length, 70.5% of the network is predicted to be P-R, 27.5% FBLE, and only 2% CBHE.

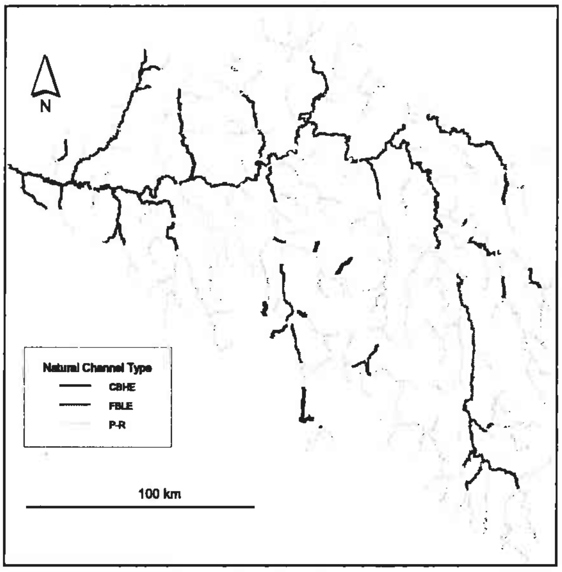

Figure 2. Predicted distribution of natural channel types across the upper Murrumbidgee catchment.

The predicted current occurrence of sand slugs across the upper Murrumbidgee (Figure 3) indicates that slugs are likely along most of the main stem of the Murrumbidgee River, as well as along significant lengths of tributary streams. By length, 30.0% of the network is predicted to be affected by sand slugs.

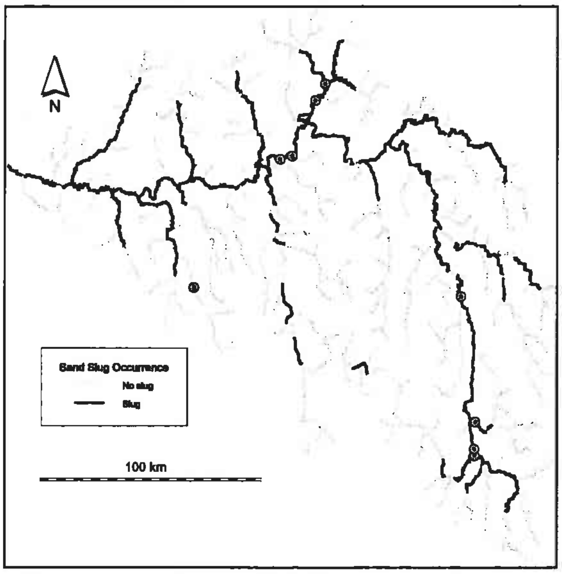

Figure 3. Reaches predicted to be sand slugs and the location of observed slugs in the upper Murrumbidgee catchment.

4. DISCUSSION

The logistic regression models predict the probability of a reach (or site) belonging each channel type class. Here, we have presented only the natural channel type that is predicted to be the most likely, and whether the presence or absence of a slug is more likely. The models provide differing degrees of confidence according to the probabilities. For example, one has greater confidence is finding a sand slug where the probability is 95% than where the probability is 55%. Where the probabilities associated with different channel types are similar for a reach, the predictions are less certain.

For the prediction of natural channel type at field sites, the measured channel slope was used to determine the transport capacity explanatory variable, while for prediction across the network the 25 m DEM slope was used. Several of the field sites that are correctly predicted using the measured slope, are incorrectly predicting using the DEM slope. Most of these incorrect predictions are for steeper sites, where the DEM reach-average slope is considerably less than that measured in the field. For the prediction of sand slugs, measured slopes were not available, and hence all predictions were based on the DEM slope.

The significant percentage (30.0%) of the network that is predicted to sand slug indicates the likely extent of this very extreme case of river habitat degradation. Of these predicted slugs, 82.2% by length are predicted to naturally be FBLE channels, and 17.8% by length are predicted to naturally by P-R channels. These degraded P-R channels are the ones with the best potential for habitat restoration, by virtue of their higher transport capacity. The models predict a total of 26 reaches in this category; their distribution is shown in Figure 4.

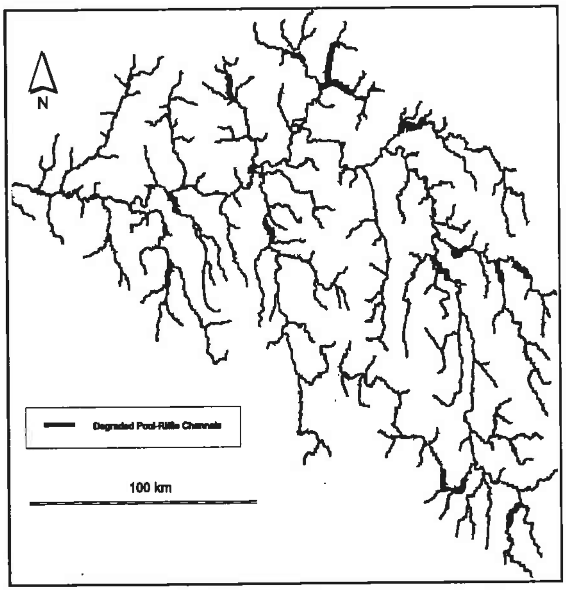

Figure 4. Predicted distribution of pool-riffle channels degraded by sand slugs in the upper Murrumbidgee catchment.

While the preliminary logistic regression models provide a reasonable level of explanation of the observed patterns, considerable variation remains unexplained. One major source of variation is error in the modelled values of the explanatory variables (sediment transport capacity and sediment supply). We will investigate the extent to which these modelled estimates can be improved by analysis of extra flow records from discontinued gauging stations, and by more sophisticated models of natural coarse sediment supply that consider the effects of source area slope, slope-channel connectivity, and downstream connectivity.

Other potential sources of variation are a result of differences in riparian vegetation and large woody debris between sites. Riparian vegetation is an important control on channel form, as it is the major determinant of bank resistance [Abernethy and Rutherfurd, 1998]. Accumulations of large woody debris are major roughness elements for the dissipation of flow energy. If large spatial differences occur in the loading of woody debris, the assumption of a constant *k* value in Equation 1 will invalidated.

Finally, the high proportional representation of P-R channels in the field data set, makes it more difficult to predict the other channel types. Additional field work is planned to improve the representation of CBHE and FBLE channels in the data sets for model development.

5. CONCLUSIONS

We have classified river channel types based on field measurements and observations. We have developed models that allow prediction of these channel types from modelled estimates of sediment transport capacity and sediment supply. By distinguishing between natural channel types, and those determined by catchment disturbance and flow regulation, we have been able to predict firstly, the occurrence of reaches degraded by sand slugs, and secondly, the natural channel type of these degraded reaches. These models allow those reaches that are both badly degraded, but also have a reasonable potential for restoration to be identified. Our approach to river channel type classification therefore provides a process-basis for better targeting of river restoration efforts.

6. ACKNOWLEDGMENTS

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