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Seasonality and spacing determine the effect of juvenile floodplain willows (*Salix alba* and *Salix viminalis*) on water current velocities

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1. Introduction

Species life history traits largely influence landscape morphodynamics (Corenblit, 2018). Different colonization behaviours lead to landscape self-organization across different biogeomorphic systems, and potentially the long-term resilience of these landscapes to disturbances (Schwarz et al., 2018). Borsje et al. (2011) recommend the application of different biogeomorphic systems for coastal protection along different scales; e.g. mussel and oyster beds prevent erosion on the mesoscale; dunes and salt marshes protect coasts when applied on the mega scale. Willow floodplains were suggested for reduction of wave overtopping of dikes on the macro scale. White willows belts that were planted on newly created banks along the dikeline in a river dominated tidal freshwater system were predicted to reduce the wave heights by 60–80% in modelling results (Borsje et al., 2011). Levee manipulation can be cost-effective to restore riparian *Salicaceae* forests (González et al., 2018).

“Nature-based” flood defense by conserving and restoring vegetated floodplain habitats may promote climate change mitigation and adaptation (Duarte et al., 2013). Estuarine biota is adapted to macrotidal systems high inherent variability in hydrodynamics, salinity balance, and geomorphological evolution that may confer a high degree of resistance and resilience to environmental change including climate change (Ducrottoy et al., 2019). Vegetated wetland restoration is strongly suggested for ecosystem based coastal defense (Temmerman et al., 2013). However, biologically mediated modifications of the abiotic environment are subject to biophysical traits that vary among relevant ecosystem engineering species. The drag and dissipation were higher in vegetation with stiff leaves (salt marsh plants) sensitive to hydrodynamic forces compared to seagrasses with leaves that easily bend with the flow (Bouma et al., 2005). Seagrass posture was found to play a key role by posture-based force balance including posture-dependent drag and the restoring forces due to vegetation stiffness and buoyancy (Nepf,

2012). Beside wave conditions and water depth, plants height and flexibility determined the effect of two salt marsh species on flow velocity reduction in a flume experiment where stem folding and breakage occurred in stiff stems under storm surge conditions (Rupprecht et al., 2017).

Salicaceae (poplars and willow species in the willow plant family) have been planted worldwide for ecosystem services since millenia. The use of floodplain *Salicaceae* species became particularly popular to protect banks from soil erosion and for streamside restoration by creating riparian buffers (FAO, 2014). In active floodplains of large rivers, disturbance resulting from erosion and sedimentation processes during high flow interacts with the *Salicaceae* (Karrenberg et al., 2002). The habitat acts as template on which evolution forges determine characteristic life history traits (e.g. Townsend and Hildrew, 1994; Grime, 2001). Floodplain willows have developed flexible branches that bend but do not break in high flood waters (e.g. Vischer and Oplatka, 1998). Kouwen and Fathi-Moghadam (2000) and Oplatka (1998) determined a linear relationship between the drag force and the mean flow velocity for flexible, submerged plants. This contradicts (e.g. Petryk and Bosmajian, 1975) where study species were regarded as rigid cylinders, which, uniformly distributed along the bed channel, increased the drag with the square of the velocity. The willow high shoot flexibility during juvenile stage and narrow leaf blades are also adaptations to withstanding high flow velocities (Ellenberg and Leuschner, 2010). Similarly, model blades from flexible aquatic vegetation remained upright when hydrodynamic forcing is small but when exceeding the restoring forces, the blades are pushed over by the flow, and the quadratic drag law no longer applies for natural systems ranging from seagrasses to marine macroalgae (Nepf, 2012). Complex, flexible, and dense woody vegetation bends in response to high currents reduces velocities thereby inducing lower turbulence levels. This vegetation type may be regarded as suitable for bank stabilization and erosion control, especially when applied in high individual density. To the contrary, stiff

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and dense mature woody vegetation reduces current velocities but does not bend. Large woods may thus cause turbulences, reduce a river discharge cross section and cause flooding (Florineth, 2004). However, mangroves and salt marshes mitigate flood risks along coasts, whereas the storm surge spreading through the tidal wetlands was found to be correlated to the wetland area (Van Coppenrolle et al., 2018). In addition to the foreshore width, the effectiveness of wave attenuation by intertidal habitats decreases with flooding depth (Bouma et al., 2014).

Willows are characteristic in riverine floodplains (Ellenberg and Leuschner, 2010) and settle along estuaries in the temperate climate high in the intertidal (Markus-Michalczyk and Hanelt, 2019) where they tolerate a semidiurnal flooding at least up to 60 cm (Markus-Michalczyk et al., 2016). Floodplain plants affect the flow field by additional drag reducing the velocity within vegetated regions relative to unvegetated ones (Wilson et al., 2003). Floodplain forests are characterized by *Salix alba* trees e.g. in the Danube Delta (Dickmann and Kuzovkina, 2014) and in the Elbe and the Scheldt estuaries above the mean high-water line (Struyf et al., 2009) and up to the mesohaline estuarine stretch (Markus-Michalczyk et al., 2014). *Salix viminalis* specimen form thickets fringing the floodplain forest along the water edge (Ellenberg and Leuschner, 2010). Both *Salix* species developed life history traits adapted to the floodplain ecosystem, e.g. disperse by vegetative propagates that are fragmented by wind and water currents (Karrenberg et al., 2002). An important determinant of the survival and growth of propagules are base flows and subsequent floods with various magnitude and frequency that may bury or cause scour on establishing willows (González et al., 2018) and flow velocities must be taken in account in floodplain forest conservation, restoration and the use of the willow in flooding defense. We include seasonal (leafy status in summer versus leafless status in winter) and spatial differences as factors in our study: Spacing can produce complex flow patterns since a branching network of channels in areas of vegetation provides most of the flow conveyance whereas densely vegetated regions are predicted to provide most of the ecosystem function and particle trapping (Nepf, 2012). We report results from our flume study on effects of living rooted juvenile willows grown from vegetative propagules on water flow velocities. The use of living rooted juvenile willows in flume tests is for the first-time. We used willows based on findings in a former experiment on high bending modulus values of one-year old *S. alba* (mean 440.6) and *S. viminalis* (664.1) plants grown from cuttings that were tested in a previous mesocosm experiment (Markus-Michalczyk et al., 2019). We analysed the current-vegetation interaction in the canopy of two keystone species (*Salix alba* L. and *Salix viminalis* L.) to answer the following questions:

- (1) How do seasonal differences in the willow biophysical traits during (i) leafy status in summer and (ii) leafless status in winter affect the current flow velocity?
- (2) Does the spatial design (i) among the two willow species, (ii) within the willows (dense versus sparse), and (iii) the spatial width (single versus doubled vegetation test section length) affect the current flow velocity?

2. Material and methods

2.1. Study species

We used the vegetative reproduction capacity in both *Salix* species (*S. alba* and *S. viminalis* are able to regenerate via fragmented vegetative propagules), to generate juvenile willow plants for the experimental set up in our flume study. On January 3rd, 2017, forty willow cuttings of both ten *S. alba* and ten *S. viminalis* individuals were collected in tidal wetlands along the tidal freshwater section of the Elbe estuary near Hamburg (53°24'04.98''N; 10°11'55.66''O). These cuttings were stored completely submerged in water and placed in plastic boxes in 7 °C in a refrigerator until March. On March 17th a sieved (sieve size 17 mm × 40 mm) mixture of half river sand and planting soil containing 10% organic

component (Terrafin BV) was filled in plastic pots (13 cm high; 13 cm width and length). The *Salix* cuttings were equally shortened to 20 cm length, weighed (0.1g precision), planted in the pots and placed in plastic mesocosms to grow under ambient conditions in the outdoor ground at NIOZ Yerseke, NL (51°29'17.18'' N; 4°03'26.00'' O).

We recorded important biophysical traits of the willows used in the flume tests. These traits were recorded in different seasons (summer/July - directly after the flume tests on the willows in the leafy status and winter/November - directly after the flume tests on the willow in the leafless status). Stem density was used as a factor. The stem density was recorded as stems per square metre. The number of shoots with more than one-centimetre length that developed as individual twigs from the cutting were recorded. The number of leaves were recorded by the number of each fully developed leaf per cutting and species. Shoot height was measured with a folding ruler for each shoot that was grown from the cutting. When multiple shoots were developed, the average shoot height was calculated. Shoot diameter was measured at the base of each newly grown shoot using a digital caliper. Bending modulus values were recorded in a previous experiment on similar aged *S. alba* (mean 440.6) and *S. viminalis* (mean 664.1) plants grown from cuttings (Markus-Michalczyk et al., 2019).

2.2. Experimental set up

We tested seasonal and spatial effects of two willow species on flow velocities in an experimental set up in the flume. For the first time, a series of tests on flow dissipation over living key floodplain willow species (*S. alba* and *S. viminalis*) in both the leafy status and leafless status were carried. The experiment was conducted in a 17 m long, 0.6 m wide, and 0.8 m deep annular flume at Royal Netherlands Institute for Sea Research NIOZ, Yerseke, NL. For a more detailed flume description see Bouma et al. (2005).

The flume tests were carried out in two different seasons by using the same willow individuals – during summer, when the juvenile willows were foliated (August 2017) and during winter, when their leaves have fallen (November 2017). The juvenile willows were maintained in the outdoor ground at NIOZ Yerseke, NL. Immediately before the velocity measurements they were placed in the movable flume boxes. After the velocity measurement they were removed and returned to the plant pool. A vegetated test section was constructed via two movable steel flume boxes (100 cm length x 58 cm width x 13 cm height per each). We arranged the juvenile willows that established in pots within these flume boxes. The soil surface of the pots was covered and levelled with gravel. Afterwards the flume boxes containing the willows were placed within the flume. The vegetated test section was levelled by using gravel and flattened at the same level as the front and the subsequent area of the flume. The water height above the vegetated test section was 40 cm corresponding to the water height that *S. alba* and *S. viminalis* were found to tolerate experimentally in semidiurnal flooding (Markus-Michalczyk et al., 2016) and under field conditions in tidal wetlands (Markus-Michalczyk et al., 2019).

2.2.1. Vegetated test section design

We designed two general arrangements for the vegetated test section: the first by using one flume box and thus applying a vegetated test section length of 100 cm (Fig. 1a); in the second arrangement the vegetated test section was doubled by arranging two flume boxes in a row and thus applying a vegetated test section length of 200 cm (Fig. 1b).

Within the first arrangement, the willows were arranged in a dense design (one willow per 181.25 cm²) with 32 willows in one flume box and in a sparse design (one willow per 362.5 cm²) with 16 willows in one flume box (Fig. 1a). Within the second arrangement, the willows were arranged in a dense design (one willow per 181.25 cm²) with 64 willows in two flume boxes, and in a sparse design (one willow per 362.5 cm²), resulting in 32 willows in two flume boxes. In the double box

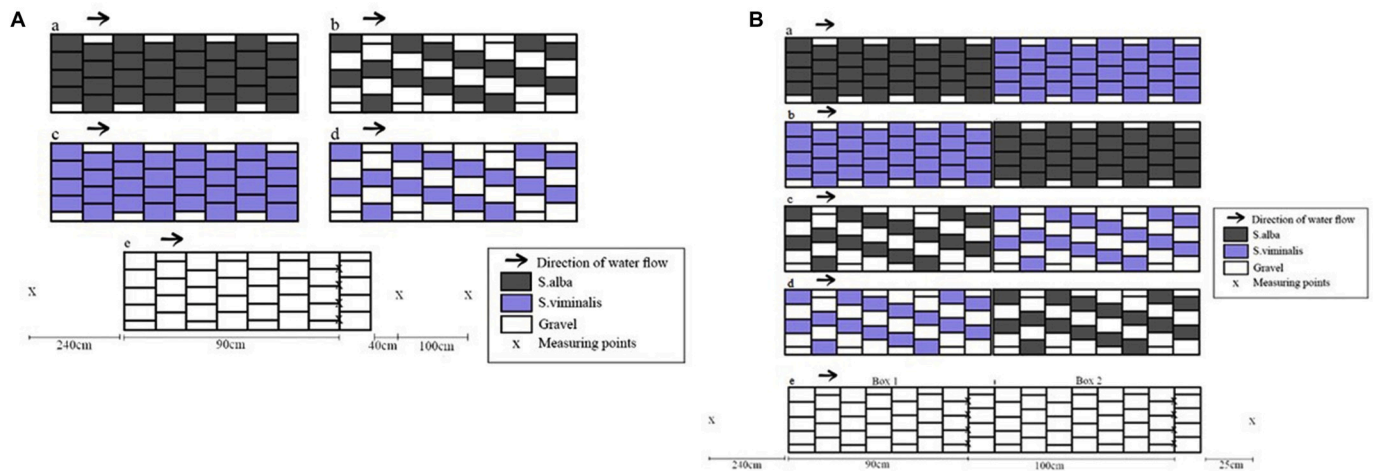


Fig. 1. Vegetated test section design of juvenile willows (*Salix alba* and *Salix viminalis*) in single (one flume box) (a) and doubled (two flume boxes) (b) vegetated test section length applied in flume test series at NIOZ Yerseke, NL.

arrangement, the juvenile willow of two species were arranged in two different orders: *Salix alba* in front of *S. viminalis* and vice versa in both the dense and the sparse design (Fig. 1b). The second arrangement with a vegetated test section length of two meter (two flume boxes in a row) was only applied for the tests during the dormant stage of the willows during November 2017. The willows that were used for the arrangements in the vegetated test section were chosen randomly by using a random generator from the plant pool.

2.2.2. Experimental programme

Three water flow velocities (respectively 0.2, 0.3, 0.4 m/s) were applied in series to willows that were randomly selected from the plant pool to analyse the vegetation-current interaction in canopies of *S. viminalis* (Fig. 2a) and *S. alba* (Fig. 2b) in different designs. Velocity measurement points for the first arrangement (using one flume box) were located 240 cm in front of the vegetated test section, 90 cm within, and 40 cm and 100 cm behind the vegetated test section. Velocity measurement points for the second arrangement (using two flume boxes) were located 240 cm in front of the vegetated test section, 90 cm and 190 cm within, and 30 cm after the vegetated test section.

An Acoustic Doppler Velocimeter Profiler (Nortek®), which measures a small 3 cm velocity profile split in 30 1-mm cells, was positioned at four heights in the water column, (6, 8, 16 and 30 cm) in the centre of the flume - equidistant from each side - to obtain a velocity profile ranging from the near-bed zone to just below the water table. The ADV was set to record flow velocity at 75Hz for at least three minutes in order to obtain reliable velocity data. Data was filtered on data quality before being analysed. The minimum Signal to Noise Ratio (SNR) was set to 30, minimum reflectance amplitude was set to -25Hz, and the minimum correlation value was set to 95. Remaining velocity measurements were averaged over time and over the 3.0 cm profile to obtain single point measurements, reducing errors due to possible fluctuations in velocity caused by the constant movement of the willows and bias due to the positioning of the ADV relative to the willows.

2.3. Data analyses

We applied ANOVAs to test for the effects of species (*S. alba* versus *S. viminalis*), seasonality (leafy willows in summer versus leafless willows in winter) and spacing (dense versus sparse design) on current velocity in a height of 8 cm, 16 cm and 30 cm above the bed on both the results tests on single box and double boxes used in the flume test section.

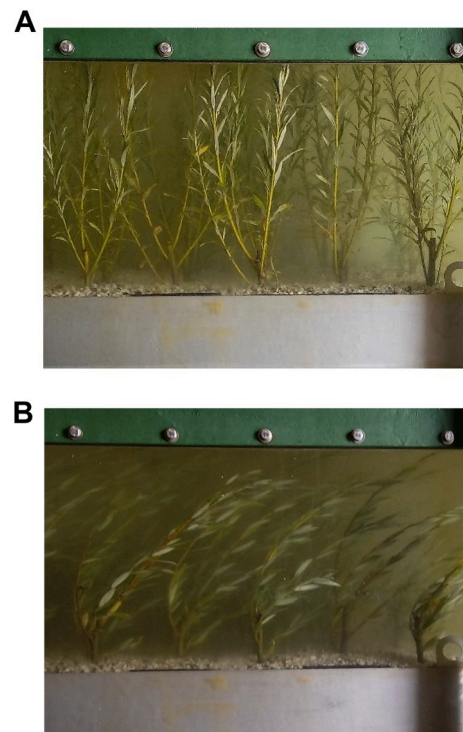


Fig. 2. Detail of the side view on the vegetated test section with flume boxes containing juvenile floodplain willows (a: *Salix viminalis* without applied current velocity; b *Salix alba* with an applied current velocity 0.4 m/s), water height 40 cm, in a flume test series at NIOZ Yerseke, NL.

3. Results

3.1. Biophysical traits of *Salix alba* and *S. viminalis*

Salix alba and *S. viminalis* differed with respect to their shoot and leaf number, shoot height and shoot diameter among summer in the leafy and winter in the leafless status (Table 1). In summer (corresponding to the flume tests on the willows in the leafy status), the mean shoot number per juvenile willow was higher in *S. alba* compared to *S. viminalis* whereas leaf density was higher in *S. viminalis* compared to *S. alba*. In winter (corresponding to the flume tests in the leafless status in November) shoot density remained similar in both species. Shoot

Table 1

Biophysical traits of the shoots (number per cutting; diameter and shoot length) and the leaves (average number per developed shoot per cutting) of the willows - juvenile specimen of *Salix alba* (Fig. 2a) versus *S. viminalis* (Fig. 2b) - in the vegetated test section of the flume. Data were recorded in summer (July - corresponding to flume tests on willows in leafy status) and in winter (November - corresponding to flume tests on willows in leafless status) (N = 32; mean ± -SD).

	shoots		leaves	
	no/cutting	diameter (mm)	length (cm)	no/cutting
<i>S. alba</i> /leafy	5.2 ± 1.7	3.0 ± 0.4	22.5 ± 6.7	20.0 ± 3.3
<i>S. viminalis</i> /leafy	3.4 ± 1.3	4.0 ± 0.7	31 ± 7.8	47 ± 11.1
<i>S. alba</i> /leafless	5.2 ± 1.7	3.8 ± 0.6	31 ± 8	-
<i>S. viminalis</i> /leafless	3.4 ± 1.3	4.8 ± 0.7	38 ± 11	-

diameter was larger in *S. viminalis* compared to *S. alba* and mean shoot length was similar larger in *S. viminalis* compared to *S. alba* in September. In winter, a small increase in shoot diameter was found for both *S. alba* and *S. viminalis*, and in mean shoot length (*S. alba* 31 cm versus *S. viminalis* 38 cm).

3.2. Effects of juvenile willows on flow velocities in flume tests

Generally, the flow reduction directly behind the vegetated test section of the single box design was highly significant ($p < 0.001$) at an ADV-height of 8 cm ($F = 19.87$), 16 cm ($F = 8.77$) and for 30 cm ADV height ($F = 17.82$) for both willow species (*S. alba* and *S. viminalis*) in both densities (dense and sparse) and during both seasons (leafy status during summer; leafless status during winter). The flow reduction

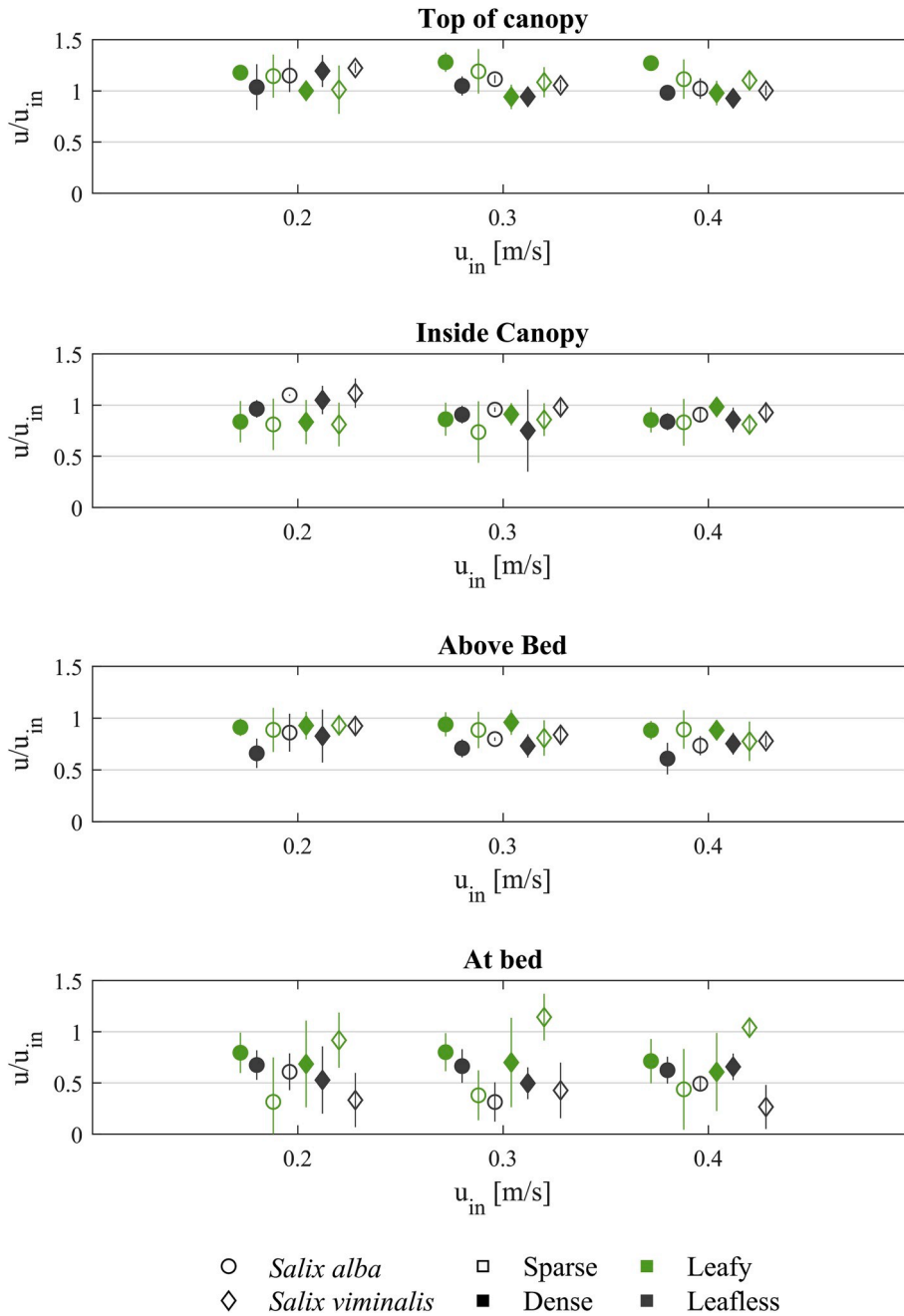


Fig. 3. Effects of juvenile floodplain willows of two species (*Salix alba* and *Salix viminalis*) in two designs (sparse/dense) during two seasons (summer/winter) on three applied flow velocities (u_{in} : 0.2, 0.3 and 0.4 m/s; u/u_{in} is the measured velocity relative to the free stream velocity) in four different measurement heights (top of canopy, inside canopy, above bed, at bed) in a flume test series at NIOZ Yerseke, NL.

directly behind the double box design during the leafless status of the willows was also highly significant ($p < 0.001$) at an ADV-height of 8 cm ($F = 12.65$), 16 cm ($F = 62.56$) and for 30 cm ADV height ($F = 27.26$) (Fig. 3).

All of the four vegetated test section designs applied by using one flume box - dense and sparse design with *S. alba*, and dense and sparse design with *S. viminalis* - demonstrated an effect of seasonal differences (effect of presence and absence of foliage) on the water flow velocity (Figs. 3–5). Seasonality influenced flow velocity significantly at 8 cm height ($F = 10.51$; $p < 0.01$) whereas flow was more reduced during winter. The effect of species was highly significant ($F = 11.84$; $p < 0.001$) whereas *S. alba* reduced the flow less compared to *S. viminalis* in a height of 30 cm. Moreover, the test on the double box set up showed significant reducing effects of vegetation density in a height of 8 cm ($F = 6.11$; $p < 0.05$), 16 cm ($F = 10.41$; $p < 0.01$) and 30 cm ($F = 6.09$; $p < 0.05$) above the bed. Furthermore, the order of boxes influenced the flow velocity significantly in a height of 8 cm near the bed. The arrangement of *S. viminalis* in front of *S. alba* reduced the flow velocity significantly more compared to *S. viminalis* ($F = 4.27$; $p < 0.05$).

3.2.1. Seasonal effects (presence and absence of leaves) of juvenile willows on flow velocity in flume tests

All of the four vegetated test section designs applied by using one flume box - dense and sparse design with *S. alba*, and dense and sparse design with *S. viminalis* - demonstrated an effect of the seasonal differences on the water flow velocity.

In the applied flow velocities of 0.2, 0.3, and 0.4 m/s, the velocity in the canopy decreased to a larger extent in the leafless status. To the contrary, the velocity decrease above the bed is less pronounced in the leafless status compared to the leafy willows. Generally, seasonal differences among the flow velocities in the canopy decreased towards the higher flow velocities. The differences between the sparse and dense design were minor. However, the higher plants number per area was found to slightly emphasize the flow velocity reduction during winter. To the contrary, the sparse design may increase flow velocity reduction during summer. Regarding interspecific differences, *Salix alba* seemed to be slightly more efficient in flow attenuation during winter compared to *Salix viminalis*, both near the bed and within the leaf canopy (Fig. 3).

Seasonal effects were found in the vertical flow profiles for the dense willow design in the vegetated test section with the contrasting effects between the leafy (summer) and leafless (winter) *Salix alba* and both species, *S. alba* and *S. viminalis* (Fig. 4). During summer, the flow velocity decreased within the leafy canopy of *Salix alba* but flow velocity increased at the top of the canopy. We suggest, that the flow velocity may have induced the bending of the flexible shoots of the *Salix alba*

leafy canopy (Fig. 2b) and thus decreased. However, the bending may have induced a deflection of the flow energy towards the top of the canopy at the surface where the canopy is less dense (not so many shoots and leaves) and thus led to the increased flow velocity. Similarly, the flow velocity below the leafy canopy was less reduced compared to the flow within the canopy. During winter the flow velocity inside the *Salix alba* canopy is higher compared to summer. The increasing flow velocity towards the gravel bed are not present as more water can flow through the canopy, thus the flow profile is roughly lognormal. Therefore, near-bed flow reduction is greater during winter. Leafy *Salix viminalis* does not have such a clear influence on the vertical flow profile. During both summer and winter flow velocity is only reduced by 3 cm/s inside the canopy. Like in *Salix alba*, the flow profile is roughly lognormal during winter, and near-bed flow reduction is greater in winter than during summer.

The seasonal differences (presence versus absence of leaves) in flow velocity reduction are larger in comparison with the interspecific differences (*Salix alba* versus *Salix viminalis*) (Fig. 4). In particular above the bed both willow species induced a larger velocity decrease in the leafy status during summer compared to the leafless status during winter. Inside the canopy, the flow velocity reduction was similar for both species and for both the presence of leaves during summer compared to the absence of leaves during winter.

3.2.2. Spatial effects of juvenile willows on flow velocity in flume tests

All of the four applied vegetated test section designs (*Salix alba* and *S. viminalis* in both dense and sparse arrangement) showed an effect of the spatial differences on the water flow velocity (Fig. 5).

Generally, the flow reduction increased with the increased vegetated test section length (Fig. 5). At the first measurement point behind the vegetated test section, the flow velocity decreased to a larger extent compared to the second measurement point behind the vegetated test section. Thus, the flow velocity was most reduced directly behind the willows. The velocity decreased with increasing vegetated test section length: two flume boxes with a doubled number of willows led to a doubled velocity decrease compared to the application of one flume box and half the used number of willows in the single vegetated test section length. Moreover, interspecific differences affected flow velocity. *Salix alba* reduced the velocity more effective within the vegetated test section whereas *Salix viminalis* reduced the flow velocity more effective behind. In addition, similarities between the doubled and single vegetated test section length indicate that the order of *Salix* species matters as the species that occurs first in the arrangement seems to determine the total amount of flow reduction.

The graphs on the effects of the single vegetated test section length show that the flow velocity starts to increase again after the largest reduction directly behind the test section. This may be due to largely reduced flow velocity in the centre of the willow canopy in parallel to the increased flow velocity at the willow surface (Fig. 2b; Fig. 4). The overall flow of both from the canopy and the surface may have added up and induced the increased flow velocity in more distant behind the vegetated test section. Unfortunately, it is not possible to determine at what distance the flow velocity normalizes due to the flumes limited straight length. However, overall all presented graphs show a unifying velocity decrease optimum right behind the end of the vegetated test section.

4. Discussion

We studied seasonal (summer - leafy willows - versus winter - leafless willows) and spatial (density and linear extent of cover) effects of two floodplain willow species on water current velocity in the flume. Our results showed that juvenile willows generally reduce the flow velocity. The velocities were most effective in reducing flow velocity during the dormant stage in winter. The flow velocity was most reduced directly behind the willow vegetation independent from the linear extent of

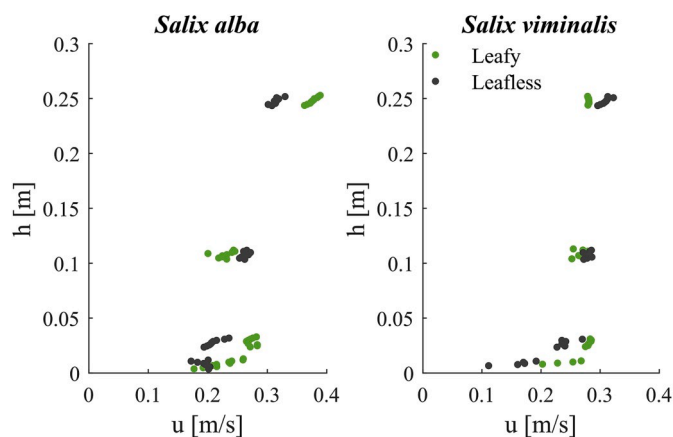


Fig. 4. Seasonal effects of 0.3 m/s flow velocity (verticale profile) on juvenile floodplain willows of two species (*Salix alba* and *Salix viminalis*) in a dense design (one willow per 181.25 cm²) during two seasons (summer/winter) at a water column height of 40 cm in a flume test series at NIOZ Yerseke, NL.

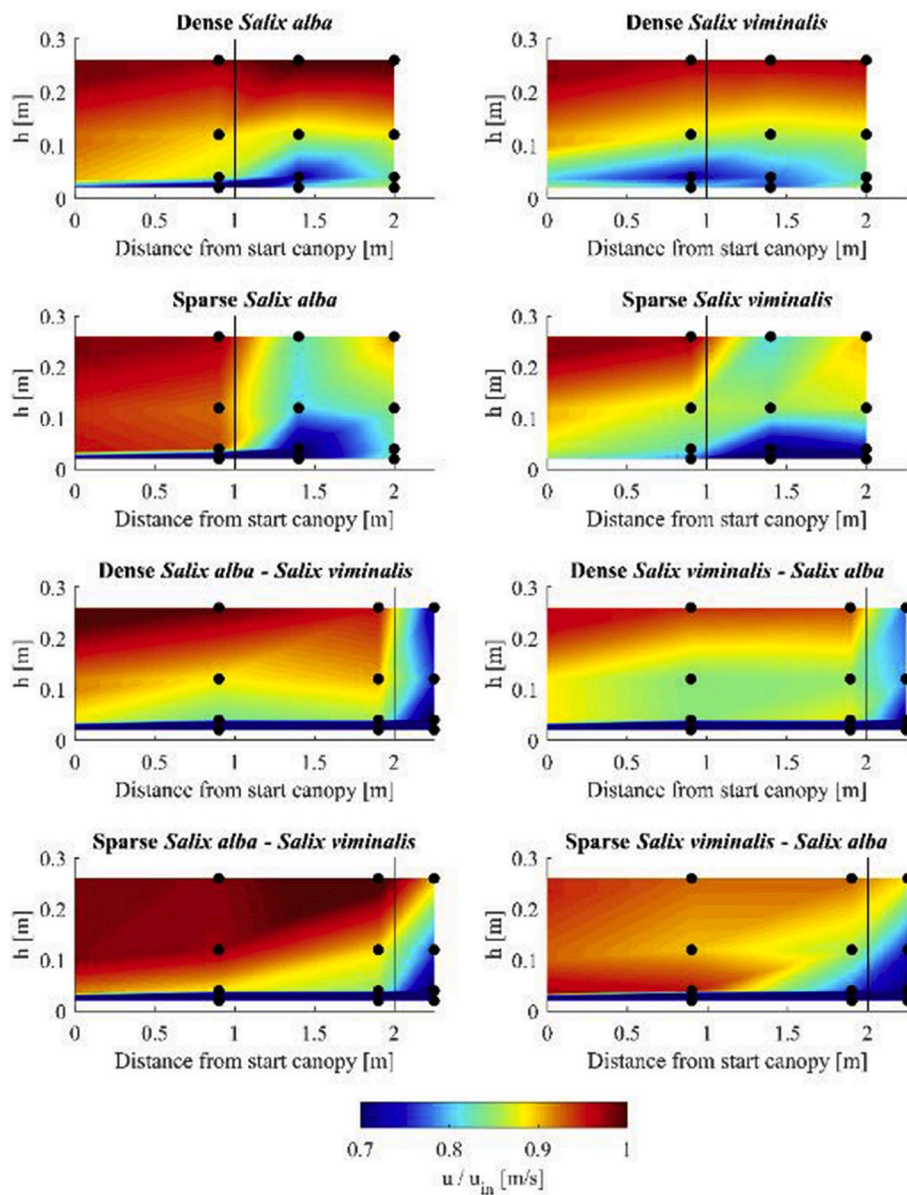


Fig. 5. Horizontal flow velocity profiles (ADV height 16 cm (a) and 8 cm (b)) on spatial effects of a doubled (upper graph series) and a single (graph series at the bottom) vegetated test section length containing juvenile floodplain willows of two species (*Salix alba* (A) and *Salix viminalis* (V)) in both a dense design (one willow per 181.25 cm²), (D), and a sparse design (one willow per 362.5 cm²), (S), in a flume test series on plants in the dormant stage at NIOZ Yerseke, NL. The vertical line represents the end of the vegetated test section.

willow cover. However, during the winter (absence of leaves) spatial effects differed among the willow species: *S. alba* reduced the flow primarily within the vegetation but *S. viminalis* attenuated behind the boxes of vegetated test section in the flume.

4.1. Biophysical traits of *Salix alba* and *Salix viminalis*

The effect of plants on flow velocity has been earlier described as a simple schematization (e.g. Petryk and Bosmajian, 1975) where study species were regarded as rigid cylinders, which, uniformly distributed along the bed channel, increased the drag with the square of the velocity. Pasche and Rouvè (1985) highlighted already that in case of groups of plants the “cylinders” cannot be treated as isolated, and the reference velocity is in turn affected by the plants. Kouwen and Fathi-Moghadam (2000) and Oplatka (1998) determined a linear relationship between the drag force and the mean flow velocity for flexible, submerged plants. Flow velocity was counterbalanced by the deflection of plant leaf area and by the reduction of drag coefficient due to the more streamlined configuration of the plant (bending of leaves and shoots, Fig. 2b). We found a similar pattern behind the vegetated test section in

particular in the single box set up.

Floodplain willows are adapted to currents e.g. by a high flexibility (Ellenberg and Leuschner, 2010) whereas for shoots grown from cuttings a bending modulus of 440.6 was found for juvenile *S. alba* and 664.7 for *S. viminalis* plants (Markus-Michalczyk et al., 2019). Since these were similar juvenile plants as in the flume study it is assumed that the bending values are comparable. Further plant traits that affect flow velocity are the plant density in the canopy (Florineth, 2004), and shoot length and diameter (Västilä and Järvelä, 2014; Wang et al., 2015). Our results on *Salix* shoots and leaves were interspecifically different (Table 1): *Salix alba* showed a larger shoot density (shoots per cutting) during both seasons, whereas *S. viminalis* developed longer shoots and larger diameters; *Salix viminalis* showed a larger leaf density in summer compared to *S. alba* (Table 1).

As this was found for the willow plants foliage (Armanini et al., 2005) an increasing diameter led to increasing friction while water flow velocity decreased (Zhao et al., 2016). Their findings on flow velocity reduction may correspond to our above-mentioned findings on interspecific similarities in seasonal and spatial effects on flow velocity reduction in *S. alba* and *S. viminalis*. Contrary to juvenile willows flexible

shoots, strong tree trunks may cause severe turbulences that lead to erosion and bank destabilization (Florineth, 2004).

4.2. Seasonal effects of juvenile willows on flow velocity in flume tests

The larger velocity reduction above the bed during winter compared to the larger velocity reduction in the canopy during summer was found to be a contrasting seasonal effect. The large flow velocity reduction during winter may have important implications for bed stability. Vice versa, the high willow leaf density of more than 20 per plant in *S. alba* and more than 30 per plant in *S. viminalis* during summer may have increased the drag and thus deflected the flow more towards the bed. A contribution to the resistance by the foliage of the flexible willow was found in flume experiments (Armanini et al., 2005). Here, the flexibility of willows in submerged conditions led to a decreasing drag coefficient with increasing flow velocity because of the decreasing absorbing area of the studied *S. alba* plants. This corresponds to our findings on decreasing flow velocity differences in the canopy between summer and winter with increasing free flow velocity, possibly due to the reconfiguration of the leaves and shoots at higher flow velocities. The leaves are keeping the drag more constant: as during summer the velocity reduction inside the canopy remained equal for all velocity settings. To the contrary, the bending of the leafless shoots apparently decreased the drag coefficient, hence the decreasing flow reduction with increasing velocity setting. A vegetation reconfiguration according to flow direction with increasing velocity consequently reduces the willow plant roughness (e.g. Kouwen and Fathi-Moghadam, 2000). Järvelä (2002) found a higher friction factor of leafy compared to leafless willows by two to three folds whereas the maximum was obtained when the flow velocity in the flume was low which corresponds to our results.

Generally, floodplain willows are characterized by narrow leaves. Moreover, *S. alba* as the key species in lowland floodplain forests develops highly flexible juvenile branches that easily bend adapted to high flow velocities along streams (Ellenberg and Leuschner, 2010). Juvenile willows of species used in bank stabilization adapt their shape to water velocity by bending and merging their branches: Drag force and flow velocity follow a linear relation for flexible bodies (Oplatka, 1998). However, turbulence intensities indicate that the additional frontal plant alters the momentum transfer between the within-canopy and surface flow regions. While the frond foliage induces larger drag forces, shear-generated turbulence is reduced due to the inhibition of momentum exchange by the frond surface area (Wilson et al., 2003). The contribution of the leaves to the plants frontal area may thus be the reason for the unexpected lower velocity reduction of the near bed velocity during summer compared to the larger effect of the leafless willows on flow velocity decrease during winter. This unexpected lower velocity reduction during summer was true for both willow species in our experiment. These results correspond to adaptations which follow both streamlining water flow velocities in the floodplain environment: the more flexible juvenile branches in *S. alba*; more linear long leaf blades in *S. viminalis* (Ellenberg and Leuschner, 2010). Accordingly, our observed seasonal differences are more pronounced compared to the interspecific differences in flow attenuation. However, resistance values generally increase with willow age and stem diameter (Oplatka, 1998), and although juvenile twigs show a high bending stability, older branches easily break off and plant fragments serve a vegetative propagule dispersed by powerful floods (Karrenberg et al., 2002). Willows have a high resprouting capacity, thus, this sort of natural coppicing of the older willows may enhance the production of more new flexible shoots that are more efficient for flow reduction during winter. Willows with juvenile flexible branches may be more useful for flow reduction during the stormy season in winter and more efficient in trapping sediments due to flow reduction during their dormant stage. Oplatka (1998) highlights both juvenile shrubby and treelike floodplain willows with flexible branches up to five years age as appropriate for the use in bioengineering.

The impact of different arrangements of leafless willows on the friction factor was negligible in a flume study on natural combinations of willows and grasses (Järvelä, 2002), which corresponds to our results. For leafless willows, the friction factor while independent from the flow velocity increased linearly with the water depth. However, in that study, the use of unrooted willow branches may have biased the results whereas in our experiment the willow was allowed to develop both aboveground and belowground biomass for month and thus approximates natural conditions. The different willow arrangements in our study – dense and sparse – seemed almost negligible but increasing plant density slightly reduced the flow velocity, eventually promoted by deep-rooted leafless willows during winter.

Although *S. viminalis* showed larger mean diameter and shoot length, *S. alba* appeared to be slightly more efficient in flow attenuation during winter, both near the bed and inside the canopy possibly due to the recorded nearly doubled willow shoot density. Järvelä (2002) similarly found increasing friction factor with doubled willow density in the variation of vegetation spacing. However, nothing was said about the *Salix* species selection in that study, although willows show large interspecific differences in growth and shape (e.g. Dickmann and Kukovkina, 2014). Righetti (2008) simulated the porosity of vegetation evaluated on the banks of naturalized torrents in flume experiments for the sparse and dense configurations of *Salix pentandra*, a willow used in restoration works along mountain streams, e.g. in Trentino. With increasing vegetation density and for a given discharge, the drag per unit bed surface tended to increase, while the drag exerted by a single willow decreased. The flow velocity, the vegetation density and the plant flexibility were suggested as driving parameters. Since *Salix* shows large interspecific differences in shoots flexibility (e.g., *S. viminalis* showed a higher tendency to resist bending compared to *S. alba*), it is important to select *Salix* species for restoration projects with care (Markus-Michalczyk et al., 2019). Flow resistance may similarly be influenced by the reconfiguration of flexible blades (Nepf, 2012) and thus the willows' use should be applied with respect to the seasonal differences in flow attenuation. Our findings on contrasting spatial effects among the two studied floodplain willow species may add up and enlarge attenuating effects. During winter (absence of leaves), *S. alba* reduced the flow primarily within the vegetation but *S. viminalis* attenuated behind the vegetation. We thus suggest to carry out field studies to test whether interplanting of the two willow species or row plantations with *S. alba* close to the stream bed and *S. viminalis* on the shoreward side may enhance flood protection in riverine floodplains, and tidal wetlands estuarine and coastal environment.

Findings on our observed effects of leafy willows due to the large flow attenuation of the dense canopy on both above and below the canopy should be taken into account. However, the observed channelling of flow under the foliage along the bed may increase scour and erosion. Destabilisation may be particularly high in natural substrate - sand in a lowland estuary - and it would be interesting to test the effect of root density. However, in our study we wanted to test for the effect of plant traits on flow velocity. Thus, a moving substrate may have biased the results. We added "gravel" in the text to clarify the use of a relatively stable bed in our study. We thank you for the comment and suggest that it would be interesting to test the effects of root density on flow velocity in natural substrate in the future. Since the higher permeability of *S. alba* plants during winter increased flow reduction sparse plantation schemes might be better for long term benefits in flood control.

Our finding on the linear flow reduction of leafless willows from the bed up to the tip of the canopy is in particular important for a possible contribution of willows in coastal engineering since flooding and storm surges along estuaries and the coast are principally more severe during winter. Bouma et al. (2014) state, to contribute to coastal defence, ecosystems should provide either year-round high standing biomass that directly causes wave attenuation or have a biogeomorphic effect on the for-shore bathymetry that enhances wave attenuation. In herbaceous plants seasonality affects attenuating effects e.g. seagrass meadows or

coastal salt marshes lose their aboveground biomass during winter (Koch et al., 2009). Thus, the presence of flexible shoots that maintain their function and even optimise water flow reduction during winter may be an outstanding advantage for the use of the willow in flooding defence. However, we conducted our study on one-year-old willows with flexible shoots. We suggest to investigate older willows with larger shoots or trunks that may enhance the attenuating effect on flow velocities, break, or even cause adverse turbulences. Moreover, the high extraction resistance of willows (e.g. three to six-year-old willows grown from cuttings showed a five-fold stronger resistance to the flow than a velocity of 4 m/s affects on the plants (Oplatka, 1998) would allow to apply higher flow velocities compared to the limited dimension of our used flume. Rooted willow cuttings (after planting in April 2014) grew to juvenile trees when planted in tidal floodplains: *S. alba* height increased to 3.5m (± 0.7 m SD) and *S. viminalis* height increased to 2.9m (± 0.6 m SD) in summer 2016 (Markus-Michalczyk and Michalczyk, 2018). Thus, future flow reduction tests on older willows with larger shoots should be applied either in a larger flume or in the field.

4.3. Spatial effects of juvenile willows on flow velocity in flume tests

Largest effects of juvenile willows on flow velocity reduction were recorded directly behind the vegetated test section in the flume. This may be due to reduced flow energy within the willow patch, so that directly behind the largest vegetation width the flow is lowest. Thus, willow patches may be planted perpendicular to the flow in horizontal lines in front of objects worthy of protection (e.g., the dike). Effects of flexible and permeable floodplain plants prevent local erosion while enhancing deposition of sediments. The level of flexibility and permeability determines the ecosystem engineering capacity (Euler et al., 2014).

The applied vegetation test section length also played a crucial role in spatial effects. The doubled number of used willows in the doubled vegetated test section length induced a doubled reduction of flow velocity closely behind the willows in our experiment and may have important implication for flooding protection. Natural selection of ecosystem-engineering species may have consequences for the surface processes and often feed back to the structure and function of the ecosystem and to adaptation and speciation of engineer species (Corenblit et al., 2011). Accordingly, the ecosystem engineering species differed in spatial effects on flow reduction in our study: *S. alba* showed stronger effects within the vegetated test section but *S. viminalis* was more effective in reducing the flow behind. This applies similarly to the order of the species for the doubled test section length: The first positioned species may determine the amount of flow reduction, as shown by the similarity between the first species of the double box setup and the species of the single box setup. In the floodplain environment, *S. viminalis* occurs at lower elevations in the horizontal vegetation zonation compared to *S. alba*. The shrubby species forms a belt community with other willow species (e.g. *S. purpurea*, *S. triandra*) that protects against highest levels of physical disturbance. The white willow floodplain forest acts as sediment trap at locations above MHW level (Ellenberg and Leuschner, 2010) that experience flooding mainly in winter corresponding to our finding on *S. alba* higher efficiency on flow attenuation during the dormant stage when the highly flexible branches remain active.

5. Conclusions

We showed that juvenile floodplain willows reduce flow velocities particularly during winter in the dormant stage when the storm season occurs due to enhanced canopy permeability but simultaneously maintained shoot length and diameters. Different spatial effects between the two studied floodplain willow species may add up and enlarge attenuating effects: *S. alba* reduced the flow primarily within the vegetation but *S. viminalis* attenuated behind. Estuarine biota is adapted to the

estuarine systems high inherent variability (Ducrottoy et al., 2019) what may also confer on the willow resistance and resilience to stream flow velocities. More research is needed for willow forest restoration and flooding protection in tidal wetlands of the estuarine and coastal environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Heike Markus-Michalczyk: Conceptualization, Methodology, Investigation, Data curation, Supervision, Writing - original draft. **Jaco de Smit:** Methodology, Visualization, Supervision. **Zhenchang Zhu:** Methodology. **Alexander Mchedlishvili:** Investigation, Data curation. **Janneke van Bree:** Investigation, Data curation, Visualization. **Tjeerd J. Bouma:** Conceptualization, Supervision.

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Appendix A. Supplementary data

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