View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Queen Mary Research Online

**This is the peer reviewed version of the following article: Robert C. Grabowski, Angela M. Gurnell, Lydia Burgess-Gamble, Judy England, David Holland, Megan J. Klaar, Ian Morrissey, Chris Uttley, and Geraldene Wharton (2019). The current state of the use of large wood in river restoration and management which was accepted for publication on 11.1.19. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Self-Archiving.**

# The current state of the use of large wood in river restoration and management

Robert C. Grabowski[1]*, Angela M. Gurnell[2], Lydia Burgess-Gamble[3], Judy England[4], David Holland[5] MCIWEM, C.WEM, Megan J. Klaar[6], Ian Morrissey[7], Chris Uttley[8], and Geraldene Wharton[2]

[1] Cranfield Water Science Institute, School of Water, Energy and Environment, Cranfield University, UK
[2] School of Geography, Queen Mary University of London, UK
[3] Environment Agency, Flood Risk Research Team, Worthing, UK
[4] Environment Agency, Wallingford, UK
[5] Salix River & Wetland Services Ltd, Swansea, UK
[6] School of Geography, water@leeds, University of Leeds, UK
[7] Atkins, SNC-Lavalin Group, Derby, UK
[8] Stroud District Council, Stroud, UK

## Abstract

Trees fall naturally into rivers generating flow heterogeneity, inducing geomorphological features, and creating habitats for biota. Wood is increasingly used in restoration projects and the potential of wood acting as leaky barriers to deliver natural flood management by "slowing the flow" is recognised. However, wood in rivers can pose a risk to infrastructure and locally increase flood hazards. The aim of this paper is to provide an up-to-date summary of the benefits and risks associated with using wood to promote geomorphological processes to restore and manage rivers. This summary was developed through a workshop that brought together academics, river managers, restoration practitioners and consultants in the UK to share science and best-practice on wood in rivers. A consensus was developed on four key issues: (i) hydro-geomorphological effects, (ii) current use in restoration and management, (iii) uncertainties and risks, and (iv) tools and guidance required to inform process-based restoration and management.

Key words: fluvial geomorphology, natural flood risk management, hydromorphology, catchment management, river basin management, flood risk

*Corresponding author

# Introduction

Over the last 20 years, the importance of vegetation in influencing fluvial geomorphological processes and forms has been increasingly recognised in the academic literature, particularly the fundamental roles of woody riparian vegetation, large wood, and aquatic macrophytes in buffering hydrodynamics forces, trapping and stabilising sediment (for reviews, see Gurnell, 2014; Picco *et al*., 2017). Simultaneously, river managers and restoration practitioners are seeking nature-based approaches that 'work with natural processes' to deliver management and conservation outcomes. Thus, insights from academic research are being incorporated into management strategies and goals, but increased practical guidance is needed to aid implementation. This is particularly true when using large wood in river restoration and management, when goals of working with natural processes can conflict with society's perceptions of risk and uncertainty (Chin *et al.*, 2008).

Academic researchers, managers, practitioners and the wider community are collaborating to diagnose problems and propose solutions to river restoration and management (Wohl, Lane and Wilcox, 2015). River restoration is a multi-million pound industry in the UK (including £6m from the Catchment Restoration Fund for England in 2014/15 and the current Water Environment Grant (WEG) offering £27m over 3 years across the UK) with *ca.* $2 billion spent annually on restoration worldwide (Roni and Beechie, 2012). River restoration practitioners were early adopters of large wood, developing a range of wood features (i.e. structures, measures) to improve modified and degraded rivers with rapid up-take supported by best-practice guidance (e.g. River Restoration Centre, 2018). However, the emphasis was on wood as a design or engineering feature rather than on understanding and using wood in reinstating natural geomorphological processes to develop sustainable landforms. Similarly, large wood is increasingly used in flood risk management. Wood features are placed in rivers and hillside gullies to store and slow the flow of surface water runoff or to encourage water to be stored on floodplains. If used correctly these features have beneficial geomorphological and ecological effects, which can be harnessed to deliver multiple benefits. However, there are barriers that prevent large wood from being used more frequently and in a manner that works more effectively with natural processes to deliver integrated, sustainable management solutions.

This paper aims to provide an up-to-date assessment of the benefits, risks, and challenges of incorporating large wood into river restoration and management. Here, *large wood* is defined as any woody material that exceeds 1 m in length and 10 cm in diameter that is placed or falls naturally into a river channel. The focus is on the geomorphological impact of wood within river corridors, which encompasses the river channel and floodplain, along the entire channel network. To reach this aim, the authors solicited the opinions of a panel of UK experts representing different environmental management sectors through a one-day workshop. In this paper we present the findings of the workshop and support expert opinions with evidence from the scientific literature.

# Methodology

For this study, we assembled a panel of 30 experts to debate and agree an up-to-date summary of benefits, risks and challenges of the use of large wood for river restoration and rivers. Participants of the workshop (the authors and those listed in the acknowledgments) represented a diversity of organisations across a range of sectors related to river restoration and management. Their expertise included fluvial geomorphology, aquatic ecology, conservation, restoration implementation, community health and wellbeing, river basin management, flood risk and natural flood management. Participants were asked to view their specialisation within the prism of fluvial geomorphological processes, and reflect on how wood alters hydraulic conditions, creates geomorphological features, and modifies the aquatic and terrestrial components of the river corridor to generate outcomes aligned with their sector's goals.

The workshop centred around a series of activities designed to encourage the sharing of knowledge and best-practice on the following topics:

1) Current understanding of the hydro-geomorphological and ecological processes initiated by large wood (Hydro-geomorphological effects of wood)
2) How wood and the hydro-geomorphological processes it promotes are currently being harnessed in river restoration and management (Current use of wood in restoration and management)
3) Uncertainties in our understanding of the interactions between wood and river hydro-geomorphological processes and the resulting risk (Uncertainties and risks)
4) The tools and guidance needed to inform the use of wood in river restoration and management (Tools and guidance)

Experiences, observations and expert opinions of the participants were shared and debated in small groups for each topic and a consensus reached in a final workshop activity and in follow-up communications. These findings are reported below with, where appropriate, support from the scientific literature.

# Analysis

## Hydro-geomorphological effects of wood

Considerable research has been conducted on wood in rivers (for recent reviews see Gurnell, 2013; Ruiz-Villanueva *et al*., 2016a; Wohl, 2017). Wood is a natural component of most river systems, which is delivered to channels via a variety of mechanisms (e.g. windfall, bank erosion, landslides, beavers). Once in the river channel, it becomes a fundamental agent of geomorphic change, along with river discharge, channel slope, sediment size, and sediment loads. Wood has profound impacts on many aspects of the river system that are directly related to issues of management concern: river channel and floodplain hydrology, hydraulics and geomorphology, and the ecology of the river corridor.

Even in undisturbed wooded river corridors, wood occurs in highly variable quantities and accumulates in different locations depending upon the position in the river network (notably reflecting proximity of the river to hillslopes, channel size and gradient), and the geomorphological style of river channel and floodplain (Abbe and Montgomery, 2003; Gurnell *et al*., this volume). The following summary of hydro-geomorphological and ecological effects of wood in rivers is not exhaustive. It includes the hydrological, hydraulic, geomorphological and ecological effects that the expert panel agreed were most relevant to river restoration and management and which could be harnessed to reach their management goals.

### *Hydrology and Hydraulics*

Hydrological effects relate to the way that wood interacts with flowing water. Although wood is delivered to rivers near-continuously by a wide variety of processes, it is rearranged locally and transported downstream and between river and floodplain mainly during high flow events, which may be characteristic of particular seasons or particular extreme climatological and catchment hydrological conditions (Senter *et al.*, 2017). How far wood moves during these events, and where it is retained, varies enormously depending upon flow, catchment, floodplain, river channel and riparian woodland characteristics as well as the quantity of wood in transport (Braudrick and Grant, 2001; Ruiz-Villanueva, Zawiejska and Hajdukiewicz, 2016; Kramer and Wohl, 2017), but much of it is retained in accumulations (3 or more pieces of wood) on the floodplain and in the river channel (e.g. Morris, Goebel and Palik, 2007). Large accumulations of wood in rivers can attenuate flows of water and transported materials, increase channel-floodplain hydrological connectivity and sustain ponded water and flows in the river channel during dry periods (Dixon *et al.*, 2016; Puttock *et al.*, 2017). While these effects are most obvious around large channel-spanning wood jams, smaller wood accumulations and large individual pieces located in river channels have similar but smaller effects, and floodplain wood can also slow and divert movement of water across the floodplain surface, particularly where it is washed into large accumulations or jams around standing trees. Furthermore, floodplain wood can sustain areas of relatively higher soil moisture on floodplains by reducing evaporation from the ground surface.

Hydrological interactions with wood are accompanied by hydraulic effects. Wood obstructions can divert and concentrate water flows, creating local areas of high velocity and shear stress separated by wood-sheltered areas where velocities and shear stresses are drastically reduced (Gurnell, 2013). Since most large wood is less dense than water, flows can also occur under wood accumulations once the water depth is sufficient for wood flotation, which can cause localised high shear stress and scour.

### *Geomorphology*

Interactions between flows, sediment, dead and living wood, other smaller pieces of organic material, floodplain and channel sedimentary surfaces and standing vegetation generate a range of geomorphological impacts. Wood accumulations retain sediment (e.g. Ryan, Bishop and Daniels, 2014), including fine sediment (Parker *et al.*, 2017) and both dead and living organic material (Jochner *et al.*, 2015). Wood accumulations or large individual wood pieces can induce local bed, bank or floodplain stabilisation or scour and the mobilisation, sorting and deposition of sediment and organic matter. Within river channels, these processes can lead to the development of ‘forced’ pools, bars, benches and bank erosion (e.g. Gurnell and Sweet, 1998). In addition, the presence of in-channel wood accumulations increases water-surface elevations relative to adjacent river banks, increasing hydrological connectivity with the floodplain and, where large long-lived wood jams are present, the potential for the channel to avulse (i.e. change course) or for secondary channels to develop (Brummer *et al.*, 2006) resulting in complex channel patterns and floodplain evolution processes (Jeffries, Darby and Sear, 2003)

### *Ecology*

Wood influences the functioning of aquatic ecosystems, provides a habitat and food source for biota, particularly invertebrates (e.g. Braccia and Batzer, 2008) and biofilms (Eggert and Wallace, 2007), and provides in-river cover for fish and basking and perching locations for reptiles and birds. The hydrological, hydraulic and geomorphological impacts of wood lead to a complex and often dynamic mosaic of in-channel and floodplain habitats, including spawning, feeding and refuge habitats that support many different organisms and life cycle stages (Gurnell *et al.*, 2005; Keeton, Kraft and Warren, 2007).

Complex feedbacks exist between wood, living trees and other riparian and aquatic plants. Seeds and living wood pieces transported by flowing water are retained in and around wood accumulations, creating local regeneration niches for riparian vegetation (Steiger, Gurnell and Petts, 2001; Pettit and Naiman, 2006; Osei, Gurnell and Harvey, 2015) and biogeochemical hotspots for microbial activity (Krause *et al.*, 2014). Dead and living wood incorporated into the floodplain (e.g. Arseneault, Boucher and Bouchon, 2007) can form ‘hard points’ that are resistant to erosion supporting the longer-term development of riparian vegetation, particularly large trees that provide a future wood supply to the river system (Collins *et al.*, 2012). Finally, sustained floodplain inundation induced by large wood accumulations can lead to tree mortality and subsequent enhanced wood delivery to the river (Brummer *et al.*, 2006).

## Current use of wood in restoration and management

Large wood is used in various forms and for a variety of purposes in river restoration and management. The group of experts highlighted three main current and growing uses: habitat creation, river engineering, and downstream flood hazard reduction.

### *Habitat creation*

Many early restoration projects focused on the creation of flow heterogeneity in modified channels to support fish communities (Wohl, Lane and Wilcox, 2015), and wood has long been used as a design feature for this aim (Roni *et al.*, 2015). Large wood is placed, and often secured, in rivers to alter local hydraulic conditions (Figure 1). It diverts water flows, increases local water levels, and introduces turbulence, creating a mosaic of fast and slowing flowing areas. This hydraulic effect is essentially immediate, but varies with river discharge and level (Matheson *et al.*, 2017), providing essential shelter and refugia during high flow events for fish.

However, wood interacts directly and indirectly (i.e. through alterations of local hydraulic conditions) with the sediment that is being transported down the river, altering the characteristics of suspended and deposited sediments and channel form. The precise geomorphological impacts of introduced large wood in a river is difficult to predict, but are widely reported (Davidson and Eaton, 2013; Roni *et al.*, 2015; Addy and Wilkinson, 2016; Harvey *et al.*, 2017). The combined effect of spatial variations in hydraulic conditions, sediment grain size, and the deposition of organic material can foster a higher diversity of macroinvertebrates (Pilotto *et al.*, 2014) and impact the entire food web (Thompson *et al.*, 2018). However, wood is not universally beneficial to all species so it is important to consider the habitat requirements of the fish community at all life history stages (Langford, Langford and Hawkins, 2012).

The workshop panel noted that although many restoration projects continue to use wood as an immediate design feature, often within modified channels (Smith, Clifford and Mant, 2014), wood is increasingly being used to kick-start geomorphological processes to let the river “do the work”, e.g. River Bure, UK (Harvey *et al.*, 2017). In the River Wensum (Norfolk, UK), large wood has been positioned across the channel above the average water level so that it interacts with the flow at high discharges. This type of placement minimises potential negative impacts on this low-energy, gravel-bed chalk stream at normal and low flows (e.g. backwater effect, siltation), but promotes geomorphological activity at high flows (Figure 1b). More projects are considering the wider river corridor and the potential for wood to increase local water levels and improve lateral hydrological connectivity and reconnecting and creating floodplains to support wetland conservation. Large wood is also being used to improve water quality by trapping and storing of fine sediment, itself a diffuse pollutant, and sediment-bound contaminants (Janes *et al.*, 2017).

Large wood is also seen by the panel as an approach to increase the resilience of river ecosystems to climate change. The hydraulic, hydrological, and geomorphological changes triggered by wood creates physical (and flow) refugia during seasonal low flow periods or supra-annual droughts (Gurnell, 2013). Increased lateral connectivity of the river and floodplain, and creation of floodplain geomorphological features during overbank flows provide increased resilience for riparian vegetation to high (e.g. flow attenuation) and low flows (e.g. increase soil moisture). Deep pools and shading from wood and riparian trees also reduce water temperature locally (Nichols and Ketcheson, 2013).This temperature moderation effect may also be affected by local downwelling induced by wood, which forces surface water down into the sediment where it interacts with groundwater (i.e. hyporheic exchange flow) (Sawyer and Cardenas, 2012). Finally, wood is important for carbon storage, both as a component of the carbon cycle and its through its hydro-geomorphological influences on process and fluxes of organic material (Wohl *et al.*, 2017).

### *River engineering*

Wood and woody material is used frequently for river engineering to reduce lateral channel migration, influence the deposition or erosion of bed sediment, or to protect infrastructure. It is viewed as a more environmentally-friendly alternative to harder forms of engineering (Wohl, Lane and Wilcox, 2015). Indeed, the concept of ‘engineered wood jams’ has been promoted for at least the last 15 years as a measure for river rehabilitation (Abbe *et al.*, 2003). There is considerable overlap in how wood is used in practice; adding large wood features may have more than one function (e.g. habitat creation and narrowing of flows to flush fines), and this section focuses on the use of wood for hydrological and geomorphological effects.

In low energy rivers, wood and woody material is often used to increase velocities, mobilise bed sediment, create variations in the longitudinal profile (e.g. pools), and flush fine sediment deposited on and in the bed. Engineered or constructed wood features can be woven wicker panels (i.e. willow spiling) and brushwood mattresses to protect banks and other features (e.g. earthen berms) or flow deflectors (i.e. groynes) to narrow the channel or scour pools (Figure 1c) (Pagliara and Kurdistani, 2017). Wood is also used to locally raise bed levels in significantly over-deepened sections to reduce the amount of imported substrate required to create glides/riffles.

In higher energy rivers, the wood used is larger, placement must be more carefully designed, often based on hydraulic modelling, and securing requires significant consideration and investment. Whole tree trunks and root wads are commonly used to add hydraulic roughness to deflect flows, similar in function to groynes (Jamieson, Rennie and Townsend, 2013), and increase turbulence and energy dissipation to protect banks and reduce streamwise flow velocities upstream of infrastructure, such as bridge sills (Blanckaert *et al.*, 2012). Engineered log jams or wood features in these higher energy situations are often secured by large posts, inserted vertically into the river bed, but they are designed to work with geomorphological processes to store sediment, control bed levels, and modify channel gradients (Addy and Wilkinson, 2016)

### *Downstream flood hazard reduction*

The panel noted that that the most significant change in the use of large wood for river management has been the shift towards natural flood management to reduce downstream flood hazard. Natural flood management aims to reduce the frequency and magnitude of flooding by modifying the land surface, floodplain and river channel to reduce surface runoff generation, store water, and slow the flow of water through the catchment (Dadson *et al.*, 2017; Environment Agency, 2017).

Whilst many measures can be included within natural flood management, large wood is used similarly whether on land or in river channels. On land, fallen trees or log jam structures (i.e. debris dams, timber bunds, leaky dams) are placed on hillslopes or in ephemeral headwater streams to increase hydraulic roughness and store small volumes of water temporarily during storm events to slow its delivery to the river (Figure 1f). In the perennial river network, introduced large wood structures operate in a similar manner with the added benefit of increased over-bank flooding and reconnection of the river to the floodplain (Dixon *et al.*, 2016; Puttock *et al.*, 2017).

Whether placed on land or in the river, structures designed to “slow the flow” require maintenance or replacement as the wood decays naturally. This replenishment of wood can be done artificially, but, where riparian woodland of sufficient maturity, be as part of the natural wood cycle so wood structures can become self-sustaining features. Furthermore, woodland cover along river corridors provides surface roughness which attenuates floodplain surface flows, retains floating wood, encourages the deposition of fine sediment and infiltration of floodwaters into the floodplain, and encourages the retention and uptake of nutrients. Therefore, if engineered wood features are incorporated as part of reinstatement of the full cycle of trees and large wood, there many multiple benefits (e.g. Dosskey et al., 2010)

## Uncertainties and risks

Despite the widespread use of large wood for river restoration and increasingly as a natural component of flood risk management in the UK, the experts agreed that there are numerous uncertainties, obstacles and unquantified risks that should be the subject of future study to enable large wood to be used with confidence more widely. These include uncertainties in the type and placement of wood for different uses and in different locations (i.e. specification); increased risk to people, infrastructure or the environment local to wood features; increased risk to locations upstream or downstream of wood features; liability and maintenance; and public perception (Table 1). The expert panel agreed that these risks and uncertainties must be addressed if there is to be more widespread use of large wood. There was a general consensus that putting wood in rivers was considered ‘natural’ and ‘good’ from a river processes perspective, but at present there was insufficient evidence to address the long list of uncertainties and risks.

Some issues become less problematic if the full wood cycle is considered in the restoration or management design. For example, maintenance costs can be reduced or removed in the long-term if riparian forests are planted or allowed to grow, as the natural wood recruitment will sustain features (Moore and Rutherfurd, 2017). Riparian trees can also be managed by coppice rotation to ensure replacement wood is available in the longer term. These wood features will also become less mobile as the size of trees and thus individual large wood elements increases, as illustrated by the high retention of natural wood in channels that are narrower than the height of the riparian trees (Gurnell 2013). In some projects, large wood is also fixed in place to minimise natural movement. Similarly, research has shown that accumulations of large wood are likely to occur at artificial structures within channels (e.g. bridges) during flood events, particularly if there is a ready supply of wood (Comiti, Lucía and Rickenmann, 2016). Therefore, downstream hazard to infrastructure can be reduced by installing wood retention structures upstream of bridges.

Other issues can be minimised if stakeholder and community engagement is an integral part of the design process. Wohl *et al.* (2015) argue that rivers should be viewed as a 'hybrid of nature and culture' and restoration schemes should be informed or co-produced by the community. This engagement can also help to overcome concerns about liability, and maintenance. For example, the Stroud Rural SuDS Project, a partnership between the Environment Agency, Stroud District Council and Gloucestershire County Council in England, developed clear guidelines to assign responsibilities for wood debris structures for natural flood risk management which supported landowner participation in the project. However, the panel agreed that additional scientific research is needed to quantify uncertainty, reduce risks, and inform future management practices (Table 2).

## Tools and guidance - Recommendations

Whilst gaps remain in our scientific understanding of large wood and its effects on rivers (i.e. hydraulic, hydrological, geomorphological, water quality and ecological), the expert panel agreed that it is imperative that existing tools and guidance are improved or new ones created for use by all parties involved in river restoration and management (Table 3).

Excellent resources exist to inform people about the use of wood for different management purposes. For example, natural flood risk management has received increasing interest, and national environmental regulators have responded with user-oriented guides on the design and placement of flood-attenuation features, which are often wood-based. The Scottish Environmental Protection Agency produced a natural flood management handbook (SEPA, 2015), and the Environment Agency recently published a summary of the evidence for 'working with natural processes' in flood risk management (Environment Agency, 2017). For river restoration, practical advice and case study examples of wood used for habitat enhancement and river engineering is available from The UK River Restoration Centre in their Manual of River Restoration Techniques (River Restoration Centre, 2018). Considerable information on assessment and implementation of river restoration measures can be found on the European Union funded REFORM project website (www.reformrivers.eu), including an easily accessible 'wiki' and links to scientific publications. All of the guides provide background information on processes, practical information on design, and advice on assessing multiple benefits and working with stakeholders.

However, the panel agreed a series of recommended tools and guidance are needed to address the uncertainties and risks identified above (Table 1) and facilitate the wider use of large wood for restoration and management (Table 3). This guidance should be informed by improved understanding of how wood may be retained in rivers of different hydro-geomorphological type as their natural function and dynamics are restored.

The experts felt strongly that direction is needed from environmental regulators and managers to advise on liability and maintenance uncertainties, to link multiple policies, and guide practitioners in planning and decision-making. Key recommendations highlighted by the panel are to:

- Develop a framework to support the use of wood for restoration and management (more detail provided in Table 3).
- Establish acceptable levels of uncertainty and devise ways to assess and monitor risk.

- Formulate approaches to link riparian and channel management (e.g. flood risk management, forestry, water quantity and quality, biodiversity) to maximise beneficial impacts.
- Create mechanisms to link agricultural land management (e.g. agri-environment schemes) and environmental benefits.
- Advise on natural capital and ecosystem service approaches to compare options and to benefits of wood for restoration and natural flood risk management.

For consultants and practitioners, the panel agreed that more emphasis could be placed on communication with project partners and stakeholders to explain how and why wood is being used in a design, what the options are and how they affect risks and multiple benefits, and the final plan meets their project goals (Wohl, Lane and Wilcox, 2015). In particular, the panel recommended that consultants and practitioners:

- Ensure the purpose of putting wood in rivers is clear to project partners, flood risk managers, stakeholders, and wider public.
- Foster the creation and implementation of a shared vision for 'their' river with stakeholders and local communities so there is sustained interest and social investment.
- Develop clear and measurable objectives in the planning stages.
- Incorporate local hydrological knowledge into the design and planning.
- Consider the uncertainty inherent in the design and its potential geomorphological evolution over the medium- term to create risk-based end points.

Finally, the expert panel emphasised that successful use of wood in restoration and management was dependent on public acceptance and support. The shift towards 'nature-based solutions' that 'work with natural processes' is a significant change in management policy. Whilst it is generally perceived positively by managers, practitioners and scientists, panel members have spoken to numerous members of the public who either did not know about this shift or considered it counter to their understanding of river management. For generations, society has controlled river discharges, straightened and deepened channels, added reinforcement to prevent bank erosion, protected floodplains from flooding, and removed wood from rivers. Against this background, letting wood back into rivers may appear to be a complete U-turn in management practice and fundamentally disagree with people's perception of what a river should look like. Therefore, in addition to the above recommendations for consultants and practitioners, the panel suggested that all involved with river restoration and management work closely with catchment partnerships and other organisations to highlight the wider benefits of an 'untidy' landscape and increase the publicity of demonstration sites (e.g. Stroud Rural SuDS).

# Conclusions

This paper summarises the current use of wood in river restoration and management based on the experience and expertise of a panel of academics, river managers, restoration practitioners and consultants in the UK. The paper illustrates that a great deal is known about how large wood functions in rivers and how some of this knowledge is being incorporated into using wood in many river management contexts including habitat creation, river engineering, and flood hazard reduction. However, it also notes that many uncertainties and risks remain, which are very significant in the densely populated landscape of much of the UK. Whilst many tools and guidance already exist, the potential to fully integrate wood and trees in catchment and river restoration, rehabilitation, and management is being held back by a lack of knowledge on many issues. Addressing these knowledge gaps is the key to a new era of increasing harmony between more naturally functioning river environments and the health and well-being of those who live in and near these environments.

## Acknowledgements

The workshop was funded through an outreach grant from the British Society for Geomorphology with additional support from the Royal Geographical Society (with IGB). We would like to thank all the workshop participants for their contributions to the ideas summarised in this paper. In addition to the authors, they are: Martijn Antheunisse, Chris Bromley, Dave Brown, Simon Dixon, Jo Hodgkins, Martin Janes, Oliver Lowe, Glenn Maas, Jenny Mant, Kenny McDougall, Hamish Moir, Luke Neal, Annie Ockleford, Leanne Sargeant, David Sear, Kevin Skinner, Brian Smith, Huw Thomas, Lee Tyson and Jenny Wheeldon. We would also like to thank two anonymous reviewers for their useful advice and suggestions.

## References

Abbe, T. B. and Montgomery, D. R. (2003) 'Patterns and processes of wood debris accumulation in the Queets river basin, Washington', *Geomorphology*. Elsevier, 51(1–3), pp. 81–107. doi: 10.1016/S0169-555X(02)00326-4.

Abbe, T. B., Press, G., Montgomery, D. R. and Fether (2003) 'Integrating engineered wood jam technology into river rehabilitation', in Montgomery, D. R., Bolton, S., Booth, D. B., and Wall, L. (eds) *Restoration of Puget Sound Rivers*. Seattle, Washington: University of Washington Press, pp. 443–482.

Addy, S. and Wilkinson, M. (2016) 'An assessment of engineered log jam structures in response to a flood event in an upland gravel-bed river', *Earth Surface Processes and Landforms*. Wiley-Blackwell, 41(12), pp. 1658–1670. doi: 10.1002/esp.3936.

Arseneault, D., Boucher, É. and Bouchon, É. (2007) 'Asynchronous forest-stream coupling in a fire-prone boreal landscape: Insights from woody debris', *Journal of Ecology*. Wiley/Blackwell (10.1111), 95(4), pp. 789–801. doi: 10.1111/j.1365-2745.2007.01251.x.

Blanckaert, K., Duarte, A., Chen, Q. and Schleiss, A. J. (2012) 'Flow processes near smooth and rough (concave) outer banks in curved open channels', *Journal of Geophysical Research: Earth Surface*. John Wiley & Sons, Ltd, 117(F4), p. n/a-n/a. doi: 10.1029/2012JF002414.

Braccia, A. and Batzer, D. P. (2008) 'Breakdown and invertebrate colonization of dead wood in wetland, upland, and river habitats', *Canadian Journal of Forest Research*, 38(10), pp. 2697–2704. doi: 10.1139/X08-113.

Braudrick, C. A. and Grant, G. E. (2001) 'Transport and deposition of large woody debris in streams: a flume experiment', *Geomorphology*. Elsevier, 41(4), pp. 263–283. doi: 10.1016/S0169-555X(01)00058-7.

Brummer, C. J., Abbe, T. B., Sampson, J. R. and Montgomery, D. R. (2006) 'Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA', *Geomorphology*. Elsevier, 80(3–4), pp. 295–309. doi: 10.1016/J.GEOMORPH.2006.03.002.

Chin, A., Daniels, M. D., Urban, M. A., Piégay, H., Gregory, K. J., Bigler, W., Butt, A. Z., Grable, J. L., Gregory, S. V., Lafrenz, M., Laurencio, L. R. and Wohl, E. (2008) 'Perceptions of Wood in Rivers and Challenges for Stream Restoration in the United States', *Environmental Management*. Springer-Verlag, 41(6), pp. 893–903. doi: 10.1007/s00267-008-9075-9.

Collins, B. D., Montgomery, D. R., Fetherston, K. L. and Abbe, T. B. (2012) 'The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion', *Geomorphology*. Elsevier, 139–140, pp. 460–470. doi: 10.1016/J.GEOMORPH.2011.11.011.

Comiti, F., Lucía, A. and Rickenmann, D. (2016) 'Large wood recruitment and transport during large floods: A review', *Geomorphology*. Elsevier B.V., 269, pp. 23–39. doi: 10.1016/j.geomorph.2016.06.016.

Dadson, S. J., Hall, J. W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., Heathwaite, L., Holden, J., Holman, I. P., Lane, S. N., O'Connell, E., Penning-Rowsell, E., Reynard, N., Sear, D., Thorne, C. and Wilby, R. (2017) 'A restatement of the natural science evidence concerning catchment-based "natural" flood management in the UK', *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science*, 473(2199), p. 20160706. doi: 10.1098/rspa.2016.0706.

Davidson, S. L. and Eaton, B. C. (2013) 'Modeling channel morphodynamic response to variations in large wood: Implications for stream rehabilitation in degraded watersheds', *Geomorphology*. Elsevier, 202, pp. 59–73. doi: 10.1016/J.GEOMORPH.2012.10.005.

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*. John Wiley and Sons Ltd, 41(7), pp. 997–1008. doi: 10.1002/esp.3919.

Dosskey, M. G., Vidon, P., Gurwick, N. P., Allan, C. J., Duval, T. P. and Lowrance, R. (2010) 'The role of riparian vegetation in protecting and improving chemical water quality in streams', *Journal of the American Water Resources Association*, 46(2), pp. 261–277. doi: 10.1111/j.1752-1688.2010.00419.x.

Eggert, S. L. and Wallace, J. B. (2007) 'Wood biofilm as a food resource for stream detritivores', *Limnology and Oceanography*. Wiley-Blackwell, 52(3), pp. 1239–1245. doi: 10.4319/lo.2007.52.3.1239.

Environment Agency (2017) *Working with natural processes - the evidence base*. Available at: https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk (Accessed: 23 March 2018).

Gurnell, A. M. (2013) 'Wood in fluvial systems', in Shroder Jr., J. and Wohl, E. (eds) *Treatise on Geomorphology*. San Diego, CA, USA: Academic Press, pp. 163–188.

Gurnell, A. M. (2014) 'Plants as river system engineers', *Earth Surface Processes and Landforms*, 39(1), pp. 4–25. doi: Doi 10.1002/Esp.3397.

Gurnell, A. M. and Sweet, R. (1998) 'The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream', *Earth Surface Processes and Landforms*. Wiley-Blackwell, 23(12), pp. 1101–1121. doi: 10.1002/(SICI)1096-9837(199812)23:12<1101::AID-ESP935>3.0.CO;2-O.

Gurnell, A., Tockner, K., Edwards, P. and Petts, G. (2005) 'Effects of deposited wood on biocomplexity of river corridors', *Frontiers in Ecology and the Environment*. Wiley-Blackwell, 3(7), pp. 377–382. doi: 10.1890/1540-9295(2005)003[0377:EODWOB]2.0.CO;2.

Harvey, G. L., Henshaw, A. J., Parker, C. and Sayer, C. D. (2017) 'Re-introduction of structurally complex wood jams promotes channel and habitat recovery from overwidening: Implications for river conservation', *Aquatic Conservation: Marine and Freshwater Ecosystems*. John Wiley and Sons Ltd. doi: 10.1002/aqc.2824.

Jamieson, E. C., Rennie, C. D. and Townsend, R. D. (2013) 'Turbulence and Vorticity in a Laboratory Channel Bend at Equilibrium Clear-Water Scour with and without Stream Barbs', *Journal of Hydraulic Engineering*, 139(3), pp. 259–268. doi: 10.1061/(ASCE)HY.1943-7900.0000673.

Janes, V. J. J., Grabowski, R. C. C., Mant, J., Allen, D., Morse, J. L. L. and Haynes, H. (2017) 'The Impacts of Natural Flood Management Approaches on In-Channel Sediment Quality', *River Research and Applications*, 33(1), pp. 89–101. doi: 10.1002/rra.3068.

Jeffries, R., Darby, S. E. and Sear, D. A. (2003) 'The influence of vegetation and organic debris on flood-plain sediment dynamics: case study of a low-order stream in the New Forest', *Geomorphology*. Elsevier, 51(1–3), pp. 61–80. doi: 10.1016/S0169-555X(02)00325-2.

Jochner, M., Turowski, J. M., Badoux, A., Stoffel, M. and Rickli, C. (2015) 'The role of log jams and exceptional flood events in mobilizing coarse particulate organic matter in a steep headwater stream', *Earth Surface Dynamics*, 3(3), pp. 311–320. doi: 10.5194/esurf-3-311-2015.

Keeton, W. S., Kraft, C. E. and Warren, D. R. (2007) 'Mature and old-growth riparian forests: Structure, dynamics, and effects on adirondack stream habitats', *Ecological Applications*. Wiley-Blackwell, 17(3), pp. 852–868. doi: 10.1890/06-1172.

Kramer, N. and Wohl, E. (2017) 'Rules of the road: A qualitative and quantitative synthesis of large wood transport through drainage networks', *Geomorphology*. Elsevier, 279, pp. 74–97. doi: 10.1016/J.GEOMORPH.2016.08.026.

Krause, S., Klaar, M. J., Hannah, D. M., Mant, J., Bridgeman, J., Trimmer, M. and Manning-Jones, S. (2014) 'The potential of large woody debris to alter biogeochemical processes and ecosystem services in lowland rivers', *Wiley Interdisciplinary Reviews: Water*. Wiley-Blackwell, 1(3), pp. 263–275. doi: 10.1002/wat2.1019.

Langford, T. E. L., Langford, J. and Hawkins, S. J. (2012) 'Conflicting effects of woody debris on stream fish populations: implications for management', *Freshwater Biology*. Wiley/Blackwell (10.1111), 57(5), pp. 1096–1111. doi: 10.1111/j.1365-2427.2012.02766.x.

Matheson, A., Thoms, M., Southwell, M. and Reid, M. (2017) 'Does reintroducing large wood influence the hydraulic landscape of a lowland river at multiple discharges?', *Ecohydrology*. Wiley-Blackwell, 10(6), p. e1854. doi: 10.1002/eco.1854.

Moore, H. E. and Rutherfurd, I. D. (2017) 'Lack of maintenance is a major challenge for stream restoration projects', *River Research and Applications*. Wiley-Blackwell, 33(9), pp. 1387–1399. doi: 10.1002/rra.3188.

Morris, A. E. L., Goebel, P. C. and Palik, B. J. (2007) 'Geomorphic and riparian forest influences on characteristics of large wood and large-wood jams in old-growth and second-growth forests in Northern Michigan, USA', *Earth Surface Processes and Landforms*. Wiley-Blackwell, 32(8), pp. 1131–1153. doi: 10.1002/esp.1551.

Nichols, R. A. and Ketcheson, G. L. (2013) 'A Two-Decade Watershed Approach to Stream Restoration Log Jam Design and Stream Recovery Monitoring: Finney Creek, Washington', *Journal of the American Water Resources Association*. Blackwell Publishing Inc., 49(6), pp. 1367–1384. doi: 10.1111/jawr.12091.

Osei, N. A., Gurnell, A. M. and Harvey, G. L. (2015) 'The role of large wood in retaining fine sediment, organic matter and plant propagules in a small, single-thread forest river', *Geomorphology*. Elsevier, 235, pp. 77–87. doi: 10.1016/J.GEOMORPH.2015.01.031.

Pagliara, S. and Kurdistani, S. M. (2017) 'Flume experiments on scour downstream of wood stream restoration structures', *Geomorphology*. Elsevier, 279, pp. 141–149. doi: 10.1016/J.GEOMORPH.2016.10.013.

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*. Wiley-Blackwell, 42(11), pp. 1693–1703. doi: 10.1002/esp.4123.

Pettit, N. E. and Naiman, R. J. (2006) 'Flood-deposited wood creates regeneration niches for riparian vegetation on a semi-arid South African river', *Journal of Vegetation Science*. Wiley/Blackwell (10.1111), 17(5), pp. 615–624. doi: 10.1111/j.1654-1103.2006.tb02485.x.

Picco, L., Bertoldi, W. and Comiti, F. (2017) 'Dynamics and ecology of wood in world rivers', *Geomorphology*, 279, pp. 1–2. doi: 10.1016/j.geomorph.2016.11.020.

Pilotto, F., Bertoncin, A., Harvey, G. L., Wharton, G. and Pusch, M. T. (2014) 'Diversification of stream invertebrate communities by large wood', *Freshwater Biology*. Wiley/Blackwell (10.1111), 59(12), pp. 2571–2583. doi: 10.1111/fwb.12454.

Puttock, A., Graham, H. A., Cunliffe, A. M., Elliott, M. and Brazier, R. E. (2017) 'Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands', *Science of The Total Environment*. Elsevier, 576, pp. 430–443. doi: 10.1016/J.SCITOTENV.2016.10.122.

River Restoration Centre (2018) *Manual of river restoration techniques*. Available at: http://www.therrc.co.uk/manual-river-restoration-techniques (Accessed: 23 March 2018).

Roni, P. and Beechie, T. J. (2012) *Stream and watershed restoration : a guide to restoring riverine processes and habitats.* Edited by P. Roni and T. J. Beechie. Chichester, UK: Chichester, West Sussex ; Hoboken, NJ : John Wiley & Sons, 2013. (Advancing river restoration and management). doi: 10.1002/9781118406618.

Roni, P., Beechie, T., Pess, G. and Hanson, K. (2015) ‘Wood placement in river restoration: fact, fiction, and future direction’, *Canadian Journal of Fisheries and Aquatic Sciences*. Edited by B. Jonsson. NRC Research Press, 72(3), pp. 466–478. doi: 10.1139/cjfas-2014-0344.

Ruiz-Villanueva, V., Piégay, H., Gurnell, A. A., Marston, R. A. and Stoffel, M. (2016) ‘Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges’, *Reviews of Geophysics*. doi: 10.1002/2015RG000514.

Ruiz-Villanueva, V., Zawiejska, J. and Hajdukiewicz, M. (2016) ‘Factors controlling large-wood transport in a mountain river’, *Geomorphology*. Elsevier, 272, pp. 21–31. doi: 10.1016/J.GEOMORPH.2015.04.004.

Ryan, S. E., Bishop, E. L. and Daniels, J. M. (2014) ‘Influence of large wood on channel morphology and sediment storage in headwater mountain streams, Fraser Experimental Forest, Colorado’, *Geomorphology*. Elsevier, 217, pp. 73–88. doi: 10.1016/J.GEOMORPH.2014.03.046.

Sawyer, A. H. and Cardenas, M. B. (2012) ‘Effect of experimental wood addition on hyporheic exchange and thermal dynamics in a losing meadow stream’, *Water Resources Research*. Wiley-Blackwell, 48(10). doi: 10.1029/2011WR011776.

Senter, A. E., Pasternack, G. B., Piégay, H., Vaughan, M. C. and Lehyan, J. S. (2017) ‘Wood export varies among decadal, annual, seasonal, and daily scale hydrologic regimes in a large, Mediterranean climate, mountain river watershed’, *Geomorphology*. Elsevier, 276, pp. 164–179. doi: 10.1016/J.GEOMORPH.2016.09.039.

SEPA (2015) *Natural flood management handbook*. Available at: https://www.sepa.org.uk/media/163560/sepa-natural-flood-management-handbook1.pdf.

Smith, B., Clifford, N. J. and Mant, J. (2014) ‘Analysis of UK river restoration using broad-scale data sets’, *Water and Environment Journal*. Wiley/Blackwell (10.1111), 28(4), pp. 490–501. doi: 10.1111/wej.12063.

Steiger, J., Gurnell, A. M. and Petts, G. E. (2001) ‘Sediment deposition along the channel margins of a reach of the middle River Severn, UK’, *Regulated Rivers-Research & Management*, 17(4–5), pp. 443–460.

Thompson, M. S. A., 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*. Edited by M.-J. Fortin. Wiley/Blackwell (10.1111), 55(2), pp. 895–904. doi: 10.1111/1365-2664.13013.

Wohl, E. (2017) ‘Bridging the gaps: An overview of wood across time and space in diverse rivers’, *Geomorphology*, 279, pp. 3–26. doi: 10.1016/j.geomorph.2016.04.014.

Wohl, E., Hall, R. O., Lininger, K. B., Sutfin, N. A. and Walters, D. M. (2017) ‘Carbon dynamics of river corridors and the effects of human alterations’, *Ecological Monographs*. Wiley-Blackwell, 87(3), pp. 379–409. doi: 10.1002/ecm.1261.

Wohl, E., Lane, S. N. and Wilcox, A. C. (2015) ‘The science and practice of river restoration’, *Water Resources Research*. Wiley-Blackwell, 51(8), pp. 5974–5997. doi: 10.1002/2014WR016874.

Word count: 6,452 + 1 small figure (250 words) + 3 tables (1 small and 2 large, ~750 words)

# Figure legends

Figure 1: (a) Large wood used in a restoration scheme on the lowland River Gade, UK (J. England). (b) Large poplar spanning the channel with visible wood-induced geomorphic features (e.g. sediment sorting, leaf litter) (I. Morrissey). (c) Large wood functioning as a pool scouring and interacting with flows at both low and high discharges on the River Wensum, Norfolk, UK (I. Morrissey). Root wads for bank protection on the Afon Dulais: (d) at

installation and (e) 2 years post (D. Holland). (f) Large wood in an ephemeral headwater in the Stroud River, Frome catchment for natural flood management (C. Uttley).

# Tables

*Table 1: Uncertainties in the use of large wood in river restoration and management*

| **Type** | **Uncertainties** |
|---|---|
| Specification - local | • What wood to use or encourage growth of at the site?<br>◦ Quantity<br>◦ Species: existing trees on site or planting of native species, flotation, decay, local availability<br>◦ Stability: wood piece size, the need to pin/anchor, roots in or out, living or dead wood<br>• What is the best form to use in that location and for that intended purpose?<br>◦ wood dams (size, location, design), individual large wood pieces, or natural fallen timber?<br>• Which designs can provide widest range of ecosystem services benefits |
| Specification - catchment | • Where should wood be used along the river network to maximise its designed effect?<br>• Are different local specifications needed for different locations in the network? (e.g. headwaters vs lowland)<br>How does the type and size of wood features influence flood risk reduction? |
| Local risk | • Local flood hazard (reduction of channel capacity, increase in hydraulic roughness)<br>• Reduction in land drainage; impacts on arterial drainage<br>• Local increases in groundwater<br>• Bank erosion and channel migration – loss of land<br>• Infrastructure: undercutting/destabilisation of roads, buildings, bank protection, flood defence measures, pipelines, etc.<br>• Dislodging of dams causing downstream blockages<br>• Trash retention<br>• Backwater effects<br>• Potential impacts on fish passage |
| Upstream / downstream risk | • Impact risk to infrastructure – bridges, power cables, etc.<br>• Blockage risk – increase flood hazard<br>• Backwater effect<br>• Cascade effect of multiple dam failure |
| Maintenance, liability, public safety | • Who owns and who maintains these structures??<br>• What maintenance is needed?<br>• How long does a geomorphic habitat feature persist once the wood decays?<br>• Small scale is often considered safe or low 'risk', but risks are not quantified, and benefits may be greater with larger schemes<br>• Stability of natural dams/jams is uncertain (as compared to ones that have been designed)<br>• Legal questions around who is liable if dams dislodge, cause a blockage elsewhere, and lead to flooding<br>• Can the Statutory Authority's maintenance strategy be aligned with restoration objectives? In other words, can a |

| | |
|---|---|
| | fallen tree that would normally be removed for flood risk be left in situ or adapted (e.g. trimming/fixing)? |
| Disease | • Use of imported wood and the potential for introduction of invasive species or disease<br>• Increase in standing water and biting insects |
| Public perception | • Flood, infrastructure and disease risk<br>• Wood has been commonly removed from rivers, and is often perceived as ‘debris’ that should be removed<br>• Conflicts with other watercourse users, because wood may limit their activity, e.g. fishing and canoeing |

*Table 2: Future scientific research needed to support the use of large wood in river restoration and management*

| Type | Studies / Questions / Requirements |
|---|---|
| Fieldwork | • Region/ location specific field studies are needed to determine generalised hydraulic, hydrological and geomorphological effects How predictable is wood accumulation? What factors influence the quantity of large wood in the river network and where it naturally accumulates? In other words, where would wood measures be self-sustaining?<br>• More evidence is needed to quantify ecological and water quality benefits of different types of wood features in different river types. and how it changes over time |
| Modelling / Fieldwork | • Can modelling help to provide confidence / rules of thumb of scale of impact (hydrological, hydraulic, geomorphological)?<br>• More monitoring needed to quantify hydraulic roughness of woody material in the channel and floodplain so that they can be better represented in existing flood models<br>• Hydraulic modelling needed to predict the downstream flood risk reduction benefits of different types, numbers, and scales of wood features. |
| Economic | • More studies are needed that quantify the full range of wider benefits (e.g. ecology, water quality, amenity, fisheries, etc).<br>• Testing of natural capital and ecosystem approaches to benefit identification and quantification.<br>• Cost-benefit analysis of wood compared to other approaches for different purposes |

*Table 3: Tools and guidance needed to support use of large wood in river restoration and management*

| Types | Tools / guidance |
|---|---|
| General | <u>Framework for using wood</u><br>• Explanation of the 'wood cycle', effects in rivers/floodplains<br>• Design guide - right approach in the right place<br>• Primary drivers - funding opportunities<br>• Context for you and your river type<br>• Design principles<br>• Case study examples |
| Specific | • What is wood likely to do under specific local conditions (river type, flow regime, catchment size, geology, etc)?<br>• Temporal and spatial scale of response to different techniques |
| Communication | • Better promotion and increased use of existing tools to engage with stakeholders and assist in the planning and execution of restoration and natural flood risk management<br>• Improved guidance on the prioritisation and targeted placement of wood features or tree planting (i.e. most effective and cost-effective locations and measures)<br>• Case study examples that illustrate multiple benefits, how to monitor benefits, and ways to minimise risks (e.g. lessons learnt)<br>• Demonstration sites / catchments - to share knowledge and build confidence |
| Opportunity mapping | • Input data layers<br>    ○ Wood cycle, source<br>    ○ Land use, geology, soil type/ runoff potential, hill slope, channel gradient.<br>    ○ Contributing area / flow timing<br>    ○ Risk of erosion / channel movement<br>    ○ Flood hazard mapping<br>    ○ Location and type of infrastructure<br>• Where is wood 'good', and where is wood 'risky' (considering local and downstream risks and benefits)?<br>    ○ Where not to put wood (or let it establish), where to put it (or let it grow) with conditions, and where you can do what you like?<br>    ○ Do nothing - Do minimum - Do something - Do a lot<br>    ○ Guidance on monitoring and adaptive management / maintenance |

Figure 1: (a) Large wood used in a restoration scheme on the lowland River Gade, UK (J. England). (b) Large poplar spanning the channel with visible wood-induced geomorphic features (e.g. sediment sorting, leaf litter) (I. Morrissey). (c) Large wood functioning as a pool scouring and interacting with flows at both low and high discharges on the River Wensum, Norfolk, UK (I. Morrissey). Root wads for bank protection on the Afon Dulais: (d) at installation and (e) 2 years post (D. Holland). (f) Large wood in an ephemeral headwater in the Stroud River, Frome catchment for natural flood management (C. Uttley).