Received: 25 December 2020 | Revised: 23 June 2021 | Accepted: 27 June 2021

DOI: 10.1002/wat2.1546

OVERVIEW

WIREs WATER WILEY

# Potential secondary effects of in-stream wood structures installed for natural flood management: A conceptual model

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**Edited by:** Stuart N. Lane, Editor-in-Chief

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**Abstract**

The use of in-stream wood is one of the most commonly employed natural flood management (NFM) techniques. The effectiveness of NFM wood structures in reducing flood risks (i.e., their "primary" effect) has been relatively well documented. However, their additional or "secondary" effects on other natural processes have not been fully evaluated. These secondary effects can be inferred by reviewing previous studies that scrutinized natural wood accumulations or artificial wood structures constructed for purposes other than NFM. The degree of contact with base flows and the stream bed provides a broad classification of NFM wood structures. Having considered the similarities between NFM wood structures and other in-stream wood types, it is suggested that the following geomorphic effects are common to all types of NFM wood structures: pool formation; accumulation of clasts immediately upstream; buffering against stream bed coarsening; and bank erosion, causing channel widening and the formation of floodplain channels. These geomorphic changes contribute to stream bed heterogeneity, potentially creating new niches for aquatic organisms such as macroinvertebrates. Moreover, NFM wood structures may retain benthic organisms accidentally flushed away during flood events, serving as sources of colonists during phases of recovery. Geomorphic changes induced by NFM wood structures may also contribute to spatial variation in rates of biogeochemical processing. Accumulation of fine sediments in some areas may provide more surfaces for the attachment of organic matter and micro-organisms, hence increasing benthic metabolic rates. Stream bed scouring in other areas may lead to sediment instability, suppressing the growth of micro-organisms and benthic metabolic rates.

This article is categorized under:

Water and Life > Conservation, Management, and Awareness
Science of Water > Water Extremes
Engineering Water > Sustainable Engineering of Water

KEYWORDS

biogeochemistry, ecology, geomorphology, in-stream wood, natural flood management

## 1 | INTRODUCTION

The use of wood structures (Figure 1) has become a well-established technique for natural flood management (NFM; Burgess-Gamble et al., 2018). Wood structures installed specifically for NFM (hereafter "NFM wood structures") have been reported in many countries, including the United Kingdom (UK), for example in: Pickering Beck, North Yorkshire (Nisbet et al., 2015); Black Water, Hampshire (Addy et al., 2018); Belford Burn, Northumberland (Nicholson et al., 2018); and Blackbrook, Merseyside (Norbury et al., 2018). They are thought to be effective in slowing the rate of water transfer from uplands to lowlands owing to two hydraulic effects (Dadson et al., 2017; Lane, 2017): first, they impound water in the channel; second, they act as significant roughness elements that increase local flow resistance. These two processes decrease flow velocities and increase water levels such that water subsequently flows out of the channel, into storage areas such as upland floodplains (Gregory et al., 1985; Keys et al., 2018; Thomas & Nisbet, 2012; Wenzel et al., 2014), thereby reducing stream discharge and contributing to flood peak attenuation (Dixon et al., 2016). In addition, flood peaks from multiple tributaries can be delayed such that they will not converge upon reaching the main channel, greatly reducing the magnitude of flood events in urban areas downstream (Lane, 2017).

While the "primary" effects of NFM wood structures in reducing flood risks are fairly well documented, only a few empirical studies have quantified their secondary effects on local geomorphic, ecological, and biogeochemical processes (e.g., Deane et al., 2021; Janes et al., 2017; Short et al., 2019). Filling the knowledge gaps pertaining to the secondary effects of NFM wood structures is important for two reasons. First, if they are confirmed to be associated with a wide range of additional benefits, it will be more justifiable to make use of them in future flood management (Barlow et al., 2014). Second, before installing NFM wood structures, it is important to ensure that they will not cause adverse effects, such as disturbing aquatic ecosystems or causing blockage downstream upon breaking up (Ruiz-Villanueva et al., 2014; Schmocker & Hager, 2011).

The core aim of this article is to propose a conceptual model of the potential secondary effects of NFM wood structures by making inferences from previous studies focusing on natural in-stream wood accumulations or artificial wood structures deployed for purposes other than NFM. The conceptual model can then be empirically verified by future studies. There is a wide range of NFM wood structures (Dixon, 2016). To simplify matters in this article, NFM wood structures are broadly classified into four categories based on their degree of interaction with the water column, which would determine the hydraulic effect of the structure (Manners et al., 2007) and potentially its geomorphic, ecological, and biogeochemical effects. Type 1 structures (Figure 2(a)) refer to those completely spanning the channel and not interacting with base flows at all. Type 2 structures (Figure 2(b)) are also full-spanning, but they interact with base flows while maintaining some gaps with the stream bed. Type 3 structures (Figure 2(c)) are full spanning with complete contact with the stream bed. Finally, Type 4 structures (Figure 2(d)) include those that only maintain contact with one bank.

It is the explicit consideration of NFM contexts that differentiates this review from existing reviews that have documented the general geomorphic (Montgomery et al., 2003; Wohl, 2013; Wohl & Scott, 2017) and ecological (Benke &


FIGURE 1 (a) NFM woody dam and (b) natural woody debris in the upper river cover catchment, North Yorkshire, UK

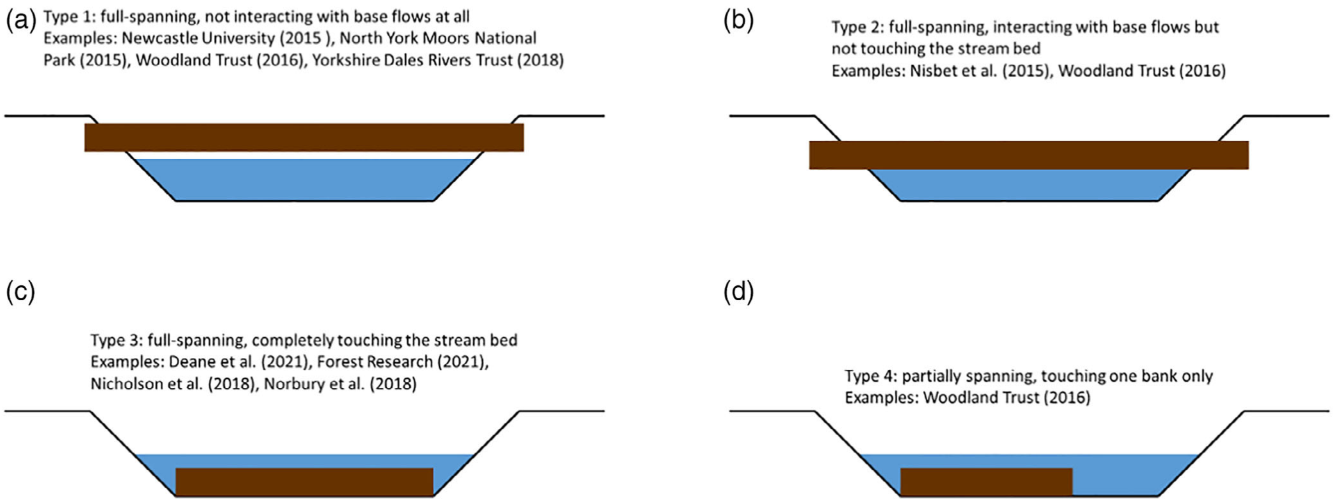


**FIGURE 2** (a–d) Different types of NFM wood structures currently in use

Wallace, 2003; Dolloff & Warren, 2003; Gurnell et al., 2005; Lester & Boulton, 2008) effects of in-stream wood. Moreover, very few reviews have adopted an interdisciplinary perspective. For example, Montgomery et al. (2003) provided a comprehensive summary of the geomorphic effects of in-stream wood, but the same detailed treatment was not given to the effects on ecosystems; Grabowski et al. (2019) covered more aspects, but the effects on biogeochemical cycling were not discussed. In contrast, this review summarizes the geomorphic, ecological, and biogeochemical effects of in-stream wood simultaneously to highlight the interaction between them. This review also complements recent entries in *WIREs Water*, such as that by Wohl (2015) on perceptions of in-stream wood and that by Addy & Wilkinson (2019) on incorporating wood in hydraulic models.

More than 500 peer-reviewed primary research articles published in scientific journals (details of which are provided in the Appendix S1) were consulted to extract information potentially relevant to NFM wood structures. The effects of in-stream wood most commonly reported by these research articles are summarized in Figure 3. Sections 2 to 4 discuss the extent to which these geomorphic, ecological, and biogeochemical effects are associated with the four categories of NFM wood structures identified earlier. Section 5 summarizes hypotheses pertaining to NFM wood structures that need to be verified by further empirical research.

## 2 | POTENTIAL GEOMORPHIC EFFECTS OF NATURAL FLOOD MANAGEMENT WOOD STRUCTURES

The most commonly recorded geomorphic effects of in-stream wood were pool formation, sediment storage, and influencing bank morphology (Figure 3(a)). These effects are also likely to be associated with NFM wood structures and are further elucidated in this section.

### 2.1 | Pool formation

NFM wood structures will lead to pool formation wherever they concentrate flows (Wallerstein, 2003; Figure 4: connection between "hydraulics" and "pool formation"). However, the four types of NFM wood structures would concentrate flows in different ways, so they are expected to form different types of pools. Type 1 structures force water to flow beneath them and may therefore lead to the formation of underflow pools (Schalko et al., 2019; Robison & Beschta, 1990; Wallerstein et al., 2003). In contrast, Type 3 structures do not maintain any gap with the stream bed, and water can only flow over them, leading to the formation of plunge pools immediately downstream (Baillie & Davies, 2002; Bendix & Cowell, 2010; Bilby & Ward, 1989, 1991; Keller & Swanson, 1979; Zelt & Wohl, 2004). Mao et al. (2008) suggested that a single wood structure of this type could create a pool as large as 20 m$^3$. Type 2 structures also concentrate water underneath them, but since they block parts of the water column, some water may be forced to

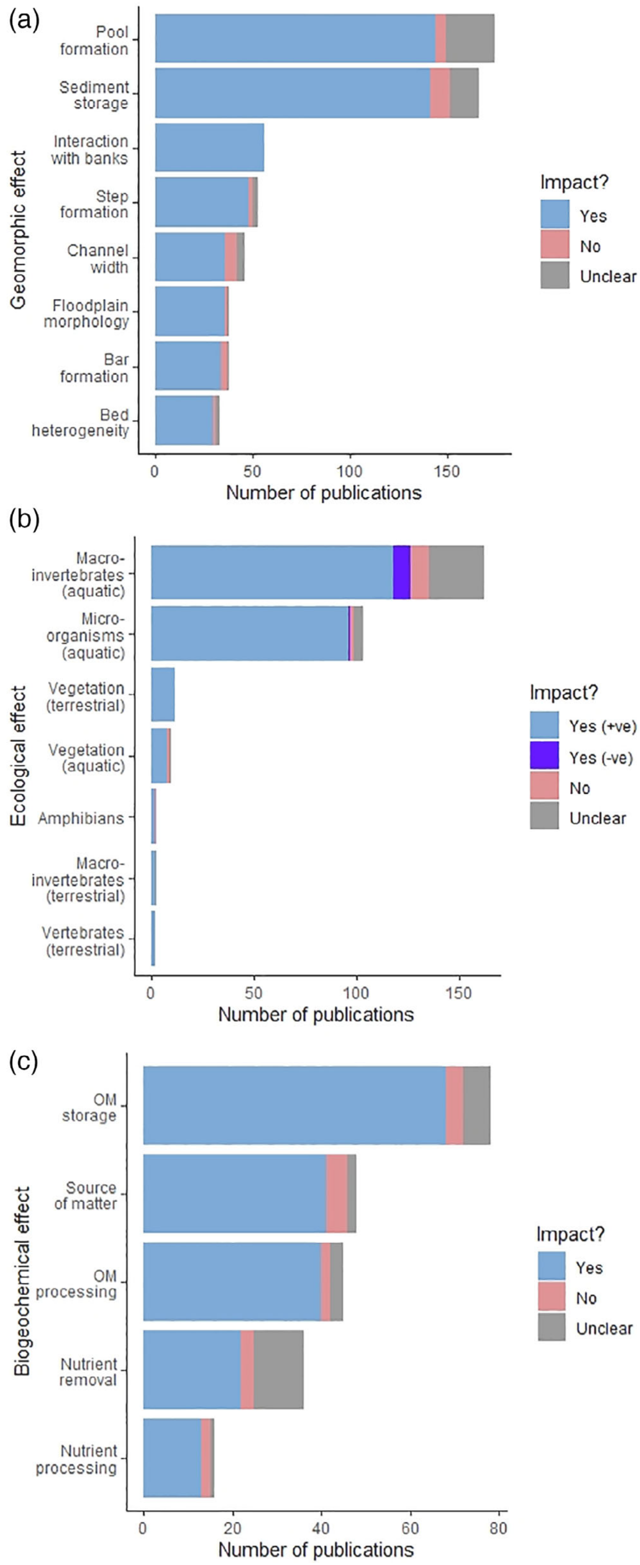


**FIGURE 3** Frequently reported (a) geomorphic, (b) ecological, and (c) biogeochemical effects of in-stream wood in the 527 research articles reviewed

flow over them as well. Therefore, both plunge pools and underflow pools may be formed. Type 4 structures will divert flows away from the bank to which they are attached, likely forming deflector pools in the center of the channel or near the opposite bank (Gallisdorfer et al., 2014).

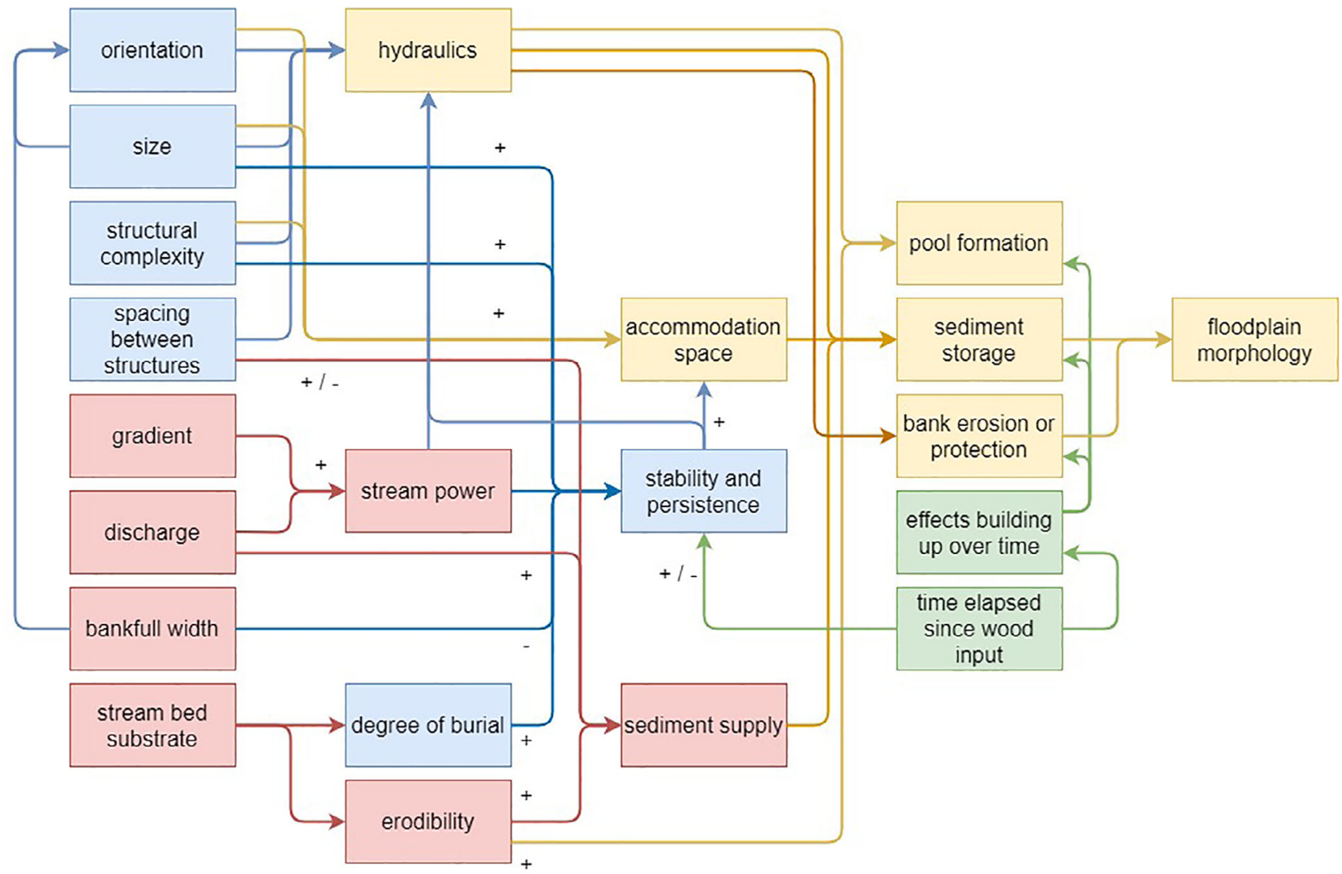


**FIGURE 4** Factors influencing the geomorphic significance of NFM wood structures (yellow: Frequently observed geomorphic effects; blue: Wood structure characteristics; red: Stream characteristics; green: Temporal factors; positive sign: Accelerating; negative sign: Inhibiting)

A few factors have been identified to potentially limit the ability of NFM wood structures in forming pools. First, high stream power (Figure 4) is required. For example, Jackson & Sturm (2002) found that, although the small streams in the Coast Ranges (Washington State, The United States) had high wood loads and channel gradients (32%), their discharge and stream power were insufficient to carve pools. Osei et al. (2015b) studied wood placements in River Bure (UK) and found that well-defined pools had not yet appeared although scouring around wood pieces had started to expose the gravel layer previously buried under sand. They suggested that more high flows were needed for such pools to develop (Figure 4: "effects building up over time"). These observations are particularly relevant to Type 1 structures as they only concentrate flows when water levels are sufficiently high. The time required for pools associated with Type 1 structures to develop should therefore depend on the frequency of flood events. Scouring induced by Type 1 structures will stop completely during moderate flows, and the pools may become gradually infilled with sediments (Elosegi et al., 2017).

Next, the size of wood pieces needs to be sufficiently large. Mao et al. (2008) observed that wood pieces with small diameters failed to carve deep plunge pools as they only provided small drops in elevation. Conversely, Bilby & Ward (1989) found that wood structures with greater volumes generally produced more extensive pools (Figure 4: relationship between "size," "hydraulics," and "pool formation"). Moreover, there needs to be a minimum distance separating two wood structures, otherwise hydraulic interactions between the two will suppress pool formation (Bennett et al., 2015; Nakamura & Swanson, 1993; Figure 4: "spacing between structures" affecting "hydraulics"). In upland streams, the stream bed is dominated by bedrock and boulders. These roughness elements are also effective pool-forming agents, so the number of wood-related pools may be outweighed by the number of boulder-related pools (Hilderbrand et al., 1997; Kraft et al., 2002). Moreover, bedrock and boulders are relatively resistant to erosion, making it more difficult to carve pools in these streams (Figure 4: link between "erodibility" and "pool formation").

## 2.2 | Sediment storage

There are two modes of sediment storage associated with NFM wood structures. First, where they maintain contact with the stream bed (particularly Type 3 structures), they will intercept bed load particles and lead to the build-up of sediments immediately upstream (Comiti et al., 2008; Janzen & Westbrook, 2011; Mosley, 1981; Nakamura & Swanson, 1993; Thompson, 1995; Figure 4: creation of "accommodation space" to be filled by sediments). The typical volume of material retained by each structure would lie between 10 and 100 $m^3$ (Andreoli et al., 2007; Mao et al., 2008). In cases with high storage, local channel gradients will be significantly reduced (Davidson & Eaton, 2013; Larson et al., 2001; Montgomery & Abbe, 2006). Type 2 structures may retain less material than Type 3 structures as they are partially suspended above the stream bed and sediments may be released from the gaps (Smith et al., 1993). Type 3 structures made of few logs with little interstitial space may also be ineffective in retaining sediments (Andreoli et al., 2007; Mao et al., 2008; Figure 4: "size" and "structural complexity" influencing "accommodation space"). Type 4 structures may easily release sediments as well as they do not completely span the channel (Martin et al., 2016; Smock et al., 1989; Figure 4: "orientation" affecting "accommodation space"). Type 1 structures are completely suspended above the stream bed and may not intercept any fine material at all, but cobbles and boulders that are too large to pass through the gap will still be retained (Scott et al., 2014).

The second mode of sediment storage involves reach-scale textural fining following wood input (Assani & Petit, 1995; Gerhard & Reich, 2000; Merz, 2001; Nagayama et al., 2012; Shields & Smith, 1992). This is due to the additional flow resistance introduced by the wood itself, which results in A lower average flow velocity and less energy available for sediment transport (Manga & Kirchner, 2000; Figure 4: linkage between "hydraulics" and "sediment storage"). Type 2, Type 3, and Type 4 structures permanently interact with the water column, so they may lead to textural fining during base flows as well as buffer against coarsening during high flows. On the other hand, Type 1 structures may only buffer against coarsening as they do not interact with base flows.

Two catchment-scale factors influence the effectiveness of NFM wood structures in storing sediments. First, sediment supply is important. In streams in central Sierra Nevada (California, The United States), although wood had created extra accommodation space, there was insufficient material to fill it (Berg et al., 1998; Figure 4: "sediment storage" as a product of both "accommodation space" and "sediment supply"). Sediment supply could be mediated by the presence of other structures upstream (Figure 4: "spacing between structures" controlling "sediment supply"). In the Rocky Mountain National Park (Colorado, The United States), Wohl & Beckman (2014) observed that woody dams retaining large amounts of sediments were usually followed by those with much lower storage downstream. In contrast, in the case of Osei et al. (2015a), where two wood structures were monitored, the downstream structure retained more sediments because the upstream structure (a deflector) caused intense scouring. At the other extreme, when sediment supply is excessive, it will be difficult to determine if in-stream wood is storing sediments or simply co-existing with them (Short et al., 2015; Wohl et al., 2009).

Second, high flows can erode sediments stored by the structures. For example, Nakamura & Swanson (1993) observed repeating cycles of aggradation and degradation in the vicinity of wood pieces in Lower Lookout Creek (Oregon, The United States), indicating that some sediments stored by in-stream wood must have been reworked during high flows. Similar reworking of stored sediments was reported by Shields et al. (2008) in Little Topashaw Creek (Mississippi, The United States). Wood-induced sediment storage will also be negligible if stream power is so low that particles will settle onto the stream bed even without the influence of wood (Smock et al., 1989).

## 2.3 | Interaction with banks and changing channel widths

Full-spanning NFM wood structures oriented perpendicular to the flow are likely to divert water to the two sides, resulting in channel widening via the erosion of both banks (Nakamura & Swanson, 1993). Bank erosion associated with Type 1 and Type 2 structures should be more pronounced than that caused by Type 3 structures because the former would divert faster-flowing water in the upper part of the water column experiencing less friction offered by the stream bed into the two banks (Wallerstein et al., 2003). Type 4 structures will concentrate the flow to one side of the channel, leading to erosion along one bank but greater stability along the other (Gallisdorfer et al., 2014). When NFM wood structures are displaced by high flows and become parallel to the bank, they can probably protect the bank from the erosive power of the flow (Burrows et al., 2012). These effects on channel width are typically localized in areas in the vicinity of in-stream wood. If there are numerous structures deployed, higher mean widths at the reach scale may result (Jackson & Sturm, 2002; Shields & Smith, 1992). These streams also tend to have higher variance in width (Robison & Beschta, 1990) as areas influenced by wood are interspersed with those that are not.

### 2.4 | Other geomorphic effects

NFM wood structures may lead to higher stream bed heterogeneity. First, this is due to the increase in the variety of channel units (Roni & Quinn, 2001). In addition to causing pool formation, Type 3 structures also trigger the development of other channel units such as steps (Erskine et al., 2012; Parkyn et al., 2009; Ruffing et al., 2015; Scott et al., 2014; Wohl et al., 1997), which offer extra spill resistance (Curran & Wohl, 2003) and play a role in limiting erosion downstream. Type 1 and Type 2 structures may also cause step formation only if the gap between the structure and the stream bed is entirely clogged. Type 4 structures likely induce bar formation — as they do not completely span the channel, water will flow around them, creating zones of no flow immediately downstream (Abbe & Montgomery, 1996; Gurnell et al., 2001). Channels with shallow depths, low stream power and fairly high supplies of sediments are more conducive to bar formation (Gurnell & Petts, 2006; Lisle et al., 1991). Type 1 and Type 2 structures are unlikely to create bars immediately downstream, but they may still induce bar formation further downstream by supplying sediments through the scouring of pools or the sudden release of sediments during failure. NFM wood structures may also increase stream bed heterogeneity through: (a) increasing the number of sedimentary facies (Elosegi et al., 2017); (b) the formation of a more rugged stream bed with greater topographic variation (Ruffing et al., 2015); and (c) increasing variation in flow velocities and directions (Klaar et al., 2011).

NFM wood structures likely influence floodplain morphology as well. Type 1 and Type 2 structures directly divert water onto the floodplain, and the resulting overbank flow may be concentrated and erosive enough to carve new channels on the existing floodplain (Andreoli et al., 2007; Collins et al., 2012; Sear et al., 2010; Wohl, 2011). Even without the creation of new channels, overbank erosion and deposition associated with Type 3 and Type 4 structures will add spatial heterogeneity and roughness to the floodplain, further contributing to the primary objective of flood-risk reduction. However, if the new floodplain channels formed ultimately reconnect with the main stem through shorter paths as in meander cut-offs (Keller & Swanson, 1979; O'Connor et al., 2003), NFM efforts will be undermined because water is being transported downstream more quickly. In-channel sediment accumulations upstream of Type 3 and Type 4 structures may also integrate with the existing floodplain in the long run if they are not reworked (Montgomery & Abbe, 2006).

### 2.5 | Importance of structural stability

The stability and persistence of NFM wood structures determine how long their geomorphic influence will last (Cadol & Wohl, 2011). First, stability is contributed by the structural complexity (Figure 4) of wood structures. Compared with conifers, deciduous trees are more likely to interlock with each other and form stable structures in channels because they have more irregular forms (Gurnell & Sweet, 1998). For the same reason, wood pieces with root wads attached also tend to form more stable dams (Baillie et al., 2008). Some wood species such as willow (Mikuś et al., 2013) and alder (Klaar et al., 2011) can resprout and develop roots into the stream bed, contributing to stability. Second, attachment to the banks or partial burial (Figure 4) in the stream bed increases structural stability (Baillie et al., 2008). Conversely, small and short pieces either float on the water surface or are only attached to one bank, so they will be easily rotated and transported by the flow (Piégay & Gurnell, 1997; Robison & Beschta, 1990). Third, time is an important factor. NFM wood structures will become more complex and stable if they trap small wood pieces over time, but they will also undergo decomposition (Merten et al., 2013), making them less likely to sustain their geomorphic influence (Cadol & Wohl, 2011; Figure 4: unclear relationship between "stability and persistence" and "time elapsed since wood input"). Even displaced structures can exert some influence on channel morphology. Wood pieces in transit can scour the bed and the banks mainly through abrasion (Nakamura & Swanson, 2003). When they eventually get deposited at preferential locations (e.g., along the outer bank of a bend, at the upstream end of an exposed bar, behind bridge piers or other wood structures downstream), they may continue to exert their geomorphic influences at those places (Melville & Dongol, 1992; Pagliara et al., 2011; Piégay & Gurnell, 1997).

# 3 | POTENTIAL ECOLOGICAL EFFECTS OF NATURAL FLOOD MANAGEMENT WOOD STRUCTURES

The influence of NFM wood structures on fish is not discussed in this review as relevant information could be extracted from existing reviews (Dolloff & Warren, 2003; Nagayama & Nakamura, 2010; Smokorowski & Pratt, 2007; Zalewski et al., 2003). Swanson et al. (2021) also pointed out that the response of fish to in-stream wood had received disproportionately more attention than that of other organisms, so heavier weighting should be placed on aquatic micro-organisms and aquatic macroinvertebrates. Other taxonomic groups reported to be benefited by in-stream wood include aquatic vegetation, amphibians, terrestrial macroinvertebrates, and terrestrial vertebrates (Figure 3(b)), but due to the lack of evidence, it is uncertain if findings can be applied to NFM contexts. This section will therefore focus on aquatic macroinvertebrates, aquatic micro-organisms, and riparian vegetation.

## 3.1 | Aquatic macroinvertebrates

The submerged surfaces of Type 2, Type 3, and Type 4 structures should harbor a high diversity of aquatic macroinvertebrates (Benke & Wallace, 2003). Some of these species are xylophagous, ingesting wood fragments as the major component of their diet (Anderson et al., 1984; Collier & Halliday, 2000; Steedman & Anderson, 1985). External food sources on the wood surface can be exploited by other functional feeding groups: scrapers (Collier et al., 2004; Tank & Winterbourn, 1996), filter-feeders (Cudney & Wallace, 1980), and collector-gatherers (Smock et al., 1989). The structures offer benefits beyond nutrition as some species make use of them for pupation, emergence, and oviposition (Hoffmann & Hering, 2000). Which group dominates depends on wood species and decay status (Magoulick, 1998). There is normally a transition from dominance by surface dwellers to dominance by xylophagous borers as the wood piece softens over time to become more palatable (Gurnell et al., 1995). Species compositions on wood surfaces are sometimes distinct from those living on inorganic substrates (Benke et al., 1984; Dossi et al., 2018; Phillips, 2003; Shields et al., 2008; Warmke & Hering, 2000), but more commonly the individuals found on wood surfaces are simply opportunists facultatively associated with wood (Dudley & Anderson, 1982; Lester & Wright, 2009; Valente-Neto et al., 2015). Filter-feeding species, by constructing nets on elevated wood surfaces instead of sediment surfaces, can gain access to the more nutritious particles suspended higher in the water column (Cashman et al., 2016). Predators also prefer wood surfaces as there is a higher prey availability (Phillips & Kilambi, 1994).

Macroinvertebrate communities in the vicinity of NFM wood structures are also likely to be diversified. First, this may be due to the interception of organic particles that serve as favorable food sources for some macroinvertebrates (Gerhard & Reich, 2000; Winkler, 1991; Figure 5). In other situations, increased diversity may be due to increased habitat heterogeneity, enabling the habitat needs of more species to be satisfied (Yarnell, 2006; Figure 5). For example, large wood diversified the stream bed of Pliszka River, Poland, into distinct patches of sand, gravel, and organic matter, and each of these three types harbored a distinct faunal assemblage (Pilotto et al., 2014). Another study conducted in the Ume River catchment, Sweden, showed that locally increased flow velocities and sediment sizes induced by in-stream wood favored a distinct assemblage of species (Frainer et al., 2017). Moreover, buried wood was found to increase the densities of invertebrates such as ostracods, mites, and annelid worms inhabiting the subsurface (Crenshaw et al., 2002). Since Type 1 structures only interact with the water column occasionally, their constituent wood pieces are unlikely to be persistently inhabited by aquatic macroinvertebrates. They are also unlikely to intercept much floating organic matter and benefit shredders during base flows. However, Type 1 structures may retain macroinvertebrates flushed away from their benthic habitats during high flows and serve as sources of colonists after catastrophic events (Borchardt, 1993; Hax & Golladay, 1998; Figure 5). Moreover, as Type 1 structures could potentially drive geomorphic changes, they may diversify macroinvertebrate communities on the stream bed. The creation of new floodplain channels and the subsequent increase in stream bed area may increase the population size at the landscape scale (Venarsky et al., 2018).

NFM wood structures may sometimes have limited effects on macroinvertebrates in upland streams. First, this may be due to the prominence of coarse sediments (Jähnig & Lorenz, 2008; Phillips & Kilambi, 1994), which provide favorable habitats for macroinvertebrates (Drury & Kelso, 2000; Imbert et al., 2005). Consequently, there is no incentive for them to migrate to wood surfaces. Conversely, fine substrates are less attractive due to their low stability, so the addition of wood in streams dominated by these substrates will lead to the concentration of macroinvertebrates on wood surfaces (Benke, 1984). Second, as mentioned earlier, it may be more difficult for the structures to modify the physical

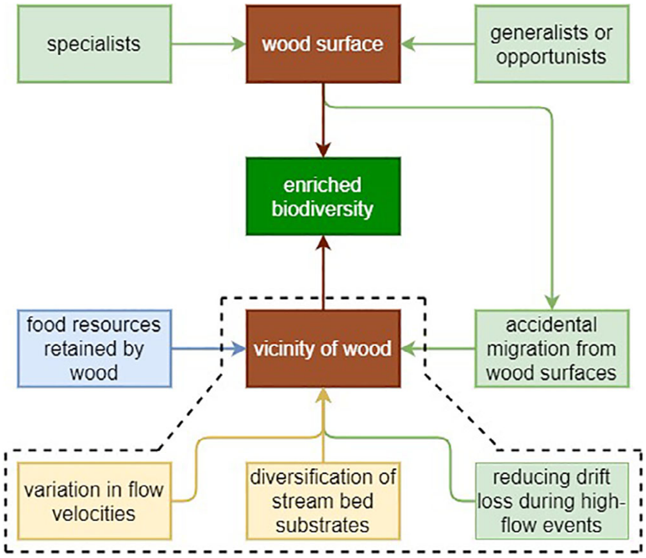


**FIGURE 5** Mechanisms through which NFM wood structures diversify macroinvertebrate communities (yellow: Mechanisms associated with geomorphic changes; green: Mechanisms associated with movements of organisms; blue: Mechanisms associated with biogeochemical changes); pathways most relevant to Type 1 structures enclosed by dotted box

habitat in upland streams, hence offering no new niches for additional species. For instance, in Barbours Creek (Virginia, The United States), the addition of wood did not cause any increase in the number of pools, so no new habitat was created for species preferring slow-flow habitats (Hilderbrand et al., 1997). In other situations, factors independent of the presence of wood may be more important in limiting macroinvertebrate diversity, including the inability of organisms to disperse and colonize favorable sites (McKie & Cranston, 2001; Jähnig et al., 2010), the availability of sunlight (Carlson et al., 1990), the amount of fine sediment supply (Larson et al., 2001), and the frequency of extreme events that could cause physical disturbances and affect water quality (Testa et al., 2010).

Finally, it is worth highlighting situations where NFM wood structures may harm benthic macroinvertebrates. Arimoro & Osakwe (2006) observed that wood fragments smothered the stream bed and released harmful leachates, ultimately leading to the loss of pollution-sensitive genera such as *Baetis* and *Centroptilum*. Peters et al. (1976) also discovered that toxic substances released from wood (e.g., lignans and tropolones) could reduce survival rates of mayfly and caddisfly larvae. Physical disturbances to the stream bed during the installation process were found to be harmful to benthic macroinvertebrates, but signs of recovery were recorded in 1 year (Collier & Bowman, 2003). Three other studies (Entrekin et al., 2007; Spänhoff et al., 2006; Walther & Whiles, 2011) also reported lower numbers of macroinvertebrates in stream reaches containing high wood loads, but no explanation was provided. Most likely, some of the other factors cited above were more important in structuring benthic community structure in these cases.

## 3.2 | Aquatic micro-organisms

NFM wood structures benefit micro-organisms in at least two ways. First, the submerged parts of Type 2, Type 3, and Type 4 structures provide spaces for the attachment of biofilms, which are made up of algae and other heterotrophic organisms such as fungi and bacteria (Collier & Halliday, 2000; Díez et al., 2002; Findlay et al., 2002; Tank & Webster, 1998; Tank & Winterbourn, 1996; Tsui et al., 2000). Second, they act as food sources for these heterotrophs, as reflected by the presence of enzymes involved in the degradation of wood components such as lignin and cellulose on wood surfaces (Bucher et al., 2004; Gómez et al., 2016; Zare-Maivan & Shearer, 1988). However, the relative contributions of wood tissues, autochthonous production by epixylic algae, and organic matter intercepted from the stream flow toward microbial metabolism remain unclear. Type 1 structures are expected to have minimal influence on epixylic microbial communities owing to their infrequent contact with the water column. However, by modifying stream bed sedimentary characteristics, they may still influence epilithic microbial communities.

### 3.3 | Terrestrial vegetation

Type 3 and Type 4 structures may cause water table levels in the river banks to rise during base flows, and soils will become more frequently saturated with water (Gurnell et al., 1995). Riparian plant communities are therefore driven toward domination by water-tolerant species. Furthermore, they may promote riparian forest development (Collins et al., 2012). Osei et al. (2015b) analyzed sediment samples collected from five different types of locations (within wood jams, on bank faces near wood jams, on bank faces far from wood jams, on gravel bars, and on the floodplain) in Highland Water, UK, and observed that plant propagule abundance and species richness were both significantly higher in samples obtained from bank faces near wood jams. Similar results were obtained from other surveys in River Bure, UK (Osei et al., 2015a) and Fiume Tagliamento, Italy (Gurnell et al., 2001). When the propagules germinate and grow into mature plants, they retain more sediments and lead to the expansion of floodplains (Abbe & Montgomery, 1996; Montgomery & Abbe, 2006). It should be noted, however, that when NFM wood structures disintegrate during flood events, the mobilized wood pieces can cause physical disturbances to riparian forests (Johnson et al., 2000). Since Type 1 and Type 2 structures maintain a gap with the stream bed, significant sediment accumulation and vegetative colonization may not occur in their vicinity. However, since they force water onto the floodplain during flood events, plant propagules may deposit further in the interior of the floodplain, resulting in the development of vegetation there instead.

## 4 | POTENTIAL BIOGEOCHEMICAL EFFECTS OF NATURAL FLOOD MANAGEMENT WOOD STRUCTURES

Previous studies on in-stream wood mainly focused on the influence of in-stream wood on local carbon and nitrogen cycling (Figure 3(c)). These findings are suggested to be relevant to NFM contexts as well.

### 4.1 | Carbon and organic matter cycling

Particulate organic matter (POM) storage by NFM wood structures is achieved via three mechanisms. First, Type 2, Type 3, and Type 4 structures can directly intercept POM in transport (Pfeiffer & Wohl, 2018; Figure 6: "intercepting coarse POM"). For example, Smock et al. (1989) recorded high amounts of POM trapped within the interlocking structure of woody dams (i.e., 3326 $g/m^2$, compared with only 548 $g/m^2$ on the sediment surface). Type 1 structures may intercept POM during flood events, but as the discharge decreases, the POM will be transported underneath the dams. Second, NFM wood structures induce pool formation, and POM will settle onto the stream bed in these slow-flow areas (Livers & Wohl, 2016; Livers et al., 2018; Figure 6: linkage between "pool formation" and "deposition of POM"). Third, accumulation of fine grains upstream of Type 3 structures, reach-scale textural fining associated with Type 2, Type 3, and Type 4 structures, and reduced coarsening associated with Type 1 structures all imply an increase in the total sediment surface area available for the attachment of OM (Sutherland, 1999; Figure 6: linkage between "textural fining" and "adsorption on grain surface"). Pilotto et al. (2014) surveyed a river in western Poland and observed that sediments in reaches with wood contained two times more OM than those in reaches without wood (2.26 vs. 0.77%). Trotter (1990) also compared streams with and without in-stream wood and saw that the former stored as much OM as 885 $g/m^2$, roughly two times that of the latter. These comparative studies were supported by a field experiment: Daniels (2006) measured that, in a lowland river in northern Illinois, the percentage mass of OM adhered to benthic sediments decreased from 6.35 to 4.23% after wood removal. In addition to POM, submerged structures may retain dissolved OM — Baldwin et al. (2014) reported its uptake by epixylic biofilms (Figure 6: "dissolved OM in water column" uptaken by "epixylic biofilm"). Finally, constituent wood pieces of NFM structures themselves represent a form of OM storage (Figure 6: "OM in wood tissues"). Beckman & Wohl (2014) studied 30 woody dams, observing that the mass of carbon stored within wood tissues was four times as much as that stored in sediments trapped by the dams.

NFM wood structures may also accelerate degradation of OM. Blaen et al. (2018) observed that the rate of respiration in Hammer Stream (West Sussex, UK) increased by more than three times when the amount of in-stream wood doubled. Similar relationships between in-stream wood and reach-scale metabolic rates were also reported for some streams in Piedmont, eastern USA (Sweeney et al., 2004). Two major mechanisms can account for accelerated OM processing. First, submerged wood surfaces of NFM structures provide space for the attachment of epixylic biofilms, which can produce 10 times more carbon dioxide than benthic communities (Gulis et al., 2008; Tank et al., 1993;

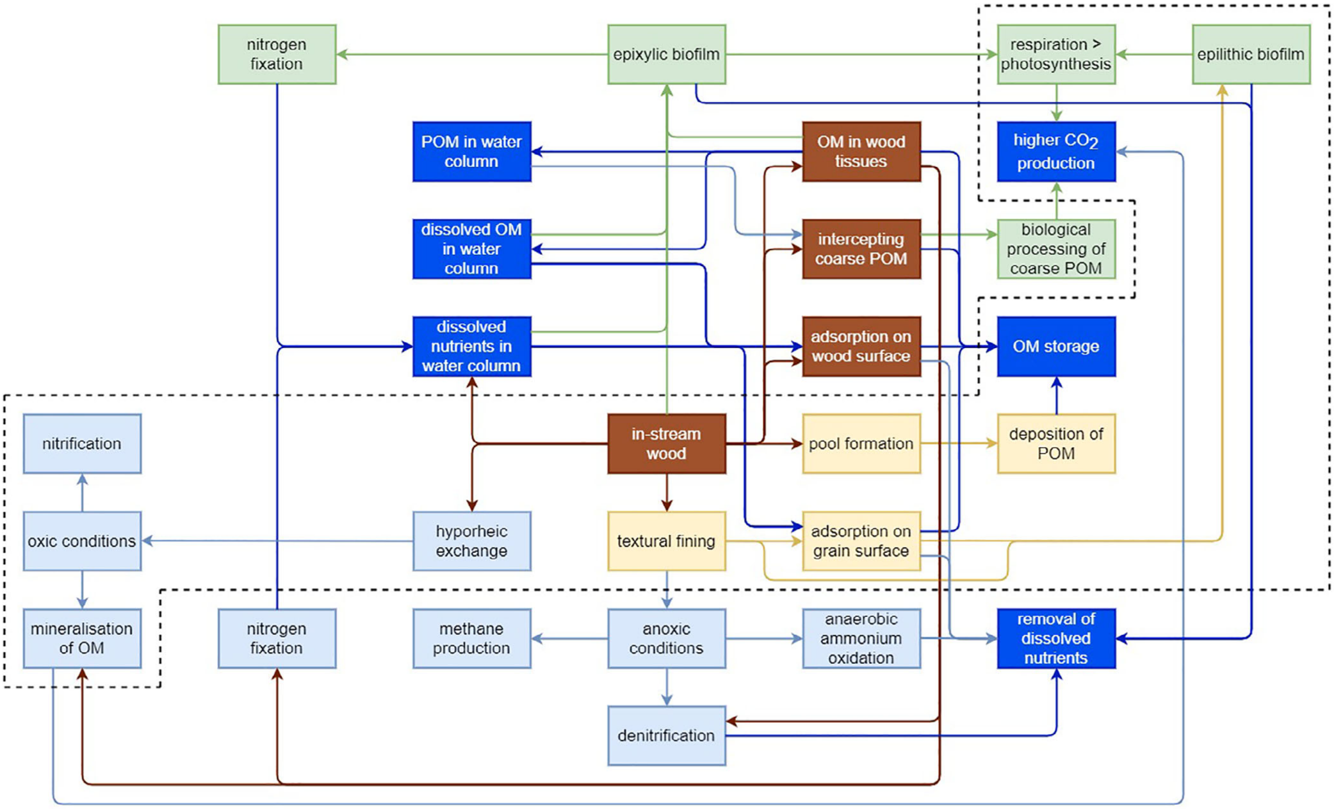


**FIGURE 6** Impact of NFM wood structures on carbon and nutrient cycling (brown: Wood features; dark blue: Biogeochemical consequences; yellow: Geomorphic factors; green: Processes on the surface; light blue: Processes in the subsurface); pathways considered most relevant to Type 1 structures enclosed by dotted box

Figure 6: "epixylic biofilm" having "respiration > photosynthesis"). Epixylic biofilms respire both OM derived from wood tissues and that intercepted from the water column, but the precise partitioning is unclear. Second, there is also enhanced OM processing in channel locations other than wood surfaces. Increases in the standing stock of coarse POM and epilithic OM on the stream bed associated with Type 3 and Type 4 structures likely favor more faunal and microbial activities, resulting in an increase in the absolute amount of OM being transformed (Acuña et al., 2013; Figure 6: "biological processing of coarse POM"). Even when there is no increase in the standing stock of OM, increased densities of macroinvertebrates in association with stream bed heterogeneity induced by Type 1 and Type 2 structures can result in higher rates of coarse POM decomposition and carbon dioxide production (Frainer et al., 2017). Finally, anoxic sediments retained by Type 3 structures may support anaerobic respiration pathways such as methanogenesis (Baker et al., 1983; Crenshaw et al., 2002; Figure 6: "methane production" arising from "anoxic conditions").

## 4.2 | Inorganic nutrient cycling

Submerged parts of NFM wood structures may remove dissolved nutrients from the water column. Comparing reaches with wood and those without, the removal rates of phosphate (Valett et al., 2002; Warren et al., 2007; Webster et al., 2000) and ammonium (Acuña et al., 2013; Roberts et al., 2007; Sweeney et al., 2004) were both found to be at least two times higher in the former. Bernhardt et al. (2003) observed a 10-fold increase in the removal rate of nitrate following wood input. A few mechanisms can contribute to accelerated nutrient removal. First, increases in the concentrations of nitrogen and phosphorus on wood surfaces after prolonged submergence in streams suggest that dissolved nutrients get either physically adsorbed to the wood surface or incorporated into the biomass of the micro-biota inhabiting the wood surface (Aumen et al., 1985; del Campo & Gómez, 2016; Ferreira et al., 2006; Sinsabaugh et al., 1993; Figure 6: linkages between "dissolved nutrients in water column," "epixylic biofilm," and "adsorption on wood surface"). Second, textural fining or reduced coarsening associated with NFM wood structures may result in a larger surface area for the adsorption of nutrients (Warren et al., 2007; Figure 6: connection between "dissolved nutrients in water column" and "adsorption on grain surface"). Third, increased rates of biogeochemical transformations within the anoxic sediments mostly associated with Type 3 structures can also contribute to faster removal (Figure 6: "textural fining" giving rise to "anoxic conditions"). For example, Groffman et al. (2005) observed higher rates of denitrification in sediments trapped within organic debris dams than in gravel bars. There is also some evidence of enhanced anaerobic ammonium oxidation (anammox) in areas around wood pieces, as they increase the time of contact between biogeochemically active surfaces and stream water rich in reactants (Shelley et al., 2017). Anammox removes dissolved nitrite and ammonium from the water column and converts them into nitrogen gas. Wood-induced transformations of phosphorus are seldom reported; adsorption and biological assimilation may be more important in accounting for its removal.

NFM wood structures may also favor biogeochemical reactions that release nutrients in inorganic forms that can be readily utilized by micro-organisms. For example, OM stored by Type 3 and Type 4 structures may provide energy for nitrogen fixation (Baker et al., 1983) and lead to more ammonium being produced. Type 1 and Type 2 structures may stimulate aerobic processes such as nitrification (Briggs et al., 2013; Crenshaw et al., 2002) and the mineralization of inorganic compounds (Hale & Groffman, 2006) in the hyporheic zone by forcing oxygen-rich surface water into the subsurface (Krause et al., 2014; Lautz et al., 2006; Lautz & Siegel, 2006; Sawyer et al., 2011; Sawyer & Cardenas, 2012; Stofleth et al., 2008; Figure 6: "hyporheic exchange" leading to "oxic conditions"), resulting in the production of dissolved nitrogen ions. Overall, these processes may be slower than those described above, resulting in net nutrient removal.

## 4.3 | Source of matter for downstream ecosystems

Physical breakdown and biological processing of the constituent wood pieces of NFM structures will transfer POM into the water column (Jacobson et al., 1999; Merten et al., 2013; Ward & Aumen, 1986; Figure 6). Wood tissues are also a source of dissolved substances as leaching releases water-soluble compounds in wood tissues rapidly upon submergence (Díez et al., 2002; Gonçalves et al., 2007; Jones et al., 2019; Spänhoff & Gessner, 2004). These chemicals can influence

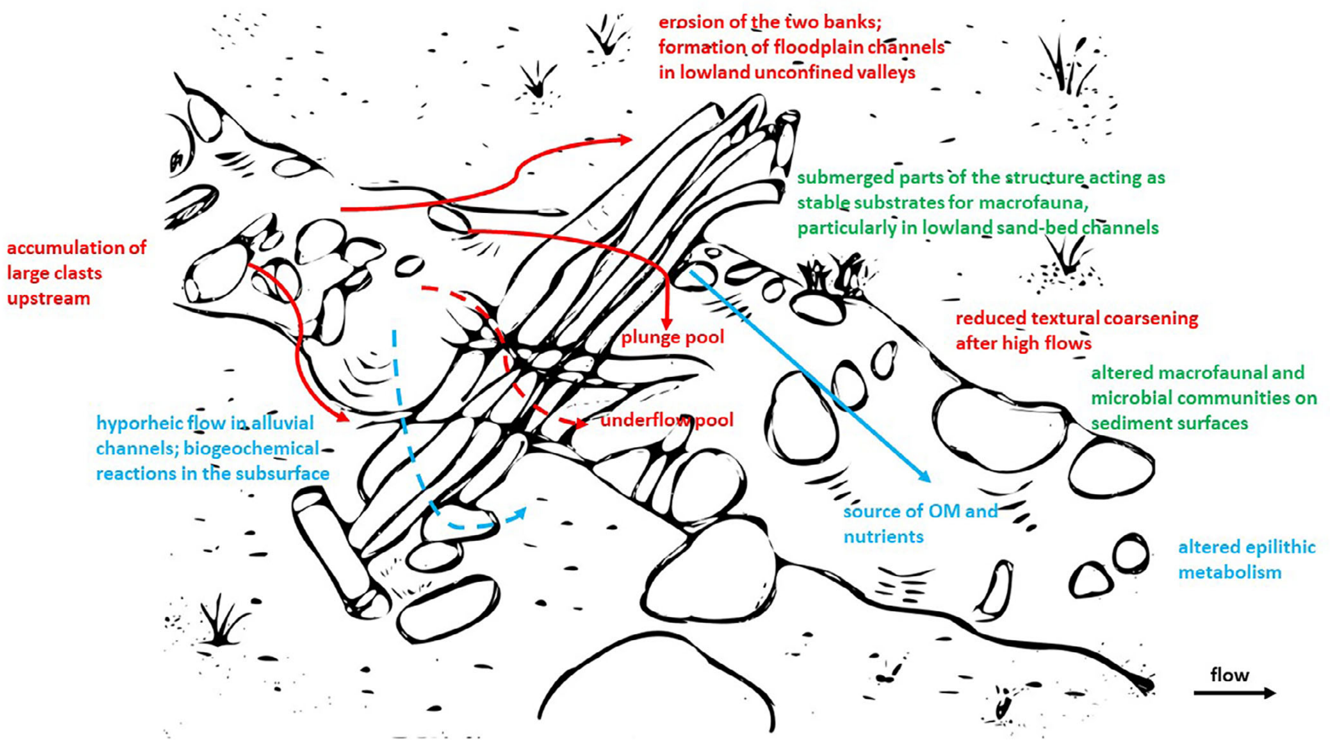


**FIGURE 7** Conceptual model describing the potential secondary effects of NFM wood structures (red: Geomorphic effects; green: Ecological effects; blue: Biogeochemical effects)

ecosystem functioning downstream (Fisher & Likens, 1972), so catchment-scale carbon and nutrient budgets must take into account these extra sources of materials provided by NFM wood structures. Although Type 1 structures are generally not submerged in water, physical breakdown of their aerial parts may also contribute particulate matter to the stream flow. In addition, rainwater falling onto the structures may transfer dissolved substances originating from wood tissues into the stream (Reiners & Olson, 1984).

## 5 | CONCLUSION: TESTING THE SECONDARY EFFECTS OF NATURAL FLOOD MANAGEMENT WOOD STRUCTURES

The preceding review of the existing literature has provided important insights into the plausible secondary effects of NFM woody dams and highlighted important research gaps. First, there is a clear need to evaluate the geomorphic effects of NFM wood structures. Having considered the key features of the different types of NFM wood structures, it is suggested that the they can likely lead to the following geomorphic effects (Figure 7; Table 1): (a) formation of plunge

**TABLE 1** Geomorphic, ecological, and biogeochemical effects of in-stream wood, highlighting those that are considered to be relevant to NFM wood structures (Figure 7) in particular

| Potential secondary effects | Type 1 | Type 2 | Type 3 | Type 4 |
|---|---|---|---|---|
| Pool formation | | | | |
| • Deflector pools | | | | ✓ |
| • Plunge pools | | ✓ | ✓ | |
| • Underflow pools | ✓ | ✓ | | |
| Sediment storage | | | | |
| • Accumulation of fine sediments | | | ✓ | |
| • Accumulation of large clasts | ✓ | ✓ | ✓ | ✓ |
| • Textural fining during base flows | | ✓ | ✓ | ✓ |
| • Reduced coarsening during flood events | ✓ | ✓ | ✓ | ✓ |
| Influencing bank morphology | | | | |
| • Bank erosion | ✓ | ✓ | ✓ | ✓ |
| • Bank protection | | | | ✓ |
| Step formation | | | ✓ | |
| Bar formation | ✓ | ✓ | ✓ | ✓ |
| Influencing floodplain morphology | | | | |
| • Creating new floodplain channels | ✓ | ✓ | | |
| • Enlargement of existing floodplains | | | ✓ | ✓ |
| Aquatic macroinvertebrates and micro-organisms | | | | |
| • On wood surfaces | | ✓ | ✓ | ✓ |
| • On the stream bed | ✓ | ✓ | ✓ | ✓ |
| Carbon cycling | | | | |
| • OM storage and processing within the structure | | ✓ | ✓ | ✓ |
| • OM storage and processing on the stream bed | ✓ | ✓ | ✓ | ✓ |
| Nitrogen and phosphorus cycling | | | | |
| • Adsorption/ biological uptake onto wood surfaces | | ✓ | ✓ | ✓ |
| • Adsorption/ biological uptake onto grain surfaces | ✓ | ✓ | ✓ | ✓ |
| • Accelerated anoxic processes in the subsurface | | | ✓ | |
| • Accelerated oxic processes in the subsurface | ✓ | ✓ | | |
| Source of dissolved and particulate matter | ✓ | ✓ | ✓ | ✓ |

**TABLE 2** Types of research designs employed by the studies reviewed; "impact" refers to study reaches with in-stream wood; "control" refers to those free of in-stream wood; "independent" means that the reaches are in separate catchments, not longitudinally connected; within each "control-impact pair", the control reach and the impact reach are longitudinally connected

| Research design | Observational | Experimental |
|---|---|---|
| 1 impact reach | 174 (33%) | 14 (3%) |
| >1 independent impact reaches | 179 (34%) | 6 (1%) |
| 1 control-impact pair in a stream | 22 (4%) | 30 (6%) |
| 1 control reach, 1 impact reach, independent | 2 (0.4%) | 5 (1%) |
| >1 control reaches, 1 impact reach, independent | 1 (0.2%) | 3 (0.6%) |
| 1 control reach, >1 impact reaches, independent | 1 (0.2%) | 2 (0.4%) |
| >1 independent control-impact pairs | 13 (2%) | 21 (4%) |
| >1 control reaches, >1 impact reaches, independent | 11 (2%) | 2 (0.4%) |

pools and underflow pools; (b) trapping of sediments in the gap between the structure and the stream bed; (c) textural fining during base flows or reduced coarsening of the stream bed after high flows; (d) erosion of both banks; and (e) formation of floodplain channels. High-resolution, three-dimensional surveys can help reveal these geomorphic changes (Carrivick & Smith, 2018).

Further empirical analyses of how these geomorphic effects drive further changes in ecosystem structure and functioning are also necessary. Since some NFM wood structures are not persistently submerged in water, their surfaces may not be important to aquatic macroinvertebrates and micro-organisms. However, modifications of the physical habitat that they induce (e.g., diversification of stream bed substrates) may still drive ecological changes (e.g., diversification of benthic macrofaunal communities; Figure 7; Table 1). The relationship between macroinvertebrates and wood-induced geomorphic changes has not been extensively empirically tested. The study by Pilotto et al. (2014) was one of the few exceptions, but it was limited to a lowland river. More benthic community studies involving NFM wood structures in upland environments are therefore required.

Geomorphic changes driven by NFM wood structures have biogeochemical implications as well. For example, when the dams reduce sediment coarsening under high flows, there will be an increase in the area for the attachment of OM and nutrients (Sutherland, 1999; Warren et al., 2007), promoting the growth of micro-organisms. In contrast, the growth of micro-organisms will be inhibited where the dams promote scouring and lead to sediment instability (Atkinson et al., 2008). Ultimately, biogeochemical processes driven by these micro-organisms will be altered (Figure 7; Table 1). To date, this connection has not been thoroughly scrutinized. Shelley et al. (2017) studied biogeochemical reactions in sediments near wood, but only anaerobic nitrate reduction pathways were investigated. Aerobic processes such as respiration and photosynthesis were not quantified. How wood-induced changes in sedimentary characteristics influenced biogeochemical processes was also not examined. By isolating and measuring the metabolic rates of sediments from areas that are expected to undergo geomorphic changes upon the input of wood (including NFM wood structures), the contribution of wood-induced geomorphic changes, relative to the other mechanisms described in Figure 6, to the overall alteration in reach-scale metabolism can be precisely identified. In addition, understanding how in-stream wood influences benthic metabolism and the production of carbon dioxide enables more accurate quantifications of the various processes leading to carbon outgassing from inland waters. Outgassing is thought to play a crucial role in the global carbon cycle, but relevant quantitative information is still lacking (Battin et al., 2009).

All these secondary effects are best investigated using a full before-after control-impact (BACI) research design, which was seldom employed in previous studies (Table 2). Through a full BACI design, we can most reliably isolate local changes driven by NFM wood structures from those caused by natural variations (Underwood, 1992) and quantify the resulting secondary effects robustly.

## ACKNOWLEDGMENTS

Thanks go to Prof. Lee Brown, Dr. Mervyn Peart, and the two anonymous reviewers for giving comments to earlier versions of this article.

## AUTHOR CONTRIBUTIONS

**Ho Wen Lo:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; validation; visualization; writing - original draft; writing-review & editing. **Mark Smith:** Supervision; writing-review & editing. **Megan Klaar:** Supervision; writing-review & editing. **Clare Woulds:** Supervision; writing-review & editing.

## CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Lo, H. W., Smith, M., Klaar, M., & Woulds, C. (2021). Potential secondary effects of in-stream wood structures installed for natural flood management: A conceptual model. *Wiley Interdisciplinary Reviews: Water*, *8*(5), e1546. https://doi.org/10.1002/wat2.1546