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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.

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

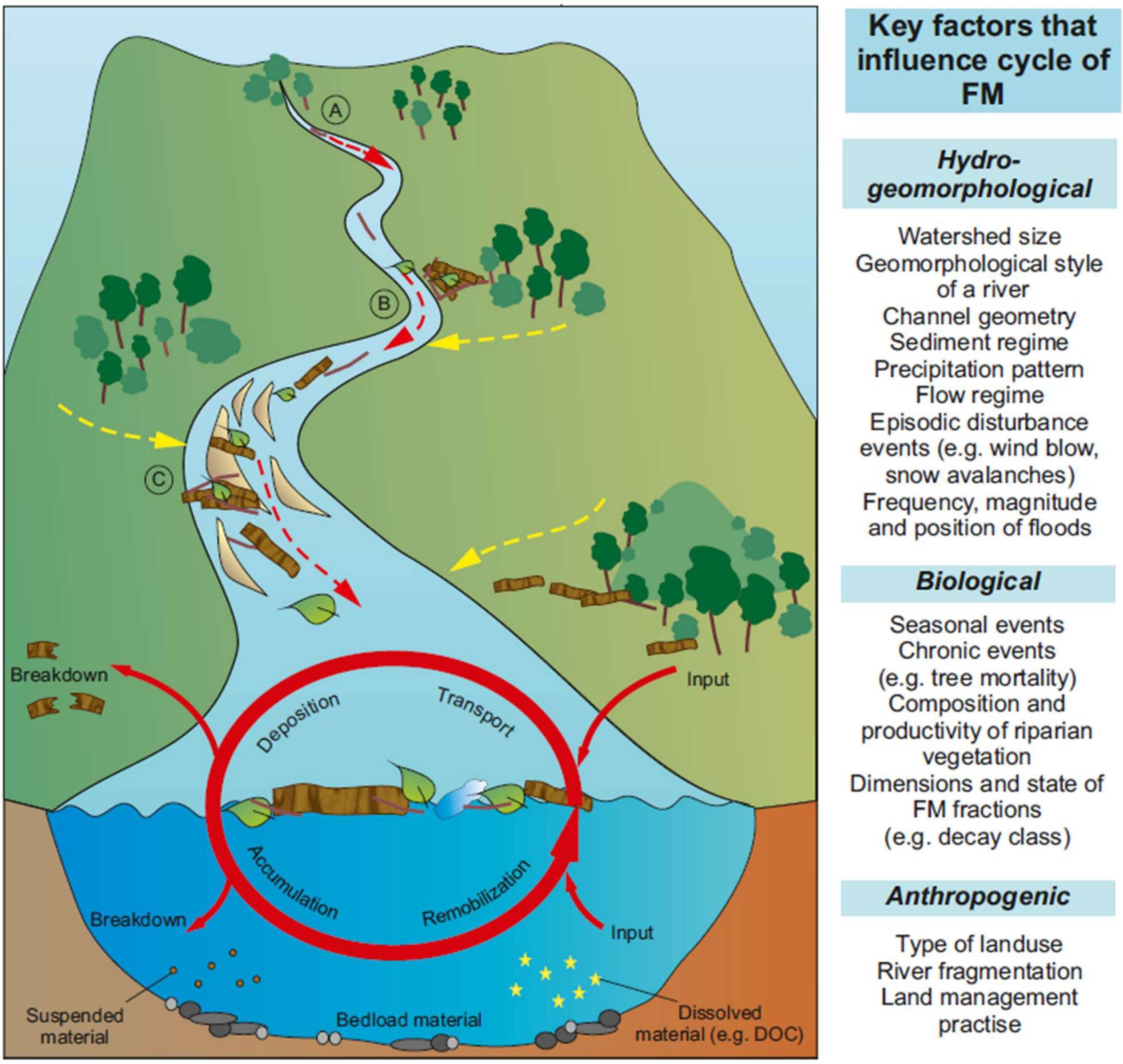
(a) Floating wood and leaves along the shore of Lake Müggelsee (Germany);

(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)



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)

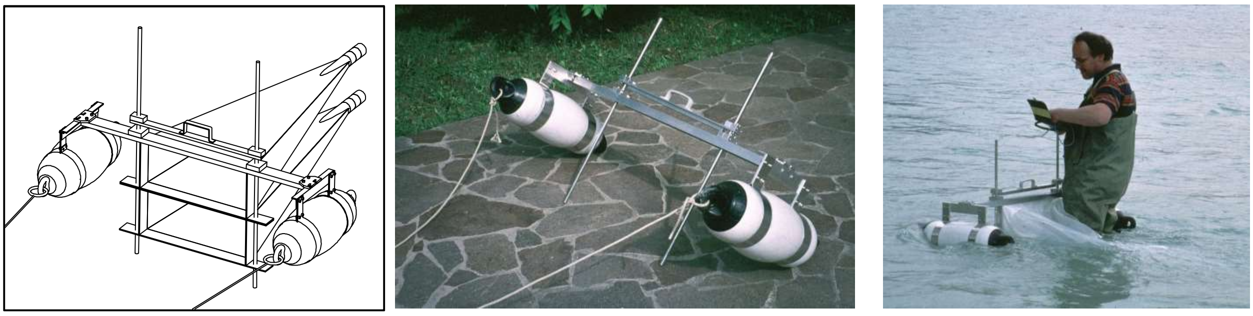


Table 1. Mean density of living terrestrial invertebrates associated with floating matter in selected European rivers compared to the mean density of soil arthropods (individuals/100 L, forest mulch layer: 0-0.2 m depth) (adopted from Trottmann 2004).

	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, km²	Forested area within the catchment, %	Size of the 200m channel buffer, km²	Forested area within the 200m channel buffer, %	Average annual discharge, m³/sec	Average annual precipitation, mm	Average annual volume of material ± SD, m³/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	
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	-	-	URS Corporation Gomez and Sullivan Engineers (2012)
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	
9	Flumenthal (Switzerland)	47.23; 7.59	Aare	4346.8	35.4	355.6	28.2	80.8	924.0	774.3±2 74.4			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±2 62.4	1981-2003*	97	90-92	3-4	5-6	Trottmann (2004)
11	Wynau (Switzerland)	47.26; 7.79	Aare	4630.1	35.6	381.0	28.7	85.1	970.0	650.6±2 60.1			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±1 23.8						

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	
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	-	Hauenstein (2003)
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.

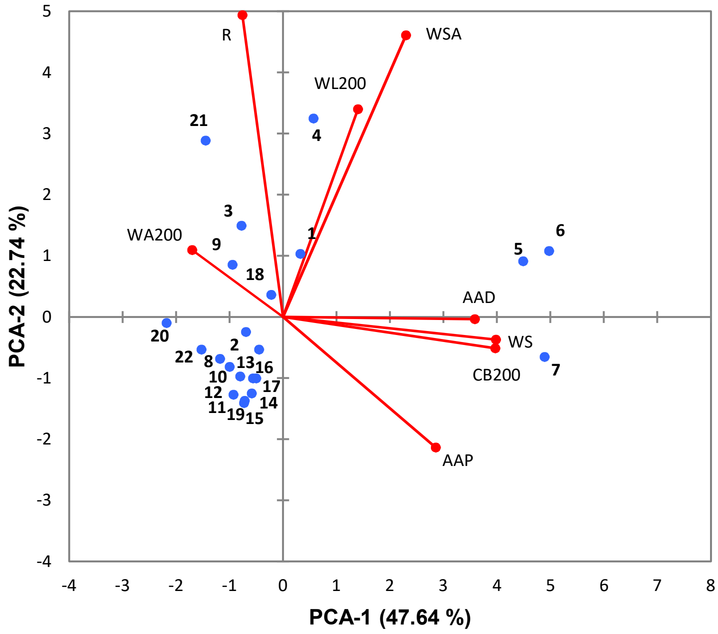

Fig S1. Multivariate ordination (PCA) of dams based on catchment descriptors. The percentage of explained variation for each principal component is shown in brackets. The points represent the scores of the samples (dams) on the first two principal components and the lines represent the loadings of each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