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Opposing effects of aquatic vegetation on hydraulic functioning and transport of dissolved and organic particulate matter in a lowland river: A field experiment

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ABSTRACT

The presence of instream aquatic vegetation (macrophytes) has an impact on the ecological functioning of rivers through their effects on transport and retention of dissolved and particulate matter, and also on the hydraulic functioning of rivers by increasing the hydraulic resistance, which results in higher water levels and may induce an increased flooding risk. In order to unravel these opposing effects, two field studies were conducted in 2013 and 2014 in a lowland river reach of 50 m with a high initial vegetation cover (>76%). We quantified the effects of three treatments – initial vegetation, partially mowed and vegetation free – on the hydraulic functioning (hydraulic resistance) and ecological functioning (transport and retention of dissolved and particulate tracers).

Firstly, the partially vegetated treatment (after partial vegetation removal) resulted in reduced hydraulic resistance compared to the vegetated treatment and in enlarged retention of particulate matter compared to the vegetation free treatments. The longitudinal dispersion and transient storage zones were similar to the vegetated treatment. Moreover, the most heterogeneous flow field was also found in these partially vegetated treatments. Secondly, the vegetation free treatments (after complete vegetation removal) had the lowest hydraulic resistance, the highest flow velocity, the highest longitudinal dispersion coefficient, the largest transient storage zone, and the lowest retention of particulate matter. Thirdly, vegetated treatments had the highest hydraulic resistance, the lowest flow velocity, the lowest longitudinal dispersion coefficient, smallest transient storage zone, and the highest retention for particulate organic matter.

We conclude that partial removal of the vegetation leads to an optimal trade-off between minimizing the flow velocity and maximizing the retention of particulate organic matter while minimizing the hydraulic resistance compared to the fully vegetated and vegetation free treatment.

1. Introduction

The hydraulic and ecological functioning of lowland rivers is influenced to a great extent by instream aquatic vegetation (Newbold et al., 1982; Runkel, 2007). The presence of macrophytes leads to reduced flow conveyance, higher water levels, decreased stream velocities, and enhanced sediment deposition on the river bed (Old et al., 2014). Therefore macrophytes are often mechanically removed to increase flow conveyance and reduce flooding risk (Boerema et al., 2014; Lopez and Garcia, 2001). The vegetation can either be completely removed (Old et al., 2014) or partly (Bal et al., 2011; Vereecken et al., 2006). Changes to the hydraulics directly affect the ecological functioning of lowland rivers (Hensley and Cohen, 2012) through its effects on the transport and retention of dissolved (Wilcock et al., 1999) and particulate matter (Horvath 2004; Warren et al., 2009).

Nutrient cycling of dissolved matter is influenced by both hydraulic transport processes (advection, dispersion, inflow, transient storage) and non-hydraulic processes (uptake rates, biomass standing stock, temperature) (Runkel, 2007). The hydraulic transport processes can be separated into three processes: (i) advection, which is the transport by the bulk motion of the water flow; (ii) dispersion, which is the combination of molecular or turbulent dif-

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fusion and of three dimensional processes, leading to shear flow separation and enhancing the dispersion (Taylor, 1954); and (iii) transient storage, which is the temporary retention and release of molecules in certain transient storage zones within the river system (Bencala and Walters, 1983; Jackman et al., 1984; Pedersen, 1977; Thankston and Schnelle, 1970). One or multiple transient storage zones can be present which can be linked in serial or in parallel to the main channel (Hensley and Cohen, 2012). Transient storage zones are regions with low to zero flow velocity, and the exchange of dissolved matter with the main flow is driven by the concentration difference in the main channel and within the transient storage zone (Gonzalez-Pinzon et al., 2013). In a one dimensional approach, these three processes are cross-sectionally averaged and can be described by a longitudinal dispersion-advection model with transient storage (Czernuszenko and Rowinski, 1997).

The hydraulic transport processes can be quantified in river reaches through the use of conservative dissolved tracers. A dissolved conservative tracer is injected upstream of a river reach and its concentration in function of time is recorded at the downstream end of this reach to obtain time series (Das et al., 2002; Govindaraju and Das, 2002). Temporal moments of these time series can be used to parametrize the coefficients of the longitudinal dispersion-advection model with transient storage (Czernuszenko and Rowinski, 1997; Nash, 1959). The first, second and third temporal moment can also be used to investigate the transport and mixing properties in rivers: (i) the first temporal moment is linked with the mean travel time of the tracer through the reach; (ii) the second temporal moment is the variance and is associated with the longitudinal dispersion of the tracer; and (iii) the third temporal moment characterizes the skewness and is related to the magnitude of the transient storage zone (Lees et al., 2000; Sukhodolova et al., 2006). Multiple transport and mixing processes are acting simultaneously in rivers, so the first three temporal moments are strongly linked with each other. A constant relationship between the second and third normalized temporal moment was found in an extensive meta-analysis of 384 tracer experiments conducted over a large range of discharges (7 orders of magnitude) and river lengths (5 orders of magnitude) (Gonzalez-Pinzon et al., 2013). However, the effect of instream vegetation was not considered.

It may be expected that instream vegetation can affect each of the three aforementioned processes. First, vegetation increases hydraulic resistance, hence reducing flow velocities and increasing water depth (De Doncker et al., 2009b; Franklin et al., 2008), which will affect advection of dissolved matter. Lower flow velocities will in turn increase the residence time which is beneficial for the water quality. For example the denitrification is positively correlated with the residence time (Seitzinger et al., 2006). Second, the influence of vegetation on longitudinal dispersion is less clear. Macrophytes may enhance turbulence and diminish the vertical shear stress, resulting in a decreased longitudinal dispersion (Nepf et al., 1997; Wilcock et al., 1999). However, the longitudinal dispersion may also increase by enhanced mechanical dispersion (Nepf et al., 1997). The latter is a known phenomenon in porous media in which each particle follows its own route, with a different length, through a network of pores. Third, transient storage zones can be present as wake zones behind the vegetation stems (Nepf et al., 1997), within and behind dense vegetation patches in the main channel (Sukhodolova et al., 2006) or riparian vegetation along the banks (Wilcock et al., 1999). The net result of macrophytes on the transient storage zone is therefore difficult to predict.

The potential effects of instream aquatic vegetation on the transport and retention of organic solid particles is expected to be twofold: (i) by creating a sieve-like structure in the water column the particles are physically trapped by both leaves and organisms living on the plants (Cotton et al., 2006; Pluntke and Kozerski, 2003), and (ii) by increasing the hydraulic resistance and reducing the flow velocity the residence time and settling chance of the particles is increased (Folkard 2011). Cordova et al. (2008) investigated the transport of coarse particulate organic matter (CPOM) in lowland rivers. They found that approximately 50–83% of the particle transport could be explained by particle settling, while the remaining part could be explained by particle trapping on the plant surface. Besides discharge (Defina and Peruzzo, 2010), particle trapping depends on vegetation properties: increased submerged vegetation cover increases the retention of particles (Riis and Sand-Jensen, 2006), yet the configuration of the vegetation does not affect the retention of particles (Defina and Peruzzo, 2010). It also depends on the particle properties: larger particles have a higher chance to be trapped (Ehrman and Lamberti, 1992) and highly buoyant particles have a higher potential travel distance (Boedeltje et al., 2004; Danvind and Nilsson, 1997; Riis and Sand-Jensen, 2006; van den Broek et al., 2005). The second process, particle settling, is well studied for mineral particles (Church, 2006; Wood and Armitage, 1997) and is determined by the settling velocity (Dietrich, 1982). This velocity is proportional to the surface area of the particle, the difference in density between the particle and the water, and inversely proportional to the dynamic viscosity of the water (Dietrich, 1982).

Previous studies mainly focused on either of these effects of vegetation in natural rivers or in laboratory experiments: hydraulic functioning (Bal et al., 2011; Green, 2005b), solute transport (Nepf et al., 1997; Sukhodolova et al., 2006), and particle transport (Defina and Peruzzo, 2010; Horvath, 2004). The majority of field studies quantifying both aspects are either executed in different study sites, (e.g. Hensley and Cohen, 2012; Riis and Sand-Jensen, 2006; Sand-Jensen et al., 1999; Sand-Jensen and Mebus, 1996), or are executed in one site, but at multiple moments in time with a varying discharge and stream velocity (e.g. Sukhodolova et al., 2006; Wilcock et al., 1999). Since these season and site specific characteristics (such as channel dimensions, bed forms, discharge etc.) also influence the transport processes (Gonzalez-Pinzon et al., 2013), it is important to perform experiments in the same study reach wherein vegetation cover is experimentally alerted in order to quantify the specific effects of these changes in vegetation cover.

The aim of this paper is to quantify the opposing effects of instream aquatic vegetation cover on the drainage and transport capacity of lowland rivers. We address following research questions and hypotheses:

1. How do changes in macrophyte cover (through partial and complete experimental vegetation removal) affect the hydraulic functioning of lowland rivers, more specifically by affecting the hydraulic roughness, mean flow velocity and water level? We hypothesize that vegetation cover is positively correlated with the hydraulic resistance and negatively correlated with mean flow velocity.
2. How do changes in macrophyte cover affect transport and retention of dissolved and particulate matter? With decreasing vegetation cover, we hypothesize that decreased residence times of dissolved organic matter (DOM) and changes in the magnitude of the dispersion coefficient and transient storage zone. We also hypothesize that decreasing macrophyte cover increases the mean travel distance and reduces the retention of coarse particulate organic matter (CPOM).
3. What is the combined effect of changes in macrophyte cover on both the hydraulic functioning and organic matter transport? We hypothesize that there are opposing effects, where macrophytes negatively affect hydraulic functioning (through increased hydraulic roughness, decreased mean flow velocity, and hence increasing water levels and flood risks), but positively affect water quality (through decreased transport and increased retention of dissolved and particulate matter).