Floating matter: A neglected component of the ecological integrity of rivers

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Abstract

Floating matter (FM) is a pivotal, albeit neglected, element along river corridors contributing to their ecological integrity. FM consists of particulate matter of natural (e.g. wood, branches, leaves, seeds) and anthropogenic (e.g. plastic, human waste) origin as well as of organisms that, due to its properties, is able to float on the water surface. In this paper, we provide a comprehensive overview of the FM cycle and the fundamental environmental functions FM provides along rivers. Indeed, FM serves as an important geomorphological agent, a dispersal vector for animals and plant propagules, a habitat, a resource, and a biogeochemical component. Furthermore, we collected data on the amount of FM accumulating at dams and in reservoirs, and related it to key characteristics of the respective catchments. River fragmentation truncates the natural dynamics of FM through its extraction at damming structures, alteration in the flow regime, and low morphological complexity, which may decrease FM retention. Finally, we identify key knowledge gaps in relation to the role FM plays in supporting river integrity, and briefly discuss FM management strategies.

Keywords: geomorphological agent, dispersal vector, resource function, habitat, fragmentation, catchment management

1. Introduction

Rivers form dendritic networks embedded in a terrestrial matrix. Functionally, they link upstream with downstream sections as well as the main channel with floodplain and upland areas (e.g., Ward et al. 2002; Harvey and Gooseff 2015). At the same time, rivers transfer, transform, and store large amounts of energy and material (Vannote 1980; Pringle 2003; Sponseller et al. 2013; Wohl et al. 2015), thereby controlling the ecological integrity of the river corridor – i.e. the capability to support and maintain physical, chemical, and biological functions and processes essential for ecosystem sustainability (Moog and Chovanec 2000).

The dynamics of bedload, and suspended and dissolved material (classification based on size classes and position within the water column during transport) has been well studied along rivers (e.g., Walling et al. 2008; Covino 2017; Vercruysse et al. 2017). However, material floating at the water surface has received much less attention (e.g., Robinson et al. 2002; Bunte et al. 2016; Kramer and Wohl 2016). Floating matter (FM) consists of (i) natural particulate organic material such as wood, twigs, leaves, seeds, carcasses, or faeces, (ii) human waste including microplastic (particles <5 mm, Hurley et al. 2018), plastic debris, timber, or styrofoam (Fig. 1), and (iii) living (and dead) organisms, in particular plant propagules and terrestrial animals.

Up to now, FM studies have mainly focused on the marine environment (Box 1), standing inland waters (floating mats, neuston, surface biofilms; for definitions: see glossary) (e.g., Gladyshev 1986; Burchardt and Marshall 2003; Marshall and Burchardt 2005; Wotton and Preston 2005; Azza et al. 2006), and on deposits along riverine, estuarine, and coastal shores (e.g., Strayer and Findlay 2010; Harris et al. 2014; Heerhartz et al. 2016; Gittman et al. 2016; Del Vecchio et al. 2017). In standing waters, research has focused on floating macrophytes and floating mats; in particular their formation, density, and dynamics (Ngari et al. 2008; Sarneel et al. 2011; Downing-Kunz and Stacey 2011), the role of floating mats in distributing emergent vegetation (Azza et al. 2006), facilitating seedling establishment (Shin et. al. 2015), providing a feeding resource (Adams et al. 2002), and influencing water exchange between open areas and areas covered with floating vegetation (Zhang and Nepf 2011). Free floating macrophytes have also been studied with regards to their ability to purify water from an excess of nutrients and heavy metals (Nahlik and Mitsch 2006, Dhote and Dixit 2009). In addition, several studies have focused on the structure and composition of neuston in aquatic ecosystems (Burchardt and Marshall 2003; Marshall et al. 2005; Marshall and Gladyshev 2009), the biophysical properties of neuston (Gladyshev 2002), and its role as a trophic resource (e.g., Saveanu and Martín 2015).

Along rivers, research has focused on the dynamics of large wood (e.g., Gurnell et al. 2005; Le Lay et al. 2013; Kramer and Wohl 2016; Nakamura et al. 2017; Piégay et al. 2017; Picco et al. 2017; see glossary), the transport and cycling of coarse particulate organic matter (CPOM) (Langhans et al. 2013; Turowski et al. 2013; Bunte et al. 2016), and the dispersal of plant propagules (e.g., Merritt and Wohl 2002, 2006; Nilsson et al. 2010; Soons et al. 2016; Tonné et al. 2017). Recently, the release and accumulation of plastic debris and microplastics in freshwaters have emerged as a research topic too (Moore et al. 2011; Faure et al. 2015; Kooi et al. 2018).

Land-use change, river regulation, and fragmentation (e.g., Allan et al. 2004; Grill et al. 2015; Zarfl et al. 2015; Wohl et al. 2015) alter the natural dynamics of FM. However, a comprehensive understanding of the multiple functions of the various components of FM on the ecological integrity of rivers is missing.

The main objectives of the present study are to conceptualize the natural cycle of FM along rivers and to identify and discuss the key ecosystem functions FM provides. More specifically, we focus on the geomorphological functions of FM, particularly that provided by large wood but also other FM components, as well as on the role of FM as a dispersal vector, a resource, a habitat, and as a biogeochemical component. Furthermore, we compiled quantitative information on the amount of FM entrapped upstream of dams and related these data to catchment characteristics in order to evaluate whether the amount of FM can be predicted. In addition, we briefly discuss challenges and strategies to better integrate FM into river management. Finally, we identified key research gaps related to FM dynamics along rivers. Throughout the paper, we primarily focus on organic FM, while acknowledging anthropogenic FM when relevant. In addition, as most of the present literature focuses on large wood, we distinguish between large wood and other fractions of FM when relevant.

2. Composition and dynamics of FM in river ecosystems

The composition of FM differs in origin (i.e., natural or anthropogenic) and size (i.e., from microplastics and seeds to large logs) (Table S1, Supplementary Information). For example, senescence of leaves and seed fall, both largely seasonal, provide important natural fractions of FM input, while substantial inputs of anthropogenic FM derive from urban surface runoff and wastewater overflow (e.g., Gurnell 2007; Moore et al. 2011; Krejčí and Máčka 2012; Zupanski and Ristic 2012; Chen et al. 2013; Kooi et al. 2018). By volume, the main fraction of organic FM is comprised of small and large wood (Table S1). Other natural components of FM such as leaves, plant propagules, and seeds have not been considered adequately so far in research and management (e.g. Kleinschmidt Energy and Water consultants, 2008; URS Corporation Gomez and Sullivan Engineers, 2012; Turowski et al., 2013; Bunte et al., 2016). Wood is also the main focus of reports from hydropower companies that monitor the amount of FM trapped in reservoirs; although the non-woody fraction (leaves, grass) may comprise, by volume, up to 80-90% of natural FM (Table S1). In urbanized catchments, FM delivered to reservoirs can be entirely anthropogenic in origin (e.g., Zupanski and Ristic 2012), including human-cut wood, plastic bottles, bags, styrofoam, car tyres, parts of structures located along rivers (piers, wharves, bulkheads), and household waste, among others.

FM exhibits a dynamic cycle of input, transport, deposition (including accumulation), and remobilization (e.g., Pozo et al. 1997; Benda and Sias 2003; Trottmann 2004; Langhans 2006; Gurnell 2007; Seo et al. 2008; Fremier et al. 2010; Le Lay et al. 2013; Wohl 2013; Bunte et al, 2016; Kooi et al. 2018) (Fig. 2). This cycle is controlled by hydrogeomorphological, biological, and anthropogenic factors (Fig. 2) (Webster and Meyer, 1997; Gurnell et al. 2002; Quinn et al., 2007; Tank et al., 2010; Fremier et al. 2010; Le Lay et al. 2013; Turowski et al. 2013; Seo et al. 2015; Ruiz-Villanueva et al. 2016a,b; Kramer and Wohl 2016; Bunte et al, 2016; Kooi et al. 2018, and references therein). The dynamics of FM along rivers are frequently interconnected with those of mineral sediments as demonstated for seeds, vegetative particles of plants, and large wood (e.g. Goodson et al., 2003; Gurnell 2007; Nilsson et al. 2010; Nakamura et al., 2017). Indeed, parallels can be drawn with regards to transport and deposition, which in both cases are controlled by the flow regime, hydraulic conditions, and the morphology of the river channel (Gurnell 2007; Hoover et al. 2006; Wohl and Scott 2016; de Brouwer et al. 2017; Nilsson et al. 2010; Nakamura et al. 2017). Comparable to the instream movement of inorganic particles, transport of FM occurs through nonlinear and episodic processes, and reflects similar thresholds limiting sediment mobilization and grain-grain interaction during movement (Merritt and Wohl 2006; Nilsson et al. 2010; Trodden 2012; Bertoldi et al. 2014; Wohl et al. 2015), with FM generally occupying one end of a density continuum of particles that are transported by rivers.

Similar to mineral sediments, FM is affected by river fragmentation and trapped by dams (Merritt and Wohl 2006; Nakamura et al. 2017). The results of our analysis on the amount of FM trapped in front of dams (Box 2) showed that it is correlated with catchment area, average annual precipitation, and land-cover. Because of its lower density and thus lower potential to settle out from the water column compared to sediments, FM may have a higher potential to pass through dam obstructions. This is particularly likely where the water volume can exceed the hydraulic capacity of a dam and water can overtop a dam structure or pass through spillways that drain water from the reservoir surface (e.g., dams on Susquehanna river, URS Corporation Gomez and Sullivan Engineers 2012).

The **input** of FM into rivers varies significantly depending on catchment area, and thus the area generating FM, the flow regime, and energy available to mobilise material (dependent on discharge and river gradient), the type and density of riparian vegetation, the season, as well as local pulsed events that may cause releases of FM (wood fraction: Pozo et al. 1997; Reeves et al. 2003; Montgomery et al. 2003; Gurnell 2007; Fremier et al. 2010; Kramer and Wohl 2016; Piégay et al. 2017; Senter 2017a,b; leaf litter: Pozo et al. 1991; Abelho 2001; Hart et al. 2013; plant propagules and seeds: Nilsson et al. 2010). For example, the creation and input of FM in headwater streams mainly result from direct inputs (seed fall, senescence of leaves, tree breakage, toppling, shredding) and through episodic events (landslides, debris flows, wind, snow, fires) that can release significant quantities of FM to the river network (e.g., Adelho 2001; Reeves et al. 2003; Hart et al. 2013; Comiti et al. 2016). In downstream sections, as well as in confined and unconfined rivers, where the river channel is increasingly separated from hillslopes by a floodplain, main input processes are bank erosion, particularly for the large wood fraction of FM (e.g., Martin and Benda 2001; Gurnell 2002; Benda and Sias 2003; Reeves et al. 2003; Seo and Nakamura 2009; Seo et al. 2010; Lucía et al. 2015a; Comiti et al. 2016; Steeb et al. 2017), and overbank flooding (e.g., Pettit et al. 2005; Steeb et al. 2017; Cuffney 1988; Tonin et al. 2018). Anthropogenic FM originates from wastewater treatment plants, seawage sludge application in terrestrial environments and diffuse sources such as littering areas and direct stormwater run-off (Horton et al. 2017; Kooi et al. 2018).

Transport of FM was most extensively studied for the large wood fraction. The main factors that control the transport of large wood are its properties (i.e., density, size, shape) in relation to the dimensions of the river channel (width and depth) (e.g., Bunte et al. 2016; Ruiz-Villanueva et al. 2016c), channel morphology (Gurnell et al. 2002; Fremier et al. 2010; Kramer and Wohl 2016), and discharge (Koljonen et al. 2012; Senter 2017a, b). For example, the density of wood differs with species and degree of decay and may change during transport and therefore affect transport distance (Ruiz-Villanueva et al. 2016b,c; Haga et al. 2017). In cases where wood density exceeds water density, wood rolls, slides, or bounces along the river bed (rather than floats as part of the FM) similarly to mineral bed sediments. The downstream movement of smaller fractions of FM, such as leaves or CPOM that have low specific gravity, is mainly controlled by bed roughness and discharge that define whether transported material can be entrapped by roughness elements such as coarse-grained sediments and stones (Hoover et al. 2006; de Brouwer et al. 2017). Transport of seeds is controlled by the hydrologic regime (timing, duration, magnitude of flow and rate of change in flow) and their ability to float (Merrit and Wohl 2006; Carthey et al. 2016). Thus, seeds may be transported by flotation or as suspended or bed material, leading to complex transport-deposition-remobilization patterns as the seeds interact with river flows (Gurnell et al. 2007, 2008). In general, FM with a smaller surface-to-volume ratio is expected to be transported over longer distances (Spänhoff and Meyer 2004; West et al. 2011), whereas large, irregular FM pieces such as branches, trunks, and root wads are more likely to become snagged. Thus they only move relatively short distances. The transport of anthropogenic FM also depends on its density, biofouling, and agglomeration with FM of organic origin within the time of floating as well as on water surface area, depth, wind, and currents (Horton et al. 2017; Kooi et al. 2017). Temporally, transport of FM is more variable in streams than in rivers (Richardson et al. 2005). Along intermittent rivers, transport of FM exhibits a distinctive pulsed character with notable peaks during first flush events following dry periods (Corti and Datry 2012; Rosado et al. 2014; Abril et al. 2016).

Deposition and **accumulation** of FM depends on the morphology of the river channel and its floodplain and varies with river type (e.g., meandering, braided), local irregularities and roughness structures (e.g., vegetation), which determine locations for potential FM storage (Piégay and Gurnell 1997; Abelho 2001; Quinn et al. 2007). In addition, transported mineral sediment can anchor or bury FM, further contributing to its retention and residence time in storage (e.g., Gurnell 2007; Nilsson et al. 2010; Osei et al. 2015a, b; Parker et al. 2017). The type and physical properties of FM also affect the likelihood that FM will be retained (e.g., Adelho 2001; Richardson et al. 2009; Nilsson et al. 2010; Carthey et al. 2014). For example, some plant material, including wood from riparian tree species, can sprout once deposited, increasing its likely retention and residence time at the deposition location as a result of root anchorage (Gurnell et al. 2005). The residence time of FM in a river storage location affects its properties, including properties that may in turn affect the potential for remobilisation. Thus, biological decay, water absorption, and physical breakage influence the size, shape, and buoyancy of the deposited FM (Ruiz-Villanueva et al. 2016b,c; Nilsson et al. 2010) and may facilitate the mineralization of FM during deposition (Merten et al. 2013). Anthropogenic FM, such as plastic, can be deposited due to biofilm growth on its surface. It can be highly resistant to biodegradation, although photodegradation and mechanical fragmentation are common degradation processes (Horton et al. 2017; Rummel et al. 2017).

Remobilization of accumulated FM back to the floating phase occurs as a result of processes similar to those that determine its input, most notably flow energy (i.e. a combination of discharge and channel gradient) that is sufficient to induce erosion of the stored material (e.g., Abelho 2001; Pettit et al. 2005; Merten et al. 2010; Wohl 2013). The exposure of stored FM to remobilisation is also influenced by channel morphology, stabilisation by vegetation, the degree to which it is buried by deposited mineral sediments as well as FM characteristics such as its dimensions and density. In addition, FM accumulated in reservoirs can be remobilized due to the release of methane, when methanogenic decomposition occurs underneath it (Kosten et al. 2016; Grasset et al. 2018).

Thus, FM can undergo a complex cycle of remobilization, transport, and deposition as it moves downstream (Abelho 2001; Moulin and Piégay 2004; Nilsson et al. 2010). During this cycle, FM properties are changed through a variety of biogeochemical and mechanical processes. The spatial dimension and temporal duration of the individual phases reflect an integration of catchment, river network and local properties that interact with the transferred FM. Thus, the transport of FM serves as an indicator of landscape integrity (Nilsson et al. 2010; Nakamura et al. 2017). In addition, the natural cycle of FM partly resembles the nutrient spiralling concept proposed by Newbold et al. (1981). Similar to nutrient cycling, the path of FM can be viewed as a spiral of input, transport, retention, accumulation, and remobilization – again back to the flowing water. The nutrient spiralling concept has been already described for components of FM from CPOM to large wood (Quinn et al. 2007; Tank et al. 2010; Elosegi et al. 2016; Kramer and Wohl 2017).

3. The functional role of FM in rivers

The functions performed by FM shift during its natural cycle. During transport, FM acts as a dispersal vector for attached organisms (e.g., Tenzer 2003; Trottmann 2004). Once deposited, it serves as a habitat (e.g., Harmon et al. 1986; Braccia and Batzer 2001) and a geomorphic driver (particularly the large wood fraction, e. g., Montgomery et al. 2003; Gurnell 2013). During both transport and deposition it can be a nutritional resource and a biogeochemical component affecting carbon and nutrient cycling (e. g., Xiong and Nilsson 1997; Krause et al. 2014). Despite similarities with the cycling and functions performed by mineralic particles along rivers, FM exhibits distinctive and unique features supporting the geomorphological, hydrological and biological integrity of rivers. In the following sections, we focus on the various functions of natural FM, and refer to anthropogenic FM when relevant.

3.1. FM as a geomorphological agent

The morphology and size of river channels, the morphological character of floodplains and the freshwater habitats that they support are dictated by the interaction between flow, water-transported materials and the materials comprising the channel boundary and floodplain surfaces (Montgomery et al. 2003; Hassan et al. 2005; Lester et al. 2009; Elosegi et al. 2010; Gurnell et al. 2012; Gurnell 2013, 2014). FM, both living and dead, is crucial in this context not only because it forms a major part of the transported materials but also because it contributes to the character of the channel boundary and evolving floodplain (Gurnell et al. 2016).

It is not surprising that the substantial geomorphological role of the large wood component of FM has been emphasised in the literature (recent reviews include Gurnell 2013, Wohl 2013, 2014). In some cases it has been proposed that this most stable FM fraction can have similar importance to mineral sediments in relation to influencing changes in channel morphology (e.g. Kramer and Wohl 2016). This is especially true when wood pieces are very large or are able to sprout, and thus anchor themselves into sediments and soils once deposited (Collins et al. 2012; Gurnell et al. 2016). However, smaller fractions of FM, such as small wood, leaves and plant propagules can also have a geomorphic effect, whether in combination with large wood or more generally as they become transported and deposited by a river in a similar manner to mineral sediments (Gurnell et al. 2007).

Individual pieces and accumulations of large wood obstruct and interact with water flowing in river channels to increase hydraulic heterogeneity, the complexity of flow pathways, and the variability of flow velocity for any given discharge. Typical local effects of in-channel wood accumulations include water ponding and sediment retention upstream; scour pools both below, laterally and downstream; bank erosion, avulsions and the scour of new channels in the adjacent floodplain; fluvial sorting and the deposition of the scoured sediment in the form of bars and benches (Montgomery et al. 2003; Gurnell 2013; Wohl 2013; Elosegi et al. 2017; Matheson et al. 2017; Parker et al. 2017). Furthermore, wood removal from river channels is rapidly followed by the disappearance of many of these scoured and depositional features (e.g. Gurnell and Sweet 1998). At a larger scale, deposited large wood can interact with transported mineral sediments, reinforcing them and driving floodplain development, including lateral bar accretion and the development of scrolled floodplains (Nanson 1980; Zen et al. 2017), island development within braided rivers (Gurnell et al. 2005), and even the transition from one to another river and floodplain type (Bertoldi et al. 2015). All of these processes are accelerated by the sprouting of wood pieces or the germination of seeds deposited with the wood and sediment, because of the increased flow resistance offered by the developing vegetation canopy and the reinforcement of sediments by the below-ground biomass (Holloway et al. 2017 a,b).

However, other components of FM have geomorphic effects in their own right as well as in combination with large wood. For example, plant propagules (sexual and asexual) form an important part of the FM load of rivers (Goodson et al. 2003; Nilsson et al. 2010; Schwab et al. 2018). Research on the hydrochorous dispersal and retention of plant propagules has largely focused on seeds, demonstrating the importance of their flotation characteristics, hydraulic conditions at the time of dispersal and the availability of retention structures that can trap them. These processes have been recently modelled by Cunnings et al. (2016), and seed deposition and retention at different elevations across the river bed and margins have been observed in the field (e.g. Gurnell et al. 2007, 2008; Fraaije et al. 2017). Furthermore, seed deposition tends to be particularly high around particular retention structures including bed forms, bars, riparian and aquatic vegetation, and large wood (Gurnell et al. 2007, 2018; Osei et al. 2015 a, b; Defina and Peruzzo 2012; Yoshikawa et al. 2013; Corenblit et al. 2016). The retention of the plant propagule component of FM and the ensuing development of a vegetation cover can have important geomorphological effects by retaining mineral sediments to create vegetated landforms that in turn retain more FM. The most widely reported aspect of such interactions relates to riparian tree species, whose life cycle is often closely attuned to the river flow regime (Karrenberg et al. 2002). While this close association with the flow regime is crucial to species recruitment (Mahoney and Rood 1998; Rood et al. 2016), it also leads to geomorphic effects, particularly the accretion of side and mid-channel bars, natural levées and islands as the young plants grow through and reinforce co-deposited sediments and then retain further sediments and FM (Gurnell 2014). Similar processes can be observed when vegetative propagules, including living pieces of large wood and the rhizomes of aquatic plants, are retained and sprout (Gurnell et al. 2010, 2012, 2016; Gurnell 2014). Furthermore, other smaller, dead, retained components of organic FM contribute to soil development and the release of nutrients, accelerating vegetation growth, establishment and sediment accretion to build landforms and thus influence the morphology and dynamics of river channels and floodplains (Mardhiah et al. 2014, 2015; Gurnell et al. 2018). Anthropogenic FM can also form accumulations with natural FM and sediments creating so-called 'plastiglomerates" (Horton et al. 2017). For example vast quatities of wet wipes accumulating in the River Thames in London are changing the shape of the river bed as they combine with and reinforce fine sediments (van der Zee 2018).

The geomorphological effect of FM of all sizes within river reaches, whether acting separately or in combination, links lateral, vertical, and longitudinal dimensions (e.g., Johnson et al. 2000; Gerhard and Reich 2000; Gurnell et al. 2002; Montgomery et al. 2003; Trottmann, 2004; Krause et al. 2014; Elosegi and Pozo 2016; Haga et al. 2017). For example, FM deposited on shorelines increases the hydrological connectivity between rivers and their floodplains by increasing the area of the riparian zone (Gerhard and Reich 2000). Accumulations of natural FM also intensify hydrological interactions between stream water and groundwater by creating steps in the water surface profile, which may induce infiltration of surface water into the river bed and also drive sediment sorting, erosion, and deposition that form a mosaic of surface-subsurface exchange patches (Malard et al. 2002; Krause et al. 2014; Czarnecka 2015; Haga et al. 2017). These processes lead to an increase in the volume of the hyporheic zone and affect the rate of exchange flow within it (Wondzell and Swanson 1999; Pilotto et al. 2016).

Despite some similarities in the cycling of FM and mineral sediments that allow us to draw comparisons concerning their geomorphological functions, important differences exist (Gurnell, 2007). Whereas mineral sediments are transported as bedload or in suspension in the water column, FM mainly floats on or is transported near the water surface, particularly during turbulent flood flows. Furthermore, compared to mineral sediment particles, the range of size fractions of FM is larger (from seeds to large logs), and its shape (root wads, branches, whole trees, logs, leaves, seeds) and composition (from easily decomposable organic particles to wood with a high proportion of lignin) are more diverse. Certain fractions of FM such as seeds, rhizomes and wood from some tree species (e.g. Salicaceae species) have the ability to germinate or sprout, further promoting their retention and landform building potential (Edwards et al., 1999; Gurnell 2014). Indeed, burial of large quantities of slow-decaying wood has been identified as an important element in the reinforcement of some floodplains (Nanson et al. 1995; Abbe and Montgomery 2006; Collins et al. 2012; Wohl 2013). These properties enable FM to perform an even more complex range of roles as a geomorphic agent than mineral sediments.

3.2. FM: a key dispersal vector for terrestrial animals

Rivers form pivotal dispersal corridors for both aquatic and terrestrial organisms (Johansson 1996; Bilton et al. 2001; Nilsson et al. 2010; Altermatt 2013). Obligate aquatic species (e.g., fish and aquatic invertebrates) move longitudinally and laterally, thereby connecting upstream and downstream sections as well as the floodplain with the main channel (Malmqvist 2002; Grant et al. 2007). Downstream drift of aquatic organisms provides access to suitable habitats, sustains gene flow among populations, and therefore maintains population variability (e.g., Malmqwist 2002; Naman et. al. 2016). Similarly, the dispersal of plant propagules by water (i.e. hydrochory) maintains riparian plant species and genetic diversity along river corridors (Andersson et al. 2000; Nathan and Muller-Landau 2000; Gurnell et al. 2008; Nilsson et al. 2010), and allows terrestrial plants to colonize new habitats. For example, specific alpine plants – so-called ”Alpenschwemmlinge” (e.g. *Campanula cochleariifolia, Dryas octopetala, Leontopodium nivale, Linaria alpina, Saxifraga caesia*) – disperse with water flow and can be found in downstream and lowland river sections at high diversity (Tinner et al. 2008).

For terrestrial invertebrates and vertebrates, rivers are usually considered dispersal barriers (e.g., Puth and Wilson 2001). However, FM may offer a medium on or within which terrestrial animals can be transported, potentially over long distances. Hence, FM can be considered an important dispersal vector, both spatially (unidirectional stepwise transport downstream) and temporally (with respect to seasonal and event dynamics of FM) (Henderson and Hamilton 1995; Shiesari 2003; Luiz et al. 2012; Čejka et al. 2015). Furthermore, FM serves as a "passive sampler" for terrestrial animals, since it accumulates species from the entire river corridor. Therefore, fresh FM deposits form "hot spots" for riparian animal (and plant) assemblages (Trottmann 2004; Pettit et al. 2006). Along rivers, very similar to the marine environment (Box 1), dispersal of terrestrial organisms associated with FM may facilitate the colonisation of new sites and maintain species and genetic diversity of terrestrial animals and riparian plants along river corridors (e.g. Tenzer 2003; Trottmann, 2004; Langhans 2000, 2006). Moreover, anthropogenic FM may serve as a dispersal vector for microbial assemblages, depending on ambient environmental conditions and nutrient concentrations (Oberbeckmann et al. 2018).

The dispersal of terrestrial species associated with FM has long been overlooked. This is partly due to the short-term release and transfer of FM during the rising limb of the hydrograph, which may constrain sampling (e.g., Tockner et al. 1997; West et al. 2011; Corti and Datry 2012; Rosado et al. 2014; Bunte et al. 2016). Data concerning the dispersal of terrestrial animals with FM has been gathered mostly by entomologists who have studied fresh FM deposits. Along European perennial rivers, transport distances for terrestrial invertebrates attached to FM may vary from 20 km (Tenzer 2003) to 300 km (Czogler and Rotarides 1938). At the same time, it has been shown that around 50% of the terrestrial invertebrates associated with FM are eggs or juveniles (Boness 1975; Trottmann 2004). After deposition, FM can release large quantities of terrestrial animals that mix with the local fauna. For example, Trottmann (2004) recorded a peak emergence (i.e., on average about 1,900 living terrestrial invertebrates per 100 g of dry FM) ten days after collection of fresh FM from a site upstream of a dam. This underpins the major role FM plays as a dispersal vector for all life stages of terrestrial athropods.

The density and composition of terrestrial animals rafting on FM depends on the FM's physical properties (e.g., physical structure, buoyancy), degree of decay, fate of FM within the floodplain (residence time, deposition location), season of the transport, and land-use along the river corridor (Haden et al. 1999; Tenzer 2003; Thiel and Gutow 2005a; Carthey et al. 2016; Čejka et al. 2015). Among FM components, wood has been recognised as a "hot spot" for terrestrial (and aquatic) invertebrates during transport and deposition (Haden et al. 1999; Braccia and Batzer 2001; Tenzer 2001, 2003; Trottmann 2004; Langhans 2000, 2006; Horáčková et al. 2015). Indeed, the density of Aranea, Coleoptera, Diptera, and Gastropoda associated with FM can be even higher than the density in the adjacent mulch soil layer, although such a comparison must be considered with care (Trottmann 2004; Table 1).

More recently, mass dispersal of terrestrial organisms has also been observed along dry rivers too (Corti and Datry 2012; Rosado et al. 2014). At the onset of first flush events, FM that has accumulated at the river bed and margin surfaces during the dry phase, including ground-dwelling arthropods, is resuspended and transported downstream, often over long distances (e.g., Corti and Datry 2012). After floods, deposits of fresh FM are colonized by both arthropods dislodged from upstream and arthropods from local riparian areas (Rosado et al. 2014). Thus, fresh FM deposits have much higher densities of arthropods compared to the river bed, despite similar arthropod compositions (Rosado et al. 2014).

3.3. Habitat function

In accordance with the habitat template concept (Southwood 1977), the physical properties of riverine habitats determine the structure and functions of biological assemblages along fluvial corridors. Aquatic and terrestrial organisms at different stages of their life cycle are sensitive to the composition and distribution of habitat types. FM, being a physical substrate, can facilitate the formation of habitats when deposited and may serve as a habitat itself during transport and deposition.

Once deposited, the large wood fraction of FM may shape channel morphology, initiate island development and induce scour of permanent and ephemeral ponds (Gurnell et al. 2005). Large and small wood, together with macroalgae wrack and litter hovels formed by debris floating downstream offer protection against desiccation and thermal stress upon deposition, provide shelter against predators, and can dissipate turbulence caused by wave action. Consequently, such deposits are rapidly colonized by animals and plants (e.g., Loeser et al., 2006; Gabel et al. 2008; Harris et al. 2014; Czarnecka et al. 2014; Heerhartz et al. 2016; Brien et al. 2017). The importance of deposited FM as a habitat is also determined by the degree of decay, moisture retention, physical orientation in relation to flow (for large wood), and the composition, density, and size distribution of FM components (Harmon et al. 1986; Loeser et al. 2006; Harris et al. 2014; Heerhartz et al. 2016; Brien et al. 2017). The formation of biofilms and detritus food webs on FM also attract fungal decomposers and larger animals such as small mammals and birds (Xiong and Nilsson 1997; Vadeboncoeur et al. 2006), which have feedback effects on the structure and composition of the FM deposits (Xiong and Nilsson 1997; Vogt 2007). Decay further increases the complexity of FM surfaces, which again leads to an increase in the abundance and biomass of associated macroinverterbate assemblages (Loeser et al. 2006; Schneider and Winemiller 2008; Czarnecka et al. 2014; Harris et al. 2014). Some insects (e.g., ants, termites) can use the large wood fraction of FM as a nesting site (Harmon et al. 1986). Terrestrial arthropods may also use it as a refugium during floods and prolonged periods of high discharge (Braccia and Bratzer 2001; Loeser et al. 2006). In addition to being an attractive habitat for animals, FM deposits retain and accumulate seeds and sediments, facilitating plant regeneration after floods (Harmon et al. 1986; Langlade and Décamps, 1994; Pettit and Naiman 2006; Gurnell 2014) in both perennial and intermittent rivers (Rosado et al. 2014). Anthropogenic FM, such as plastic, may serve as a habitable surface for biofilm-forming microorganisms to which they can be attached (Rummel et al. 2017; Oberbeckmann et al. 2018). As such, FM increases and diversifies habitats that can be used by aquatic, terrestrial, and semi-terrestrial animals and plants during different stages of their life cycle (e.g., Harmon et al. 1986; Loeser et al. 2006; Harris et al. 2014).

When FM is mobilized by water and starts floating, it can also serve as a substrate for invertebrates (e.g., Haden et al. 1999; Braccia and Batzer 2001; Trottmann 2004) and resting stages of zooplankton (Battauz et al. 2017). Floating at the water surface, it disperses synchronously with flow, reducing abrasion and increasing the survival of attached organisms. Floating FM stimulates biofilm development, as it is exposed to light and, in contrast to deposited FM, does not accumulate mineral sediments transported within the water column (Tank et al. 1993; Golladay and Sinsabaugh 1991; Haden et al. 1999). Furthermore, FM may provide a shelter against visual predators for juvenile fish (e.g., floating mats in the Parana river, Brazil; Bulla et al. 2011).

3.4. FM: a resource along river corridors

FM is an ephemeral nutritional resource as well as a foraging ground (Yang et al. 2008). As the transport of FM is a stepwise process, it also forms a component of nutrient spiraling along river corridors (Ensign and Doyle 2006). In addition, it serves as a component of stoichiometric flow (redistribution of material and nutrients) that can introduce variabilities in resources within ecosystems (Massol et al. 2017).

FM can primarily be seen as a resource during the deposition phase. Organisms attached to FM can consume it or feed on organisms associated with the FM (Bowen et al. 1998; Haden et al. 1999; Hoffmann and Hering 2000; Eggert and Wallace 2007; Harris et al. 2014; Heehrhartz et al. 2016). Components of FM vary in their composition and, therefore, may have different nutritional value (Thiel and Gutow 2005a; Loeser et al. 2006; Harris et al. 2014). Leaves that have been transported and deposited are a well-known allochthonous source and conveyor of energy and nutrients for microorganisms and macroinvertebrates (e.g., Vannote 1980). Invertebrates associated with depositions of wrack can serve as food for crabs, lizards, birds, rodents, and even bears (Heerhartz et al. 2016). The woody fraction of FM is more recalcitrant and can be an important resource for xylophagous species (Harmon et al. 1986). Less is known about the role of finer fractions of FM such as seeds and pollen as a nutritional resource along rivers. Artificial FM, such as plastic, has low nutritional value. Therefore, most organisms attached to it are suspension feeders (e.g., examples from marine environment, Thiel and Gutow 2005a; Kiessling et al. 2015).

FM is also a resource during its rewetting phase, as wet conditions facilitate organic carbon and nitrogen release (Xiong and Nilsson 1997; Strayer and Findlay 2010; Wohl et al. 2017). In addition, during rewetting and subsequent decomposition, microbial conditioning of FM surface layers increases their protein content and allows macroinvertebrates to obtain sufficient nitrogen and other nutrients to complete their life-cycles (Cummins 1974; Le Lay et al. 2013). This affects primary and higher trophic levels, and food web dynamics in general (Rossi 2007; Spiller 2010). The wood fraction of FM is also an important foraging ground due to the algae and bacteria associated with it and the higher organic matter content in surrounding riverbed sediments (e.g., Pilotto et al. 2014; Czarnecka 2015). High densities of macroinverterbrates on FM may further provide foraging opportunities for fish (Schneider and Winemiller 2008). In addition, FM itself can be a site where trophic interactions and energy transfer occur among macroinverterbate species (e.g., Loeser et al. 2006). For example, the diet of predaceous terrestrial invertebrates found on large wood contained up to 70-90% of aquatic species (Hering and Plachter 1997; Braccia and Batzer 2001). Neuston, as a component of FM, can be a trophic resource when other feeding resources are absent. For example, Saveanu and Martin (2015) showed that aquatic apple snails were feeding on neuston as an alternative food resource under laboratory and natural conditions.

The meaning of FM as a nutritional resource varies depending on the characteristics of the river ecosystem, stream order, and season. For example, in low-order desert streams the importance of FM is limited, but it plays a crucial role in food webs of high-order streams with limited autochthonous production (Haden 1997; Haden et al. 1999). Floating macroalgae, on the other hand, can be an important food resource in autumn, while during spring and summer they serve mainly as a refugium (Thiel and Gutow 2005a).

3.5. Biogeochemical function of FM

FM is subject to transportation over long distances, making it a highly mobile and pulsed component of the carbon cycle. Most studies report on carbon redistribution within river networks, and from rivers to oceans, focusing on coarse particulate organic matter (CPOM) and its contribution to the total organic carbon load (TOC) (e.g. Turowski et al. 2016; West et al. 2011). We identified few studies that aimed to access the contribution of FM to the TOC fluxes. At 2%, the average annual contribution of FM to total organic carbon (TOC) export at the catchment scale is considered minimal (Seo et al. 2008). However, during extreme events, FM can reach up to 30-60% of the total carbon mobilized (West et al. 2011).

Deposited FM is a component of biogeochemical processes that take place at the river reach scale in both vertical and horizontal dimensions. In the vertical dimension, FM deposits may affect key drivers of biogeochemical cycling and microbial activities such as hyporheic water residence time, oxygen conditions on the surface of sediments, temperature, and access to bioavailable organic matter (examples for large wood: Krause et al. 2014; Czarnecka 2015; for wrack: Strayer and Findlay 2010; Heerhartz et al. 2016). Different assemblages will be present in adjusted aerobic and anaerobic zones, and denitrification may occur within anaerobic zones of deposited FM (Pusch et al. 1998; Czarnecka 2015). Accumulations of woody debris intensify the vertical exchange of particulate and dissolved substances from surface water layers to the hyporheic zone, where they are degraded microbially, thereby increasing the self-cleaning capacity of the water body (Pusch et al. 1998; Krause et al. 2014). Regarding the horizontal dimension, FM leads to nutrient retention within the channel and its margins due to sediment deposition and accumulation of finer organic matter (e.g. by large wood: Comiti et al. 2008; Pilotto et al. 2014; Wohl and Scott 2016; Elosegi et al. 2017, by wrack: Strayer and Findlay 2010; Harris et al. 2014; Heerhartz et al. 2016). In addition, deposited large wood, which can contain up to 45-50% of carbon, may serve as a component of carbon storage within the floodplain (Chen et al. 2005).

Biofilms associated with FM also play important biogeochemical functions. They represent sites of intensive chemical tranformation with carbon, nitrate, and phosphate uptake (Baldwin et al. 2014; Collins et al. 2012). Indeed, the presence and density of FM deposits affects the functioning of ecosystems by promoting biofilms (Baldwin et al. 2014). Surface biofilms as components of FM may be as heterogeneous as benthic biofilms, contributing to a continuous arrival of new microorganism assemblages due to their advection (e.g., Wotton and Preston 2005). These assemblages play an important role in the physical and chemical processes at the air-water interface such as photosynthesis, attenuation of solar radiation, and production of exudates.

4. Management of FM

Management of FM in freshwaters is challenging due to its dual nature. As shown above, FM is a pivotal component of ecosystem integrity. However, at the same time, the large wood fraction of FM can cause damage and flood hazards when it accumulates in reservoirs, at bridges, and around other bankside infrastructure that impede its longitudinal transport (e.g., Diehl 1997; Lucía et al. 2015a; Comiti et al. 2016; Gschnitzer et al. 2017). Accumulations of plant material or wrack on bankshores are usually negatively perceived and are therefore often removed (Strayer and Findlay 2010). In addition, FM of anthropogenic origin can spread pollutants such as hydrophobic organic contaminants (Rummel et al. 2017).

Currently, the natural cycle of FM has been greatly modified due to anthropogenic activities. These reduce the ability of FM to reach a river channel, to be transported, and deposited (e.g., for wrack deposits (Strayer and Findlay 2010), for plant propagules (Merritt and Wohl 2006; Nilsson et al. 2010)), and induce a shift in the composition of FM towards an increasing anthropogenic fraction (e.g., Krejčí and Máčka 2012). Modifications of river corridors often reduce the interaction of the river with its floodplain, which reduces the amount and quality of natural FM that potentially enters the river (e.g., Harris et al. 2014; Nilsson et al. 2010). FM that has reached the channel and has been transported may be trapped behind dams in reservoirs (see Box 2) or at other near shore structures.

Material that accumulates behind dams may cause damage and may contribute to greenhouse gas emissions to the atmosphere (carbon dioxide, methane) due to its decomposition (Abril et al. 2013). The large wood fraction of FM is usually removed in order to ensure the safe operation of turbines and to prevent potential flood hazards (e.g., Diehl 1997; Hauenstein 2003; Moulin and Piégay 2004; Bradley et al. 2005; Le Lay and Moulin 2007; Seo et al. 2008; VAW 2008). The proportion of FM that passes downstream (including woody debris and plant propagules) may also be affected by the operation of water facilities: it can be pulverized, and its transport and deposition patterns may be affected by changes in downstream hydrodynamic conditions including reductions in the area subject to flooding (Shannon et al. 1996; Andersson et al. 2000; Tenzer 2003; Merritt and Wohl 2006;

Kleinschmidt Energy and Water Consultants, 2008; Nilsson et al. 2010). In addition, the deposition of freshwater wrack is impeded due to steepening or smoothing of river banks (Strayer and Findlay 2010; Heerhartz et al. 2016).

Management of FM in rivers can greatly benefit from a range of recent empirical and modeling approaches that target large wood transport and retention (e.g., described in SedAlp 2014, Bertoldi et al. 2014; Lucía et al. 2015b; Ruiz-Villanueva et al. 2016b,d; Wohl et al. 2016; Mazzorana et al. 2017; Senter et al. 2017a,b). Quantifying FM transport and retention remains a major challenge because of the complex geomorphic, hydrological, and biological processes that control FM dynamics in catchments. At present, an approach to evaluate large wood budgets proposed by Benda and Sias (2003) is used as a tool to understand wood dynamics during certain periods or events, ranging from single events (Lucía et al. 2015b, Steeb et al. 2017) to interdecadal scales (Boivin et al. 2017).

New approaches to monitor large wood are currently under development, including radio frequency identification tags and tracking with geographic positioning system devices, video observations, time-lapse photography, or oblique images (Macvicar and Piégay 2012; Schenk et al. 2014; Kramer and Wohl 2014; Ravazzolo et al. 2015b; Benacchio et al. 2017). These monitoring systems will enhance our understanding of the pathways of the large wood fraction of FM within river networks and thus help to improve FM quantification. However, these methods are applicable mainly to large wood, and more attention should be given to developing methods to monitor and quantify other fractions of FM, such as the deployment of traps to monitor the transport of CPOM, used by Turowski et al. (2013), as well as of FM mixtures that can have a variety of transport patterns. For example, the qualitative characteristics of plastic (low density, persistence, broad range of size and shape) compared to the large wood fraction of FM, require a different modeling approach, although some parallels can be drawn from finer fractions of FM such as seeds (Kooi et al. 2018; Merrit and Wohl 2002).

5. Conclusions and research gaps

We have provided a short and by no means all-encompassing synthesis on the various environmental functions of FM, sustaining the ecological integrity of river corridors. Indeed, we are just at the beginning of understanding the multiple functions FM may play along rivers – as well as in lake and marine systems.

Indeed, a number of research gaps remain. First, the factors that determine the quantity and quality of natural and anthropogenic components of FM in rivers require more attention. Results of our analysis (Box 2) show that coarse-scale characteristics of a catchment can only partly predict the amount of FM trapped in reservoirs. In addition, most attention has been given to the large wood component of FM along rivers, while other fractions have been neglected so far. To some extent this can be explained by difficulties in FM sampling, although the use of neuston samplers may offer a solution (Fig. 3).

With respect to the role of FM as a dispersal vector for organisms, there is a need for investigating the quantity and composition of transported species, transport distances, and the importance of FM in maintaining species and genetic diversity along river corridors. This information is crucial to predict current and future consequences of FM extraction for aquatic and riparian biodiversity, including potential evolutionary consequences, which we are unable to estimate so far.

Our understanding of the role of FM as a physical element also needs to be improved. FM is important in structuring the geomorphological complexity of river channels, and the abundance of resources and habitat conditions for many organisms. Therefore, FM shapes entire ecosystems. Hence, FM should be embedded within the framework of existing geomorphological and ecological concepts, such as the River Continuum Concept (Vannote et al. 1981), River Flood Pulse Concept (Junk et al. 1989), the Nutrient Spiralling Concept (Newbold et al. 1981), and the Serial Discontinuity Concept (Ward and Stanford 1983).

Finally, appropriate management strategies should be developed in order to balance environmental needs and human safety. So far, no studies have been done on management and maintainance of FM post-flood accumulations deposited naturally along river corridors (Loeser et al. 2006, but see study on eco-engineering recovering wrack subsidies by Strain et al. 2018). In fragmented systems, FM that is entrapped at water-associated structures cannot be extracted and passed downstream completely as, under current conditions, it often contains a large fraction of anthropogenic waste (see Box 2). Therefore, we need to understand how to manage mixed FM. Potential reintroduction of FM into rivers (such as reintroduction of wood or wrack) faces challenges due to negative human perceptions of its effects (Piégay et al. 2005; Strayer and Findlay 2010). Hence, we need to better predict the transport of FM and the likely locations of FM accumulation – in connected and in fragmented systems, in order to avoid hazardous effects and to identify FM's "hot-spots".

Glossary (selected terms, in alphabetical order)

Coarse particulate organic matter (CPOM) – particulate organic matter larger than 1 mm in diameter with a size range spanning from seeds to entire trees (Fisher and Likens 1973; Turowski et al. 2013).

Floating mats – buoyant accumulations that include living plant biomass, dead organic material and mineral sediments held together by rhizomes and roots secured by attachment to soils (Azza et al. 2006).

Floating matter (FM) – particulate matter of natural and anthropogenic origin (wood, branches, leaves, seeds, waste) that, due to its properties, is able to float on the water surface.

Free floating macrophytes – plants that grow unattached within or upon the water layer (Hasan and Chakrabarti 2009).

Large wood – pieces of wood larger than 1 m in length and more than 0.1 m in diameter (Montgomery et al. 2003).

Small wood - pieces of wood with a diameter 0.05-0.1 m (Lester et al. 2009).

Macrolitter - items of natural and anhropogenic origin >2 cm in size (Suaria et al. 2014).

Neuston – organisms associated with the air-water interface in aquatic habitats, including small vascular plants and inactive life stages of other organisms (e.g., seeds, spores) (Marshall and Gladyshev 2009).

Surface biofilms – complex of organic compounds and microorganisms that aggregate at the water-air interface and extend a few micrometers (µm) from the surface into the bulk water (Wotton and Preston 2005).

Wrack – organic matter washed onto shores (Harris et al. 2014).

Box 1. Floating matter in marine systems

Currently, thousands of tons of natural and anthropogenic material are floating at the surface of oceans and seas (e.g., Thiel et al. 2011; van Sebille et al. 2015). Rivers form key corridors for the transfer of FM from land to sea, including microplastic and natural wood (e.g., Moore et al. 2011; Sadri and Thompson 2014; Steelandt et al. 2015; Hurley et al. 2018; Kooi et al. 2018). For example, the Danube River delivers on average 1,533 tons of plastic to the Black Sea per year, and the River Rhone 208 tons to the Mediterranean Sea (Kooi et al. 2018). According to recent calculations, more than 62 million macro-litter items (items of natural and anhropogenic origin >2 cm in size) are currently floating at the surface of the Mediterranean sea (Suaria et al. 2014). Because of these large quantities, the role of FM as a dispersal vector, a habitat, and a resource as well as a potential environmental and socio-economic threat has already received significant attention (Thiel and Gutow 2005a,b; Suaria et al. 2014; Thiel et al. 2011).

Rafting on floating objects is a well-known dispersal mechanism in the marine environment (Thiel and Gutow 2005a,b and references therein). More than 1,200 species are reported to have used FM for dispersal of up to 1,000 km or more (Thiel and Gutow 2005a,b; Schuchert 1935). Consequently, FM facilitates the colonization of islands and larger land masses (Gathorne-Hardy et al. 2000). Censky et al. (1998), for example, described the colonization of the island of Anguilla (Carribean Sea) by green iguana floating on logs. During transport across the open ocean, even salt-intolerant species such as amphibians are able to survive (Henderson and Hamilton 1995; Schiesari et al. 2003; Measey et al. 2007; Bell et al. 2015). For example, lizards, snakes, and small mammals were observed as far as 1,600 km from the mouth of the Amazon and Orinoco Rivers (Schuchert 1935). Such survival rates of terrestrial organisms over large transport distances emphasize the importance of FM for evolutionary processes too (Thiel and Haye 2006).

FM may also support the spreading of nonnative and invasive species (Kiessling et al. 2015), bloom-forming algae (Masó et al. 2003), pathogens (Zettler et al. 2013), and pollutants (Holmes et al. 2010). For marine fish and vertebrates, FM provides a shelter and additional resource, explaining why these organisms often aggregate around floating objects and can disperse over long distances (e.g., Luiz et al. 2012).

Dispersal of marine and freshwater biota can be further facilitated by the increasing amount of anthropogenic FM such as plastic (Barnes and Milner 2005). For example, Kiessling et al. (2015) reported a total of 387 taxa (pro- and eukaryotic microorganisms, seaweeds, and invertebrates) attached to artificial FM in marine environments.

Marine FM is also important for ecosystems after deposition. Deposits of FM along coastal areas (so called “wrack deposits”) are suppliers of food and habitat and can immediately boost abundance and biodiversity of primary and secondary consumers (Spiller et al. 2010; Del Vecchio et al. 2017; Brien et al. 2017). Shore wrack is especially important in hostile areas such as the Arctic region (Lastra et al. 2014).

The role of surface biofilms in seas and oceans has also been recognized with respect to their role in biogeochemical processes, air-sea gas and heat exchange, source and sink of pollutants, and a habitat for distinct assemblages (Zaitsev 1997; Dandonneau et al. 2008; Wurl et al. 2017).

Box 2. FM trapped in reservoirs in relation to catchment characteristics

Dams and reservoirs represent “observational windows” where trapped FM can be monitored with respect to a specific point or period of time. Based on information available in research papers and reports of hydropower companies, we collected data on the amount and composition of FM accumulated behind 31 dams located within catchments of 13 rivers (Table S1, Supplementary Information). Our aim was to estimate whether the amount of FM observed in reservoirs can be explained by available bulk characteristics of their catchments.

Based on the results of multiple linear regressions (for details on methods and statistical analysis see Supplementary Information), we identified that bulk characteristics of the catchment such as size of the catchment area above the reservoir (as far as the next upstream trapping structure), average annual precipitation, ratio of ‘woodshed’ (catchment area to the next upstream dam) to catchment area, percentage of forest cover, and artificial areas within 200 m of the river channel buffer (polygons with a 200 m radius from channel network data) explained around 56.5% of the variation in trapped FM. This indicates that further environmental parameters should be taken into account, e.g., flood magnitude during the time period of wood trapping, position of the flood within the annual hydrograph (e.g., Moulin and Piégay 2004; Steeb et al. 2017), or the lag effect of events that lead to the emission of FM (suggested by Fremier et al. 2010; Seo et al. 2015). We were not able to test the effects of these factors due to the limited information that is currently available. In addition, we analyzed relatively large catchments with a mean catchment size of around 13,000 km^2, in contrast to Seo et al. (2008) and Rickenmann (1997) who analyzed the amount of accumulated large wood in catchments between 6.2 – 2,369.5 km^2 and between 0.76 – 6,273 km^2 in size. In addition, in contrast to studies that correlate the characteristics of catchments with the amount of large wood only (see recent studies by Steeb et al 2017; Senter et al. 2017a, b), in our analysis we did such kinds of correlation for the bulk amount of FM. We also suggest that flood magnitude should be considered in relation to the hydraulic capacity of the dams that are present. If the hydraulic capacity of dams located upstream is not exceeded, FM remains trapped and cannot pass downstream (see report by URS Corporation Gomez and Sullivan Engineers 2012). Furthermore, different recruitment processes that lead to the introduction of FM into water bodies are potentially important factors that should be considered (e.g., Diehl 1997; Bradley et al. 2005; Mazzorana et al. 2009, 2011; Mayer and Rimböck 2014; Steeb et al. 2017). However, more detailed case studies are needed to take into account specific recruitment processes, also including smaller spatial scales than those analysed here. Finally, reference conditions for entrapment, particularly time since the last flood, could be incorporated to indicate the potential quantity of FM that accumulates within the floodplain and is delivered to the river.

References

Abbe TB, Montgomery DR (2006) Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old-growth forest valley, Queets River, Washington, USA. Quaternary Research 65:147–155

Abelho M (2001) From litterfall to breakdown in streams: a review. The Scientific World Journal 1:656–680

Abril G, Parize M, Pérez MAP, Filizola N (2013) Wood decomposition in Amazonian hydropower reservoirs: An additional source of greenhouse gases. J S Am Earth Sc 44:104–107

Abril M, Muñoz I, Menéndez M (2016) Heterogeneity in leaf litter decomposition in a temporary Mediterranean stream during flow fragmentation. Science of the Total Environment, 553:330–339

Adams CS, Boar RR, Hubble DS, Gikungu M, Harper DM, Hickley P, Tarras-Wahlberg N (2002) The dynamics and ecology of exotic tropical floating plant mats: Lake Naivasha, Kenya. Hydrobiologia 488:115–122

Allan JD (2004) Landscapes and riverscapes: the influence of land use on stream ecosystems. Annu Rev of Ecol Syst 35:257–284

Altermatt F (2013) Diversity in riverine metacommunities: a network perspective. Aquat Ecol 47:365–377

Andersson E, Nilsson C, Johansson ME (2000) Effects of river fragmentation on plant dispersal and riparian flora. Regulated Rivers: Research and Management 16:83–89

Arsenault D, Boucher E, Bouchon E (2007) Asynchronous forest–stream coupling in a fire-prone boreal landscape: insights from woody debris. J Ecol 95:789-801

Azza N, Denny P, van de Koppel J, Kamsiime F (2006) Floating mats : their occurrence and influence on shoreline distribution of emergent vegetation. Freshw Biol 51:1286–1297

Baldwin DS, Whitworth KL, Hockley CL (2014) Uptake of dissolved organic carbon by biofilms provides insights into the potential impact of loss of large woody debris on the functioning of lowland rivers. Freshw Biol 59:692–702

Barnes DK, Milner P (2005) Drifting plastic and its consequences for sessile organism dispersal in the Atlantic Ocean. Mar Biol 146:815–825

Battauz YS, de Paggi SBJ, Paggi JC (2017) Macrophytes as dispersal vectors of zooplankton resting stages in a subtropical riverine floodplain. Aquat Ecol 51:191–201

Bell RC, Drewes RC, Channing A, Gvozdik V, Kielgast J, Lötters S, Stuart BL, Zamudio KR (2015) Overseas dispersal of Hyperolius reed frogs from Central Africa to the oceanic islands San Tome and Prıncipe. J Biogeogr 42:65–75

Benacchio V, Piégay H, Buffin-Bélanger T, Vaudor L (2017) A new methodology for monitoring wood fluxes in rivers using a ground camera: potential and limits. Geomorphology 279:44–58

Benda LE, Sias JC (2003) A quantitative framework for evaluating the mass balance of in-stream organic debris. For Eco Manage 172:1–16

Bertoldi W, Welber M, Mao L, Zanella S, Comiti F (2014) A flume experiment on wood storage and remobilization in braided river systems. Earth Surf Process Landf 39:804–813

Bertoldi W, Welber M, Gurnell AM, Mao L, Comiti F, Tal M (2015) Physical modelling of the combined effect of vegetation and wood on river morphology. Geomorphology 246:178–187

Bilton DT, Freeland JR, Okamura B (2001) Dispersal in freshwater invertebrates. Annu Rev of Ecol Syst 32:159–181

Boivin M, Buffin-Bélanger T, Piégay H (2017) Estimation of large wood budgets in a watershed and river corridor at interdecadal to interannual scales in a cold-temperate fluvial system. Earth Surf Process Landf 42:2199-2213

Boness M (1975) Arthropoden im Hochwassergenist von Flüssen. - Bonn. Zool. Beitr. 26:383–401 (in German)

Bowen KL, Kaushik NK, Gordon AM (1998) Macroinvertebrate communities and biofilm chlorophyll on woody debris in two Canadian oligotrophic lakes. Archiv fűr Hydrobiologie 141:257–281

Braccia A, Batzer DP (2001) Invertebrates associated with woody debris in a Southeastern U.S. forested floodplain wetland. Wetlands 21:18–31

Bradley J, Richards D, Bahner C (2005) Debris Control Structures - Evaluation and Countermeasures. Salem, OR: U.S. Department of Transportation: Federal Highway Administration

Brien ALO, Morris L, Keough MJ (2017) Rapid invertebrate responses to macroalgal wrack : two novel field experiments on intertidal mudflats in Southern Australia. Marine Ecology 38:1–17

Bulla CK, Gomes LC, Miranda LE, Agostinho AA (2011) The ichthyofauna of drifiting macrophyte mats in the Ivinheima River, upper Paraná River basin, Brazil. Neotropical Ichthyology 9:403–409

Burchardt L, Marshall HG (2003) Algal composition and abundance in the neuston surface micro layer from a lake and pond in Virginia (U.S.A.). J Lim 62:139–142

Bunte K, Swingle KW, Turowski JM, Abt SR Cenderelli, DA (2016) Measurements of coarse particulate organic matter transport in steep mountain streams and estimates of decadal CPOM exports. Journal of Hydrology 539:162–176

Carthey AJR, Fryirs KA, Ralph TJ, Bu H, Leishman MR (2016) How seed traits predict floating times: A biophysical process model for hydrochorous seed transport behaviour in fluvial systems. Freshw Biol 61:19-31

Censky EJ, Hodge K, Dudley J (1998) Over-water dispersal of lizards due to hurricanes. Nature 395:556

Čejka T, Čiliak M, Šteffek J (2015) Molluscan diversity in stream driftwood. Relation to land use and river section. Polish Journal of Ecology 63:124–134

Chen X, Wie X, Scherer R (2005) Influence of wildfire and harvest on biomass, carbon pool, and decomposition of large woody debris in a forested stream of southern interior British Columbia. For Eco Manage 208:101–114

Chen SC, Chao YC, Chan HC (2013) Typhoon-dominated influence on wood debris distribution and transportation in a high gradient headwater catchment. J Mt Sci 10:509–521

Collins BD, Montgomery DR, Fetherston KL, Abbe TB (2012) The floodplain large-wood cycle hypothesis: a mechanism for the physical and biotic structuring of temperature forested alluvial valleys in the North Pacific coastal ecoregion. Geomorphology 139–140:460–470

Comiti F, Andreoli A, Mao L, Lenzi MA (2008) Wood storage in three mountain streams of the Southern Andes and its hydro-morphological effects. Earth Surf Process Landf 34:155–161

Comiti F, Lucía A, Rickenmann D (2016) Large wood recruitment and transport during large floods : a review. Geomorphology 269:23–39

Corenblit D, Vidal V, Cabanis M, Steiger J, Garofano-Gomez V, Garreau A, Hortobagyi B, Otto T, Roussel E, Voldoire O (2016) Seed retention by pioneer trees enhances plant diversity resilience on gravel bars: Observations from the river Allier, France. Advances in Water Resources 93:182–192

Corti R, Datry T (2012) Invertebrate and sestonic matter in an advancing wetted front travelling down a dry riverbed (Albarine, France). Freshw Sci 31:1187–1201

Covino T (2017) Hydrologic connectivity as a framework for understanding biogeochemical flux through watersheds and along fluvial networks. Geomorphology 277:133–144

Cuffney TF (1988) Input, movement and exchange of organic matter within a subtropical coastal black water river-flood plain system. Freshw Biol 19:305–320

Cummins KW (1974) Structure and Function of Stream Ecosystems. BioScience 24:631-642

Cunnings A, Johnson E, Martin Y (2016) Fluvial seed dispersal of riparian trees: transport and depositional processes. Earth Surf Process Landforms 41:615–625

Czarnecka M (2015) Coarse woody debris in temperate littoral zones: implications for biodiversity, food webs and lake management. Hydrobiologia 767:13–25

Czarnecka M, Pilotto F, Pusch MT (2014) Is coarse woody debris in lakes a refuge or a trap for benthic invertebrates exposed to fish predation? Freshw Biol 59:2400–2412

Czogler K, Rotarides M (1938) Analyse einer vom Wasser angeschwemmten Molluskenfauna. Arb Ungar Biol Forsch Inst 10:8–43 (in German)

Dandonneau Y, Menkes C, Duteil O, Gorgues T (2008) Concentration of floating biogenic material in convergence zones. Journal of Marine Systems 69:226–232

de Brouwer JHF, Eekhout JPC, Besse-Lototskaya AA, Hoitink AJF, Ter Braak CJF, Verdonschot PFM (2017) Flow thresholds for leaf retention in hydrodynamic wakes downstream of obstacles. Ecohydrology 10:e1883

del Vecchio S, Jucker T, Carboni M, Acosta ATR (2017) Linking plant communities on land and at sea: the effects of Posidonia oceanica wrack on the structure of dune vegetation. Estuarine, Coastal and Shelf Science 184:30–36

Defina A, Peruzzo P (2012) Diffusion of floating particles in flow through emergent vegetation: Further experimental investigation. Water Resources Research 48.

Dhote S, Dixit S (2009) Water quality improvement through macrophytes – a review. Environmental Monitoring and Assessment 152:149–153

Diehl T (1997) Potential drift accumulation at bridges. US Department of Transportation Federal Highway Administration Research and Development, Turner-Fairbank Highway Research Center, Report No FHWA-RD-97-028, Washington DC

Downing-Kunz M, Stacey M (2011) Flow-induced forces on free-floating macrophytes Hydrobiologia 671:121–135

Dunger W (1983) Tiere im Boden. A. Ziemsen Verlag, Wittenberg Lutherstadt (in German)

Eggert SL, Wallace JB (2007) Wood biofilm as a food resource for stream detritivores. Limnology and Oceanography 52:1239–1245

Edwards PJ, Kollmann J, Gurnell AM, Petts GE, Tockner K, Ward JV (1999) A conceptual model of vegetation dynamics on gravel bars of a large alpine river. Wetlands Ecology and Management 7:141–153

Elosegi A, Díez J, Mutz M (2010) Effects of hydromorphological integrity on biodiversity and functioning of river ecosystems. Hydrobiologia 657:199–215

Elosegi A, Pozo J (2016) Altered organic matter dynamics in rivers and streams: ecological consequences and management implications. Limnetica 35:303–322.

Elosegi A, Díez JR, Flores L, Molinero J (2017) Pools, channel form, and sediment storage in wood-restored streams: potential effects on downstream reservoirs. Geomorphology 279:165–175

Ensign SH, Doyle MW (2006) Nutrient spiraling in streams and river networks. Journal of Geophysical Research: Biogeosciences 111:1–13

Faure F, Demars C, Wieser O, Kunz M, de Alencastro LF (2015) Plastic pollution in Swiss surface waters: nature and concentrations, interaction with pollutants. Environ Chem 12: 582–591

Fisher SG, Likens GE (1973) Energy flow in Bear Brook, New Hampshire: An integrative approach to stream ecosystem metabolism. Ecological Monographs 43:421–439

Fraaije RGA, Moinier S, van Gogh I, Timmers R, van Deelen JJ, Verhoeven JTA, Soons MB (2017) Spatial patterns of water-dispersed seed deposition along stream riparian gradients. Plos One 12(9)

Fremier AK, Seo JI,Nakamura F (2010) Watershed controls on the export of large wood from stream corridors. Geomorphology 117:33–43

Gabel F, Garcia X-F, Brauns M, Sukhodolov A, Leszinski M, Pusch MT (2008) Resistance to ship-induced waves of benthic invertebrates in various littoral habitats. Freshw Biol 53:1567–1578

Gathorne-Hardy FJ, Jones DT, Mawdsley NA (2000) The recolonization of the Krakatau islands by termites (Isoptera), and their biogeographical origins. Botanical Journal of the Linnean Society 71:251–267

Gerhard M, Reich M (2000) Restoration of streams with large wood: Effects of accumulated and built-in wood on channel morphology, habitat diversity and aquatic fauna. International Review of Hydrobiology 85:123–137

Gerken B, Böttcher H, Böwingloh F, Dörfer K, Leushacke-Schneider C, Robinson A, Wienhöfer M (1998) Treibgut und Genist - Landschaftsmüll oder Quelle und Antrieb dynamischer Lebensvorgänge in Auen? Auenregeneration, Fachbeiträge 1:1-24 (in German)

Gittman RK, Scyphers SB, Smith CS, Neylan IP, Grabowski JH (2016) Ecological consequences of shoreline hardening: a meta-analysis. Bioscience 66:763-773

Gladyshev MI (1986) Neuston of inland waters (A review). Hydrobiol J 22:1-7

Gladyshev MI (2002) Biophysics of the Surface Microlayer of Aquatic Ecosystems. IWA Publishing, London

Golladay SW, Sinsabaugh RL (1991) Biofilm development on leaf and wood surfaces in a boreal river. Freshw Biol 25:437–450

Goodson JM, Gurnell AM, Angold PG, Morrissey IP (2003) Evidence for hydrochory and the deposition of viable seeds within winter flow-deposited sediments: The River Dove, Derbyshire, UK. River Res Appl 19:317–334

Grant EHC, Lowe WH, Fagan WF (2007) Living in the branches: Population dynamics and ecological processes in dendritic networks. Ecology Letters 10:165–175

Grasset C, Mendonça R, Villamor Saucedo G, Bastviken D, Roland F, Sobek S (2018) Large but variable methane production in anoxic freshwater sediment upon addition of allochthonous and autochthonous organic matter. Limnol Oceanogr. doi: 10.1002/lno.10786

Grill G, Dallaire CO, Chouinard EF, Sindorf N, Lehner B (2014) Development of new indicators to evaluate river fragmentation and flow regulation at large scales: a case study for the Mekong River Basin. Ecological Indicators 45:148–159

Gschnitzer T, Gems B, Mazzorana B, Aufleger M (2017) Towards a robust assessment of bridge clogging processes in flood risk management. Geomorphology 279:128–140

Gurnell AM, Sweet R (1998) The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. Earth Surf Process Landf 23:1101–1121

Gurnell AM, Petts GE, Hannah DM, Smith BPG, Edwards PJ, Kollmann J, Ward JV, Tockner K (2001) Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surf Process Landf 26:31–62

Gurnell AM, Piegay H, Swanson FJ, Gregory SV (2002) Large wood and fluvial processes. Freshw Biol 47:601–620

Gurnell A, Tockner K, Edwards P, Petts G (2005) Effects of deposited wood on biocomplexity of river corridors. Frontiers in Ecology and the Environment 3:377–382

Gurnell AM (2007) Analogies between mineral sediment and vegetative particle dynamics in fluvial systems. Geomorphology 89:9–22

Gurnell AM, Goodson J, Thompson K, Clifford N, Armitage P (2007) The river bed: a dynamic store for viable plant propagules? Earth Surf Process Landf 32:1257–1272

Gurnell AM, Thompson K, Goodson JM, Moggridge H (2008) Propagule deposition along river margins: linking hydrology and ecology. J Ecol 96:553–565

Gurnell AM, Bertoldi W, Corenblit D (2012) Changing river channels: the roles of hydrological processes, plants and pioneer landforms in humid temperate, mixed load, gravel bed rivers. Earth Sci Rev 111:129-141

Gurnell AM (2013) Wood in fluvial systems. In: Shroder J Jr, Wohl E (eds) Treatise on Geomorphology. Academic Press, San Diego, CA, USA, pp 163–188

Gurnell AM (2014) Plants as river system engineers. Earth Surf Process Landf 39:4-25

Gurnell AM, Corenblit D, García de Jalón D, González del Tánago M, Grabowski RC, O'Hare MT, Szewczyk M (2016) A conceptual model of vegetation–hydrogeomorphology interactions within river corridors. River Res Appl 32:142–163

Gurnell AM, Bertoldi W, Francis RA, Gurnell J, Mardhiah U (2018) Understanding processes of island development on an island braided river over timescales from days to decades. Earth Surf. Process. Landforms. doi:10.1002/esp.4494

Haden A (1997) Benthic Ecology of the Colorado River System through the Colorado Plateau Region. MSc Thesis. Northern Arizona University

Haden GA, Blinn DW, Shannon JP, Wilson KP (1999) Driftwood: an alternative habitat for macroinvertebrates in a large desert river. Hydrobiologia 397:179–186

Haga H, Moriishida T, Morishita N, Fujimoto T (2017) Properties of small instream wood as a logjam clogging agent: Implications for clogging dynamics based on wood density, water content, and depositional environment. Geomorphology 296:1–10

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Cummins K. (1986) Ecology of coarse woody debris in temperate ecosystems. Adv Ecol Res 15:133–302

Harris C, Strayer DL, Findlay S (2014) The ecology of freshwater wrack along natural and engineered Hudson River shorelines. Hydrobiologia 722:233–245

Hart SK, Hibbs DE, Perakis SS (2013) Riparian litter inputs to streams in the central Oregon Coast Range. Freshwater Science 32:343–358

Harvey J, Gooseff M (2015) River corridor science: Hydrologic exchange and ecological consequences from bed forms to basins. Water Resour Res 51:6893–6922

Hasan MR, Chakrabarti R (2009) Use of algae and aquatic macrophytes as feed in small-scale aquaculture: a review. FAO Fisheries and Aquaculture Technical Paper No 531. Rome, FAO. 123p

Hassan MA, Church M, Lisle TE, Brardinoni F, Benda L, Grant GE (2005) Sediment transport and channel morphology of small, forested streams. Journal of the American Water Resources Association 41:853–876

Hauenstein W (2003) Entsorgungspflicht versus Nutzen von Totholz im Gewässer - ein Interessenkonflikt für die Wasserkraft. Wasser Energie Luft 95:363–366 (in German)

Heerhartz SM, Toft JD, Cordell JR, Dethier MN, Ogston AS (2016) Shoreline armoring in an estuary constrains wrack-associated invertebrate communities. Estuar Coasts 39:171–188

Henderson PA, Hamilton HF (1995) Standing crop and distribution of fish in drifting and attached floating meadow within an upper amazonian Varzea Lake. Journal of Fish Biology 47:266–276

Hering D, Plachter H (1997) Riparian Ground Beetles (Coeloptera, Carabidae) Preying on Aquatic Invertebrates: A Feeding Strategy in Alpine Floodplains. Oecologia 111:261–270

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25:1965–1978

Hoffmann A, Hering D (2000) Wood-associated macroinvertebrate fauna in Central European streams. International Review of Hydrobiology 85:25–48

Holloway JV, Rillig MC, Gurnell AM (2017a) Underground Riparian Wood: Buried Stem and Coarse Root Structures of Black Poplar (Populus nigra L.). Geomorphology 279:188–198

Holloway JV, Rillig MC, Gurnell AM (2017) Physical environmental controls on riparian root profiles associated with black poplar (Populus nigra L.) along the Tagliamento River, Italy. Earth Surf Process Landforms 42:1262–1273

Holmes LA, Turner A, Thompson RC (2012) Adsorption of trace metals to plastic resin pellets in the marine environment. Environ Pollut 160:42–48

Horáčková J, Podroužková Š, Juřičková L (2015) River floodplains as habitat and bio-corridors for distribution of land snails: their past and present. Journal of Landscape Ecology 8:23–39

Horton AA, Walton A, Spurgeon DJ, Lahive E, Svendsen C (2017) Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. Sci Total Environ 586:127−141

Hoover TM, Richardson JS, Yonemitsu N (2006) Flow substrate interactions create and mediate leaf litter resource patches in streams. Freshw Biol 51: 435–447

Hurley R, Woodward J, Rothwell JJ (2018) Microplastic contamination of river beds significantly reduced by catchment-wide flooding. Nat Geosci 11:251–257

Johansson ME, Nilsson C, Nilsson E (1996) Do rivers function as corridors for plant dispersal? J Veg Sci 7:593–598

Johnson SL, Swanson F, Grant G, Wondzell S (2000) Riparian forest disturbances by a mountain flood - the ifnluence of floated wood. Hydrol Process 14:3031–3050

Junk W, Bayley PB, Sparks RE (1989) The flood pulse concept in river-floodplain systems. In: Dodge DP (ed) Proceedings of the International Large River Symposium (LARS). Canadian Special Publication of Fisheries and Aquatic Sciences 106, pp 110-127

Karrenberg S, Edwards PJ, Kollmann J (2002) The life history of Salicaceae living in the active zone of floodplains. Freshw Biol 47:733–748

Kiessling T, Gutow L, Thiel M (2015) Marine litter as a habitat and dispersal vector. In: Bergmann M, Gutow L, Klages M (eds) Marine anthropogenic litter, pp 141–181

Koljonen S, Louhi P, Mäki-Petäys A, Huusko A, Muotka T (2012) Quantifying the effects of in-stream habitat structure and discharge on leaf retention: implications for stream restoration. Freshw Sci 31:1121–1130

Kooi M, Besseling E, Kroeze C, van Wezel AP, Koelmans AA (2018) Modeling the Fate and Transport of Plastic Debris in Freshwaters: Review and Guidance. In: Wagner M., Lambert S. (eds) Freshwater Microplastics. The Handbook of Environmental Chemistry, vol 58. Springer, Cham

Korpachev V (2004) Problems of prediction of pollution and clogging by woody mass and organic matter in reservoirs of high-pressure hydropower plants. Conference proceedings “Success of contemporary science” (in Russian)

Kosten S, Pineiro M, de Goede E, de Klein J, Lamers LPM, Ettwig K (2016) Fate of methane in aquatic systems dominated by free-floating plants. Water Research 104:200–207

Kleinschmidt Energy and Water consultants (2008) Appalachian Power Company, Claytor Lake Hydroelectric Project. Debris study final report. Roanoke, Virginia

Kramer N, Wohl E (2014) Estimating fluvial wood discharge using time-lapse photography with varying sampling intervals. Earth Surf Process Landf 39:844–852

Kramer N, Wohl E (2016) Rules of the road: a qualitative and quantitative synthesis of large wood transport through drainage networks. Geomorphology 279:74–97

Krause S, Klaar MJ, Hannah DM, Mant J, Bridgeman J, Trimmer M, Manning-Jones S (2014) The potential of large woody debris to alter biogeochemical processes and ecosystem services in lowland rivers. Wiley Interdisciplinary Reviews: Water 1:263–275

Krejčí L, Máčka Z (2012) Anthropogenic controls on large wood input, removal and mobility: Examples from rivers in the Czech Republic. Area 44:226–236

Lancaster ST, Grant GE (2006) Debris dams and the relief of headwater streams. Geomorphology 82:84–97

Langhans SD (2000) Schwemmgut: Indikator der ökologischen Integrität einer Flussaue. Diplomarbeit. EAWAG/ETH Zürich (in German)

Langhans SD (2006) Riverine floodplain heterogeneity as a controller of organic matter dynamics and terrestrial invertebrate distribution. Thesis. ETH Zürich

Langhans, SD, Richard U, Rueegg J, Uehlinger U, Edwards P, Doering M, Tockner K (2013) Environmental heterogeneity affects input, storage, and transformation of coarse particulate organic matter in a floodplain mosaic. Aquat Sci 75:335–348

Langlade, L-R, Décamps O (1994) Plant colonization on river gravel bars: the effect of litter accumulation. C R Acad Sci Paris 317:899–905

Lastra M, Rodil IF, Sánchez-Mata A, García-Gallego M, Mora J (2014) Fate and processing of macroalgal wrack subsidies in beaches of Deception Island, Antarctic Peninsula. Journal of Sea Research 88:1–10

Lehner B, Döll P (2004) Development and validation of a global database of lakes, reservoirs and wetlands. Wetlands 296:1–22

Le Lay Y-F, Moulin B (2007) Les barrages face à la problématique des bois flottants: collecte, traitement et valorisation La Houille Blanche. Revue internationale de l'eau 3:96–103 (in French)

Le Lay YF, Piégay H, Moulin B (2013) Wood entrance, deposition, transfer and effects on fluvial forms and processes, problem statements and challenging issues. In: Shroder J, Wohl E (eds) Treatise on Geomorphology, vol 12, Academic Press, San Diego, CA, pp 20–36

Lester RE, Wright W, Jones-Lennon M, Rayment P (2009) Large versus small wood in streams: the effect of wood dimension on macroinvertebrate communities. Fundam Appl Limnol / Arch für Hydrobiol 174:339–351

Loeser MR, McRae BH, Howe MM, Whitham TG (2006) Litter hovels as havens for riparian spiders in an unregulated river. Wetlands 26:13–19

Lucía A, Antonello A, Campana D, Cavalli M, Crema S, Franceschi S, Marchese E, Niedrist M, Schneiderbauer S, Comiti F (2015a) Monitoring and modeling large wood transport in a mountain basin of North-eastern Italy. In: Lollino G, Arattano M, Rinaldi M, Giustolisi O, Marechal J-C, Grant GE (eds) Engineering Geology for Society and Territory-River Basins. Reservoir Sedimentation and Water Resources, Vol 3, Springer, Torino, pp 155-158

Lucía A, Comiti F, Borga M, Cavalli M, Marchi L (2015b) Dynamics of large wood during a flash flood in two mountain catchments. Nat Hazards Earth Syst Sci 15: 1741-1755

Luiz OJ, Madin JS, Robertson DR, Rocha LA, Wirtz P, Floeter SR (2012) Ecological traits influencing range expansion across large oceanic dispersal barriers: insights from tropical Atlantic reef fishes. Proc R Soc B: Biol Sci 279:1033–1040

Macvicar B, Piégay H (2012) Implementation and validation of video monitoring for wood budgeting in a wandering piedmont river, the Ain River (France). Earth Surf Process Landf 37:1272–1289

Mahoney JM, Rood SB (1998) Streamflow requirements for cottonwood seedling recruitment: an integrative model. Wetlands 18: 634–645

Malard F, Tockner K, Dole-Olivier M-J, Ward V (2002) A landscape perspective of surface-subsurface hydrological exchanges in river corridors. Freshw Biol 47:621–640

Marshall HG, Burchardt L (2005) Neuston: its definition with a historical review regarding its concept and community structure. Arch Hydrobiol 164:429–448

Marshall HG, Gladyshev MI (2009) Neuston in aquatic ecosystems. In: Likens GE (ed) Encyclopedia of Inland Waters, Vol 1, Elsevier, Oxford, pp 97–102

Martin DJ, Benda LA (2001) Patterns of instream wood recruitment and transport at the watershed scale. Trans Am Fish Soc 130:940–958

Massol F, Altermatt F, Gounand I, Gravel D, Leibold MA, Mouquet N (2017) How life-history traits affect ecosystem properties: effects of dispersal in metaecosystems. Oikos 126:532–546

Matheson A, Thoms M, Southwell M, Reid M (2017) Does reintroducing large wood influence the hydraulic landscape of a lowland river at multiple discharges? Ecohydrology, https://doi.org/10.1002/eco.1854

Malmqvist B (2002) Aquatic invertebrates in riverine landscapes. Freshw Biol 47:679–694

Mardhiah U, Caruso T, Gurnell AM, Rillig MC (2014) Just a matter of time: Fungi and roots significantly and rapidly aggregate soil over four decades along the Tagliamento River, NE Italy. Soil Biology and Biochemistry 75:133–142

Mardhiah U, Rillig MC, Gurnell A (2015) Reconstructing the development of sampled sites on fluvial island surfaces of the Tagliamento River, Italy, from historical sources. Earth Surf Process Landforms 40:629–64

Masó M, Garcés E, Pagès F, Camp J (2003) Drifting plastic debris as a potential vector for dispersing Harmful Algal Bloom (HAB) species. Sci Mar 67:107–111

Mazzorana B, Zischg A, Largiader A, Hübl J (2009) Hazard index maps for woody material recruitment and transport in alpine catchments. Nat Hazards Earth Syst Sci 9:197–209

Mazzorana B, Hübl J, Zischg A, Largiader A (2011) Modelling woody material transport and deposition in alpine rivers. Nat Hazards 56:425–449

Mazzorana B, Ruiz-Villanueva V, Marchi L, Cavalli M, Gems B, Gschnitzer T, Mao L, Iroumé A, Valdebenito G (2017) Assessing and mitigating large wood-related hazards in mountain streams: recent approaches: Journal of Flood Risk Management, https://doi.org/10.1111/jfr3.12316

Merten E, Finlay J, Johnson L, Newman R, Stefan H, Vondracek B (2010) Factors influencing wood mobilization in streams, Water Resour Res 46: W10514, https://doi.org/10.1029/2009WR008772

Merten EC, Vaz PG, Decker-Fritz JA, Finlay JC, Stefan HG (2013) Relative importance of transport, breakage, and decay as processes depleting large wood from streams. Geomorphology 190:40–47

Meyer J, Rimböck A (2014) GIS basierter Ansatz zur Abschätzung des Schwemmholzpotenzials in Wildbächen; Internationales Symposium „Wasser- und Flussbau im Alpenraum", 25.-27.06.2014 in Zürich; Tagungspublikation S. 443 ff; Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glazialogie der Eidgenössischen Technischen Hochschule Zürich Nr. 228; Zürich (in German)

Merritt DM, Wohl EE (2002) Processes governing hydrochory along rivers: hydraulics, hydrology, and dispersal phenology. Ecological Applications 12:1071–1087

Merritt DM, Wohl EE (2006) Plant dispersal along rivers fragmented by dams. River Res Appl 22:1–26

Measey GJ, Vences M, Drewes RC, Chiari Y, Melo M, Bourles B (2007) Freshwater paths across the ocean: molecular phylogeny of the frog Ptychadena newtoni gives insights into amphibian colonization of oceanic islands. J Biogeogr 34:7–20

Montgomery DR, Collins BD, Buffington JM, Abbe TB (2003) Geomorphic effects of wood in rivers. In: Gregory SV, Boyer KL, Gurnell AM. The Ecology and Management of Wood in World Rrivers. Am. Fish. Soc, Bethesda, MD, pp 21–47

Moog O, Chovanec A (2000) Assessing the ecological integrity of rivers: walking the line among ecological, political and administrative interests. Hydrobiologia 422:99–109

Moore CJ, Lattin GL, Zellers AF (2011) Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California. J Integr Coast Zone Manag 11:65–73

Moulin B, Piégay H (2004) Characteristics and temporal variability of large woody debris trapped in a reservoir on the River Rhone (Rhone): Implications for river basin management. River Res Appl 20:79–97

Nahlik AM, Mitsch WJ (2006) Tropical treatment wetlands dominated by free-floating macrophytes for water quality improvement in Costa Rica. Ecol Eng 28:246–257

Nakamura F, Seo JI, Akasaka T, Swanson FJ (2017) Largewood, sediment, and flow regimes: their interactions and temporal changes caused by human impacts in Japan. Geomorphology 279:176–187

Naman SM, Rosenfeld JS, Richardson JS (2016) Causes and consequences of invertebrate drift in running waters: from individuals to populations and trophic fluxes. Can J Fish Aquat Sci 73:1292–1305

Nanson GC (1980) Point bar and floodplain formation of the meandering Beatton River, northeastern British Columbia, Canada. Sedimentology 27:3–29

Nanson GC, Barbetti M, Taylor G (1995) River stabilisation due to changing climate and vegetation during the late Quaternary in western Tasmania, Australia. Geomorphology 13:145–158

Nathan R, Muller-Landau HC (2000) Spatial patterns of seed dispersal, their determinants and consequences for recruitment. Trends Ecol Evol 15:278–285

Newbold JD, Elwood JW, O’Neill RV, Winkle WV (1981) Measuring nutrient spiraling in streams. Can J Fish Aquat Sci 38:860–863

Ngari AN, Kinyamario JI, Ntiba MJ, Mavuti KM (2008) Factors affecting abundance and distribution of submerged and floating macrophytes in Lake Naivasha, Kenya. African J Ecol 47:32–39

Nilsson C, Brown RL, Jansson R, Merritt DM (2010) The role of hydrochory in structuring riparian and wetland vegetation. Biological Reviews of the Cambridge Philosophical Society 85:837–858

Oberbeckmann S, Kreikemeyer B, Labrenz M (2018) Environmental factors support the formation of specific bacterial assemblages on microplastics. Front Microbiol 8. https://doi.org/10.3389/fmicb.2017.02709

Osei NA, Gurnell AM, Harvey GL (2015a) The role of large wood in retaining fine sediment, organic matter and plant propagules in a small, single-thread forest river. Geomorphology 235:77–87

Osei NA, Harvey GL, Gurnell AM (2015b) The early impact of large wood introduction on the morphology and sediment characteristics of a lowland river. Limnologica 54:33–43

Parker C, Henshaw AJ, Harvey GL, Sayer CD (2017) Reintroduced large wood modifies fine sediment transport and storage in a lowland river channel. Earth Surf Process Landf https://doi.org/10.1002/esp.4123

Pettit NE, Naiman RJ, Rogers KH, Little JE (2005) Post-flooding distribution and characteristics of large woody debris piles along the semi-arid Sabie River, South Africa. River Res Appl 21:27–38

Pettit NE, Naiman RJ (2006) Flood-deposited wood creates regeneration niches for riparian vegetation on a semi-arid South African river. J Veg Sci 17:615– 624

Pettit NE, Latterell JJ, Naiman RJ (2006) Formation, distribution and ecological consequences of flood-related wood debris piles in a bedrock confined river in semi-arid South Africa. River Res Appl 22:1097–1110

Picco L, Bertoldi W, Comiti F (2017) Dynamics and ecology of wood in world rivers. Geomorphology 279:10–11

Piégay H, Gurnell A (1997) Large woody debris and river geomorphological pattern: Examples from S.E. France and S. England. Geomorphology 19:99–116

Piégay H, Gregory KJ, Bondarev V et al (2005) Public Perception as a Barrier to Introducing Wood in Rivers for Restoration Purposes. Environm Manag 36:665–674

Piégay H, Moulin B, Hupp C (2017) Assessment of transfer patterns and origins of in-channel wood in large rivers using repeated field surveys and wood characterisation (the Isère River upstream of Pontcharra, France). Geomorphology 279:27–43

Pilotto F, Bertoncin A, Harvey GL, Wharton G, Pusch MT (2014) Diversification of stream invertebrate communities by large wood. Freshw Biol 59:2571–2583

Pilotto F, Harvey GL, Wharton G, Pusch MT (2016) Simple large wood structures promote hydromorphological heterogeneity and benthic macroinvertebrate diversity in low-gradient Rivers. Aquat Sci 78:755–766

Pozo J, Gonzalez E, Díez R, Molinero J, Elosegi A (1991) Inputs of particulate organic matter to streams with different riparian vegetation. J N Am Benthol Soc 16:602–611

Pringle CM (2003) What is hydrological connectivity and why is it ecologically important? Hydrol Process 17:2685–2689

Pusch M, Fiebig D, Brettar I, Eisenmann H, Ellis BK, Kaplan LA, Lock MA, Naegeli MW, Traunspurger W (1998) The role of micro-organisms in the ecological connectivity of running waters. Freshw Biol 40:453–495

Puth LM, Wilson KA (2001) Boundaries and corridors as a continuum of ecological flow control: Lessons from rivers and streams. Conserv Biol 15:21–30

Quinn JM, Ngaire RP, Parkyn SM (2007) Factors influencing retention of coarse particulate organic matter in streams. Earth Surf Process Landforms 32:1186–1203

R Core Team (2015) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org/

Ravazzolo D, Mao L, Picco L, Sitzia T, Lenzi MA (2015a) Geomorphic effects of wood quantity and characteristics in three Italian gravel-bed rivers. Geomorphology 246:79–89

Ravazzolo D, Mao L, Picco L, Lenzi MA (2015b) Tracking log displacement during floods in the Tagliamento River using RFID and GPS tracker devices. Geomorphology 228:226–233

Reeves GH, Burnett KM, Mcgarry EV (2003) Sources of large wood in the main stem of a fourth-order watershed in coastal Oregon. Can J For Res 33:1363–1370

Richardson JS, Bilby RE, Bondar CA (2005) Organic matter dynamics in small streams of the Pacific Northwest. Journal of the American Water Resources Association 41:921–934

Richardson JS, Hoover TM, Lecerf A (2009) Coarse particulate organic matter dynamics in small streams: towards linking function to physical structure. Freshw Biol 54:2116–2126

Rickenmann D (1997) Schwemmholz und hochwasser. Wasser, Energie, Luft 89:115–119 (in German)

Robinson CT, Tockner K, Ward JV (2002) The fauna of dynamic riverine landscapes. Freshw Biol 47:661–677

Rood SB, Kaluthota S, Gill KM, Hillman EJ, Woodman SG, Pearce DW, Mahoney JM (2016) A Twofold Strategy for Riparian Restoration: Combining a Functional Flow Regime and Direct Seeding to Re-establish Cottonwoods. River Res Appl 32:836–844

Rosado J, Morais M, Tockner K (2015) Mass dispersal of terrestrial organisms during first flush events in a temporary stream. *River Res Appl* 31:912–917

Rossi F (2007) Recycle of buried macroalgal detritus in sediments : use of dual-labelling experiments in the field. Mar Biol 150:1073–1081

Ruiz-Villanueva V, Wyżga B, Zawiejska J, Hajdukiewicz M, Stoffel M (2016a) Factors controlling large-wood transport in a mountain river. Geomorphology 272:21–31

Ruiz-Villanueva V, Piégay H, Gurnell A, Marston RA, Stoffel M (2016b) Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges. Rev Geophys: 54:611–652

Ruiz-Villanueva V, Piégay H, Gaertner V, Perret F, Stoffel M (2016c) Wood density and moisture sorption and its influence on large wood mobility in rivers. Catena 140:182–194

Ruiz-Villanueva V, Badoux A, Boes R, Rickenmann D, Rickli C, Schalko I, Schmocker L, Schwarz M, Steeb N, Stoffel M, Weitbrecht V (2016d) Large wood management in rivers - a practice-oriented research project in Switzerland. In: Proc 13th Congress Interaprevent, Lucerne, Switzerland, ISBN 978-3-901164-23-1:244-245

Rummel CD, Jahnke A, Gorokhova E, Kühnel D, Schmitt-Jansen M (2017) Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. Environ Sci Technol Lett 4:258–267

Sadri SS, Thompson RC (2014) On the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary, Southwest England. Mar Pollut Bull 81:55–60

Saveanu L, Martín PR (2015) Neuston: a relevant trophic resource for apple snails? Limnologica 52:75–82

Sarneel JM, Soons MB, Geurts JJ, Beltman B, Verhoeven JT (2011) Multiple effects of land-use changes impede the colonization of open water in fen ponds. J Veg Sci 22:551–563

Schenk ER, Moulin B, Hupp CR, Richter JM (2014) Large wood budget and transport dynamics on a large river using radio telemetry. Earth Surf Process Landf 39:487–498

Schneider KN, Winemiller KO (2008) Structural complexity of woody debris patches influences fish and macroinvertebrate species richness in a temperate floodplain-river system. Hydrobiologia 610:235–244

Schuchert C (1935) Historical geology of the Antillean-Caribbean region. Wiley & Sons, 79–110

Schwab A, Stammel B, Kiehl K (2018) Seed dispersal via a new watercourse in a reconnected floodplain: differences in species groups and seasonality. Restoration Ecology 26:103–113

SedAlp (2014) Third SedAlp Milestone First set of practically applicable bedload/wood transport relations and models. Authors: Aigner J, Habersack H, Rindler R, Schober B, Wagner B, Comiti F, Recking A, Moser M, Piégay H, Rimböck A, Lenzi MA, Picco L, Moretto J, Ravazzolo D

Senter AE, Pasternack GB, Piégay H, Vaughan MC (2017a) Wood export prediction at the watershed scale. Earth Surf Process Landf 42:2377–2392

Senter AE, Pasternack GB, Piégay H, Vaughan MC, Lehyan JS (2017b) Wood export varies among decadal, annual, seasonal, and daily scale hydrologic regimes in a large, Mediterranean climate, mountain river watershed. Geomorphology 276:164–179

Seo J-I, Nakamura F, Akamura D, Nakano H, Ichiyanagi H, Chun W (2008) Factors controlling the fluvial export of large woody debris, and its contribution to organic carbon budgets at watershed scales. Water Resour Res 44, W04428, https://doi.org/ doi:10.1029/2007WR006453

Seo JI, Nakamura F (2009) Scale-dependent controls upon the fluvial export of large wood from river catchments. Earth Surf Process Landf 34:786–800

Seo JI, Nakamura F, Chun KW (2010) Dynamics of large wood at the watershed scale: a perspective on current research limits and future directions. Landscape Ecol Eng 6:271–287

Seo JI, Nakamura F, Chun KW, Kim SW, Grant GE (2015) Precipitation patterns control the distribution and export of large wood at the catchment scale. Hydrol Process 29:5044–5057

Siepe A (1989) Untersuchungen zur Besiedlung einer Auen-Catena am südlichen Oberrhein durch Laufkäfer (Coleoptera: Carabidae) unter besonderer Berücksichtigung der Einflüsse des Flutgeschehens. Dissertation, Universität Freiburg (in German)

Shannon JP, Blinn DW, Benenati PL, Wilson KP (1996) Organic drift in a regulated desert river. Can J Fish Aquat Sci 53:1360–1369

Shin CJ, Nam JM, Kim JG (2015) Floating mat as a habitat of Cicuta virosa, a vulnerable hydrophyte. Landscape Ecol Eng 11:111–117

Schiesari L, Zuanon J, Azevedo-Ramos C, Garcia M, Gordo M, Messias M, Vieira EM (2003) Macrophyte rafts as dispersal vectors for fishes and amphibians in the Lower Solimões River, Central Amazon. Journal of Tropical Ecology 19:333–336

Soons MB, de Groot GA, Cuesta Ramirez MT, Fraaije RGA, Verhoeven JTA, de Jager M (2017) Directed dispersal by an abiotic vector: wetland plants disperse their seeds selectively to suitable sites along the hydrological gradient via water. Functional Ecology 31:499–508

Southwood TRE (1977) Habitat, the templet for ecological strategies. Journal of Animal Ecology 46:337–365

Spiller DA, Piovia-Scott J, Wright AN, Yang LH, Takimoto G, Schoener TW, Iwata T (2010) Marine subsidies have multiple effects on coastal food webs. Ecology 91:1424–1434

Spänhoff B, Meyer EI (2006) Breakdown rates of wood in streams. J N Am Benthol Soc 23:189–197

Sponseller RA, Heffernan JB, Fisher SG (2013) On the multiple ecological roles of water in river networks. Ecosphere 4:17. http://dx.doi.org/10.1890/ES12-00225.1

Steeb N, Rickenmann D, Badoux A, Rickli C, Waldner P (2017) Large wood recruitment processes and transported volumes in Swiss mountain streams during the extreme flood of August 2005. Geomorphology 279:112–127

Steelandt S, Marguerie D, Bhiry N, Delwaide A (2015) A study of the composition, characteristics, and origin of modern driftwood on the western coast of Nunavik (Quebec, Canada) J Geophys Res Biogeosci 120:480–501

Strain EMA, Heath T, Steinberg PD, Bishop MJ (2018) Eco-engineering of modified shorelines recovers wrack subsidies. Ecological Engineering 112:26–33

Strayer DL, Findlay SEG (2010) Ecology of freshwater shore zones. Aquat Sci 72:127–163

Suaria G, Aliani S (2014) Floating debris in the Mediterranenan Sea. Mar Pollut Bull 86:494-504

Tank JL, Webster JR, Benfield EF (1993) Microbial respiration on decaying leaves and sticks in a southern Appalachian Stream. J N Am Benthol Soc 12:394–405

Tank JJL, Rosi-Marshall EJE, Griffiths NA, Entrekin SA, Stephen ML (2010) A review of allochthonous organic matter dynamics and metabolism in streams. J North Am Benthol Soc 29:118–146

Tenzer C (2000) Passive Ausbreitung terrestrischer Wirbelloser über Fliessgewässer unter besonderer Berücksichtigung der Landgehäuseschnecken. Jahrestagung der Gesellschaft für Ökologie. Parey Buchverlag Berlin, Kiel (in German)

Tenzer C (2003) Ausbreitung terrestrischer Wirbelloser durch Fliessgewässer. Dissertation. Philipps-Universität Marburg (in German)

Tenzer C (2001) Passive Ausbreitung terrestrischer Wirbelloser über Fliessgewässer. 31. Jahrestagung der Gesellschaft für Ökologie 31:218 (in German)

Thiel M, Gutow L (2005a) The ecology of rafting in the marine environment. I. The floating substrata. Oceanog Mar Biol 42:181–264

Thiel M, Gutow L (2005b) The ecology of rafting in the marine environment. II. The rafting organisms and community. Oceanog Mar Biol 43:279–418

Thiel M, Haye PA (2006) The Ecology Of Rafting In The Marine Environment. III. Biogeographical and evolutionary consequences. Oceanog Mar Biol 44:323–429

Thiel M, Hinojosa IA, Joschko T, Gutow L (2011) Spatio-temporal distribution of floating objects in the German Bight (North Sea). Journal of Sea Research 65:368–379

Tinner U, Walburger E (2008) Kiesbänke im Rhein – von Landquart zum Bodensee. Bot Helv 118:72–76 (in German)

Tockner K, Waringer JA (1997) Measuring drift during a receding flood: results from an Austrian mountain brook (Ritrodat-Lunz). Internationale Revue der Gesamten Hydrobiologie 82:1–13

Tonin AM, Gonçalves JF, Bambi P, et al (2018) Plant litter dynamics in the forest-stream interface: precipitation is a major control across tropical biomes. Sci Rep 7(1):10799

Tonné N, Beeckman H, Robert E, Koedam N. (2016) Towards an unknown fate: The floating behaviour of recently abscised propagules from wide ranging Rhizophoraceae mangrove species. Aquat Bot140:23–33

Trodden LRB (2012) Local physical and hydraulic factors affecting leaf retention within streams. PhD Thesis, Cardiff University

Trottmann N (2004) Schwemgut – Ausbreitungsmedium terrestrischer Invertebraten in Gewässerkorridoren. Diplomarbeit. ETH Zürich/EAWAG

Turowski JM, Badoux A, Bunte K, Rickli C, Federspiel N, Jochner M (2013) The mass distribution of coarse particulate organic matter exported from an alpine headwater stream. Earth Surface Dynamics 1:1–11

Turowski JM, Hilton RG, Sparkes R (2016) Decadal carbon discharge by a mountain stream is dominated by coarse organic matter. Geology 44:27–30

URS Corporation Gomez and Sullivan Engineers (2012) Conowingo Hydroelectric Project. Final Study Report, Debris Management Study

Vadeboncoeur Y, Kalff J, Christoffersen K, Jeppesen E (2006) Substratum as a driver of variation in periphyton chlorophyll and productivity in lakes. J N Am Benthol Soc 25:379–392

van der Zee, B. (2018). Wet wipe pollution 'changing the shape of British riverbeds'. Guardian (2 May), Available online at: https://www.theguardian.com/environment/2018/may/02/wet-wipes-boom-is-changing-the-shape-of-british-riverbeds

van Sebille E, Wilcox C, Lebreton L, Maximenko N, Hardesty BD, van Franeker JA, Eriksen M, Siegel D, Galgani F, Law KL (2015) A global inventory of small floating plastic debris. Environ Res Lett 10: 124006 https://doi.org/10.1088/1748-9326/10/12/124006

Vannote RL, Minshall GW, Cummins KW, Sedell JR, Gushing E (1980) The river continuum concept. Can J Fish Aquat Sci 37:130–137

Vercruysse K, Grabowski RC, Rickson RJ (2017) Suspended sediment transport dynamics in rivers : Multi-scale drivers of temporal variation. Earth Sci Rev 166:38–52

Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW) (2008) Ereignisanalyse Hochwasser 2005: Teilprojekt Schwemmholz. Bericht 4240. ETH Zurich, Switzerland (in German)

Viquerat P-A, Lachal B, Beck J, Pampaloni E, Sella F (2006) Bois flottants a Verbois: dechets ou ressource? Caracterisation physico-chimique et valorisation energetique. Archives des Sciences (Geneva) 59:279–290 (in French)

Vogt K, Rasran L, Jensen K (2007) Seed deposition in drift lines: opportunity or hazard for species establishment? Aquat Bot 86:385–392

Walling DE, Collins AL, Stroud RW (2008) Tracing suspended sediment and particulate phosphorus sources in catchments. Journal of Hydrology 350:274–289

Ward JV, Tockner K, Arscott DB, Claret C (2002) Riverine landscape diversity, Freshw Biol 47:517–539

Ward JV, Stanford JA (1983) The serial discontinuity concept of lotic ecosystems. In: Fontaine TD, Bartell SM (eds) Dynamics of lotic ecosystems. Ann Arbor Science Publishers, Ann Arbor, Michigan, USA, pp 29–42

Webster JR, Meyer JL (1997) Organic matter budgets for streams: a synthesis. J North Am Benthol Soc 16:141–161

Wohl E (2013) Floodplains and wood. Earth Sci Rev 123:194–212

Wohl E, Bledsoe BP, Jacobsen RB, Poff NL, Rathbun SL, Waters DM, Wilcox AC (2015) The natural sediment regime in rivers: Broadening the foundation for ecosystem management. BioScience 65:358–371

Wohl E, Bledsoe BP, Fausch KD, Kramer N, Bestgen KR, Gooseff MN (2016) Management of large wood in streams: an overview and proposed framework for hazard evaluation. Journal of the American Water Resources Association (JAWRA) 52:315–335

Wohl E, Scott DN (2016) Wood and sediment storage and dynamics in river corridors, Earth Surf Process Landf https://doi.org/10.1002/esp.3909

Wohl E, Hall RO, Lininger KB, Sutfin NA, Walters DM (2017) Carbon dynamics of river corridors and the effects of human alterations. Ecol Monogr 87:379–409

Wotton RS, Preston TM (2005) Surface films : areas of water bodies that are often overlooked. BioScience 55:137–145

Ward JV, Tockner K, Arscott DB, Claret C (2002) Riverine landscape diversity. Freshw Biol 47:57–539

Welber M, Bertoldi W, Tubino M (2013) Wood dispersal in braided streams: Results from physical modeling. Water Resour Res 49:7388–7400

West AJ, Lin C-W, Lin T-C, Hilton RG, Liu S-H, Chang C-T, Lin K-C, Galy A, Sparkes RB, Hovius N (2011) Mobilization and transport of coarse woody debris to the oceans triggered by an extreme tropical storm. Limnology and Oceanography 56:77–85

Wondzell SM, Swanson FJ (1999) Floods, channel storage and the hyporheic zone. Water Resour Res 35:555–567

Wurl O, Ekau W, Landing WM, Zappa CJ (2017) Sea surface microlayer in a changing ocean – A perspective. Elem Sci Anth 5:31 http://doi.org/10.1525/elementa.228

Xiong S, Nilsson C (1997) Dynamics of leaf litter accumulation and its effects on riparian vegetation: a review. Botanical Review 63:240–264

Yang LH, Bastow JL, Spence KO, Wright AN (2008) What can we learn from resource pulses. Ecology 89:621–634

Yoshikawa M, Hoshino Y, Iwata N (2013) Role of seed settleability and settling velocity in water for plant colonization of river gravel bars. Journal of Vegetation Science 24:712–723

Zarfl C, Lumsdon AE, Berlekamp J, Tydecks L, Tockner K (2015) A global boom in hydropower dam construction. Aquat Sci 77:161–170

Zaitsev YP (1997) Neuston of seas and ocean. In: Liss P, Duce R (eds) The Sea Surface And Global Change. Cambridge University Press, New York, pp 371-382

Zen S, Zolezzi G, Toffolon M, Gurnell AM (2016) Biomorphodynamic modelling of inner bank advance in migrating meander bends. Adv Water Resour 93:166–181

Zen S, Gurnell AM, Zolezzi G. Surian N (2017) Exploring the role of trees in the evolution of meander bends: The Tagliamento River, Italy. Water Resour Res 53:5943–5962

Zettler ER, Mincer TJ, Amaral-Zettler LA (2013) Life in the ’plastisphere’: microbial communities on plastic marine debris. Environ Sci Technol 47:7137–7146

Zupanski D, Ristic R (2012) Floating debris from the Drina river. Carpathian Journal of Earth and Environmental Sciences 7:5–12

Fig. 1. Floating matter (FM) in freshwaters (reproduced with permission)

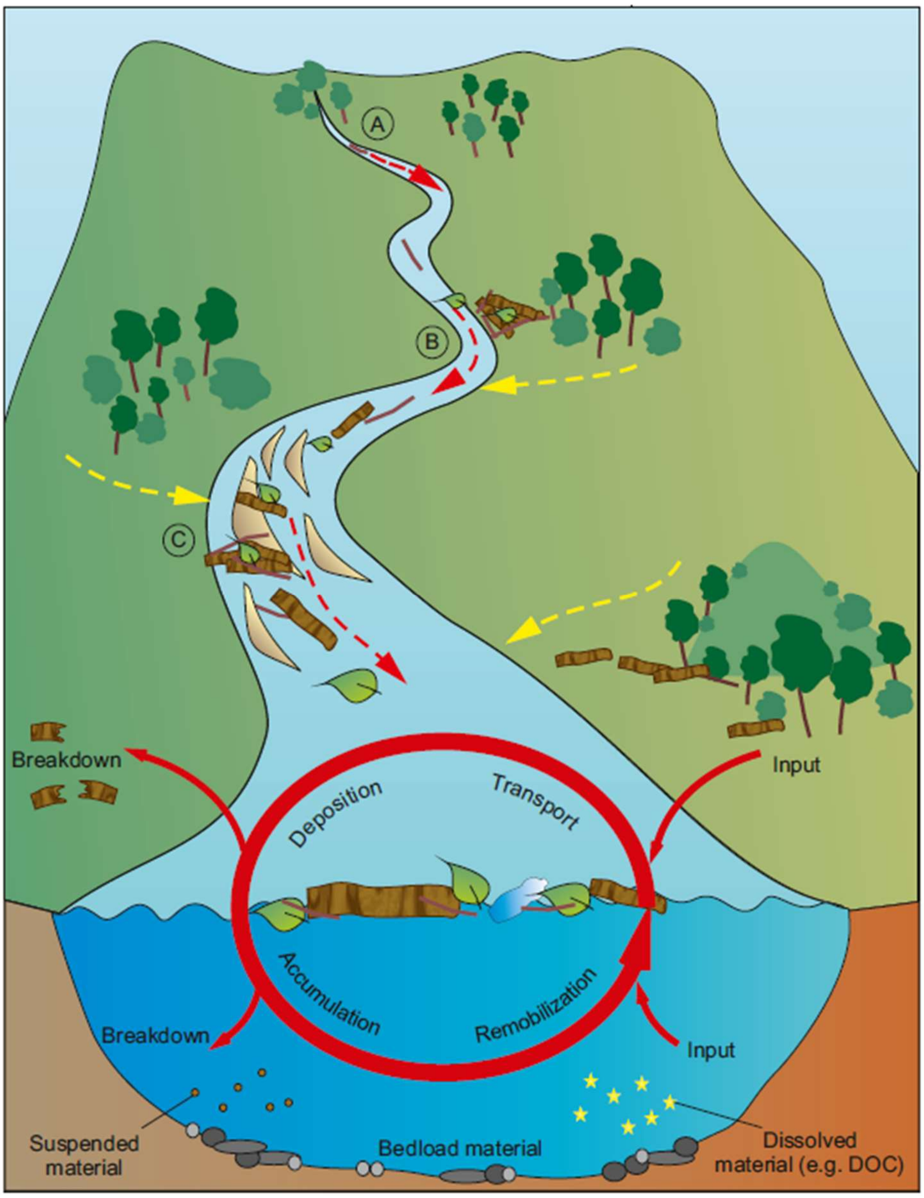
(a) Floating wood and leaves along the shore of Lake Müggelsee (Germany);

(b) FM composed of natural material and anthropogenic waste (source: Kleinschmidt Energy and Water Consultants 2008);

(c) FM in front of a sluice along the River Spree (Germany).

Fig 2. Conceptual model of the cycling of floating matter along rivers

(Figure was created using CorelDraw software)



Key factors that influence cycle of FM

Hydro-geomorphological

Watershed size
Geomorphological style of a river
Channel geometry
Sediment regime
Precipitation pattern
Flow regime
Episodic disturbance events (e.g. wind blow, snow avalanches)
Frequency, magnitude and position of floods

Biological

Seasonal events
Chronic events (e.g. tree mortality)
Composition and productivity of riparian vegetation
Dimensions and state of FM fractions (e.g. decay class)

Anthropogenic

Type of landuse
River fragmentation
Land management practise

At a reach scale, straight river sections (A) facilitate FM transfer, while meanders (B) and braided sections (C) facilitate FM deposition. However, within reaches, landform and vegetation irregularities and roughness elements including artificial obstructions such as bridges, weirs, and dams retain FM. Dashed red arrows represent downstream transport of FM in sequential steps in time. Dashed yellow arrows represent transport of FM from floodplains to river channels. Within the vertical transect across a river channel natural cycle of FM includes accumulation, transportation, deposition, and remobilisation. DOC – dissolved organic carbon.

Fig. 3. Example of a sampler to collect FM and its deployment (source: S.D. Langhans)

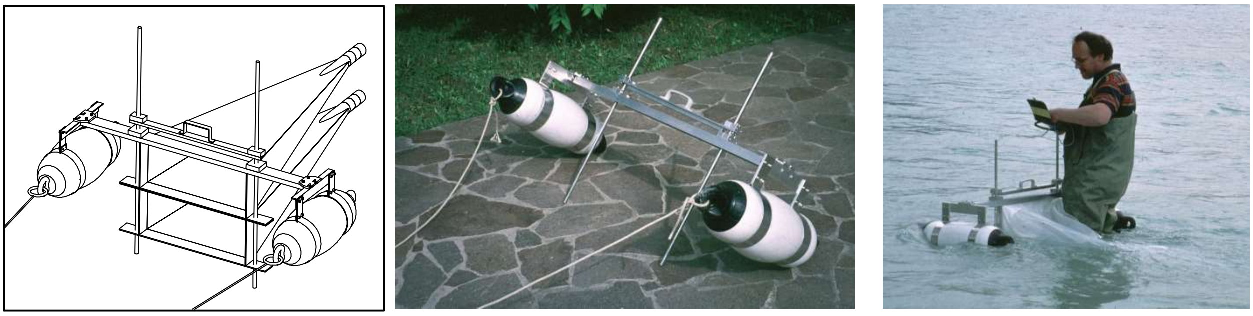


Table 1. Mean density of living terrestrial invertebrates associated with floating matter in selected European rivers compared to the mean density of soil arthropods (individuals/100 L, forest mulch layer: 0-0.2 m depth) (adopted from Trottmann 2004).

	Density of soil arthropods (Dunger 1983)	**Floating matter**		**River***	**Reference**
	Ind/100L	Ind/100L	Ind/100g of dry weight		
Aranea	**100**	48	-	Lahn (G)	Tenzer (2003)
		204	2.5	Aare (S)	Trottmann (2004)
Coleoptera	**300**	600-800	-	Oberrhein (G)	Siepe (1989)
		779	-	Lahn, Weschnitz (G)	Tenzer (2000)
		1214	-	Lahn, Weschnitz (G)	Tenzer (2000)
		2181	26.8	Aare (S)	Trottmann (2004)
		1962	-	Lahn (G)	Tenzer (2003)
		2960	-	Oberweser (G)	Gerken et al. (1998)
		5000	-	Rhein, Wupper (G)	Boness (1975)
Diptera	**500**	1213	14.9	Aare (S)	Trottmann (2004)
		5000	-	Rhein, Wupper (G)	Boness (1975)
Hymenoptera	**-**	93	-	Lahn (G)	Tenzer (2003)
		293	3.6	Aare (S)	Trottmann (2004)
		25000	-	Rhein, Wupper (G)	Boness (1975)
Gastropoda	**500**	1724	-	Rhein (G)	Tenzer (2003)
		2500	30	Tagliamento (It)	Langhans (2000)

* Geographical location of rivers: G – Germany, S – Switzerland, It – Italy

SUPPLEMENTARY INFORMATION

Floating matter: A neglected component of the ecological integrity of rivers

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Table S1. Amount and composition of floating matter (FM) trapped at dams and reservoirs worldwide

№	Dam	Coordinates (latitude, longitude)	River	Size of the catchment, km^2	Forested area within the catchment, %	Size of the 200m channel buffer, km^2	Forested area within the 200m channel buffer, %	Average annual discharge, m^3/sec	Average annual precipitation, mm	Average annual volume of material ± SD, m^3/year	Years of observation	Composition, % (if available)				Reference
												Natural	Woody	Non-woody***	Anthropogenic	
1	Kembs (France)	47.66; 7.52	Rhine	28482.0	38.1	2290.7	39.7	659.3	742.0	4500.0	2002	90	90	0	10	Le Lay and Moulin (2007)
2	Genissiat (France)	46.05; 5.81	Rhone	5786.9	33.9	476.3	31.7	175.7	997.0	5321.0	1989-1999	-	-	-	-	Moulin and Piegay (2004)
3	Verbois Dam (France)	46.19; 6.03	Rhone	5067.5	33.0	423.0	29.8	149.8	957.0	1000.0	2005	95	95		5	Viquerat et al. (2006)
4	Claytor Lake (Virginia, USA)	37.08; -80.58	New River	6193.5	94.2	471.7	93.9	99.0	990.0	916.4±579.9	2003-2007	-	Only wood volume was estimated	-	-	Kleinschmidt Energy and Water consultants (2008)
5	York Haven (Maryland, USA)	40.11; -76.71	Susquehanna	64726.1	84.5	5460.4	79.2	914.9	1001.0	3822.8	1985	95	5	90	5	URS Corporation Gomez and Sullivan Engineers (2012)
6	Safe Harbour (Pennsylvania, USA)	39.92; -76.39	Susquehanna	67543.1	83.6	5672.3	79.2	948.2	1036.0	3792.2±2915.5	2005-2010	-	Only wood volume was estimated	-	-	
7	Conowigo Dam (Maryland, USA)	39.66; -76.17	Susquehana	70072.6	82.8	5887.6	79.0	976.5	1114.0	2000.1±1119.0	1989-1998	75	-	-	25	
8	Brügg (Switzerland)	47.12; 7.26	Aare	3022.9	30.3	250.1	26.6	141.0	908.0	43.5±20.7	1996-2003	100	63	37	0	Trottmann (2004)
9	Flumenthal (Switzerland)	47.23; 7.59	Aare	4346.8	35.4	355.6	28.2	80.8	924.0	774.3±274.4	1981-2003*		Only wood volume was estimated			
10	Bannwil (Emme) (Switzerland)	47.23; 7.73	Aare	4617.0	35.6	378.7	28.6	85.0	947.0	588.9±262.4		97	90-92	3-4	5-6	
11	Wynau (Switzerland)	47.26; 7.79	Aare	4630.1	35.6	381.0	28.7	85.1	970.0	650.6±260.1			Only wood volume was estimated			
12	Ruppoldingen (Switzerland)	47.31; 7.88	Aare	4885.2	36.0	402.8	28.9	89.1	982.0	135.9±123.8						

13	Gösgen (Switzerland)	47.37; 7.98	Aare	5633.2	36.5	462.2	28.0	100.9	1028.0	1674.9± 676.5						
14	Aarau-Stadt (Switzerland)	47.39; 8.04	Aare	5667.7	36.6	464.9	28.1	101.4	1006.0	320.5±2 59.0						
15	Aarau-Rüchlig (Switzerland)	47.40; 8.05	Aare	5673.2	36.6	465.3	28.1	101.5	1006.0	105.5±5 5.1						
16	Rupperswil-Auenstein (Switzerland)	47.41; 8.11	Aare	6075.6	36.8	497.0	27.9	108.0	1033.0	1710.7± 850.5						
17	Wildegg-Brugg (Switzerland)	47.47; 8.17	Aare	6442.7	36.6	527.1	27.7	114.5	1019.0	581.5±2 53.9						
18	Beznau (Switzerland)	47.56; 8.24	Aare	7997.8	37.2	666.7	29.7	147.7	1020.0	1525.2± 540.4						
19	Klingnau (Aare) (Switzerland)	47.59; 8.23	Aare	8094.7	37.1	674.6	29.5	149.5	1019.0	1018.7± 437.3						
20	Mühleberg (Aare,Wohlen See) (Switzerland)	46.97; 7.28	Aare	674.0	40.8	57.9	36.0	13.6	954.0	1500.0	5 years	90	10-50	40 - 80	10	Hauenstein (2003)
21	Niederried/Kallnach (Aare, Saane) (Switzerland)	47.00; 7.24	Aare	2119.2	40.0	178.7	44.8	39.5	902.0	740.0	5 years	100	99	11	-	
22	Hagneck (Aare, Saane) (Switzerland)	47.06; 7.18	Aare	2163.7	40.0	183.4	44.6	40.2	902.0	414.0	9 years	100	80	20	-	
23	Kandergrund (Switzerland)	46.54; 7.66	Kander	37.8	50.3	4.7		1.1	1389.0	33.0	5 years	100	84	16	-	
24	Zvornik (Serbia)	44.37; 19.11	Drina	17474.2	47.0	1317.0	56.1	367.3	860.0	2176.0± 256.8	2009-2011**	-	18	81	All fractions reported as “waste”	Zupanski and Ristic (2012)
25	Bijina Basta (Serbia)	43.96; 19.41	Drina	14738.7	44.8	1102.9	54.8	346.1	947.0	12138.7 ± 6058.9	2009-2011	-	-	-	-	
26	Potpec (Serbia)	43.52; 19.58	Lim	3493.3	42.0	261.9	49.8	95.5	1022.0	1200.0	2011	-	-	-	-	
27	Krasnoyarsk (Russia)	55.94; 92.29	Yenisei	593781.7	5.2	57884.0	3.9	2090.5	496.0	104000.0	1995	-	Only wood volume was estimated	-	-	Korpachev (2004)
28	Sayano–Shushenskaiy (Russia)	52.82; 91.37	Yenisei	483345.0	2.1	47278.4	1.8	1125.4	453.0	1000000.0						

29	Bratsk (Russia)	56.29; 101.79	Angara	797385.3	7.2	78878.7	3.4	2404.8	342.0	2200000.0						
30	Ust-Ilimsk (Russia)	57.97; 102.69	Angara	748744.1	6.5	73806.7	3.2	2179.5	354.0	900000.0						
31	Shihmen Reservoir (Taiwan)	24.81; 121.25	Dahan	760.2	95.6	47.1	86.1	42.4	2417.0	54000.0	2004	-	Only wood volume is reported	-	-	Chen et al. (2013)

* Information on composition of material was recorded during 8 years only

** Information on composition of material was recorded in 2009 only

*** Non-woody fraction refers to leaves and grass

Approach and methods used for the analysis of the results presented in Box 2 “FM trapped in reservoirs in relation to catchment characteristics”.

For “material observed in dams”, we consider material that was either extracted behind dams or that arrived and was recorded to pass downstream. In total, we collected information on 31 dams located within the catchment of 13 rivers and used these data for the regression analysis. For each dam, we identified the average annual volume of FM extracted based on data available per year of observation. Four dams (dams 27-30, Table S1) were excluded from the final analysis due to the comparatively large size of their catchments and therefore the likely complexity of processes that contribute to the delivery of FM. We also excluded three dams with a significantly higher percentage of anthropogenic waste in FM (>80%) (dams 24 -26, Table S1) and three dams that did not have trapping structures upstream (dams 22, 23, 31, Table S1).

Data on the amount of observed material was normalized to bulk m^3. Data given in tons (dams 4-7, Table S1) were converted to volume using the average density of instream wood extracted from the Genissiat dam (660 $kg \cdot m^{-3}$) that was given in Ruiz-Villanueva et al (2016c).

We aimed to correlate the volume of trapped material with the following characteristics of the catchments:

- size of the catchment (WS),
- size of the catchment located upstream until the next trapping structure (WSA), the so-called “woodshed” as described in Fremier et al. 2010. Compared to a catchment, which is defined as the whole collection area of water, “woodshed” is an area where material, which can become floating, is able to reach the stream and be passed downstream.
- average annual discharge at the dam locations (AAD) (as suggested by Seo et al. 2008),
- average annual precipitation at the dam locations (AAP),

- size of the 200 m river buffer along both banks of the river channel - area of polygons with a 200 m radius from channel network data (CB200) (suggested by Seo et al. 2015),
- type of landcover (percentage forested area and percentage of artificial area with urban coverage) within the 200 m river channel buffer (WL200 and WA200 respectively).

In addition, we calculated the ratio of WSA to WS, further abbreviated as “R”, to evaluate the remaining areal fraction potentially contributing to material supply if upstream dams are considered (approach suggested by Fremier et al. 2010).

All spatial data analyses were carried out using the geographical information system software ArcGIS 10.4.1 TM. We calculated the catchment area using the digital elevation model (DEM) derived from the HydroSheds dataset (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales) of the United States Geological Survey (USGS), which is based on shuttle radar topographic mission (SRTM) data. Dam catchments were delineated using Global SRTM data in 1 arcsec resolution. All catchments were delineated within a continental lambert conic conformal projection. Size was calculated within the equal area Mollweide projection.

Average annual discharge at the dam locations (long-term data) was calculated using the ArcHydro tool of the ArcGIS software and based on the runoff shapefile from Lehner and Döll 2004.

Landcover analysis of the catchments and within the 200 m river channel buffer was based on ESA Globcover Version 2.3 from 2009. All land cover analysis was carried out within the Mollweide projection. Categories assigned to the type “forested” were:

- Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
- Closed (>40%) broadleaved deciduous forest (>5m)
- Closed (>40%) needleleaved evergreen forest (>5m)
- Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m).

In addition, we calculated % forested area within the 200 m river buffer according to the method described in Seo et al. (2008).

Long-term data on annual precipitation at the dam locations (average for the years 1970-2000) were acquired from the set of global climate layers, WorldClim, with 5 min spatial resolution (http://www.worldclim.org/, Hijmans et al. 2005).

A Principal Component Analysis (PCA) was performed to exclude variables that were colinear (Fig. S1). PCA was conducted with the statistical software XLSTAT (XLSTAT 2017.1, Addinsoft, Germany). The first two principal components explained 70.37 % of the variation in the explanatory variables.

On the basis of a visual analysis of the PCA plot and the obtained correlation matrix (variables with correlation coefficients ≥0.7 were defined as colinear) (Table S3), the following variables were selected for further analysis:

- Size of the catchment until the next trapping structure (WSA);
- Average annual precipitation (AAP);
- Ratio of woodshed to catchment (R);
- % of forest within the river buffer (WL200);
- % of artificial areas within the river buffer (WA200).

All data were log-transformed to fit the assumptions of homogeneity of variance and normality of distributions. Further statistical analyses were performed in R 3.2.2 (R Core Team 2015). The application of a multiple linear regression model with the given catchment variables explained 56.52 % of the variance in the amount of FOM and was statistically significant ($p<0.05$, $F_{5,16}=6.459$). Obtained model coefficients are given in Table S4.

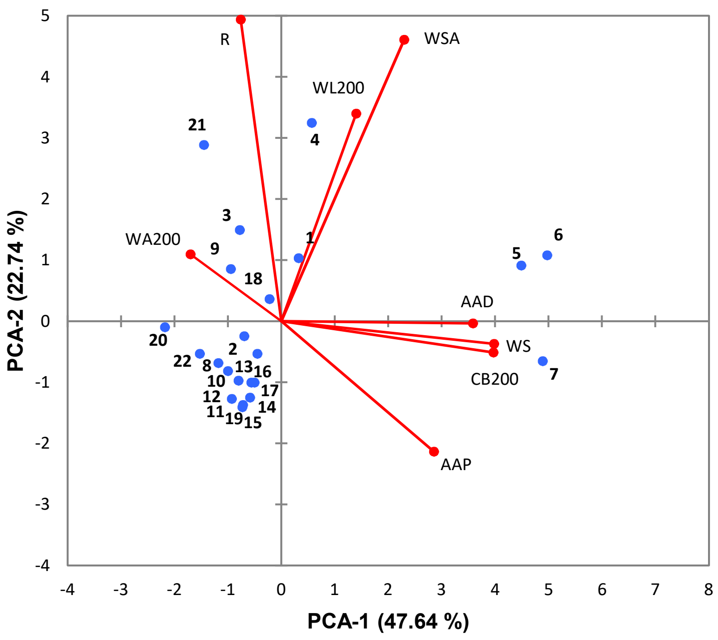

Fig S1. Multivariate ordination (PCA) of dams based on catchment descriptors. The percentage of explained variation for each principal component is shown in brackets. The points represent the scores of the samples (dams) on the first two principal components and the lines represent the loadings of each descriptor on these components.

Abbreviations used: AAD – average annual discharge, m^3/sec; WS – size of the catchment, km^2; AAP – average annual precipitation, mm; WSA - size of the catchment area located upstream until the next trapping structure, km^2; R - ratio of woodshed to catchment; CB200 – size of the 200 m channel buffer, km^2; WL200 - forest area within the river buffer, %; WA200 – artificial area within the river buffer, % (Numbers refer to respective dams in Table S1)

Table S3. Correlation matrix of variables

Variables	AAD	WS	AP	WSA	R	CB200	WL200	WA200
AAD	**1**	**0.850**	0.506	0.464	-0.160	**0.866**	0.203	0.205
WS		**1**	0.675	0.482	-0.234	**0.997**	0.290	-0.334
AP			**1**	0.135	-0.237	0.687	-0.088	-0.257
WSA				**1**	0.589	0.460	0.534	-0.215
R					**1**	-0.249	0.093	0.264
CB200						**1**	0.259	-0.299
WL200							**1**	-0.073
WA200								**1**

Abbreviations used: AAD – average annual discharge, m^3/sec; WS – size of the catchment, km^2; AP – average annual precipitation, mm; WSA - size of the catchment area located upstream until the next trapping structure, km^2; R - ratio of woodshed to catchment; CB200 – size of the 200 m channel buffer, km^2; WL200 - forest area within the river buffer, %; WA200 – artificial area within the river buffer, %. Numbers in bold indicate colinear variables.

Table S4. Coefficients of the linear regression model*

	Intercept	**WSA**	**AP**	**R**	**WL200**	**WA200**
coefficients	-14.588	0.7446	1.299	0.2494	1.2922	1.1674
p	0.382	**0.003**	0.585	**0.035**	**0.042**	**0.002**

** All parameters were log transformed for the regression analysis.*

Abbreviations used: WSA - size of the catchment area located upstream until the next trapping structure, km^2; AP - annual precipitation, mm; R - ratio of woodshed to catchment; WL200 - forest area within the river buffer, %; WA200 – artificial area within the river buffer, %. Numbers in bold indicate statistically significant coefficients in the model.