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Published in:
Hydrological Processes

DOI:
[10.1002/hyp.13403](https://doi.org/10.1002/hyp.13403)

Published: 30/04/2019

Document Version
Peer reviewed version

Please cite the original version:

Przyborowski, Ł., Łoboda, A. M., Bialik, R. J., & Västilä, K. (2019). Flow field downstream of individual aquatic plants—Experiments in a natural river with *Potamogeton crispus* L. and *Myriophyllum spicatum* L. *Hydrological Processes*, 33(9), 1324-1337. <https://doi.org/10.1002/hyp.13403>

**Flow field downstream of individual aquatic plants –
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Journal:	<i>Hydrological Processes</i>
Manuscript ID	HYP-18-0540.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	01-Dec-2018
Complete List of Authors:	Przyborowski, Łukasz; Polska Akademia Nauk Instytut Geofizyki, Hydrology and Hydrodynamics Łoboda, Anna; Polska Akademia Nauk Instytut Geofizyki, Hydrology and Hydrodynamics Bialik, Robert; Polska Akademia Nauk Instytut Biochemii i Biofizyki, Antarctic Biology Västilä, Kaisa; Aalto University, Water Engineering
Keywords:	aquatic plants, flow velocity measurements, turbulent kinetic energy, flexible vegetation, biomechanical properties

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Short informative: This paper, as one of the first, is concentrated on the flow-aquatic plant interactions at the individual plant scale.

Running title: Experiments in a natural river with two different aquatic plants

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Keywords: aquatic plants, turbulent kinetic energy, biomechanical properties, reconfiguration, acoustic Doppler velocimetry, flexible vegetation, velocity field, turbulence

ACKNOWLEDGMENTS

This work was supported by the National Science Centre, Poland, Grant No. UMO-2014/13/D/ST10/01123 ‘Field experimental investigation of hydrodynamics of water flow-vegetation-sediment interactions at the scale of individual aquatic plants’. The publication has been partially financed from the funds of the Leading National Research Centre (KNOW) received by the Centre for Polar Studies for the period 2014-2018. Additional funding was provided by Maa- ja vesitekniikan tuki ry (Grant No. 33271) and Maj and Tor Nessling Foundation (Grant No 201800045).

Flow field downstream of individual aquatic plants – experiments in a natural river with *Potamogeton crispus* L. and *Myriophyllum spicatum* L.

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Abstract: Flow disturbances generated by individual patches of submerged, flexible aquatic vegetation were investigated for two naturally growing macrophyte species, *Potamogeton crispus* L. and *Myriophyllum spicatum* L., in a sandy lowland river. Through acoustic Doppler velocimetry, 24 vertical profiles of the 3D velocity field were recorded downstream of each of the patches. The morphological features and biomechanical properties of the plants were also evaluated. The experiments showed the relationship between biomechanical characteristics and turbulence statistics. *M. spicatum*, which was stiffer and therefore less prone to dynamic reconfiguration, showed a greater effect on velocity damping, causing an increase in Reynolds stresses, turbulence intensities and turbulent kinetic energy downstream of the patch. These effects were present in regions both above and below plant height. In contrast for *P. crispus*, these effects were present only below plant height. The stiffer plant produced a mixing layer in its wake similar to that of dense plant canopies. The patch of less stiff and more streamlined *P. crispus* with longer leaves presented a much weaker effect on the flow. In contrast to previous studies conducted with rigid plant surrogates, we concluded that reconfiguration of the living flexible plants allows the plants to minimize drag forces, and

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2
3 34 therefore, their influence on the flow field was weaker than the effects reported for rigid
4
5 35 surrogates.
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8 36 **Keywords:** *aquatic plants, turbulent kinetic energy, biomechanical properties,*
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10 37 *reconfiguration, acoustic Doppler velocimetry, flexible vegetation, velocity field, turbulence*
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12 38 **1. INTRODUCTION**
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14 39 Riverine vegetation influences transport processes, modifies channel morphology and
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16 40 contributes to flow resistance (Folkard, 2011; Nepf, 2012; Västilä & Järvelä, 2017). These
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18 41 aspects have been extensively examined under controlled, simplified laboratory conditions,
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20 42 but new technologies for velocity recording and bed scanning with the use of laser (Cameron
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22 43 et al., 2013) and acoustic methods (Sukhodolov, Federle, & Rhoads, 2006) allow the
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24 44 evaluation of smaller-scale vegetative effects on turbulent flow under complex natural
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26 45 conditions. Plant patches of finite length at scales much smaller than the width of the stream
27
28 46 are very common in natural rivers (Sand-Jensen & Pedersen 2008; Siniscalchi, Nikora, &
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30 47 Aberle, 2012b), and thus, it is vital to understand their effect on the flow at this particular
31
32 48 scale. In vegetated flows, a mixing layer present within and downstream of the patches is
33
34 49 formed with an exterior boundary layer above the canopy (Nikora, 2010). In addition, the
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36 50 lateral shear layers generated at the sides of porous obstacles tend to merge at some distance
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38 51 downstream (Ghisalberti & Nepf, 2009). From that perspective, vortices, eddies and other
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40 52 coherent structures are expected downstream of finite patches of vegetation, and therefore,
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42 53 this wake region is one of the best positions to study flow instabilities (Siniscalchi et al.,
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44 54 2012b).
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47 55 Plant biomechanical properties, along with morphological characteristics, are among
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49 56 the main factors required to understand flow-plant interactions (Nikora, 2010). Therefore,
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51 57 experiments with living specimens, which are flexible and have a complex, heterogeneous
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53 58 morphology with a pronounced porosity (Łoboda, Bialik, Karpiński, & Przyborowski, 2018a;
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Łoboda, Przyborowski, Karpiński, Bialik, & Nikora, 2018b), are preferable to simulations with the more rigid, artificial plant surrogates used often in laboratory studies (e.g., Kubrak, Kubrak, & Rowiński, 2008; Siniscalchi et al., 2012b; Zong & Nepf, 2012). However, studies investigating the wake flows caused by complex aquatic vegetation under real field conditions remain limited. As a result, there is scarce information on how the findings obtained with plant surrogates can be extended to field conditions where the flow field is affected not only by the presence of the natural plants but also by the presence of other phenomena such as a moving bed.

A proper characterization of patch and plant morphology and plant flexibility is crucial for improving our understanding of the behavior of natural plants in flow-biota interactions. The studies of Aberle and Järvelä (2013) and Tymiński and Kałuža (2012) stressed the importance of plant flexibility because the drag force caused by submerged vegetation increases with water velocity at different rates depending on plant rigidity (Sand-Jensen, 2003). Stem diameter and the flexural rigidity of a submerged plant are two characteristics that influence the drag force of aquatic macrophytes, and the relation between these can be described by an empirical formula (Łoboda, Karpiński, & Bialik, 2018c). Together, these factors impact plant reconfiguration (Siniscalchi & Nikora, 2012a) and in turn contribute to flow instabilities downstream of the plant. That contribution has been evaluated for simple plant morphologies based on the flow blockage factor, defined as plant density multiplied by the patch diameter and the drag coefficient of the plants (Ortiz, Ashton, & Nepf, 2013). The drag coefficient, C_D , can be derived from drag force (Tanino & Nepf, 2008), which can be obtained from experiments or from similarity numbers (Nikora, 2010); however, notable uncertainty remains for complex vegetation (e.g. Västilä & Järvelä, 2017) and the calculation of parameters such as drag coefficient is very difficult given the spatial heterogeneity of the plant stand (Aberle & Järvelä, 2013). Thus, a more general approach for evaluating the impact

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3 84 of single aquatic patches on the flow in natural conditions is needed, taking into account
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5 85 morphological and biomechanical characteristics.
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8 86 The aim of this paper is to investigate the flow structure downstream of finite patches
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10 87 of two natural flexible macrophyte species under their natural growing conditions in a
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12 88 lowland, sand-bed river. The experiment was designed specifically to explore how species-
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14 89 specific biomechanical and morphological properties, such as the shape of leaves and flexural
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16 90 rigidity, impact turbulent flow structure and its disturbances, allowing comparison to previous
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18 91 work conducted with rigid artificial surrogates.
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21 92 **2. MATERIALS AND METHODS**
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24 93 Experiments were conducted on the Świder River (52°06'21.2"N 21°13'42.0"E) on
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26 94 July 12, 2017, using *Potamogeton crispus* L. and on August 4, 2017, using *Myriophyllum*
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28 95 *spicatum* L. The sediment was composed of a medium, poorly sorted sand, and no other
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30 96 plants were present. Velocimeters were mounted on a steel platform and oriented parallel to
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32 97 the flow. Each plant was collected from a nearby part of the river on the same day that the
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34 98 experiment was conducted and planted in the sand at the same chosen location, approximately
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36 99 3 m from the right river bank. The discharge in the Świder River was stable and ranged from
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38 100 $1.1 \text{ m}^3 \cdot \text{s}^{-1}$ to $1.2 \text{ m}^3 \cdot \text{s}^{-1}$ throughout the experiment on July 12 and from $1.7 \text{ m}^3 \cdot \text{s}^{-1}$ to $1.8 \text{ m}^3 \cdot \text{s}^{-1}$
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40 101 on August 4, which corresponded to a minimum of 25 cm and a maximum of 40 cm of water
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42 102 depth at the location due to the occurrence of moving sand dunes. During the measurements,
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44 103 the maximal change in the bottom elevation at a point downstream of a plant during 3 minutes
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46 104 of recording was approximately 0.04 m, although the total height of the passing dunes could
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48 105 be higher. The locally and temporarily changing bed elevation was taken into account by
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50 106 presenting the measurement height in the normalized form Z/H , where Z is the height above
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52 107 the riverbed and H is the local water depth.
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Individual stems of *P. crispus* floated at a maximum height of 0.15 m, and stems of *M. spicatum* floated at a maximum height of 0.2 m above the bottom, corresponding to the normalized height of $Z/H=0.4-0.5$; however, the main bodies of the plants were positioned at approximately $Z/H=0.25$ and $Z/H=0.3$ respectively. *P. crispus* was planted densely in a narrow cone approximately 0.2 m long and created a slender patch 1.1 m long and 0.2 wide with an aspect ratio of 5.5 under the investigated conditions (Figure 1a). *M. spicatum* was planted in a round area 0.2 m in diameter, and a whole patch was 1.0 m long and 0.25 m wide with an aspect ratio of 4 (Figure 1b).

Given the complex structure of the patches, the patch dimension (Figure 2) was temporally averaged to take into account the dynamic motions exhibited by the plants. After the in situ measurements, the plants' biomechanical properties were studied in a laboratory to characterize the plants (see section 2.2).

2.1. Measurements of plant biomechanics

The biomechanical properties of *P. crispus* and *M. spicatum* were studied with three-point bending and tension tests conducted on a Tinius Olsen Bench Top Testing Machine, 5ST Model (Tinius Olsen, Redhill, United Kingdom). In the three-point bending test, the following parameters were investigated: the maximum force, maximum stress, maximum deflection, flexural strain, flexural rigidity and flexural modulus; the tension test yielded information about the breaking force, stress, strain and Young's modulus. Biomechanical traits were calculated based on formulas from Łoboda et al. (2018b), Niklas (1992) and ASTM (2003) using the following four basic parameters obtained during laboratory work: stem diameter, force, strain and deflection. Each test was performed on approximately 20 individual samples per species in submerged conditions (Łoboda et al., 2018b). The collected plants were transported to the laboratory and then stored in a 112 L circular flow through tank (details in Łoboda et al., 2018b). Prior to measurement, each stem was divided into 7 cm

pieces, and the diameter of each sample was measured using a microscope or caliper. Next, in tension tests, it was necessary to glue short strips of sandpaper to the ends of the specimen to prevent them from slipping out of the machine clamps (Łoboda et al., 2018b). The stems were prepared one at the time to minimize exposure of the specimens to dry conditions.

2.2. Measurements of flow fields

Instantaneous 3D velocity fields downstream of each plant were measured using two Vectrino Profiler (VP) acoustic Doppler velocimeters, (version 2779/1.32, Nortek AS, Rud, Norway). The devices were set up with a velocity range of $0.1 \text{ m}\cdot\text{s}^{-1}$ above the maximum observed longitudinal velocity to prevent the occurrence of “phase wrapping” in the recorded signal. A recording frequency of 50 Hz was chosen. To match the turbulent character of the flow, the minimum ping algorithm with a high power level was chosen (<http://nortek.no/>). Measurements of the velocity field consisted of 24 profiles in a grid of 6 lines and 4 rows (Figure 2). The location of the 6 lines was selected to capture the patch wake zone expected to be centered at line 4, the potential patch edge shear layers extending between lines 2 or 3 to line 5, and the ambient flow unaffected by the patch (reference lines 1 and 6).

Each velocity profile consisted of 7 to 11 points (depending on depth) with a consistent spacing of 0.03 m between points. At each point, the velocity was recorded for at least 3 minutes. Unlike most acoustic Doppler velocimeters, VP collects samples from closely spaced adjustable volumes, called further cells, each with varying sample quality (Craig, Loadman, Clement, Rusello, & Siegel, 2011). To maximize the accuracy of data acquisition, the following setup was used: cells of 1 mm size, minimum ping algorithm and velocity range $0.1 \text{ m}\cdot\text{s}^{-1}$ above maximal observable during the test run (Przyborowski, Łoboda, Karpiński, & Bialik, 2018).

The velocity records from the VP were filtered to eliminate potential spikes, utilizing parts of the code from MITT open source MATLAB algorithms (MacVicar, Dilling, & Lacey,

2014). First, from each point in a profile, the individual cell that had the best signal accuracy was chosen for further processing, usually at a specific distance from the transducer called the sweet spot (as recommended by Brand, Noss, Dinkel, & Holzner, 2016; Koca, Noss, Anlanger, Brand, & Lorke, 2017; Thomas, Schindfessel, McLelland, Creëlle, & De Mulder, 2017). Second, the record from that cell was filtered with regard to the signal-to-noise ratio and correlation values. Recorded points below thresholds of 15 dB and 70% were discarded and replaced using linear interpolation. Finally, the phase-space thresholding filter developed by Goring and Nikora (2002) and modified by Wahl (2003) and Parsheh, Sotiropoulos and Porté-Agel (2010) was used with three iterations to remove and replace spikes.

Filtered data were used to calculate flow characteristics, namely, the mean velocity and turbulent kinetic energy:

$$TKE = \frac{1}{2}(\overline{(u')^2} + \overline{(v')^2} + \overline{(w')^2}), \quad 1)$$

turbulence intensities normalized by velocity magnitude:

$$TI_U = \frac{\sqrt{\overline{u'^2}}}{\sqrt{\overline{U^2} + \overline{V^2} + \overline{W^2}}}, TI_V = \frac{\sqrt{\overline{v'^2}}}{\sqrt{\overline{U^2} + \overline{V^2} + \overline{W^2}}}, TI_W = \frac{\sqrt{\overline{w'^2}}}{\sqrt{\overline{U^2} + \overline{V^2} + \overline{W^2}}} \quad 2)$$

and tangential Reynolds stresses:

$$\overline{u'v'}, \overline{u'w'}, \overline{v'w'}, \quad 3)$$

where U, V, and W represent the instantaneous velocity and u' , v' , and w' represent the velocity fluctuation in the longitudinal, lateral and vertical directions, respectively, while the overbars denote time-averaged values. The turbulent kinetic energy and turbulence intensities were formulated as noise free using redundant information of two independent vertical velocity records and the transformation matrix available in VP to calculate noise variance for horizontal components (Hurther & Lemmin, 2001; Voulgaris & Trowbridge, 1998). The flow

field downstream of the macrophyte was complex, but no systematic differences were observed between rows A-D (Nikora, Goring, McEwan, & Griffiths, 2001). Therefore, to achieve a representative understanding of the turbulent flow field, the normalized turbulence intensities and Reynolds stresses are reported as the mean values for points below the main body of the plants ($Z/H \leq 0.3$), in the layer immediately above the main body of the plants ($0.3 < Z/H < 0.55$) and in the free overflow ($Z/H > 0.55$) with spatial averaging across rows A-D.

The power spectral densities were calculated using scripts implemented in MATLAB, i.e., the Welch method with discrete Fourier transform points equal to 512. With a default Hamming window function and 50% overlap, example 3 minute record consisting of 9128 samples resulted in a power spectral density averaged from 15 segments (Welch, 1967).

The data obtained from the VPs were of good quality, particularly considering the complex field conditions: the correlation and signal-to-noise ratio filter replaced an average of 3.5% of all the recorded values, while the phase-space thresholding method filter corrected an average of 12.5%.

3. RESULTS

3.1. Biomechanical properties of the two macrophyte species

M. spicatum had thicker stems than *P. crispus*. The mean diameters in the three-point bending and tension tests were 2.45 and 2.41 mm for *M. spicatum* and 1.97 mm and 1.65 mm for *P. crispus* (Tables I and II). For bending traits, the maximum force and maximum deflection were similar for both species (Table I), while *M. spicatum* had higher flexural strain (Table I). *M. spicatum* was also characterized by higher flexural rigidity, 32.12 N·mm² in comparison to 26.15 N·mm² of *P. crispus* (Table I), and thus, along with the higher stiffness, *M. spicatum* had a lower flexural modulus, 17.99 MPa (Table I), which was 58% lower than that for *P. crispus*, i.e., 42.56 MPa. The three-point bending tests showed that *M. spicatum* was characterized by a 1.5 times greater bending strength (maximum stress)

(Table I). Moreover, the tension tests revealed similar results, and *P. crispus* had a lower tensile strength (breaking stress), equaling 1.43 MPa (Table II). The breaking force of *M. spicatum* was higher at 3.78 N, than that of *P. crispus* at 2.34 N (Table II). *M. spicatum* displayed a mean breaking strain of 14.70%, and *P. crispus* exhibited a mean breaking strain of 6.43% (Table II). The differences in the moduli of elasticity were highly prominent; *M. spicatum* had a Young's modulus of 6.77 MPa, whereas *P. crispus* had a Young's modulus of 29.16 MPa (Table II).

3.2. Mean flow and turbulence downstream of the natural plant patches

The mean streamwise velocity in the region closest to *P. crispus* showed a 65% and 49% drop at the height of the main body of the plant (Figure 3a, $Z/H=0.25$, row A, lines 4 and 3, in reference to Figure 2) in comparison to the point above. Farther downstream, the differences between these regions were smaller (in points close to the bottom at $Z/H=0.1-0.15$, the mean velocity increased from $0.25 \text{ m}\cdot\text{s}^{-1}$ to $0.45 \text{ m}\cdot\text{s}^{-1}$ in the two farthest rows). At the height of the main body of the plant ($Z/H=0.25$), the mean lateral velocity did not show any deviation (Figure 4a), and the vertical component showed a shift toward surface-directed flow at the point closest to the plant (Figure 5a, row A, line 4). In the case of *M. spicatum*, the mean longitudinal velocity in a region closest to bottom and the plant decreased by 47% and by 89% compared to the area at the height of the plant (row A, lines 4 and 5 at $Z/H=0.2$ compared to $Z/H=0.25-0.3$); however, similar drops were also observed in the outlying reference lines 1, 2 and 6 (Figure 3b). The mean lateral velocity showed negative mean values in the closest profile downstream of the plant (Figure 4b, row A, line 4), whereas farther profiles had notably less negative or positive values. The mean vertical velocity indicates movement toward the river bottom in the majority of the profiles (Figure 5b).

The turbulent kinetic energy (TKE) downstream of the *P. crispus* was comparable to that at the outlying reference profiles except for 2 points nearest the plant and close to the

bottom (line 4, row A – $0.014 \text{ m}^2\cdot\text{s}^{-2}$ at $Z/H=0.026$; line 4, row B – $0.013 \text{ m}^2\cdot\text{s}^{-2}$ at $Z/H=0.15$; Figure 6a). In the case of the *M. spicatum*, around the top of the main plant body (at $Z/H=0.27-0.36$), the TKE values were consistently highest immediately downstream of the patch in the two closest rows, decreasing toward the reference lines expected to lay outside the wake zone, corresponding to a maximal value of $0.01 \text{ m}^2\cdot\text{s}^{-2}$ at line 4 and a minimum value of $0.002 \text{ m}^2\cdot\text{s}^{-2}$ at line 6 (Figure 6b). Values of TKE equal to zero were obtained at points where the subtracted noise variance was greater than the measured velocity variance itself (Hurther & Lemmin, 2001).

The normalized turbulence intensity in the longitudinal direction (TI_U) below $Z/H=0.3$ was roughly two times greater than that above the main body of the plants ($0.3<Z/H<0.55$), while the lowest values were generally recorded in the free overflow ($Z/H>0.55$) (Figure 7a, b). Among the points at $0.3<Z/H<0.55$, TI_U directly downstream of the plant had the highest values (0.21 for *P. crispus* and 0.23 for *M. spicatum* on average from lines 3 and 4), which was a sign of plant influence on the flow energy around the top of the canopy. The lateral and vertical normalized turbulence intensities (TI_V , TI_W) above the main body of the plants ($0.3<Z/H<0.55$) were significantly increased directly downstream of *M. spicatum* (lines 3 and 4) but not in the other four lines (Figure 7d, f). A similar situation was also observed below the main body of the plants ($Z/H\leq 0.3$). In contrast, lateral and vertical turbulence intensities for *P. crispus* did not show such high values. However, some points very close to the bottom had velocities below $0.1 \text{ m}\cdot\text{s}^{-1}$ (see Figure 3); therefore, turbulence statistics in those points could be mainly influenced by the bottom shear layer.

The absolute values of Reynolds stresses in all three planes ($|\overline{u'v'}|$, $|\overline{u'w'}|$, $|\overline{v'w'}|$) are shown using the same spatial averaging as for the turbulence intensities. The points directly behind *P. crispus* (lines 3 and 4) above its main body showed, on average, the smallest values in comparison to outlying lines for all three stresses, although no such trend was observed

below the main body of the plant (Figure 8a, c, e). The percentage values of the ratio between the middle and lower layer showed that at middle lines (3, 4 and 5), the stress values above the main body the plant were usually lower than those below the main body, but for outlying points (lines 1 and 6), the opposite was found. Notably, for *M. spicatum*, the highest values of $|\overline{u'v'}|$ equal to $1.1 \times 10^{-3} \text{ m}^2\cdot\text{s}^{-2}$, were observed directly downstream of the plant (line 4) above its main body, while at the outer boundary between the plant and free flow (line 5), the highest value was $0.8 \times 10^{-3} \text{ m}^2\cdot\text{s}^{-2}$, and these values were higher than the corresponding points below the main body of the plant (Figure 8b). The outlying points had notably lower values of approximately $0.3 \times 10^{-3} \text{ m}^2\cdot\text{s}^{-2}$. The values of the $|\overline{u'w'}|$ and $|\overline{v'w'}|$ stresses directly downstream and above the main body of the plant were two times higher than those in outlying points (Figure 8d, f).

The power spectral densities of fluctuating u' and w' velocities are shown for two heights, i.e., above and below the main body of the plant for lines 2 and 4 (Figure 9) in row A. Reference line 2 was chosen because its normalized point height was similar to that of line 4. The calculated noise floor (Hurther & Lemmin, 2001) had a value of less than $6 \times 10^{-6} \text{ m}^2\cdot\text{s}^{-2}\cdot\text{Hz}^{-1}$. At line 2, the magnitude of energy was similar at both heights. The magnitude on line 4 for the *P. crispus* energy of u' and w' within the main body of the plant ($z/H=0.15$) was an order of magnitude higher than that above it ($Z/H=0.45$; Figure 9a). For *M. spicatum*, the energy of u' and w' was equal below and above plant height (Figure 9b).

4. DISCUSSION

Our study is one of a few exploring the structure of the wake flow downstream of individual flexible aquatic plants under their natural growing conditions. In general, theory and laboratory studies describe that in the presence of aquatic vegetation, the longitudinal velocity is lower immediately downstream of a plant body and is higher on the edges, while the lateral and vertical velocities are higher on the wake edges due to the occurrence of lateral

and vertical vortices (e.g., Nepf, 2012). Our practical experiment showed that under complex natural conditions where the effects on flow are controlled, e.g., by the density and drag coefficient of the patch (e.g., Chen, Jiang & Nepf, 2013), such phenomena were not only dependent on the patch characteristics but also weakly represented in the downstream flow field due to the presence of ambient turbulence. Specifically, our results were mostly influenced by the extremely low flexural rigidity of both species (Tables I-II), which resulted in flapping-like motions and highly streamlined shapes of the plant stems. These flapping motions minimize the drag forces on such flexible plants (Siniscalchi & Nikora, 2013).

4.1. Flexibility-induced effects on plant behavior

The flexibility and reconfiguration of the vegetation were expected to significantly affect wake flow compared to studies where plants were simulated with rigid cylinders (e.g., Ortiz et al., 2013). For instance, Boothroyd, Hardy, Warburton and Marjoribanks (2017) found that vertical compression of the plants and the decrease in their porosity with increasing velocity strengthen the vortices in the shear layer and lower the height of the wake region. Our study showed limited flow area affected by the plants, similar to the study by Ortiz et al. (2013), but with less pronounced boundaries of a wake. Ortiz et al. (2013) and Sukhodolova and Sukhodolov (2012a) also showed that the flow can be deflected from the patch in the lateral and vertical directions depending on patch density.

Due to the low flexural rigidity and streamlined patch morphology (Figure 1, Table I), the drag coefficient of the investigated aquatic macrophytes was likely notably lower than that of flexible riparian plants (Boothroyd et al., 2017) or rigid cylinders (Ortiz et al., 2013). The Young's modulus of the studied plants was more than 90% lower than that of the artificial elements used by Ghisalberti and Nepf (2006). The extremely high flexibility enables these plants to exhibit dynamic reconfiguration in response to the flow field, which lessens the cross sectional area and exposed surface area, causing lower shear stresses than those experienced

by rigid vegetation under the same forcing (Ghisalberti & Nepf, 2006). Thus, the influence of flexible aquatic vegetation on turbulence characteristics can be difficult to distinguish under field conditions because flow structures from upstream penetrate a patch rather than being deflected as for a rigid obstacle (Ghisalberti & Nepf, 2002, 2006). For this reason, taking into account the facts that the plant dimensions and approaching flow velocity were comparable for both species, the differences in biomechanical properties and morphology between *M. spicatum* and *P. crispus* are expected to be the key features in explaining the measured disturbances in the flow fields downstream of the patches.

4.2. Plant effects on mean velocities

The biomechanical tests showed that *M. spicatum* was more resistant to bending and was more durable to tension forces because its stems were thicker than those of *P. crispus* (Tables I and II). The main differences between the plants were as follows: (1) *P. crispus* had a densely packed internal stem structure, and the stems were prone to bending and had undulating and relatively large leaves (Figure 1a, c); (2) *M. spicatum* had a wheel-like internal structure, conferring greater stiffness, and fragile, short leaves (Łoboda et al., 2018b) (Figure 1b, d). We expect these differences led to the former plant being more prone to dynamic reconfiguration as the leaves created a large flow-blocking area. In contrast, the leaves of the latter plant likely had less of an effect on drag force, and the resulting stress had less of an influence on stem motions. Our results confirmed findings of Asaeda, Sanjaya and Kaneko (2017) who observed a zone of decreased velocity immediately downstream of the main body of *P. crispus*. However, similar irregularities in the velocity profiles of outlying lines might be a result of a flow separation above the crests of sand dunes (Sukhodolov et al., 2006). Given the small area of the plant stand and that the passage of sand dunes was visible below the measurement points, the possibility that the results were biased by the sand dunes is unavoidable. A larger and denser patch would probably suppress such an effect.

Neither patch showed clear flow deflection, as no notable increases in velocity were observed around the patch, although closer-spaced measurement points could have provided a more detailed picture. In comparison to the study of Oritz et al. (2013), which used a flexible vegetation surrogate, our results indicated that the velocity profile regained its logarithmic shape closer to the patch, i.e., at lengths of $x/D=2$ for *P. crispus* and $x/D=3-4$ for *M. spicatum* compared to $x/D=4.8$ (where x is the distance from the patch and D is the diameter of the patch), likely because the drag coefficient and density of the present patches were smaller. The shorter wake region for *P. crispus* than for *M. spicatum* could be explained by the more flexible stems of the former (Table I). Therefore, the *P. crispus* patch preserved denser, more coherent structures moving harmonically with currents from upstream, which together with the influence of its leaves (Asaeda et al., 2017) decreased the flow velocity over a smaller area. The nonuniform wake shape in the case of *M. spicatum* might indicate a strong occurrence of a “bleed flow” due to plant porosity, as was also noticed by Boothroyd et al. (2017).

The lateral velocity data indicate that the mean direction of the flow changes in certain profiles. This finding suggests that the direction of the main flow was not uniformly parallel across the measured part of the stream, and thus, some of the flow was deflected horizontally from the patch. The vertical velocity was deflected toward the bottom downstream of the patch (Figure 5), which is consistent with the experiments of Chen et al. (2013) and Hu, Lei, Liu, and Nepf (2018), while deflection upwards was assumed to occur at the leading edge of the patch.

4.3. Plant effects on turbulence and mixing

The presence of flexible plant parts, such as leaves, weakens TKE magnitude and can result in increased sedimentation in the wake of the patch (e.g., Hu et al., 2018). Cameron et al. (2013) and Hu et al. (2018) showed increased TKE values above the plant canopy height,

which is in agreement with the present case. However, within the main body mass of *P. crispus* the change was minimal, because of long leaves of that plant (Hu et al., 2018). The highest measured TKE behind *M. spicatum* was $0.011 \text{ m}^2\cdot\text{s}^{-2}$, almost half the maximal value observed for *R. penicillatus* by Biggs et al. (2016). Furthermore, the ratio between TKE in the wake and in the shear layer on the patch edge (lines 2-3 and 5) was the inverse of that observed by Biggs et al. (2016), which could be because their patch was twice as large as those in this study or could be due to differences in leaf morphology that might also be decisive in determining plant reconfiguration capabilities.

The measured normalized turbulence intensities indicated that flow disturbances in the longitudinal direction were elevated directly downstream of the plant patch, just above the patch and around the top of the patch (Figure 7a, b), proving that a mixing layer developed (Chen et al., 2013; Siniscalchi & Nikora, 2013). The same phenomena were observed for the lateral and vertical turbulence intensities in *M. spicatum*, as those values were higher than those outside the patch wake, similar to the findings of Biggs et al. (2016). Zong and Nepf (2012) stressed that the patch diameter is one of the parameters that is positively correlated with the generation of von Karman vortex streets. The observed lateral turbulence intensity distribution (Figure 7c, d, e, f) indicated that vortex streets (Lyn, Einav, Rodi & Park, 1995) occurred only for *M. spicatum*, which was consistent with the findings of Boothroyd et al. (2017), as the patch was larger and had more rigid stems than *P. crispus*.

Ghisalberti and Nepf (2006) determined that asymmetry in the $|\overline{u'w'}|$ Reynolds stress profile is weaker in flexible waving vegetation than in stiffer vegetation and that the wake resembles a mixing layer. This pattern was visible in the present results: the maximal *M. spicatum* $|\overline{u'w'}|$ stress occurred at the height of the plant canopy (also, e.g., Cameron et al., 2013; Chen et al., 2013;), and elevated *P. crispus* $|\overline{u'w'}|$ stress occurred only below the main plant body (below $Z/H=0.3$, Figure 8a, b line 4). Biggs et al. (2016) noticed increased values

for the $|\overline{u'v'}|$ and $|\overline{v'w'}|$ stresses behind the patch and attributed these increases to the lateral turbulent transport of momentum and flow convergence. The present results agreed with those observations; for example, the centermost line 4 showed elevated values for the $|\overline{u'v'}|$ and $|\overline{v'w'}|$ stresses.

Consistent with the work of Ghisalberti and Nepf (2006) and Sukhodolov and Sukhodolova (2012b), the power spectral density indicated the presence of a mixing layer through higher energy of vertical velocity fluctuations in the wake of *P. crispus* (Figure 9a). This phenomenon might be caused by the presence of small vortices generated by the boundary layer/flow separation of stem/leaf origin (Nikora, 2010) due to the specific shape of the leaves of *P. crispus*. In the case of *M. spicatum*, differences between the energy distribution in the points above and below the canopy level were of smaller magnitude compared to those in the free flow area of line 2 (Figure 9b). Noticeably, the spectra of u' in the frequencies between 2 and 9 Hz mostly deviated from the -5/3 power law exhibited by points above the canopy. This result indicated that energy dispersion was inhibited because our observations showed that some of the flow disturbances were directed over the patch and did not accelerate at the edges. Similar behavior was observed in the study of Liu, Hu, Lei and Nepf (2017) with patch heights of $Z/H=0.21$ and 0.36 .

5. CONCLUSIONS

In this paper, we report results for the wake flow downstream of individual patches of two aquatic plant species. The findings are valuable as one of the first insights into the influence of flexible living macrophytes on the patch-scale flow structure in their natural riverine habitat. Our observations indicate that the interspecies differences in measured turbulence in the wakes were mainly the combined result of the nonuniform spatial distribution of the patches, the varied leaf shape, the differences in stem rigidity, and the influence of the plant motions (Albayrak, Nikora, Miler, & O'Hare, 2012; Västilä & Järvelä,

2017). Specifically, the results of biomechanical tests showed differences in the stem resistances to bending and tension, with the *M. spicatum* specimen being stiffer. Although both plants had comparable stem diameters, they featured different internal structures (Figure 1). These findings, merged with flow field records, proved to be valuable in understanding of the flow-biota interactions.

Similar to other experiments conducted in natural rivers, e.g., Sukhodolov and Sukhodolova (2012b) and Cameron et al. (2013), the observed disturbances downstream of aquatic vegetation patches did not include flow separation on the scale of the whole obstacle. Turbulence characteristics revealed regions of wake downstream of both plants, but stronger effects on the mean and fluctuating velocities were observed downstream of *M. spicatum*. In addition, TKE values were higher for the stiffer plant, especially above and around the top of the patch. The distribution of Reynolds stresses indicated that stiffer stems produce a mixing layer not only at the patch level but also extending above the patch. The power spectral density of u' indicated that the macrophyte specimens affected the distribution of turbulent energy in their wakes compared to points outside the wake region. The results showed major differences from other results obtained using artificial surrogates, which are typically denser, less flexible and less complex in morphology than the present natural species but are typically used in laboratory flumes: the present macrophytes demonstrated less flow deflection, less extensive wake flow regions and weaker wake turbulence in relation to the ambient turbulence level. Overall, our study demonstrated that the morphological and biomechanical characteristics of natural species are important in controlling turbulence statistics. Future studies including more species, biomechanical tests, and analyses of plant motions (e.g., Siniscalchi & Nikora, 2013) and assessment of the vertical distribution of plant density are recommended to compare the results and demonstrate patterns emerging in flow-vegetation interactions under natural conditions.

ACKNOWLEDGMENTS

This work was supported by the National Science Centre, Poland, Grant No. UMO-2014/13/D/ST10/01123 ‘Field experimental investigation of hydrodynamics of water flow-vegetation-sediment interactions at the scale of individual aquatic plants’. The publication has been partially financed from the funds of the Leading National Research Centre (KNOW) received by the Centre for Polar Studies for the period 2014-2018. Additional funding was provided by Maa- ja vesiteknikan tuki ry (Grant No. 33271) and Maj and Tor Nessling Foundation (Grant No 201800045).

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TABLES

Table I. Diameter and three-point bending test results for *P. crispus* and *M. spicatum*.

		<i>P. crispus</i>		<i>M. spicatum</i>	
		13 th of July		6 th of August	
		20 samples		22 samples	
Parameter		Mean ± S.D.	Median	Mean ± S.D.	Median
Diameter	[mm]	1.97 ± 0.51	2.13	2.45 ± 0.35	2.50
Maximum force	[N]	0.080 ± 0.040	0.077	0.072 ± 0.036	0.074
Maximum stress	[MPa]	0.027 ± 0.011	0.025	0.040 ± 0.015	0.037
Flexural strain	[%]	7.84 ± 2.35	8.19	9.32 ± 1.56	9.23
Max. deflection	[mm]	14.85 ± 3.08	15.86	14.10 ± 1.83	13.66
Sec. m. of area	[mm ⁴]	0.998 ± 0.725	1.004	1.901 ± 0.917	1.854
Flexural rigidity	[N·mm ²]	26.15 ± 20.19	19.62	32.12 ± 21.38	30.31
Flexural modulus	[MPa]	42.56 ± 37.52	30.16	17.99 ± 9.96	18.82

Table II. Diameter and tension test results for *P. crispus* and *M. spicatum*.

		<i>P. crispus</i>		<i>M. spicatum</i>	
		13 th of July		6 th of August	
		20 samples		19 samples	
Parameter		Mean ± S.D.	Median	Mean ± S.D.	Median
Diameter	[mm]	1.65 ± 0.60	1.48	2.41 ± 0.35	2.49
Breaking force	[N]	2.34 ± 0.72	2.25	3.78 ± 1.61	3.86
Breaking stress	[MPa]	1.43 ± 0.98	1.05	2.21 ± 0.64	2.19
Breaking strain	[%]	6.43 ± 1.78	6.16	14.70 ± 4.29	14.75
Young's modulus	[MPa]	29.16 ± 19.96	23.51	6.77 ± 2.17	6.38

FIGURE LEGENDS

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Figure 1 (a) *P. crispus*, Świder River, sampled on July 12 (b) *M. spicatum* Świder River, sampled on August 4 (c) *P. crispus* laboratory sample and cross-section (d) *M. spicatum* laboratory sample and cross-section.

Figure 2 Schemes of plants and corresponding measurement profiles downstream of: (a) *P. crispus* on July 12; (b) *M. spicatum* on August 4.

Figure 3 Mean longitudinal velocities downstream of (a) *P. crispus* in July and (b) *M. spicatum* in August. Letters (A,B,C,D) represent the rows as shown in Figure 2. The normalized maximum height of the plants was $Z/H=0.4-0.5$ while the main body of the plants was positioned at approximately $Z/H=0.25-0.3$.

Figure 4 Mean lateral velocities downstream of (a) *P. crispus* in July and (b) *M. spicatum* in August. Letters (A,B,C,D) represent rows as showed in Figure 2.

Figure 5 Mean vertical velocities downstream of (a) *P. crispus* in July and (b) *M. spicatum* in August. Letters (A,B,C,D) represent rows as showed in Figure 2.

Figure 6 Turbulent kinetic energy downstream of (a) *P. crispus* in July and (b) *M. spicatum* in August. Letters (A,B,C,D) represent rows as showed in Figure 2.

Figure 7 Normalized turbulence intensities in lines downstream of *P. crispus* in July (a, c, e) and *M. spicatum* in August (b, d, f). The marks in blue represent the mean values and mean height across points in rows A-D above $Z/H=0.55$, those in gray represents points $Z/H=0.3-0.55$ and those in red represent points below $Z/H=0.3$. The percentages denote the relation of values of $Z/H=0.3-0.55$ to values below $Z/H=0.3$ in each line. Each point is the spatially averaged value over 2 to 5 measurement points.

Figure 8 Absolute Reynolds stresses in lines downstream of *P. crispus* in July (a, c, e); and *M. spicatum* in August (b, d, f). The marks in blue represent the mean values and mean height

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across points in rows A-D above $Z/H=0.55$, those in gray represents points $Z/H=0.3-0.55$ and those in red represent points below $Z/H=0.3$. The percentages denote the relation of values of $Z/H=0.3-0.55$ to values below $Z/H=0.3$ in each line. Each point is the spatially averaged value over 2 to 5 measurement points.

Figure 9 Spectral energy of vertical and longitudinal fluctuating velocities on row A for *P. crispus* (a) and *M. spicatum* (b); line 4 represents directly downstream of a plant, and 2 representing free flow. Blue color indicates points near the bottom of the river, in the wake of the patch in the case of line 4, and red color indicates points above the plant height.

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Figure 1 (a) *P. crispus*, Świder River, sampled on July 12 (b) *M. spicatum* Świder River, sampled on August 4 (c) *P. crispus* laboratory sample and cross-section (d) *M. spicatum* laboratory sample and cross-section.

253x206mm (300 x 300 DPI)

Figure 2 Schemes of plants and corresponding measurement profiles downstream of: (a) *P. crispus* on July 12; (b) *M. spicatum* on August 4.

440x284mm (300 x 300 DPI)

Figure 3 Longitudinal velocities downstream of (a) *P. crispus* in July and (b) *M. spicatum* in August. Letters (A,B,C,D) represent the rows as shown in Figure 2. The normalized maximum height of the plants was $Z/H=0.4-0.5$ while the main body of the plants was positioned at approximately $Z/H=0.25-0.3$.

508x473mm (300 x 300 DPI)

Figure 4 Lateral velocities downstream of (a) *P. crispus* in July and (b) *M. spicatum* in August. Letters (A,B,C,D) represent rows as showed in Figure 2.

508x473mm (300 x 300 DPI)

Figure 5 Vertical velocities downstream of (a) *P. crispus* in July and (b) *M. spicatum* in August. Letters (A,B,C,D) represent rows as showed in Figure 2.

508x473mm (300 x 300 DPI)

Figure 6 Turbulent kinetic energy downstream of (a) *P. crispus* in July and (b) *M. spicatum* in August. Letters (A,B,C,D) represent rows as showed in Figure 2.

508x473mm (300 x 300 DPI)

Figure 7 Normalized turbulence intensities in lines downstream of *P. crispus* in July (a, c, e) and *M. spicatum* in August (b, d, f). The marks in blue represent the mean values and mean height across points in rows A-D above Z/H=0.55, those in gray represents points Z/H=0.3-0.55 and those in red represent points below Z/H=0.3. The percentages denote the relation of values of Z/H=0.3-0.55 to values below Z/H=0.3 in each line. Each point is the spatially averaged value over 2 to 5 measurement points.

504x362mm (300 x 300 DPI)

Figure 8 Absolute Reynolds stresses in lines downstream of *P. crispus* in July (a, c, e); and *M. spicatum* in August (b, d, f). The marks in blue represent the mean values and mean height across points in rows A-D above $Z/H=0.55$, those in gray represents points $Z/H=0.3-0.55$ and those in red represent points below $Z/H=0.3$. The percentages denote the relation of values of $Z/H=0.3-0.55$ to values below $Z/H=0.3$ in each line. Each point is the spatially averaged value over 2 to 5 measurement points.

504x362mm (300 x 300 DPI)

Figure 9 Spectral energy of vertical and longitudinal fluctuating velocities on row A for *P. crispus* (a) and *M. spicatum* (b); line 4 represents directly downstream of a plant, and 2 representing free flow. Blue color indicates points near the bottom of the river, in the wake of the patch in the case of line 4, and red color indicates points above the plant height.

358x242mm (300 x 300 DPI)