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RESEARCH ARTICLE

Flow thresholds for leaf retention in hydrodynamic wakes downstream of obstacles

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Abstract

Leaves are the major component of terrestrial litter input into aquatic systems. Leaves are distributed by the flow, accumulate in low flow areas, and form patches. In natural streams, stable leaf patches form around complex structures, such as large woody debris. Until now, little is known about flow conditions under which leaf patches persist. This study aims to quantify flow conditions for stable leaf patches and entrainment of leaf patches. We hypothesize that entraining flow processes, such as turbulence, Reynolds stress, or lift forcing (vertical flow velocity), best explain local leaf retention. This study was performed in an unscaled flume experiment, which conditions coincide with conditions found in low-energetic lowland streams. We positioned a wooden obstacle perpendicular to the flow on the bed of the flume. A leaf patch was positioned downstream from the wooden obstacle. The experiment was performed under 5 flow conditions. We monitored leaf patch cover and near-bed flow conditions in the area downstream of the wooden obstacle. We showed that near-bed flow velocities explain leaf retention better than more complex flow velocity derivatives such as turbulence, Reynolds stress, and vertical flow velocity. The entrainment near-bed flow velocity for leaves ranges from 0.037 to 0.050 m/s. Flow velocities frequently exceed those values, even in low-energetic lowland streams. Therefore, complex structures, such as woody debris, create flow conditions to support stable leaf patches. Thus, adding instead of removing obstacles may be a key strategy in restoring biodiversity in deteriorated streams.

KEYWORDS

current velocity, flow velocity, leaves entrainment, leaves transport, lowland streams, wake

1 | INTRODUCTION

Leaves are the major component of terrestrial litter input into aquatic ecosystems (Abelho, 2001). Leaves are periodically deposited in very large quantities (Richardson, Bilby, & Bondar, 2005; Webster et al., 1999; Webster & Meyer, 1997) and are biologically processed and transported by the flow (Hoover, Richardson, & Yonemitsu, 2006; Webster et al., 1999). In stretches where flow velocity is lowered, for example, due to the presence of woody debris, leaves may form stable patches. Leaf patches are often densely colonized biodiversity hotspots in streams (Kobayashi & Kagaya, 2004, 2005), that is, refuges that offer shelter and food (Lancaster, 2008; Lancaster & Belyea, 1997; Lancaster & Hildrew, 1993; Richardson, 1992). A substantial decrease of leaf patches may therefore lead to a decline in species abundance and diversity (Richardson, Zhang, & Marczak, 2010; Rowe & Richardson, 2001) potentially affecting ecosystem functioning (Bunn & Arthington, 2002; Hart & Finelli, 1999; Poff et al., 1997; Poff, Olden, Merritt, & Pepin, 2007).

Many lowland streams are low-energetic. Although single-thread streams in lowland areas often appear to be highly sinuous, they remain virtually fixed in time. Active morphological processes such as the development of alternate bars and chute cut-off may occur as a response to human measures (Eekhout & Hoitink, 2015; Eekhout, Hoitink, & Mosselman, 2013), but after an initial period of adjustment, the streams tend to maintain stable (Eekhout, Fraaije, & Hoitink, 2014).

Eekhout, Hoitink, de Brouwer, and Verdonschot (2015) showed that typical deteriorated lowland streams have cross-sectional-averaged flow velocities of 0.08–0.13 m/s and homogeneous bed substrate. In contrast, natural stream bottoms consist of a combination of mineral (50%) and organic microhabitats (50%; Verdonschot et al., 1995), respectively ranging from silt, sand, and gravel, to fine and coarse particulate organic matter (e.g., fallen leaves), mosses, local stands of vascular hydrophytes, and course woody debris (logs and debris dams). As the organic material plays a dominant role, these stream types are often indicated as organic streams. Leaves are particularly important in these lowland stream ecosystems, where they serve as one of the major food sources for macroinvertebrates (Verdonschot et al., 1995). The ecological importance of leaf input, processing, and transport has been recognized for decades (e.g., Hynes, 1970) and linked to organic matter budgets, ecosystem metabolism, and decomposition (reviewed in Tank, Rosi-Marshall, Griffiths, Entrekin, & Stephen, 2010). However, leaf retention is still poorly understood (Hoover et al., 2006; Statzner, 2008).

Bed load transport of sediment depends on the physical particle characteristics and the degree of exposure to flow, that is, particles are distributed according to shape, size, and specific weight (Hynes, 1970). Due to their relatively high surface-weight ratio, the transport of leaves obviously behaves differently from the transport of sediment (Young, Kovalak, & Del Signore, 1978). Previous studies showed that leaf patch stability relates to discharge in the field (e.g., Gorecki, Fryirs, & Brierley, 2006; Hoover et al., 2006; Larrañaga, Díez, Elosegi, & Pozo, 2003; Li & Dudgeon, 2011; Young et al., 1978) and to cross-sectional-averaged flow velocity in flumes (Koljonen, Louhi, Mäki-Petäys, Huusko, & Muotka, 2012; Trodden, 2012). Discharge and cross-sectional-averaged flow velocity are bulk parameters though, which are not interchangeable from one stream to another due to site specific dimensions and environmental heterogeneity (e.g., Trodden, 2012).

Previous research showed that local structural heterogeneity increases the leaf retention capacity of streams (e.g., Canhoto & Graça, 1998; Cordova, Rosi-Marshall, Tank, & Lamberti, 2008; Ehrman & Lambert, 1992; James & Henderson, 2005; Koljonen et al., 2012; Speaker, Moore, & Gregory, 1984; Trodden, 2012; Young et al., 1978). Stable leaf patches are scarce in fast flowing zones without obstacles but are often present in still water zones such as backwaters, margins, and eddies or in riffle areas with obstacles (Abelho, 2001; Nakajima, Asaeda, Fujino, & Nanda, 2006). The general view is that flow velocities should be near zero for stable leaf patches to persist (e.g., Kemp, Harper, & Crosa, 2000; Trodden, 2012), although leaves entrain at sites with high flow velocities. Stream structures and obstacles deflect the flow and create wakes where flow velocities are reduced or become negative relative to the normal flow (Daniels & Rhoads, 2004; Manga & Kirchner, 2000; Manners, Doyle, & Small, 2007), thus creating conditions for leaf patch formation. Leaves stick to these obstacles (Cordova et al., 2008; Ehrman & Lambert, 1992) or deposit in still water zones (Hoover, Marczak, Richardson, & Yonemitsu, 2010). The number of leaves retained from drift increases with the number of structures, unless high densities of structures evoke strong interferential currents and fail to effectively retain leaves (Trodden, 2012).

Although the mechanism of leaf retention by stream structures is clearly linked to flow reductions, until now, no direct relationship has been reported between flow conditions and leaf retention. Hence, little is known about the flow conditions under which leaf patches form and stabilize and entrain in streams. Therefore, the aim of this study was to quantify the flow conditions for leaf patch stability and leaf entrainment. To this purpose, we tested leaf patch stability and quantified near-bed flow conditions in a wake behind a wooden obstacle in an unscaled flume experiment, which conditions coincide with conditions found in lowland streams (Eekhout et al., 2015). We hypothesize that leaf patch size and shape are determined by the incipient motion of leaves and that leaf patch stability is best explained by hydraulic properties including turbulence, Reynolds stress, and lift forcing (vertical flow velocity), analogously to sediment transport theory.

2 | MATERIALS AND METHODS

2.1 | Experimental set-up

The experiments were performed in a straight, tilting laboratory flume in the Kraijenhoff van de Leur Laboratory for Water and Sediment Dynamics at Wageningen University. The flume has an internal width of 1.2 m, an internal height of 0.5 m, and a total length of 14.4 m. The flume bottom was covered with a moveable 0.1-m-thick sand bed layer (median grain size: 390 μm). A rectangular wood piece was fixed to the bottom of the flume and to one side of the flume wall. The wooden obstacle deflected the homogeneous flow and created a variable flow pattern in the test section. The submerged wooden obstacle emerged 0.06 m from the sand bed and covered half the width of the flume. The test section was located 5 m from the beginning of the flume (Figure 1). Each

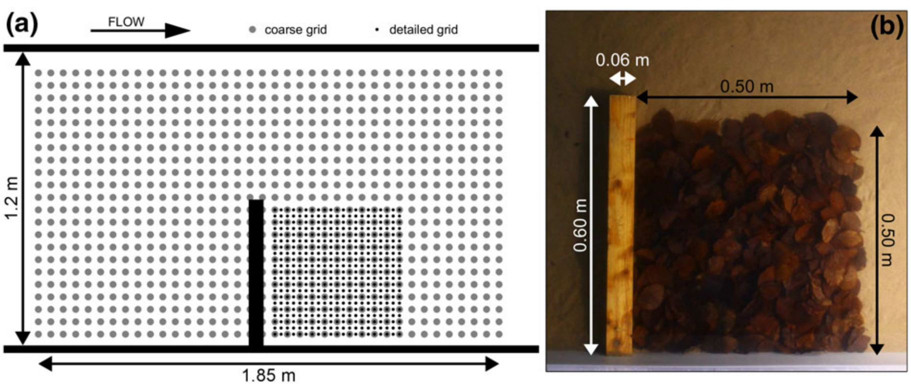

FIGURE 1 (a) Positions of near-bed flow velocity measurements in and around the test section. The black bar represents the wooden obstacle upstream of the test section. (b) Picture of the test section at the start of an experimental run

experimental run lasted for a period of 75 min. The experimental runs were repeated 15 times for each flow condition.

Five flow conditions were tested in the experiments (Table 1). Test runs showed that leaves did not entrain at cross-sectional-averaged flow conditions of 0.04 m/s and that the majority of leaves were entrained at 0.12 m/s. Therefore, we set these two conditions as the minimum (I) and maximum (V), respectively, and added three additional conditions with 0.02-m/s increments. These test conditions are further referred to as I, II, II, IV, and V (Table 1). The water depth was kept constant throughout the experiment at 0.15 m. To achieve this, discharge was kept constant and the flume was tilted such that a water depth of 0.15 m could be maintained throughout the experiment. All the physical conditions used in the experiment, that is, flow depth, cross-sectional-averaged flow velocities, and bed material, coincide with conditions previously found in low-energetic lowland streams (Eekhout et al., 2015).

2.2 | Flow velocity measurements

Flow velocity measurements were performed with an Acoustic Doppler Velocimeter (ADV, Nortek Vectrino), which is able to measure the flow velocity in three directions (two horizontal and one vertical) at a frequency of 20 Hz. The ADV was mounted on a movable carriage to obtain spatially distributed flow velocity data. The vertical position of the ADV was kept constant at a height of 0.03 m from the bed, which was the vertical position of the ADV closest to the bed without interference with bed forms and leaves. We employed two measurement strategies. First, flow velocities were measured on a coarse grid with 0.05-m intervals, with the aim of obtaining insight into the flow in the area surrounding the test section. These measurements covered the test section and the area surrounding the test section (Figure 1a). At each grid cell, flow velocities were obtained continuously over a period of 30 s. Second, flow velocities were measured on a detailed grid with 0.025-m intervals. The detailed grid only covered the area of the test section. At each grid cell, flow velocity was obtained continuously over a period of 300 s. The high-resolution velocity measurements aimed at linking mean horizontal flow velocities (time averaged at each grid cell), turbulence kinetic energy (TKE), vertical flow velocities, and Reynolds stress to leaf cover in the test section. After decomposing flow velocity into a mean and a fluctuating component, denoted with a prime, TKE is here defined per unit mass as in

$$TKE = \frac{1}{2}\left(u'^2 + v'^2\right).$$

TABLE 1 Flow conditions tested in the experiments and the corresponding bulk discharge, Froude number, and cross-sectional-averaged flow velocities

Class	Q (dm^3/s)	Fr	U_{av} (m/s)
Very low	7.2	0.033	0.04
Low	10.8	0.050	0.06
Intermediate	14.4	0.066	0.08
High	18	0.082	0.1
Very high	21.6	0.099	0.12

The vertical fluctuating component w' is left out of the equation, because it is smaller than the horizontal components, and includes comparatively many spikes due to acoustic side lobes from the bed. The main Reynolds stress tensor components are the ones that quantify vertical exchange of momentum, represented by $\left(\overline{u'w'}, \overline{v'w'}\right)$.We tested the absolute value of the latter vector as a metric controlling positive (upward) and negative (downward) lift forces. The components of the vector can be considered as a covariance, which is little affected by the outliers in the vertical fluctuations.

2.3 | Leaf patch monitoring

European beech (*Fagus sylvatica*) leaves were used in the experiment, a common Western European species with relatively low variance in leaf shape. Dry fallen leaves were collected, stored, and wetted during 24 hr. Trodden (2012) showed that leaves soaked water to saturation in 10 hr after which their weight remains equal for at least 48 hr. Exactly 600 leaves were positioned in the test section in stagnant water before each run (Figure 1b). At the start of each experimental run, discharge was slowly increased to the target discharge (1 dm^3/s increase every 2 s). Pictures were taken with a digital single-lens reflex camera (CANON EOS 400D) equipped with a polarized lens. The camera was mounted on a frame, 2 m above the leaf patch. Photos were taken at intervals of 1 min over the 75-min test period. Leaves were distinguished from sand and wood using photo analysis. The photos were transformed to grey scale, and leaves were distinguished from the sand and wood using a threshold value for the grey-scale intensity. Both the temporal and spatial evolution of the leaf patch was analysed from the photos (Figure 2). The percentage leaf cover with respect to the initial cover was determined for each subsequent photo, which allowed obtaining the temporal evolution of the percentage leaf cover for each flow condition. The percentage leaf cover was determined at the locations of the high-resolution velocity measurements. The spatial distribution of leaf cover was obtained at the end of each 75-min test run based on the last photo, when equilibrium conditions were achieved. The spatial distribution was averaged over the 15 replicate runs. This way, we obtained a relationship between leaf cover and the flow parameters TKE, the absolute Reynolds stress |(−uw,−vw)|, mean vertical flow velocity (W), and average flow velocity (U,V). All flow properties apply to the conditions at 0.03 m above the bed.

2.4 | Regression curves

The Bayesian P-splines (Appendix I) with credible bands were used to determine the range of entrainment flow velocities for the leaves and to show the stability of leaves on the stream bed at different flow velocities. We hypothesize that leaves are stable at velocities below the lower end of the entrainment range (stability threshold, 85% cover) and highly probable to entrain at the upper end of the entrainment range (entrainment threshold, 15% cover). Credible intervals (CI) for "stable" and "entrainment" were estimated from the intersection points of the 15% and 85% cover levels, with the 95% credible bands of the P-splines. If the level intersects an upper or lower band, twice the average of the intersection points was taken.

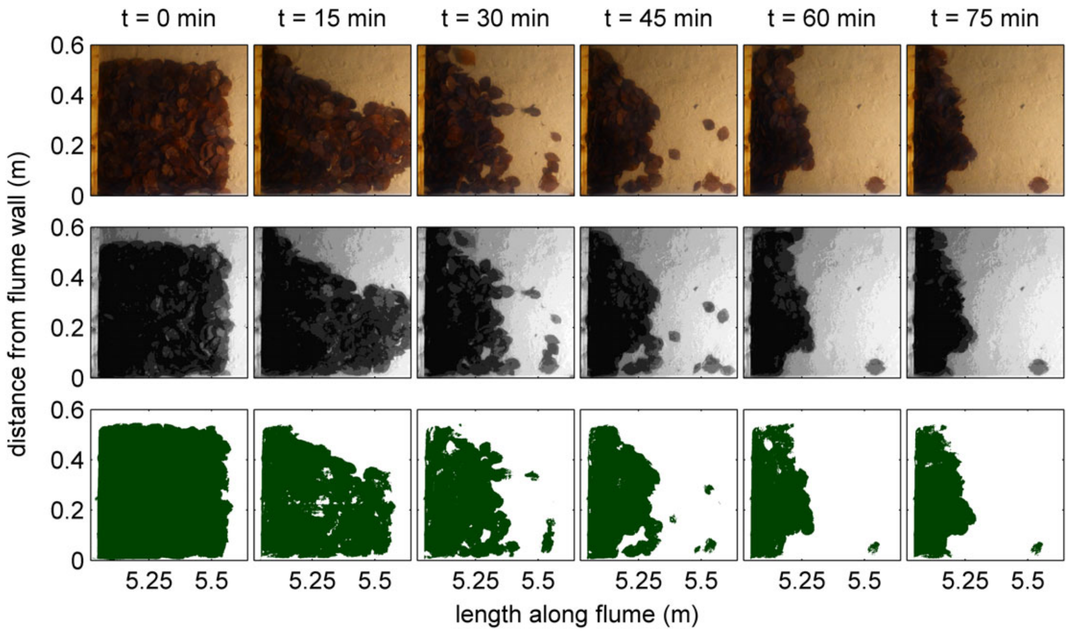

FIGURE 2 Example of temporal leaf patch development. The figure shows the procedure to distinguish the leaves from the sand and the wood. The example shows data from discharge condition III (0.08 m/s)

3 | RESULTS

3.1 | Leaf patch development

Figure 3 shows the results of the temporal evolution of the leaf patch cover. The leaf patches developed towards a stable equilibrium within 75 min of each experiment. The results from flow condition III differ from this observation and showed more variation among the 15 replicates compared to flow conditions I, II, IV, and V. Figure 3 clearly shows that leaf patch cover developed towards distinct equilibrium values, ranging from 95% cover for flow condition I to 20% for flow condition V.

3.2 | Flow conditions

Figure 4 shows the results of the course grid flow measurements. The figure shows that under each flow condition, the near uniform flow upstream of the wooden obstacle was deflected by the wood. Near-bed flow velocities downstream of the wood decreased in the test section and created a wake. The flow velocity increased at the tip of the wood, from which a mixed flow expanded downstream and directed towards the side of the channel at an angle of 45° to 85° until it was deflected by the wall. The collision with the wall created a flow towards the wood and circulation, due to interaction with the flow of the water streaming over the wood. The area downstream of the wooden obstacle can be considered a still water zone because of the relatively low flow velocities. However, the test section still showed a wide spectrum of flow velocities.

3.3 | Spatial leaf cover in relation to flow conditions

Figure 5 shows the results of the leaf patch monitoring and the detailed-grid flow velocity measurements in the test section. Figure 5 a shows the average cover percentage at the end of each experiment.

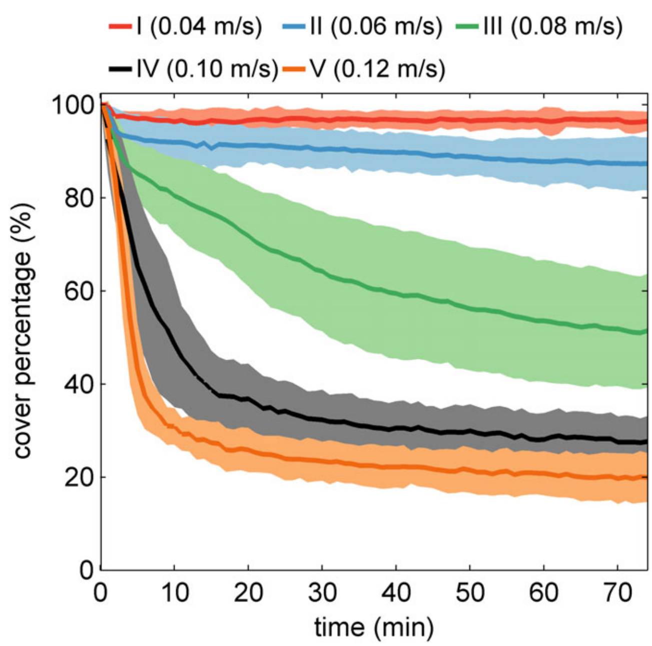

FIGURE 3 Temporal evolution of the average (n = 15) leaf cover percentage and standard deviation in the test section for the five discharge conditions

The figure shows that the leaf patches developed towards a stable equilibrium, where size and shape depended on the flow condition, in agreement with the observations on the temporal leaf patch development (Figure 3). Only the results from flow condition III differed from this observation. In general, most leaves entrained in the mixing layer that extends diagonally downstream from the tip of the wood towards the flume wall. Leaves were most stable in the area near the wood. When visually comparing the final leaf cover and the flow velocity results, it becomes apparent that the time-averaged near-bed flow

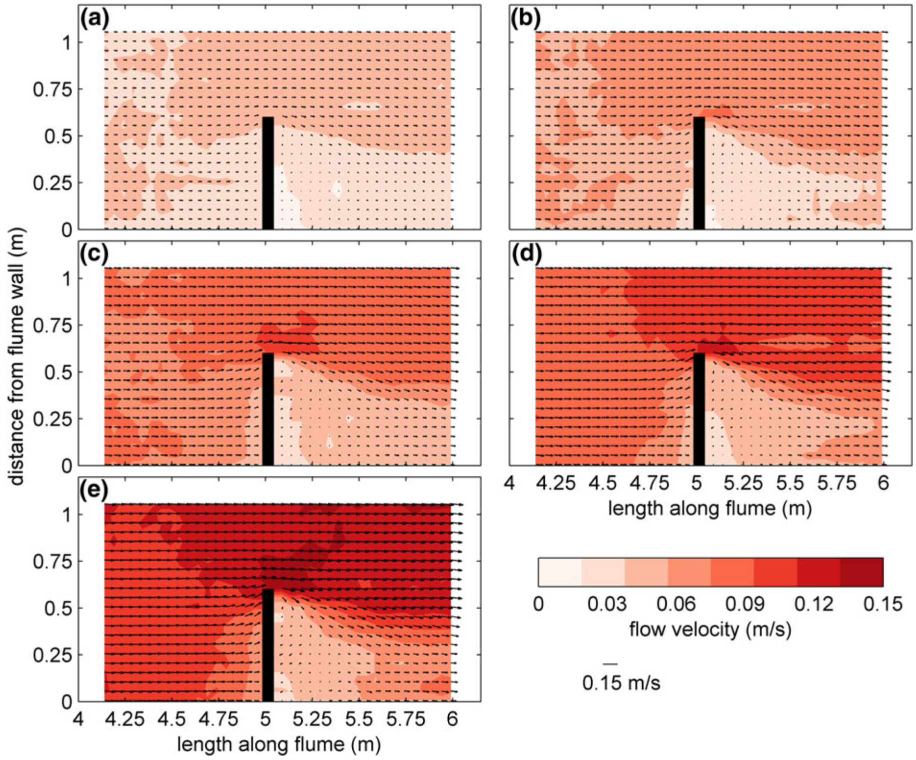

FIGURE 4 Time-averaged flow velocity from the course grid flow measurements, for the discharge conditions: (a) I (0.04 m/s), (b) II (0.06 m/s), (c) III (0.08 m/s), (d) IV (0.10 m/s), and (e) V (0.12 m/s). The flow vectors show the time-averaged horizontal flow direction. The length of the flow vectors represents the magnitude of the time-averaged flow velocity

velocities were consistently low directly downstream of the wood where the leaves accumulated and highest at the downstream end of the test section where the leaves entrained, regardless of discharge (Figure 5b). Most of the sites where leaves entrained had a relatively high average flow velocity (Figure 5b), TKE (Figure 5c), and Reynolds stress (Figure 5e). Leaf patches were more stable at locations with high vertical flow velocities (Figure 5d).

3.4 | Entrainment conditions

The results obtained from Figure 5 allowed us to relate the final leaf cover to the flow velocity derivatives. From Figure 5a, we obtained the leaf cover at each location where the detailed flow velocity measurements were taken and related these leaf covers to the time-averaged flow velocity, TKE, vertical flow velocity, and Reynolds stress (Figures 6 and 7). The most consistent relationship was obtained for the time-averaged flow velocity (Figure 6). A P-spline was fitted to the results of the time-averaged flow velocity (Figure 6). The P-spline shows a clear entrainment range of near-bed flow velocities: 0.037–0.050 m/s. Leaf cover was high at near-bed flow velocities under the stability threshold (0.037 m/s) and low when the drift threshold was exceeded (0.050 m/s; Table 2). The other flow velocity derivatives, that is, TKE, vertical flow velocity, and Reynolds stress, resulted in scattered leaf cover percentages, thus poorly explaining leaf cover (Figure 7).

4 | DISCUSSION

In this study on leaf entrainment, we showed that near-bed flow velocities better explain leaf patch stability than basic turbulence properties. We defined an entrainment range of near-bed flow velocities between 0.037 to 0.050 m/s. The mean near-bed flow velocity, given the narrow entrainment flow velocity range, proved to be the best indicator of leaf patch stability. Moreover, these entrainment values of near-bed flow parameters can potentially be extrapolated to any lotic waterbody and help to describe and predict stability of leaf patches in natural streams.

Near-bed flow velocity is thus a promising variable to determine conditions for leaf retention, because it induces shear stress forcing on bed load (Nezu & Nakagawa, 1993). The distance from the bed up to which the vertical velocity profile can be described by the law of the wall, implying it to be logarithmic, will be limited in a wake region as created in the experiments. Consequently, we cannot easily infer a depth-averaged flow velocity threshold for leaf entrainment. Strictly speaking, our results on leaf stability require flow velocities at 0.03 m/s above the bed, to be applied. Despite this, the corresponding cross-sectional-averaged velocities for the experiments offer an indication of the range of flow velocities for which leaves may be expected to be cleared from lowland streams.

The physical approach based on driving hydraulic forcing and stabilizing forcing of sediment enabled engineers to produce mathematical models that predict hydraulic and morphologic processes (reviewed in Dey & Papanicolaou, 2008). An analogous approach may seem feasible to explain entrainment of leaves. However, it is not trivial to define a threshold for incipient motion of leaves due to the stochastic nature of entrainment events. Even in sediment transport, particle properties pose difficulty to modelling accuracy, because grains always have some deviation from perfect spheres (Bridge & Bennett, 1992; Papanicolaou, Elhakeem, Krallis, Prakash, & Edinger,

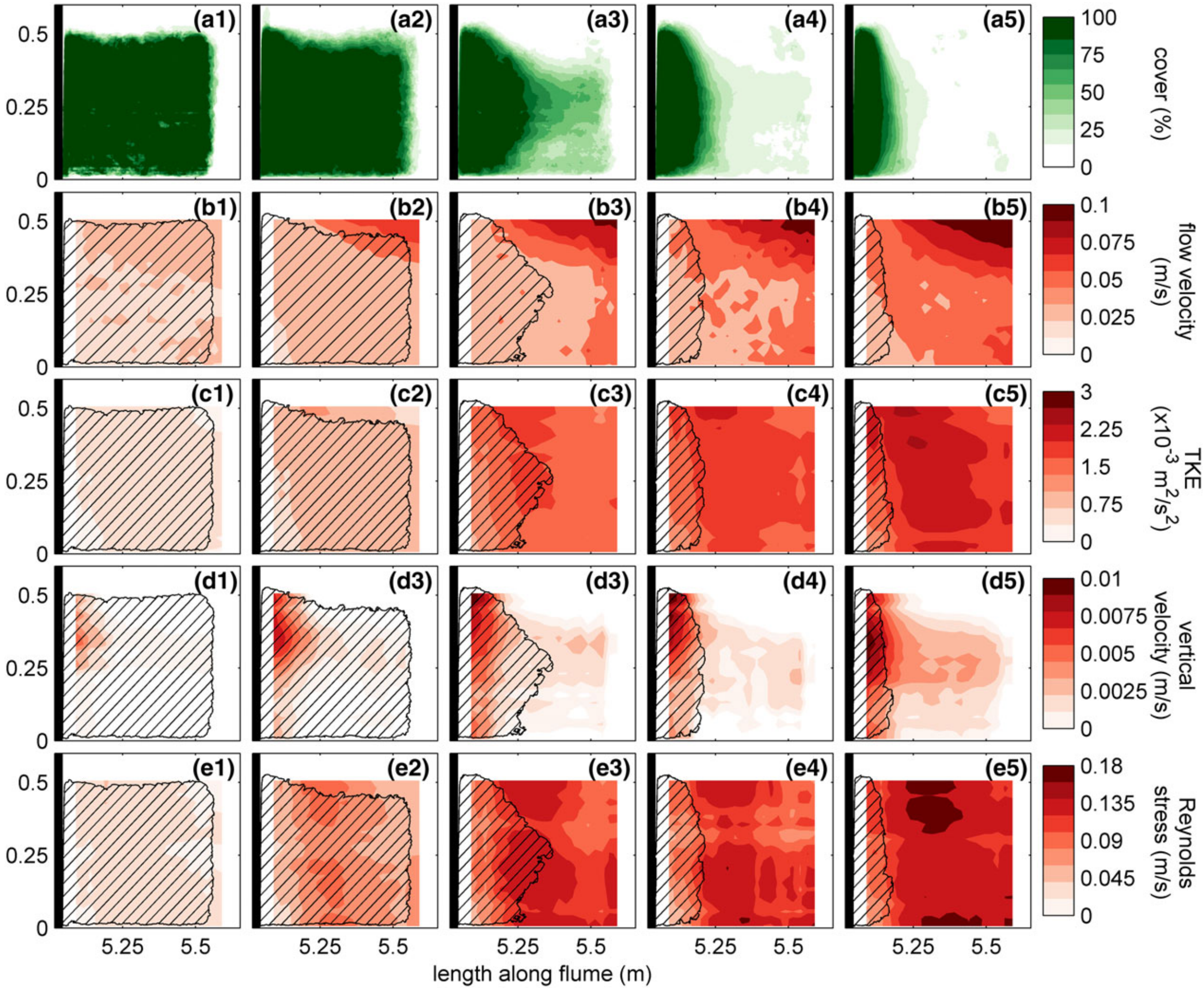

FIGURE 5 (a) Average (n = 15) leaf cover percentage at the end of the 75-min test runs. (b–e) Detailed flow velocity measurements in the test section, with (b) the time-averaged flow velocity, (c) turbulence kinetic energy (TKE), (d) vertical flow velocity, and (e) Reynolds stress. The shaded area indicates the average leaf cover percentage obtained from the upper panels (a). Indices 1–5 correspond to discharge conditions I (0.04 m/s), II (0.06 m/s), III (0.08 m/s), IV (0.10 m/s), and V (0.12 m/s)

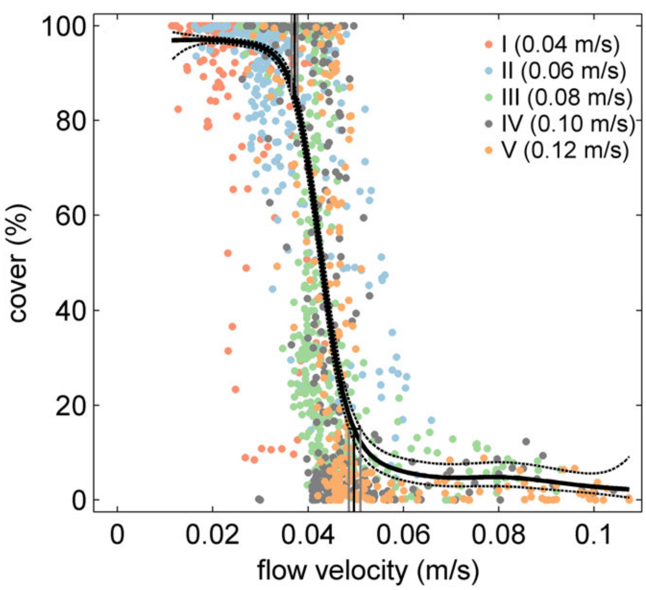

FIGURE 6 Regression curve (P-spline) to relate the final leaf cover percentage to the time-averaged flow velocity. The straight black lines in contact with the spline at 15% and 85% cover correspond to the boundaries of the entrainment flow velocity range

2008). Compared to sediment grains, leaves include more complex properties, such as the shape, size, orientation, variable density, stage of decay, and colonization of periphytic diatoms (Hoover et al., 2010; Kochi, Asaeda, Chibana, & Fujino, 2009; Statzner, Gore, & Resh, 1988; Steart, Boon, Greenwood, & Diamond, 2002). The current study shows that mean flow velocities are a better indicator for leaf patch stability than more complex hydraulic parameters. TKE, vertical flow velocity, and Reynolds stress explained the leaf cover poorly, despite their undisputed influence on the entrainment process and the stability of single leaves. Patterns of TKE, vertical flow velocity, and Reynolds stress in the test section differed from patterns of the main flow. In some areas of the grid, a substantial Reynolds stress occurred, despite low mean flow velocities. The leaves can be lifted in such areas without being transported elsewhere, or lifted and dragged towards a more stable area of the wake. In this fashion, the physical flow parameters have a direct effect on leaves without correlating to leaf cover. Only when leaves would be dragged towards the instable edge of the wake Reynolds stress would contribute to a lower leaf cover.

The choice of metrics quantifying the effect of turbulence was restricted to basic descriptors, which can readily be inferred from numerical flow models. Possibly, more complex metrics quantifying

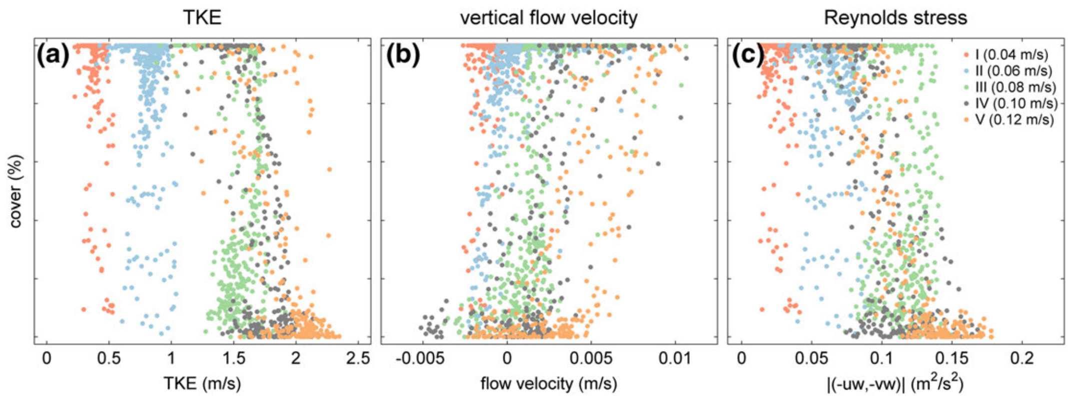

FIGURE 7 Final leaf cover percentage plotted against flow velocity derivatives: (a) turbulence kinetic energy (TKE), (b) vertical flow velocity, and (c) Reynolds stress

TABLE 2 The near-bed entrainment flow velocity range of beech leaves determined using the Bayesian P-spline method

		P-spline	
	Coverage (%)	U (m/s)	Credible interval
Stability threshold	85	0.0371	(0.0366–0.0375)
Median	50	0.0429	(0.0424–0.0434)
Drift threshold	15	0.0497	(0.0492–0.0502)

Note. The low end of the range is the stability threshold, and high end is the entrainment threshold.

accelerations during mutually dissimilar, evanescent turbulent flow events may outperform the mean flow as a predictor for entrainment. Also, the metrics capturing the three-dimensional aspects of the flow may be considered. However, it is likely that such metrics will heavily depend on details of the set-up of the experiment, including leaf type, sediment characteristics, and geometry of the wooden obstacle. Hence, a generic, robust metric that outperforms the predictive capacity of the mean flow is yet to be identified.

Previous studies have presented flow conditions in wakes downstream of obstacles. For example, increased flow velocities in the mixed flow layer directing downstream from the tip of the wood is a phenomenon previously observed near groynes (McCoy, Constantinescu, & Weber, 2008; Uijttewaal, 2005; Weitbrecht, Socolofsky, & Jirka, 2008). Studies that showed different flow patterns in wakes behind obstacles used multiple obstacles that caused mixed flow and flow circulation (Brevis, García-Villalba, & Niño, 2014; McCoy et al., 2008; Sukhodolov, 2014; Uijttewaal, Lehmann, & van Mazijk, 2001; Weitbrecht et al., 2008). Shape, permeability, and the level of emergence or submergence of obstacles influence the flow field within the wake (Sukhodolov, 2014; Uijttewaal, 2005). Studies that used submerged single obstacles, or presented flow data of wakes of the last obstacle in line, showed a similar pattern of horizontal flow velocity vectors, despite different dimensions and characteristics of the obstacle, that is, a mixed flow layer towards the side of the channel and a still water zone behind the obstacle (McCoy, Constantinescu, & Weber, 2007; Yeo & Kang, 2008). Likewise, in the current study, we showed that near-bed flow velocities in the still water zone increases with discharge, as expected, but an area of low flow remained near the wood at all flow conditions allowing the retention of leaf patches.

Our observations thus stress the importance of obstacles for leaf retention, similar to earlier studies that showed how structures contribute to leaf retention during low and high flows, that is, leaves retain in heterogeneous environments (Canhoto & Graça, 1998; Hoover et al., 2006; Hoover et al., 2010; Koljonen et al., 2012; Young et al., 1978). Quantified measurements of the flow behind the wood showed that the deflected flow creates a wake of low flow, directed towards the wood. Leaf patches remain locally stable in the low flow areas, regardless of bulk flow conditions. This way, dynamic stream environments that have heterogeneous bed texture and complex structures sustain leaves in a mosaic on the bed sediment, even when cross-sectional-averaged flow velocities exceed entrainment thresholds for leaves.

4.1 | Implications for leaf retention

The conditions used in the experiment coincide with conditions found in lowland streams, where leaves are an important food source for macroinvertebrates (Verdonschot et al., 1995). The average flow velocity in natural lowland streams is in the average range of 0.2–0.3 m/s (Tolkamp, 1980; Verdonschot, 1995) with frequent low flows down to almost zero and possible high flows up to 0.8 m/s. Channel and catchment modifications in the 20th century, such as channelization, increase of channel dimensions, and increased drainage density, had major consequences for flow velocity patterns (Verdonschot et al., 1995) and caused the discharge to become increasingly flashy (Meijles & Williams, 2012). The channel bed of disturbed streams are often homogeneous and are therefore characterized by a uniform flow velocity, causing a low coverage of organic matter (Feld, 2013). Restoration measures aim to improve the ecological status of streams, decrease peak discharges, and increase spatial heterogeneity of the channel bed (Eekhout et al., 2015).

The low observed entrainment flow velocity range for stable leaf patches indicates that most leaf coverage is temporary. In morphologically homogeneous streams, the slightest flow velocity increase would thus induce entrainment. The majority of leaves are transported before being fully broken down in situ (Webster et al., 1999), which is enhanced by the shortening of the residence time in modified stream channels. Hence, natural decomposition processes, that supply the stream of resources, are disturbed in homogeneous streams with a flashy hydrograph, where leaves would entrain en masse. Moreover, wood and plant removal, often used to "clean" streams, further reduces the structural complexity of the channel bed (Bilby & Ward, 1991; Buffington & Montgomery, 1997). In contrast, wood addition can restore bed complexity (Davidson & Eaton, 2013) and is a promising restoration measure for streams. Adding obstacles to streams can enhance organic matter storage and macroinvertebrate abundance (Negishi & Richardson, 2003). Our study shows that obstacles are needed to create local zones of fast flow in combination with still water zones, where leaf patches may retain.

5 | CONCLUSIONS

Here, we presented the results of a laboratory experiment on the stability of leaf patches under various flow conditions. The flow was disturbed by a wooden obstacle, which caused the formation of a wake. Our study showed that local stability of a leaf patch and wake size relates to mean flow conditions here measured at 0.03 m above the bed. Cross flow velocity, however, does not explain the spatial coverage in a steady state. Focussing on spatial patterns of cover, our study showed that time-averaged near-bed flow velocity corresponded better to leaf patch cover than more complex flow properties such as TKE, vertical flow velocity, and Reynolds stress. We observed that leaf entrainment occurs within the near-bed flow velocity range of 0.037 to 0.050 m/s. Flow velocities remained stable and low downstream of the wooden obstacle. The low entrainment range and the formation of wakes downstream of the wooden obstacle illustrate the importance of in-stream structures for stable leaf patches in natural environments. Adding instead of removing obstacles may therefore be a key strategy in restoring biodiversity in deteriorated streams.

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