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

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24 **Abstract**
25

26 Trees fall naturally into rivers generating flow heterogeneity, inducing geomorphological
27 features, and creating habitats for biota. Wood is increasingly used in restoration projects
28 and the potential of wood acting as leaky barriers to deliver natural flood management by
29 “slowing the flow” is recognised. However, wood in rivers can pose a risk to infrastructure
30 and locally increase flood hazards. The aim of this paper is to provide an up-to-date
31 summary of the benefits and risks associated with using wood to promote geomorphological
32 processes to restore and manage rivers. This summary was developed through a workshop
33 that brought together academics, river managers, restoration practitioners and consultants in
34 the UK to share science and best-practice on wood in rivers. A consensus was developed on
35 four key issues: (i) hydro-geomorphological effects, (ii) current use in restoration and
36 management, (iii) uncertainties and risks, and (iv) tools and guidance required to inform
37 process-based restoration and management.
38

39 Key words: fluvial geomorphology, natural flood risk management, hydromorphology,
40 catchment management, river basin management, flood risk
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45

Introduction

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

57

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

76

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

86

87

Methodology

88 For this study, we assembled a panel of 30 experts to debate and agree an up-to-date
89 summary of benefits, risks and challenges of the use of large wood for river restoration and
90 rivers. Participants of the workshop (the authors and those listed in the acknowledgments)
91 represented a diversity of organisations across a range of sectors related to river restoration
92 and management. Their expertise included fluvial geomorphology, aquatic ecology,
93 conservation, restoration implementation, community health and wellbeing, river basin

94 management, flood risk and natural flood management. Participants were asked to view their
95 specialisation within the prism of fluvial geomorphological processes, and reflect on how
96 wood alters hydraulic conditions, creates geomorphological features, and modifies the
97 aquatic and terrestrial components of the river corridor to generate outcomes aligned with
98 their sector's goals.

99
100 The workshop centred around a series of activities designed to encourage the sharing of
101 knowledge and best-practice on the following topics:

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

111
112 Experiences, observations and expert opinions of the participants were shared and debated
113 in small groups for each topic and a consensus reached in a final workshop activity and in
114 follow-up communications. These findings are reported below with, where appropriate,
115 support from the scientific literature.

116
117

Analysis

118 **Hydro-geomorphological effects of wood**

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

127
128 Even in undisturbed wooded river corridors, wood occurs in highly variable quantities and
129 accumulates in different locations depending upon the position in the river network (notably
130 reflecting proximity of the river to hillslopes, channel size and gradient), and the
131 geomorphological style of river channel and floodplain (Abbe and Montgomery, 2003;
132 Gurnell *et al.*, this volume). The following summary of hydro-geomorphological and
133 ecological effects of wood in rivers is not exhaustive. It includes the hydrological, hydraulic,
134 geomorphological and ecological effects that the expert panel agreed were most relevant to
135 river restoration and management and which could be harnessed to reach their management
136 goals.

137

138 *Hydrology and Hydraulics*

139 Hydrological effects relate to the way that wood interacts with flowing water. Although wood
140 is delivered to rivers near-continuously by a wide variety of processes, it is rearranged locally
141 and transported downstream and between river and floodplain mainly during high flow
142 events, which may be characteristic of particular seasons or particular extreme climatological

143 and catchment hydrological conditions (Senter *et al.*, 2017). How far wood moves during
144 these events, and where it is retained, varies enormously depending upon flow, catchment,
145 floodplain, river channel and riparian woodland characteristics as well as the quantity of
146 wood in transport (Braudrick and Grant, 2001; Ruiz-Villanueva, Zawiejska and Hajdukiewicz,
147 2016; Kramer and Wohl, 2017), but much of it is retained in accumulations (3 or more pieces
148 of wood) on the floodplain and in the river channel (e.g. Morris, Goebel and Palik, 2007).
149 Large accumulations of wood in rivers can attenuate flows of water and transported
150 materials, increase channel-floodplain hydrological connectivity and sustain ponded water
151 and flows in the river channel during dry periods (Dixon *et al.*, 2016; Puttock *et al.*, 2017).
152 While these effects are most obvious around large channel-spanning wood jams, smaller
153 wood accumulations and large individual pieces located in river channels have similar but
154 smaller effects, and floodplain wood can also slow and divert movement of water across the
155 floodplain surface, particularly where it is washed into large accumulations or jams around
156 standing trees. Furthermore, floodplain wood can sustain areas of relatively higher soil
157 moisture on floodplains by reducing evaporation from the ground surface.

158
159 Hydrological interactions with wood are accompanied by hydraulic effects. Wood
160 obstructions can divert and concentrate water flows, creating local areas of high velocity and
161 shear stress separated by wood-sheltered areas where velocities and shear stresses are
162 drastically reduced (Gurnell, 2013). Since most large wood is less dense than water, flows
163 can also occur under wood accumulations once the water depth is sufficient for wood
164 flotation, which can cause localised high shear stress and scour.

165 166 *Geomorphology*

167 Interactions between flows, sediment, dead and living wood, other smaller pieces of organic
168 material, floodplain and channel sedimentary surfaces and standing vegetation generate a
169 range of geomorphological impacts. Wood accumulations retain sediment (e.g. Ryan, Bishop
170 and Daniels, 2014), including fine sediment (Parker *et al.*, 2017) and both dead and living
171 organic material (Jochner *et al.*, 2015). Wood accumulations or large individual wood pieces
172 can induce local bed, bank or floodplain stabilisation or scour and the mobilisation, sorting
173 and deposition of sediment and organic matter. Within river channels, these processes can
174 lead to the development of 'forced' pools, bars, benches and bank erosion (e.g. Gurnell and
175 Sweet, 1998). In addition, the presence of in-channel wood accumulations increases water-
176 surface elevations relative to adjacent river banks, increasing hydrological connectivity with
177 the floodplain and, where large long-lived wood jams are present, the potential for the
178 channel to avulse (i.e. change course) or for secondary channels to develop (Brummer *et al.*,
179 2006) resulting in complex channel patterns and floodplain evolution processes (Jeffries,
180 Darby and Sear, 2003)

181 182 *Ecology*

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

190
191 Complex feedbacks exist between wood, living trees and other riparian and aquatic plants.
192 Seeds and living wood pieces transported by flowing water are retained in and around wood
193 accumulations, creating local regeneration niches for riparian vegetation (Steiger, Gurnell

194 and Petts, 2001; Pettit and Naiman, 2006; Osei, Gurnell and Harvey, 2015) and
195 biogeochemical hotspots for microbial activity (Krause *et al.*, 2014). Dead and living wood
196 incorporated into the floodplain (e.g. Arseneault, Boucher and Bouchon, 2007) can form
197 'hard points' that are resistant to erosion supporting the longer-term development of riparian
198 vegetation, particularly large trees that provide a future wood supply to the river system
199 (Collins *et al.*, 2012). Finally, sustained floodplain inundation induced by large wood
200 accumulations can lead to tree mortality and subsequent enhanced wood delivery to the
201 river (Brummer *et al.*, 2006).

202

203 **Current use of wood in restoration and management**

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

207

208 *Habitat creation*

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

217

218 However, wood interacts directly and indirectly (i.e. through alterations of local hydraulic
219 conditions) with the sediment that is being transported down the river, altering the
220 characteristics of suspended and deposited sediments and channel form. The precise
221 geomorphological impacts of introduced large wood in a river is difficult to predict, but are
222 widely reported (Davidson and Eaton, 2013; Roni *et al.*, 2015; Addy and Wilkinson, 2016;
223 Harvey *et al.*, 2017). The combined effect of spatial variations in hydraulic conditions,
224 sediment grain size, and the deposition of organic material can foster a higher diversity of
225 macroinvertebrates (Pilotto *et al.*, 2014) and impact the entire food web (Thompson *et al.*,
226 2018). However, wood is not universally beneficial to all species so it is important to consider
227 the habitat requirements of the fish community at all life history stages (Langford, Langford
228 and Hawkins, 2012).

229

230 The workshop panel noted that although many restoration projects continue to use wood as
231 an immediate design feature, often within modified channels (Smith, Clifford and Mant,
232 2014), wood is increasingly being used to kick-start geomorphological processes to let the
233 river "do the work", e.g. River Bure, UK (Harvey *et al.*, 2017). In the River Wensum (Norfolk,
234 UK), large wood has been positioned across the channel above the average water level so
235 that it interacts with the flow at high discharges. This type of placement minimises potential
236 negative impacts on this low-energy, gravel-bed chalk stream at normal and low flows (e.g.
237 backwater effect, siltation), but promotes geomorphological activity at high flows (Figure 1b).
238 More projects are considering the wider river corridor and the potential for wood to increase
239 local water levels and improve lateral hydrological connectivity and reconnecting and
240 creating floodplains to support wetland conservation. Large wood is also being used to
241 improve water quality by trapping and storing of fine sediment, itself a diffuse pollutant, and
242 sediment-bound contaminants (Janes *et al.*, 2017).

243

244 Large wood is also seen by the panel as an approach to increase the resilience of river
245 ecosystems to climate change. The hydraulic, hydrological, and geomorphological changes
246 triggered by wood creates physical (and flow) refugia during seasonal low flow periods or
247 supra-annual droughts (Gurnell, 2013). Increased lateral connectivity of the river and
248 floodplain, and creation of floodplain geomorphological features during overbank flows
249 provide increased resilience for riparian vegetation to high (e.g. flow attenuation) and low
250 flows (e.g. increase soil moisture). Deep pools and shading from wood and riparian trees
251 also reduce water temperature locally (Nichols and Ketcheson, 2013). This temperature
252 moderation effect may also be affected by local downwelling induced by wood, which forces
253 surface water down into the sediment where it interacts with groundwater (i.e. hyporheic
254 exchange flow) (Sawyer and Cardenas, 2012). Finally, wood is important for carbon storage,
255 both as a component of the carbon cycle and its through its hydro-geomorphological
256 influences on process and fluxes of organic material (Wohl *et al.*, 2017).
257

258 *River engineering*

259 Wood and woody material is used frequently for river engineering to reduce lateral channel
260 migration, influence the deposition or erosion of bed sediment, or to protect infrastructure. It
261 is viewed as a more environmentally-friendly alternative to harder forms of engineering
262 (Wohl, Lane and Wilcox, 2015). Indeed, the concept of 'engineered wood jams' has been
263 promoted for at least the last 15 years as a measure for river rehabilitation (Abbe *et al.*,
264 2003). There is considerable overlap in how wood is used in practice; adding large wood
265 features may have more than one function (e.g. habitat creation and narrowing of flows to
266 flush fines), and this section focuses on the use of wood for hydrological and
267 geomorphological effects.
268

269 In low energy rivers, wood and woody material is often used to increase velocities, mobilise
270 bed sediment, create variations in the longitudinal profile (e.g. pools), and flush fine
271 sediment deposited on and in the bed. Engineered or constructed wood features can be
272 woven wicker panels (i.e. willow spiling) and brushwood mattresses to protect banks and
273 other features (e.g. earthen berms) or flow deflectors (i.e. groynes) to narrow the channel or
274 scour pools (Figure 1c) (Pagliara and Kurdistani, 2017). Wood is also used to locally raise
275 bed levels in significantly over-deepened sections to reduce the amount of imported
276 substrate required to create glides/riffles.
277

278 In higher energy rivers, the wood used is larger, placement must be more carefully designed,
279 often based on hydraulic modelling, and securing requires significant consideration and
280 investment. Whole tree trunks and root wads are commonly used to add hydraulic
281 roughness to deflect flows, similar in function to groynes (Jamieson, Rennie and Townsend,
282 2013), and increase turbulence and energy dissipation to protect banks and reduce
283 streamwise flow velocities upstream of infrastructure, such as bridge sills (Blanckaert *et al.*,
284 2012). Engineered log jams or wood features in these higher energy situations are often
285 secured by large posts, inserted vertically into the river bed, but they are designed to work
286 with geomorphological processes to store sediment, control bed levels, and modify channel
287 gradients (Addy and Wilkinson, 2016)
288

289 *Downstream flood hazard reduction*

290 The panel noted that that the most significant change in the use of large wood for river
291 management has been the shift towards natural flood management to reduce downstream
292 flood hazard. Natural flood management aims to reduce the frequency and magnitude of
293 flooding by modifying the land surface, floodplain and river channel to reduce surface runoff

294 generation, store water, and slow the flow of water through the catchment (Dadson *et al.*,
295 2017; Environment Agency, 2017).

296

297 Whilst many measures can be included within natural flood management, large wood is used
298 similarly whether on land or in river channels. On land, fallen trees or log jam structures (i.e.
299 debris dams, timber bunds, leaky dams) are placed on hillslopes or in ephemeral headwater
300 streams to increase hydraulic roughness and store small volumes of water temporarily
301 during storm events to slow its delivery to the river (Figure 1f). In the perennial river network,
302 introduced large wood structures operate in a similar manner with the added benefit of
303 increased over-bank flooding and reconnection of the river to the floodplain (Dixon *et al.*,
304 2016; Puttock *et al.*, 2017).

305

306 Whether placed on land or in the river, structures designed to “slow the flow” require
307 maintenance or replacement as the wood decays naturally. This replenishment of wood can
308 be done artificially, but, where riparian woodland of sufficient maturity, be as part of the
309 natural wood cycle so wood structures can become self-sustaining features. Furthermore,
310 woodland cover along river corridors provides surface roughness which attenuates floodplain
311 surface flows, retains floating wood, encourages the deposition of fine sediment and
312 infiltration of floodwaters into the floodplain, and encourages the retention and uptake of
313 nutrients. Therefore, if engineered wood features are incorporated as part of reinstatement
314 of the full cycle of trees and large wood, there many multiple benefits (e.g. Dosskey *et al.*,
315 2010)

316

317 **Uncertainties and risks**

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

330

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

344

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

355

356

357 **Tools and guidance - Recommendations**

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

362

363 Excellent resources exist to inform people about the use of wood for different management
364 purposes. For example, natural flood risk management has received increasing interest, and
365 national environmental regulators have responded with user-oriented guides on the design
366 and placement of flood-attenuation features, which are often wood-based. The Scottish
367 Environmental Protection Agency produced a natural flood management handbook (SEPA,
368 2015), and the Environment Agency recently published a summary of the evidence for
369 'working with natural processes' in flood risk management (Environment Agency, 2017). For
370 river restoration, practical advice and case study examples of wood used for habitat
371 enhancement and river engineering is available from The UK River Restoration Centre in
372 their Manual of River Restoration Techniques (River Restoration Centre, 2018).

373 Considerable information on assessment and implementation of river restoration measures
374 can be found on the European Union funded REFORM project website
375 (www.reformrivers.eu), including an easily accessible 'wiki' and links to scientific
376 publications. All of the guides provide background information on processes, practical
377 information on design, and advice on assessing multiple benefits and working with
378 stakeholders.

379

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

385

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

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

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

401

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

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

416

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

432

433

434

Conclusions

435 This paper summarises the current use of wood in river restoration and management based
436 on the experience and expertise of a panel of academics, river managers, restoration
437 practitioners and consultants in the UK. The paper illustrates that a great deal is known
438 about how large wood functions in rivers and how some of this knowledge is being
439 incorporated into using wood in many river management contexts including habitat creation,
440 river engineering, and flood hazard reduction. However, it also notes that many uncertainties
441 and risks remain, which are very significant in the densely populated landscape of much of
442 the UK. Whilst many tools and guidance already exist, the potential to fully integrate wood

443 and trees in catchment and river restoration, rehabilitation, and management is being held
444 back by a lack of knowledge on many issues. Addressing these knowledge gaps is the key
445 to a new era of increasing harmony between more naturally functioning river environments
446 and the health and well-being of those who live in and near these environments.

447
448

449

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Figure legends

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

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

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

Type	Uncertainties
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: existing trees on site or planting of native 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 ecosystem services 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 the type and size of wood features influence flood risk reduction?
Local risk	<ul style="list-style-type: none"> • Local flood hazard (reduction of channel capacity, increase in hydraulic roughness) • Reduction in land drainage; impacts on arterial drainage • Local increases in groundwater • 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 downstream blockages • Trash retention • Backwater effects • Potential impacts on fish passage
Upstream / downstream risk	<ul style="list-style-type: none"> • Impact risk to infrastructure – bridges, power cables, etc. • Blockage risk – increase flood hazard • Backwater effect • Cascade effect of multiple dam failure
Maintenance, liability, public safety	<ul style="list-style-type: none"> • Who owns and who maintains these structures?? • What maintenance is needed? • How long does a geomorphic habitat feature persist once the wood decays? • 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 lead to flooding • 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 | <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• Wood has been commonly removed from rivers, and is often perceived as 'debris' that should be removed• Conflicts with other watercourse users, because wood may limit their activity, e.g. fishing and canoeing |

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

Type	Studies / Questions / Requirements
Fieldwork	<ul style="list-style-type: none"> • 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? • 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	<ul style="list-style-type: none"> • Can modelling help to provide confidence / rules of thumb of scale of impact (hydrological, hydraulic, geomorphological)? • 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 • Hydraulic modelling needed to predict the downstream 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

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

Types	Tools / guidance
General	<u>Framework for using wood</u> <ul style="list-style-type: none"> • Explanation of the '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 and spatial scale of response to different techniques
Communication	<ul style="list-style-type: none"> • 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 • Improved guidance on the prioritisation and targeted placement of wood features or tree planting (i.e. most effective and cost-effective locations and measures) • Case study examples that illustrate multiple benefits, how to monitor 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. ○ Contributing area / flow timing ○ 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, and where you can do what you like? ○ Do nothing - Do minimum - Do something - Do a lot ○ Guidance on monitoring and adaptive management / maintenance

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673 Figure 1: (a) Large wood used in a restoration scheme on the lowland River Gade, UK (J.
674 England). (b) Large poplar spanning the channel with visible wood-induced geomorphic
675 features (e.g. sediment sorting, leaf litter) (I. Morrissey). (c) Large wood functioning as a pool
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