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Hydromorphological, hydraulic and ecological effects of restored wood: findings and reflections from an academic partnership approach

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ABSTRACT

Large wood (re)introduction has the potential to deliver multiple benefits for river restoration schemes, but there is a dearth of the detailed and longer-term post-project monitoring and evaluation required for improving best practice. We present findings from post-project monitoring and evaluation, based on successive MSc research projects on restored large wood in the Loddon catchment, UK. Field and modelling data reveal: (i) key differences in large wood features between restored and natural reaches; (ii) increased hydraulic retention and changes to mesohabitats associated with large wood; (iii) differences in macroinvertebrate community composition around large wood but a lack of site-level effects; (iv) interactions between macrophytes and large wood that may be specific to restored reaches; (v) a need for further field and modelling studies to inform the accurate representation of large wood in hydraulic models. Some key challenges in partnership working are identified to aid planning and effectiveness of future collaborations.

KEYWORDS: logjams, large woody debris, hydromorphology, river restoration, post project monitoring, post project appraisal

INTRODUCTION

Large wood is a naturally occurring feature of river systems and performs critical hydromorphological and ecological functions. Large wood increases channel roughness and creates diverse hydraulic habitats, including areas of scour and sediment deposition (Keller and Swanson, 1979; Linstead and Gurnell, 1999; Montgomery *et al.*, 2003). In-channel large wood retains organic matter (Daniels, 2006; Flores *et al.*, 2011), increases availability of food resources (Cashman *et al.*, 2016) and attenuates nutrients (Krause *et al.*, 2014). As a result, large wood can increase diversity and biomass of benthic invertebrates and fish (e.g. Benke *et al.*, 1985; Schneider and Windemiller, 2008; Benke and Wallace, 2003; Pilotto *et al.*, 2014; 2016). Despite its important instream functions, large wood has been removed from the majority of river systems over long timescales (Wohl, 2014) through land use change, flow regulation and embankment (Erskine and Webb, 2003), and through direct removal in response to concerns over conveyance capacity and blockage risk at structures (Gippel *et al.*, 1996; Erskine and Webb, 2003; Diehl, 1997; Lassetre and Kondolf, 2012).

Growing recognition of the important role of large wood in river channels has led to increasing use of large wood in restoration schemes. There has been a tendency for large wood restoration to favour simpler flow deflectors over more structurally complex wood features (Gippel, 1996; Cashman *et al.* in press), reflecting concerns over increased stage and flood risk (Linstead and Gurnell, 1999) and the potential for mobilisation and risks to downstream structures (Gippel *et al.*, 1996; Erskine and Webb, 2003; Roni *et al.*, 2015). More recently, however, some projects have incorporated more complex wood jams (e.g. Nisbet *et al*., 2015; Harvey *et al.*, 2018). While large wood can contribute to flood risk by increasing frictional resistance and constricting flow, to generate a backwater or damming effect (Gippel *et al.*, 1995; 1996), it can also deliver flood risk benefits. Large wood can increase the upstream storage of flood waters and floodplain connectivity thereby 'slowing the flow', desynchronising flood peaks, and trapping sediment which may reduce the need for dredging downstream (Environment Agency, 2017). As a result, restored wood features or 'leaky barriers' are increasingly installed as part of Natural Flood Management (NFM) schemes (Environment Agency, 2017), but the nature and extent of the hydrological effects will reflect a range of factors including the positioning, number, sequencing and structural properties of features (Odoni and Lane, 2010; Thomas and Nisbet, 2012; Dixon *et al.*, 2016; Lane, 2017; Environment Agency, 2017).

River restoration projects using large wood therefore have the potential to deliver multiple benefits including water quality, habitat, climate regulation, low flow mitigation and flood risk benefits (Environment Agency, 2017). Restored large wood has been shown to deliver a range of instream habitat improvements including modifying sediment dynamics at the patch and reach scale (Parker *et al.* 2017), creating complex marginal habitats and promoting channel recovery from over-widening (Harvey *et al.*, 2018), and improving biodiversity across riverine food webs (Thompson *et al.*, 2017). Extensive meta-analyses of large samples of restoration projects, however, have identified considerable variability in restoration outcomes and, while trends are generally positive, not all projects show statistically significant ecological improvements (e.g. Palmer *et al.*, 2010; Miller *et al.*, 2010; Feld *et al.*, 2011; Roni *et al.*, 2015; Verdonshot *et al.*, 2016). Similarly, the Environment Agency (2017) identified a "mixed level of confidence" in flood risk benefits of large wood, reflecting ‘medium’ understanding of local impacts and ‘low’ understanding at larger catchment scales and during higher magnitude flow events. Importantly, there is no standard means of representing large wood in hydraulic models; previous studies have tended to either manipulate the Manning’s n value or incorporate a channel blockage function (Thomas and Nisbet, 2012; Environment Agency, 2017).

Learning from past successes and failures in restoration is vital to the development best practice (Kondolf, 1998; Kondolf *et al*., 2001; Downs and Kondolf, 2002; Palmer *et al.*, 2005). Unfortunately, opportunities are limited due to an overall lack of detailed and longer-term project appraisal (Bernhardt *et al.,* 2005; Kail *et al.,* 2007; Morandi *et al.*, 2014; Cashman *et al.*, in press 2018). PhD and MSc research can make important contributions to post-project monitoring and assessment of river restoration projects, with the potential for successive cohorts to extend the temporal reach of monitoring. This paper brings together research on the hydromorphological, hydraulic and ecological outcomes of large wood restoration in the Loddon catchment, UK, from successive MSc projects. The projects arose from an academic partnership between the Environment Agency Operations Delivery and Fisheries, Biodiversity and Geomorphology teams and Queen Mary University of London. This includes partnership working with the Loddon Catchment Partnership, flood groups and the Loddon Fisheries Conservation Consultative (LFCC).

The objectives of this research were to: (i) characterise the physical structure of restored large wood jams; (ii) quantify the effects of large wood on hydromorphology and mesohabitats; (iii) assess benthic invertebrate diversity and community composition in large wood features and associated habitats; and (iv) assess the extent to which the method used to represent large wood features (Manning’s n or blockage ratio) influences modelled stage using a 1D hydraulic model.

METHODS

Field sites

This research was conducted at four field sites in the River Loddon catchment in South East England (Figure 1). Three of the sites were on the River Blackwater, a predominantly urbanised catchment underlain by superficial gravels and London Clay. The fourth site was on the River Whitewater, a predominantly rural catchment underlain by chalk. The Loddon catchment has a long history of anthropogenic impacts associated with urbanisation and water milling, including channel modification, reduction of the riparian corridor, over-widening, fine sediment problems, and water quality issues associated with treated sewage effluents (Blackwater Valley Countryside Partnership, 2013).

Ongoing restoration in the catchment incorporates the installation of in-stream large wood in the river channel. Introduction of large wood features was undertaken at Hawley Meadows on the River Blackwater in 2007 and 2012, and at Greywell on the River Whitewater in 2010 (Figure 1). Reaches where large wood was introduced are referred to as R1a, R1b and R1c for Hawley Meadows and R2 for the Greywell site. Naturally occurring large wood features were also identified at two reaches on the River Blackwater: Shepherd's Meadows (N1) and Moor Green Lakes (N2) and used for comparison in some of the hydromorphological and macroinvertebrate studies. Control reaches with no wood features were established at two restored sites: Hawley Meadows (CR1a and CR1b) and Greywell (CR2) and at one of the natural wood sites (Moor Green Lakes, CN2). Research was conducted over six years between 2011 and 2017 through five MSc projects.

Large wood characteristics

Large wood is typically defined as wood with dimensions >1 m in length and >0.1 m in diameter (Thevenet *et al.*, 1998) and accumulates in jams of diverse structure (Abbe and

Montgomery, 1996; Gurnell *et al.*, 2001; Gurnell *et al.*, 2002). To characterise restored and natural jam characteristics, large wood surveys captured key parameters identified in the research literature (Gregory *et al.*, 1985; Wohl *et al.*, 2010): jam class (partial, active and complete) representing increasing hydraulic influence (Gregory *et al.*, 1985; Gregory and Gurnell, 1998); number of key wood pieces; and total number of wood pieces. On the Blackwater, jam characteristics were recorded in 2012, capturing five jams in each of the restored reaches (R1a and R1b) and three jams in the natural wood reach (N2). At Greywell on the Whitewater (R2) eight restored jams were surveyed in 2017.

Hydromorphology

Flow velocity was measured at reaches R1a, R1b and CR1a in June 2012 ($Q = 0.41\ m^3s^{-1}$; exceedance = Q_{50} at nearby gauging station 3.7 km downstream at Farnborough ref. 39123) using a FlowTracker Handheld Acoustic Doppler Velocimeter (ADV) recording mean velocity averaged over 30 seconds at 0.6 of the flow depth (Kondolf and Piegay, 2003). A period of heavy rainfall preceded the measurement period and therefore measurements were conducted under relatively high flow conditions. Four measurements were taken along cross sections spaced 10 m apart throughout the 100 m reach. Novel flow tracer experiments were performed in R1a and CR1a, adapted from Milner and Gilvear (2012). Perforated plastic golf balls or ‘aqua-spheres’ float just below the water surface enabling assessment of hydraulic retention within river reaches (Milner and Gilvear, 2012). 100 aqua-spheres were released in the centre of the channel at the upstream extent of reaches R1a and CR1a, and their travel times through the reach were recorded up to a cut-off time of 15 minutes based on the mean thalweg velocity. The number and locations of aqua-spheres retained in each reach were recorded after the experiment, identifying major retention features.

Mesohabitats were assessed visually and mapped in the field using gridded basemaps at 1 m - 5 m resolution (Tickner *et al.*, 2000) and digitised using ArcGIS to enable computation of mesohabitat area. Mesohabitat mapping was undertaken at R1b, N1 and CR1b in 2013 on the River Blackwater and in R2 and C2 on the River Whitewater in 2017. For the Whitewater, mesohabitats were used to compute a Spatial Diversity Index (SDI; Fortin *et al.*, 1999) based on proportional area and spatial arrangement of meso-habitats (Sundermann *et al.*, 2011).

Benthic invertebrates

Benthic invertebrate samples were collected using a Surber Sampler with a 250 µm mesh net in different mesohabitats using standard field procedures (Freshwater Biological Association, 2013; Stauffer-Olsen, 2016). Wood mesohabitats were sampled by scrubbing the wood surface with a brush to dislodge invertebrates into a net (Cuffney *et al.*, 1993; Pilotto *et al.*, 2014; 2016), covering an area comparable to the Surber Sampler (Surber, 1937). Taxa were identified to family level where possible (exceptions: Acari, Araneae, Diptera, Hydrozoan, Ostracoda and Oligochaeta). Invertebrates were sampled across mesohabitats around restored jams (R1b), natural jams (N1) and a respective control reach (CR1b) in June 2013 (5 samples per reach). Invertebrates were also sampled across mesohabitats in R2 around 8 large wood features and in the control reach C2 (4 replicates per habitat patch) in June 2017. Kruskall-Wallis tests were used to identify significant differences between sites and mesohabitats using abundance and diversity (Shannon-Weiner) metrics. To explore mesohabitat differences in community composition (for R2), non-metric multidimensional scaling (nMDS) was performed based on a Bray-Curtis similarity matrix using the square-root transformed abundance data (Clarke and Warwick, 2001) using only taxa present in more than five samples.

1D hydraulic modelling of large wood

The selection of a hydrodynamic modelling approach requires consideration of computational efficiency, data availability and expertise constraints in relation to the adequate prediction of relevant variables at an appropriate resolution and level of accuracy (Hunter *et al.*, 2007). Linked 1D river to 2D floodplain models are a common choice in flood risk decision making (Teng *et al.*, 2017) whereby water levels modelled in 1D are used to drive a 2D floodplain inundation model. Representing large wood in linked models is achieved by manipulating discrete cross sections in the 1D river model, and analysis therefore focused on the 1D modelling component in order to assess the impact of different methods of large wood representation on stage. 1D hydraulic models of a subsection of R1a (700 m in length) were constructed using Flood Modeller (Jacobs, 2018) under steady flow conditions. Existing Environment Agency cross section surveys were combined with additional cross sections surveyed using an RTK GPS in July 2014. A systematic error affecting elevation values was identified, relating to combining EA cross sections with the newer field data and data were manually corrected based on field observations. These manual corrections preclude accurate 2D inundation modelling and detailed flood risk assessments, but enable comparisons to be drawn between methods of large wood representation in a 1D river model. Discharge was measured in the field using the velocity-area method and a handheld impeller flow meter (Shaw *et al.*, 2011).

Four large wood features (“LW1” - “LW4”) were represented in the model using two approaches (i) manipulating values of Manning’s n at cross sections with large wood and (ii) using blockage ratios calculated using the length of large wood relative to channel width. In both cases model calibration involved manual adjustment of roughness values and comparison of predicted and measured water levels. Cross sections without large wood were assigned Manning’s n values of 0.05 – 0.2 based on field observations and relevant literature (Chow, 1959; Conveyance and Afflux Estimation System, 2018). For the Manning’s approach, Manning’s n values were assigned to wood features based on their characteristics and published literature (Chow, 1959; Anderson *et al.*, 2006;

Sterling, 2010; H.R. Wallingford, 2014): bare logs = 0.040; substantial emergent and submerged macrophyte cover = 0.150; thicker branches with established leaf cover and thick foliage = 0.150; thinner leaf cover or new shoots = 0.125. For the blockage ratio approach, blockage ratios of 40%, 37.7%, 74.1% and 45.2% were used to represent LW1-LW4 based on field observations. Model scenarios were: Q_{Low} (measured flow, Q = 0.283 m^3s^{-1}); and recurrence intervals of 1 year (Q_{RI1} = 1.31 m^3s^{-1}); 2 years (Q_{RI2} = 3.25m^3s^{-1}) and 5 years (Q_{RI5} = 5.67 m^3s^{-1}). Blockage ratios of 50%, 60%, 70%, 80% and 95% were also explored for all large wood features across all four scenarios. The blockage ratio approach used baseline contraction and expansion coefficients of 0.1 and 0.3 respectively.

RESULTS

Characteristics of restored and natural large wood jams

Large wood jam characteristics are presented in Figure 2. Almost all restored wood jams were classified as 'partial' jams except for three active jams at R2 on the Whitewater. In contrast, the natural reach (N2) contained a combination of partial, active and complete jams. Most restored jams were anchored in place using posts or pins, with two rooted or braced against a tree and one unanchored jam. All three natural jams were rooted or buried in the river bank. Restored jams on the Blackwater were simpler structures comprising one key piece and an average of two large wood pieces per jam, compared to more complex structures in R2 (Whitewater) and the natural jams (N2) which comprised, on average, three and five key pieces and five and seven wood pieces respectively.

Large wood and hydromorphology

The influence of large wood on hydromorphology and hydraulic retention was explored on the River Blackwater. Mean streamwise flow velocity was higher and more variable in reaches with jams compared to the respective control sites for both restored large wood (R1a and R1b) and natural large wood (N2) (Figure 3a). The greatest flow variability was observed for the natural large wood reach (N2), followed by the more recently restored reach (R1b). Vertical velocities were more variable in restored reaches relative to controls, and stronger downwelling (negative values) were evident in large wood reaches (both natural and restored; Figure 3b). The hydraulic retention experiment revealed the highest levels of retention (i.e. greatest proportion of aqua-spheres retained and high variability in aqua-sphere travel times) in the natural large wood reach (N2), intermediate levels of retention in the restored large wood reach (R1a) and the lowest hydraulic retention in control reaches (CR1a and CN2; Figure 3a and b). No aqua-spheres were retained in the control reach CN2. Wood jams were the most effective habitat patch in the hydraulic retention of aqua-spheres, retaining 71% in N2 and 60% in R1a, with a lower contribution from marginal and emergent vegetation and other channel margin areas (Figure 3d).

Mesohabitat patches identified across all sites were fine sediment, gravel, submerged vegetation, emergent vegetation and large wood. On the Blackwater, the spatial organisation of mesohabitats was patchy in the restored large wood reach (R1c) and natural large wood (N1) reach compared to a linear structure associated with a higher proportion of emergent and submerged macrophytes at the control reach (CR1b; Figure 4a). Emergent and submerged vegetation patches were more frequent at the restored wood reach (R1c) compared to the natural wood reach (N1), where considerable deposits of fine sediment were a key characteristic. At Greywell on the Whitewater, riffle-pool sequences dominated channel morphology at control reach CR2 with smaller proportions of silt and macrophyte habitats, while the restored wood reach (R2) had a higher proportion of submerged macrophytes and a lower proportion of riffle, pool and silt mesohabitats (Figure 4b). The majority of jams were associated with very low proportions (<20% coverage) of silt, but two partial jams on a meander bend were associated with >60% silt coverage, increasing the overall mean. Overall, all but one jam created a higher mesohabitat spatial diversity index compared to the control reach (mean R2= 0.37; C2 = 0.2).

Large wood and macroinvertebrates

At the site level, there were no significant differences between invertebrate abundance and diversity between large wood reaches (restored or natural) and the respective control sites on the Blackwater and the Whitewater (Kruskal-Wallis $P>0.05$). Some statistically significant differences between mesohabitats were identified, however. Notably, for R1b (Blackwater) macroinvertebrate diversity on large wood was lower than in gravel and submerged vegetation and the difference between the habitats was statistically significant (Kruskal-Wallis $P<0.05$). Large wood diversity was not significantly different from fine sediment and emergent vegetation patches, however. At R2 (Whitewater), invertebrate abundance was higher for gravel and macrophyte habitats and differences in abundance were statistically significant for these habitats (Kruskal-Wallis $P< 0.05$). There were no statistically significant differences in diversity between mesohabitats. Some differences in community composition were also identified. On the Blackwater, Thaumaleidae, Leuctridae, Goeridae, Leptoceridae, Pediciidae, Ephemeridae and Glossiphoniidae were found exclusively in the restored large wood reach R1c, and Elmidae exclusively on the large wood surface in R1c (Figure 5a). Differences in community composition were observed at R2 on the Whitewater, with large wood and key associated habitats (silt and macrophytes) occupying distinct areas on the nMDS plot (Figure 5b).

1D Hydraulic modelling of large wood

Figure 6a presents the modelled stage using Manning's n and blockage ratio approaches compared with measured water levels for R1a at the measured discharge (Q_{Low}). The two models generated very similar stage profiles, with both models underpredicting stage in the upper section of the reach upstream of LW1 and LW2 but overpredicting stage downstream of this point including for LW3 and LW4 (Figure 6a). The blockage model showed an optimum overall fit of 0.190 between predicted and observed water levels; whilst the Manning's n approach showed SSE of 0.191.

Figure 6b presents the differences in predicted stage between the two models for cross sections across all four discharge scenarios. For Q_{Low}, Q_{RI1} and Q_{RI2}, values are similar between models, although with some spatial variability in the over/under-prediction of stage by the blockage ratio approach relative to the Manning's approach. This indicates some variation in the nature of differences between the two approaches according to the type of wood feature modelled. Greater variability between models was observed for Q_{RI5}, the highest discharge modelled, where the blockage ratio approach predicted higher stage values relative to the Manning's approach throughout most of the reach. Afflux increased gradually as blockage ratio increased between 50% and 80% but a pronounced increase in afflux occurred for the 95% blockage ratio (Figure 6c).

Discussion

Restored large wood jams surveyed in the River Loddon catchment were structurally simpler than naturally occurring examples, containing fewer key pieces and extending only part way across the channel width. This is consistent with the tendency to use more conservative large wood features in restoration design (Cashman *et al*., in press), but more complex jams (e.g. Nisbet *et al*., 2015) may be more effective in delivering channel and habitat recovery (Harvey *et al.*, 2018) and biodiversity goals (Thompson *et al.*, 2018). This is illustrated by our hydromorphological data which show increasing hydraulic diversity and retention from control, to restored wood to natural wood reaches. Large wood features, and the more complex natural jams in particular, were the most effective patch type for hydraulic retention, underlining their significance in relation to key functions such as trapping sediment and organic material (Bilby and Ward, 1998) and providing flow refugia for aquatic organisms (Thomson, 2014).

Similar mesohabitat patches were identified across all sites, and variations in their spatial organisation and diversity were linked with the presence of large wood jams. Interestingly, emergent and submerged macrophytes were more dominant within the restored wood reaches relative to the natural wood reach on the Blackwater and relative to the control on the Whitewater. This has been observed on other lowland rivers (Harvey *et al.*, 2018) and suggests a unique interaction between large wood and aquatic vegetation in modified lowland rivers with high nutrient inputs and reduced shading. As such, large wood features in restored systems may be considerably different in biophysical characteristics and functions to naturally occurring large wood in wooded reaches.

Significant differences in invertebrate abundance and diversity were not observed at site level between control and large wood reaches, which is not uncommon in restoration evaluations (Palmer *et al.*, 2010; Miller *et al.*, 2010; Feld *et al.*, 2011; Nisson *et al.*, 2014; Roni *et al.*, 2015; Verdonshot *et al.*, 2016). Some differences between mesohabitats were observed which become more pertinent when paired with the accompanying large wood-driven changes in mesohabitat proportions, but there are a number of possible explanations for the lack of consistent relationships between habitat heterogeneity and biodiversity in restored systems (Palmer *et al.*, 2010). For example, in this case we have shown that the restored large wood was structurally different to naturally occurring large wood which may contribute to the nature of the ecological response. More fundamentally, however, baseline 'pre-restoration' datasets are not available, as is often the case in restoration schemes, and the use of control sites represents a space-for-time substitution. The lack of clear trends, therefore, may not equate to a lack of ecological improvements, but this cannot be measured directly without comprehensive baseline data. Upstream influences on source communities (Lorenz and Feld, 2013) and nutrient enrichment (O'Neill and Hughes, 2014) may also limit the extent to which large wood can generate biodiversity gains in catchments with considerable anthropogenic influences. In contrast, large wood biodiversity benefits can sometimes be more pronounced in situations where surrounding habitats are hostile for invertebrates, for example in sand bed rivers (Benke and Wallace, 2003; Pilotto *et al.,* 2016), illustrating the complexity of relationships and importance of catchment context.

1D hydraulic modelling was used to assess differences in modelled water levels arising from two different methods for representing large wood features in hydraulic models. Data quality issues and the scope of the MSc research precluded further analysis of floodplain inundation through a linked 1D-2D approach, and hence we do not include assessment of inundation extent and flood storage here. The blockage ratio and Manning's n approaches to representing large wood features generated similar stage profiles and both had issues associated with under and over prediction of stage values in different parts of the reach. It is likely that this reflects a combination of factors including: data quality; cross section spacing and positioning, which is subjective (Hunter et al., 2007); and the accurate representation of roughness elements. As discussed previously, the interactions between large wood and aquatic vegetation in restored reaches can differ from naturally occurring wood and may also influence accurate representation of roughness in hydraulic models, indicating a need for further field research.

Manning's n values and blockage ratios were assigned to each wood feature individually based on field assessment of their characteristics. Spatial variability in the difference between the models, therefore, indicates that the characteristics of the wood feature influence the nature and magnitude of the difference between model outputs. This likely represents variation in the ease with which roughness and blockage ratio can be estimated in the field for different styles of wood accumulation and associated colonising vegetation. Given that the interactions between macrophytes and large wood are likely to characterise many lowland, low energy, unshaded and nutrient enriched sites where large wood restorations are undertaken (Harvey *et al.*, 2018), the accurate representation of restored wood features (including any colonising aquatic and riparian vegetation) needs further attention in field and modelling studies.

Differences between stage predictions from the two models were greatest at the highest modelled discharge where the blockage ratio approach generated higher stage values throughout most of the reach. This is significant, since uncertainty around the nature of large wood large wood influences on flood risk at high magnitude flows remains a key knowledge gap (Environment Agency, 2017). Experimentation with different blockage ratios indicated a threshold between 80% and 95% where a pronounced increase in afflux occurred. This is consistent with previous work showing that blockage ratios greater than 0.8 generate the greatest influences on flow conveyance (Gippel, 1995; Young, 1991). The pronounced increase in afflux noted for high blockage ratios suggests that development of more ambitious restoration designs (e.g. using active and complete jams rather than the partial jams identified at our restored sites) also requires further research to support the accurate quantification of blockage ratios for different types of wood feature.

The academic partnership approach taken here offers a rare opportunity to secure important longer-term (>3 years) post-project monitoring and data sets (Palmer *et al.,* 2010) and assess the outcomes of river restoration projects. Notwithstanding inevitable limits to data quality and analytical depth given the timeframe of an individual project (approximately six months from inception to completion), such partnerships nevertheless represent an important opportunity for generating considerable post-project monitoring data to evaluate and inform management and contribute to best practice restoration design. Our experiences identified some key challenges that may usefully be considered in future partnership approaches to project appraisal. First, repeat sampling over multiple years may be most useful from a monitoring perspective, but each research thesis must generate an original contribution to knowledge. Careful strategic planning of partnerships is therefore required to ensure that successive projects effectively combine repeat measurements with novel elements to simultaneously deliver useful river management information and achieve academic goals. Student independence and ownership of research is important and needs to be balanced against wider partnership goals to reconcile intellectual freedom with delivery of relevant and integrated data sets. A complicating factor is selection of control sites in space-for-time substitutions since different types of control may be perceived to be more or less appropriate depending on parameters studied. For instance, shading and water quality are critical factors in biodiversity assessments but less significant if focusing solely on the hydraulic effects of large wood. A strategic approach to longer-term planning of sequential projects is likely to be beneficial in reconciling these issues.

Conclusions and recommendations

This paper demonstrates the valuable role postgraduate research can play in the monitoring and assessment of river management and restoration activities. Effective partnerships can enable longer-term, detailed and wide-reaching evaluation of projects which may help to reduce uncertainty in outcomes and encourage cost-effective best practice. Engaging communities on an ongoing basis is critical to establishing large wood restoration as an accepted, evidence based sustainable practice contributing to targeted flood maintenance, property protection and legal objectives including WFD and the Government’s 25 Year Environment Plan goal of leaving the environment in a healthier state.

Key findings to inform future research and development:

(i) Hydromorphological effects of simple deflector-style large wood differ from both natural jams and more ambitious restored wood features. This has potential to influence ecological outcomes and further research is required to inform structural design of wood features.

(ii) As a result, leaving naturally occurring and secured large wood in place, where possible, is preferable to installing artificial structures from a hydromorphological and ecological perspective, and offers economic benefits.

(iii) Interactions between macrophytes and large wood in restored reaches are likely to influence the nature and magnitude of the hydromorphological, hydraulic and ecological effects of large wood and generate impacts that are distinct from naturally occurring jams in wooded reaches.

(iv) Accurate representation of large wood in hydraulic models is a key area for development, in particular, the parameterisation of wood features colonised with aquatic vegetation and the accurate quantification of more complex features with high blockage ratios.

This partnership enabled co-design and shared learning between practitioners and interested parties, with community engagement critical to each study. MSc students disseminated and discussed research at various meetings including Loddon Fisheries and Conservation Consultative, Catchment Partnership, National conferences and visits, and through posters and non-technical summaries. As a result, findings and management recommendations have reached a variety of audiences. This research provided a case study for the updated 2015 Thames River Basin Management Plan demonstrating improvements to the ecological potential of the River Blackwater, the Environment Agency's Quick Guide to Managing Wood in Rivers and the Blackwater and Loddon policy for maintenance and enhancing the environment.

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FIGURES

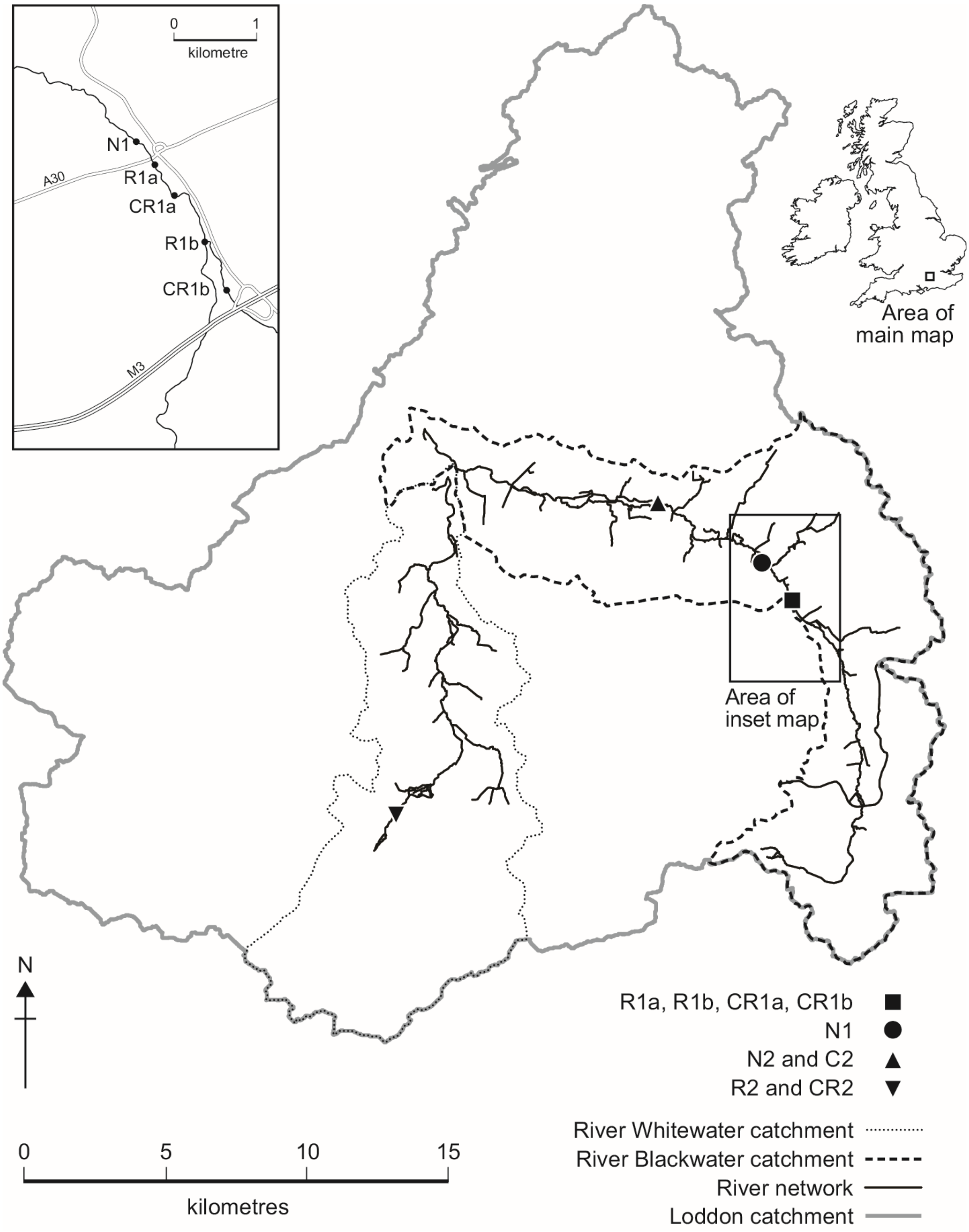

Figure 1: Location map for field sites within the Loddon catchment used in the academic partnership.

Increasing jam complexity, size and flow influence →

		Restored LW (R1a)	Restored LW (R1b)	Restored LW (R2)	Natural LW (N2)
Jam class	Partial	5	5	5	1
	Active	0	0	3	1
	Complete	0	0	0	1
	None	0	0	1	0
Anchorage	Rooted	0	0	1	3
	Braced	1	0	0	0
	Staked	4	5	6	0
No. key pieces		1	1	3	5
No. LW pieces		2	2	5	7
Length of largest piece		6.8	5.1	6.7	11.0
Diameter of large piece		0.1	0.2	0.2	0.3
LW length: Channel width		1.1	0.8	1.4	1.3
Decay	Intact (living)	2	2	3	0
	Some bark	2	2	5	3
	No bark	1	1	0	0

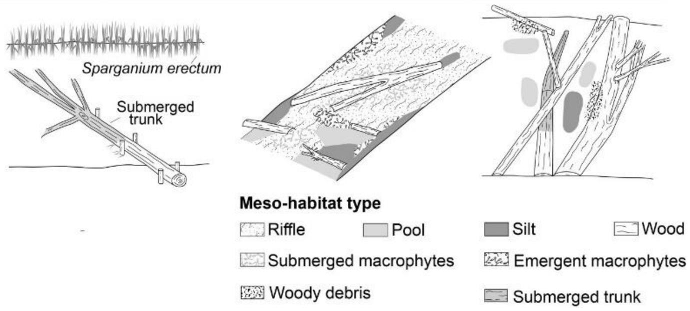

Figure 2: Structural characteristics of the large wood jams (“LW”) at restored and natural wood reaches. Number and dimensions of wood pieces represent mean values for each reach. Sketches illustrate representative large wood features for each reach.

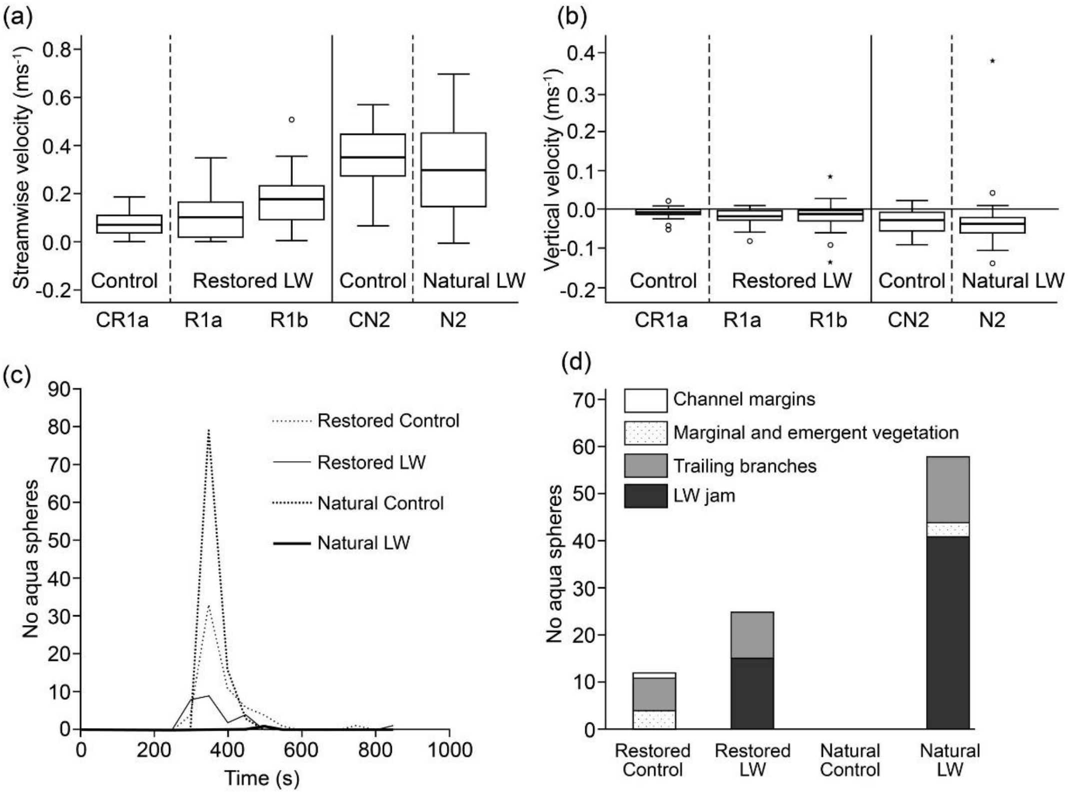

Figure 3: Hydromorphological data for paired adjacent natural large wood ("LW")/control and restored large wood/control reaches on the Blackwater: (a) streamwise velocity median and variability range for paired; (b) vertical velocity median and variability; (c) frequency distributions of aqua sphere transfer times; and (d) number of aqua spheres retained in different patch types within each reach.

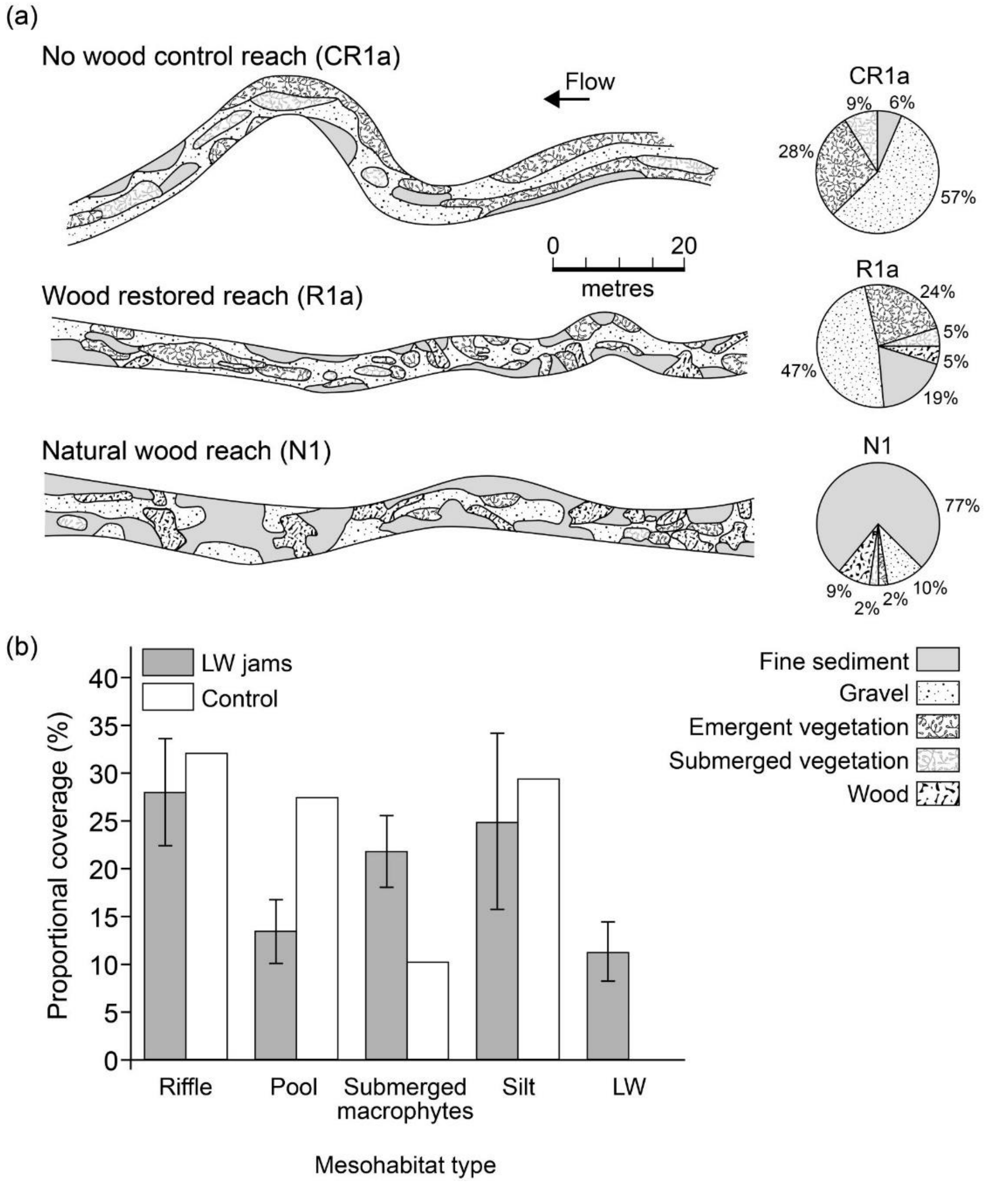

Figure 4: (a) Mesohabitat maps for control, restored large wood and natural large wood reaches on the Blackwater. Adjacent pie charts show proportional coverage of mesohabitats for each reach respectively; (b) proportional coverage of mesohabitats for wood (“LW”) units on the Whitewater (mean and standard error derived from eight jams), compared with the control reach.

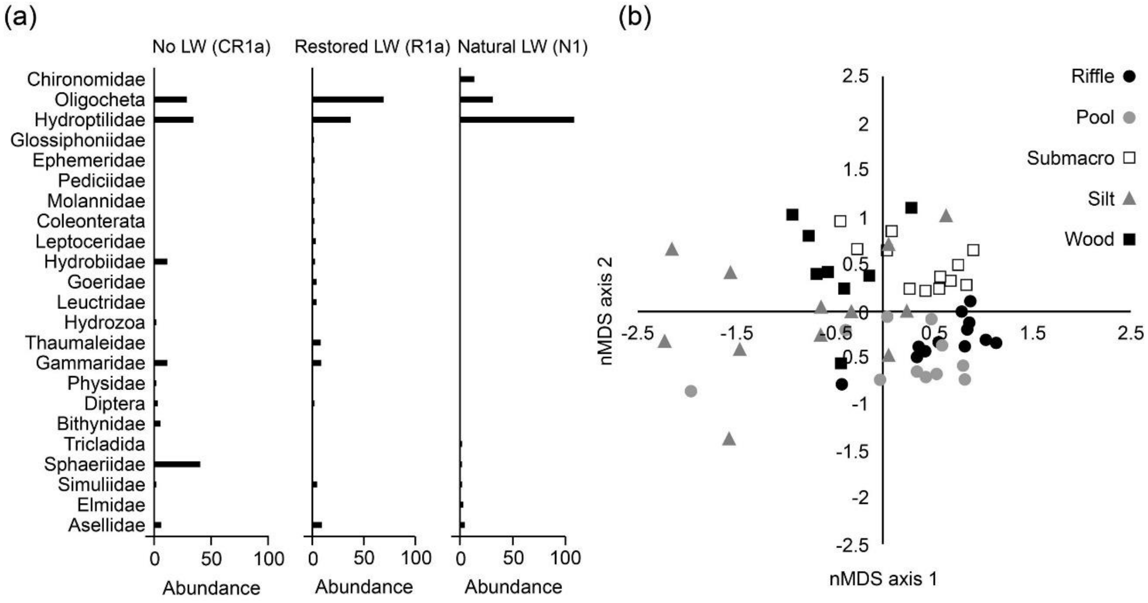

Figure 5: (a) Invertebrate abundance for control, restored large wood (“LW”) and Natural large wood reaches on the Blackwater and (b) nMDS plot showing differences in macroinvertebrate community composition for mesohabitats on the Whitewater.

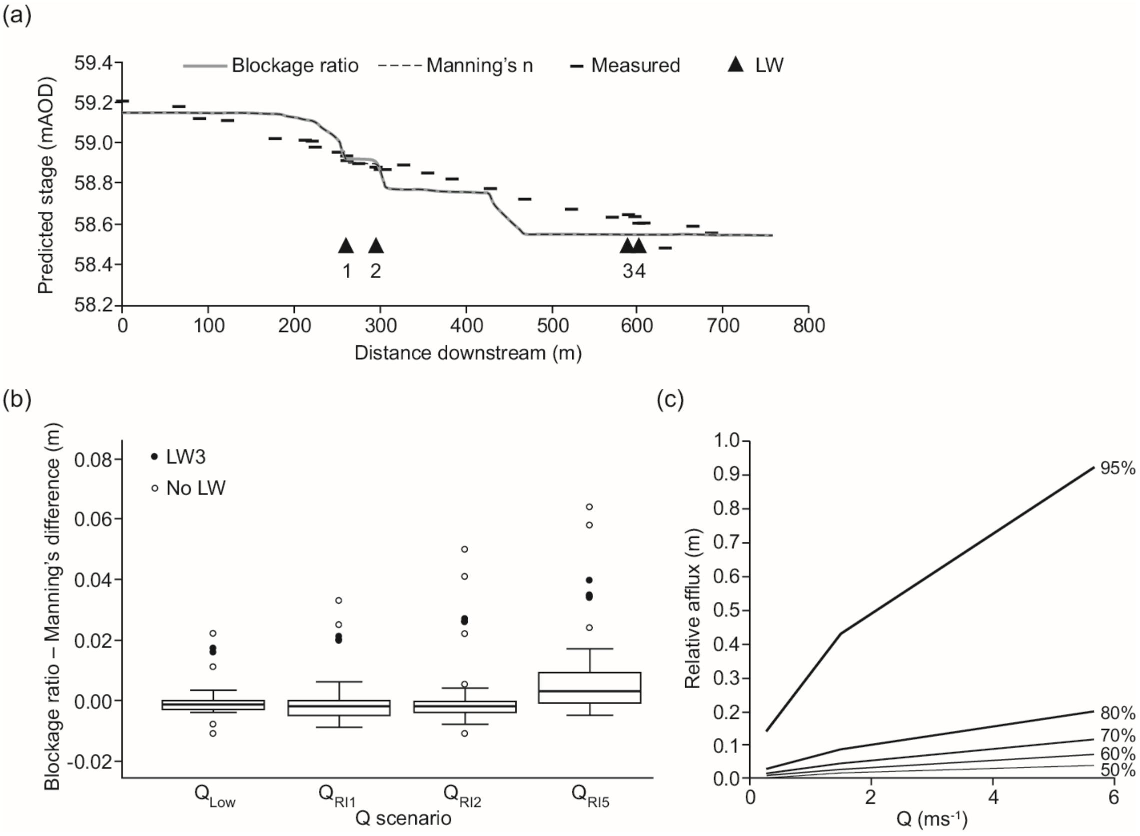

Figure 6: (a) Measured and modelled water surface elevations for Q_{Low} using Blockage ratio and Manning's approaches for the modelled subsection of reach R1a on the Blackwater; (b) differences in model predictions between the two approaches across the different discharge scenarios; and (c) relative afflux for different blockage ratios across the different flow scenarios (% values show the blockage ratios).

REFERENCES

Abbe, T. B. and Montgomery, D. R. (1996) Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research & Management*, 12(2-3), pp201-221.

Anderson B.G., Rutherfurd I.D. and Western A.W. (2006) An analysis of the influence of riparian vegetation on the propagation of flood waves. *Environmental Modelling and Software,* 21, pp1290-1296.

Benke, A. C., Henry III, R. L., Gillespie, D. M., and Hunter, R. J. (1985). Importance of snag habitat for animal production in southeastern streams. *Fisheries,* 10(5), pp8-13.

Benke, C. and Wallace, J. B. (2003) Influence of wood on invertebrate communities in streams and rivers. In: Gregory, S. V., Boyer, K. L. and Gurnell, A. M. (eds). *The ecology and management of wood in world rivers.* American Fisheries Society: Bethesda: pp149-177.

Bernhardt, E. S., Palmer, M. A., Allan, J. D., Alexander, G., Barnas, K., Brooks, S., Carr,J., Clayton, S., Dahm,C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Katz, S., Kondolf, G.M., Lake, P.S., Lave, R., Meyer, J.L., O'Donnell, T. K., Pagano,L., B. Powell, B. and Sudduth, E. (2005). Synthesizing US river restoration efforts. *Science* 308(5722), pp636-637.

Bilby, R.E and Ward, J.W. (1989). Changes in characteristics and function of woody debris with increasing size of streams in Western Washington. *Transactions of the American Fisheries Society*, 118, pp. 368-378.

Blackwater Valley Countryside. (2013) River Blackwater [online], available: http://www.blackwater-valley.org.uk/river_about.html, [accessed:15.07.13].

Cashman M.J., Pilotto F., Harvey G.L., Wharton, G. and Pusch, M.T. (2016). Combined stable-isotope and fatty-acid analyses demonstrate that large wood increases the autochthonous trophic base of a macroinvertebrate assemblage. *Freshwater Biology,* vol. 61, (4), pp549-564.

Cashman et al., in press, 2018 (this issue)

Chow V.T. (1959) *Open channel flow,* McGraw-Hill Book Company: Singapore.

Clarke, K. R., and Warwick, R. M. (2001). A further biodiversity index applicable to species lists: variation in taxonomic distinctness. *Marine ecology Progress series*, 216, 265-278.

Conveyance and Afflux Estimation System (2018) CES/AES [website]. Available at: http://www.river-conveyance.net/index.html. Accessed 07/08/2017.

Cuffney, T.F., Gurtz, M.E. and Meador, M.R. (1993) Methods for collecting benthic invertebrate samples as part of the National Water-Quality Assessment Program. U.S. Geological Survey Open-File Report 93-406. U.S.G.S., Raleigh, North Carolina. 65pp.

Daniels, M. D. (2006) Distribution and dynamics of large woody debris and organic matter in a low-energy meandering stream. *Geomorphology*, 77, pp286–298.

Diehl, T. H. (1997). Potential drift accumulation at bridges. US Department of Transportation, Federal Highway Administration, Research and Development, Turner-Fairbank Highway Research Center.

Dixon, S. J., Sear, D. A., Odoni, N. A., Sykes, T., and Lane, S. N. (2016). The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surface Processes and Landforms*, 41(7), pp997-1008.

Downs, P. W., and Kondolf, G. M. (2002). Post-project appraisals in adaptive management of river channel restoration. *Environmental Management*, 29(4), pp477-496.

Environment Agency. (2017). Working with natural processes to reduce flood risk. Available:https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk. Last accessed 1st August 2018.

Erskine, W. D., and Webb, A. A. (2003). Desnagging to resnagging: new directions in river rehabilitation in southeastern Australia. *River Research and Applications*, 19(3), pp233-249.

Feld, C. K., Birk, S., Bradley, D. C., Hering, D., Kail, J., Marzin, A., Melcher, A., Nemitz, D., Pedersen, M.L., Pletterbauer, F., Pont, D., Verdonschot, P.F.M. and Friberg, N. (2011). From natural to degraded rivers and back again: a test of restoration ecology theory and practice. *Advances in ecological research*, 44, pp119-209.

Flores, L., Larranaga, A., Diez, J. and Elosegi, A. (2011) Experimental wood addition in streams: effects on organic matter storage and breakdown. *Freshwater Biology*, 56(10), pp2156-2167.

Fortin, M. J., Payette, S., and Marineau, K. (1999). Spatial vegetation diversity index along a postfire successional gradient in the northern boreal forest. *Ecoscience*, 6(2), pp204-213.

Freshwater Biological Association (2013) 'Freshwater benthis macroinvertebrate standard sampling procedure', [online], available: http://www.fba.org.uk/practical-guidance-sampling-and-collecting [accessed 02.08.13].

Gippel, C.J., (1995) Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering*, 121, pp388–395.

Gippel, C.J., O'neill, I.C., Finlayson, B.L. and Schnatz, I., (1996) Hydraulic guidelines for the re-introduction and management of large woody debris in lowland rivers. *Regulated rivers: research & management*, 12, pp223-236.

Gregory, K.J., Gurnell, A.M (1998) Vegetation and river channel form and process. In Viles, H. (Ed.), *Biogeomorphology*. Blackwell: Oxford, pp. 11-42.

Gregory, K.J., Gurnell, A.M., Petts, G.E. (1995) The role of dead wood in aquatic ecosystems in forests. In: Brown, I.R. (Ed.), Forests and Water. Institute of Chartered Foresters, Edinburgh, pp158-192.

Gurnell, A. M., Petts, G. E., Hannah, D. M., Smith, B. P., Edwards, P. J., Kollmann, J., Ward, J.V. and Tockner, K. (2001). Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, 26(1), pp31-62.

Gurnell, A. M., Piegay, H., Swanson, F. J. and Gregory, S. V. (2002) Large wood and fluvial processes. *Freshwater Biology,* 47(4), pp601-619.

Gurnell, A. (2014). Plants as river system engineers. Earth Surface Processes and Landforms, 39(1), pp4-25.

Harvey G.L., Henshaw A.J., Parker, C. et al. (2018). Re-introduction of structurally complex wood jams promotes channel and habitat recovery from overwidening: Implications for river conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 28(2), pp395-407.

H.R.Wallingford (2014) *Conveyance Estimation System* (v2.0.0.3) [Software] available at: http://www.river-conveyance.net/index.html [accessed 01.04.14].

Jacobs (2018) Flood Modeller [website]. Available at: https://www.floodmodeller.com. Accessed 07/08/2018.

Kail, J., Hering, D., Muhar, S., Gerhard, M. and Preis, S. (2007) The use of large wood in stream restoration: Experiences from 50 projects in Germany and Austria. *Journal of Applied Ecology*, 44(6), pp1145-1155.

Keller, E.A., Swanson, F.J. (1979) Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes*, 4, pp362–380.

Kondolf, G. M. (1998). Lessons learned from river restoration projects in California. *Aquatic Conservation: marine and freshwater ecosystems*, 8(1), pp39-52.

Kondolf, G. M., Smeltzer, M. W., and Railsback, S. F. (2001). Design and performance of a channel reconstruction project in a coastal California gravel-bed stream. *Environmental Management*, 28(6), pp761-776.

Krause, S., M. J. Klaar M J., D. M. Hannah D.M., J. Mant J., J. Bridgeman J., M. Trimmer M., and S. Manning-Jones S (2014). The potential of large woody debris to alter biogeochemical processes and ecosystem services in lowland rivers. WIREs Water, (1), pp263–275.

Lane, S. N. (2017). Natural flood management. *Wiley Interdisciplinary Reviews: Water*, 4(3), pp1211.

Lassettre, N. S., and Kondolf, G. M. (2012). Large woody debris in urban stream channels: redefining the problem. *River research and applications*, 28(9), pp1477-1487.

Linstead, C., and Gurnell, A.M. (1999) Large woody debris in British headwater rivers. Physical habitats and management guidelines. *Bristol: Environment Agency.*

Lorenz, A.M. and Feld, C.K. (2013) Upstream river morphology and riparian land use overrule local restoration effects on ecological status assessment. *Hydrobiologia*, 704(1), pp489-501.

Miller, S. W., Budy, P., and Schmidt, J. C. (2010). Quantifying macroinvertebrate responses to in-stream habitat restoration: applications of meta-analysis to river restoration. *Restoration Ecology*, 18(1), pp8-19.

Milner, V.S. and Gilvear, D.J. (2012). Characterization of Hydraulic Habitat and Retention Characteristics Across Different Channel Types; Introducing a New Field-based Technique. *Hydrobiologia*, 694 (1), pp219-233.

Montgomery, D.R., Collins, B.D., Buffington, J.M. and Abbe, T.B. (2003) Geomorphic effects of wood in rivers. *American Fisheries Society Symposium,* 37, pp21-47.

Morandi, B., Piégay, H., Lamouroux, N., and Vaudor, L. (2014). How is success or failure in river restoration projects evaluated? Feedback from French restoration projects. *Journal of Environmental Management*, 137, pp178-188.

Nisbet, T.R. (2015) Project RMP5455: Slowing the Flow at Pickering Final Report Phase II. Defra FCERM Multi-objective Flood Management Demonstration project.

Odoni, N. A., and Lane, S. N. (2010). Assessment of the impact of upstream land management measures on flood flows in Pickering Beck using overflow. Project RMP55455: Slowing the flow at Pickering.

O'Neill, R. and Hughes, K. (2014) *The State of England's Chalk Streams*. World Wildlife Fund.

Palmer, M. A., Bernhardt, E. S., Allan, J. D., Lake, P. S., Alexander, G., Brooks, S., ... and Galat, D. L. (2005). Standards for ecologically successful river restoration. J*ournal of applied ecology*, 42(2), pp208-217.

Palmer, M. A., Menninger, H. L. and Bernhardt, E. (2010) River restoration, habitat heterogeneity and biodiversity: a failure of theory or practice?. *Freshwater Biology,* 55, pp205-222.

Parker, C., Henshaw, A.J., Harvey, G.L. and Sayer, C.D. (2017) Reintroduced large wood modifies fine sediment transport and storage in a lowland river channel. *Earth Surface Processes and Landforms*, 42, pp1693-1703.

Pilotto, F., Bertoncin, A., Harvey, G. L., Wharton, G., and Pusch, M. T. (2014). Diversification of stream invertebrate communities by large wood. *Freshwater biology,* 59(12), pp2571-2583.

Pilotto, F., Harvey, G.L., Wharton, G. and Pusch, M.T. (2016). Simple large wood structures promote hydromorphological heterogeneity and benthic macroinvertebrate diversity in low-gradient rivers. *Aquatic Sciences*¸ 78(4), pp755-766.

Roni, P., Johnson, C., De Boer, T., Pess, G., Dittman, A., and Sear, D. (2015). Interannual variability in the effects of physical habitat and parentage on Chinook salmon egg-to-fry survival. *Canadian journal of fisheries and aquatic sciences*, 73(7), pp1047-1059.

Schneider, K.N. and Winemiller, K.O. (2008) Structural complexity of woody debris patches influences fish and macroinvertebrate species richness in a temperate floodplain-river system. *Hydrobiologia*, 610(1), pp235-244.

Shaw E.M., Beven K.J., Chappell N.A. and Lamb R. (2011) *Hydrology in Practice,* 4th Edition, Spon Press: London.

Stauffer-Olsen, N. (2016). Aquatic Macroinvertebrate Sampling for Restoration Projects. Available: https://meadows.ucdavis.edu/resources/19776. Last accessed 18th May 2017.

Sterling M. (2010) *Large woody debris and its impact on flood risk on the River Loddon, England,* MSc Thesis: Cranfield University.

Sundermann, A., Antons, C., Cron, N., Lorenz, A. W., Hering, D., and Haase, P. (2011). Hydromorphological restoration of running waters: effects on benthic invertebrate assemblages. *Freshwater biology,* 56(8), pp1689-1702.

Surber, E.W. (1937) Rainbow trout and bottom fauna production in one mile of stream. *Transactions of the American Fisheries Society*, 66, pp193-202.

Thevenet, A., Citterio, A., and Piégay, H. (1998). A new methodology for the assessment of large woody debris accumulations on highly modified rivers (example of two French piedmont rivers). *Regulated Rivers: Research and Management: An International Journal Devoted to River Research and Management*, 14(6), pp467-483.

Thomas, H. and Nisbet, T., 2012. Modelling the hydraulic impact of reintroducing large woody debris into watercourses. *Journal of Flood Risk Management*, 5(2), pp. 164-174.

Thompson, M. S. A. (2014). The effect of large woody debris restoration on stream ecosystems (unpublished PhD Thesis). Department of Geography, University of London and Department of Life Sciences, Natural History Museum.

Thompson, R. M., King, A. J., Kingsford, R. M., Mac Nally, R., and Poff, N. L. (2017). Legacies, lags and long-term trends: Effective flow restoration in a changed and changing world. *Freshwater Biology.*

Thompson, M. S., Brooks, S. J., Sayer, C. D., Woodward, G., Axmacher, J. C., Perkins, D. M., and Gray, C. (2018). Large woody debris “rewilding” rapidly restores biodiversity in riverine food webs. *Journal of Applied Ecology*, 55(2), pp895-904.

Tickner, D., Armitage, P.D., Bickerton, M.A. and Hall, K.A. (2000) Assessing stream quality using information on mesohabitat distribution and character. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 10, pp179-196.

Verdonschot, R. C., Kail, J., McKie, B. G., and Verdonschot, P. F. (2016). The role of benthic microhabitats in determining the effects of hydromorphological river restoration on macroinvertebrates. *Hydrobiologia,* 769(1), pp55-66.

Young, W. J., (1991) Flume study of the hydraulic effects of large woody debris in lowland rivers. *Regulated rivers: research and management,* 6(3), pp203-211.

Wohl, E. (2014). A legacy of absence: wood removal in US rivers. *Progress in Physical Geography*, 38(5), pp637-663.