

## RESEARCH ARTICLE

## Ecohydraulic modelling of anabranching rivers

Neil Entwistle<sup>1</sup>  | George Heritage<sup>2</sup> | David Milan<sup>3</sup> 

<sup>1</sup>School of Environment and Life Sciences,  
University of Salford, Salford, UK

<sup>2</sup>AquaUoS, University of Salford, Salford, UK

<sup>3</sup>School of Environmental Sciences, University  
of Hull, Hull, UK

## Correspondence

N. Entwistle, University of Salford, Peel  
Building, Salford. M5 4WT, UK.  
Email: n.s.entwistle@salford.ac.uk

D. Milan, School of Environmental Sciences,  
University of Hull, Hull, HU6 7RZ, UK.  
Email: d.milan@hull.ac.uk

## Abstract

In this paper we provide the first quantitative evidence of the spatial complexity of habitat diversity across the flow regime for locally anabranching channels and their potential increased biodiversity value in comparison to managed single-thread rivers. Ecohydraulic modelling is used to provide evidence for the potential ecological value of anabranching channels. Hydraulic habitat (biotopes) of an anabranching reach of the River Wear at Wolsingham, UK, is compared with an adjacent artificially straightened single-thread reach downstream. Two-dimensional hydraulic modelling was undertaken across the flow regime. Simulated depth and velocity data were used to calculate Froude number index, known to be closely associated with biotope type, allowing biotope maps to be produced for each flow simulation using published Froude number limits. The gross morphology of the anabranching reach appears to be controlling flow hydraulics, creating a complex and diverse biotope distribution at low and intermediate flows. This contrasts markedly with the near uniform biotope pattern modelled for the heavily modified single-thread reach. As discharge increases the pattern of biotopes altered to reflect a generally higher energy system, interestingly however, a number of low energy biotopes were activated through the anabranching reach as new subchannels became inundated and this process creates valuable refugia for macroinvertebrates and fish, during times of flood. In contrast, these low energy areas were not seen in the straightened single-thread reach. Model results suggest that anabranching channels have a vital role to play in regulating flood energy on river systems and in creating and maintaining hydraulic habitat diversity.

## KEYWORDS

anabranching channel, biotope, floodplain re-naturalization, LiDAR DTM, patch dynamics, water surface flow types

## 1 | INTRODUCTION

Anabranching rivers are characterized by a multithread channel network divided by generally stable vegetated islands and are the prevailing river pattern found along alluvial tracts of the world's largest rivers (Jansen & Nanson, 2004). Anabranching river channels in the United Kingdom were arguably the dominant channel type prior to human

modification, with palaeo evidence of these systems preserved extensively in valley bottom deposits (Brown & Keough, 1992; Brown, Keogh, & Rice, 1994; Lewin, 2010). Anabranching rivers are now rare in the United Kingdom due to channel and floodplain management practices; however, Heritage, Milan, and Entwistle (2016) and Entwistle, Heritage, and Milan (2018) have identified reach-scale establishment of anabranching channels in the United Kingdom,

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2019 The Authors River Research and Applications Published by John Wiley & Sons Ltd.

developing on a meandering or wandering morphological template through vegetative succession and subsequent stabilization, or through lateral extension, where channel widening and bar complex development have been initiated.

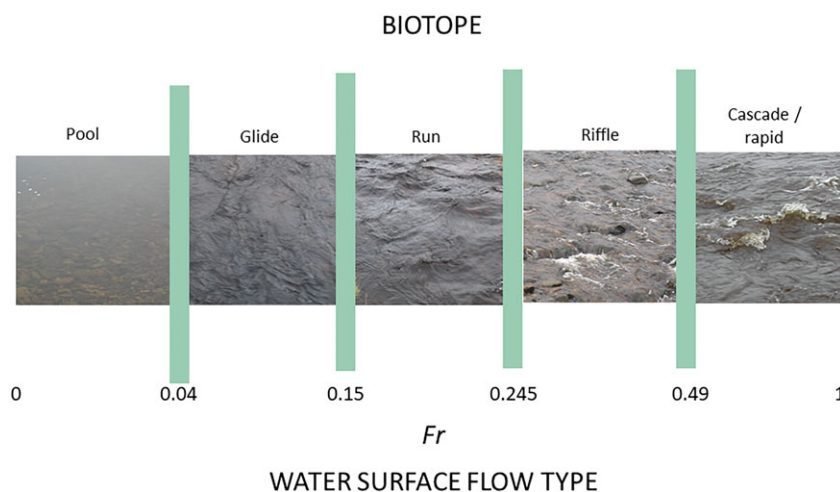
Although there have been numerous studies on the geomorphology of anabranching rivers (e.g. Carling, Jansen, & Meshkova, 2014; Kleinens, de Haas, Lavooi, & Makaske, 2012; Knighton & Nanson, 1993; Nanson & knighton, 1996; Makaske, 2001), few of these have documented processes in any detail (with the exception of Harwood & Brown, 1993), and none have examined their ecohydraulics over the flow regime (sensu Maddock, Harby, Kemp, & Wood, 2013), despite their high biodiversity value (Puckridge, Walker, & Costelloe, 2000), ecotone provision (Naiman, Décamps, Pastor, & Johnston, 1988), and their significance as potential refugia (Sedell, Reeves, Hauer, Stanford, & Hawkins, 1990). With recent drives towards renaturalization of floodplains for natural flood management and heightened interest in restoring rivers and floodplains (Dixon, Sear, Odoni, Sykes, & Lane, 2016), practitioners of river management require evidence to demonstrate the potential ecological value of anabranching systems at the reach-scale. In a companion paper Entwistle et al. (2018) use 2D hydraulic modelling to demonstrate stage-dependent contrasts in hydraulics between anabranching and managed single-thread channels; demonstrating how locally anabranching channels may be important for dissipating flood flow energy and reducing morphological destabilization further downstream. This study uses the 2D hydraulic modelling outputs from Entwistle et al. (2018) to explore stage-dependent variations of instream habitat (biotopes) for the same anabranching reach of the River Wear, UK, with the aim of (a) quantifying spatial and temporal biotope availability and patterns over the flow regime and (b) highlight the ecological significance of anabranching channels through a comparison with an adjacent heavily modified single-thread reach situated downstream.

### 1.1 | Biotope quantification

Physical habitat can be represented by the interplay between flow depth, velocity, and bed roughness (Newson & Newson, 2000; Milan,

Heritage, Large, & Entwistle, 2010; Fryirs & Brierley, 2013; Gurnell, Rinaldi, Belletti, Bizzi, Blamauer, Braca, Buijse, Bussetini, Camenen, Comiti, Demarchi, García De Jalón, González Del Tánago, Grabowski, Gunn, Habersack, Hendriks, Henshaw, Klösch, Lastoria, Latapie, Marcinkowski, Martínez Fernández, Mosselman, Mountford, Nardi, Okruszko, O'Hare, Palma, Percopo, Surian, van de Bund, Weissteiner, & Ziliani, 2016, 2016; Belletti et al., 2017). Variation between these three variables results in a variety of habitat units known as *biotopes* that may be visually identified through their characteristic *water surface flow type* (Figure 1). The physical character of the water surface in a river therefore reflects the local hydraulic conditions, both in space (Dyer & Thoms, 2006; Large & Heritage, 2012; Thomson, Taylor, Fryirs, & Brierley, 2001; Wadeson & Rowntree, 1998) and over time with changing flows (Newson, Harper, Padmore, Kemp, & Vogel, 1998; Heritage, Milan, & Entwistle, 2009). Biotopes represent a robust approximation of complex aquatic environments that integrate fluvial geomorphological and ecological principles and are regarded as significant in defining system biodiversity under the European Union Water Framework Directive (Belletti et al., 2017; Dodkins et al., 2005). In addition, biotopes have been used in the development of typologies to underpin the *Habitat Quality Index* (Raven, Fox, Everard, Holmes, & Dawson, 1997), providing a means of integrating ecological, geomorphological, and water resource variables for management purposes. Biotope characterization has also been built into the UK River Habitat Survey, used by the UK Environment Agency and through research internationally including Sweden (Rydgren et al., 2005), Austria (Muhar, Schwarz, Schmutz, & Jungwirth, 2000), Australia (Thomson et al., 2001), and South Africa (King & Louw, 1998). However, there are still limited studies that have explicitly identified the links between biotopes and instream biota (Hill, Maddock, & Bickerton, 2008; Reid & Thoms, 2008; Schwartz & Herricks, 2008; Demars, Kemp, Friberg, Usseglio-Polatera, & Harper, 2012) and hard biotope thresholds have been criticized in favour of more fuzzy transitions (Clifford, Harmor, Harvey, & Petts, 2006).

Biotope assessment has largely been confined to characterization of river habitat at a single flow stage from at-a-station measurements of depth and velocity (Padmore, 1998). More recently, reach-scale mapping of biotopes has been attempted through mapping water



**FIGURE 1** Biotope character and Froude number associations [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

surface roughness using both terrestrial light detection and ranging (LiDAR; Milan et al., 2010) and drone-derived structure-from-motion photogrammetry (Woodget, Visser, Maddock, & Carbonneau, 2016) and through use of spatially distributed measurements of depth and velocity using Acoustic Doppler Velocimetry (Bentley et al., 2016; Entwistle, Milan, & Heritage, 2010; Milan & Heritage, 2012). Changes in the spatial distribution of biotopes over the flow regime in anabranching river systems have not yet previously been described. However, Stalnaker, Bovee, and Waddle (1996), Newson et al. (1998), Clifford et al. (2006), and Heritage, Hetherington, Milan, Large, and Entwistle (2009) do present findings for single-thread systems, where it has been noted that flow types can display high temporal variability, depending on flow stage (Zavadil & Stewardson, 2013).

The most widely utilized flow variable for characterizing biotopes is the Froude number ( $Fr$ ; Jowett, 1993; Wadeson, 1994; Padmore, 1998) that defines the ratio of the inertial to gravity forces in the flow:

$$Fr = \frac{V}{\sqrt{gd}}, \quad (1)$$

where  $V$  is the local flow velocity,  $g$  is the gravitational acceleration, and  $d$  is the local flow depth.

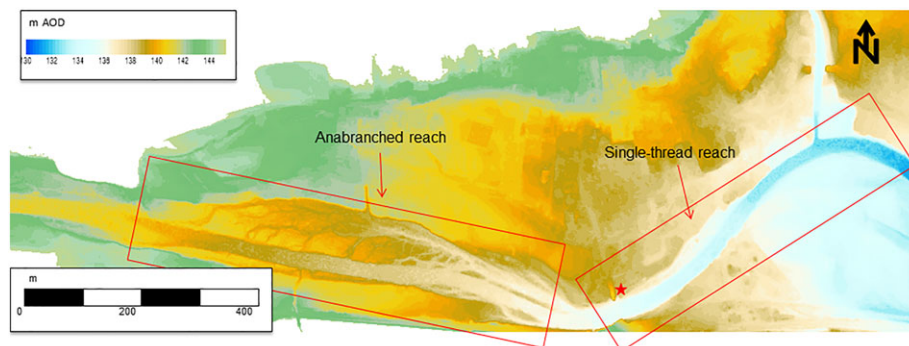
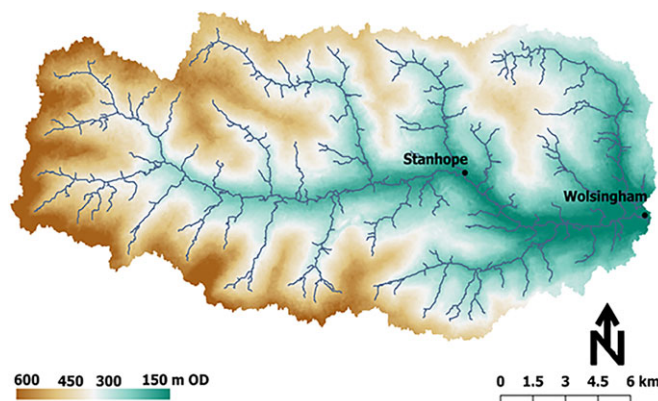
At values below 1, gravitational forces are dominant and flow is subcritical; where  $Fr$  exceeds 1, internal forces dominate, and flow is

supercritical. Despite describing flow based on the water column rather than at the bed,  $Fr$  has been shown to be associated with the distribution of benthic macroinvertebrates (Demars et al., 2012; Jowett, 2003; Hill et al., 2008; Reid & Thoms, 2008) and has been used as a hydraulic delimiter to support the existence and ecological relevance of biotopes (Wadeson & Rowntree, 1998; Padmore, 1998; Newson et al., 1998; Newson & Newson, 2000; Clifford et al., 2006; Harvey, Clifford, & Gurnell, 2008). It is clear from these studies that biotopes exist on a continuum across the range of  $Fr$  conditions experienced and distinct biotope types have been associated with a characteristic range of  $Fr$  values (Figure 1).

## 2 | STUDY LOCATION

This study focused on a 1.5-km reach of the upper River Wear at Wolsingham, County Durham, situated at around 140-m A.O.D. (Figure 2). The catchment drains impermeable Carboniferous Limestone, overlain by peat in the headwaters and till and alluvium in the middle reaches. The river has been impounded in its upper reaches by Burnhope reservoir, since 1937. The river valley at Wolsingham is dominated by two late glacial and three Holocene terraces (Moore, 1994). The river bed is composed of coarse gravels and cobbles

**FIGURE 2** Wolsingham study site location, Stanhope gauging station, and catchment topography for the River Wear, Northumberland, UK [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 3** Base digital terrain model of the extended study site used to simulate 2D flow hydraulics. Flow direction is from left to right; star indicates high flow validation position at bridge [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

( $D_{50} = 35$  mm), and the mean channel gradient is 0.007. Interrogation of the LiDAR digital terrain model for the study reach reveals a well-developed channel network, not at first visible from aerial imagery of the reach due to dense riparian vegetation cover (Figure 3). The mean daily discharge recorded at Stanhope situated upstream of the study site is  $3.92 \text{ m}^3/\text{s}$ , and the  $Q_{95}$  (equating to a typical summer low flow) is  $0.5 \text{ m}^3/\text{s}$ . Data for peak flows (since 1958) indicate that the two most significant flood events were in 2005 ( $247 \text{ m}^3/\text{s}$ ) and 1995 ( $233.1 \text{ m}^3/\text{s}$ ).

Despite historical degradation of the River Wear during the early twentieth century, water quality shows a steady improvement since the 1970's. Fish species include the Atlantic Salmon (*Salmo salar*), Brown trout (*Salmo trutta*), European eel (*Anguilla Anguilla*), and Brook lamprey (*Lampetra planeri*); all UK Biodiversity Action Plan priority species may be found, in addition to the Bullhead (*Cottus gobio*). The Brown Trout and Bullhead are also listed under Annex II of the Habitats and Species Directive (92/43/EEC).

### 3 | METHODS

Tonina and Jorde's (2013) review of hydraulic modelling for ecohydraulic studies note that there is no general rule as to which modelling approach to apply and why when simulating river flow; however, they do state that 2D models are appropriate for scales ranging from geomorphic unit to reach and that 2D modelling is becoming a preferred approach for ecohydraulic studies concerned with developing a strong spatial understanding of fundamental hydraulic parameters such as depth, velocity, and shear stress. Tonina and Jorde (2013) also note that generally 2D hydraulic models are applied at the morphologic unit to reach scale (10–50 channel widths), which is appropriate to this study; however, longer multikilometre reach models have been published using advanced computer processing (Alabyan & Lebedeva, 2018) with progress being made in quantifying stream mesohabitats (Demarchi, Bizzi, & Piégay, 2016).

We ran 2D hydrodynamic simulations using the CAESAR-Lisflood FP code in reach mode (Coulthard et al., 2013; Milan, Heritage, Entwistle, & Tooth, 2018) to simulate depth-averaged hydraulics, for a range of hydrographs ranging from  $16 \text{ m}^3/\text{s}$ , equivalent to the daily flow exceeded 5% of the time, to  $198 \text{ m}^3/\text{s}$ , approximately equivalent to the 40-year return period flow. The hydrodynamic 2D flow model is based on the Lisflood FP code (Bates & De Roo, 2000) that conserves mass and partial momentum, and is optimized for rapid convergence to steady-state conditions to simulate in-channel hydraulic processes. Model requirements include a terrain model (including submerged surfaces), roughness estimate(s), upstream flow inputs, and downstream flow controls. Of particular importance is the model surface representation, which should be at a resolution that captures the morphology to define the form roughness (Tonina & Jorde, 2013) and hydraulic (Casas, Lane, Yu, & Benito, 2010) and ecological processes (Railsback, 1999) being studied.

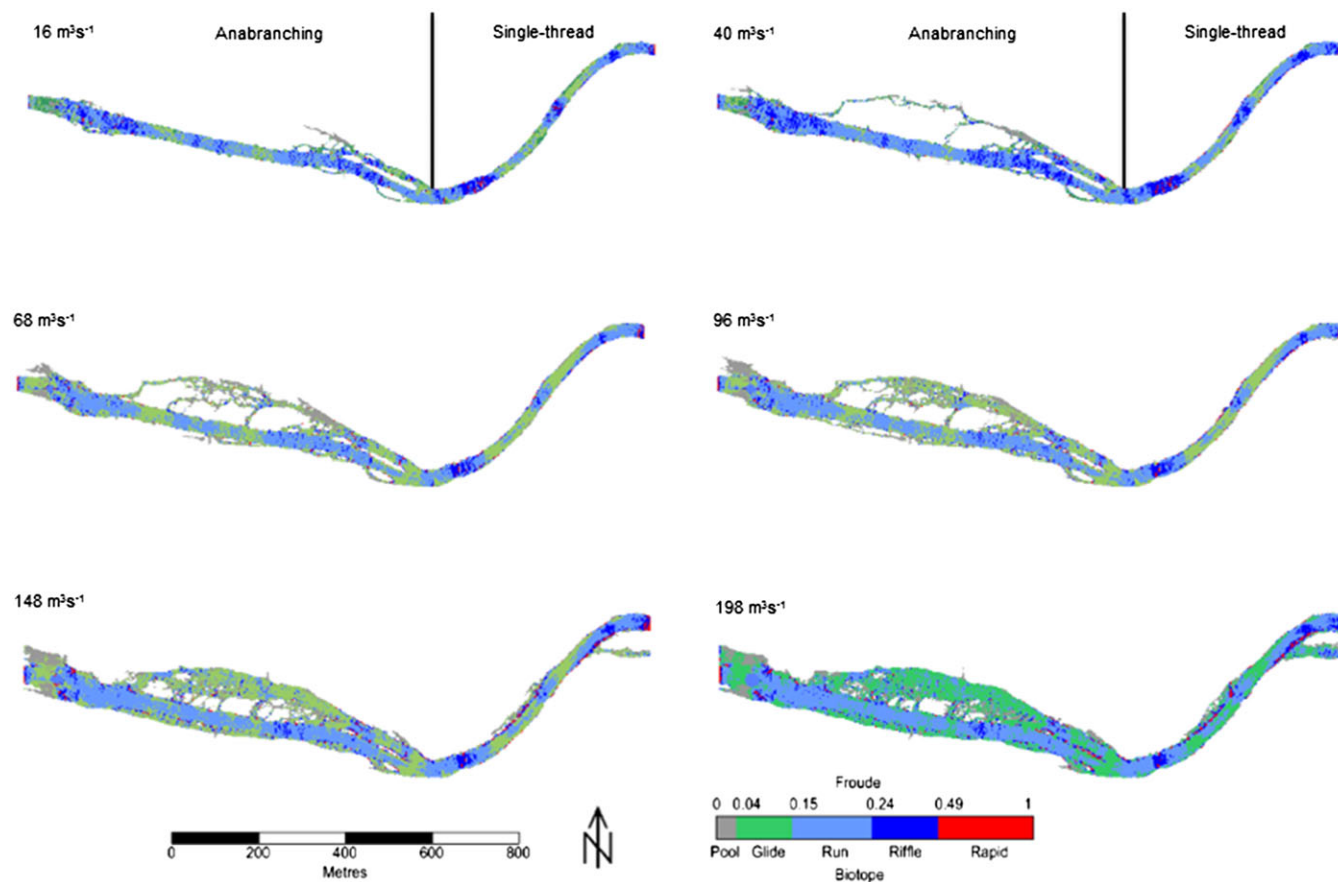
The model simulated depth-averaged hydraulics on a 1-m digital terrain model of the study reach using bare-earth LiDAR, sourced from the EA Geomatics group (Figure 2), a resolution reported as suitable

for fish micro-habitat simulations (Pasternack & Senter, 2011). The LiDAR data accurately records form roughness elements generated by the diverse morphologic units present across a varied terrain through the anabranching reach, dominated by short interlinked channel networks flowing between small island/bar units. Through a Wolman (1954) grid survey we measured 38 mm as the reach  $D_{50}$  rather than making out that we are relying on a reach-scale measurement taken 10 yrs ago! This undermines our science! Suggest taking out the reference to Wishart here, just say we used a reach average grain size of 38mm taken from a Wishart, Warburton, and Bracken (2008) describes the water course as a uniform single-thread gravel bed channel surface grain size for the study reach measured using grid-by number sampling (Wolman, 1954) revealed a reach  $D_{50}$  of 65 mm,  $D_{84}$  of 107 mm, and  $D_{99}$  of 175 mm, generally coarser than the bulk sample grain size reported by Wishart et al. (2008). In the absence of spatially variable grain-size data we assumed a uniform Mannings  $n$  value of 0.03 to characterize skin resistance based upon reach bed surface grain size measurements, with form resistance implicitly accounted for within the 1-m scale resolution of the LiDAR DEM (see Entwistle et al., 2018). The model was validated using differential Global Positioning System, where water surface height measurements were taken at two different discharges ( $5.2$  and  $7.8 \text{ m}^3/\text{s}$ ). A peak flood strandline elevation located at Causeway Road Bridge (Figure 2), equating to a peak flow discharge of  $159.45 \text{ m}^3/\text{s}$  (5 December 2012), was obtained using internet imagery (Glenister, 2015), and in conjunction with the LiDAR DEM was used to validate the higher discharge simulations (see Entwistle et al., 2018). The two-low-flow differential Global Positioning System elevations were found to be within  $\pm 0.01$  m of the simulations, and the high-flow estimate retrieved from the internet imagery resulted in only a 2.5% over-estimation in discharge compared with the gauge readings at nearby Stanhope, suggesting that the model hydraulics are also robust at high flows. No field data were collected on the channel bathymetry; however, the authors maintain that the modelled surface is an accurate representation as demonstrated by the hydraulic validation data presented in Entwistle et al. (2018).

#### 3.1 | Biotope mapping

CAESAR-Lisflood FP predictions of velocity and depth were computed at a  $1\text{-m}^2$  grid resolution across the study reach including both the heavily modified single-thread and anabranching channel network, and these were used to compute Fr maps using Equation (1). The Fr maps were then classified into biotopes using the delimiters shown in Figure 3. These data were then visualized and quantified in Golden Software Surfer allowing comparisons to be made between biotope distribution in the upstream anabranching and downstream heavily modified single-thread reach.

We also used the FRAGSTATS software package (see McGarigal, Cushman, & Ene, 2012) to provide summary spatial statistics on biotope coverage and distribution, thus employing a *landscape ecological metrics* approach to spatially integrate the spatial patch dynamics of instream biotopes (Forman & Godron, 1986).



**FIGURE 4** Spatial distribution of biotopes classified by the delimiters across the flow regime for the anabranching and single-thread reaches on the study river [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

## 4 | RESULTS

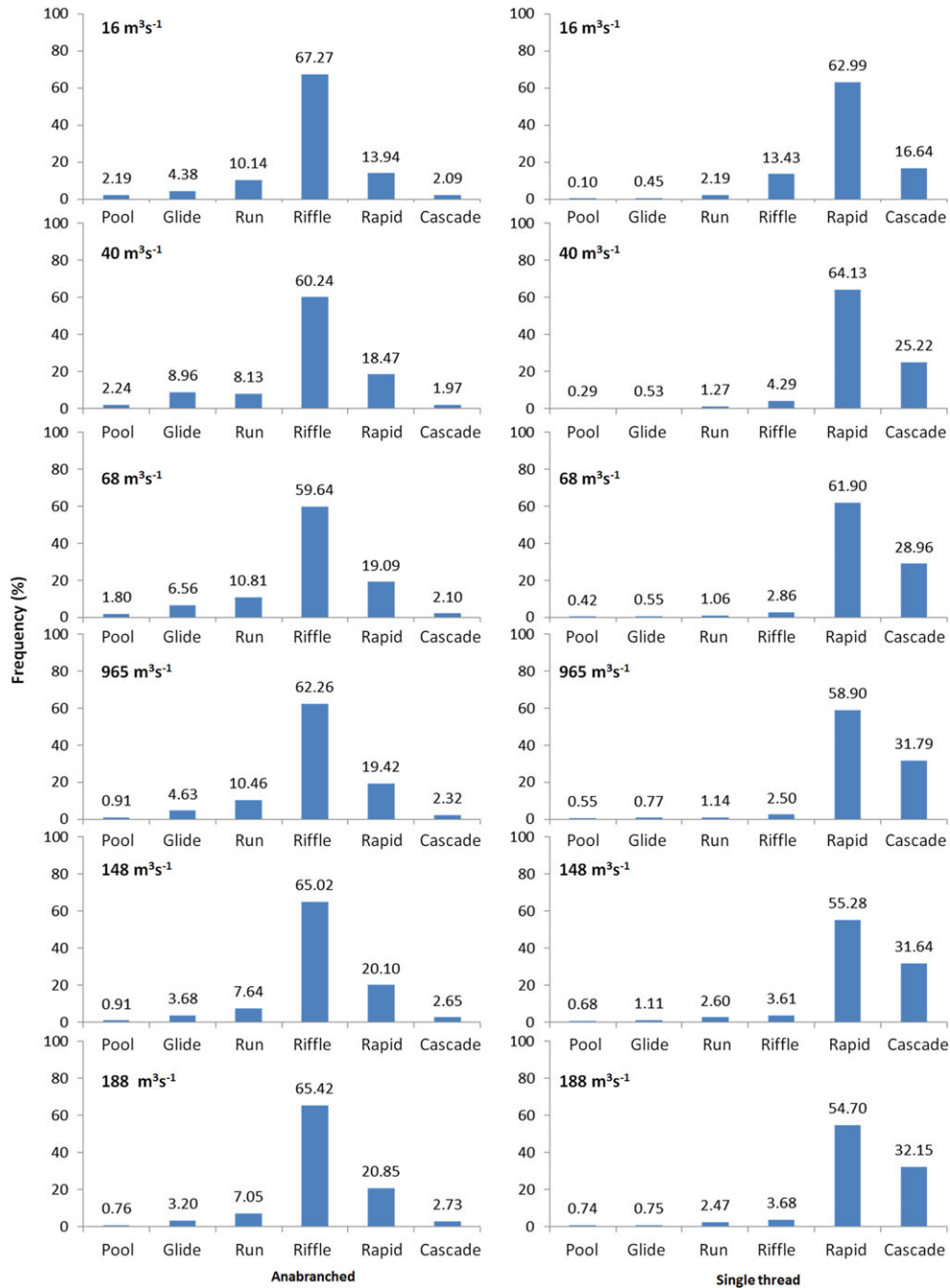
At low flows the anabranching reach displays similar biotope characteristics to the single-thread reach downstream, with both dominated by runs and riffles (Figure 4). As discharge increases the hydraulic behaviour of the two channel types diverges with the anabranching reach responding by increasing its flow area and flow resistance through the transfer of additional flow into a complex series of secondary channels extending off of the left bank of the main channel. This is particularly noticeable at discharges  $>68 \text{ m}^3/\text{s}$ . Flow in the single-thread reach remains confined to the main channel.

As the anabranching channel network becomes progressively activated, a new network of low to moderate energy biotopes including pools and glides appears compared with a set of higher energy biotopes developing through the single-thread reach. This trend of moderated energy and high biotope diversity in the anabranching reach compared with increasingly energetic biotopes in the single-thread reach persists across the flow regime and can be seen clearly in Figure 5, which illustrates the changing areal composition of the two channel types. Rapids and cascades appear to be the most common biotope in the single-thread reach, typically accounting for over 80% of the biotopes present, with little variation in their occurrence over the flow regime. The anabranching reach tends to exhibit less

energetic and more diverse range of biotopes, with glides, runs, riffles, rapids, and cascades all significant at some stage over the flow regime. There is also a more noticeable change in the distribution of biotopes over the flow regime, linked to the activation of the ephemeral network of channels, in the anabranching reach.

Further investigation of the spatial statistics (shape and distribution) of biotopes across the flow regime was conducted on the data (Figure 6). The area-weighted mean patch fractal dimension was calculated to define the complexity of each patch shape (McGarigal et al., 2012). A fractal dimension around 1 indicates that shapes with very simple perimeters (circles/squares) values approaching 2 indicate a highly convoluted perimeter. All biotopes in the anabranching reach are highly complex (area-weighted mean patch fractal dimension 1.7–1.9), which compares to the single-thread reach where patches are generally more uniform (area-weighted mean patch fractal dimension 1.6–1.8), with the exception of runs. Patch complexity is maintained across the flow regime in the anabranching reach, contrasting with a more mixed response as flow increases in the single-thread section.

Patch numbers in the landscape (Figure 7) were used to characterize patchiness (McGarigal et al., 2012). The number of patches shows a rapid increase in the anabranching reach before levelling off at  $52 \text{ m}^3/\text{s}$  discharge, with chutes and runs exhibiting the greatest patchiness. This compares to the single-thread reach where there are consistently fewer

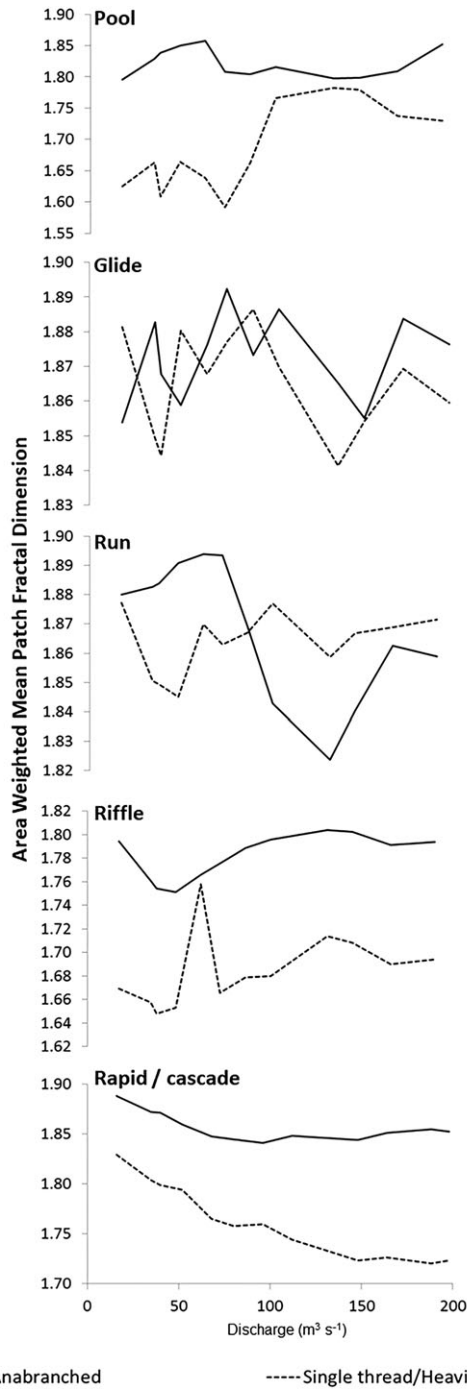


patches and less variability in patch numbers across the flow regime. Chutes are the most patchy of the available biotopes across the flow regime, and pools form more coherent units through the reach.

The patch (biotope) size coefficient of variation provides a measure of uniformity (McGarigal et al., 2012). It returns a value of 0 when all patches in the landscape are the same size or when only a single patch increases as patch shape variation increases. Both anabranching and single-thread lower energy biotopes (pool, glide, and run) exhibit similar moderate patch size variation across the flow regime (Figure 8). Higher energy chutes and cascades are more varied in both

channel types with variation increasing significantly after discharge  $112 \text{ m}^3/\text{s}$ . This suggests that existing subchannels are dividing and/or new channels of varying size are forming. Riffles show a marked increase for the anabranching reach with increasing discharge, in comparison to the single-thread reach, where they show little increase with discharge. These represent new features rather than the growth of existing units reflecting the inundation of ephemeral channels in the anabranching reach.

Overall these statistics suggest a more complex biotope patch structure in the anabranching reach, which is most pronounced around

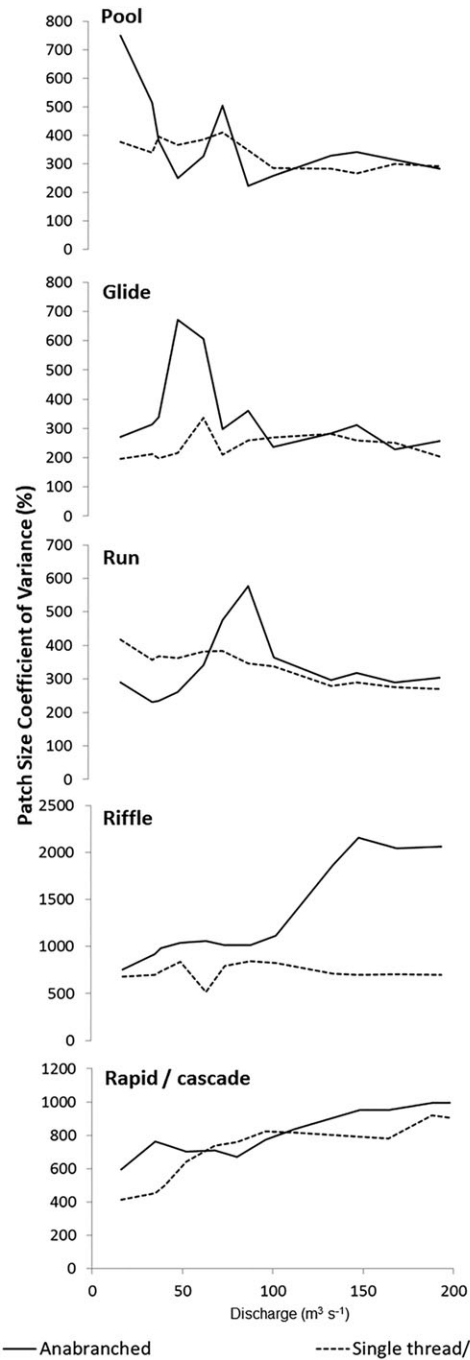


**FIGURE 6** Area-weighted mean patch fractal dimension, defining the complexity of each patch (biotope) shape for the anabranch and single-thread reaches on the study river

discharges 96–112 m<sup>3</sup>/s, in contrast to the generally more uniform single-thread reach.

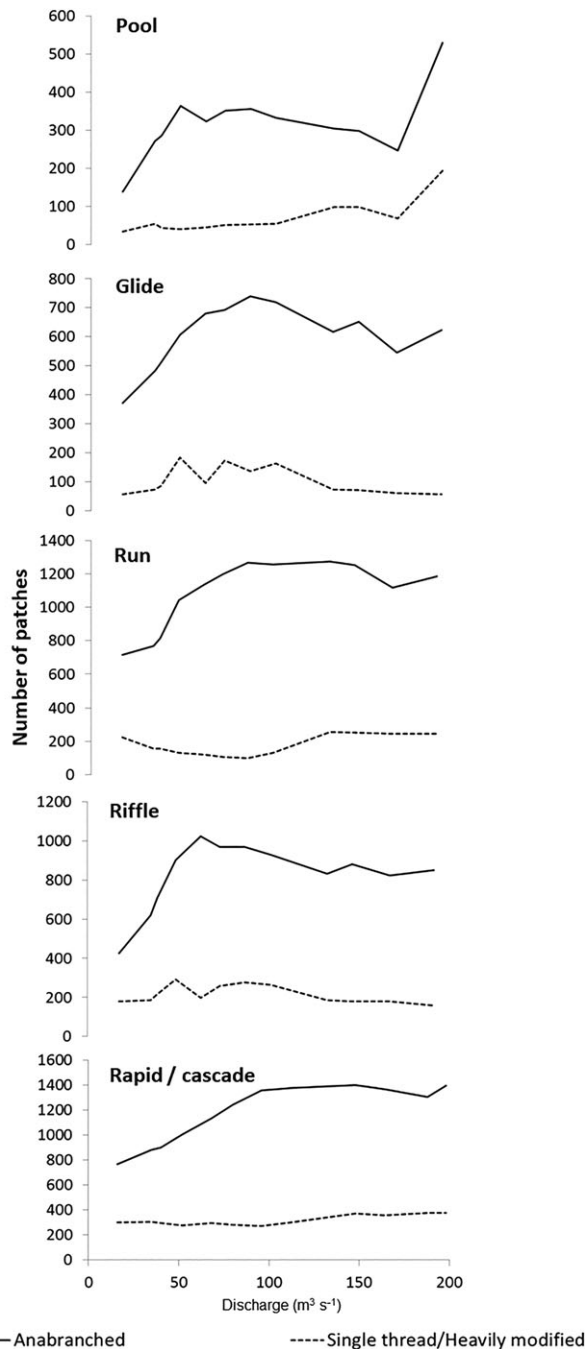
## 5 | DISCUSSION

High-resolution morphological data permit detailed 2D hydraulic modelling and mapping over the flow regime. When the hydraulic



**FIGURE 7** Patch (biotope) number for the anabranch and single-thread reaches on the study river

variables are converted into a meaningful habitat metric (e.g., Fr), it is possible to map spatial and temporal patterns of instream habitat across flow regime. This clearly has advantages over reach-average approaches of habitat classification (e.g., Lamouroux & Jowett, 2005) that fail to adequately predict hydraulic habitat distribution at a representative scale. The subsequent hydraulic outputs were converted to biotope maps for each channel type using Fr as a discriminator. The results of the biotope mapping provide a detailed habitat scale appraisal of conditions across the flow regime and the patterns of



**FIGURE 8** Patch (biotope) size coefficient of variation for the anabranching and single-thread reaches on the study river, providing a measure of patch uniformity

biotope distribution and dominance offer insights into hydraulic habitat character rarely, if ever, measured in nature.

The gross morphology of the anabranching reach appears to be controlling the flow hydraulics, creating a complex and diverse biotope distribution across the site, most notably at low and intermediate flows (Figure 4). This contrasts markedly with the near uniform biotope pattern predicted for the heavily modified single-thread reach (Figure 4). As flow discharge increased the pattern of hydraulic habitats alters to reflect a generally higher energy system; interestingly,

however, a number of low energy biotope areas were activated through the anabranching reach as new subchannels were inundated. These biotopes are likely to create valuable ecological refugia during times of flood, which are unavailable along the single-thread channel.

The anabranching reach exhibits a more diverse range of biotopes over the flow regime and hence will also show the most variability in flow structure (Harvey & Clifford, 2009). This heterogeneity in hydraulic habitat has been recognized in river system structure and habitat since the pioneering work of Hynes (1970) and Vannote, Minshall, Cummins, Sedell, and Cushing (1980) and reinforced by Rinaldi et al. (2015) with many species occupying different habitats at different stages of their life cycle (Hynes, 1970). Pringle et al. (1988) described how environmental heterogeneity influences the dynamics of virtually all ecological processes within rivers. The greater morphological diversity displayed by the anabranching reach is also likely to increase the range of niches available for different species, and this has been shown by Shmida and Wilson (1985) to reduce the likelihood of competitive exclusion, thereby increasing the likelihood of a more diverse biotic community compared with the single-thread reach.

## 5.1 | Implications for fish species

Although little is known about the movements of different species into anabranching channels during floods, good knowledge exists concerning the velocity and depth preferences of certain species. Few studies report Fr number preferences for freshwater fish species. However, Ayllón, Almodóvar, Nicola, and Elvira (2010) report optimum Fr numbers for Brown trout for different age classes 0+ of Fr = 0.49 (rapid), 1+ Fr = 0.38 (rapid), and >1+ Fr = 0.78 (cascade). This suggests that juvenile (<1 + year) habitats show a steady increase with increasing discharge (rapids over the anabranching areas), yet decreases at a flow of 68 m<sup>3</sup>/s in the single-thread channel. Vezza, Parasiewicz, Calles, Spairani, and Comoglio (2014) have shown velocity and depth preferences for the Bullhead (*Cottus gobio*) of 0.35–0.45 m/s velocity range and 0.15–0.30-m depth, respectively, approximating to a Fr number of 0.27 (riffle/rapid). The anabranching reach consistently shows a greater frequency of riffle habitat over the flow regime in comparisons to the single-thread reach, and shows a steady increase in riffle availability after a discharge of 96 m<sup>3</sup>/s. Bullheads have also been reported to utilize deadwater zones as refuges during high flow conditions (Perrow, Punchard, & Jowitt, 1997).

Numerous studies suggest low-velocity preferences for juvenile fish that are likely to be found in the anabranching channels as these become inundated with increasing discharge. For example, De Jalón and Gortazar (2007) indicate an optimum velocity for Atlantic Salmon fry parr and adults to be around 0.2 m/s. For the European eel, adults and juveniles show velocity preference around 0.5 m/s, and depth preferences of 0.18 m (Bermudez, Puertas, Cea, Pene, & Balairon, 2010). Flow rates over Brook Lamprey ammocoete beds of 0.4 m/s at a depth of 25 cm, have been recorded (Maitland, 2003). Although, Hardisty (1986) has recorded velocities of 0.08–0.10 m/s over



lamprey burrows. These lower velocity ranges are increasingly likely to be located in the anabranching channel network as this becomes inundated with increasing discharge.

## 5.2 | Habitat complexity

Change in patch complexity across the flow regime was highlighted for both reach types, although complexity decreased at higher flows in the single-thread reach. As such, competitive exclusion processes would be less in the anabranching reach as flow change induced disturbances open new habitat patches for colonization by inferior competitors before they can be completely excluded from the landscape by superior competitors (see early work by Hutchinson, 1951).

The value of biotope patch complexity discussed above may be contrasted with the work of Naiman et al. (1988), who demonstrated that some species prefer large unbroken habitat patches to thrive and hence may favour the biotope character shown in the single-thread reach. They contrasted this with other species, which were found to exploit the interface between patches, as a result, river reaches displaying biotope assemblages and patterns that are too patchy (the anabranching reach), or insufficiently patchy (the single-thread reach), may be detrimental to certain species. However, Downes, Lake, Schreiber, and Glaister (1998) suggest that a patchier watercourse configuration displaying a high diversity of habitats at large, intermediate, and local spatial scales supports increased abundance and species richness of benthic invertebrates.

Other studies have considered both the configuration and persistence of hydraulic habitat in influencing biotic diversity and resilience. Townsend (1989) emphasized the important roles of disturbance refugia, with the value of patches as refugia shown to be dependent upon their size and arrangement (Lancaster & Hildrew, 1993), and frequency of disturbance (Silver, Wooster, & Palmer, 2004), which impacts on their recolonization potential (Gjerløv, Hildrew, & Jones, 2003; Matthaei et al., 2004). Again in this study the spatial and temporal character of the anabranching channel type (complex, diverse, and quite resilient with refugia patches present) appears to offer greater potential for species diversity over the more uniform spatial and temporal biotope assemblage modelled for the single-thread reach. This uniformity of patch type has also been shown to hinder the formation of refugia by conveying disturbances across the network (Hanski, 1999). The impact of such a conclusion is strengthened by studies that demonstrate the use of multiple habitats by many species which move from one biotope to another seeking flood refuge associated with the presence of slower moving water and more stable substrates (Rempel, Richardson, & Healey, 1999). Highly connected patches, such as those seen in the single thread reach, may thus lead to a reduced range of species in the river.

Recolonization following flood disturbance has been shown to occur in larger stable patches (Holyoak, Leibold, & Holt, 2005), a condition more prevalent in the single-thread reach, and also from adjacent patch populations (Roughgarden, Gaines, & Pacala, 1987), such as those found in the anabranching reach. This feature is particularly

evident where some biotope patches remain during a flood event forming undisturbed locations to recolonize disturbed areas and promoting resilience (Labbe & Fausch, 2000). Persistence has been shown to be highest for the anabranching reach at Wolsingham; however, larger floods do see a change to higher energy hydraulic habitats.

## 6 | CONCLUSIONS

Anabranching channels provide a morphological template for the development of complex, diverse and resilient biotopes. Anabranching channels provide refugia during high flows and are likely to be both more biologically diverse and ecologically resilient compared with single-thread reaches, although it is acknowledged that certain species are well adapted to the more uniform but temporally less stable environment present along the single-thread reach. For river managers, river rehabilitation back towards an anabranching planform, where appropriate, may provide a means of protecting species sensitive to increases in flood magnitude, resulting from climate change or urbanization.

We argue that anabranching reaches, increasingly seen on unmanaged temperate rivers (Heritage et al., 2016), provide a more diverse range of hydraulic conditions in both time and space, which, as a consequence, promotes greater ecological diversity. Where possible, river managers should encourage renaturalization processes leading to the development of such systems and this could be as simple as promoting naturalization through vegetative succession. Fuller, Passmore, Heritage, Large, Milan, and Brewer (2002) noted that prevention of grazing in riparian zones and on bars across some multithread wandering gravel-bed channels found in United Kingdom allowed vegetation succession to stabilize bars promoting transition towards an anabranching system.

On a practical level, the availability of high-quality morphological data from LiDAR and the ease with which a 2D flow model may be constructed results in high-quality hydraulic outputs that may be used to provide spatial and temporal habitat information, linked to river management targets (Logan, McDonald, Nelson, Kinzel, & Barton, 2011). This makes this an excellent tool for use in predicting changes to reach hydromorphology, a process that is critical to achieving the pan-European Water Framework Directive objectives. In addition, modelling results can help to restore rivers in a sustainable and ecologically meaningful way and provide a usable measure to monitor instream habitat health and issues triggered as a result of human intervention.

### ORCID

Neil Entwistle  <https://orcid.org/0000-0002-5799-0506>

David Milan  <https://orcid.org/0000-0002-9914-2134>

### REFERENCES

- Alabyan, A. M., & Lebedeva, S. V. (2018). Flow dynamics in large tidal delta of the Northern Dvina River: 2D simulation. *Journal of Hydroinformatics*, 20(4), 798–814. <https://doi.org/10.2166/hydro.2018.051>

- Ayllón, D., Almodóvar, A., Nicola, G. G., & Elvira, B. (2010). Ontogenetic and spatial variations in brown trout habitat selection. *Ecology of Freshwater Fish*, 19(3), 420–432. <https://doi.org/10.1111/j.1600-0633.2010.00426.x>
- Bates, P. D., & De Roo, A. P. J. (2000). A simple raster-based model for flood inundation simulation. *Journal of Hydrology*, 236(1–2), 54–77. [https://doi.org/10.1016/S0022-1694\(00\)00278-X](https://doi.org/10.1016/S0022-1694(00)00278-X)
- Belletti, B., Rinaldi, M., Bussettini, M., Comiti, F., Gurnell, A. M., Mao, L., ... Vezza, P. (2017). Characterising physical habitats and fluvial hydromorphology: A new system for the survey and classification of river geomorphic units. *Geomorphology*, 283, 143–157. <https://doi.org/10.1016/j.geomorph.2017.01.032>
- Bentley, S. G., England, J., Heritage, G., Reid, H., Mould, D., & Bithell, C. (2016). Long-reach biotope mapping: Deriving low flow hydraulic habitat from aerial imagery. *River Research and Applications*, 32(7), 1597–1608. <https://doi.org/10.1002/rra.3000>
- Bermudez, M., Puertas, J., Cea, L., Pene, L., & Balairon, L. (2010). Experimental and numerical evaluation of sixteen different designs of vertical slot fishways. In G. Chritodoulou, & A. Stamou (Eds.), *Environmental hydraulics*. London: Taylor and Francis. ISBN 978-0-415-58475-3
- Brown, A. G., & Keough, M. (1992). Holocene floodplain metamorphosis in the Midlands, United Kingdom. *Geomorphology*, 4, 433–445. [https://doi.org/10.1016/0169-555X\(92\)90037-O](https://doi.org/10.1016/0169-555X(92)90037-O)
- Brown, A. G., Koegh, M. K., & Rice, R. J. (1994). Floodplain evolution in the East Midlands, United Kingdom: the Lateglacial and Flandrian alluvial record from the Soar and Nene valleys. *Philosophical Transactions of the Royal Society of London, Series a*, 348, 261–293.
- Carling, P., Jansen, J., & Meshkova, L. (2014). Multichannel rivers: Their definition and classification. *Earth Surface Processes and Landforms*, 39, 26–37. <https://doi.org/10.1002/esp.3419>
- Casas, A., Lane, S. N., Yu, D., & Benito, G. (2010). A method for parameterising roughness and topographic sub-grid scale effects in hydraulic modelling from LiDAR data. *Hydrology and Earth System Sciences*, 14(8), 1567–1579.
- Clifford, N. J., Harmor, O. P., Harvey, G., & Petts, G. E. (2006). Physical habitat, eco-hydraulics and river design: a review and re-evaluation of some popular concepts and methods. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 16(4), 389–408. <https://doi.org/10.1002/aqc.736>
- Coulthard, T. J., Neal, J. C., Bates, P. D., Ramirez, J., Almeida, G. A., & Hancock, G. R. (2013). Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: Implications for modelling landscape evolution. *Earth Surface Processes and Landforms*, 38, 1897–1906. <https://doi.org/10.1002/esp.3478>
- De Jalón, D. G., & Gortazar, J. (2007). Evaluation of instream habitat enhancement options using fish habitat simulations: Case-studies in the river Pas (Spain). *Aquatic Ecology*, 41(3), 461–474. <https://doi.org/10.1007/s10452-006-9030-x>
- Demarchi, L., Bizzi, S., & Piégay, H. (2016). Remote sensing hierarchical object-based mapping of riverscape units and in-stream mesohabitats using LiDAR and VHR imagery. *Remote Sensing*, 8(2), 97. <https://doi.org/10.3390/rs8020097>
- Demars, B. O., Kemp, J. L., Friberg, N., Usseglio-Polatera, P., & Harper, D. M. (2012). Linking biotopes to invertebrates in rivers: Biological traits, taxonomic composition and diversity. *Ecological Indicators*, 23, 301–311. <https://doi.org/10.1016/j.ecolind.2012.04.011>
- Dixon, S. J., Sear, D. A., Odoni, N. A., Sykes, T., & Lane, S. N. (2016). The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surface Processes and Landforms*, 41, 997–1008. <https://doi.org/10.1002/esp.3919>
- Dodkins, I., Rippey, B., Harrington, T. J., Bradley, C., Chathain, B. N., Kelly-Quinn, M., ... Trigg, D. (2005). Developing an optimal river typology for biological elements within the Water Framework Directive. *Water Research*, 39, 3479–3486. <https://doi.org/10.1016/j.watres.2005.06.008>
- Downes, B. J., Lake, P. S., Schreiber, E. S. G., & Glaister, A. (1998). Habitat structure and regulation of local species diversity in a stony upland stream. *Ecological Monographs*, 68, 237–257. [https://doi.org/10.1890/0012-9615\(1998\)068\[0237:HSAROL\]2.0.CO;2](https://doi.org/10.1890/0012-9615(1998)068[0237:HSAROL]2.0.CO;2)
- Dyer, F. J., & Thoms, M. C. (2006). Managing river flows for hydraulic diversity: An example of an upland regulated gravel-bed river. *River Research and Applications*, 22, 257–267. <https://doi.org/10.1002/rra.909>
- Entwistle, N., Heritage, G., & Milan, D. (2018). Flood energy dissipation in anabranching channels. *River Research and Applications*, 34(7), 709–720. <https://doi.org/10.1002/rra.3299>
- Entwistle, N. S., Milan, D. J., & Heritage, G. L. (2010). Biotope mapping using combined LiDAR and acoustic doppler profiler survey. In British Hydrological Society—third international symposium, Newcastle, UK. Conference details: BHS. Role of Hydrology in Managing Consequences of a Changing Global Environment.
- Forman, R. T., & Godron, M. (1986). *Landscape ecology* (p. 619). New York: John Wiley & Sons.
- Fryirs, K. A., & Brierley, G. J. (2013). *Geomorphic analysis of river systems: An approach to reading the landscape*. Chichester, UK: John Wiley and Sons.
- Fuller, I. C., Passmore, D. G., Heritage, G. L., Large, A. R. G., Milan, D. J., & Brewer, P. A. (2002). Annual sediment budgets in an unstable gravel bed river: The River Coquet, northern England. In S. Jones, & L. Frostick (Eds.), *Sediment flux to basins: causes, controls and consequences* (pp. 115–131). London Special Issue, 191: Geological Society of London.
- Gjerløv, C., Hildrew, A. G., & Jones, J. I. (2003). Mobility of stream invertebrates in relation to disturbance and refugia: A test of habitat template theory. *Journal of the North American Benthological Society*, 22, 207–223. <https://doi.org/10.2307/1467993>
- Glenister, D. (2015). Storm Desmond—River Wear Wolsingham (2015). Available at: <https://www.youtube.com/watch?v=bZgH5PvaO-g> [Accessed 27 March 2018].
- Gurnell, A. M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., ... Ziliani, L. (2016). A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. *Aquatic Sciences*, 78(1), 1–16. <https://doi.org/10.1007/s00027-015-0424-5>
- Hanski, I. (1999). *Metapopulation ecology*. Oxford, UK, and New York, NY: Oxford University Press.
- Hardisty, M. W. (1986). Petromyzontiforma. In J. Holcik (Ed.), *The freshwater fishes of Europe*. Wiesbaden: Aula-Verlag.
- Harvey, G. L., & Clifford, N. J. (2009). Microscale hydrodynamics and coherent flow structures in rivers: Implications for the characterization of physical habitat. *River Research and Applications*, 25, 160–180. <https://doi.org/10.1002/rra.1109>
- Harvey, G. L., Clifford, N. J., & Gurnell, A. M. (2008). Towards an ecologically meaningful classification of the flow biotope for river inventory, rehabilitation, design and appraisal purposes. *Journal of Environmental Management*, 88(4), 638–650. <https://doi.org/10.1016/j.jenvman.2007.03.039>
- Harwood, K., & Brown, A. G. (1993). Fluvial processes in a forested anastomosing river: flood partitioning and changing flow patterns. *Earth Surface Processes and Landforms*, 18, 741–748. <https://doi.org/10.1002/esp.3290180808>

- Heritage, G. L., Hetherington, D., Milan, D. J., Large, A. R. G., & Entwistle, N. (2009). Temporal characterisation of biotope units across the flow regime using repeat LiDAR survey. *Proceedings of the 7th International Symposium on Ecohydraulics*, Concepción, Chile, January 12–16, 2009.
- Heritage, G. L., Milan, D., & Entwistle, N. (2016). Alluvial anastomosed channels: The preferred channel type on active UK rivers. In J. A. Webb, J. F. Costelloe, R. Casas-Mulet, J. P. Lyon, & M. J. Stewardson (Eds.), *Proceedings of the 11th International Symposium on Ecohydraulics*. Melbourne, Australia, 7–12 February 2016: The University of Melbourne. ISBN: 978 0 7340 5339 8
- Heritage, G. L., Milan, D. J., & Entwistle, N. S. (2009). An investigation of the role of geomorphology in influencing biotope distribution. *IAHS Publication*, 20, 68.
- Hill, G., Maddock, I., & Bickerton, M. (2008). River habitat mapping: Are surface flow type habitats biologically distinct? In: Sustainable hydrology for the 21st century, 15–17 September 2008, University of Exeter.
- Holyoak, M., Leibold, M. A., & Holt, R. D. (2005). *Metacommunities: Spatial dynamics and ecological communities*. Chicago and London: University of Chicago Press.
- Hutchinson, G. E. (1951). Copepodology for the ornithologist. *Ecology*, 32, 571–577. <https://doi.org/10.2307/1931746>
- Hynes, H. B. N. (1970). *The ecology of running waters*. Toronto, Ontario: University of Toronto Press.
- Jansen, J. D., & Nanson, G. C. (2004). Anabranching and maximum flow efficiency in Magela Creek, northern Australia. *Water Resources Research*, 40(4), W04503. <https://doi.org/10.1029/2003WR002408>
- Jowett, I. G. (2003). Hydraulic constraints on habitat suitability for benthic invertebrates in gravel-bed rivers. *River Research and Applications*, 19, 495–507. <https://doi.org/10.1002/rra.734>
- Jowett, L. G. (1993). A method of objectively identifying pool, run and riffle habitats from physical measurements. *New Zealand Journal of Marine and Freshwater Research*, 27, 241–248. <https://doi.org/10.1080/00288330.1993.9516563>
- King, J., & Louw, D. (1998). Instream flow assessments for regulated rivers in South Africa using the building block methodology. *Aquatic Ecosystem Health & Management*, 1(2), 109–124. [https://doi.org/10.1016/S1463-4988\(98\)00018-9](https://doi.org/10.1016/S1463-4988(98)00018-9)
- Kleinens, M. G., de Haas, T., Lavooi, E., & Makaske, B. (2012). Evaluating competing hypotheses for the origin and dynamics of river anastomosis. *Earth Surface Processes and Landforms*, 37, 1337–1351. <https://doi.org/10.1002/esp.3282>
- Knighton, A. D., & Nanson, G. C. (1993). Anastomosis and the continuum of channel pattern. *Earth Surface Processes and Landforms*, 18, 613–625. <https://doi.org/10.1002/esp.3290180705>
- Labbe, T. R., & Fausch, K. D. (2000). Dynamics of intermittent stream habitat regulate persistence of a threatened fish at multiple scales. *Ecological Applications*, 10, 1774–1791. [https://doi.org/10.1890/1051-0761\(2000\)010\[1774:DOISHR\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[1774:DOISHR]2.0.CO;2)
- Lamouroux, N., & Jowett, I. G. (2005). Generalized instream habitat models. *Canadian Journal of Fisheries and Aquatic Sciences*, 62, 7–14. <https://doi.org/10.1139/f04-163>
- Lancaster, J., & Hildrew, A. G. (1993). Characterizing in-stream flow refugia. *Canadian Journal of Fisheries and Aquatic Sciences*, 50, 1663–1675. <https://doi.org/10.1139/f93-187>
- Large, A., & Heritage, G. (2012). Ground based LiDAR and its application to the characterisation of fluvial forms. *Fluvial Remote Sensing for Science and Management*, pp.323–339.
- Lewin, J. (2010). Medieval environmental impacts and feedbacks: The lowland floodplains of England and Wales. *Geoarchaeology: An International Journal*, 25, 267–311. <https://doi.org/10.1002/gea.20308>
- Logan, B. L., McDonald, R. R., Nelson, J. M., Kinzel, P. J., & Barton, G. J. (2011). Use of multidimensional modeling to evaluate a channel restoration design for the Kootenai River, Idaho (No. 2010-5213, pp. i-68). US Geological Survey.
- Maddock, I., Harby, A., Kemp, P., & Wood, P. J. (2013). *Ecohydraulics: An integrated approach* John Wiley & Sons. <https://doi.org/10.1002/9781118526576>
- Maitland, D. (2003). *Ecology of the River, Brook and Sea Lamprey*. Conserving Natura 2000 Rivers Ecology Series No. 5. English Nature, Peterborough.
- Makaske, B. (2001). Anastomosing rivers: A review of their classification, origin and sedimentary products. *Earth Science Reviews*, 53, 149–196. [https://doi.org/10.1016/S0012-8252\(00\)00038-6](https://doi.org/10.1016/S0012-8252(00)00038-6)
- Matthaei, C. D., Townsend, C. R., Arbuttle, C. J., Peacock, K. A., Guggelberger, C., Küster, C. E., & Huber, H. (2004). Disturbance, assembly rules and benthic communities in running waters: a review and some implications for restoration projects. Assembly rules and restoration ecology: bridging the gap between theory and practise. Island Press, Washington, DC, pp.367–388.
- McGarigal, K., Cushman, S. A., & Ene, E. (2012). FRAGSTATS v4: Spatial pattern analysis program for categorical and continuous maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. Available at the following web site [www.umass.edu/landeco/research/fragstats/fragstats.html](http://www.umass.edu/landeco/research/fragstats/fragstats.html)
- Milan, D., Heritage, G., Entwistle, N., & Tooth, S. (2018). Morphodynamic simulation of sediment deposition patterns on a recently stripped bedrock anastomosed channel. *Proc. IAHS*, 377, 51–56. <https://doi.org/10.5194/piahs-377-51-2018>, 2018.
- Milan, D. J., & Heritage, G. L. (2012). LiDAR and ADCP use in gravel bed rivers: Advances since GBR6. In M. Church, P. Biron, & A. Roy (Eds.), *Gravel-bed rivers: Processes, tools, environments* (pp. 286–302). Chichester: John Wiley & Sons. <https://doi.org/10.1002/9781119952497.ch22>
- Milan, D. J., Heritage, G. L., Large, A. R. G., & Entwistle, N. S. (2010). Mapping hydraulic biotopes using terrestrial laser scan data of water surface properties. *Earth Surface Processes and Landforms*, 35(8), 918–931. <https://doi.org/10.1002/esp.1948>
- Moore, E. N. (1994). *Glacial geology and geomorphology of Weardale*. Unpublished PhD Thesis, University of Durham, UK.
- Muhar, S., Schwarz, M., Schmutz, S., & Jungwirth, M. (2000). *Identification of rivers with high and good habitat quality: Methodological approach and applications in Austria*. In *Assessing the Ecological Integrity of Running Waters* (pp. 343–358). Dordrecht: Springer.
- Naiman, R. J., Décamps, H., Pastor, J., & Johnston, C. A. (1988). The potential importance of boundaries of fluvial ecosystems. *Journal of the North American Benthological Society*, 7, 289–306. <https://doi.org/10.2307/1467295>
- Nanson, G. C., & Knighton, A. D. (1996). Anabranching rivers: Their cause, character and classification. *Earth Surface Processes and Landforms*, 21, 217–239. [https://doi.org/10.1002/\(SICI\)1096-9837\(199603\)21:3<217::AID-ESP611>3.0.CO;2-U](https://doi.org/10.1002/(SICI)1096-9837(199603)21:3<217::AID-ESP611>3.0.CO;2-U)
- Newson, M. D., Harper, D. M., Padmore, C. L., Kemp, J. L., & Vogel, B. (1998). A cost-effective approach for linking habitats, flow types and species requirements. *Aquatic conservation: Marine and Freshwater Ecosystems*, 8, 431–446. [https://doi.org/10.1002/\(SICI\)1099-0755\(199807/08\)8:4<431::AID-AQC302>3.0.CO;2-W](https://doi.org/10.1002/(SICI)1099-0755(199807/08)8:4<431::AID-AQC302>3.0.CO;2-W)
- Newson, M. D., & Newson, C. L. (2000). Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography*, 24(2), 195–217. <https://doi.org/10.1177/030913330002400203>

- Padmore, C. L. (1998). The role of physical biotopes in determining the conservation status and flow requirements of British rivers. *Aquatic Ecosystem Health & Management*, 1(1), 25–35.
- Pasternack, G. B., & Senter, A. E. (2011). 21st Century instream flow assessment framework for mountain streams. California Energy Commission, PIER. CEC-500-2013-059.
- Perrow, M., Punchard, N., & Jowitt, A. (1997). *The habitat requirements of bullhead (Cottus gobio) and brown trout (Salmo trutta) in the headwaters of selected Norfolk rivers: Implications for conservation and fisheries* (p. 48). Eastern Area, Ipswich: Environment Agency.
- Pringle, C. M., Naiman, R. J., Bretschko, G., Karr, J. R., Oswood, M. W., Webster, J. R., ... Winterbourn, M. J. (1988). Patch dynamics in lotic systems: The stream as a mosaic. *Journal of the North American Benthological Society*, 7, 503–524. <https://doi.org/10.2307/1467303>
- Puckridge, J. T., Walker, K. F., & Costelloe, J. F. (2000). Hydrological persistence and the ecology of dryland rivers. *Regulated Rivers: Research & Management*, 16, 385–402. [https://doi.org/10.1002/1099-1646\(200009/10\)16:5<385::AID-RRR592>3.0.CO;2-W](https://doi.org/10.1002/1099-1646(200009/10)16:5<385::AID-RRR592>3.0.CO;2-W)
- Railsback, S. (1999). Reducing uncertainties in instream flow studies. *Fisheries*, 24(4), 24–26.
- Raven, P. J., Fox, P., Everard, M., Holmes, N. T. H., & Dawson, F. H. (1997). River habitat survey: A new system for classifying rivers according to their habitat quality. In P. J. Boon, & D. L. Kowell (Eds.), *Freshwater quality: Defining the indefinable?* (pp. 215–234). London, UK: HMSO.
- Reid, M. A., & Thoms, M. C. (2008). Surface flow types, near-bed hydraulics and the distribution of stream macroinvertebrates. *Biogeosciences*, 5, 1043–1055. <https://doi.org/10.5194/bg-5-1043-2008>
- Rempel, L. L., Richardson, J. S., & Healey, M. C. (1999). Flow refugia for benthic macroinvertebrates during flooding of a large river. *Journal of the North American Benthological Society*, 18, 34–48. <https://doi.org/10.2307/1468007>
- Rinaldi, M., Gurnell, A. M., Belletti, B., Berga Cano, M. I., Bizzi, S., Bussetini, M., ... Vezza, P. (2015). Final report on methods, models, tools to assess the hydromorphology of rivers, Deliverable 6.2, Part 1, of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.
- Roughgarden, J., Gaines, S., & Pacala, S. (1987). Supply side ecology: The role of physical transport processes. In J. H. R. Gee, & P. S. Giller (Eds.), *The 27th Symposium of the British Ecological Society: In organization of communities, past and present* (pp. 491–518). London, UK: Blackwell Scientific Publications.
- Rydgren, B., Kyläkorpi, L., Bodlund, B., Ellegård, A., Grusell, E., & Miliander, S. (2005). Experiences from five years of using the biotope method, a tool for quantitative biodiversity impact assessment. *Impact Assessment and Project Appraisal*, 23(1), 47–54. <https://doi.org/10.3152/147154605781765760>
- Schwartz, J. S., & Herricks, E. E. (2008). Fish use of ecohydraulic-based mesohabitat units in a low-gradient Illinois stream: Implications for stream restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 18(6), 852–866. <https://doi.org/10.1002/aqc.905>
- Sedell, J. R., Reeves, G. H., Hauer, F. R., Stanford, J. A., & Hawkins, C. P. (1990). Role of refugia in recovery from disturbances: Modern fragmented and disconnected river systems. *Environmental Management*, 14(5), 711–724. <https://doi.org/10.1007/BF02394720>
- Shmida, A., & Wilson, M. V. (1985). Biological determinants of species diversity. *Journal of Biogeography*, 12, 1–20. <https://doi.org/10.2307/2845026>
- Silver, P., Wooster, D., & Palmer, M. A. (2004). Chironomid responses to spatially structured, dynamic, streambed landscapes. *Journal of the North American Benthological Society*, 23, 69–77. [https://doi.org/10.1899/0887-3593\(2004\)023<0069:CRTSSD>2.0.CO;2](https://doi.org/10.1899/0887-3593(2004)023<0069:CRTSSD>2.0.CO;2)
- Stalnaker, C. B., Bovee, K. D., & Waddle, T. J. (1996). Importance of the temporal aspects of habitat hydraulics to fish population studies. *Regulated Rivers: Research and Management*, 12, 145–153. [https://doi.org/10.1002/\(SICI\)1099-1646\(199603\)12:2/3<145::AID-RRR386>3.0.CO;2-H](https://doi.org/10.1002/(SICI)1099-1646(199603)12:2/3<145::AID-RRR386>3.0.CO;2-H)
- Thomson, J. R., Taylor, M. P., Fryirs, K. A., & Brierley, G. J. (2001). A geomorphological framework for river characterization and habitat assessment. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 11, 373–389. <https://doi.org/10.1002/aqc.467>
- Tonina, D., & Jorde, K. (2013). Hydraulic modelling approaches for ecohydraulic studies: 3D, 2D, 1D and non-numerical models. *Ecohydraulics: An integrated approach*, pp. 31–74. <https://doi.org/10.1002/9781118526576.ch3>
- Townsend, C. R. (1989). The patch dynamics concept of stream community ecology. *Journal of the North American Benthological Society*, 8, 36–50. <https://doi.org/10.2307/1467400>
- Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*, 37, 130–137. <https://doi.org/10.1139/f80-017>
- Veza, P., Parasiewicz, P., Calles, O., Spairani, M., & Comoglio, C. (2014). Modelling habitat requirements of bullhead (*Cottus gobio*) in Alpine streams. *Aquatic Sciences*, 76(1), 1–15. <https://doi.org/10.1007/s00027-013-0306-7>
- Wadeson, R. A. (1994). A geomorphological approach to the identification and classification of instream flow environments. *South African Journal Aquatic Sciences*, 20, 38–61. <https://doi.org/10.1080/10183469.1994.9631349>
- Wadeson, R. A., & Rowntree, K. M. (1998). Application of the hydraulic biotope concept to the classification of instream habitats. *Aquatic Ecosystem Health and Management*, 1, 143–157. [https://doi.org/10.1016/S1463-4988\(98\)00019-0](https://doi.org/10.1016/S1463-4988(98)00019-0)
- Wishart, D., Warburton, J., & Bracken, L. (2008). Gravel extraction and planform change in a wandering gravel-bed river: The River Wear, Northern England. *Geomorphology*, 94(1–2), 131–152. <https://doi.org/10.1016/j.geomorph.2007.05.003>
- Wolman, M. G. (1954). A method of sampling coarse river gravels. *Transactions - American Geophysical Union*, 35, 951–956.
- Woodget, A. S., Visser, F., Maddock, I. P., & Carbonneau, P. E. (2016). The accuracy and reliability of traditional surface flow type mapping: Is it time for a new method of characterizing physical river habitat? *River Research and Applications*, 32(9), 1902–1914. <https://doi.org/10.1002/rra.3047>
- Zavadii, E., & Stewardson, M. (2013). The role of geomorphology and hydrology in determining spatial-scale units for ecohydraulics. *Ecohydraulics: an integrated approach*, 125–142.

**How to cite this article:** Entwistle N, Heritage G, Milan D. Ecohydraulic modelling of anabranching rivers. *River Res Applic.* 2019;1–12. <https://doi.org/10.1002/rra.3413>