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

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15
16 **Abstract**

17
18 Trees fall naturally into rivers generating flow heterogeneity, inducing geomorphological
19 features, and creating habitats for biota. Wood is increasingly used in restoration projects
20 and the potential of wood acting as leaky barriers to deliver natural flood management by
21 “slowing the flow” is recognised. However, wood in rivers can pose a risk to infrastructure
22 and locally increase flood hazards. The aim of this paper is to provide an up-to-date
23 summary of the benefits and risks associated with using wood to promote geomorphological
24 processes to restore and manage rivers. This summary was developed through a workshop
25 that brought together academics, river managers, restoration practitioners and consultants in
26 the UK to share science and best-practice on wood in rivers. A consensus was developed on
27 four key issues: (i) hydro-geomorphological effects, (ii) current use in restoration and
28 management, (iii) uncertainties and risks, and (iv) tools and guidance required to inform
29 process-based restoration and management.

30
31 Key words: fluvial geomorphology, natural flood risk management, hydromorphology,
32 catchment management, river basin management, flood risk

33
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Introduction

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

49

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

68

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

78

79

Methodology

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

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

91
92 The workshop centred around a series of activities designed to encourage the sharing of
93 knowledge and best-practice on the following topics:

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

103
104 Experiences, observations and expert opinions of the participants were shared and debated
105 in small groups for each topic and a consensus reached in a final workshop activity and in
106 follow-up communications. These findings are reported below with, where appropriate,
107 support from the scientific literature.

108
109

Analysis

110 Hydro-geomorphological effects of wood

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

119
120 Even in undisturbed wooded river corridors, wood occurs in highly variable quantities and
121 accumulates in different locations depending upon the position in the river network (notably
122 reflecting proximity of the river to hillslopes, channel size and gradient), and the
123 geomorphological style of river channel and floodplain (Abbe and Montgomery, 2003;
124 Gurnell et al., this volume). The following summary of hydro-geomorphological and
125 ecological effects of wood in rivers is not exhaustive. It includes the hydrological, hydraulic,
126 geomorphological and ecological effects that the expert panel agreed were most relevant to
127 river restoration and management and which could be harnessed to reach their management
128 goals.

129

130 Hydrology and Hydraulics

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

135 and catchment hydrological conditions (Senter et al., 2017). How far wood moves during
136 these events, and where it is retained, varies enormously depending upon flow, catchment,
137 floodplain, river channel and riparian woodland characteristics as well as the quantity of
138 wood in transport (Braudrick and Grant, 2001; Ruiz-Villanueva, Zawiejska and Hajdukiewicz,
139 2016; Kramer and Wohl, 2017), but much of it is retained in accumulations (3 or more pieces
140 of wood) on the floodplain and in the river channel (e.g. Morris, Goebel and Palik, 2007).
141 Large accumulations of wood in rivers can attenuate flows of water and transported
142 materials, increase channel-floodplain hydrological connectivity and sustain ponded water
143 and flows in the river channel during dry periods (Dixon et al., 2016; Puttock et al., 2017).
144 While these effects are most obvious around large channel-spanning wood jams, smaller
145 wood accumulations and large individual pieces located in river channels have similar but
146 smaller effects, and floodplain wood can also slow and divert movement of water across the
147 floodplain surface, particularly where it is washed into large accumulations or jams around
148 standing trees. Furthermore, floodplain wood can sustain areas of relatively higher soil
149 moisture on floodplains by reducing evaporation from the ground surface.

150

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

157

158 Geomorphology

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

173

174 Ecology

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

182

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

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

194

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

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

199

200 **Habitat creation**

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

209

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

221

222 The workshop panel noted that although many restoration projects continue to use wood as
223 an immediate design feature, often within modified channels (Smith, Clifford and Mant,
224 2014), wood is increasingly being used to kick-start geomorphological processes to let the
225 river "do the work", e.g. River Bure, UK (Harvey et al., 2017). In the River Wensum (Norfolk,
226 UK), large wood has been positioned across the channel above the average water level so
227 that it interacts with the flow at high discharges. This type of placement minimises potential
228 negative impacts on this low-energy, gravel-bed chalk stream at normal and low flows (e.g.
229 backwater effect, siltation), but promotes geomorphological activity at high flows (Figure 1b).
230 More projects are considering the wider river corridor and the potential for wood to increase
231 local water levels and improve lateral hydrological connectivity and reconnecting and
232 creating floodplains to support wetland conservation. Large wood is also being used to
233 improve water quality by trapping and storing of fine sediment, itself a diffuse pollutant, and
234 sediment-bound contaminants (Janes et al., 2017).

235

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

249

250 River engineering

251 Wood and woody material is used frequently for river engineering to reduce lateral channel
252 migration, influence the deposition or erosion of bed sediment, or to protect infrastructure. It
253 is viewed as a more environmentally-friendly alternative to harder forms of engineering
254 (Wohl, Lane and Wilcox, 2015). Indeed, the concept of 'engineered wood jams' has been
255 promoted for at least the last 15 years as a measure for river rehabilitation (Abbe et al.,
256 2003). There is considerable overlap in how wood is used in practice; adding large wood
257 features may have more than one function (e.g. habitat creation and narrowing of flows to
258 flush fines), and this section focuses on the use of wood for hydrological and
259 geomorphological effects.

260

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

269

270 In higher energy rivers, the wood used is larger, placement must be more carefully designed,
271 often based on hydraulic modelling, and securing requires significant consideration and
272 investment. Whole tree trunks and root wads are commonly used to add hydraulic
273 roughness to deflect flows, similar in function to groynes (Jamieson, Rennie and Townsend,
274 2013), and increase turbulence and energy dissipation to protect banks and reduce
275 streamwise flow velocities upstream of infrastructure, such as bridge sills (Blanckaert et al.,
276 2012). Engineered log jams or wood features in these higher energy situations are often
277 secured by large posts, inserted vertically into the river bed, but they are designed to work
278 with geomorphological processes to store sediment, control bed levels, and modify channel
279 gradients (Addy and Wilkinson, 2016)

280

281 Downstream flood hazard reduction

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

286 generation, store water, and slow the flow of water through the catchment (Dadson et al.,
287 2017; Environment Agency, 2017).

288
289 Whilst many measures can be included within natural flood management, large wood is used
290 similarly whether on land or in river channels. On land, fallen trees or log jam structures (i.e.
291 debris dams, timber bunds, leaky dams) are placed on hillslopes or in ephemeral headwater
292 streams to increase hydraulic roughness and store small volumes of water temporarily
293 during storm events to slow its delivery to the river (Figure 1f). In the perennial river network,
294 introduced large wood structures operate in a similar manner with the added benefit of
295 increased over-bank flooding and reconnection of the river to the floodplain (Dixon et al.,
296 2016; Puttock et al., 2017).

297
298 Whether placed on land or in the river, structures designed to “slow the flow” require
299 maintenance or replacement as the wood decays naturally. This replenishment of wood can
300 be done artificially, but, where riparian woodland of sufficient maturity, be as part of the
301 natural wood cycle so wood structures can become self-sustaining features. Furthermore,
302 woodland cover along river corridors provides surface roughness which attenuates floodplain
303 surface flows, retains floating wood, encourages the deposition of fine sediment and
304 infiltration of floodwaters into the floodplain, and encourages the retention and uptake of
305 nutrients. Therefore, if engineered wood features are incorporated as part of reinstatement
306 of the full cycle of trees and large wood, there many multiple benefits (e.g. Dosskey et al.,
307 2010)

308

309 **Uncertainties and risks**

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

322

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

336
337 Other issues can be minimised if stakeholder and community engagement is an integral part
338 of the design process. Wohl et al. (2015) argue that rivers should be viewed as a 'hybrid of
339 nature and culture' and restoration schemes should be informed or co-produced by the
340 community. This engagement can also help to overcome concerns about liability, and
341 maintenance. For example, the Stroud Rural SuDS Project, a partnership between the
342 Environment Agency, Stroud District Council and Gloucestershire County Council in
343 England, developed clear guidelines to assign responsibilities for wood debris structures for
344 natural flood risk management which supported landowner participation in the project.
345 However, the panel agreed that additional scientific research is needed to quantify
346 uncertainty, reduce risks, and inform future management practices (Table 2).

347
348

349 **Tools and guidance - Recommendations**

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

354

355 Excellent resources exist to inform people about the use of wood for different management
356 purposes. For example, natural flood risk management has received increasing interest, and
357 national environmental regulators have responded with user-oriented guides on the design
358 and placement of flood-attenuation features, which are often wood-based. The Scottish
359 Environmental Protection Agency produced a natural flood management handbook (SEPA,
360 2015), and the Environment Agency recently published a summary of the evidence for
361 'working with natural processes' in flood risk management (Environment Agency, 2017). For
362 river restoration, practical advice and case study examples of wood used for habitat
363 enhancement and river engineering is available from The UK River Restoration Centre in
364 their Manual of River Restoration Techniques (River Restoration Centre, 2018).
365 Considerable information on assessment and implementation of river restoration measures
366 can be found on the European Union funded REFORM project website
367 (www.reformrivers.eu), including an easily accessible 'wiki' and links to scientific
368 publications. All of the guides provide background information on processes, practical
369 information on design, and advice on assessing multiple benefits and working with
370 stakeholders.

371

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

377

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

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

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

393
394 For consultants and practitioners, the panel agreed that more emphasis could be placed on
395 communication with project partners and stakeholders to explain how and why wood is being
396 used in a design, what the options are and how they affect risks and multiple benefits, and
397 the final plan meets their project goals (Wohl, Lane and Wilcox, 2015). In particular, the
398 panel recommended that consultants and practitioners:

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

408
409 Finally, the expert panel emphasised that successful use of wood in restoration and
410 management was dependent on public acceptance and support. The shift towards ‘nature-
411 based solutions’ that ‘work with natural processes’ is a significant change in management
412 policy. Whilst it is generally perceived positively by managers, practitioners and scientists,
413 panel members have spoken to numerous members of the public who either did not know
414 about this shift or considered it counter to their understanding of river management. For
415 generations, society has controlled river discharges, straightened and deepened channels,
416 added reinforcement to prevent bank erosion, protected floodplains from flooding, and
417 removed wood from rivers. Against this background, letting wood back into rivers may
418 appear to be a complete U-turn in management practice and fundamentally disagree with
419 people’s perception of what a river should look like. Therefore, in addition to the above
420 recommendations for consultants and practitioners, the panel suggested that all involved
421 with river restoration and management work closely with catchment partnerships and other
422 organisations to highlight the wider benefits of an ‘untidy’ landscape and increase the
423 publicity of demonstration sites (e.g. Stroud Rural SuDS).

424
425
426

Conclusions

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

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

439
440
441

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450
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642 **Figure legends**

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

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

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653 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

- Use of imported wood and the potential for introduction of invasive species or disease
- Increase in standing water and biting insects

Public perception

- 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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657 Table 2: Future scientific research needed to support the use of large wood in river
 658 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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661 Table 3: Tools and guidance needed to support use of large wood in river restoration and
 662 management

Types	Tools / guidance
General	<p data-bbox="475 304 826 331"><u>Framework for using wood</u></p> <ul style="list-style-type: none"> <li data-bbox="480 338 1286 365">• Explanation of the ‘wood cycle’, effects in rivers/floodplains <li data-bbox="480 371 1129 398">• Design guide - right approach in the right place <li data-bbox="480 405 1018 432">• Primary drivers - funding opportunities <li data-bbox="480 439 970 465">• Context for you and your river type <li data-bbox="480 472 746 499">• Design principles <li data-bbox="480 506 802 533">• Case study examples
Specific	<ul style="list-style-type: none"> <li data-bbox="480 584 1334 651">• What is wood likely to do under specific local conditions (river type, flow regime, catchment size, geology, etc)? <li data-bbox="480 658 1334 685">• Temporal and spatial scale of response to different techniques
Communication	<ul style="list-style-type: none"> <li data-bbox="480 723 1366 824">• 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 <li data-bbox="480 831 1366 931">• Improved guidance on the prioritisation and targeted placement of wood features or tree planting (i.e. most effective and cost-effective locations and measures) <li data-bbox="480 938 1366 1005">• Case study examples that illustrate multiple benefits, how to monitor benefits, and ways to minimise risks (e.g. lessons learnt) <li data-bbox="480 1012 1366 1059">• Demonstration sites / catchments - to share knowledge and build confidence
Opportunity mapping	<ul style="list-style-type: none"> <li data-bbox="480 1104 1366 1373">• Input data layers <ul style="list-style-type: none"> <li data-bbox="555 1137 855 1164">○ Wood cycle, source <li data-bbox="555 1171 1366 1238">○ Land use, geology, soil type/ runoff potential, hill slope, channel gradient. <li data-bbox="555 1245 986 1272">○ Contributing area / flow timing <li data-bbox="555 1279 1066 1305">○ Risk of erosion / channel movement <li data-bbox="555 1312 890 1339">○ Flood hazard mapping <li data-bbox="555 1346 1042 1373">○ Location and type of infrastructure <li data-bbox="480 1379 1366 1641">• Where is wood ‘good’, and where is wood ‘risky’ (considering local and downstream risks and benefits)? <ul style="list-style-type: none"> <li data-bbox="555 1447 1366 1536">○ 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? <li data-bbox="555 1543 1270 1570">○ Do nothing - Do minimum - Do something - Do a lot <li data-bbox="555 1576 1286 1641">○ Guidance on monitoring and adaptive management / maintenance

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



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