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.

Keywords: macrophytes, hydraulic resistance, longitudinal dispersion, transient storage

Highlights

- Tracer experiments matter are performed with dissolved and particulate
- The effect of vegetation covers investigated in situ at river reach scale
- Plants reduce the longitudinal dispersion coefficient and transient storage zone
- The most heterogeneous flow field is found when part of the vegetation is removed

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 diffusion 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).

2. Materials and methods

1. Study area

The Brzozówka river is a lowland river (bottom slope of 0.0005 m m^{-1}) in the North East of Poland (Fig. 1). A straight reach of 50 m long with a width ranging from 7 m to 10 m is selected to perform the experiments (Fig. 2). This reach is outside the nature conservation area. The initial bathymetry was measured at 0.5 m intervals along cross-sectional transects which were located every 5 m along the whole study reach. There is no lateral inflow in the study reach. The sediment on the river bed consists for 97.4 % of sand (diameter > 63 µm) and for 2.6 % of silt (2-63 µm), and the average organic matter content is 1.6 %. Concentration of the main solutes in the surface water are: 8.56 mg L^{-1} Cl, 7.29 mg L^{-1} Na, 0.034 mg L^{-1} PO_4^{3-}-P, 0.64 NO^{3-}N mg L^{-1}, 0.09 NH_4^+-N. The treatments did not disturb biota nor the ecological status of the river.

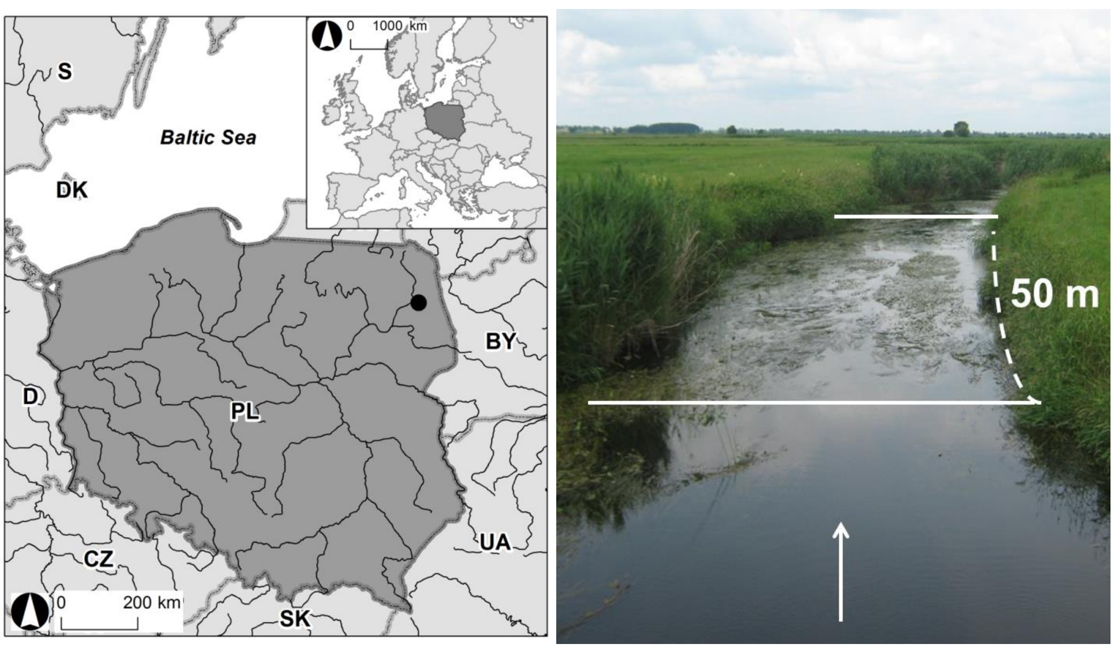

Figure 1: (a) Location of the study reach in the Brzozòwka river in the North East of Poland, indicated by the black dot. (b) Study area in 2014 is shown with initial vegetation cover within the study reach (between white lines) and a vegetation free section upstream of the study reach. Main flow direction is indicated with an arrow.

2. Vegetation mapping

The initial species composition was recorded along cross-sectional transects with a cross-sectional resolution of 5 cm along each transect, and a longitudinal interval of 1 m between the transects (Fig. 2a and b). Seven submerged macrophyte species were found in the study reach: *Nuphar lutea* Sm., *Potamogeton crispus* L., *Potamogeton natans* L., *Potamogeton pectinatus* L., *Potamogeton perfoliatus* L., *Sparganium emersum* Rehmann, and. *Sagittaria sagittifolia* L. The emergent riparian vegetation at the river banks is all classified as riparian vegetation and not further identified.

The effect of vegetation cover on the hydraulic functioning and transport of dissolved and particular organic matter was experimentally tested for three treatments with different vegetation covers. The first treatment was with all natural initial vegetation present, referred to as *full* vegetation cover. For the second treatment with a partial vegetation cover, a part of the vegetation was removed to create an instream block pattern (Fig. 2c), referred to as *partial* vegetation cover. Finally all vegetation was removed for the third treatment, which is the *no* vegetation cover. The aboveground biomass of each of the seven species was determined by sampling quadrants of 0.25 m^2 positioned in monotopic stands of each species respectively, no replicates were taken. This was done in the study reach, when the pattern for the second treatment was being cut. The vegetation samples were oven dried at 70°C for 48 h to obtain the dry weight (DW). All treatments and measurements were done in June 2013 and repeated in June 2014, except the type of CPOM (see explanation below) varied between both years.

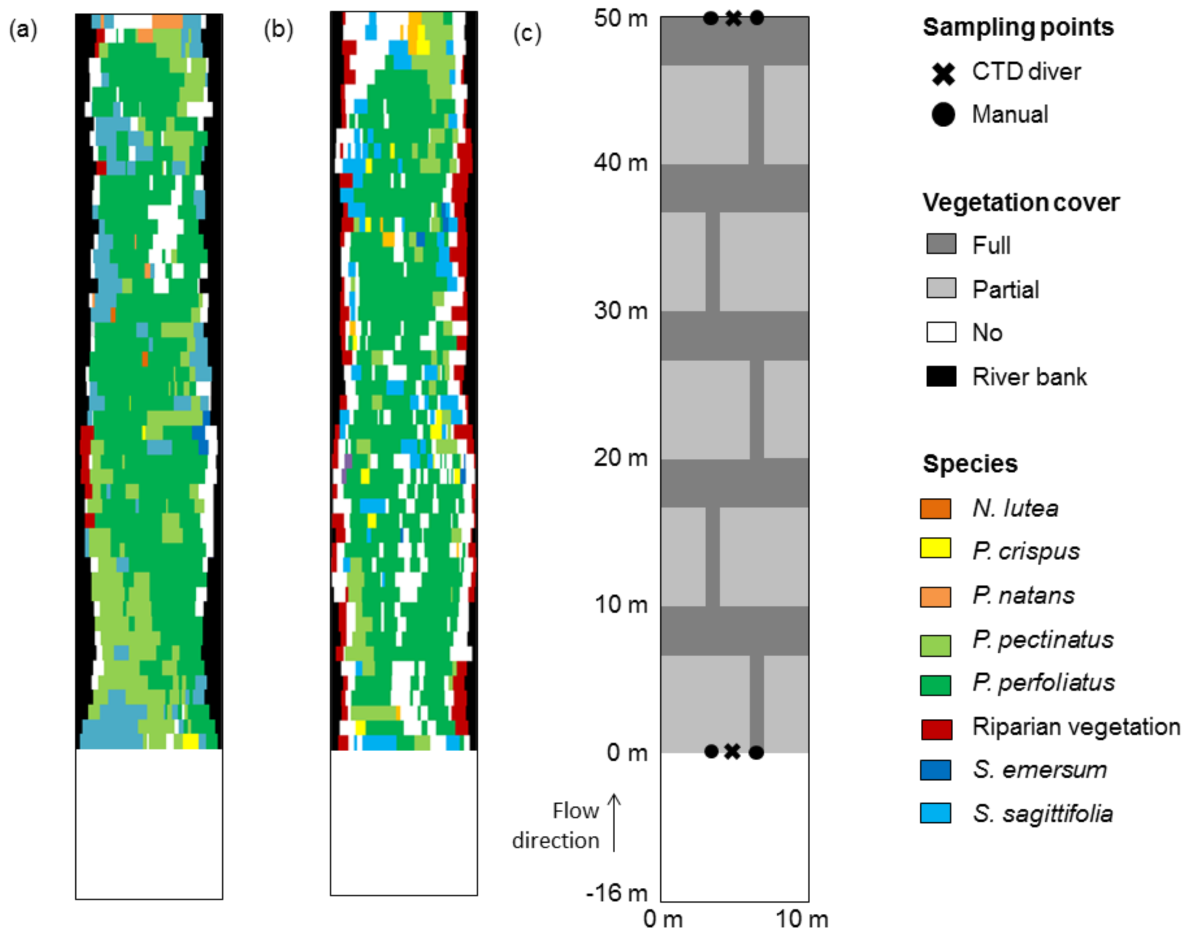

Figure 2: (a, b) Maps of the initial vegetation cover in the study area in 2013 and 2014 respectively. Colors are according to the dominance of the species, with *P. perfoliatus* being the most dominant species, followed by *P. pectinatus*, *S. sagittifolia*, *N. lutea*, *P. natans*, *P. crispus*, riparian vegetation and *S. emersum*. (c) Schematic overview of the location of the CDT divers (✖) and manual sampling points (⬤). The vegetation cover for three treatments is shown: exp. 1: all initial vegetation is present (called *full* vegetation cover); exp. 2: the vegetation is partly removed (*partial*); exp. 3: all vegetation is removed (*no*). The direction of the water flow is indicated with an arrow.

3. Hydraulic measurements

Each treatment started with the measurement of stream velocities with an electromagnetic flow meter (EMF, Valeport model 801, Totnes, UK) with a depth-interval of 20 cm, every meter along the cross-section at the upstream edge of the study reach. The velocity-area method was used to calculate the discharge (Bal and Meire 2009). The difference in water level is measured with a laser leveler (Spectra

Precision, Coudere/geoservice, Brugge, BE). The water level slope is the difference of the upstream and downstream water level divided by the reach length (50 m). The hydraulic resistance is expressed as a Manning coefficient (Chow, 1959) and calculated as:

$$n = \frac{A}{Q} R^{2/3} S^{1/2} \quad \text{(Eq. 1)}$$

with n (s m$^{-1/3}$) the Manning coefficient, A (m^2) the cross-sectional area, Q (m^3 s^{-1}) the discharge, R (m) the hydraulic radius which is the cross-sectional area divided by the wetted perimeter, S (m m^{-1}) the water level slope. After transport was measured with tracer experiments (see below) for the first treatment with full vegetation cover, part of the vegetation was manually removed according to the scheme on Fig. 2c to create the partial vegetation cover of the second treatment. The second treatment started the next day, after a 20 h acclimatization period to minimize the external effects associated with the vegetation removal like sediment suspension. This procedure was repeated after removal of all vegetation, i.e. the case of no vegetation cover. As such, the whole procedure resulted in three similar sets of measurements for full partial and no vegetation cover in both June 2013 and June 2014.

4. Solute transport

Two releases (with a time interval of 2h) of the dissolved tracer were performed, by adding 12 kg NaCl that was dissolved in 6 buckets of 10 L river water. Only one release was done in 2013 with the partial vegetation cover. Salt was used as a conservative tracer, so that no uptake or conversion to other molecules is expected, within the timespan of the experiment (i.e. 20 min). One automated and two manual sampling points were placed at both the upstream and downstream edge of the study reach (Fig. 2c). The conductivity was measured automatically with a frequency of 1 Hz (CTD divers, Eijkelkamp, Geisbeek, NL). Additionally manual samples of 40 mL were taken at the upstream border, every 10 s during the first 2 min after the release, then every 5 s up to 6 min after the release and every 20 s up to 10 min after the release. Manual downstream sampling started after 3 min 15 s with an interval of 20 s, up to 15 min 15 s after the release, resulting in a total of 37 samples. Three additional samples were taken with an interval of 60 s, so the sampling ended after 18 min 15 s. The conductivity of the manually taken samples was measured with a multimeter (Multil 340/SET, Weilheim, GE). The conductivity is converted to NaCl concentrations with a linear calibration curve of six NaCl standards in the range of 2.2 to 610 µS cm^{-1}.

Break through curves (BTS), which show the concentration in function of time after the release, are zeroed to background concentrations of the river water (Gonzalez-Pinzon et al. 2013). The fractional mass recovery is the mass recovered (the area under the curve multiplied with the discharge) divided by the initial mass (Gonzalez-Pinzon et al. 2013). The start time (T_{start}) and end time (T_{end}) are defined as the start and end of the BTC, respectively. The difference between T_{end} and T_{start} is the duration of the signal. The median residence time (T_{med}) is the time needed for the passage of 50% of the salt through the study reach. The peak time (T_{peak}) is the time of the peak concentration (C_{peak}) at the downstream edge of the study reach. The incoming velocity is used as a reference velocity (U_{ref}) and is calculated as the discharge divided by the cross-sectional area. The reference time (T_{ref}) is the average time that the bulk water flow would need to pass the study reach without external influences and is defined as the reach length divided by U_{ref}. All times are divided by the reference time (T_{ref}) to correct for small differences in incoming velocities between the treatments with different vegetation covers and in 2013 and 2014. The median velocity (U_{med}) and mean velocity (U_{mean}) correspond to the reach length divided by T_{med} and T_{peak}, respectively. Similarly, these velocities, U_{med} and U_{mean}, are corrected for differences in incoming velocities by dividing them by U_{ref}.

The temporal moments of the time series are calculated to investigate solute transport (Das et al. 2002; Govindaraju and Das 2002). The n^{th} absolute moment is defined as:

$$\mu_n = \int_0^\infty t^n \, C(t) dt \qquad \text{(Eq. 2)}$$

The n^{th} normalized absolute moment is given by:

$$\mu_n^* = \frac{\mu_n}{\mu_0} \qquad \text{(Eq. 3)}$$

The normalized absolute moments are used to calculate the normalized central moments of order 1 (m_1, mean travel time), order 2 (m_2, variance on the travel time which can be due to higher dispersion) and order 3 (m_3, skewness on the travel time which can be due to larger transient storage) (Gonzalez-Pinzon et al. 2013) as:

$$m_1 = \mu_1^*$$

$$m_2 = \mu_2^* - \mu_1^{*2} \qquad \text{(Eq. 4)}$$

$$m_3 = \mu_3^* - 3\mu_1^* \mu_2^* + 2\,\mu_1^{*3}$$

The transient storage model (Gonzalez-Pinzon et al. 2013) is given by:

$$\frac{dC}{dt} = -U\,\frac{dC}{dx} + D\,\frac{d^2C}{dx^2} - \beta\,\alpha\,(C - C_s) \qquad \text{(Eq. 5)}$$

$$\frac{dC_s}{dt} = \alpha\,(C - C_s)$$

with C (g m^{-3}) the concentration of the solute in the main channel, C_s (g m^{-3}) the concentration of the solute in the storage zone, U (m s^{-1}) the flow velocity, D (m^2 s^{-1}) the dispersion coefficient, β (-) the spatially average transient storage zone volume fraction $\beta = A_s/A$, A_s (m^2) the cross-sectional area of the transient storage zone, A (m^2) the cross-sectional area of the main channel, α (s^{-1}) the mass-exchange rate coefficient between the main channel and the transient storage zone, t (s) the time, x (m) distance (Gonzalez-Pinzon et al. 2013).

The theoretical moments can be used to calculate the parameters of the transient storage model and are defined by (Czernuszenko and Rowinski 1997) for a general boundary condition:

$$m_{1,fit} = \frac{2D}{U^2} + \frac{L}{U}(1 + \beta)$$

$$m_{2,fit} = \frac{8D^2}{U^4} + \frac{L}{U}\frac{2D}{U^2}(1 + \beta) + \frac{2L}{U}\frac{\beta^2}{\alpha} \quad \text{(Eq. 6)}$$

$$m_{3,fit} = \frac{2L^2}{U^2}\frac{D}{U^2}(1 + \beta)^2\beta + \frac{64D^3}{U^6} + \frac{L}{U}\left[\frac{12D^2}{U^4}(1 + \beta)^2 + \frac{4D}{U^2}\frac{\beta^2}{\alpha}(\beta + 2) + \frac{6\beta^3}{\alpha^2}\right]$$

with the same variables as explained above and L (m) the reach length, 50 m. We have three unknown variables: dispersion coefficient (D), mass-exchange rate (α) and spatially average transient storage zone volume fraction (β), and three equations (Eq. 6). All BTC of each vegetation cover are used to determine the variables D, α, β. The flow velocity (U) is the reach length divided by moment 1 and is averaged for all experiments per vegetation cover. A pseudo randomized algorithm followed by a Levenberg-Marquardt algorithm is used to minimize the cost function (CF).

$$CF = \sum_{i=1}^{3}\sum_{k=1}^{K}\left[(m_{i,fit} - m_{i,k})/stdv(m_{i,k})\right]^2 \quad \text{(Eq. 7)}$$

with K the number of BTC per vegetation cover.

R (v. 3.2.0 R Core Team) was used to perform the statistical analyses. A two-way ANOVA followed by a post-hoc Tukey test were performed to compare the parameters according to the three vegetation covers.

5. Particle transport and retention

The transport and retention were investigated with three coarse particulate organic matter (CPOM) types: oats, wood chips and cornflakes. The tracers were characterized in the laboratory (Tab.1). Firstly, the surface area of pictures of 70 - 150 particles was calculated using ArcGIS software (v. 10.1, ESRI Inc, Redlands, USA). Secondly, the buoyancy in standing and gently stirred water was measured by placing a fixed amount of each tracer in a circular aquarium (80 g oats, 20 g wood chips and 20 g cornflakes). The aquarium had a water depth of 0.15 m and three replicate tests per tracer were carried out under standard laboratorial conditions (20 °C). After 20 min all floating and all sunken particles were collected, dried (72h, 70 °C) and weighted. The buoyancy is expressed as the ratio of the weight of floating particles to the weight of all particles (Tab. 1). Thirdly, as part of the tracers' mass can get lost in the river due to small detaching particle components that could not be recovered, a conversion factor is calculated by the ratio of the initial DW and final DW after being in the water for 20 min. The conversion factor is used to convert the final weight of tracers in the field experiments.

Table 1: Characteristics of the three particulate tracers: oats, wood chips and cornflakes. The mean and standard deviation of the buoyancy in standing and stirred water is given. The conversion factor accounts for the detaching of particle components.

		Oats	Wood chips	Cornflakes
Surface area	mm^2 ± sd	19.9 ± 9.5	14.4 ± 9.5	179.7 ± 78.0
Buoyancy standing	% ± sd	0.60 ± 0.2	57.8 ± 1.1	98.4 ± 1.4
Buoyancy stirred	% ± sd	0.62 ± 0.7	34.4 ± 7.3	45.7 ± 1.5
Conversion factor	mean ± sd	1.53 ± 0.07	1.08 ± 0.01	1.33 ± 0.02

The field experiments with oats were conducted in 2013 with a release of 3.00 kg oats at each vegetation cover. The same protocol was repeated in 2014 with 2.50 kg cornflakes and 3.00 kg wood chips. The floating part of tracers was captured downstream of the study reach with small nets in the top 0.15 m of the water column. The collected tracers were oven dried (72h, 70 °C), weighted and multiplied with the conversion factor. The retention is the mass of the tracer that remained in the study reach relative to the initial mass. The amount of particles in transport along the reach can be approached by an exponential decrease (Lamberti,1996) and is calculated using the following equation:

$$P_d = P_0\, e^{-kd} \qquad \text{(Eq. 8)}$$

with P_d (g) the amount of particles in transport downstream of the reach, P_0 (g) the initial amount of particles, k (m^{-1}) the instantaneous retention rate, d (m) the length of the study reach. The mean travel distance is the inverse of the mean instantaneous retention rate. Finally, the depositional velocity is calculated to enable the comparison of our results to reaches with different velocities and sizes. The depositional velocity expresses the rate at which tracers leave the water column (Warren et al. 2009):

$$V_{dep} = k\,u\,h \qquad \text{(Eq. 9)}$$

with V_{dep} (m s^{-1}) the depositional velocity, k (m^{-1}) the instantaneous retention rate, u (m s^{-1}) the mean velocity and h (m) the water depth.

3. Results

1. Vegetation

The vegetation maps are shown in Fig. 2. The species specific vegetation cover and biomass at the initial situation is given in Tab. 2. A higher initial vegetation cover is present in 2013, 89.6 %, compared to 2014, 76.6 %. The mean dry weight in the whole reach is 297.9 gDW m^{-2} in 2013, which is also higher than 232.9 gDW m^{-2} in 2014 (Tab. 2). In the vertical dimension (not shown in Fig. 2), the submerged vegetation fills the whole water column and the majority of the vegetation reaches the water surface.

Table 2: Species specific vegetation cover and biomass at the full vegetation cover. Data are collected in June 2013 and June 2014 over a reach of 50 m.

	June 2013		June 2014	
	Cover (%)	Biomass (gDW m^{-2})	Cover (%)	Biomass (gDW m^{-2})
N. lutea	0.35	174.4	0.30	186.8
P. crispus	0.76	NA	4.81	264.8
P. natans	5.50	298.8	5.41	94.0
P. pectinatus	23.71	224.8	7.74	278.4
P. perfoliatus	36.36	383.2	32.66	455.6
S. emersum	0.52	NA	1.28	126.8

S. sagittifolia	20.81	376.8	15.66	146.4
Riparian vegetation	1.41	NA	8.82	NA
No vegetation	10.40	0	23.32	0
Total vegetation cover	89.6	279.9	76.7	232.9

2. Hydraulics

The hydraulic parameters are summarized in Tab. 3. The discharge ranges between 0.76 and 1.09 $m^3\ s^{-1}$ between the treatments (different days). During the experiment of one treatment in one year the discharge is assumed to be constant. The magnitude of the reference velocity (U_{ref}) and reference time (T_{ref}) reflect the differences in the prevailing discharge between the treatments. In both years a positive relationship is observed between the Manning coefficient and vegetation cover (Tab. 3). The highest Manning coefficient of 0.30 $s\ m^{-1/3}$ coincides with the highest vegetation cover of 89.6 %. The water level slope has a similar trend with being 5 to 15 times higher in the vegetated reach compared to the vegetation free reach (Tab. 3).

Table 3: Hydraulic parameters of the study reach in 2013 and 2014 at three vegetation covers (full, partial and no vegetation cover).

		June 2013			June 2014		
Vegetation cover		Full	Partial	No	Full	Partial	No
Macrophyte cover	%	89.6	56.3	0	76.7	47.9	0
Discharge upstream	$m^3\ s^{-1}$	0.82	0.90	0.78	1.09	0.76	0.82
Cross-sectional area upstream	m^2	7.45	8.33	7.24	9.72	8.23	8.76
U_{ref}	$m\ s^{-1}$	0.110	0.108	0.108	0.112	0.092	0.093
T_{ref}	s	454	463	464	446	541	534
Hydraulic radius	m	0.78	0.83	0.76	0.94	0.81	0.86
Water depth	m	0.87	0.90	0.82	0.97	0.86	0.86
Mean width	m	8.1	8.1	8.1	8.9	8.9	8.9
Manning coefficient	$s\ m^{-1/3}$	0.30	0.24	0.08	0.28	0.27	0.14
Water level slope	$m\ m^{-1}$	0.0015	0.0009	0.0001	0.0011	0.0009	0.0002

3. Solute transport

An example of the breakthrough curves (BTC) for the three vegetation covers treatments is given in Fig. 3. The tracer is uniformly injected along the whole upstream width of the reach, which results in an equal distribution along the transverse direction. This is confirmed by the three sampling points downstream for the full and no vegetation cover treatment. For the partial vegetation cover a clear difference is seen between the three sampling points at the downstream end of the reach.

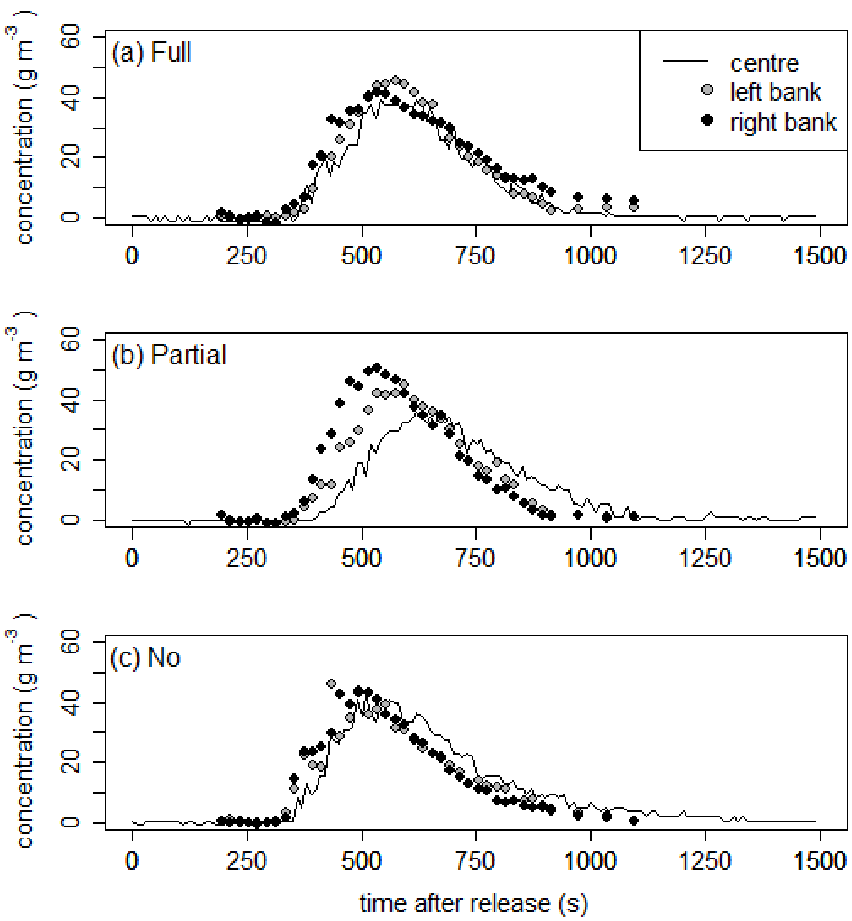

Figure 3: Breakthrough curves of NaCl concentration at the downstream edge of the reach are shown for (a) full, (b) partial and (c) no vegetation cover, results of 2014 second release. The concentrations of the center point are measured with a CTD diver (black line). Samples near the left bank (grey dots) and right bank (black dots) are taken manually.

The transport parameters of solutes are given in Tab. 4. The fractional mass recovery ranges between 85 and 106 % for all experiments. Expect for the second replica of full vegetation treatment in 2014, the fractional mass recovery was 127 %. This is probably due to an overestimation of the discharge. The experiments with a full vegetation cover have an average recovery of 107.2 %. Significant differences between full and no vegetation cover are found for the relative start time, the relative time of the peak concentration, and the relative stream velocity based on the peak concentration. This implies that vegetation significantly reduces the flow velocity and increases the travel time, regardless the upstream flow velocity. The differences are tested between the left and right bank in the partial vegetated reach. A significant higher flow velocity (U_{peak}/U_{ref}) 1.55 and 1.25 for the right bank and left bank, respectively ($p=0.03$). And a significant lower time for the peak concentration (T_{peak}/T_{ref}) are found for the right bank, 0.65, compared to the left bank, 0.80 ($p=0.04$). While the difference for U_{peak}/U_{ref} and T_{peak}/T_{ref} were not significantly different between right bank and left bank for the full and empty vegetation cover.

Next, the second and third normalized central moments significantly vary between the full and no vegetation cover (Tab. 4). For the same travel time a higher variance (second moment) and a higher skewness (third moment) is found without vegetation compared to a full vegetation cover (Fig. 4). A higher variance can be due to higher dispersion and a higher skewness can be related to transient storage. This is confirmed by the parameters of the transient storage model. The dispersion coefficient (D) and the spatially average transient storage zone volume fraction (β) increase without vegetation. The goodness of fit was estimated with the Nash-Sutcliffe model efficiency coefficient (E) (Nash 1959). This coefficient ranges between 0.71-0.96 for full vegetation cover, 0.51-0.97 for the partial vegetation cover and 0.82-0.97 for the no vegetation cover. A separate parameter fit was done for the left and right bank of the partial vegetation cover, due to the significant difference of the peak flow velocity. Similar effects of the presence of vegetation are found in this scenario. The dispersion coefficient is lower, 0.134 $m^2\ s^{-1}$, for the left bank, which is downstream of a vegetated part (Fig. 2). While a value of 0.203 $m^2\ s^{-1}$ was found for the right bank downstream of the artificial channel (Fig. 2). The mass exchange rate (α) and the volume of the transient storage zone (β) are in both cases 10^{-7} s^{-1} and 10^{-7} %, respectively. When parameter settings were applied separately for both river banks, this improved the model fit between 0.68-0.88 and 0.88-0.95 for respectively the left and right bank.

Table 4: Transport of NaCl as an analogue for the behaviour of solute transport in streams. Full: n=11, partial: n=9, no: n=12. Letters indicate significant differences ($p<0.05$) based on a two-way ANOVA followed by a post-hoc Tukey test.

		Vegetation cover		
		Full	Partial	No
General parameters				
Recovery	%	107.2 ± 6.4 ^{a}	89.1 ± 3.5 ^{b}	89.7 ± 2.5 ^{b}
T_{start} / T_{ref}	-	0.47 ± 0.02 ^{a}	0.41 ± 0.02 ^{b}	0.39 ± 0.02 ^{b}
T_{peak} / T_{ref}	-	0.83 ± 0.03 ^{a}	0.76 ± 0.03 ^{ab}	0.67 ± 0.03 ^{b}
T_{med} / T_{ref}	-	0.93 ± 0.03	0.86 ± 0.05	0.82 ± 0.03
T_{end} / T_{ref}	-	1.83 ± 0.07	1.73 ± 0.11	1.91 ± 0.09
U_{peak}/U_{ref}	-	1.22 ± 0.05 ^{a}	1.33 ± 0.06 ^{ab}	1.52 ± 0.07 ^{b}
U_{med}/U_{ref}	-	1.09 ± 0.03	1.18 ± 0.06	1.25 ± 0.05
Duration/T_{ref}	-	1.36 ± 0.07	1.31 ± 0.10	1.52 ± 0.09
C_{peak}	g m^{-3}	49.5 ± 3.2	44.7 ± 1.8	45.0 ± 1.6
Normalized central moments				
m_1	s	445 ± 12	469 ± 19	446 ± 10
m_2 x10^3	s^2	15.7 ± 1.9^{a}	18.5 ± 2.3^{ab}	26.0 ± 2.8^{b}
m_3 x 10^5	s^3	13.7 ± 3.3^{a}	17.0 ± 5.4^{ab}	40.0 ± 8.9^{b}
Transient storage model				
U (input)	m s^{-1}	0.113	0.108	0.113
D	m^2 s^{-1}	0.187	0.193	0.262
α x 10^{-7}	s^{-1}	1	1	1
β x 10^{-4}	%	0.001	0.001	1.67
E	-	0.71-0.95	0.51-0.97	0.82-0.97

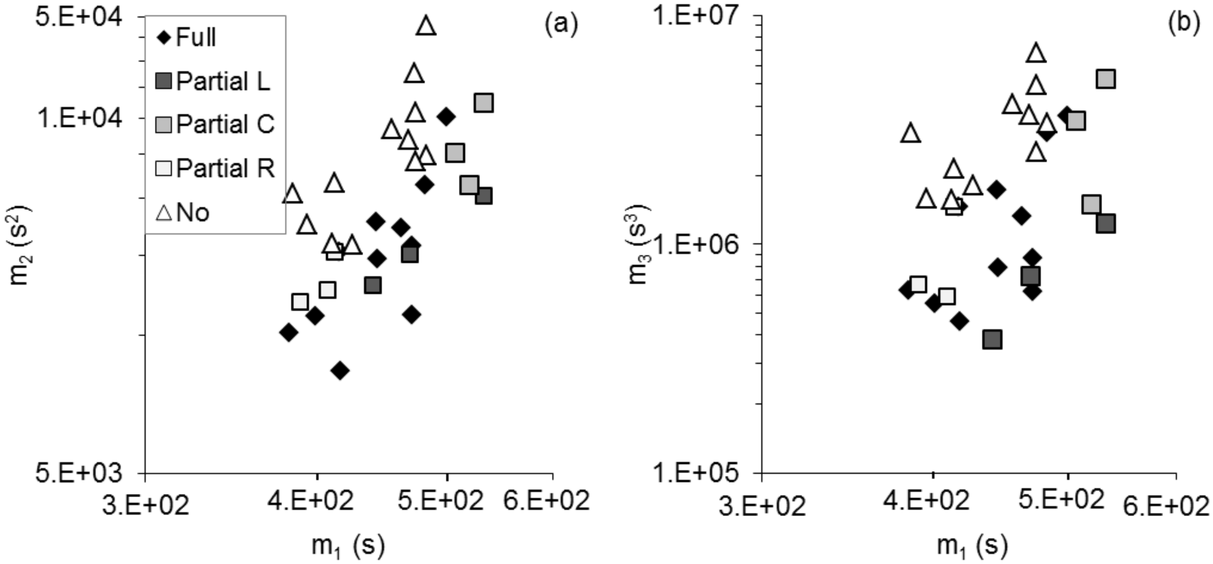

Figure 4: (a) The variance (second moment) and **(b)** skewness (third moment) in function of mean travel time (first moment) for three vegetation covers: full (diamond), partial (square) and no (triangle) vegetation cover. For the partial vegetation cover different colors are used according to the location of the sampling point (Fig. 2c), because each location has different properties according to the presence of vegetation see Fig. 2c: the sampling point at left bank is behind the vegetation (drak grey, 'partial L'), the central sampling point is in the middle of the channel (grey, 'partial C'), the sampling point at the right bank is in the open channel (light grey, 'partial R').

4. Particle transport and retention

The retention percentage and retention rate of the particular tracers is positively correlated with the vegetation cover for all substances (Fig. 5). For oats, all particles remain trapped in the study reach for the experiments with full and partial vegetation cover. Therefore it was not possible to calculate the retention rate, mean travel distance and depositional velocity (Tab. 5). The retention percentage of woodchips varied between 86.01 to 97.17 % depending on the vegetation cover. Cornflakes have the lowest retention percentage on the reach scale for all vegetation covers. The transport distance of the tracers is negatively correlated to the vegetation cover: the particles are further transported when low vegetation covers are present. A negative correlation between the depositional velocity and vegetation cover is observed for all tracers.

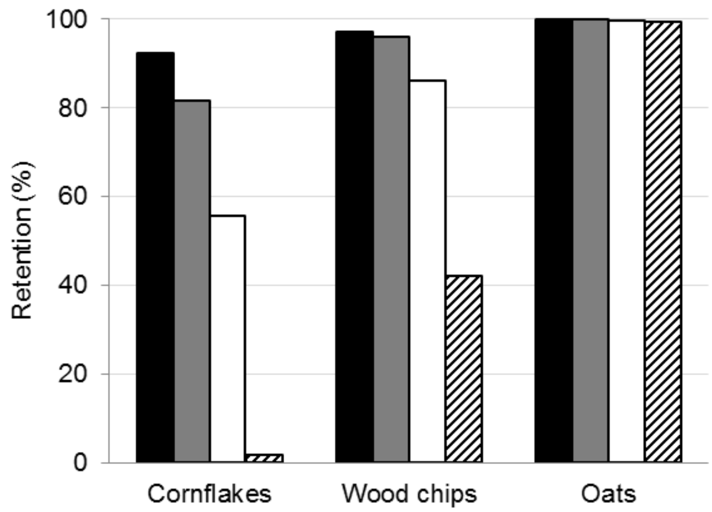

Figure 5: The retention percentage of cornflakes, wood chips and oats is given for three vegetation covers: fully vegetated (black), partially vegetated (grey), no vegetation (white). The retention percentage after 20 min. in standing water under laboratorial conditions is added (hatched).

Table 5: Retention and transport of CPOM types, oats, wood chips and cornflakes.

		Vegetation cover		
		Full	Partial	No
Oats				
Retention percentage	%	100.0	100.0	99.58
Retention rate	m^{-1}	/	/	0.11
Mean travel distance	m	/	/	9.1
Depositional velocity	$m\ s^{-1}$	/	/	0.0127
Wood chips				
Retention percentage	%	97.17	96.10	86.01
Retention rate	m^{-1}	0.071	0.065	0.039
Mean travel distance	m	14.0	15.4	25.4
Depositional velocity	$m\ s^{-1}$	8.62	6.15	0.0037
Cornflakes				
Retention percentage	%	92.24	81.54	55.77

Retention rate	m^{-1}	0.051	0.034	0.016
Mean travel distance	m	19.6	29.6	61.3
Depositional velocity	$m\ s^{-1}$	6.18	3.20	0.0016

4. Discussion

Macrophytes are generally known to have multiple effects on the functioning of river ecosystems (Gurnell 2014; O'Hare 2015). The hydraulic functioning is affected by reducing the conveyance capacity, while the transport capacity of dissolved and particulate matter is affected as well. The aim of this study is to investigate these opposing effects by tracer experiments at three vegetation covers after experimentally removing the vegetation in the same river reach. We found that (i) partially vegetated reaches had on the one hand reduced hydraulic resistance compared to the fully vegetated treatment due to flow concentration in to non-vegetated zones and on the other hand enlarged retention of particulate matter compared to the vegetation free treatment; (ii) vegetated reaches had the highest hydraulic resistance and the highest retention percentage for particulate matter; (iii) vegetation free reaches had the highest flow velocity, the highest longitudinal dispersion coefficient and the largest transient storage zone.

The highest reduction in hydraulic roughness is observed in partially vegetated reaches (Tab.3), while still maintaining the transport and retention capacity of the river (Tab. 4). The hydraulic resistance of fully vegetated reaches was two to three times higher than after complete vegetation removal, while the hydraulic resistance of the partially vegetated treatment ranged between them (Tab. 3). Similar results are found by an extensive study that compared 35 vegetated lowland rivers with different vegetation covers (Green 2005a). Manning coefficients ranged between 0.12 and 0.39 s $m^{-1/3}$ for reaches with vegetation covers of above 60 %, between 0.07 and 0.15 for covers between 35 and 60 %, whereas these values reduced to 0.09 s $m^{-1/3}$ for covers below 35 % for the same submerged macrophyte species and similar flow velocities. The relatively low hydraulic resistance in the partially vegetated treatment is caused by the presence of preferential flow paths (Bal et al. 2011) through deviation and concentration of flow to non-vegetated zones. The occurrence of this process in our study is confirmed by the significant difference of the flow velocity between the right bank and left bank in the partial vegetation cover. Similar flow deviation and concentration mechanisms to non-vegetated zones of river reaches with partial patchy vegetation has been show e.g. by Sand-Jensen and Mebus (1996) and Schoelynck et al. (2013),Verschoren et al. (2016).

Increased hydraulic resistance can lead to increased water levels (Madsen et al. 2001). In our study vegetation cover was experimentally varied over a limited reach of 50 m so that effects on water level are small, and therefore we consider the water level slope as the most relevant proxy for the effect of the varying vegetation covers on the drainage capacity. A five- to fifteen fold reduction in the water level slope was observed after the removal of all vegetation (Tab. 3). Other studies where instream vegetation was removed over a larger distance (5 km) showed a decrease of the water level between 17 and 28 % (Old et al. 2014) and 25 to 67% (Bal and Meire 2009). Simultaneously, the Manning coefficient dropped between 43 and 54 % (Old et al. 2014) and 25 to 67 % (Bal and Meire 2009) in the aforementioned studies and between 50 and 73 in our study. Along with increased water levels, macrophytes reduces the flow velocity relative to the incoming flow velocity (Tab. 4), this is a well-known phenomenon in vegetated rivers (De Doncker et al. 2009a; Franklin et al. 2008; Sand-Jensen and Pedersen 2008). Lower flow velocities reduce the advection of solutes and increase the residence time of solutes and water. Residence time is one of the major factors controlling the nutrient removal in rivers (Seitzinger et al. 2006). Consequently, the beneficial effects of solutes for the self-purification capacity of the river are reduced when macrophytes are removed (Runkel 2007).

The flow concentration to non-vegetated zones, associated with strong flow reduction within the vegetated zones, can be beneficial for the trapping and deposition of fine and coarse material in the vegetation patches, while higher stream velocities in the channels are the preferential flow path of particles and there erosion of mineral sediment can be induced (Madsen et al. 2001; Old et al. 2014). Also organic matter is accumulated in macrophytes patches, forming biogeochemical hotspots with efficient remineralization (Schoelynck 2011). Increasing macrophyte covers enhanced the retention of all three tested particle types (Fig. 5 and Tab. 5). The retention rate in vegetated reaches compared to vegetation free reaches was two- and threefold higher for wood chips and cornflakes, respectively. Similar observations with particles of other sizes were found for the influence of instream vegetation cover. The retention rate was for (i) macrophyte stem fragments (15-20 cm) 0.02-0.12 m^{-1} and 0.0005-0.0135 m^{-1} (Riis and Sand-Jensen 2006); (ii) circular paper chips (diameter 6 mm) 0.28-1.2 m^{-1} and 0.02-0.26 m^{-1} (Horvath 2004); (iii) corn pollen (diameter 85-90 µm) 0.017 m^{-1} and 0.011 m^{-1} (Warren et al. 2009) in vegetated and vegetation free streams respectively. In addition the retention rate was inversely related to the buoyancy of the particles, with the lowest retention rate (Tab. 5) for cornflakes which has the highest buoyancy (Tab. 1). Similar effects of buoyancy were observed with lower retention rates for particles with a higher buoyancy (Defina and Peruzzo 2010) for the same vegetation cover. Oats had the lowest buoyancy (Tab. 1) and no retention rate could be calculated for the fully and partial vegetated treatment because it cannot be known after which distance all particles were retained (Tab. 5). The effect of vegetation was overruled by the limited buoyancy of this tracer. Beside instream aquatic vegetation, other roughness structures can have similar effects on particle trapping, like riparian vegetation (Riis and Sand-Jensen 2006), logs, branches and tree trunks (Cordova et al. 2008; Schneider and Sharitz 1988) and substrate heterogeneity (Muotka and Laasonen 2002). This may explain the relative high retention percentage of wood chips in the vegetation free reach (Tab. 5). However, in large rivers the relationship between the retention percentage of particles and riparian vegetation cover was negative (Nilsson et al. 1991) or not significant (Andersson et al. 2000). This might be attributed to the relative smaller impact of riparian vegetation in larger rivers. In these river, the majority of particles (in these studies seeds) is transported in the main channel and is not obstructed by bank irregularities or riparian vegetation.

In addition, complex spatial flow when vegetation is present leads to distinct effects on transport and mixing processes of solutes. Flow channels between the vegetation lead to a clear peak in the concentration-time curves. Increased vegetation cover increased the magnitude of the peak concentration of the dissolved tracer (Tab. 4) and reduced the magnitude of transient storage zones (Tab. 4). The lowest dispersion coefficients are found for vegetated reaches (Tab. 4). This can be attributed to the ability of dense, uniform vegetation to reduce vertical gradients in the flow velocity (Baptist et al. 2009; Nepf et al. 1997). However a higher mechanical dispersion is expected due to the dense network of vegetation. The increase of mechanical dispersion due to the presence of vegetation can be counteracted by the decrease in stream velocity which lowers the shear stress separation and total dispersion (Folkard 2011; Lightbody and Nepf 2006). Similarly, the presence of vegetation mimics resulted in a decreased longitudinal dispersion coefficient in a flume experiment (Nepf et al. 1997). This was explained by higher turbulence and diminished vertical shear stress in the presence of vegetation. In addition, plant morphology itself can also affect the longitudinal dispersion (Lightbody and Nepf 2006) and sediment retention (Rovira et al. 2016). An equal distribution of frontal area of the canopy along the vertical results in a fairly constant velocity profile and generates relatively low vertical shear dispersion. While complex plant morphologies generate pronounced variation of the vertical velocity resulting in more shear flow dispersion (Lightbody and Nepf 2006). The vegetation consists in our study area of multiple species (Fig. 2), but we did not distinguish the effect of individual species on the longitudinal dispersion. From the above argumentation, it is clear that multiple interactions are present in these natural rivers. This leads to large variability of the effect of macrophytes on the longitudinal dispersion coefficient as well as the transient storage zone. A study conducted in vegetated spring-fed karst rivers found also a lower longitudinal dispersion coefficient but higher transient storage zone at increased vegetation cover (Hensley and Cohen 2012). This can be explained by the difference in geomorphology of the river channel dominated by karst. In contrast to our results, a field study conducted with three different levels of vegetation cover at three different moments in the year found a positive relationship between biomass and the longitudinal dispersion coefficient

(Sukhodolova et al. 2006) and the magnitude of the transient storage zone increased with vegetation cover in lowland rivers. However it was difficult to isolate effects of macrophytes on the dispersion coefficient and transient storage zone in this study, since changes in these parameters are mainly attributed to large variation in discharge between the sampling days and the presence of recirculation zones resulting from bank irregularities (Sukhodolova et al. 2006).

5. Conclusion

Our results show complex interactions between the presence of macrophytes and spatial flow patterns, and hence distinct effects on transport and mixing processes are found of dissolved and particulate tracers. After vegetation removal the hydraulic resistance expressed as a Manning coefficient is two to three times lower and water level slope drops by two to five times. The flow velocity increases when vegetation is removed, and the most heterogeneous flow field was found in the partially vegetated treatments, due to flow concentration to non-vegetated zones. The effect of vegetation on the transport of solutes and particles is twofold, vegetation decreases the longitudinal dispersion coefficient and decreases transient storage of solutes, while the retention rate of particulate tracers is two- and threefold higher. Clear differences are found between the three particulate tracers depending on their buoyancy, with the lowest retention rate for cornflakes which has the highest buoyancy. The partially removing of the vegetation leads to an optimal trade-off between maximizing the residence time and retention of organic matter while minimizing the hydraulic resistance compared to the fully vegetated and vegetation free treatment.

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