Representing natural and artificial in-channel large wood in numerical hydraulic and hydrological models

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Abstract
The influence of naturally occurring in-channel large wood (LW) on the hydraulics, hydrology and geomorphology of rivers is well documented. To inform management and better understand naturally occurring or artificially placed LW, hydraulic and hydrological models are applied to predict the possible benefits and drawbacks for habitat, sediment management and flood risk mitigation. However, knowledge and guidance on appropriate representation in models, needed to underpin realistic predictions, is lacking. This could lead to unrealistic expectations of the effectiveness of LW for different river management goals. To date, seven types of LW representation in hydraulic and hydrological models have been applied, the range partly reflecting the variety of LW, model types, scales and purposes. The most common approach is by altering channel roughness to represent flow resistance. Although qualitatively the effects of LW have been captured using models, to date quantitative validation, as well as transferable knowledge to help a priori parameterization of LW representations, remain limited. Therefore, additional empirical investigations and robust model validation are required to inform defensible LW representations for specific purposes and scales in numerical models coupled with better accounting of input uncertainty to improve confidence in predictions. Future studies should also consider a greater range of artificial and natural LW features, settings, larger spatial scales and better account for temporal variability of flow, morphology and LW configuration.

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hydraulics, in-channel, large wood, modeling, river management

1 | INTRODUCTION

In-channel large wood (LW) is recognized as a key component of naturally functioning rivers and floodplains in catchments with forest cover (Abbe & Montgomery, 1996; Wohl, 2017). LW can be defined as single or accumulated pieces of wood...
>1 m in length and > 10 cm in diameter (Thevenet, Citterio, & Piégay, 1998). This definition although arbitrary, is commonly used for convenience (Wohl et al., 2010) and is applied to this review. By obstructing flow, LW generates significant hydraulic roughness and drag (Gippel, 1995; Jeffries, Darby, & Sear, 2003). This can in turn reduce water velocities and increase temporary floodplain water storage thus influencing flooding downstream (Keys et al., 2018; Kitts, 2010; Wenzel, Reinhardt-Imjela, Schulte, & Bölischer, 2014). LW accumulations also create complex hydraulic and geomorphic conditions (Abbe & Montgomery, 1996; Buffington & Montgomery, 1999; Daniels & Rhoads, 2004; Klaar, Hill, Maddock, & Milner, 2011; Manners, Doyle, & Small, 2007) that can positively affect physical habitat (Roni, Beechie, Pess, & Hanson, 2014).

To mimic the effects of natural LW, wood is artificially added to address different river management goals. This includes Flood Risk Management (FRM; Spray et al., 2017; Wilkinson, Quinn, & Welton, 2010) and restoring habitat (Figure 1; Abbe, Pess, Montgomery, & Fetherston, 2003; Brooks, Gehrke, Jansen, & Abbe, 2004; Harvey, Henshaw, Parker, & Sayer, 2018; Kail, Hering, Muhar, Gerhard, & Preis, 2007). By affecting sediment transport processes, artificial wood placement is also an alternative to conventional engineering for managing sediment movement problems (Addy & Wilkinson, 2016; Brooks, Howell, Abbe, & Arthington, 2006; Shields, Knight, & Stofleth, 2006). Reflecting this range of different applications, artificial LW addition has become a popular river management tool in recent decades (Grabowski et al., 2019); for example, in the UK, it has greatly increased since 2008 and accounts for about one fifth of all restoration schemes (Cashman, Wharton, Harvey, Naura, & Bryden, 2019).

**FIGURE 1** Examples of naturally formed and artificial in-channel large wood. (a) A cluster of individual fallen trees (Bowmont Water, UK), (b) a channel spanning log jam (Logie Burn, UK; Carol Taylor, James Hutton Institute), (c) a mid-channel tree with its rootwad facing upstream (River Feshie, UK), (d) a dense accumulation of large wood at the head of a tree covered island (River Dee, UK), (e) a flow restrictor built of wooden planks added to a ditch and designed to reduce flow for flood risk management (Belford Burn, UK), (f) a bar apex engineered log jam on a gravel bar designed to trap coarse sediment (Bowmont Water, UK), (g) added trees with intact rootwads for restoring river habitat (Allt Lorgy, UK; Spey Catchment Initiative) and (h) an individual bank attached tree trunk designed to improve fish habitat (Gelder Burn, UK; Dee District Salmon Fishery Board)
Research has provided modeling approaches and insights that are useful for aiding the management and design of LW. Of relevance for predicting the snagging hazard posed by wood pieces, its transport dynamics can be captured with numerical modeling (De Cicco, Paris, Ruiz-Villanueva, Solari, & Stoffel, 2018; Ruiz-Villanueva, Piégay, Gurnell, Marston, & Stoffel, 2016). Force-balance modeling can be used to predict the stability of static LW to optimize longevity (Brooks, Abbe, et al., 2006; Shields et al., 2006; Shields, Knight, Cooper, & Testa, 2000) and simple empirically based equations can predict reach scale flow resistance (Shields Jr & Gippel, 1995) and afflux (Gippel, Finlayson, & O’Neill, 1996; Turcotte, Millar, & Hassan, 2016).

Despite this progress, scientific knowledge gaps remain (Grabowski et al., 2019). This includes assessment of the suitability of approaches to represent stationary LW in numerical hydraulic and hydrological models (Nisbet, Silgram, Shah, Morrow, & Broadmeadow, 2011). To date, no accepted guidance or bespoke tools are available (Metcalfe, Beven, Hankin, & Lamb, 2018; Nagai et al., 2017; Pinto et al., 2019; SEPA, 2016). In part this reflects the difficulty of modeling such complex, porous features that vary considerably in form and setting (Figure 1; Abbe & Montgomery, 1996) but also the recently developed interest in the topic. Not accounting adequately for the presence of in-channel LW can result in erroneous hydraulic predictions at the reach- (10–20 channel widths) or local-scale (< 10 channel widths) (Nahorniak et al., 2018; Pasternack, Wang, & Merz, 2004). Modeling scaled up to the catchment is needed to determine wider hydrological changes (Lane, 2017) and unrealistic representation at this scale could equally produce misleading predictions. Refinement of LW representation would improve the defensibility of predictions and aid optimal placement for FRM (Barlow, Moore, & Burgess-Gamble, 2014) and river habitat restoration purposes (Nahorniak et al., 2018; Pasternack, 2011; Pinto et al., 2019; Wheaton, Pasternack, & Merz, 2004). Therefore, a pressing need is to assess the applicability of modeling to capture the hydraulic and hydrological effects of LW in rivers.

The aims of this review are to: (a) summarize empirical knowledge of the hydraulic and hydrological effects of LW, (b) give an overview of approaches undertaken so far to model hydraulic and hydrological effects of LW using hydrodynamic or hydrological models and with reference to empirical studies and theory, consider their suitability, and (c) identify knowledge gaps to improve confidence in future modeling. In this review, the term LW is used as a catch-all term for both naturally occurring and artificially emplaced LW within river channels but not floodplains. This definition includes artificial LW features (e.g., Figure 1(e) and (f)) that may differ significantly in form to natural examples (e.g., Figure 1(a) to (d)) but which aim to create similar hydraulic and hydrological effects. Although beaver dams are functionally similar to other LW accumulations by reducing velocities and discharge downstream (Dadson et al., 2017), they are not included. As numerical modeling of LW is a relatively new research topic, reports, conference papers and theses alongside peer reviewed academic publications have been included.

## 2 EFFECTS OF LARGE WOOD ON CHANNEL HYRAULICS AND HYDROLOGY

### 2.1 Structural controls on hydraulic effects

The hydraulic effects of static in-channel LW have been observed extensively in the field and controlled flume experiments (Table 1). Understanding their effect on hydraulic processes helps to substantiate if numerical models can realistically capture their nature and thus provides a “reality-check”.

Hydraulic effects strongly depend on the geometry and complexity of a feature as summarized in Table 1, factors that vary greatly amongst different types, scales and complexities of LW (Figure 1). Broadly speaking, dense LW features that block a large extent of the channel cross section area generate the greatest flow resistance (Gippel et al., 1996; Manners et al., 2007; Wilcox & Wohl, 2006). Relative to channel area, even a small volume of in-channel wood can be a disproportionate source of flow resistance. For example, Manga and Kirchner (2000) found that roughly 50% of the roughness could be attributed to logs covering 2% of the channel area. By forcing a short, deep pool, MacVicar (2013) found that a single fallen tree generated significantly greater energy loss coefficients than an unobstructed reach containing a relatively long and shallow pool.

Typically, LW flow resistance has been measured at the reach scale through dilution tracing followed by flow resistance partitioning to isolate LW flow resistance from other sources. The Darcy–Weisbach friction factor ($f_0$) of different LW elements is usually computed as they are dimensionally correct and can be compared across regions (Curran & Wohl, 2003). However, flow resistance partitioning is uncertain and delineating the contribution of LW elements alone is difficult especially where there are interaction effects with other sources of roughness such as bedforms (Wilcox, Nelson, & Wohl, 2006).
Notwithstanding this uncertainty and the limited number of studies, a positive relationship of LW flow resistance increasing as channel slope increased has been observed suggesting LW flow resistance is scaled by slope (Dixon, 2013; Kitts, 2010).

Representing LW flow resistance with Manning’s \( n \) values rather than \( ff \) is of greater value for numerical modeling as it is a commonly used roughness parameter. Although the methods used to determine Manning’s \( n \) differ between studies thus affecting comparison, values vary greatly (Table 2). Most flow resistance studies have been undertaken in small catchments (< 15 km\(^2\)) with low channel gradients (< 0.01 m/m) and sand- or gravel-beds. Values are low for mainstem rivers in Tennessee, USA and comparatively high for coarse mountain headwater streams in Washington State, USA whereas values from the New Forest, England sit midway between these regions. Importantly, observations from the New Forest show flow resistance is dependent on LW type (Table 2). Plotting of Manning’s \( n \) values versus slope normalized by drainage area, although lacking data points from drainage areas ranging from 20 to 900 km\(^2\), shows a positive relationship (Figure 2). This indicates that LW flow resistance is scaled by the size of catchment and could provide a first-order prediction of realistic flow resistance for different catchment scales.

### Table 1

Summary of the local hydraulic effects of in-channel large wood (natural and artificial)

| Aspects researched                      | Observed hydraulic effects                                                                 |
|-----------------------------------------|-------------------------------------------------------------------------------------------|
| **Static LW geometry aspects**          |                                                                                           |
| Size                                    | • Hydraulic effects are larger for in-channel wood features that block >10% of the cross-section area (Gippel et al., 1996). |
|                                         | • Large diameter timbers are more influential on afflux than small diameter timbers (Turcotte et al., 2016). |
| Complexity and density                  | • Dense log jams are associated with the lowest upstream velocities and highest drag forces (Manners et al., 2007) and flow resistance (Wilcox & Wohl, 2006). |
|                                         | • Drag coefficients are influenced by log complexity: values are lowest for more complex or natural features and highest for the simplest features (Manners et al., 2007; Shields & Alonso, 2012). |
| Angle of feature to flow                | • Orientation of logs has been found to be important with flow resistance maximized for features orientated perpendicular to flow (Gippel et al., 1996; Wilcox & Wohl, 2006) but also not necessarily an influence on the drag coefficient (Hygelund & Manga, 2003). |
|                                         | • Shields and Alonso (2012) observed drag coefficients were inversely related to the yaw of the log with drag coefficients lowest when the axis of a log approaches a position parallel to the flow. |
| Position of timbers in the water column | • Logs positioned on the bed or just submerged are associated with the highest drag forces (Gippel et al., 1996; Shields & Alonso, 2012). |
|                                         | • This may be size dependent: the position of small diameter timbers is influential but is not for large diameter timbers (Hygelund & Manga, 2003). |
| Bark characteristics                    | • Increasing bark roughness increases lift and reduces wave drag (Shields & Alonso, 2012). |
| **Temporal changes to LW and ambient conditions** |                                                                                           |
| Upstream changes in bed elevation and roughness | • Changes in bed morphology could alter the ambient flow resistance and thus the approach flow characteristics and applied drag force on a feature (Turcotte et al., 2016). Associated scour created by LW has been observed to reduce backwater rise (Schalko, Lageder, Schmocker, Weitbrecht, & Boes, 2019). |
| Addition or loss of material due to stochastic, cumulative or seasonal factors. | • Drag force increases as a log jam density increases and in turn porosity decreases (Manners & Doyle, 2008). |
| Variation of river discharge            | • Shields and Alonso (2012) showed lift and drag forces acting on both simple and complex LW were 2–3 times greater during the rising limb of unsteady flow than steady, averaged flow conditions. |
|                                         | • Flow resistance generated by log jams decreases as flow stage increases (Dudley, Fisichenich, & Abt, 1998; Wilcox & Wohl, 2006). |
|                                         | • Effect of log jams is stage dependent. Increasing approach discharge can cause afflux and floodplain connection (Jeffries et al., 2003; Keys et al., 2018) and submerge structures reducing relative backwater rise (Geertsema, Torfs, Teuling, & Hoitink, 2017). |

*Note: References categorized according to type of study: Italicised font indicates field studies with artificially placed LW, bold font indicates flume experiments, normal font indicates empirical observations of naturally occurring LW.*
### Table 2  
Empirical Manning’s $n$ values of naturally occurring in-channel large wood from different studies

| Study                     | LW typea | Region                     | Reach slope (m/m) | Drainage area (km$^2$) | Channel type                              | Mean Manning’s $n$ | Sample N | Flow conditions          |
|---------------------------|----------|----------------------------|-------------------|-------------------------|-------------------------------------------|-------------------|----------|--------------------------|
| (Curran and Wohl (2003)   | Active   | Washington state, USA      | 0.06–0.18         | 9.6–0.13                | Step-pool, gravel/cobble bed              | 0.60 (0.2–1.5)$^b$ | 20       | Low flows < bankfull     |
| Shields Jr and Gippel (1995) | Partial | Tennessee, USA             | 0.0005–0.0008     | 927                     | Straight, sand bed                       | 0.058 (0.0435–0.0807)$^b$ | 9        | Range of flows           |
|                           | Partial  | SW Australia               | 0.001–0.0015      | —                       | Sinuous, gravel/sand bed                 | 0.075 (0.0652–0.0875)$^b$ | 3        | ≤ bankfull               |
| Dixon (2013)              | Active   | New Forest, S. England     | 0.004             | <15                     | Meandering, coarse gravel bed            | 0.24 (0.137–0.362)$^b$ | 8        | High (above 0.8 m$^3$/s) |
|                           | Partial  |                            | 0.012–0.013       |                         |                                           | 0.083 (0.027–0.199)$^b$ | 16       |                          |
| Kitts (2010)              | Active (overflow) | New Forest, S. England   | 0.0057            | 11.2                    | Meandering, coarse gravel bed            | 1.4 (0.58–2.22)$^b$ | 4        | <0.2 m$^3$/s (low)       |
|                           | Active (underflow) |                        |                   |                         |                                           | 0.27 (0.142–0.398)$^b$ | 9        |                          |
|                           | Partial (deflector) |                       |                   |                         |                                           | 0.32 (0.173–0.467)$^b$ | 12       |                          |
| Linstead and Gurnell (1998)$^c$ | Active (and complete) | New Forest, S. England | —                 | —                       | —                                         | 0.677$^c$ | 8        | Low flows < bankfull     |
|                           | Partial |                            | —                 | —                       | —                                         | 0.348$^c$ | 6        |                          |
| Gregory, Gurnell, and Hill (1985)$^c$ | Active | New Forest, S. England | —                 | <15                     | —                                         | 0.224$^c$ | 1        |                          |

$a$Using Gregory et al. (1985) definitions: active, extend across channel and induce a step in the water surface profile at all flows; complete, extend across channel but are leaky and have no significant impact on water surface profile at low flows; partial, only extend across part of the channel width.

$b$Values have been converted from original Darcy–Weisbach $f/f$ values. Values in brackets are maximum and minimum ranges.

$c$Did not use flow resistance partitioning. Based on before removal and after comparison of total reach scale Manning’s $n$ derived using the Manning’s equation. Values in brackets are maximum and minimum ranges.

**Figure 2**  
Manning’s $n$ values of naturally occurring large wood features versus channel reach slope normalized by drainage area. Further details given in Table 2.
The hydraulic effects of LW also depend on the orientation and position of timbers (Table 1) although Wilcox and Wohl (2006) suggested these factors were less important than LW complexity and size in step-pool channels. Logs located on the bed experience greater drag force than those off the bed (Gippel et al., 1996; Manners & Doyle, 2008; Shields & Alonso, 2012), although this could depend on the size of the logs (Hygelund & Manga, 2003). Orientation has also been considered in field and flume experiments with logs orientated perpendicular to flow associated with the greatest effects (Gippel et al., 1996; Shields & Alonso, 2012). Hydraulic effects are also dependent on the branching complexity and bark roughness, factors that are dependent on the species of tree (Table 1; Shields & Alonso, 2012).

### 2.2 Temporal controls on hydraulic effects

The hydraulic influence of LW can change as porosity and size vary through time (Table 1). Changes in the size depend on the catchment wood recruitment regime, rate of decay and flood frequency. Controls on the dynamics of wood transport have been extensively researched (e.g., Braudrick & Grant, 2000) and are beyond the scope of this review. However, amongst other factors, the stability of a LW feature depends on the size of the timbers relative to channel size (Dixon & Sear, 2014), the presence or not of root wads (Kang & Kimura, 2018) and buoyancy of wood as determined by the species (Shields & Alonso, 2012) and state of decay (Kail et al., 2007). Changes in size could be progressive, stochastic or seasonal. Manners and Doyle (2008) showed that porosity decreased and in turn drag force increased through four stages of log jam development: key member recruitment, framework building, accumulation and completion. By blocking interstices, Thomas and Nisbet (2012) hypothesized leaf litter accumulation behind log jams during the autumn months would decrease porosity.

The changes in the surrounding channel geometry, whether caused by a LW feature or independent catchment hydrogeomorphic factors, can also affect the hydraulic influence of LW. Turcotte et al. (2016) predicted that if the stream bed approach became hydraulically rougher, it would reduce the drag force applied on a LW feature. Upstream bed aggradation caused by the impoundment effect of log jams (Wohl & Scott, 2017), could alter bed roughness and increase the stage of the approach flow and thus the hydraulic feedbacks. In contrast, bed scour associated with the interaction between a structure and high flows can reduce backwater rise (Schalko et al., 2019).

The effects of LW are also dependent on the approach flow conditions. As inflow stage rises, afflux created by a log jam can be sufficient to connect the adjacent floodplain (Jeffries et al., 2003; Keys et al., 2018) and the rate of backwater rise tends to increase (Geertsema et al., 2017; Schalko et al., 2019). In addition, the Manning's n for a LW feature usually decreases (Dudley et al., 1998; Gregory et al., 1985) as it does in unobstructed channels (Gordon, Finlayson, & McMahon, 2004; Morvan, Knight, Wright, Tang, & Crossley, 2008). Backwater rise, however, reaches a point when the structure becomes submerged and the relative backwater rise decreases (Geertsema et al., 2017). Of relevance to LW stability, Shields and Alonso (2012) showed that lift and drag forces acting on both simple and complex LW were 2–3 times greater during the rising limb of unsteady flow than during steady, averaged flow conditions.

### 2.3 Hydrological effects

The hydraulic effects of LW result in changes in stream discharge that can affect the magnitude, celerity and timing of peak flows downstream. Empirical evidence of the catchment scale effects of log jams is rare and confined to small catchments (< 15 km²). On a low gradient stream in the New Forest, river (LW addition and meander restoration) and riparian restoration together produced a 21% reduction of flood peak magnitude and a 33% increase in flood peak travel time for flows less than 1 m³/s (equal to a 2 year recurrence interval; Kitts, 2010). However, flows over a 2-year recurrence interval “drown out” the influence of roughness features resulting in flood wave travel times similar to pre-restoration (Dixon, Sear, Odoni, Sykes, & Lane, 2016). On a 4 km reach of the same stream containing naturally occurring log jams, a comparison of flow peak travel times before and after their removal was undertaken by Gregory et al. (1985). Differences in travel time of over 100 minutes for a discharge of 0.1 m³/s and 10 minutes for a discharge of 1 m³/s were observed (Gregory et al., 1985). Both flow events were less than bankfull capacity (4.71 m³/s).

Controlled field experiments, as an alternative to catchment scale evidence gathering, have been used to assess hydrological changes due to artificial LW in small (< 5 km²) catchments. In a steep upland headwater catchment (2 km²) in southeast Germany, nine log jams over a 282 m reach were added and subjected to controlled floods to determine their hydrological effects at the outlet (Wenzel et al., 2014). During a 3.5-year recurrence interval flood, small changes were observed; the peak was delayed by 166 seconds and reduced by 2.2% (183 L/s to 179 L/s). A controlled water release experiment in a small headwater in the eastern USA (catchment area: 1 km²), with three artificial log jams installed in a 50 m reach was conducted by...
Table 3  Summary of approaches used or recommended to predict hydraulic and hydrological effects of in-channel large wood

| LW representation | Geometry adjustment | Roughness adjustment | Geometry and roughness adjustment | Hydraulic structure representation | Roughness and hydraulic equation adjustment | Explicit 3D representation | Porosity model |
|-------------------|---------------------|----------------------|----------------------------------|-----------------------------------|------------------------------------------|-------------------------------|----------------|
| Schematic         |                      |                      |                                  |                                   |                                         |                               |                |
| References        | Bair, Segura, and Lorion (2019); Rasche, Reinhardt-Imjela, Schulte, and Wenzel (2019); Xu and Liu (2017); JBA (2017); Haf, Harrison, Utz, and Dunne (2014); Valverde (2014); Abbe (2006) | Pinto et al. (2019); Rasche et al. (2019); Dixon et al. (2016); Valverde (2014); Ball, Arnott, and Samson (2012); Pasternak (2011); Kitts (2010); Odoni and Lane (2010); Liu, Gebremeskel, De Smedt, Hoffmann, and Pfister (2004) | Geertsema, Torfs, Teuling, and Eckhout (2018); Wall et al. (2016); Gillies (2016); Valverde (2014); Brooks, Abbe, Jansen, Taylor, and Gippel (2001) | Pinto et al. (2019); Cabaneros et al. (2018); Keys et al. (2018); Metcalfe, Beven, Hankin, and Lamb (2017); Hughes (2015); Thomas and Nisbet (2012) | Wu, Shidds Jr, Bennett, and Wang (2005) | Xu and Liu (2017); Allen and Smith (2012) | Xu and Liu (2017) |
| Number of studies | 7                   | 9                    | 5                                | 6                                 | 1                                       | 2               | 1              |

Note: This includes studies in which more than one large wood representation was applied. Font type denotes type of model used. Normal font indicates 1D hydraulic models, bold font indicates 2D hydraulic models, bold italicised font indicates 3D computational fluid dynamics models, and italicised normal font indicates hydrological models.
| Study | Large wood details | Model type and state | Setting | Large wood representation | Observations used for model calibration or validation | Model calibration and validation results |
|---|---|---|---|---|---|---|
| Thomas and Nisbet (2012) | Type: CS(A) Blockage: 70% N: 5 | Infoworks RS Unsteady | CA: 9.2 km² W: 5 m L: 500 m | Partial blockage function (70% of channel blocked) at each log jam cross section | Stage comparison | Calibration: Modeled peak water levels were ≤ ±0.03 m and within 30 minutes of measured levels for an observed in-channel flow (peak discharge unknown). However, the shape of the observed hydrograph was poorly captured. Validation: No results given. |
| Valverde (2014) | Type: BA(A) Blockage: 24–27% N: 1 | HEC-RAS 1D Steady | CA: 947 km² W: 22 m L: 73 m | Changing channel geometry at two cross sections representing the log jam. | Stage and Velocity Comparison | Calibration: For the higher calibration flows of 28 m³/s, 33 m³/s and 35 m³/s, the addition of ELJ geometry results in an NSE closer to 1 and bias closer to 0. Validation: At 13 m³/s, NSE closer to 1 and bias closer to 0. |
| Pinto et al. (2019) | Type: Partial(A) Blockage: 37.7–74.1% N: 4 | Flood modeler Steady | CA: Unknown W: ~8 m L: 700 m | Blockage function at an unknown number of cross sections (37.7–74.1% of channel blocked) | Stage comparison | Calibration: At a low discharge (0.283 m³/s) SSE was 0.19. However, stage was under-predicted upstream and over-predicted downstream. Validation: No results given. |
| Wu et al. (2005); He, Wu, and Douglas Shields Jr (2009) and Shields Jr, Morin, and Cooper (2004) | Type: MC(A) Blockage: Unknown N: 5 | CCHE2D Unsteady | CA: 37 km² W: 30 m L: ~200 m | Adding drag force and turbulence effects of large wood to momentum and turbulence kinetic energy equations. | Velocity comparison | Calibration: No results given. Validation: For a flow event with a peak discharge of 15.5 m³/s, simulated mean flow velocities close to the LW and channel centerline, had relative RMSEs of 40.4% and 26.4% respectively. Visual comparison of velocities also showed a “reasonable” match. |
| Kitts (2010) | Type: CS(N) Blockage: 100% N: 1 | Hydro2de Steady | CA: 7 km² W: 4 m L: 160 m | Increasing channel roughness at the log jam location. | Flood peak inundation area and velocity comparison | Calibration: A good calibration was achieved with predicted inundation extents that visually matched observed inundation extents. |
| Study                          | Large wood details<sup>a</sup> | Model type and state | Setting<sup>b</sup> | Large wood representation | Observations used for model calibration or validation<sup>c</sup> | Model calibration and validation results |
|-------------------------------|---------------------------------|----------------------|---------------------|---------------------------|---------------------------------------------------------------|-----------------------------------------|
| Keys et al. (2018)            |                                 | HEC-RAS 2D Unsteady  | CA: 1 km<sup>2</sup> | Placement of weir embankment with random orifices at each log jam location. | Calibration: At the downstream reach boundary: R<sup>2</sup>: 0.89; normalized RMSE: 9.4%; NSE: 0.92. Validation: Stage at 3 cross sections upstream of each LJ, R<sup>2</sup>: 0.71–0.89; normalized RMSE: 11.5–19.2; NSE: 0.72–0.88 | |
| Rasche et al. (2019)          |                                 | HYDRO_AS-2D Unsteady | CA: 1.8 km<sup>2</sup> | Altering the calculation mesh by adding discrete elements at each log jam location. | Discharge comparison Calibration: A good model calibration was achieved for baseline, no LW conditions: NSE: 0.99, RSR: 0.11, bias: −3.5%. Validation: At the reach outlet for a flow event with a peak flow of 0.18 m<sup>3</sup>/s (3.5 year recurrence interval), simulated hydrograph shape visually matched the observed hydrograph shape well. NSE: 0.9, RSR: 0.32, bias: −7.7. | |
| Bair et al. (2019)<sup>d</sup> |                                 | Nays2DH Unsteady     | CA: 5 km<sup>2</sup> | Altering the input channel topography by adding obstructions at each log jam location. | Stage and velocity comparison Calibration (post large wood): For a discharge of 1.49 m<sup>3</sup>/s (41% of bankfull capacity), modeled velocities had an RMSE and an R<sup>2</sup> of 0.249 and 0.75 respectively. For the same discharge, stage predictions had an RMSE of 0.039 and an R<sup>2</sup> of 0.98. Validation: No results given. | |
| Xu and Liu (2017)              |                                 | OpenFOAM Steady      | CA: Unknown W: 40.5 m | Visual comparison of velocity Calibration: No results given. Validation: Velocity and turbulent kinetic energy |                              | |

<sup>a</sup> Large wood details include type and state of the study, model type and state, and settings.

<sup>b</sup> Setting includes large wood representation, observations used for model calibration or validation, and model calibration and validation results.

<sup>c</sup> Observations used for model calibration or validation include calibration and validation results.

<sup>d</sup> Bair et al. (2019) study is marked as (Continues)
Keys et al. (2018). The floods were equivalent to a < 1-year recurrence interval flow. The log jams increased floodplain inundation depth and extent by 33% and 34% respectively and decreased maximum thalweg velocity by 10%. However, peak discharge reduction was small; discharge outflow without log jams was 53 L/s and with log jams was 48.7 L/s (8% reduction).

### 3. REPRESENTING LARGE WOOD IN HYDRAULIC AND HYDROLOGICAL MODELS

Seven different approaches have been used to represent the hydraulic and hydrological effects of LW in numerical models (Table 3). The most common representation is through the adjustment of channel roughness to simulate LW generated flow resistance. Despite the number of studies and range of methods applied, most are heuristic in nature and quantitative validation of approaches has been limited. Of the 26 studies listed (Table 3), only nine contained any form of model validation or calibration (Table 4) as defined by Refsgaard and Henriksen (2004).

#### 3.1. Geometry adjustment

Altering channel geometry by raising the channel bed to represent a LW feature as a solid obstruction has previously been recommended (Abbe, 2006; Brooks et al., 2001). Good 1D model validation for a bank attached engineered log jam (ELJ) is possible by raising a segment of a cross section (Valverde, 2014; Table 4). In a 2D model context, the obstruction effect can be represented by adding discrete elements to the calculation mesh and good predictions of hydrograph shape (Rasche et al., 2019), depths and velocities is possible (Bair et al., 2019). The complexity of the shape used to represent a LW feature can influence hydraulic predictions. Allen and Smith (2012) demonstrated using a 3D computational fluid dynamics (CFD) model, that as the shape complexity of a LW feature represented in a model increased, both the drag coefficient and turbulent kinetic energy decreased.

Although geometric adjustment to create a solid obstruction is easily implemented in numerical models and intuitively appealing, there are potential drawbacks. Previously flume based studies supported by field observations of sediment and organic matter clogging wood interstices, have assumed log jams to be solid objects thus neglecting the importance of porosity (Shields and Gippel, 1995). This assumption may not be applicable in all cases. Based on observations of a bank attached ELJ, assuming non-porosity led to a 10–20% over-prediction of drag force and a 75% over prediction of maximum shear stress at the bed (Manners et al., 2007). Consistent with this, representation of porous structures as solid geometric features leads to exaggerated hydraulic predictions at the location of the feature in 1D models (Valverde, 2014), unrealistically reduced conveyance in 2D models (Kitts, 2010) and overpredicted velocities in 3D models (Allen & Smith, 2012; Xu & Liu, 2017). Although
hydrograph shape can be captured in 2D models, it can be unrealistically delayed due to the impermeability of the altered mesh elements and the required editing is time consuming, limiting the practicality of the approach (Rasche et al., 2019).

Altering channel geometry to create solid obstructions can capture the impoundment and deflecting effects of LW and may be particularly useful for capturing sub-reach scale effects in 2D or 3D. However, the limited validation in previous studies and potentially poor representation of permeability, limits its widespread application.

### 3.2 Roughness adjustment

Increasing the roughness at the location of a LW feature or at the reach scale to simulate increased flow resistance is the most popular means of representing LW (Table 3). It has previously been recommended as an approach for modeling isolated, mid-channel debris in 2D models due to their complexity (Pasternack, 2011). At the catchment scale, using a hydrological model (OVERFLOW), empirically based Manning’s $n$ values (0.196 ± 0.08) for naturally occurring log jams in the New Forest were used (Dixon et al., 2016). Similar values have also been applied in different settings in the UK (Ball et al., 2012; Odoni & Lane, 2010).

The suitability of manipulating roughness has been explored in several studies. In a steady state 2D simulation, Kitts (2010) validated increasing Manning’s $n$ at the scale of a single naturally occurring dense log jam and showed that predictions of inundation extent matched observations well (Table 4), compared to representation through geometry adjustment. It was reasoned that the porous nature of the log jam and conveyance were better captured. Rasche et al. (2019) applied a decrease in the Strickler coefficient (increase of channel roughness) of 30% at the reach scale and 55% at the locations of nine artificial LW features, using a 2D model (HYDRO_AS-2D; Table 4). The reach scale representation resulted in a more accurate outlet hydrograph simulation explained by multiple LW features producing backwater and wake effects beyond their locations. Using 1D hydraulic models, both Valverde (2014) and Geertsema et al. (2018) showed that the prediction of upstream backwater effects was more sensitive to alteration of roughness rather than geometry at the location of the LW.

While applying empirically measured and model validated Manning’s $n$ values can be easily applied to reach or catchment scale models, the transferability of roughness values requires careful consideration. Firstly, Manning’s $n$ values derived from one source and applied to another study could be unsuitable depending on the similarity of the LW feature and river. For example, Wilcox and Wohl (2006) found LW that coincided with steps in coarse step-pool channels resulted in synergistic effects on flow resistance. However, values of LW resistance from these settings are unlikely to be applicable to lower gradient channels. Secondly, applying a static roughness value negates temporal variability of flow and LW features. Empirical studies show that flow resistance created by LW (Table 1) and open channels in general (Morvan et al., 2008) is stage dependent. As most empirical studies have been undertaken during low flows (i.e., ≤ bankfull) at the reach scale, the flow resistance is not likely to be representative of higher flows (Table 2) or sub-reach scale flow resistance. Furthermore, changes to a LW feature whether seasonal, gradual or stochastic, may considerably alter its flow resistance (Manners et al., 2007). Lastly, values of Manning’s $n$ are not universally applicable to 1D, 2D and 3D models as roughness has different meanings in different models (Morvan et al., 2008) and output is sensitive in especially in 1D models (Bozzi, Passoni, Bernardara, Goutal, & Arnaud, 2015).

Altering roughness parameters is understandably often applied as it is easy to do and the range of available empirically derived observations to draw on. Based on limited validation, its successful application is possible; however, there are important transferability and spatiotemporal limitations to be aware of.

### 3.3 Geometry and roughness adjustment

This approach involves modifying the channel geometry and roughness at the scale of a LW feature (Table 3). In HEC-RAS 1D, Valverde (2014) showed that when such a combined approach was applied, the effects of form resistance or geometry dominated cross sections containing the ELJ while roughness dominated in cross sections upstream of the ELJ. Brooks et al. (2001) observed 0.1 m of afflux when a similar combined approach was used in a 1D simulation with alteration of geometry more influential than roughness adjustment.

The Allt Lorgy case study (Gillies, 2016) provides an example of using a 2D hydraulic model (SRH-2D) combined with empirical knowledge of expected drag forces to predict the effects of isolated logs that partially block a channel cross section (Gillies, pers. comm.). Logs were simulated by both altering the bed topography and increasing the Manning’s $n$ value. Using the empirically derived function of Equation 1 presented in Hygelund and Manga (2003), the expected drag force on
each log was predicted. The apparent drag coefficient of the logs required for Equation 1 was predicted as a function of the relationship between the cylinder drag coefficient (a value of 0.8 was used in this case) and the ratio of the channel area blocked (Equation 3). The Manning’s $n$ of the log was then adjusted until the drag force in the model matched the predictions.

The above approach is like that previously suggested by Shields and Alonso (2012) but remains un validated. It relies on appropriate choice of drag coefficient to represent the LW. A value of 1.2 has been used in previous wood transport studies to represent simple, individual logs (Ruiz-Villanueva et al., 2016) as also recommended by Brooks, Abbe, et al. (2006) for modeling the hydraulic effects of static LW. However, assuming the drag values of isolated cylinders is not applicable to more complicated log pieces or log jams (Manners et al., 2007) or large diameter cylinders relative to flow depth (Turcotte et al., 2016). Moreover, Wilcox and Wohl (2006) found that a cylinder drag based approach was unreliable in step-pool channels as they do not account for flow resistance interaction effects between LW and channel steps. Other empirically derived drag coefficients up to 9.0 may be more realistic for representing dense log jams (Manners et al., 2007). In contrast, Shields and Alonso (2012) observed drag coefficients, derived from a flume experiment, ranging 0.22 to 6.27 for single non-cylindrical LW with branches.

Combining modification of channel geometry with increased roughness, has been adopted in 5 studies (Table 3) but the lack of validation limits assessment of its suitability. It relies on careful consideration of the input parameters and justification for their modification.

### 3.4 Roughness and hydraulic equation adjustment

Applying the 2D hydrodynamic model CCHE2D, Wu et al. (2005) adjusted the reach wide Manning's $n$ value to 0.028 and to represent the hydraulic effects of five artificial LW structures, added the expected drag force of the structures into the momentum equations and turbulence generation into the turbulence kinetic energy equation (Table 4). A drag coefficient of 2.0 was used for all flow conditions. Although the limited model validation showed a good result for velocities (Table 4), use of a static drag coefficient may have negated LW structure and flow variation thus affecting model performance (Wu et al., 2005).

This combined approach has only been applied in one study so far and has similarities to the geometry and roughness adjustment approach (Section 3.3). However, it too relies on careful alteration of input parameters and the paucity of validation limits an assessment of the approach.

### 3.5 Hydraulic structure representation

This approach is based on the premise that the hydraulic effects of LW are analogous to the effects of in-stream structures such as weirs or culverts (Table 3). The engineering equations representing these features are typically built into standard hydraulic modeling packages such as HEC-RAS or Flood Modeler. Keys et al. (2018) used a weir function with random orifices schematized in HEC-RAS 2D. Orifices were iteratively added until a good calibration was achieved (Keys pers. comm.; Table 4). Thomas and Nisbet (2012) applied a partial blockage factor in Infoworks to model the effects of artificial spanning log jams in a small woodland stream. Only one calibration event was used with modeled peak water levels falling within 0.03 m of measured peak water levels (Table 4) but no validation was carried out. Using a hydrological model (Dynamic TOPMODEL), Metcalfe et al. (2017) applied the hydraulic engineering formula of Kirschmer (1926) and Swamee (1992) to represent the simple form of hypothetical flow restrictors but again no validation was carried out.

Using structure representations is an appealing way of simulating artificial flow restrictors (e.g., Figure 1(e)) that have a simple geometry and channel spanning log jams. However, validation remains limited and the approach is unlikely to reliably predict the local hydraulic effects of complex natural or artificial structures.

### 3.6 Explicit 3D representation

Only 3D modeling can fully represent the pores between timber members (Table 3), however to date it has only been applied to relatively simple ELJs at sub-reach scales (Allen & Smith, 2012; Xu & Liu, 2017). Compared to treating a structure as a solid object, flow structures are better predicted in the near field using a fully resolved representation of an ELJ and good validation is possible (Xu & Liu, 2017; Table 4).

3D CFD models provide a useful means of capturing all hydraulic effects in high detail but there are considerable constraints. Firstly, creating meshes to represent the complexity of LW features is very time consuming (Lai & Bandrowski,
and there is a practical limit to the degree to which all LW aspects (e.g., tree bark texture, twigs and branches) can be captured. Secondly, 3D CFD is currently computationally demanding in contrast to other simpler models. Given these constraints, 3D CFD is more relevant to understanding the local hydraulic effects of individual LW features where accurate detail is required, or for hydraulic research purposes, rather than widespread application.

3.7 | Porosity model

An under-investigated approach is the application of a porosity model to capture the movement of water through LW interstices as applied by Xu and Liu (2017; Table 3). Porosity models have previously been used and successfully calibrated in coastal engineering applications (Jensen, Jacobsen, & Christensen, 2014).

For a simulated ELJ, the porosity model approach can yield similar results in the near-field and wake region with considerably less computational costs compared to a fully resolved 3D model (Xu & Liu, 2017). However, loss of information was observed, and careful interpretation of results was recommended.

4 | DISCUSSION

4.1 | Suitability of current large wood representations

At a qualitative level, numerical modeling has been used to successfully capture the fundamental hydraulic effects of LW at local or reach scales (Table 1). Backwater effects, reduced velocities and increased floodplain connectivity (Section 2.1 and 2.2) have been validated in hydrodynamic 1D and 2D models. At meso-catchment scales, flood wave slowing and discharge attenuation effects (Section 2.3) have been predicted in hydrological models although the effects of LW can vary depending on number and location (Dixon et al., 2016). Seven types of representation were identified that have been used in hydrodynamic and hydrological simulations (Table 3). The variety in part reflects the capabilities of the models used and the modeling objectives but also the type of LW feature considered; thus, there is no “one size fits all” approach.

Although modeling LW will always be difficult due to their variety and spatiotemporal complexity, this review highlighted shortcomings in predicting their effects through numerical modeling. Firstly, in most cases, the reasoning for the selection of different LW representations in models is not supported through adequate justification and studies that present quantitative validation or calibration results remain limited (Table 4). In some cases, only calibration is undertaken even though validation through comparison with independent observations is essential for assessing model performance (Refsgaard & Henriksen, 2004). Secondly, further testing of all LW representations is needed to compare their applicability and computer processing costs. This includes porosity model and drag coefficient based approaches which have received little attention so far. Lastly, there are knowledge gaps surrounding the representation of different types and scale contexts of LW in models; in comparison to naturally occurring LW, artificial LW has received limited attention. Instead channel spanning (active or complete) and bank attached (partial) types have been focused on so far at the reach-scale in small streams (catchment area <15 km²; Table 4). Together, these issues make it difficult to be completely confident in the ability of all models applied so far to realistically capture LW effects.

The choice of LW representation is dependent on the scale of interest and purpose of the application. For example, Valverde (2014) recommended that to predict upstream flood risk in site-scale 1D models, flow resistance parameterization was more important but for predicting hydraulic conditions close to a LW feature, correctly representing a feature as a change in geometry is more important. At the scale of a headwater stream, applying an increase in roughness throughout can produce a valid hydrograph simulation at the outlet suitable for small catchment scales (< 5 km²) but not local scale (log jam scale) applications (Rasche et al., 2019).

Altering channel roughness is the most common approach to representing LW presumably because of its simplicity. Furthermore, studies show following sufficient calibration, it can be representative of partial or complete porous LW features at the local- (Valverde, 2014) or reach-scale (Kitts, 2010; Rasche et al., 2019). Empirical research indicates that the flow resistance created by LW can be related to the type or geometry of a structure, the scale and slope of a river (Figure 2) and the magnitude of flow (Table 2). Additional empirical research and model validation of LW flow resistance, especially over catchment scales greater than 15 km², would further constrain a priori roughness parameterization. The values given in Table 2 may however represent a useful starting point if the following criteria are met. Firstly, the proposed LW type, catchment scale and river type in question are similar to these of previous studies (cf. Table 2 and Section 3.3). Secondly, the scale of representation within a model should be commensurate with the scale used to empirically determine the flow resistance which is
tymally at the reach scale (Table 2); empirical reach scale values are unlikely to be applicable at the sub-reach scale. Thus, a priori selection of empirical flow resistance parameterization should consider both scale transferability to models and justify values chosen based on LW type and hydro-geomorphic context.

A key issue when considering the realism of LW representations reported in Table 4 is the suitability of the model assessment methods used for calibration or validation. Although the model assessment approach undertaken depends on the purpose of the study and availability of data, in most cases only a single hydraulic parameter (typically stage observations) and method (either performance statistics or visual comparison) are used (Table 4). For reach scale hydraulic modeling, assessment of a range of hydraulic parameters upstream and downstream of a LW feature, using at least two basic parameters (stage and velocity), at multiple locations (e.g., Pasternack et al., 2004), would provide further confidence that models are capturing the range of effects. For hydrological change predictions typically needed at catchment scales, stage and discharge observations are needed – ideally temporal – both upstream and downstream of LW sites. Regardless of the spatial scale and purpose, clearly defining the case specific model accuracy criteria (Refsgaard & Henriksen, 2004) and applying multiple assessment statistics (e.g., Nash-Sutcliffe Efficiency, model bias, root mean square error and correlation coefficients) alongside visual scrutiny of outputs, can ensure a more confident assessment of model performance (Jackson-Blake et al., 2015).

As hydrology is an inexact science (Beven, 2018) model input parameters and thus outputs are uncertain (Bozzi et al., 2015). Regardless of the LW representation used, uncertainty of model inputs and consequently outputs thus need to be considered even if calibration and validation results meet the required criteria (Refsgaard & Henriksen, 2004). Flow resistance, channel geometry, channel slope and discharge inputs are all key uncertainties that need to be considered in model outputs (Bozzi et al., 2015). Applying an ensemble of simulations as previously recommended (Rasche et al., 2019) and applied to LW (Dixon et al., 2016; Hankin, Metcalfe, Beven, & Chappell, 2019) is a logical approach to capture model uncertainty and the range of probable effects at reach or catchment scales. Model performance assessment is also specific to the application and performance criteria used (Refsgaard & Henriksen, 2004); parameters applied to a validated model in one context might not be transferable to another. Adequate model uncertainty assessment and the assessment of a priori transferability of LW representations are particularly pertinent issues for scenario modeling needed for FRM and habitat restoration planning applications. Both careful justification of LW representation and robust uncertainty assessments should be included to improve confidence in scenario modeling.

Comparative testing of different LW representations to determine the possible equifinality of predictions is also an area requiring more research. For example, in the study of Pinto et al. (2019), for a low discharge (0.283 m$^3$/s), using a blockage factor or Manning’s $n$ representations resulted in similar predicted stages. The most parsimonious approach that is adequately supported by previous validation should be chosen over preference to more complicated representations (e.g., addition of elements to meshes). Moreover, awareness is needed that equifinality will not necessarily hold for different model inputs. Application of different models calibrated to the same level of performance could produce different predictions under different conditions (Beven, 2019).

### 4.2 Knowledge gaps of temporal variability

Computational models provide a useful means of assessing the hydraulic and hydrological effects of LW typically for a static, “as designed” state. Not all processes and effects associated with LW are necessarily relevant or possible to include in models and inclusion will depend on the purpose of the study. However, given their structurally flexible nature and the hydro-geomorphic feedbacks they create, four knowledge gaps in the approach taken to modeling the temporally variable effects of LW can be highlighted.

Firstly, the changing geometry or size of LW structures due to wood capture, weathering and hydrologic displacement can greatly influence hydraulic effects (Table 1). So far, no numerical modeling has coupled wood transport models (e.g., Ruiz-Villanueva, Bodoque, Díez-Herrero, Eguíbar, & Pardo-Igúzquiza, 2013) applied to LW features with hydraulic models of LW. Although wood transport models may only be feasible at the reach scale, at larger catchments scales, altering LW roughness could be a simpler means of capturing the hydrological effects of changing LW state.

Secondly, the interaction of LW with varying discharge including high overbank flows results in hydraulic effects that are stage dependent (Dudley et al., 1998; Manners et al., 2007; Shields & Alonso, 2012). The hydraulic effects of LW in unsteady state conditions during discrete flow events have been modeled but longer timescales over annual or seasonal scales have not been considered in models. Unsteady state modeling over longer timescales and a greater variety of flood magnitudes should be a priority.
Thirdly, in relation to lowland rivers, the hydraulic interaction of LW with aquatic vegetation, remains underexplored in empirical- and model-based studies and should also be considered (Pinto et al., 2019). Aquatic vegetation can generate significant flow resistance that can vary according to temporal growth patterns (O’Hare, Mountford, Maroto, & Gunn, 2016) and its coincidence with LW could potentially have synergistic effects on flow resistance.

Lastly, another knowledge gap is accounting for LW mediated morphological change through alteration of sediment transport processes. Morphological changes can result in altered hydraulic feedbacks (Schalko et al., 2019). Moreover, morphological change may occur at LW sites independent of their influence due to wider catchment hydro-geomorphic processes. In addition to often documented hydraulic habitat changes that can also be modeled (Bair et al., 2019; He et al., 2009), changes in morphology can alter flood risk mitigation functions of nature-based interventions including LW features (Hankin et al., 2019). Reach scale 2D morphodynamic models provide a useful tool for predicting morphological changes (Williams, Measures, Hicks, & Brasington, 2016). However, application of morphodynamic models to LW has so far been limited (Wu et al., 2005) perhaps due to their complexity. Modeling of shear stress combined with knowledge of grain size to predict erosion and deposition responses could be a useful simpler alternative, especially over larger scales (Hankin et al., 2019).

4.3 | Modeling large wood beyond the reach scale

To date, empirical and model validation studies have concentrated on short reaches with small catchment areas (Table 2 and Table 4). This partly reflects observation that channel spanning log jams are naturally more common (Gurnell, Piegay, Swanson, & Gregory, 2002) and more stable at these scales (Kramer & Wohl, 2017). Furthermore, adequate validation is difficult at larger catchment scales over a range of flows especially during floods which are rare (Metcalfe, Beven, Hankin, & Lamb, 2018) but is more manageable at local or reach scales within smaller streams where complexity is reduced.

A key catchment management and practitioner need is the defensible numerical modeling of LW or other nature-based solutions at larger catchment scales (> 10 km²). Modeling at these scales is critical for informing FRM and river restoration decision making but remains challenging. Issues include the greater requirement for input, calibration and validation observation data, peak synchronization or desynchronization effects associated with the dynamic interaction between sub-catchments and the increased computational costs (Lane, 2017). Depending on the project requirements, spatial scale and complexity of the catchment of interest, these limits may always be factors influencing the model approach undertaken.

Recent improvements in computer power and models could help overcome these constraints. Using Delft3D Flow in 2D mode combined with cloud computing, Nahorniak et al. (2018) ran 2,200 reach scale hydraulic models to efficiently quantify hydraulic habitat across multiple catchments. The coupling of 1D or 2D hydraulic models - to represent the reach scale effect of nature-based solutions including LW - with hydrological models can be used to efficiently predict hydrological changes created at catchment scales of <30 km² (Hankin et al., 2019; Metcalfe et al., 2017). This combined approach shows promise as it captures the detailed site scale hydraulic effects of multiple measures including LW across catchments potentially more reliably than a single model approach. However, to date its application to catchment scales beyond 30 km² is untested and may necessitate a decrease in modeling resolution (Hankin et al., 2019). Improved validation of downstream hydrological responses at catchment scales ranging from small (10 km²) to medium scale (100 km²) and beyond, would increase confidence for upscaling modeling to provide predictions of hydrological responses relevant for FRM, habitat or water resource management planning purposes.

5 | CONCLUSION

The addition of LW to rivers to satisfy a range of river management goals has become commonplace and in parallel the hydro-geomorphic effects of LW have been extensively researched. Numerical modeling has become a popular tool to predict hydraulic and hydrological effects. Seven types of LW representation applied in models to date were identified with manipulation of roughness the most common approach. Recent model validation studies, although limited in number and with associated issues, show the capability of modeling to capture the hydraulic and hydrological effects of LW. Despite these developments, accepted guidance to inform realistic numerical modeling remains scant. Based on available empirical knowledge and the limited number of LW model validation studies, the following recommendations are made for representing LW in hydraulic and hydrological models:

1. The effects of static LW are spatiotemporally varied reflecting not just the varying complexity and size of LW but the complex interactions with variable channel flow and morphology. Thus, consideration should be given to the characteristics
of the LW feature(s) in question in relation to the specific wood dynamics regime and hydro-geomorphic context being modeled.

2. Adjusting roughness is a suitable approach for representing the effects of single or multiple log jams at the site or reach scale. The diversity of regions, LW and river types and scale dependence of empirical measurements means that knowledge of flow resistance is not necessarily transferable. Moreover, the flow resistance generated by LW is stage dependent. Therefore, applying known values across regions and model types is uncertain. Provided that there is similarity of LW type and setting, the synthesis of values presented in Table 2 and Figure 2 could be used as a starting point for LW modeling.

3. Although with careful adjustment, geometric adjustment can represent the blockage effect of LW, empirical knowledge and some model validation evidence suggest that it could lead to exaggerated hydraulic predictions especially for highly porous LW and in 1D hydraulic models. Moreover, in 2D or 3D models, outputs are sensitive to the level of mesh editing to represent LW and can be very time consuming limiting its practicality.

4. Uncertainty in model input data, a priori representation of LW and consequently model outputs will always need to be considered given the complexity of LW, an issue that becomes even more important when predicting hypothetical LW features over large catchment scales. Application of ensemble simulations (e.g., Monte Carlo analyses) are useful for accounting for model uncertainty. To ensure robust model assessment needed for calibration and validation, multiple criteria should be applied including hydrograph shape, discharge, velocity, and water stage using multiple methods (i.e., a range of performance statistics and visual inspection of outputs).

Additional research is required to strengthen the reliability of modeling LW in future. The following represent key research needs:

1. Consideration should be given to validation of the following under-researched LW representations: using hydraulic structures, porosity models and drag coefficient-based approaches.
2. The range of representations to choose from means model equifinality is a potential issue. Further inter-comparison of different LW representations to determine advantages and disadvantages would help to inform the choice of method that is appropriate for the specific model type, application and scale of interest.
3. Further empirical investigations would substantiate relationships between LW form, channel gradient or type and flow resistance. Given the low flow conditions of most empirical research and stage dependency of LW hydraulic effects, investigation during a variety of flows is needed. Together with continuing model validation studies, this would help to create transferable guidance for informing type specific LW representations in models across different river scales and regions a priori.
4. A greater range of LW types should be researched in the field, including artificial LW, for longer periods beyond the “as-built” stage. At the same time, model validation studies should consider isolated or accumulated LW in mid-channel settings and artificial flow restrictors that differ from natural analogue LW and have received less attention to date.
5. Models have mostly been tested over small spatial (short reaches, < 15 km² catchment area) and temporal scales (single flow events). Testing and model refinement over scales greater than reach would help inform catchment-based predictions needed for confident decision making. As the hydraulic effects of LW are not static, accounting for the temporal dynamics of LW structure (size and geometry) and hydro-geomorphic feedbacks over longer temporal scales, would allow assessment of the ability of modeling to capture the range of possible effects.

The management of naturally occurring in-channel LW and its artificial addition potentially represents, as part of a suite of nature-based measures, a useful approach for addressing different river management goals. Numerical modeling represents a key decision-making aid. Through following the recommendations made above, the basis for predicting their effects, and thus the defensibility of LW decision making could be strengthened.

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CONFLICT OF INTEREST

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

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