

"This is the peer reviewed version of the following article: 'R.C. Grabowski et al. 2019. The current state of the use of large wood in river restoration and management. Water and Environment Journal 2019, early view, which has been accepted for publication in final form at DOI: 10.1111/wej.12465. 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

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Abstract

Trees and branches fall naturally into rivers generating heterogeneity in river flows, inducing geomorphological features, and creating habitats for the aquatic ecological community. However wood in rivers can increase flood hazard and pose a risk to infrastructure. Therefore attention must be given to how wood is used in river restoration and management. Through a one-day workshop, sponsored by the British Society for Geomorphology and the Royal Geographical Society (with IGB), academics, river managers, restoration practitioners and consultants were brought together to share the latest science and best-practice on wood in rivers. Participants debated the benefits and risks of using wood to 'work with natural processes', and outlined key challenges and potential solutions to delivering projects on the ground at a catchment scale. These points are summarised here, with further examples of the potential of wood to engineer river systems provided in other articles in the special issue.

Key words: fluvial geomorphology, natural flood risk management, ...

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Introduction

Over the last 20 years, the importance of vegetation in influencing fluvial processes and forms has been increasingly recognised in the academic literature, particularly the fundamental roles of woody riparian vegetation, large wood, and even aquatic macrophytes in buffering hydrodynamics forces, trapping and reinforcing sediment (for reviews, see Gurnell, 2014; Picco et al., 2017). At the same time, river managers and restoration practitioners are increasingly turning towards 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 are more difficult to translate into practice when management measures are being proposed on the ground. This is particularly true for the use of large wood in river restoration and management, for which the goals of working with natural processes often conflict with society’s expectations for 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 *et al.*, 2015). River restoration is a multimillion 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 uptake 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 run-off 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 1-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 acknowledgements) 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 well-being, 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 hydrogeomorphological and ecological processes initiated by large wood (Hydrogeomorphological effects of wood)
2. How wood and the hydrogeomorphological 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 hydrogeomorphological 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

Hydrogeomorphic effects of wood

Considerable research has been conducted in recent decades 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, landslides, beavers). Once in the river channel, it becomes one of the fundamental agents 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 geomorphic style of river channel and floodplain (e.g. single thread or multithread, straight or sinuous or meandering) (Abbe and Montgomery, 2003; Gurnell et al., this volume). The following summary of hydrogeomorphological 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 mainly relate to the degree to which the 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 of the year and 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; Kramer and Wohl, 2017; Ruiz-Villanueva et al., 2016), 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 et al., 2007). When large accumulations of wood form in river channels, they can attenuate downstream flows of water and transported materials, increase channel-floodplain hydrological connectivity across the surface and subsurface, and sustain ponded water and low flows in the river channel during dry periods. While these effects are most obvious around large channel-spanning wood jams, smaller wood accumulations and large individual wood 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, just as in-channel wood can sustain low flows, 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 flow velocity and shear stress separated by wood-sheltered areas where flow velocities and shear stresses are drastically reduced. In addition, because most large wood is less dense than water, flows can occur under wood accumulations once the water depth is sufficient for wood flotation, and this can lead to very high local shear stresses 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 et al., 2014) including fine sediment that could otherwise infiltrate and smother the bed of low energy rivers (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 and benches as well as bank erosion (e.g. Gurnell and Sweet, 1998). In addition, the presence of in-channel wood accumulations leads to increased water-surface elevations relative to adjacent river banks, increasing not only hydrological connectivity with the floodplain, but also where large long-lived wood jams are present, the potential for the channel to avulse (change course) or for secondary channels to develop (Brummer et al., 2006) resulting in complex channel patterns and floodplain evolution processes (Jeffries et al., 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 et al., 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 (Osei et al., 2015; Pettit and Naiman, 2006; Steiger et al., 2001). Dead and living wood incorporated into the floodplain (e.g. Arseneault et al., 2007) can form 'hard points' that are resistant to erosion and so support 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).

This summary of hydrogeomorphological and ecological effects of wood in rivers is not exhaustive. It includes effects that the diverse panel of experts felt were most relevant to river restoration and management, i.e. the processes that could be harnessed to reach their management goals and objectives.

Current use of wood in restoration and management

Large wood is being 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 reintroduction of flow heterogeneity to modified channels to support recovery of the fish community (Wohl et al., 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. It diverts water flows, increases local water levels, and introduces turbulence, creating a mosaic of fast and slowing flowing areas within a reach. 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 channel form and sediment characteristics. The precise geomorphic impact of introduced large wood in a river is still difficult to predict, but a mosaic of forced pools, bars, and fine sediment benches have been reported in studies (Addy and Wilkinson, 2016; Davidson and Eaton, 2013; Harvey et al., 2017; Roni et al., 2015). The combined effect of spatial variations in hydraulic conditions, sediment grain size and the deposition of organic material can foster higher diversity of macroinvertebrates (Pilotto et al., 2014) and impact the entire food web to increase populations of target fish species (Thompson et al., 2018). Though, wood is not universally beneficial to all species, so the habitat requirements of the fish community at all life history stages should be considered (Langford et al., 2012).

The workshop panel noted that although many restoration projects continue to use wood as an immediate design feature, often within modified channels (Smith *et al.*, 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 (Fig. 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, such as an increase in water levels and the scouring of pools, creates physical refugia during seasonal low flow periods or supra-annual droughts. Deep pools and shading from wood and riparian trees also reduce water temperature locally, creating thermal refugia for organisms, and more widely at the reach scale (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 hydrogeomorphological 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 *et al.* , 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 (Fig. 1c) (Pagliara and Kurdistani, 2017). Wood is also used to locally raise bed levels in significantly overdeepened sections to reduce the amount of imported substrate required to create glides/riffles.

In higher energy rivers, the wood used in river engineering projects becomes 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 deflect flows, reinforce banks, or to add hydraulic roughness to increase turbulence and reduce flow velocities to protect infrastructure, such as bridge sills. 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 geomorphic 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, particularly in the UK, has been the shift towards natural flood management to reduce downstream flood hazard. Natural flood management aims to reduce flood frequency or severity by modifying the land surface (land cover, land use or land management practices), floodplain and river channel to reinstate or enhance catchment processes that

reduce surface runoff generation, store water, or 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 and 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 (Fig. 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 complement to flood risk management in the UK, the experts agreed that that are numerous uncertainties, obstacles and unquantified risks that limit wood from being adopted in more locations. 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 (Table 2) must be addressed if large wood is to be used more in river restoration and management. They felt that there was a general consensus that putting wood in rivers was considered 'natural' and thus 'good' from a river processes perspective, but at present there was insufficient evidence to resolve 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 Rutherford, 2017). These features will become less mobile as the size of trees and thus individual large wood elements increases, as illustrated by the natural high retention of wood in channels that are narrower than the height of the riparian trees (Gurnell 2013).. 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 et al., 2016). Therefore, downstream hazard to infrastructure can be reduced by installing wood retention structures upstream of bridges or replacing with single span bridges.

Table 1: Uncertainties and risk of using large wood in river restoration and management

Type	Uncertainties and risks
Specification - local	<ul style="list-style-type: none"> • What wood to use or encourage growth of at the site? <ul style="list-style-type: none"> • Quantity • Species: flotation, decay, local availability • Stability: wood piece size, the need to pin/anchor, roots in or out, living or dead wood • What is the best form to use in that location and for that intended purpose? <ul style="list-style-type: none"> • wood dams (size, location, design), individual large wood pieces, or natural fallen timber? • Which designs can provide widest range of ES benefits
Specification - catchment	<ul style="list-style-type: none"> • Where should wood be used along the river network to maximise its designed effect? • Are different local specifications needed for different locations in the network? E.g. headwaters vs lowland • How does flood risk reduction depend on the type and scales of wood features?
Local risk	<ul style="list-style-type: none"> • Local flood hazard (reduction of channel capacity, increase in hydraulic roughness) • Bank erosion and channel migration – loss of land • Infrastructure: undercutting/destabilisation of roads, buildings, bank protection, flood defence measures, pipelines, etc. • Dislodging of dams causing d/s blockages • Litter retention • Backwater effect • Potential impacts on fish passage
Upstream / downstream risk	<ul style="list-style-type: none"> • Impact risk to infrastructure – bridges, power • Blockage risk – increase flood hazard • Backwater effect • Cascade effect of multiple dam failure
Maintenance, liability, public safety	<ul style="list-style-type: none"> • Who maintains these structures or flood risk management ‘assets’? • What maintenance is needed? • Small scale is often considered safe or low ‘risk’, but risks are not quantified, and benefits may be greater with larger schemes • Stability of natural dams/jams is uncertain (as compared to ones that have been designed) • Legal questions around who is liable if dams dislodge cause a blockage elsewhere and led to flooding
Disease	<ul style="list-style-type: none"> • Use of imported wood and the potential for introduction of invasive species or disease • Increase in standing water and biting insects
Public perception	<ul style="list-style-type: none"> • Flood, infrastructure and disease risk • What a river ‘should look like’ • Wood in rivers may be considered ‘messy’

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 coproduced 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).

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

Type	Studies / Questions / Requirements
Fieldwork	<ul style="list-style-type: none"> • More field studies, in more types of rivers, monitoring wood dynamics and the 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? • More evidence needed of ecological and water quality benefits of different types of wood features in different river types. • Scientific monitoring of sites that have used wood for restoration and management to quantify effectiveness and how it changes over time is needed.
Modelling / Fieldwork	<ul style="list-style-type: none"> • Can modelling help to provide confidence / rules of thumb • Hydraulic modelling needed to predict the flood risk reduction benefits of different types, numbers and scales of wood features
Economic	<ul style="list-style-type: none"> • More studies are needed that quantify the full range of wider benefits (e.g. ecology, water quality, amenity, fisheries, etc). • Testing of natural capital and ecosystem approaches to benefit identification and quantification • Cost-benefit analysis of wood compared to other approaches for different purposes

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 in the UK 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 (EA,

2017). For river restoration, practical advice and case study examples of wood used for habitat enhancement and river engineering is available from the 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.

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

Types	Tools / guidance
General	<p><u>Framework for using wood</u></p> <ul style="list-style-type: none"> • Wood cycle, effects in rivers/floodplains • Design guide - right approach in the right place • Primary drivers - funding opportunities • Context for you and your river type • Design principles • Case study examples
Specific	<ul style="list-style-type: none"> • What is wood likely to do under specific local conditions (river type, flow regime, catchment size, geology, etc) • Temporal scale of response to different techniques
Communication	<ul style="list-style-type: none"> • More tools to engage with stakeholders and assist in the planning and execution of restoration and NFM (e.g. opportunity mapping) • Case study examples that illustrate multiple benefits and ways to minimise risks (e.g. lessons learnt) • Demonstration sites / catchments - to share knowledge and build confidence
Opportunity mapping	<ul style="list-style-type: none"> • Input data layers <ul style="list-style-type: none"> ○ Wood cycle, source ○ Land use, geology, soil type/ runoff potential, hill slope, channel gradient. ○ Risk of erosion / channel movement ○ Flood hazard mapping ○ Location and type of infrastructure • Where is wood good, and where is wood risky (considering local and downstream risks and benefits) <ul style="list-style-type: none"> ○ Where not to put wood (or let it establish), where to put it (or let it grow) with conditions, where you can do what you like ○ Do nothing - Do minimum - Do something - Do a lot ○ Guidance on monitoring and adaptive management / maintenance

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 hydrogeomorphological 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 join up riparian and channel management (e.g. flood risk management, forestry, water quantity and quality, biodiversity) to maximise beneficial impacts
- Create mechanisms to join up 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 how the final plan meets their goals. 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 geomorphic 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 nature' 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

- (1) 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.
- (2) 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.
- (3) However, it also notes that many uncertainties and risks remain, which are very significant in densely populated landscapes, like much of the UK.
- (4) 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.
- (5) Addressing these knowledge gaps is the key to a new era of increasing harmony between more naturally functioning river environments and the health and wellbeing 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.

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Figures



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).