Predicting channel type from catchment and hydrological variables

**WILLIAM J. YOUNG, RALPH W. OGDEN,
ANDREW O. HUGHES & IAN P. PROSSER**

CSIRO Land and Water and Cooperative Research Centre for Catchment Hydrology, GPO Box 1666, Canberra, Australian Capital Territory 2601, Australia

e-mail: bill.young@csiro.au

Abstract We used field measurements to classify 36 river sites in the upper Murrumbidgee catchment (30 000 km^2), Australia, into 11 channel types. We then used pre- and post-catchment disturbance coarse sediment supply, coarse sediment transport capacity and maximum shear stress values (based on digital elevation models and hydrological regionalizations) to develop statistical models of channel type groupings, median bed surface grain size, and the occurrence of sand slugs. We applied the models to the upper Murrumbidgee catchment to predict the pre- and post-catchment disturbance spatial distribution of channel types. The predictions indicate the expected pre-disturbance attributes of degraded reaches and identify those degraded reaches that have a high potential for physical habitat restoration.

Key words river channel; bed sediment; digital elevation model (DEM); physical habitat

INTRODUCTION

River channels are a function of their hydrological and sediment regimes and the controls that bedrock and valley confinement place on channel development. River channel types therefore differ between and within catchments. Important attributes that are typically used to define river channel types include channel plan form, major bedforms, and bed surface grain size. Because of the wide range of channel forms, bed sediment sizes and flow hydraulics, different river channel types provide different habitats for riverine plants and animals. An ability to predict the distribution of river channel types across drainage networks based on an understanding of the primary catchment and hydrological controls on channel type, would therefore indicate the distribution of different riverine habitats. Such predictive models would help determine pre-disturbance reference conditions for physical habitat and provide a meaningful basis for setting physical habitat restoration targets. In addition, such models would indicate degraded reaches with the greatest restoration potential, and in undisturbed catchments would indicate the reaches that are most susceptible to disturbance.

Several classifications of river channel types have been developed (e.g. Kellerhals *et al*., 1976; Rosgen, 1994), however, robust models to predict these types from catchment and hydrologic attributes have not been developed. Existing classifications are useful for describing differences in channel form, and to a lesser extent process, but do not allow prediction of channel response to catchment disturbance or flow regulation. As such they are of limited value for guiding river restoration, or for predicting the likely responses to future disturbances such as dam construction or land clearing. We have adopted, with minor modifications, the channel classification of Montgomery & Buffington (1997), and using a combination of field measurements and spatial modelling we have developed statistical models to predict the occurrence of major channel type and median bed surface gain size. We hypothesize that channel type is largely a function of sediment supply (volume and texture), sediment transport capacity, and flow competence to move coarse sediment. Where sediment transport capacity exceeds supply a channel will erode to bedrock or other resistant base material, provided it is competent to move the largest bed material grain sizes. Bedrock and valley confinement are also expected to be controls on channel type.

METHODS

Field data collection and channel classification

We selected 36 field sites in the Murrumbidgee catchment upstream of Wagga Wagga, New South Wales, Australia (catchment area of 30 000 km^2): 20 sites on rivers with disturbed catchments, and eight sites on each of two rivers with pristine catchments. River reaches at each site were defined as at least two pool–bar sequences or two meander wavelengths, with exceptions for long white-water reaches. As many as eight riffles or steps were sampled within a single reach where they were small and closely spaced. Channel and riffles slopes, and bankfull channel widths were surveyed by laser theodolite. In straight channels bed surface sediments were sampled in one to eight (usually two or three) contiguous riffles, and in sinuous channels bed sediments were taken from point bars and inflection point deposits. At least 100 particles were measured in each reach using the method of Wolman (1954), with the number sampled in each riffle being approximately proportional to the riffle length. The number of times bedrock was encountered in the sampling was recorded.

Based on field observations of channel plan form, cross-section, major bedforms, dominant bed material and gross hydraulics we classified sites as: bedrock, cascade, step-pool, cobble pool–riffle, gravel pool–riffle, gravel meandering, sand meandering, sand slug, incised channel or organic creek (Young *et al.*, 2001a). Sand slugs are channels with shallow flow over a wide, uniform sand bed that form as a result of a large supply of sand and fine gravel in excess of transport capacity (Nicholas *et al.*, 1995). Sand slugs typically form as a result of catchment disturbances that grossly elevate the supply of fine bed-load material. In addition to the field sites, 11 sand slugs were identified from aerial photographs for use in channel type analyses.

Spatial modelling

We assumed that sediments that move as bed load are the most important for determining channel type. We considered the supply and transport of fine bed load (sand and fine gravel—up to 8 mm) and coarse bed load (coarse gravel and cobbles) separately. We assumed that coarse bed load is sourced primarily from landsliding of steep hillslopes into river channels, with erosion of bedrock underlying channels a secondary source. Fine bed load was assumed to be primarily sourced from gully erosion of colluvial material (and prior alluvial deposits), with secondary sources from landsliding and the abrasion of coarse bed load. Landsliding is a relatively minor source of fine bed load because landslides are rare events in Australian fluvial systems (Rose, 1993).

Because of the rarity of landslides, the delivery of coarse bed load to rivers in the Murrumbidgee catchment is infrequent and irregular. In the absence of direct information on either the frequency or amount of coarse bed load delivered to the channel, we developed a spatial model to estimate the relative differences in coarse bed-load supply. We assumed that landsliding occurs only on hillslopes steeper than 25° (the critical slope for landsliding measured by Rutherfurd *et al.*, 1994). We also assumed that only those steep hillslopes that extend to within 50 m of a stream channel are potential direct source areas for coarse bed load. We also considered the indirect coarse bed load supply—material that is delivered to a reach by downstream transport. For coarse bed load we assumed that the threshold for transport is more important than the transport capacity. That is, because supply rates are so low, if a channel is competent to transport a given grain size, it is assumed to have the capacity to transport all the available sediment of that grain size. We estimated competence using a dimensionless critical shear stress (θ) of 0.06. θ is the ratio of the mean critical bed shear stress (τ_{cr}) to the submerged weight per unit area of a single layer of grains:

$$\theta = \frac{\tau_{cr}}{g(\rho_s - \rho)D} \tag{1}$$

where D is the sediment grain diameter, g is the acceleration due to gravity, and ρ_s and ρ are the sediment grain and water densities respectively. Mean bed shear stress is the product of the specific weight of water, the flow depth (d) and the energy slope (approximated by the bed slope (S)). Using a sediment grain density of 2650 kg m^{-3}, the grain size a flow is competent to transport can be expressed as:

$$D = 10dS \tag{2}$$

For determining competence throughout the river network we used slopes from a 25-m-grid digital elevation model (DEM) fitted to 10-m contour data. For determining competence at field sites we used measured channel slopes. We estimated flow depth as a function of the drainage area (A) determined from the DEM. Pickup & Marks (2001) showed that 25-year annual recurrence interval floods depend on $A^{0.7}$. We assume that floods of this return period provide a reasonable indication of the largest grain size a channel is competent to move. Hydraulic geometry relationships estimate flow depth as power function of discharge, with typical exponents close to 0.3 (Richards, 1982). Flow depths for large floods can therefore be estimated as a function of $A^{0.2}$. Rating curves for gauging stations in the upper Murrumbidgee indicate that with A in km^2 and d in m, $A^{0.2}$ must be multiplied by a constant of around 1.5 to correctly estimate flow depth. The maximum bed sediment size that a reach is competent to move (assumed to be equivalent to D_{95}) can thus be estimated as:

$$D_{95} = 15SA^{0.2} \tag{3}$$

The median bed sediment size (D_{50}) was estimated to be a quarter of D_{95} reflecting typical gravel bed river grain-size distributions. Using the competence values for each link in the river network we calculated the indirect coarse sediment source areas to each link. We considered four median cobble-size competence thresholds: 215 mm, 152 mm, 108 mm and 76 mm—the mid-points of half phi unit (Wentworth scale) ranges. For each competence threshold we accumulated source areas through the drainage network. There is no evidence for an increase in landsliding since catchment disturbance in the Murrumbidgee, so the post- and pre-disturbance coarse sediment supply are assumed to be the same.

The direct post-disturbance fine bed-load supply to each network link was estimated from gully lengths measured from aerial photographs, and from an empirical prediction of bank erosion. Sediment volumes from gully erosion were estimated by assuming uniform gully cross-section dimensions and constant delivery over 100 years. Half of the total gully volume eroded was assumed to be fine bed-load supply, and half fine sediments transported in suspension. Bank erosion volumes were estimated as an empirical function of bankfull discharge and the proportion of vegetated bank length and an assumed constant bank height, based on Rutherfurd (2000). Bankfull discharge was estimated using a hydrological regionalization from Young *et al*. (2001b). The proportion of vegetated bank length was estimated from 100-m-grid remotely-sensed land-cover data that indicated the presence of woody vegetation.

The indirect post-disturbance fine bed-load supply to each network link was estimated by accumulating the direct average annual fine bed-load volumes (from gully and bank erosion) through the drainage network and depositing in each link that portion of the load that was in excess of the estimated fine bed-load transport capacity. For pre-disturbance conditions we assumed that the relative amounts of fine bed-load supply were similar to the coarse bed-load supply.

Sediment transport capacity (Ω) was calculated as:

$$\Omega = kQ^{1.4}S^{1.3} \tag{4}$$

where Q is the daily flow and k is a constant that includes parameters describing hydraulic roughness and bed sediments (Yang, 1972). We assumed that variation in k across the river network was small in comparison to variation in Q and S and so could be treated as a constant. Specific sediment transport capacity (ϖ) was calculated as Ω divided by measured channel width. We calculated mean annual values of Ω as:

$$\Omega \propto \frac{365}{n}\sum_{i=1}^{n} Q_i^{1.4} S^{1.3} \tag{5}$$

where Q_i are the daily discharges in an n-year flow record. To estimate the discharge term in equation (5) (denoted $\Sigma Q^{1.4}$, with discharge in Ml day^{-1}) for unregulated flows in each network link we used the hydrological regionalization:

$$\sum Q1.4 = 10^{-7.790} A^{1.323} Rf^{3.391} \tag{6}$$

where Rf is spatially averaged upstream mean annual rainfall (Young *et al*., 2001b). Values of A were taken from the 25-m DEM and values of Rf were derived using the 25-m DEM and a 5-km mean annual rainfall grid (http://www.dnr.qld.gov.au/silo). Flows in several of the rivers are regulated, and for sites on these rivers we estimated the current value of $\Sigma Q^{1.4}$ using post-regulation flow gauging records.

Linear and logistic regression modelling

Using the modelled values of sediment transport capacity and sediment supply variables we developed regression relationships to predict median bed surface grain size, natural channel type, and the occurrence of sand slugs. For grain size, we first used a simple decision rule to distinguish fine sediments (<32 mm) from coarse sediments (>32 mm), and then developed a linear regression relationship to predict median size for coarse sediments. We used this two-step model because in the fine-sediment-size analyses we determined only the percentage sand not the median grain size. For natural channel type and the occurrence of sand slugs we developed logistic regression relationships. Logistic regression predicts the probability of belonging to a particular class and so is suitable for ranked categorical data. Because of the very small number of some channel types we grouped types into four categories (high energy coarse bed (CBHE), cobble pool–riffle (CPR), gravel pool–riffle (GPR) and low energy fine bed (FBLE)) for the channel type analysis. For the grain size and natural channel type regressions we omitted one field site as it was a sand slug for which it was not anticipated that grain size would be related to competence and for which it was not possible to ascertain the natural channel type. One field site was treated as two separate sites because of a large change in slope within the reach.

RESULTS

A threshold value of competence was found to reasonably distinguish fine from coarse median bed sediment sizes. Threshold values of 25 mm or 35 mm both correctly distinguished fine from coarse sediment for 35 of the 36 sites. The lower threshold incorrectly classified one fine-grained site, and the higher threshold incorrectly classified one coarse-grained site. The best linear regression relationships for the coarse sediment sizes (D_{50}) were functions of confinement, specific sediment transport capacity, and indirect source area for sediment >108 mm (SA_{108}) (equations (8) and (9)).

Confined channel: $$D_{50} = 97.9 + 0.545\,\varpi + 3.04 SA_{108} \quad (8)$$

Unconfined channel: $$D_{50} = 63.4 + 0.545\,\varpi + 3.04 SA_{108} \quad (9)$$

Together these relationships explain 55% of the variance across the 28 coarse sediment sites, with a standard error of 34 mm. In addition to these models, the occurrence of cobbles (>64 mm) is well explained (35 of 36 sites) by a decision rule that requires a direct supply of coarse sediment and a competence greater than 25 mm. That the best threshold competence value for predicting cobbles is lower than the cobble-size range (>64 mm) suggests that the estimates of median grain size competence may be too low.

The best model for channel type includes competence, indirect source area for sediment >76 mm (SA_{76}), and direct coarse sediment supply as a binary variable (Y/N). SA_{76} was found to explain a similar component of the site variance as ϖ. The model misclassifies 7 from 36 sites (Table 1).

Table 1 Number of predicted and observed sites of each major channel type.

Predicted channel type	Observed channel type: CBHE	CPR	GPR	FBLE
CBHE	6	1	0	0
CPR	1	15	2	0
GPR	0	1	3	1
FBLE	0	0	1	5

The best model for sand slug occurrence (binary) included ϖ (using regulated flows) and post-disturbance sediment supply. The model misclassifies 2 of the 12 sand slug sites and 3 of the 36 non-slug sites. Two of these three "incorrectly predicted" non-slug sites were observed to be substantially impacted by sand.

Applying the models across the river network in the DEM enabled predictions of the current distribution of sand slugs and the prior channel type of these sand slugs. As higher energy channel types offer greater potential for restoration, it is possible to identify those reaches that are currently degraded by sand deposition that are candidates for restoration (Fig. 1).

The ability to predict channel types provides an ability to predict large-scale habitat features such as pools, riffles, and point bars. Pools provide resting habitat and

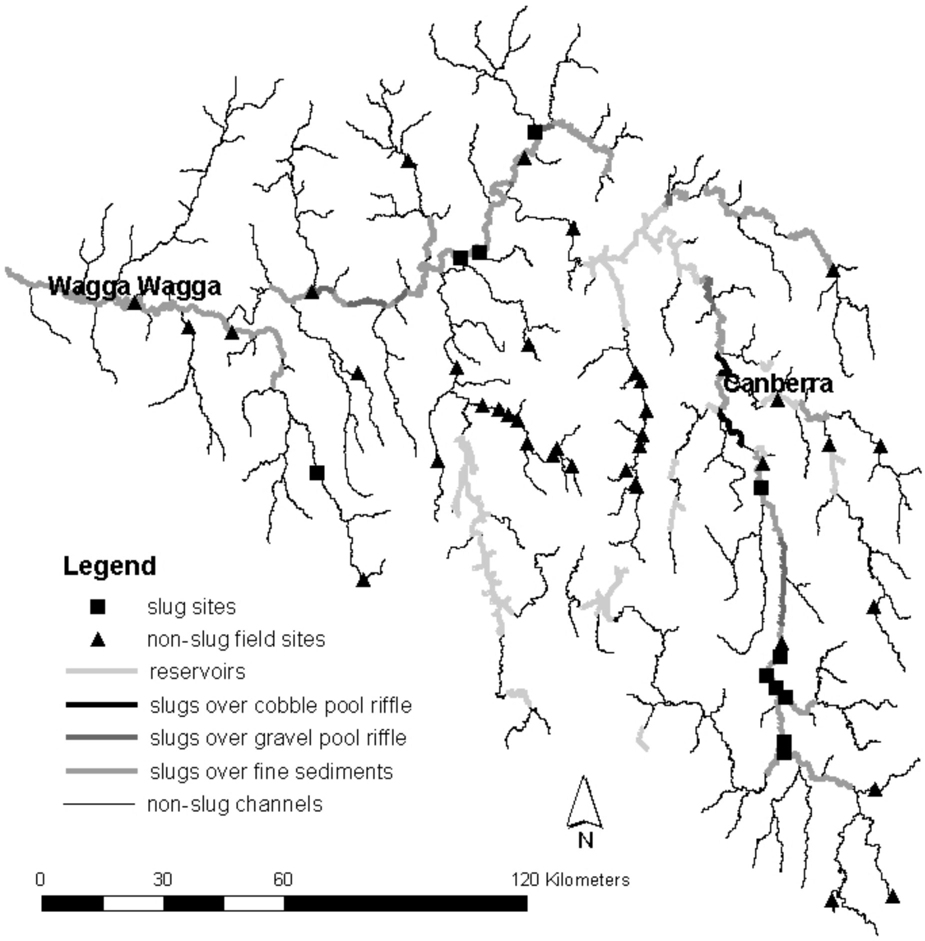

Fig. 1 Degraded river reaches with a high potential for physical habitat restoration.

refuge for fish, and allow accumulation of organic debris making them a suitable habitat for macroinvertebrates that feed on this debris. Riffles aerate the flow, increasing dissolved oxygen levels, which is important for fish survival. Up-welling of nutrient-rich water often occurs at the downstream ends of riffles, often creating "hot spots" of productivity in the stream (Boulton *et al.*, 1998) such as encouraging macrophyte growth in the upstream sections of the receiving pool (White & Hendricks, 2000).

Within these large-scale habitat features there is of course still a large variety of habitat types. Much of the finer-scale habitat variation is determined by how flows interact with the stream bed, which is a function of bed roughness. Bed roughness is largely determined by bed particle size for which we have developed useful predictive models. Bed roughness, together with the flow regime, determine the nature of near-bed flow regimes, including turbulence structure (Nikora *et al.*, 2001). The near-bed flow regime determines nutrient delivery to biofilms, particulate supply to filter-feeding macroinvertebrates, and the flushing of benthic animal toxic waste products (Hart & Finelli, 1999). Bed-material size also determines the extent of surfaces to which biofilms can attach, and together with the flow regime determines the frequency with which biofilms will be disturbed by direct scouring or stripping, or by disturbance of the substrate. Bed-material size affects macroinvertebrates community composition (e.g. Evans & Norris, 1997) and deposition of fine sediments over naturally coarse sediment beds has been demonstrated to affect macroinvertebrate colonization (Richards & Bacon, 1994).

Bed material size helps determine resident fish populations both indirectly and directly. Indirectly, by food requirements, as most Australian freshwater fish are carnivores and depend on invertebrate populations for survival. Some species however, such as the Bony herring are herbivores or detritivores (Schiller & Harris, 2001) and so are found in slower flowing habitats over finer sediments. Bed-material size has a direct influence for fish species that require coarse substrate for their eggs. Freshwater catfish (*Tandanus tandanus*) lay their eggs in nests within cobble or coarse-gravel substrates, and Macquarie perch (*Macquaria australisica*) lay sticky eggs that sink into cobble or gravel beds (Schiller & Harris, 2001). Only coarse stream beds that are not impacted by interstitial sand deposition provide suitable spawning habitat for these species. The independent ability to predict the occurrence of sand deposits over coarse stream beds allows good spawning habitat for these fish species to be identified, and in catchments where such habitat is limited and limits fish populations, the ability to predict degraded cobble and gravel reaches also allows the reaches with greatest potential for spawning habitat rehabilitation to be identified.

Although an ability to predict channel type goes some way towards habitat characterization, further research is needed firstly, to quantify the differences in habitat attributes between channel types, and secondly to demonstrate that these differences are reflected in the stream biota. In addition, understanding how sand deposition affects these differences is important information for river rehabilitation. Ongoing research is focused initially on this latter issue. Subsequently however, we will seek to quantify firstly, the differences in bed roughness, bedform profile, and near-bed flow regimes between channel types, and secondly, the biotic differences between channel types.

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