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Instream Large Wood Enhances the Benefits of e-Floods in Regulated Mountain Rivers

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ABSTRACT

Environmental high flows, or e-floods, released from dams are a key management strategy to mitigate the impacts of dam regulation and restore aquatic and riparian habitats. While there is extensive literature on the design and implementation of e-floods, the role of instream large wood—downed trees, trunks, branches, and root wads—in enhancing e-flood outcomes in regulated rivers has not been adequately explored. This paper presents insights from the Spöl River in the Swiss Alps, where years of observations highlight the significant impact of large wood on the success of e-floods. Large wood contributes to geomorphological dynamics, increases habitat complexity, and enhances ecosystem resilience, yet it has been largely overlooked in e-flood planning. The study argues that the inclusion of instream wood can define the difference between success and failure in e-floods by supporting the continuity of the wood regime, which, along with flow and sediment regimes, is crucial for ecological integrity, and emphasizes the importance of integrating wood management into e-flood design. The Spöl River serves as a case study, demonstrating how wood management during e-floods can restore or sustain essential functions, ultimately improving the ecological health of river systems. The insights gained can be applied to the management of other regulated mountain rivers.

1 | Dams Interrupt the Flow, Sediment, and Wood Regimes in Forested Mountain Rivers

Dams play a significant role in society, providing multiple services such as hydropower, flood control, water supply, recreation, and support for fluvial navigation. As a result, they are amongst the most widespread river infrastructures on Earth (World Commission on Dams WCD 2000). In Europe, dams built for hydropower tend to be concentrated in mountainous areas to exploit the high-head potential of steep sections of rivers (based on the Global Reservoir and Dam Database, GRanD; Lehner et al. 2011), particularly in the Alpine region, where a significant expansion is expected in the near future (Farinotti et al. 2019; Zarfl et al. 2015). However, this large-scale use of dams has substantially impacted freshwater ecosystems, becoming one of the main threats to freshwater biodiversity globally (Dudgeon et al. 2006; Maavara et al. 2020; Vörösmarty et al. 2010). Locally, the construction and operation of dams have significant short- and long-term implications for the downstream hydrological, morphological, ecological, and social systems (Brunner and Naveau 2023; Pahl-Wostl 2006). The disruption of flow, sediment, and wood regimes, along with changes in water biogeochemistry, has profound effects on the ecological components of rivers, often persisting for several kilometers downstream (Poff et al. 1997; Sabo et al. 2018; Wohl et al. 2015, 2019).

In regulated rivers, aquatic, riparian, and floodplain ecosystems adapt and realign their functions to meet the new environmental conditions (Bunn and Arthington 2002; Ligon et al. 1995; Power et al. 1996), sometimes leading to the degradation of essential river ecosystem services (Auerbach et al. 2014). In unregulated rivers, organisms exhibit functional, behavioral, and phenological adaptations to the natural variability of environmental conditions. This variability characterizes the biotic assemblages of rivers and the natural species turnover in fluvial ecosystems (Lytle and Poff 2004; Townsend and Hildrew 1994). Steady and homogeneous flow conditions resulting from dam regulation alter the natural gradients of plant species on riverbanks, reducing riparian vegetation diversity and diminishing the multiple ecosystem services it provides (Merritt et al. 2010). Aquatic organisms are also impacted at different life stages, affected by river network fragmentation, habitat degradation, changes in resources, and nutrient availability (Grill et al. 2019).

Natural flow, sediment, and wood regimes determine the geomorphological features of a river reach, influencing the distribution and frequency of different habitat types. High flows mobilize sediment and instream large wood, determining the so-called disturbance regime (Dufour and Piégay 2010). This ensures longitudinal and lateral connectivity, maintaining the natural "shifting habitat mosaic" of rivers (Stanford et al. 2005). Dams completely block the transport of coarse sediment, leading to channel degradation, which typically results in incision, bed coarsening, colmation (i.e., fine sediment accumulation) and the disconnection of rivers from their floodplains (Petts and Gurnell 2013). The reduced wood supply from upstream and the limited lateral recruitment from floodplain and channel banks due to flow regulation results in a decreased wood load, leading to reduced flow resistance, high flow velocity, transport capacity and erosion, significantly impacting channel morphology (Abbe and Montgomery 2003; Montgomery et al. 2003), and the vital ecological functions and services that wood provides to river ecosystems (Poledniková and Galia 2021; Verdonschot and Verdonschot 2024). While the effects of flow regulation have been widely described (e.g., Poff et al. 2007; Rosenberg et al. 2000), little is known about the ecological repercussions of wood deficit, not only by dams (e.g., Nakamura et al. 2017) but also caused by the indiscriminate removal of wood from rivers (Wohl 2014).

2 | Mitigating the Impacts of Dams: *E-Floods* in Regulated Rivers

The urgent need to halt and revert river degradation has motivated the development of operational measures for mitigating the impacts of dams, such as releasing controlled flows, or the so-called *environmental flows* (Gebreegziabher et al. 2023; The Brisbane Declaration 2007). The concept of environmental flows moved from an original focus on maintaining minimum residual flows (Acreman and Dunbar 2004; Tharme 2003) to account for some important seasonal components of the natural flow regime (Poff et al. 1997), incorporating high flows in the operational schemes of dams, referred to as experimental or artificial floods (e.g., Arthington et al. 2018; Konrad et al. 2011; Robinson et al. 2018). The term "ecomorphogenic flows" was recently proposed to describe high flows released from dams, specifically designed to produce morphological changes that enhance aquatic and riparian habitats (Loire et al. 2021). We propose using the term "ecomorphogenic-floods" (hereafter referred to as e-floods) instead of broader terms like environmental or ecological flows. This term highlights a process-based approach, explicitly addressing the interconnected hydrological, morphological, and ecological aspects while encompassing all potential expected effects.

The design of these dam water releases is inherently complex, shaped by the intricate and often conflicting interests and interactions among stakeholders, which are typical of water-related socio-ecological systems (Gerten et al. 2013; Jägermeyr et al. 2017; Pastor et al. 2014). This complexity is further amplified by the non-stationarity of water resources and aquatic ecosystems, driven by factors such as climate change impacts on hydro-climatic processes or the introduction of invasive species (Palmer et al. 2009; Poff 2018). The design of e-floods requires a deep understanding of natural regimes and their interaction during floods to quantify the extent of their alteration and identify which aspects are critical to recovery and to achieve the targeted restoration objectives (Wohl et al. 2019). Hydrological time series are used to characterize the natural (pre-dam) and regulated flow (post-dam) regimes and to quantify the impact of the reservoir operation on the flow regime (e.g., Brunner and Naveau 2023). However, analogous data for sediment regimes are much more limited, and even fewer data exist for wood regimes worldwide (Nakamura et al. 2017; Wohl et al. 2019). This is despite the recognized need to consider the interactions among these three physical master variables of rivers—flow, sediment, and wood—for successful ecosystem restoration. Focusing on only one component or pursuing narrow restoration goals (e.g., targeting a single species) can be insufficient (Messager et al. 2023; Tonkin et al. 2021; Yarnell et al. 2015). E-flood induced environmental changes can trigger shifts across multiple ecosystem components, while their repeated implementation can give momentum to ecological transitions and functional responses (e.g., Consoli et al. 2023; Cross et al. 2011; Robinson et al. 2018). Despite significant advances in recent years, implementing e-floods beyond minimum or residual flow is not yet widespread, with only a few examples existing globally (see the review by Wineland et al. 2022 or by Yarnell and Thoms 2022). Exemplary cases include the e-floods released from the Glen Canyon Dam to the Colorado River, USA (Olden et al. 2014), the e-floods on the Lower Ebro River in Spain (Gómez et al. 2013), and the long-term program on the Spöl River in the Swiss Alps, where e-floods have been released annually for a quarter of a century (Robinson et al. 2023; Figure 1). They followed existing regulatory or statutory requirements or were implemented for scientific understanding purposes (Olden et al. 2014). These e-flood programs aimed to achieve different goals, such as restoring river ecosystems by enhancing sediment dynamics, sustaining and protecting threatened and endangered species, or restoring specific features for recreational purposes. These exemplary sites demonstrated that e-floods can be successfully designed to achieve restoration and management objectives over both short- and long-term timescales. However, it is essential to adopt a holistic approach that accounts for all physical components of rivers and considers ecosystems as interconnected, and to carefully monitor outcomes for adaptive dam management. For example, in the case of the Colorado River, e-floods initially worsened sandbar erosion, highlighting the need for a thorough evaluation of the sediment budget and a reassessment of the flow release strategy (Schmidt and Grams 2011). Although generalizing the outcomes of these e-flood programs to other

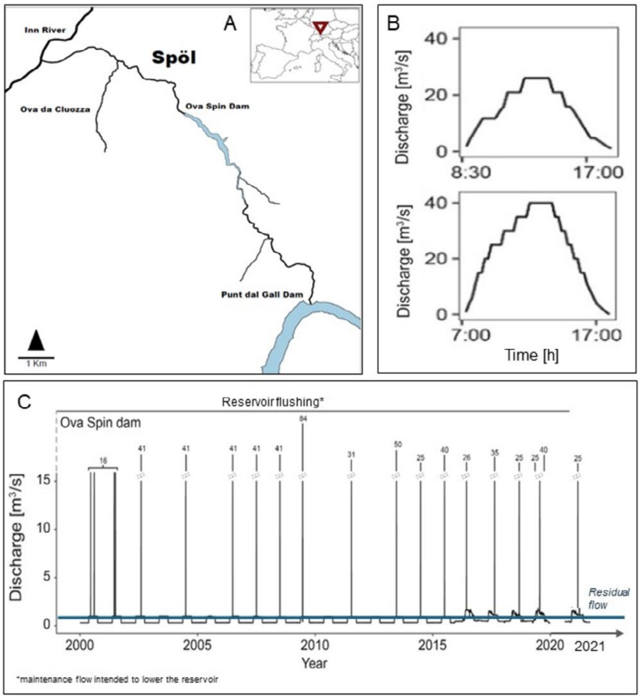

FIGURE 1 | (A) Map showing the location of the Spöl River, Punt dal Gall and Ova Spin dams, Ova da Cluozza (the main tributary in the lower reach), and the confluence with the Inn River, in southeast Switzerland; (B) Illustrative examples of hydrographs for typical e-floods released on the Spöl; (C) Discharge data series and e-floods released from Ova Spin reservoir to the Spöl River between 2000 and 2021. [Color figure can be viewed at wileyonlinelibrary.com]

sites may be challenging, they provide a valuable experimental foundation for testing hypotheses and ultimately guiding river managers in designing e-floods for other systems (Arthington et al. 2023; Olden et al. 2014).

3 | The Spöl River: A Pioneering e-Flood Program in the Alps

The Spöl River is one of these exemplary sites where e-floods have been implemented with a long-term perspective, rather than being released on an episodic basis (Scheurer and Molinari 2003). Located in the central Alps, it flows from the Punt dal Gall dam at the Livigno reservoir on the Italian-Swiss border, through a confined valley within the Swiss National Park, and into the Ova Spin dam, flowing further downstream into the Inn River at Zernez (Figure 1). Before the dams´ construction in the 1960s and 1970s, the Spöl River had a snowmelt flow regime with high spring–summer and low winter flows. Downstream from Punt dal Gall, the river flow was significantly reduced and homogenized (Figure 1), leading to a deficit in coarse sediment transport. This was exacerbated by the absence of large tributaries in this reach, resulting in channel incision, accumulation of fine material, and excess growth of algae and mosses in the uppermost reach. This homogenization caused habitat degradation and consequent functional re-arrangements, with heavy impacts on local biodiversity (Robinson and Uehlinger 2003 and references therein). Below Ova Spin, the Spöl receives water, sediment and wood inputs from unregulated tributaries, with Ova da Cluozza being the main contributor. However, due to the lack of high flows, in this section wood and sediment cannot be mobilized effectively. As a result, in its lowermost reach, the river Spöl experiences coarse sediment accumulation, aggradation, and channel widening (Consoli et al. 2022; Mürle et al. 2003).

In the year 2000, a pioneering e-flood program was established through a unique multi-stakeholder agreement involving Federal and Cantonal authorities, the hydropower company (EKW), the Swiss National Park, the Swiss Academy of Sciences, and scientists from various institutions (Scheurer and Molinari 2003). Since then, 34 e-flows have been released from the two dams (Figure 1). The goals of these e-floods were to remove fine sediment and increase streambed porosity in the upper reach, and mobilize coarse material in the lower part, enhancing sediment dynamics to increase habitat availability to support the recovery of fluvial ecosystems from impacts related to flow regulation. In 2016, PCB contamination in the upper reach following dam retrofitting led to the discontinuation of the flood program for this section, while it continued to be implemented in the lower reach. The effects of the e-floods have been regularly monitored since the start of the program (e.g., Consoli et al. 2022, 2023; Mannes et al. 2008; Mürle et al. 2003; Robinson 2012; Robinson and Uehlinger 2003). Observations revealed that the Spöl River recovered part of its alpine character, and the e-floods mitigated some of the dam's negative impacts. However, it was also noted that regulated systems tend to rapidly revert to pre-e-flood conditions, underscoring the importance of long-term planning (Robinson et al. 2023). Notably, in the upper reach, the e-floods successfully reduced streambed colmation caused by fine sediment, increased sediment grain size variability, led to a rise in alpine-related macroinvertebrate taxa abundance, while redd counts indicate a recovery of the brown trout population (Robinson et al. 2018; Robinson et al. 2023). The monitoring program also highlighted the essential role of unregulated tributaries, such as the Ova da Cluozza, in supplying flow, sediment, and wood to the main river, reducing the impacts of the river regulation and enhancing the benefits of the e-floods (Consoli et al. 2022).

Since 2017, the monitoring program has, for the first time in the global e-floods context, included observing and quantifying the instream large wood regime. The monitoring involved quantifying wood load (i.e., instream wood storage), tagging wood pieces, and tracking their movement during e-floods (Pellegrini et al. 2022; Ruiz-Villanueva et al. 2022). This was complemented by vegetation surveys to provide a comprehensive evaluation of channel processes influenced by wood dynamics, which can also serve as recruitment sources. The data and observations from this monitoring plan form the basis for describing the multiple benefits of large wood and assessing how it can enhance the effects of the e-floods in the recovery of river dynamics.

4 | Benefits Provided by Stationary Instream Large Wood Between e-Floods

Most wood stored in rivers remains stationary for extended periods. For instance, in the Spöl River, only a small proportion of the wood is mobilized during e-floods (Figure 2), a pattern similar to that observed in unregulated rivers. Deposited instream large wood in river channels significantly impacts hydraulics by producing flow resistance and energy dissipation. This creates more complex flow fields, altering turbulence and reducing flow velocity (Gippel 1995; Wilcox and Wohl 2006). Such effects are frequently observed in the Spöl River, where channel-spanning wood accumulations and individual pieces on the channel bed and banks modify water flow (Figure 3); however, these flow modifications have not been quantified yet. This additional resistance to flow results in a decline in flow transport capacity, influencing patterns of sediment deposition, storage, and sorting (Wohl and Scott 2017). Consequently, the accumulation of wood in regulated rivers provides a crucial source of flow field variability and increases sediment grain size heterogeneity. In backwater areas upstream of instream wood accumulations, sediment storage is enhanced, allowing fine sediment deposition (Faustini and Jones 2003; Osei et al. 2015), as shown in Figure 3, where wood deposits retain sand and fine gravel in an otherwise coarse gravel-bed channel (Figure 4). This sediment augmentation effect created by instream wood accumulations can promote riverbed aggradation and even sustain alluvial reaches in sediment-starved channels, which are common downstream from dams. In fact, instream wood accumulations can retain a significant proportion of the total stored sediment within a river, thereby increasing sediment residence time (Pfeiffer and Wohl 2018). Moreover, wood enhances the retention of not only inorganic sediment but also organic matter. Instream and floodplain large wood serve as important reservoirs for organic carbon, facilitating the accumulation of particulate and dissolved organic carbon (Lininger et al. 2019).

The influence of wood on sediment dynamics increases the patchiness or spatial heterogeneity of bed substrate (Haschenburger and Rice 2004; Ryan et al. 2014) and physical

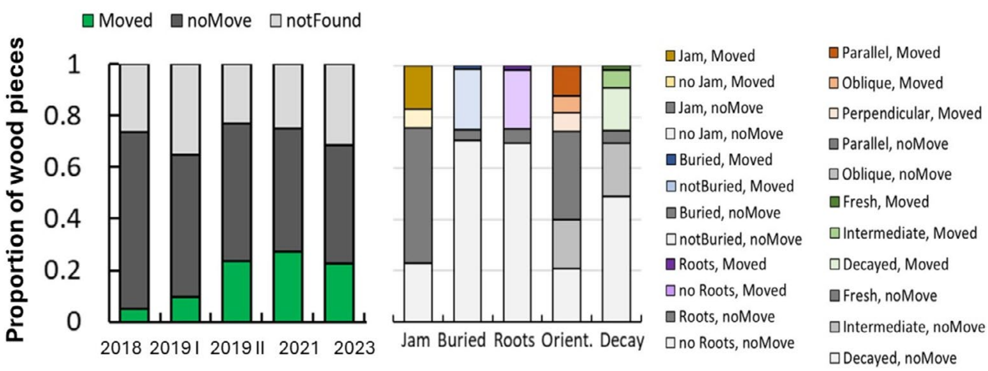

FIGURE 2 | Proportion (between 0 and 1) of wood pieces surveyed in the Spöl River and classified as moved, not moved, or not found between 2018 (pre-flood survey 2019 I) and 2023 surveys; and the main characteristics of the wood pieces in terms of being stored in jams, burial, presence of roots, orientation with respect to the flow, decay stage, and their mobility class (modified from Finch et al. 2025). [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 3 | (A) Channel-spanning wood accumulations; (B) Pioneer island featuring young trees and fine sediment retained upstream; (C) The effect of a wood accumulation on flow and turbulence; (D) Single wood piece retaining coarse sediment and smaller pieces of wood in the Spöl River (Swiss Alp). [Color figure can be viewed at wileyonlinelibrary.com]

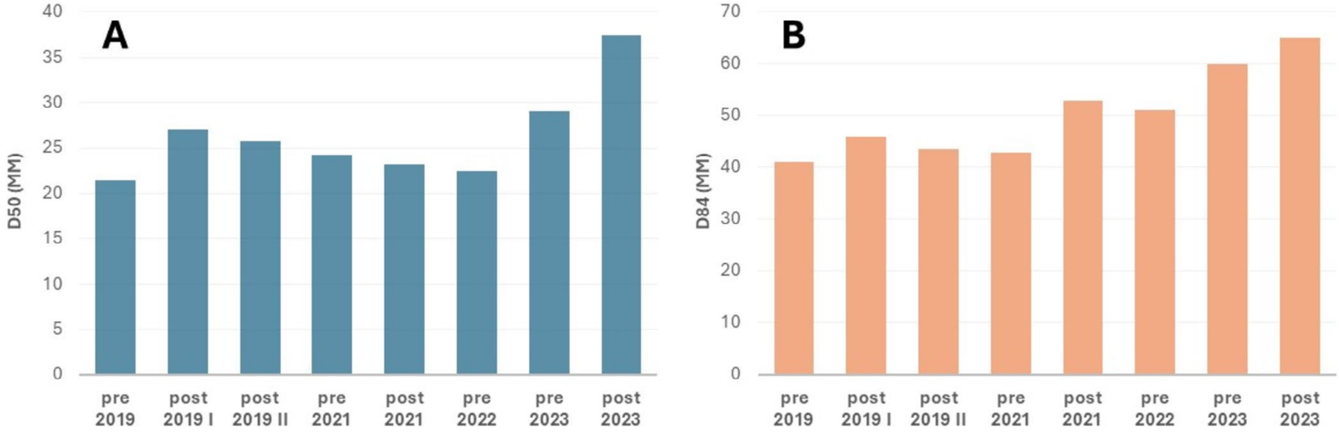

FIGURE 4 | Median (D50) and course fraction (D84) grain size in the Spöl River between 2018 and 2013 (modified from Consoli et al. in preparation). [Color figure can be viewed at wileyonlinelibrary.com]

habitat. Single, channel-spanning wood pieces and wood accumulations or jams can induce a step-pool configuration, modifying the longitudinal channel slope and controlling channel width (Comiti et al. 2008; Gurnell and Sweet 1998; Lapides and Manga 2020; Marston 1982). Wood accumulations can influence river morphology in contrasting ways. On one hand, they can divert flow and induce bank erosion, leading to channel widening and triggering avulsions. On the other hand, instream wood deposits can protect banks by reducing lateral erosion and limiting channel migration (Shields et al. 2004). Therefore, wood accumulations are fundamental components of the physical habitat template of rivers. Their presence increases morphological complexity, creating prime habitats for fish and other organisms. In dynamic streams, such as mountain rivers characterized by substrate instability, wood also provides stable substrates for microorganisms and macroinvertebrates, playing a crucial role in sustaining local biodiversity (Benke and Wallace 2003; Dolloff and Warren 2003; Magliozzi et al. 2020).

The accumulation of wood in rivers enhances the establishment of pioneer vegetation and accelerates the island formation process (Fetherston et al. 1995; Gurnell et al. 2005; Mikuś et al. 2013). The deposition of wood accumulations on gravel bars increases sediment moisture and promotes pedogenesis (Bätz et al. 2015), providing shelter for seedlings and saplings. For some riparian species with vegetative re-sprouting ability, such as willows, uprooted and transported trees can sprout after deposition and start the formation of new pioneer islands (Gurnell et al. 2019; Gurnell and Petts 2006). In regulated rivers, like the Spöl, the limited morphodynamics may result in limited island turnover and the encroachment of existing vegetation. Although this is an expected response of rivers to a decrease in their flow variability and flood magnitude and frequency (de Jalón et al. 2020), encroachment may result in the loss of pioneer habitats for different species (Williams and Cooper 2005) and have ecological and hydrological impacts (Huxman et al. 2005). Therefore, the combined effect of e-floods (Miller et al. 2013) and the enhanced island dynamics promoted by wood accumulations may be crucial. In some reaches along the Spöl River, deposited wood accumulations promote the establishment of pioneer vegetation and the development of small islands (Figure 3), supporting a variety of aquatic and terrestrial habitats that would otherwise not be present along the river. The establishment and development of this pioneer vegetation are controlled by the frequency and magnitude of the released e-floods, which in the Spöl happened mostly once a year around June and with similar peak discharges. However, higher flood frequencies, magnitudes, or different timing could lead to different developments. Before the e-flood program started, 49% of the banks in the lower Spöl were covered by mature encroached vegetation, which has decreased through the years with the release of the e-floods causing reworking of the channel, aggradation, and the inclusion of formerly bank vegetation into the widened active channel (O'Callaghan 2024). Abundant and heterogeneous island landforms promote higher diversity of plants and fauna, including fish, benthic macroinvertebrates, amphibians, and ground beetle communities (e.g., Bilby and Bisson 1998; Lemly and Hilderbrand 2000; Pilotto et al. 2014). Still, most of our knowledge about the bioecological benefits of instream wood comes from studies on fish and macroinvertebrates (e.g., Benke and Wallace 2003; Dolloff and Warren 2003; Pilotto et al. 2014). The benefits of stationary wood on the river ecosystem have been reviewed in previous works, and here we refer to these publications and the references therein for more details (Krause et al. 2014; Lo et al. 2021; Wohl and Scott 2017). Table 1 summarizes the functions and services provided by instream large wood, relating them to potential biophysical objectives of e-floods, and stresses the benefits of the wood to achieve these objectives. The characteristics of wood pieces (in terms of species, size, shape, and decay stage) and the diversity of wood pieces within a catchment are important factors in modulating such responses; however, this has not been studied or investigated in detail.

5 | Benefits Provided by Mobile Instream Large Wood During e-Floods

Instream large wood is inherently mobile in unregulated rivers. While it has been less extensively studied compared to stationary or stored wood, mobile wood is equally vital for maintaining river systems (Wohl et al. 2023; Shumilova et al. 2019). Although direct observations are lacking, we argue that mobile wood can also play a significant role in achieving restoration objectives during e-floods. Observations from a limited number of monitored sites, primarily in unregulated rivers and none under e-flood conditions,

TABLE 1 | Functions and services provided by instream large wood grouped by main biophysical objectives of e-floods, and the potential benefits of wood on the e-floods.

E-floods objectives	Functions and services provided by instream large wood	Potential benefits of wood on e-floods
Increase flow field heterogeneity	Flow resistance and energy dissipation Creation of complex flow fields Altered turbulence and flow velocity fields	Local decrease in flow transport capacity Enhance sediment deposition and sorting Enhance organic matter retention
Enhance morphodynamics and channel platform dynamics	Creation of steps and pools Decreasing longitudinal channel slope Modifying channel width, by both enhancing and preventing bank erosion Triggering avulsions and creating multi-thread channels	Amplifying the patchiness of sediment and substrate spatial heterogeneity Increased geomorphic and habitat diversity
Improve water quality and nutrient spiraling	Promotion of hyporheic exchange flows (Marshall et al. 2023)	Promote areas of cold water upwelling, important for organisms during heatwaves Enhance microbial metabolic activity and biogeochemical processing Carbon storage in sediment
Recovery of target aquatic species like fish and macroinvertebrates	Suitable spawning and nursery areas formation (Nagayama et al. 2012; Senter and Pasternack 2011) Food source and storage (Benke and Wallace 2003; Flores et al. 2011) A hard substrate to colonize, lay eggs, and use as fixed or mobile shelter during high flows (Eggert and Wallace 2007)	Protection for sensitive life stages of organisms (eggs and early developmental stages) Food web diversification Higher diversity of plants and fauna, including fish, benthic macroinvertebrates, amphibians, and terrestrial invertebrates
Sustaining riparian vegetation	Shelter for seedlings and saplings Accelerates island formation process	Establishment of pioneer vegetation Increased geomorphological diversity
Groundwater level regulation, transient storage	Backwater and more frequent overbank flows Prolonging overbank inundation	Aquifer recharge and floodplain water storage Enhanced channel-floodplain connectivity

suggest that instream large wood is primarily transported during floods, with a small proportion of the stored wood being entrained and traveling a few hundred meters (Ruiz-Villanueva et al. 2024; Wohl and Iskin 2021). On the Spöl, around 20% of the stored wood is remobilized during the e-floods, of which only a small fraction reaches the confluence with the Inn River (Finch et al. 2025). Figure 5 shows the spatial distribution of wood deposits in terms of wood density along the surveyed reach of the Spöl between 2018 and 2023, after five e-floods. This relatively low percentage of mobile wood is similar to other observations in unregulated rivers (e.g., Gregory et al. 2024). Observations on wood mobilization during floods are fundamental for estimating wood budgets in rivers. Cases like the Spöl River provide important data for understanding wood dynamics in the context of e-floods, but also in general, it allows testing hypotheses and informing the design of e-floods. Mobilized wood can get temporarily stuck during the e-flood, contributing to the creation of complex morphologies, determining geomorphic changes. Like stationary wood, mobile wood can locally increase hydraulic roughness and flow resistance, potentially reducing the energy available for sediment entrainment and transport (Wohl et al. 2023). This can lead to additional geomorphic effects during e-floods, though such processes are challenging to observe directly in the field. During e-floods, wood accumulations may locally magnify overbank flows, increasing channel-floodplain connectivity and eventually promoting water table recharge (Doble et al. 2012; Wohl and Beckman 2014).

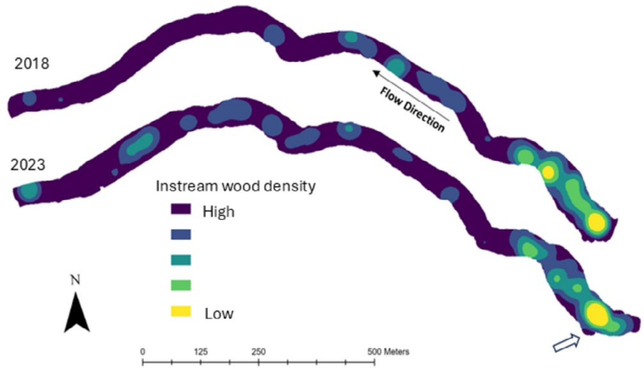

FIGURE 5 | Density maps of instream wood accumulations in 2018 and 2023 between the confluence of Ova da Cluozza (marked by the white arrow) and a wooden bridge, showing how e-floods moved the wood downstream and how density of wood has increased through time (modified from Finch et al. 2025). [Color figure can be viewed at wileyonlinelibrary.com]

Like stationary wood accumulations, mobile wood appeared to be the "hotspots" of propagules and macroinvertebrates. Some studies in unregulated rivers showed that wood supported up to 60% of total macroinvertebrate biomass and contributed over 78% of drifting macroinvertebrates (Benke et al. 1985). On the Spöl River, studies have shown that macroinvertebrate density in lithic habitats typically experiences a sharp decline immediately following an e-flood, with recovery occurring within approximately 4 weeks (Jakob, Robinson, and Uehlinger 2004; Consoli et al. 2022). Anecdotal observations by the authors after e-floods revealed remarkable densities of aquatic macroinvertebrates and the presence of freshly laid egg masses on submerged or partially submerged wood pieces. Notably, cracks, bark fragments, and other microstructures on the wood appeared to provide favorable substrate conditions for macroinvertebrates (Figure 6). This suggests that wood accumulations that present such features may serve as refugia during floods, enhancing the resistance and resilience of aquatic communities to disturbance—an observation that highlights the need for further detailed investigation on the function of wood during e-floods to draw definitive

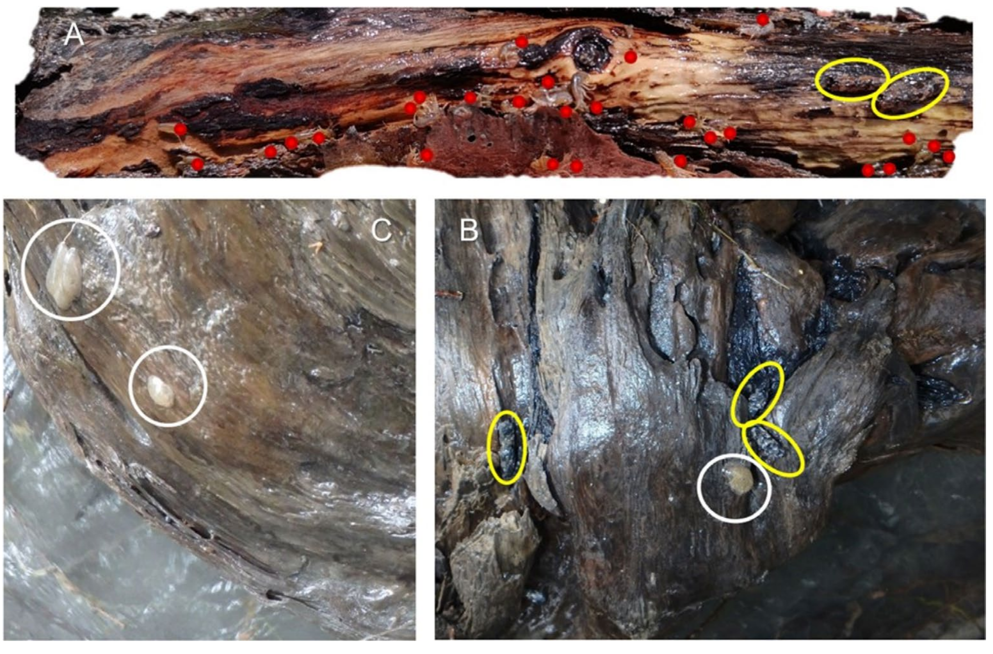

FIGURE 6 | Life on wood pieces deposited on the Spöl River shortly after an e-flood. A: Red circles show Gammarus fossarum individuals, a species ill-adapted to alpine systems; B: White circles show egg masses laid by trichoptera; C: Yellow circles mark cased caddisfly larvae. [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 7 | (A) Picture from the Genissiat dam in the Rhone River in France, where the dam managers periodically remove the floating wood from the reservoir. (B) Engineered log jam designed to retain naturally transported wood in the Sense River in Bern (Switzerland). [Color figure can be viewed at wileyonlinelibrary.com]

conclusions. Mobile pieces can provide a dispersal mechanism that may reduce abrasion of biofilm and increase the survival of attached organisms (Haden et al. 1999). Mobile wood not only sustains source populations of macroinvertebrates but also can function as a vehicle for seeds and plant propagules, potentially facilitating plant regeneration after the e-floods. The downstream drift of wood with aquatic organisms and plants provides access to suitable refugia and habitats, promoting gene flow among populations (Shumilova et al. 2019). However, most of the knowledge on the ecological function of mobilized wood during e-floods is merely anecdotal, and more research is needed to better understand and quantify the role of drifting wood in promoting river ecosystems resilience to disturbances by providing refugia during floods while representing a means for the recolonization of fluvial ecosystems for organisms after natural or e-floods.

Instream large wood serves as a nutritional resource for riverine fauna while stationary on the riverbed between e-floods. During e-floods, wetting of wood pieces enhances this resource, as wet conditions facilitate the release of organic carbon and nitrogen. However, the magnitude and duration of these effects depend on the extent and persistence of the wetting process, as well as subsequent inundation or exposure. Additionally, the decomposition of rewet wood and microbial conditioning of surface layers increase its protein content, becoming an important source of nitrogen and other nutrients for macroinvertebrates, supporting riverine food webs (Shumilova et al. 2019). However, a more thorough consideration of the temporal and spatial variability in wetting processes is crucial to understanding the consequences of e-floods on wood decomposition rates and its availability for aquatic food webs, and how different climatic and hydrological contexts can influence these processes.

6 | Enhancing the Continuity of the Wood Regime in Regulated Rivers

Analogously to sediment, dams trap wood transported from upper sections of the catchment in reservoirs (Figure 7a). This interruption of continuity results in wood-deprived and impaired downstream reaches. However, unlike sediment, the impacts of dam-related alterations to wood regimes are largely unknown but can be assumed to be equally important and of global concern (Wohl and Iskin 2021). Therefore, we advocate for the design of management measures to restore or enhance the continuity of wood transport and sustain wood mobility, similar to approaches taken for sediment (Kondolf et al. 2014).

TABLE 2 | Measures to enhance wood continuity downstream from dams, and how e-floods can help.

Measures to enhance wood continuity downstream from dams	How e-floods can help to promote wood continuity
Design or adapt dams to pass wood	Wood remobilization and distribution of close to natural wood flux, with relatively unaltered wood characteristics (in terms of size, shape, and species) and sorting
Wood augmentation: • mechanical placement of wood structures • loose wood reintroduction	Wood remobilization and distribution of a limited amount of wood, artificially placed in the river and with potentially altered sorting and characteristics
Recovery of the riparian vegetation and wood recruitment processes	Wood supply, remobilization and distribution of wood recruited from a partially altered riparian forest, whose composition and structure are influenced by the timing, frequency and magnitude of e-floods and partly limited recruitment processes driven by the e-floods

Similarly to existing management strategies designed to mitigate sediment starvation resulting from dam trapping, various techniques can be developed to restore the longitudinal continuity of wood transport in rivers (Table 2). Some dams can be designed or adapted to allow wood to pass through or around the reservoir. If structural modifications are not possible, wood augmentation downstream from dams is an alternative measure that does not require changes to the dam structure. This approach has been used for sediment (e.g., Brown and Pasternack 2008) and has also been attempted during e-floods (Stähly et al. 2019). Wood augmentation is a component of many restoration projects (Grabowski et al. 2019; Ockelford et al. 2024; Roni et al. 2015). However, it often occurs at a small scale, involving limited volumes of wood pieces or wood structures (e.g., Neuhaus and Mende 2021). This is partially because of the still prevalent but not always justified negative perception toward wood in rivers (Piégay et al. 2005; Ruiz-Villanueva et al. 2018; Wohl 2015; Wyzga et al. 2009), as well as concerns about wood stability and mobility during floods and the risk posed to infrastructures. As a result, many projects have utilized fixed wood structures such as simple deflectors or the so-called engineered log jams (Abbe et al. 2018). In many cases, this concern or negative perception could be related to a lack of understanding of the wood regime (Ockelford et al. 2024), particularly in regulated rivers, where the presence of wood is unexpected and may be perceived as unsightly or unnatural (Chin et al. 2008; Le Lay et al. 2008).

The mechanical placement of wood structures can be costly. Therefore, a more natural approach to reintroducing wood could be considered (e.g., D. Scott 2022). This could involve allowing e-floods to redistribute wood along the regulated river, similar to the methods used for sediment. Enhancing wood transport capacity artificially is a key aspect for regulated rivers (Ruiz-Villanueva, Wyżga, Mikuś, et al. 2016). Regulated rivers with simplified channel morphology—often incised single-thread channels—characterized by a lack of wood recruitment and limited stored wood, may experience higher rates of mobilization and transport (Wohl et al. 2023). In such conditions, even reintroduced wood can be mobilized quickly and may not provide the intended benefits.

However, the most sustainable measure downstream from dams would undoubtedly be the passive recovery of the riparian vegetation, which serves as the primary source of wood supply (Stout et al. 2018). In the Spöl River, following the formation of a secondary channel during an e-flood, riparian vegetation was involved in the active channel (Consoli et al. 2022). This initiated a process of tree dieback over the following years (O'Callaghan 2024). In effect, floods and e-floods can act as agents that cause tree mortality (Friedman et al. 1996), potentially supplying wood to the river in the short term, while also creating opportunities for the establishment of pioneer species (Scott et al. 1996). However, the timing and magnitude of the e-floods can significantly impact riparian structure and species composition, as high numbers of seeds are deposited in ideal conditions for their germination and establishment (Sarneel et al. 2016; Stromberg et al. 2007). This is also true for other biological processes and species, for example, the reproduction of aquatic organisms and riparian wildlife, which are influenced by the timing of the floods (e.g., Robertson et al. 2001). As for the Spöl and other systems, e-floods aim to mimic seasonal high flows, for example, following heavy precipitation or snowmelt. This guarantees that enough water is stored in reservoirs while enabling downstream receiving systems to have enough competence (i.e., capacity to transport sediment) to mobilize them, as it happens in the lower Spöl. By doing so, e-floods reintroduce elements of natural disturbance in rivers with a timing compatible with the life history adaptations of local organisms. In effect, they can successfully target non-native species and limit their abundance over time (Robinson et al. 2023), as well as remove overabundant keystone species that promote the persistence of such high densities, such as mosses (Consoli et al. 2023). E-floods must then be appropriately designed to consider the potential effects on terrestrial and aquatic organisms. For what concerns the wood regime, transport and trapping of propagules, moisture conditions in the substrates and soils, rate of water level decreases or increases, difference for recruitment from seeds versus fragmented vegetation, or formation of geomorphic surfaces associated with floodplain vegetation are all equally important elements that need to be carefully taken into account in e-flood planning. Although the passive recovery of wood sources and supply can take decades or even centuries (Stout et al. 2018), in regulated rivers, e-floods can enhance the natural wood supply and activate recruitment processes, such as bank erosion or island turnover. In this context, it would be necessary to define a target wood regime (Wohl et al. 2019) to support river reaches that maintain sufficient recruitment, storage, and transport of wood to guarantee its most essential functions.

7 | First Steps to Consider Instream Large Wood in the Design and Assessment of e-Floods

The wood regime concept (Wohl et al. 2019) can be instrumental in determining both natural and target regimes achievable under new flow conditions. Integrating large wood into the e-floods framework in terms of the wood regime is a crucial step toward developing holistic ecosystem approaches (Tonkin et al. 2021) for managing regulated rivers. The wood regime describes the processes of instream wood recruitment (i.e., supply), transport, and storage in magnitude, frequency, timing, duration, and mode (Table 3; Wohl et al. 2019). Instream wood is supplied to watercourses by several processes (Martin and Benda 2001) that can be divided into two major groups (Wohl et al. 2012 and Wohl et al. 2019): (i) continuous or steady and relatively predictable processes, such as tree mortality, characterized by frequent individual tree fall during long times, and with a slow delivery rate; and (ii) episodic, unpredictable processes, such as landslides or river bank erosion, when a mass of wood can be delivered to streams in a short time and with a rapid delivery rate. These recruitment processes vary significantly over time and within catchments, and across landscapes, influenced by factors such as climate, geology, topography, and forest composition. The great variability in the wood regime of a river results in the impossibility of determining the ideal amount of wood expected. Once supplied to watercourses, instream wood might remain stable for extended periods, particularly in regulated rivers, but it can also move. The motion of wood is controlled by wood characteristics (i.e., size, density, and presence of branches and roots), channel morphology, and hydrodynamics (Ruiz-Villanueva, Piégay, Gurnell, et al. 2016). This, combined with flow variability and sediment transport, drives the natural processes that determine the shifting habitat mosaic of river systems that are required to create and maintain the geomorphic and ecological characteristics of river ecosystems (Stanford et al. 2005). The difference between the supplied wood and how much is transported results in the wood load or storage within a river reach. As wood supply and transport might not be in equilibrium, and the processes supplying the wood may vary over time, wood load is variable.

TABLE 3 | Components of the natural wood regime for recruitment, transport, and storage as defined by Wohl et al. (2019).

Regime component and definition	Recruitment (supply or delivery)	Transport	Storage (load)
Magnitude: relative or absolute volume or mass of wood recruited, transported, or stored	Mass/Individual	Mass (i.e., congested)/ Individual (i.e., uncongested)	Abundant/ Minimal
Frequency: how often wood is recruited, mobilized and transported, or deposited in storage	Frequent/Infrequent		
Duration: length of time over which recruitment events occur, or wood is transported or stored	Short recruitment time (episodic)/ Long recruitment time (continuous)	Short transport time/Long transport time	Short residence time (mobile or quick to decay)/ Long residence time (immobile or slow to decay)
Timing: when wood is recruited, transported, and stored, with respect to either seasonal patterns or components of the flow regime	Predictable/Unpredictable		
Rate: flux (mass or volume per unit of time) at which wood is recruited or transported or the flux of wood mass lost by decay, breakage, and abrasion during storage	Rapid/Slow		
Mode: process by which wood is recruited and transported and the location and form (e.g., jams or dispersed pieces) of wood storage within the river corridor	*En masse*/Sliding/rolling/ Falling (snapping, leaning)/	Floating (limited influence from obstructions)/ Dragging (sliding, rolling)	Dispersed (ramp, bridge, parallel, oblique)/ Concentrated (channel-spanning, partial, floodplain, raft)/Buried

Regulated rivers often have limited upstream supply and restricted transport capacity. Although they are typically disconnected from their floodplains due to reduced lateral connectivity, they can still receive wood inputs from lateral sources such as tree fall, wind, and tributaries. E-floods can further enhance lateral connectivity, making it important to consider the episodic contribution of floodplains to the wood budget (Lininger et al. 2019; Wohl 2013) in regulated rivers under e-flood conditions.

Various methods can be used to assess the wood regime, ranging from field surveys and observations to remote sensing and numerical modeling (Ruiz-Villanueva et al. 2024). However, as a first step, a simple, qualitative description of the main components of the wood regime—namely wood recruitment, transport, and storage—may be sufficient. Table 3 summarizes these components, which can be characterized at multiple levels of detail and across different spatial scales, depending on the specific objectives of the assessment. The main questions to address using a regime approach are: how much, how often, and how long wood is supplied, transported, and stored in the river, and in what manner. By quantifying these regime components, river managers can assess the current situation regarding instream wood and its functions, target the root causes of wood deficiency, and plan for long-term sustainable recovery of wood dynamics and ecological benefits (D. Scott 2022). There is a threshold for wood entrainment and motion that relates to flood history and is controlled by river morphology and wood type (Ruiz-Villanueva, Wyżga, Zawiejska, et al. 2016 and c). Therefore, this motion threshold must be identified to enhance the effectiveness of e-floods in terms of wood dynamics. The placement of wood structures at specific locations can also be considered to enhance wood trapping and the formation of wood-related habitats. One important constraint in the design of e-floods and the enhancement of wood mobility is the potential hazards they may pose. E-floods should be designed with careful consideration of flow characteristics (i.e., magnitude, duration, timing) that are necessary to activate morphodynamic processes, such as bank erosion, tree recruitment, and wood remobilization. Large quantities of transported wood may create problems in the presence of infrastructure like bridges (e.g., De Cicco et al. 2018; Ruiz-Villanueva, Piégay, Gurnell, et al. 2016), while sediment accumulation or bank erosion may also cause damage. In the Spöl River, a key concern is the bed elevation under bridges, such as the wooden bridge near the town of Zernez or the railway and highway bridges, as the riverbed aggrades. This could reduce the capacity of the bridges to convey water, potentially leading to blockages from sediment and wood transported during e-floods, causing flooding in the surrounding areas. Although this has not yet occurred in the Spöl River, such trade-offs must be carefully considered when designing e-floods. Despite being—as of today—completely overlooked, the presence/absence of in-stream large wood in a regulated river where e-floods are aimed at restoring ecomorphological conditions can draw the thin line between success and failure. Disregarding the role of wood in fluvial systems and its effects on geomorphological and ecological processes distorts our understanding of river dynamics and the capacity to establish mechanistic relationships between flow restoration and ecosystem responses (Wohl et al. 2019), potentially resulting in less effective e-floods and thus, unsuccessful river management.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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