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Abstract

Large wood in rivers and logjams are linked to the presence of varied riverine morphologies and
increased abundance and diversity of aquatic biota. Current research into the ecohydrological,
morphological and geochemical effects of logjams is restricted by difficulties in comparing findings
between river systems. The problem is exacerbated by a lack of standardised metrics for recording
and reporting logjams and a scale dependence of logjam effects with river size.

In this paper a new method for analysing logjams is presented based on a set of seven dimensionless
metrics of structure and morphological effects. These metrics are used along with a cluster analysis to
identify key logjam types within a study river. The analysis framework is applied to data from a small
forest river in the UK and identifies that 73% of logjams in this system can be grouped into eight
distinct classes. Of these classes, two are logjams which only partly fill the channel and six are channel
spanning. The individual classes are differentiated from each other principally by the degree of lateral
and vertical erosion found in association with the logjams.

The dimensionless metrics are also applied qualitatively to a range of logjams described in the
literature and show the potential for the method to be applied as a standard survey and analysis

framework for logjams across diverse river environments. The potential to link logjam form with function, and therefore provision of specific habitats, has wide applicability to the design and monitoring of river restoration schemes.

1. Introduction

Logjams are a crucial element in a morphologically and ecologically diverse riverine environment (Collins et al., 2002) and the effects of logjams have been described in a wide range of river sizes and types (Gurnell et al., 2002; Montgomery et al., 2003). In small and medium sized forest rivers logjams can fill the channel cross-section (Gurnell, 2003) and act to increase the frequency and depth of pools (Montgomery et al., 1995; Abbe and Montgomery, 1996; Gurnell and Sweet, 1998; Collins et al., 2002), to trap and store sediment both behind structures and in downstream mid-channel bars (Bilby and Likens, 1980; Daniels, 2006; Fisher et al., 2010; Wohl et al., 2012; Beckman and Wohl, 2014) and to mediate the formation of perennial floodplain channels (Sear et al., 2010); all of which enhance habitat provision. In large rivers, the river is wider than the length of the largest pieces of wood delivered to it (Gurnell, 2003) and thus logjams typically do not fill the channel cross-section, rather they are formed on emergent bars or against banks (Abbe and Montgomery, 1996) and act to stabilise bar heads and banks and deflect flow, forming refuges for biota. In large braided river systems logjams can be a focus for sediment deposition and promote the aggradation of bars and islands (Gurnell et al., 2005; Bertoldi et al., 2009; Bertoldi et al., 2013; Picco et al., 2015). A common factor across rivers of all sizes is the importance of logjams in mediating geomorphological change and driving ecosystem structure and processes.

Logjams are found in a diverse array of forms ranging from simple loose accumulations of wood pieces against a river bank, to large, channel-spanning structures with complex architecture and tens or even hundreds of constituent wood pieces (Montgomery et al., 2003). Individual logjams have been shown to trap and export individual pieces of wood on inter-annual timescales changing logjam form and architecture (Dixon and Sear, 2014). The hydrological and geomorphological function of individual logjams shows a great deal of variability, can change with river stage, and shows only weak correlations with physical parameters of the structure (Dixon, 2013). Although the importance of logjams for stream diversity and ecological health has been recognised and the insertion of engineered logjams is a widespread river restoration technique (Brooks et al., 2004; Bernhardt et al., 2005; Shields Jr et al., 2006; Collins et al., 2012), the features of individual logjams which are correlated

with the creation of additional geomorphological or hydrological diversity remains unknown (Klaar et al., 2009; Dixon, 2013) and restoration techniques typically rely on increasing general geomorphic complexity (Polvi et al., 2014).

The development of a method of quantitatively comparing and contrasting logjams in varied environments is needed in order to help standardise reporting of studies and to understand quantitatively how the influence of logjams varies in different environments (Wohl et al., 2010; Máčka et al., 2011; Wohl et al., 2011; MacVicar and Piégay, 2012). Without such a system it is often only possible to develop theories of logjam effects based on localised data sets and it remains difficult to test such theories critically. Within industry, engineered logjams are often used as part of river restoration schemes, frequently with the goal of increasing hydromorphological diversity in order to improve biodiversity (Miller et al., 2010; Whiteway et al., 2010). A lack of data linking logjam form to function means the implementation of such schemes is rarely based on data and it is generally difficult to adequately monitor the success of meeting restoration project goals (Brierley et al., 2010; Nilsson et al., 2014).

In this paper a new method of statistically analysing logjam form and function is proposed using dimensionless units and a cluster analysis to identify key logjam types in a river network based solely on quantitative field data. This method is then tested in detail on a small river in the UK, before the general methodology is applied in a qualitative manner to logjams described in other papers from different geomorphological settings to demonstrate the potential wider applicability of the method. The objectives of this work are to analyse the relationships between logjam form and function in a study river and to standardise a method of describing and characterising logjams in a given study site, in order to facilitate future comparisons between studies.

2. Methods

Logjams were surveyed along a 4.5km stretch of the Highland Water in South England (Figure 1). Large wood is defined as a piece of living or dead wood at least partially within the channel and equal to, or greater than, both 0.1m diameter and 1m length. A logjam is defined as three or more pieces of large wood in contact (Wohl et al., 2011) and forming a structure in which it is apparent at least one piece of large wood has been previously mobile and has been trapped (or "racked") by another piece. The river is a 4th order tributary of the Lymington River and is located within the New Forest National Park (Figure 1). The upper and lower portions of the study reach are semi-natural floodplain woodland with a mix of *Fagus sylvatica* (beech), *Quercus petraea* (sessile oak), *Fraxinus Excelsior* (ash), *Alnus glutinosa* (alder), *Betula pendula* (birch) and some *Ilex aquifolium* (holly) (Jeffries et

al., 2003). The central part of the study reach is a forest plantation dominated by even aged cohorts of *Fagus sylvatica* estimated to be in excess of 100 years old. Mean bankful channel width is 5.1m (standard deviation ±1.5m) and mean bankful depth is 1.3m (s.d. ±0.4m) (Dixon, 2013).

Eocene Barton clay underlies the catchment, and so the study river responds quickly to rainfall and has a "flashy" hydrological regime; overlaying this clay layer is a mix of alluvial silt and gravels (Gurnell and Sweet, 1998). There is a mosaic of stream types in the catchment as a result of previous land management; in the upper and middle portion of the study reach sections were straightened to improve drainage (Tubbs, 2001; Sear et al., 2006) and more recently the upper part of the study reach has been remeandered as part of river restoration works (Millington and Sear, 2007; Dixon, 2013), there are also areas of relatively unmanaged riparian wet woodland in the lower part of the reach (Sear et al., 2010). The average slope of the channel through the study reach is 0.005, with sinuosity ranging from 1.02-1.62 (Dixon and Sear, 2014). The D50 grain size ranges from 21-37mm and riparian tree density from 18.9-41.2 trees/ha (Dixon and Sear, 2014).

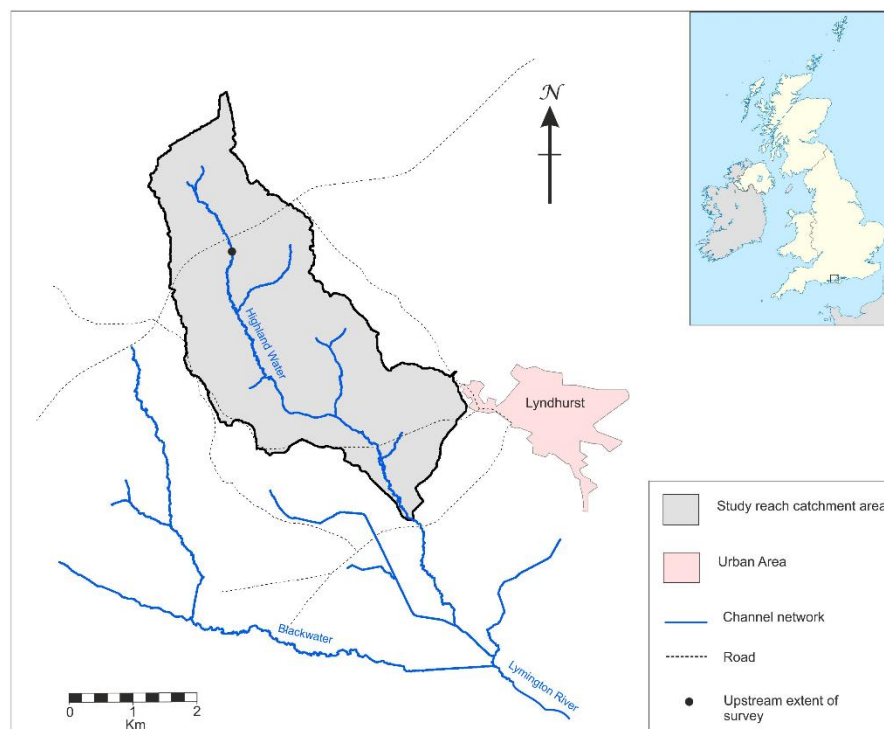Figure 1 – Map showing location of study reach for data collection, inset shows location within United Kingdom.

Building upon the recommendations in Wohl et al (2010) to standardise metrics for recording wood in rivers, it is proposed there are six measurements essential for describing the extent and structure of a logjam. These are: the width, height and length of the logjam, the porosity of the structure, the

proportion of the channel cross-sectional area filled by the logjam and the difference in water surface elevation up and/or downstream of the logjam (if any). In order to document the sediment erosion and deposition associated with logjams it is necessary to record the depth and volume of sediment deposition up and downstream of the logjam, the depth of any pool scouring and the width of any lateral erosion.

For each logjam the following information was recorded: location, number of key and racked pieces of large wood (defined as equal to, or greater than, both 0.1m diameter and 1m length), logjam width, height, and length measured along Cartesian axes with x parallel to the flow direction. The degree of channel blockage and porosity of the logjam was visually estimated. Blockage was recorded as the percentage of the channel cross-sectional area filled by the logjam, perpendicular to the flow direction. Porosity of the logjam was recorded as a visual estimate of the ratio of pore/void space within the logjam to the total cross-sectional area occupied by the logjam.

The effects of the logjam on local hydraulics and geomorphology recorded were: spill height (or height of water step induced by logjam in upstream direction), depth of scour below bed level, depth and volume of sediment deposition either upstream of dam or in downstream mid-channel bar and width of lateral erosion into channel banks. Spill height was measured as the height difference between the water surface immediately upstream and downstream of the structure. This spill height will vary with discharge and so all data on all logjams were collected over a two day low flow period in which there was no rainfall. This metric collected at low flow gives an indication of which logjams induce areas of slack water upstream and increased velocity downstream during ambient discharges.

Depth of scour was measured as the difference in elevation between the lowest point and the mean bed level up and downstream. Depth of sediment deposition was measured by probing with a graduated, tapered rod noting where there was a transition from soft deposited fines into the imbricated gravel/cobble surface underneath (Lisle and Hilton, 1992), the length and width of area of sediment deposition (parallel and perpendicular to the channel respectively) were also measured to give a volume of deposited material. Lateral erosion was measured perpendicular to the flow direction as the difference between the actual bank edge and an assumed pre-erosional bank edge taken as a smooth profile between the bank edges 10m up and downstream of the logjam. In practice areas of lateral erosion rarely exceeded 5m in length along the channel. Five measurements of bankful width and depth were taken between 10m up and downstream of the logjam and used to calculate the local mean bankful channel width and depth.

The main objective of this study is to describe and analyse the form and function of logjams in an easy to reproduce way. To that end it is important to apply the principle of Occam's razor to the collected metrics to determine the vital measurements for describing the geometric form of a logjam as well as quantifying the geomorphological effects associated with it for analysis. Increased erosion in the presence of a logjam is due to either water spilling over a logjam and scouring the bed downstream of the structure, or the logjam diverting and concentrating flow into only part of the channel cross-section (Montgomery et al., 2003). Increased deposition associated with a logjam is caused by either the creation of a barrier to sediment movement with a channel spanning logjam, or flow divergence caused by the logjam promoting deposition downstream of the structure (Montgomery et al., 2003). Therefore, the important structural controls on logjam function are the proportion of the channel cross section filled by the structure and its porosity, which can be described using a combination of logjam: width, cross-sectional blockage and porosity. The hydraulic and geomorphological function of logjams can be described by the lateral erosion, bed erosion, depth of sediment deposition and step in the water profile.

The following measurements were converted to dimensionless units by dividing by mean local channel width (lateral erosion, logjam width) or mean local channel depth (spill height, sediment depth, scour depth). These measures, together with blockage and porosity can be used as a set of seven dimensionless metrics (logjam width*, blockage, porosity, step height*, bed scour*, lateral erosion*, sediment depth*) to define the form and geomorphological function of a logjam irrespective of channel size or setting, where * indicates a dimensionless variable.

In order to establish the dominant logjam types within the system a hierarchical cluster analysis was performed on the seven dimensionless variables using Minitab. There exists in the literature a range of sophisticated methods of clustering data points within n-dimensional space (see review in Jain, 2010). In this study, a hierarchical clustering has been used due to its simplicity both in terms of computational power and availability in standard statistical packages, such as Minitab and SPSS. Furthermore, the aim of the analysis is to identify a few cohesive clusters (i.e. those which describe the key logjam types) with less cohesive clusters/points being ignored; this is a strength of hierarchical clustering as opposed to some alternative clustering methods which seek the best partition for the whole data set (Jain, 2010). Observation clustering proceeds in an agglomerative step-wise manner, starting with single member clusters and matching the two closest points/clusters in Euclidean space until a cut-off point is reached in terms of maximum join distance between two clusters (Reynolds et al., 2006). For calculating distance between clusters the mean of distances

between all individual points within the two clusters was used, which limits scatter about the cluster centroids (Bratchell, 1987).

Descriptive statistics are calculated for each cluster to enable analysis (Milligan, 1996). Variables are dimensionless and clustering is conducted using average distance between points in Euclidian space, therefore for any given cluster the mean values for all seven variables corresponds to the centroid of the cluster in n-dimensional space. Therefore the mean values for all seven dimensionless variables can be used to describe the archetypal logjam within a given cluster. The mean values for all seven dimensionless variables are plotted as radar plots for each cluster; these radar plots allow intuitive comparisons to be made between clusters with the shape of the radar plot forming a characteristic "fingerprint" for each logjam cluster. The standard deviation for each variable can be used to describe how tightly points within the cluster are grouped in any given dimension.

3. Results

A total of 70 logjams were surveyed in the 4.5km study reach. A cluster analysis based on seven dimensionless measures of logjam form and function identified eight clusters each containing 3 or more logjams (Table 1) using a maximum join distance of 0.41; 19 logjams are not identified as being part of a cluster. Because a low level of collinearity is a requirement for cluster analyses (Mooi and Sarstedt, 2011), a bivariate correlation analysis was performed on the variables. The largest correlation coefficient between variables is that for porosity and spill (ρ=0.51), all other pairs are $\rho \leq 0.40$; well below the value of $\rho \geq 0.90$ considered as highly correlated (Mooi and Sarstedt, 2011).

3.1 Types of logjam identified

For each logjam cluster identified the mean values for each of the seven dimensionless metrics can be displayed as radar plots (Figure 2).

Cluster 1 (Figure 2A) is characterised as channel spanning logjams with a blockage of ~60% of the cross-sectional channel area with moderate porosity of 45-70%. These logjams induce moderate scour pools with depths 15-35% below the local channel depth, but have no other geomorphological features associated with them (e.g. lateral erosion, sediment deposition); such logjams represent 10% of those surveyed.

Cluster 2 (Figure 2B) contains logjams which are also channel spanning, but with blockages of only 30-50% of the cross-sectional channel area. They have very low porosities of 10-20% and induce

	n	Logjam Width	Blockage	Porosity	Step Height	Scour Depth	Sediment Depth	Lateral Erosion	Description
Term		Y^*	A^*	$1-\Phi$	Z^*	E_z^*	D_{sed}^*	E_y^*	
Calculation					h_a-h_b/Z_{bf}	Z_{ero}/Z_{bf}	Z_{sed}/Z_{bf}	Y_{ero}/Y_{bf}	
Cluster 1	7	1.02 ± 0.04	0.61 ± 0.09	0.59 ± 0.14	0.00 ± 0.00	0.26 ± 0.11	0.05 ± 0.09	0.06 ± 0.09	Channel spanning jams with 60% blockage and moderate porosity. Inducing moderate scour pools (15-35% of channel depth)
Cluster 2	11	0.97 ± 0.07	0.30 ± 0.11	0.41 ± 0.18	0.00 ± 0.01	0.07 ± 0.05	0.12 ± 0.09	0.07 ± 0.08	Channel spanning jams with 30-50% blockage and very low porosity. Inducing variable, low steps in water profile and comparatively deep scour pools.
Cluster 3	13	1.00 ± 0.00	0.91 ± 0.11	0.42 ± 0.11	0.01 ± 0.04	0.18 ± 0.12	0.13 ± 0.14	0.09 ± 0.10	Channel spanning jams filling majority of channel cross-section with moderate porosity. Associated with variable, small magnitude geomorphological effects.
Cluster 4	7	0.98 ± 0.04	0.41 ± 0.13	0.16 ± 0.07	0.05 ± 0.06	0.44 ± 0.10	0.12 ± 0.09	0.11 ± 0.09	Channel spanning jams with 20-40% blockage and moderate, variable porosity (20-60%). Associated with negligible geomorphological effects.
Cluster 5	3	1.00 ± 0.00	0.93 ± 0.12	0.15 ± 0.13	0.13 ± 0.16	0.57 ± 0.03	0.16 ± 0.13	0.07 ± 0.11	Channel spanning jams with high blockage and low porosity. Induce large steps in water profile, deep scour pools and sediment deposiiton
Cluster 6	4	0.64 ± 0.10	0.43 ± 0.13	0.48 ± 0.13	0.00 ± 0.00	0.31 ± 0.08	0.04 ± 0.04	0.09 ± 0.12	Jams with moderate blockage (30-55%) and filling 50-75% of channel width with moderate porosity. Associated with moderate scour pools
Cluster 7	3	0.23 ± 0.04	0.13 ± 0.06	0.62 ± 0.20	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	Small jams filling 20-30%of channel width with blockage of 10-20% and high porosity. No associated geomorphological effects
Cluster 8	3	1.00 ± 0.00	0.23 ± 0.06	0.23 ± 0.15	0.06 ± 0.05	0.29 ± 0.16	0.20 ± 0.09	0.40 ± 0.00	Channel spanning jams with blockages of 20-30% and low porosity. Associated with lateral erosion, moderate scour pools and sediment deposition.

Table 1 – Mean dimensionless characteristics for each of the logjam clusters identified. Where h is water surface height, a and b are up and downstream of the logjam respectively, Z_{bf} and Y_{bf} are bankful channel depth and width, Z_{ero} and Y_{ero} are depth and lateral extent of erosion and Z_{sed} is depth of sediment. See text for full description of metrics.

variable, but low spill heights and are associated with comparatively deep pools of 35-55% below the local channel depth as a result of scouring; such logjams represent 10% of those surveyed.

Cluster 3 (Figure 2C) is the largest cluster representing 18.6% of logjams surveyed. These logjams are channel spanning, filling the majority of the cross-sectional channel area (blockage >80%) with moderate porosity of 30-50%; these logjams are associated with variable, but small geomorphological effects.

Cluster 4 (Figure 2D) contains channel spanning logjams representing 15.7% of logjams surveyed. These have blockages of 20-40% of the channel cross-sectional area, with variable porosity of 20-60% and associated with negligible geomorphological effects.

Cluster 5 (Figure 2E) is a small cluster of only 3 logjams (4% of those surveyed). These are channel spanning and have blockages of over 80% of the channel cross-sectional area with very low porosity. These jams induce variable but comparatively high spill steps up to 30% of the local channel depth and have deep scour pools of 50-60% of the channel depth and some sediment deposition in association with the logjam.

Cluster 6 (Figure 2F) is a small cluster representing 5.3% of logjams surveyed which have blockages of 30-55% of the channel cross-sectional area and 50-75% of channel width with moderate to high porosity of 35-60%. These logjams are associated with moderate scour of 20-40% of the channel depth but otherwise only small and variable geomorphological effects.

Cluster 7 (Figure 2G) is a small cluster of 3 logjams (4% of total) which fill 20-30% of the channel width and have blockages of just 10-20% of the cross-sectional area, with high porosity of 40-80% and no geomorphological effects in association with them.

Cluster 8 (Figure 2H) is a small cluster of 3 channel spanning logjams (4% of logjams surveyed) with blockages of 20-30% of the channel cross-sectional area and with low porosity of 10-40%. These logjams are associated with high levels of geomorphological hetrogenity with lateral erosion of 40% of channel width, moderate to high scour of 15-45% of the channel depth and a depth of sediment deposition of 10-30% of channel depth.

The importance of logjam form on the individual geomorphological variables was investigated using a stepwise general linear regression with backwards elimination and an alpha value of 0.05. Logjam: width, porosity, blockage and water surface step were used as initial predictors. The only statistically significant models were found for porosity and bed scour (p<0.001, r^2=17.11) with scour depths of 0.4
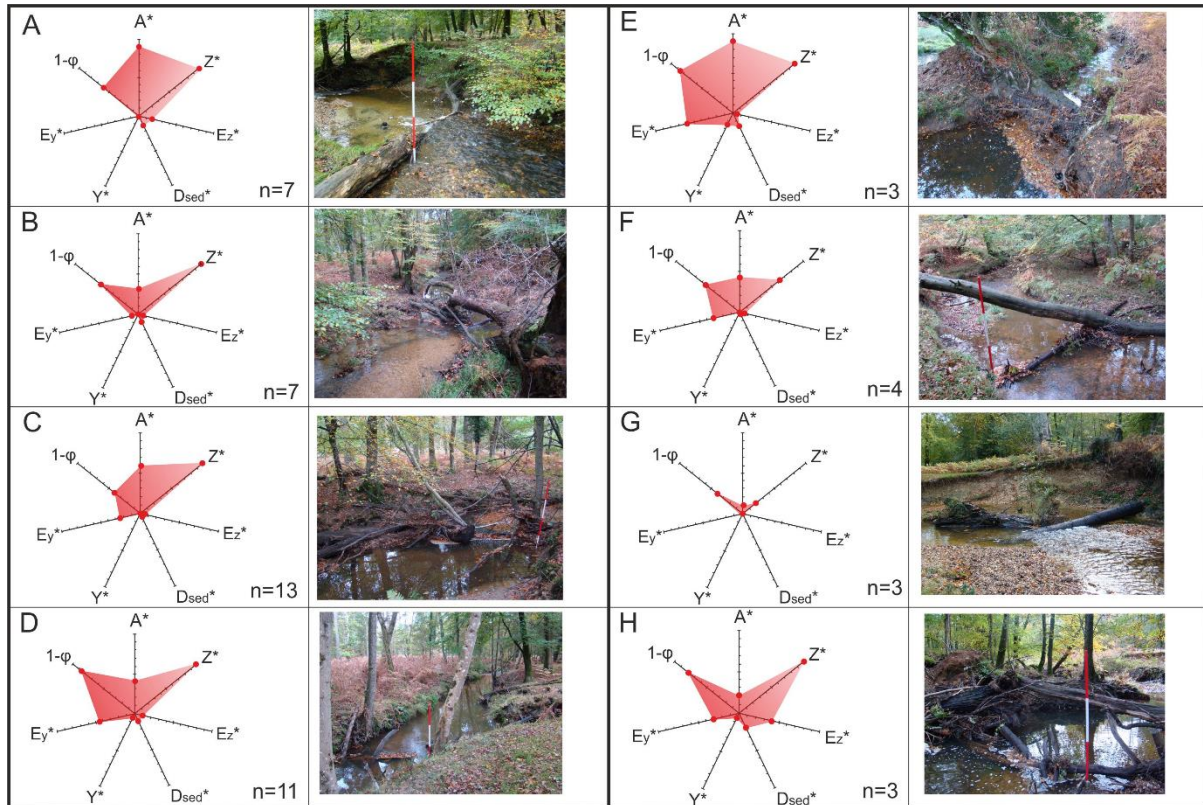
Figure 2 – Radar plots showing the 8 logjam clusters identified from the study site, with accompanying field photographs showing examples of each type. Axes are dimensionless and are scaled from 0-1, with 0 the centre point of the radar. Axis are; proportion of channel cross sectional area occupied (A^*), dimensionless logjam width (Z^*), porosity (ϕ – note axis is $1-\phi$), dimensionless lateral erosion (E_z^*), dimensionless scour depth (E_y^*), dimensionless spillway height (Y^*) and dimensionless sediment deposition depth (D_{sed}^*). See section 3.1 for explanation of each class of logjam.

or greater only found for porosity of 0.5 or less, and between porosity and lateral erosion (p=0.019, r^2=6.50) where lateral erosion of 0.2 or greater is only found for porosity of 0.5 of less. Although no statistically significant relationships were found, there are trends for scour depth to be lower for lower jam width*, with no scour found for jams less than 0.5 in width*. Lower porosity is also linked to sediment deposition with sediment depth* greater than 0.1 only found for logjams with porosity of 0.5 or less. Extensive lateral erosion* is linked to channel spanning logjams, with lateral erosion* of 0.3 or greater only found for these type of logjams.

4. Discussion

The results and analysis presented show that logjams within a small forest river can be grouped by a cluster analysis into structures sharing similar form and function. Gregory et al (1985) proposed four types of logjams based on data from the New Forest (hereafter referred to as Gregory logjam type): *complete*, which fill the entire channel width; *active*, which fill the channel width and induce a step in

the water profile; *partial*, which only fill part of the channel width, and *high water*, which include at least one log which bridges the bank tops. Gregory logjam types were recorded for all logjams in the survey and show the majority of logjams within the study reach are channel spanning (active n=18, complete n=33), with smaller numbers of partial (n=14) and high water (n=5). The cluster analysis used herein, incorporating logjam function as well as form, shows reasonable agreement with Gregory logjam type, insofar as individual clusters generally contain a single Gregory type, or in the case of channel spanning logjams, a mix of complete and active types. However, the cluster analysis shows a much greater discrimination between logjam types, identifying two distinct types of partial logjams compared to the single partial Gregory type, and six distinct channel spanning logjams with varying geomorphological effects compared to the three Gregory types; active, complete and high water.

4.1 Form and geomorphological function of logjams

This study shows that partial logjams can be divided into those that have no geomorphological effect (Figure 2G), and those with low porosity that deflect flow and cause bed scour pools due to flow constriction – "partial deflector jams" (Figure 2F). The partial deflector jams identified are similar conceptually to those described as "deflector jams" in rivers of the Northern Mississippi by Wallerstein & Thorne (1997) and lateral scour pools described by Bisson et al, (1982).

There are six distinct logjam types identified that could be classed as channel spanning (those filling 90% or greater of the channel width). The two largest channel spanning logjam clusters are associated with negligible geomorphological effects. They are distinct from each other in that the first (Figure 2C) fills around 90% of the channel cross-sectional area and has a mean porosity of 40%, indicating these are large, loose assemblages of wood which are not substantially influencing local hydraulics. The second (Figure 2B) consists of logjams which fill a mean of 30% of the channel cross-sectional area and consists predominantly of a small accumulation against one bank with one or more individual pieces extending across the channel width, or bridging the bank tops.

Two of the geomorphologically active, channel spanning logjam clusters can be identified as "scour dams" and when combined, represent 20% of the logjams surveyed. The first type of scour dam (Figure 2A) fills around 60% of the channel cross-sectional area and creates small scour pools downstream. The second (Figure 2D) fills a smaller cross-sectional area of around 40%, but has very low porosities; these logjams thus form small steps in the bed profile and have very deep scour pools of 35-55% mean channel depth similar to "plunge pools" described by Bisson et al (1982). Logjams shown in Figure 2H are identified as "lateral erosion deflector jams"; these fill less than half the

channel cross-sectional area, but have very low porosities and are observed in the field to induce lateral erosion through either undercutting at the toe of the bank, or through progressive down-cutting of ephemeral floodplain channels with eventually mass wasting in both instances.

The final logjam type identified (Figure 2E) is the most geomorphologically active, filling in excess of 80% of the channel cross-sectional area with low porosity; these logjams induce a step in the water profile causing deep scour pools of around 60% of the mean channel depth with an accompanying depositional mid-channel bar downstream and a small degree of lateral erosion (10% of width) representing slight channel widening around the logjam.

It is perhaps surprising that only two statistically significant relationships were found between the variables describing logjam form and geomorphological effects. However, it demonstrates that logjam form in respect of altering local hydraulics and erosional patterns cannot be adequately described in this study site using any single metric and is more effectively characterised using a combination of metrics as in Figure 2. In the study site porosity was found to be the most important variable in regression analysis and this reflects the importance of high flows in driving geomorphological change in this setting. Logjams which have low porosity will interact with high discharges by diverting flows around the structure, which in turn will drive erosion of the beds and banks. In this study a threshold of porosity=0.5 was found for a transition to lower bed scour, lower lateral erosion and greater sediment depth. Conversely, spill height* at low flows did not show any statistically significant relationships or trends, this is due to the importance of high discharges, as opposed to ambient flows, in driving geomorphological change in this environment. It is likely spill over logjams at ambient flows would be more important in driving geomorphological change in other, less hydrologically flashy systems.

4.2 Un-clustered logjams

There are 19 logjams which are classified as "un-clustered"; of these ten are part of two-member clusters and the remaining nine are not clustered with any other logjam. There are two possible explanations why these logjams remain un-clustered. Firstly, the sample size for this analysis may be insufficient to identify less commonly occurring logjam types, particularly in the case of the two member clusters. Formann (1984) suggests a sample size of $n=2^m$, where m is number of variables, is used to guarantee substantial segments within the cluster analysis (Mooi and Sarstedt, 2011), in this study the sample size is n=70; lower than the optimum n=128 (from seven variables). A larger sample size may have identified further logjam types that are less abundant but have important geomorphological effects; specifically no logjam types whose primary function is mediating sediment

deposition were found in this study, although they are common in other settings (c.f. Beckman and Wohl, 2014). As explained in the methods, a hierarchal cluster analysis is best suited to identify dominant clusters in a data set, as is the primary objective here, rather than assign all data points to clusters. Notably a simple cluster analysis assigns clusters as regular shapes within n-dimensional space, whereas more complex, computationally expensive clustering algorithms can assign irregularly shaped clusters to the data, potentially excluding fewer outliers.

Secondly, three of the variables have highly skewed distributions, with the majority of logjams having low values in these variables: lateral erosion*, sediment deposition depth* and spill height*. Of the un-clustered logjams, 13 possess high values in one or more of these variables; these 13 logjams thus potentially have large Euclidian distances to other jams primarily as a result of a single variable. These un-clustered logjams represent structures which are associated with atypical geomorphological effects (for the study river). It is possible to select a larger maximum Euclidian join distance between cluster members in order to reduce the number of members which are un-clustered. However, in this study that would be at the expense of meaningful discrimination between individual clusters as smaller clusters agglomerate to larger ones with greater join distances.

The dimensionless nature of this analysis means the method can be applied to any river size or type. Unfortunately, to date, there are no published studies which collect data on all of the metrics suggested above, hampering direct application to other studies. Although many studies collect comprehensive data on logjam form and channel dimensions, where geomorphological effects are considered, the focus is typically on just a single effect of interest, e.g. fine sediment deposition (Beckman and Wohl, 2014), or pool depth (Gurnell and Sweet, 1998). In order to test the applicability of the metrics proposed to describing logjams in rivers of different character and size to the study site a qualitative analysis was applied in two parts described below in sections 4.3 and 4.4. Firstly, radar plots were drawn qualitatively for logjam types described in two logjam classification schemes from the literature by Abbe & Montgomery (1996) for the large Queets River, Washington, USA and Wallerstein & Thorne (1997) for the Northern Mississippi,USA (Section 4.3). Secondly, the metrics are used to qualitatively describe logjams from three literature studies in which existing data, field photos and descriptions of the geomorphological effects of logjams allow approximate values to be inferred (Section 4.4).

4.3 Applicability to existing logjam classification systems

Logjams described by, Abbe & Montgomery (1996) on the large Queets River, Washington, USA are reproduced qualitatively using the proposed dimensionless metrics in Figure 3A-C. Abbe &

Montgomery (1996) identify three primary logjam types; those formed on the top of bars by wood deposited on falling flood stages, which have little appreciable effect on geomorphology (Bar Top Jams – 3A), those formed at the head of a mid-channel bar where the logjam promotes a scour hole at the upstream edge and sediment aggradation in the lee of the structure (Bar Apex Jams – 3B) and those formed against the outer bank of a meander bend, which cause sediment deposition and promote channel migration (Meander Jams – 3C). The three logjam types classified by Abbe & Montgomery (1996) have distinct functions and these differences can be clearly seen in the different shapes of the radar plots in Figure 3A-C. Furthermore the Abbe & Montgomery logjams from the large Queets River are all distinct from the radar plots in Figure 2 describing the characteristic logjam types of the much smaller Highland Water.

Wallerstein & Thorne (1997) describe logjams similar to those in Figures 3B and 3C in creeks of the Northern Mississippi basin; in addition they describe three additional types in these smaller river channels (Figures 3D-3F). Underflow jams are those spanning the channel and forcing water underneath the structure causing bed scour (Figure 3D). Dam jams are those spanning the channel and causing a step in the water profile such that water spills over the structure causing bed scour and the deposition of sediment upstream of the structure (Figure 3E). Finally, deflector jams are structures
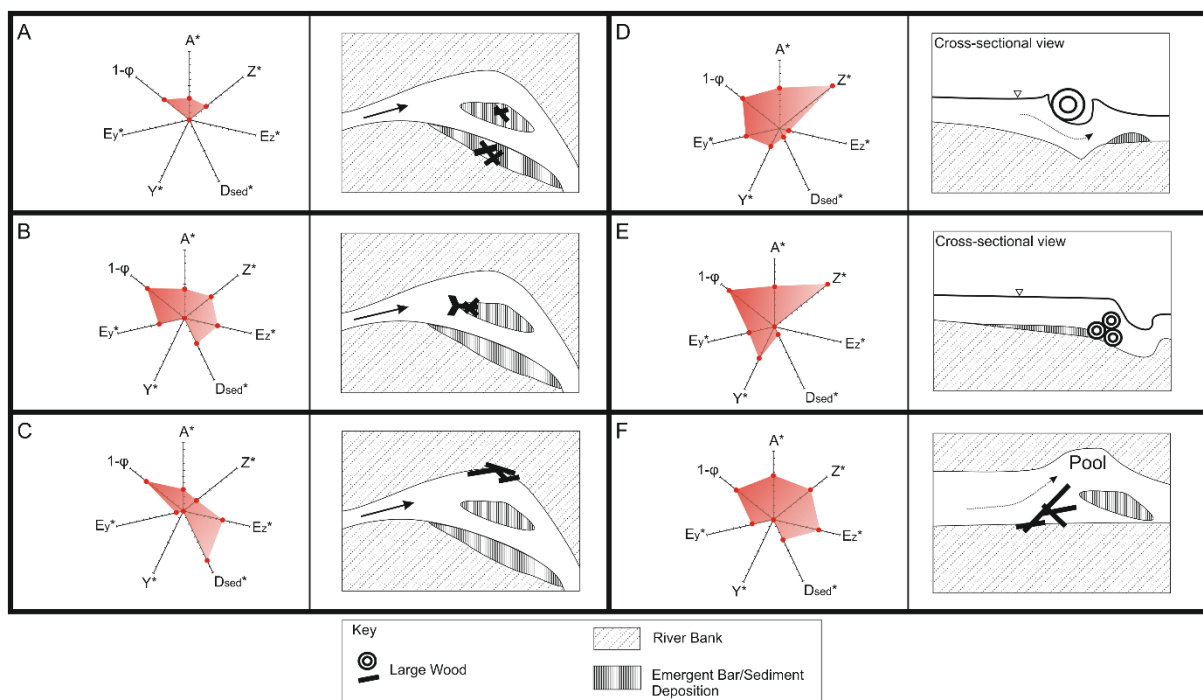
Figure 3 – Dimensionless categorisation applied to the characteristic logjam types described by Abbe & Montgomery (1996) on the Queets River, Washington (A-C) and Wallerstein & Thorne (1997) on creeks of the Northern Mississippi basin (D-F). Sketches of logjams are after Abbe & Montgomery (1996) and Wallerstein & Thorne (1997), all sketches are planform with flow from left to right, except where noted. A – Bar Top Jam, B – Bar Apex Jam, C- Meander Jam, D – Underflow Jam, E – Dam Jam, F – Deflector Jam

	Term		Abbe & Montgomery (1996)			Wallerstein & Thorne (1997)		
			Bar Top	Bar Apex	Meander	Underflow	Dam	Deflector
			A	B	C	D	E	F
Logjam Width	$Y*$		0.35	0.50	0.30	1.00	1.00	0.70
Blockage	$A*$		0.30	0.40	0.30	0.60	0.60	0.70
Porosity	$1-\Phi$		0.50	0.70	0.70	0.70	0.90	0.70
Step Height	$Z*$	$h_a\text{-}h_b/Z_{bf}$	0.00	0.00	0.00	0.30	0.50	0.00
Scour Depth	E_z*	Z_{ero}/Z_{bf}	0.00	0.40	0.10	0.50	0.40	0.30
Sediment Depth	$D_{sed}*$	Z_{sed}/Z_{bf}	0.00	0.40	0.80	0.10	0.10	0.30
Lateral Erosion	E_y*	Y_{ero}/Y_{bf}	0.00	0.30	0.60	0.40	0.00	0.70

Table 2 – Values used for logjam classification systems described by Abbe & Montgomery (1996) and Wallerstein & Thorne (1997) in Figure 3. Values were qualitatively estimated based on data, descriptions and diagrams in the two papers.

filling only part of the channel which deflect flow towards one bank and promote lateral erosion, bed scour and sediment deposition in the lee of the structure (Figure 3F). Figures 3D – 3F show the classification system is capable of describing and discriminating between the logjams categorised by Wallerstein & Thorne (1997).

The radar plots used indicate strong similarities in form and function between Abbe & Montgomery bar head jams on the Queets River (Figure 3B) and Wallerstein & Thorne deflector jams in a smaller creek (Figure 3F). Although initially this is perhaps a surprising result it should be considered that in both cases the structure is acting as a blunt object, deflecting flow and protecting the formation of a sedimentary structure in the lee of the jam, while diverting flow towards the bank(s) leading to increased lateral and bed erosion. Although the radar shapes appear very similar, the cluster analysis method will be able to discriminate between these two types of jam within the same river, as evidenced by similarities and overlaps of radar footprint within different categories within Figure 2.

Results from the Highland water show there are similarities between the logjam cluster shown in Figure 2E with an "Overflow jam" (Figure 3D) described by Wallerstein & Thorne (1997) in creeks of the Northern Mississippi, in addition there are similarities between Figure 2D and an "underflow jam" (Figure 3E). There are some similarities between Wallerstein & Thorne deflector jams (Figure 3F) and the 'partial deflector jam' identified in the Highland Water (Figure 2F), however the Highland Water category only induce lateral erosion and not the scour pools and downstream bar deposition reported by Wallerstein & Thorne (1997). Given there are similarities between the Highland Water and the creeks studies by Wallerstein & Thorne (1997) in both absolute river channel size, as well as river channel size relative to tree height, it is not surprising that logjams of similar form and function are found in both systems. The results from the Highland Water identifying sub-categories of logjam with the Gregory classification method suggest that although Wallerstein & Thorne (1997) may have captured dominant or characteristic logjam types in terms of hydromorphological effect within their study creeks, there are likely to be further identifiable logjam clusters using the technique reported in this paper.

In addition to visually comparing radar plots, each logjam type identified by a cluster analysis can also be described by the means and standard deviations of the seven dimensionless metrics. Therefore the logjam types identified through cluster analysis from two or more studies can not only be compared qualitatively as above, but could be analysed using simple statistical tests such as multivariate analysis of variance (MANOVA).

4.4 Application of classification method to range of river styles

The dimensionless analysis has been further applied to individual logjams described in the literature from river systems that differ from the study site and the rivers of the Northern Mississippi and Queets River (Curran and Wohl, 2003; Gurnell et al., 2005; Klaar et al., 2011) to further test the applicability of the method (Figure 4). Figure 4 shows the classification method is capable of describing logjams in rivers ranging in size from 1st and 2nd order step-pool channels (Figure 4C based on Curran and Wohl, 2003) up to large braided rivers (Figure 4D based on Gurnell et al., 2005), furthermore it is possible to discriminate between logjams across these environments. It is interesting to note similarities in the radar plots for a small logjam in Glacier Bay which is creating an area of slack water in the lee of the structure (Figure 4B), a logjam mediating formation of a pioneer island in the braided Tagliamento River (Figure 4D) and a logjam formed at the outside of a meander bend on the large Queets River (Figure 3C). When described with dimensionless metrics all these logjams can be characterised as occupying a low proportion of the channel width and cross section, with moderate structure porosity, inducing the deposition of sediment as the dominant geomorphological function. Within their respective fluvial environments these three logjam types can be said to be fulfilling a similar geomorphological function, albeit at different order of magnitude scales.

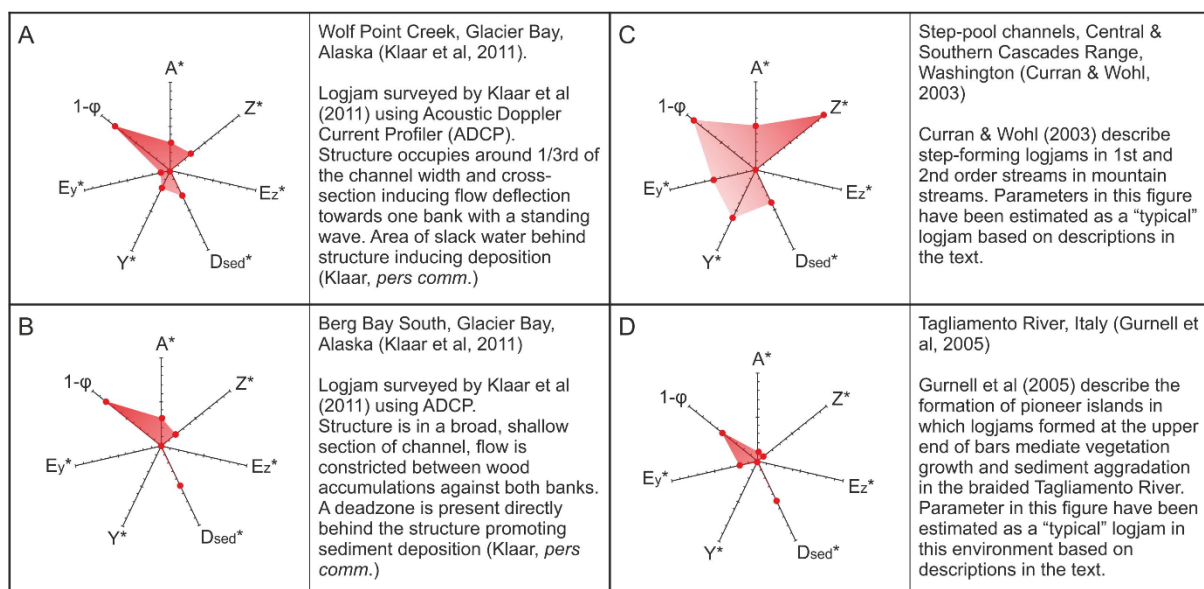| A	Wolf Point Creek, Glacier Bay, Alaska (Klaar et al, 2011). Logjam surveyed by Klaar et al (2011) using Acoustic Doppler Current Profiler (ADCP). Structure occupies around 1/3rd of the channel width and cross-section inducing flow deflection towards one bank with a standing wave. Area of slack water behind structure inducing deposition (Klaar, *pers comm*.)	C	Step-pool channels, Central & Southern Cascades Range, Washington (Curran & Wohl, 2003) Curran & Wohl (2003) describe step-forming logjams in 1st and 2nd order streams in mountain streams. Parameters in this figure have been estimated as a "typical" logjam based on descriptions in the text.
B	Berg Bay South, Glacier Bay, Alaska (Klaar et al, 2011) Logjam surveyed by Klaar et al (2011) using ADCP. Structure is in a broad, shallow section of channel, flow is constricted between wood accumulations against both banks. A deadzone is present directly behind the structure promoting sediment deposition (Klaar, *pers comm*.)	D	Tagliamento River, Italy (Gurnell et al, 2005) Gurnell et al (2005) describe the formation of pioneer islands in which logjams formed at the upper end of bars mediate vegetation growth and sediment aggradation in the braided Tagliamento River. Parameter in this figure have been estimated as a "typical" logjam in this environment based on descriptions in the text.

Figure 4 – Radar plots for 4 logjams in contrasting river types described in the literature. A and B –logjams surveyed by Klaar et al (2011) in Glacier Bay, Alaska formed as a result of glacial retreat, C – logjam in step-pool headwater streams described by Curran & Wohl (2003) in mountains of the Central & Southern Cascades, Washington, D – logjam formed at bar heads in the braided Tagliamento River, Italy, such logjams promote the formation of pioneer islands in this system as described by Gurnell et al (2005).

	Term		Klaar et al, 2011	Klaar et al, 2011	Curran & Wohl, 2003	Gurnell et al, 2005
			Wolf Point Creek	Berg Bay South	Step Pool logjam	Tagliamento River
Logjam Width	Y^*		0.30	0.20	1.00	0.10
Blockage	A^*		0.30	0.30	0.50	0.10
Porosity	$1-\Phi$		0.80	0.80	0.90	0.50
Step Height	Z^*	h_a-h_b/Z_{bf}	0.20	0.00	0.60	0.00
Scour Depth	E_z^*	Z_{ero}/Z_{bf}	0.10	0.00	0.50	0.20
Sediment Depth	D_{sed}^*	Z_{sed}/Z_{bf}	0.30	0.50	0.40	0.50
Lateral Erosion	E_y^*	Y_{ero}/Y_{bf}	0.00	0.00	0.00	0.00

Table 3 – Values used to describe logjams in Figure 4 from Klaar et al (2011), Curran & Wohl (2003) and Gurnell et al (2005). Values have been qualitatively estimated from data, descriptions and field photos/diagrams in the papers. In the case of Klaar et al (2011) the values are for two specific logjams measured and described in the paper, in Curran & Wohl (2003) and Gurnell et al (2005) the values are for a typical or characteristic logjam in the respective study sites.

4.5 Temporal considerations for logjam surveying

It is important to note that any survey of logjams and their potential geomorphological effects is capturing a snap-shot of on-going temporal processes. Logjams form, change structure and break-up on annual to decadal time-scales (Curran, 2010; Sear et al., 2010; Collins et al., 2012; Dixon and Sear, 2014; Schenk et al., 2014), however stability of logjams is a prerequisite for geomorphological change (Millington and Sear, 2007; Curran, 2010; Sear et al., 2010; Dixon and Sear, 2014). The scouring of pools in association with logjams, for example, will take a period of time dependent on calibre and rate of bed material supply and the frequency of high flow events (Buffington et al., 2002). Similarly the volume of sediment retained behind jams has been linked to logjam age (Beckman and Wohl, 2014). There is, therefore, a time lag between the formation of a logjam and the maximum potential geomorphological change induced by it. It is likely that any survey of logjam effects will measure some logjams which have not been in situ for sufficient time to induce potential maximum geomorphological change. In this study for example it is possible the logjam clusters shown in Figures 2A and 2E are essentially the same logjam type, but of different ages; the main difference between them is the much greater scour depth found in Figure 2E which could reflect the logjams having been in place for longer. The age of logjams in situ is thus an important additional consideration, albeit one that challenging to measure in the field; direct measurements of logjam age are normally only possible using the time since death of constituent pieces of wood through dendrochronology (Hyatt and Naiman, 2001) or through dating sprouting plants (Wohl et al., 2010), which is difficult to measure outside of experimental catchments. Alternative dating methods involve use of aerial photography to establish time of bank erosion and recruitment of wood to the channel (Latterell and Naiman, 2007; Bertoldi et al., 2013) although this may be more suitable to date logjams in braided rivers where wood is trapped close to its input point (c.f. Bertoldi et al., 2013; Welber et al., 2013), than meandering rivers with long transport lengths (Dixon and Sear, 2014).

4.6 Future applications

The method of describing logjams using seven dimensionless metrics and classifying them by means of a cluster analysis has several practical applications. For research it will allow direct comparison of logjam form and morphological function between study sites, including those with disparate hydromorphological characteristics. It is currently difficult to make meaningful comparisons between logjam data sets in different study sites due to a lack of common metrics (Wohl et al., 2010) and the use categorical and subjective classifications which transfer poorly outside of the river system(s) for which they were developed. Furthermore the analysis framework described herein will allow future work on wider logjam functions, such as ecological and geochemical effects, to be linked to a standard

framework allowing direct comparisons between sites. Linking geomorphological effects to logjam age by dating logjams using historic aerial photography series is a promising avenue for future study using the survey method described herein but would limit application for those catchments for which data is available, and maybe confounded by unobservable changes in form and function over time (Dixon and Sear, 2014).

By linking logjam form and morphological function within an analysis framework which allows classification it will be possible to better plan and monitor river restoration projects using engineered logjams, particularly those projects seeking to improve ecohydrological diversity. Data of dominant logjam types from undisturbed, analogue streams can be used to plan installation of engineered logjams whose distribution of form and function will closely match that of template sites. Furthermore, in the case of projects which intend to use engineered logjams to increase geomorphological and habitat diversity, the analysis framework will enable long-term post-project quantitative assessment of the proportion of logjams inducing sediment erosion & deposition.

The metrics for describing logjams proposed in this paper should be tested in future studies, using data from a diverse range of river sizes and styles in order to verify their transferability.

5. Conclusions

Logjams within a small forested stream have been analysed and described using an innovative cluster analysis method using dimensionless metrics. This analysis demonstrates that distinct logjam types, sharing similar architecture and having similar hydromorphological functions, can be identified and described within the study river. The results show there are eight identifiable clusters, of which two are logjams only partially filling the channel cross-section and six which are channel spanning. Distinct geomorphological functions can be seen in each cluster, such as logjams primarily causing bed scour and those primarily causing lateral erosion. The findings of this study demonstrate that logjams sharing ostensibly similar architecture and form can mediate diverse erosional and depositional functions.

The survey and analysis framework described herein using dimensionless metrics has been shown to be applicable for qualitatively describing logjams reported in other studies from rivers of diverse environments and sizes. In addition to being able to describe and plot logjams from other studies, the method is capable of both discriminating between logjam types, as well as indicating where logjams in differing environments may share similar relative form and function. The method will need to be tested with data sets from other rivers of varying size and environment to confirm its applicability.

The method has applications as a survey tool for planning river restoration projects using engineered logjams as well as assessing the success of such projects after implementation. As a research tool the method described introduces a framework for categorising logjam based on form and function that allows direct comparisons between sites in different locations and rivers of different scales.

Acknowledgements

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