

# Flow Structures Within Aquatic Vegetation under Combined Current and Wind-driven Wave Conditions: Field Observations in Floodplains of Poyang Lake, China

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## Abstract

Field measurements were conducted in floodplains of Poyang Lake (China) to study the influence of aquatic vegetation on flow structures under combined current and wave conditions. Wave and turbulent velocity components were decomposed from the time series of instantaneous velocity and analyzed separately. With weak wave-plant interaction, indicated as the ratio of wave excursion to stem spacing  $Ew/S < 0.5$  in present study, the vertical distributions of time-averaged velocity ( $U_{horiz}$ ) and turbulent kinetic energy (TKE) with the presence of vegetation were similar to that under pure current conditions. For emergent conditions,  $U_{horiz}$  and TKE distributed uniformly through the entire water column or increased slightly toward the water surface. Similar distributions were present in the lower part of submerged vegetation, above which the  $U_{horiz}$  and TKE increased with increasing distance to bed bottom and TKE reached its maximum near the top of vegetation. With small  $Ew/S$  the wave orbital velocity ( $U_w$ ) was not attenuated within vegetation compared with that above the vegetation or near the water surface, and  $U_w$  through the entire water column can be predicted by the linear wave theory. However, the turbulence generated near the top of canopy can penetrate a deeper depth into vegetation with the presence of wind-driven waves than without.

## 1 Introduction

Aquatic vegetation (AV) provides a wide range of ecosystem services. As a primary producer, AV supplies food for herbivorous animals and creates habitats and shelter areas for fish and shellfish (e.g., **Green & Short, 2003** ; **Waycott, Longstaff, & Mellors, 2005** ). In rivers, lakes, and coastal zones, AV protects shorelines, inhibits erosion, and enhances local water quality (e.g., **Barbier et al., 2011**; **Mitsch & Gosselink, 1986** ). AV can also provide significant carbon storage and support infauna diversity (e.g., **Fourqurean et al., 2012** ; **Irlandi & Peterson, 1991** ). Many of these ecosystem services arise as AV has the ability to alter local hydrodynamic conditions. For example, AV can reduce sediment resuspension by damping wave energy (e.g., **Wang, Wang, & Wang, 2010**; **Ros et al., 2014** ; **Luhar, Infantes, & Nepf, 2017** ), and thereby increase light penetration, creating a positive feedback for continued vegetation growth and a stable state with clear water (e.g., **Carr, Dodorico, Mcglathery, & Wiberg, 2010** ; **Scheffer & Carpenter, 2003** ; **Scheffer, Carpenter, Foley, Folke, & Walker, 2001** ; **van der Heide et al., 2007** ). Besides, by reducing sediment resuspension AV suppresses the release of nutrients associated with bed material and thus efficiently inhibits algal bloom (e.g., **McGlathery, Sundback, & Anderson, 2007** ). Therefore, the changes in water motion associated with vegetation need to be investigated to fully understand the ecological function of AV.

In the last decades, flow resistance and structures with the presence of AV under pure-current conditions

have been widely studied in the laboratory (e.g., Ghisalberti & Nepf, 2002, 2004, 2006; Jarvela, 2005; Okamoto & Nezu 2009; Tanino & Nepf, 2008a, b; Yang, Kerger, & Nepf, 2015; Zhang, Lai, & Jiang, 2016 ), in the field (e.g., Cameron et al., 2013; Leonard & Croft, 2006; Leonard & Luther, 1995; Lightbody & Nepf, 2006; Neumeier & Amos, 2006; Zhang et al., 2020 ), and using analytical methods or numerical models (e.g., Etminan, Ghisalberti, & Lowe, 2018; Neary, 2003; Nicolle & Eames, 2011; Pu, Shao, & Huang, 2014; Ricardo, Grigoriadis, & Ferreira, 2018 ). Nepf (2012) has reviewed the mean and turbulent flow structures in detail, and emphasized on the canopy- and stem-scale turbulence generated by AV and their effects on mass transport. Many previous studies have also investigated the interaction between water motion and AV under pure-waves, and most of them were mainly on the damping of waves by vegetation (e.g., Bradley & Houser, 2009; Lovstedt & Larson, 2010; Luhar, Infantes, & Nepf, 2017; Mendez & Losada, 2004 ), the mean and turbulent flow structures within canopy (e.g., Abdolahpour, Hambleton, & Ghisalberti, 2017; Lowe, Koseff, & Monismith, 2005; Luhar, Coutu, Infantes, Fox, & Nepf, 2010; Luhar, Infantes, Orfila, Terrados, & Nepf, 2013; Pujol, Serra, Colomer, & Casamitjana, 2013 ). For example, Lowe et al. (2005) studied the velocity attenuation within a model rigid canopy and a theoretical model was developed to predict the magnitude of in-canopy wave orbital velocity under oscillatory flow. Luhar et al. (2010, 2013) investigated the flow structures within and above a model seagrass meadow and found that a mean current in the direction of wave propagation was generated within the meadow. Zhang et al. (2018) revealed the turbulent structures within submerged seagrass meadow forced by oscillatory flow, and noted that compared with bare bed the turbulence level within meadow was enhanced when the ratio of wave excursion to stem spacing  $E_w / S > 0.5$ .

In many natural settings (e.g., estuaries, shallow lakes connecting to rivers), AV is exposed to conditions with currents and waves coexisted, for which only a handful of studies have considered. Related studies have focused on the wave damping by AV with the presence of currents (e.g., Hu, Suzuki, Zitman, Uittewaal, & Stive, 2015; Lei & Nepf, 2019; Li & Yan, 2007; Losada, Maza, & Lara, 2016; Paul, Bouma, & Amos, 2012 ). For example, Paul et al. (2012) conducted flume experiments with flexible model vegetation and observed that the presence of current reduced wave dissipation by vegetation. Using real vegetation, Losada et al. (2016) found that wave damping was enhanced by current flowing in the opposite direction, but reduced by current in the same direction with wave propagation. However, to our knowledge, few studies concentrated on the flow structures with the presence of AV under combined current and wave conditions.

Field observations were conducted to study the flow structures influenced by AV in floodplains of Poyang Lake. Connected to Yangtze River, Poyang Lake has running water all the year around with stable flow directions from its upstream basin to Yangtze River. Combined with surface wind frequently occurring, the hydrodynamic environment of our study area is dominated by both currents and wind-driven waves. In natural world, the wave field under the direct effect of local wind is an interaction of large numbers of component with different wave periods, direction of propagations and phases, characterized as an erratic (irregular) pattern (e.g., Toffoli & Bitner-Gregersen, 2017 ). This is much more complicated than waves generated by the paddle wavemaker in most lab studies, for which the whole water mass was subjected to wave forcing and the waves generated were regular and linear. In this study, wave and turbulent velocity components were decomposed from the velocity time series by velocity spectrum and analyzed separately. The goals of present study are to investigate the influence of both emergent and submerged vegetations on the vertical distributions of time-averaged velocity, wave orbital velocity, and turbulent kinetic energy ( $TKE$ ) under combined current and wave conditions.

## 2 Study Area

Poyang Lake, the largest freshwater lake in China, is located in the south bank of middle reach of Yangtze River (28°24' ~ 29deg46'N, 115deg49' ~ 116deg46'E). It has a drainage basin area of 162,225 km<sup>2</sup>, occupying about 9% of the Yangtze River basin (Tan, Tao, Jiang, & Zhang, 2015 ). Poyang lake receives inflow via five tributaries, i.e., Xiushui, Ganjiang, Fuhe, Xinjiang, Raohe, and discharges into Yangtze river through a

narrow outlet located in Hukou (Fig. 1a). With seasonal changes of inflow from the five tributary rivers, the water level in Poyang Lake varies dramatically through the year and the maximum inundation area could be 13 times larger than the minimum (Feng et al., 2012). Extreme variability in water level provides favorable condition for the growth of various types of vegetation, making a unique wetland ecosystem formed in Poyang Lake. The vegetation distribution in the floodplains of Poyang Lake is characterized with ringed pattern along the elevation gradient (Wang, Han, Xu, Wan, & Chen, 2014). For example, submerged vegetations (e.g., *Vallisneria natans*, *Potamogeton malaianus*) are distributed in the lower elevation of floodplains with its surface inundated all year round. In the seasonal-inundated floodplains with its elevation between the water level of dry and flood seasons, some emergent aquatic vegetations (e.g., *Carex cinerascens*, *Artemisia selengensis*, and reeds) grow.

The study area (black square in Fig. 1a) was chosen at the southwest part of Poyang Lake. Two sites, located at floodplains formed in Ganjiang River, were selected and named sites A and B from upstream to downstream the Ganjiang River, respectively (Fig. 1b). Water flows from the south to the north (shown by the black arrows in Fig. 1b, 1c, and 1d). As the water surface was also influenced by wind, the hydrodynamic conditions of our study sites were dominated by combined currents and waves. For each site, five cases (Fig. 1c and 1d) with their distribution vertical to the flow direction were selected for velocity measurements in the elevation between dry and flood water level, so that stem densities can be estimated when the floodplain was not flooded. In order to make comparison, a bare-bed case (i.e., S0) located in the mainstream of Ganjiang River was also considered (Fig. 1c). The dominant vegetations of cases in sites A (A1-A5) and B (B1-B5) were different. For site A, the cases were dominated by *Carex cinerascens* and *Artemisia selengensis*, and all the five cases in site B were in the *Phalaris arundinacea* communities. The specific dominant vegetation of each case was listed in Table 1. Velocity measurements were conducted from August 18 to August 24 in the year of 2015. As Duchang Station (with its location shown in Fig. 1a) is the nearest hydrological station to our study area, variation of water level in our measurement sites was assumed to be same with that of Duchang Station. Just as shown in Figure 2a, water level varied within 0.8% from Aug. 18 to 24, indicating that the hydrological condition was stable during the velocity measurements. The wind directions in our study area were mainly toward north during measurements, which can be indicated from the meteorological records (Fig. 2b) observed by the Poyang Lake Wetland Observation Station, Chinese Academy of Sciences, in Xingzi (Fig. 1a). Therefore, surface waves propagated in the same direction with the flow during measurements.

### 3 Methods and Materials

#### 3.1 Vegetation measurements

The dominant vegetations of all cases in present study were *Carex cinerascens*, *Artemisia selengensis*, and *Phalaris arundinacea* (Table 1). For each case, 15 strains of plant were randomly selected during velocity measurement and the vegetation height ( $h_v$ ), stem diameter ( $d$ ), and the blade width were measured to describe the plant morphology. *C. cinerascens* is a kind of herbaceous plant. It has basal blades with a mean of 12 blades for each plant. The blades of *C. cinerascens* are lanceolate and the blade width decreased gradually from the base to the top. According to our survey, the mean blade width was 0.3 cm. *A. selengensis* has rigid and cylinder-like stems with a mean diameter of 0.5 cm for each. Several stems are grown for each individual plant and these stems are divided at the base. The blades of *A. selengensis* are palmate and distributed uniformly from top to bottom of the stem. *P. arundinacea* has stem with a mean diameter of 0.5 cm, and usually 6 ~ 8 knots where blades grow are distributed for each stem. The blades of *P. arundinacea* are lanceolate with the length of 6 ~ 30 cm and maximum width of 1.8 cm for each. For *A. selengensis* and *P. arundinacea*, the blade width near the top of stem is smaller than that of the rest part of stem because new and fresh blades always grow at the top.

The stem density ( $m$ , stems per bed area) was measured one week after the velocity measurements when the flood had already receded to Ganjiang River and the measurement points in sites A and B were exposed to the air. For each case, the stem density was estimated by randomly choosing three 1 m x 1 m quadrats within a 5-m radius of the measurement point. As the stems of *C. cinerascens* are very short, its stem

density was estimated as the number of blades, not individual plants, per unit area in our study. The stem density for each case was listed in Table 1.

### 3.2 Velocity measurements

Instantaneous velocities were collected using a 3-D Acoustic Doppler Velocimeter (ADV, Nortek Vector) in the East-North-Up (ENU) coordinate system. With ENU coordinate system the instantaneous velocities in the east, north, and upward directions can be represented as  $u_e$ ,  $u_n$ , and  $u_u$ , respectively. As ADV measures flow velocity at a specific point (i.e., 15 cm below the probe tip), the measurements of velocity profile need to move ADV vertically, and this was accomplished by using a self-made field observation system, which was described by **Zhang et al. (2020)** in detail. Velocity was recorded for 150 s with sampling frequency of 32 Hz at each measurement point. For all cases except the bare-bed case S0, velocity was measured starting from 5 cm above the bed (i.e.,  $z = 5$  cm with  $z = 0$  representing the bed bottom) at 5 cm vertical increment. With large water depth, velocity profile of the case S0 was measured at 10 cm vertical increment to reduce the uncertainty caused by the variation of hydrodynamic and meteorological conditions (i.e., water level, flow velocity, and wind speed) during measurements. To keep too many blades from blocking the ADV beams, vegetation was removed within a 15 cm diameter of the measurement position.

### 3.3 Data processing

In flows with both waves and currents, the variance in velocity associated with waves is often much larger than that associated with turbulence, and some form of wave-turbulence decomposition must be performed (**Trowbridge, 1998**). For combined wave-current flow, the instantaneous velocity, taking velocity in the east direction ( $u_e$ ) for example, can be decomposed into three parts:

$$u_e = U_e + u_{we} + u_e' \quad (1)$$

in which  $U_e$  is the time-averaged velocity,  $u_{we}$  is the unsteady wave velocity, and  $u_e'$  is the turbulent velocity fluctuation, and similarly for  $u_n$  and  $u_u$ . Spikes in the velocity record were removed using the acceleration threshold method that the instantaneous acceleration (i.e., the difference between two adjacent instantaneous velocity records divided by the sampling interval) should be less than the acceleration of gravity (**Goring & Nikora, 2002**). After de-spiking, the time-averaged velocity was calculated as:

$$U_e = \frac{1}{T_d} \int_0^{T_d} u_e(t) dt \quad (2)$$

in which  $T_d$  is the time duration for each measurement point, and similar for  $U_n$  and  $U_u$ . As the flow direction was not the same for all cases, the time-averaged horizontal velocity,  $U_{horiz}$ , was used for comparison between different cases and can be calculated as:

$$U_{horiz} = \sqrt{U_e^2 + U_n^2} \quad (3)$$

The time-averaged vertical velocity,  $U_{vert}$ , can then be expressed as  $U_{vert} = U_u$ .

In present study, a method of spectral decomposition was employed to decompose the wave and turbulent velocities. In the power spectral density (PSD) of the instantaneous velocity of flow with both waves and currents, wave signal (grey circles in Fig. 3a) is indicated as peaks around the dominant wave frequency and spectra outside the wave domain (black line in Fig. 3a) indicate the signal of flow turbulence. Velocity in east direction was used as an example to show the specific procedures of wave-current decomposition. First, the Fast Fourier Transform (FFT) of a time series of instantaneous velocity ( $u_e(t)$ ) is computed (labeled as  $F_{ue}$ ), and the real and imaginary parts of  $F_{ue}$  are labeled as  $R(F_{ue})$  and  $I(F_{ue})$ , respectively. Second, the frequency window of wave signal is chosen and the boundaries are represented as  $f_l$  (low frequency boundary) and  $f_h$  (high frequency boundary) (Fig. 3a). The amplitude ( $A_s = \sqrt{(R(F_{ue}))^2 + (I(F_{ue}))^2}$ ) and phase angle ( $\varphi$ ) of the signal within the wave frequency window are determined. Third, a broader frequency window (with its boundaries labeled as  $f_L$  and  $f_H$ ) containing the wave domain is chosen, and a straight line is fit between the amplitudes within the frequency range of  $f_L \sim f_l$  and  $f_h \sim f_H$ . Within the wave frequency range (i.e.,  $f_l \sim f_h$ ), the interpolated amplitudes constitute the amplitudes of turbulence ( $A_t$ ) in  $f_l \sim f_h$ ,

and the amplitudes of wave signal are computed as  $A_w = A_s - A_t$ . Percentage of wave signal amplitudes on total power energy in PSD was then estimated by  $P_w = \frac{\int_{f_l}^{f_h} A_w df}{\int_0^F A_s df}$  (with  $F (= 16 \text{ Hz})$  representing the half of sampling rate), and  $P_w > 10\%$  indicates that water motion was influenced by wind waves (**Hansen & Reidenbach, 2013**). Fourth, combined the  $A_s$  outside wave frequency window (i.e.,  $f < f_l$  and  $f > f_h$ ) and the interpolated amplitudes within  $f_l \sim f_h$ , the Fourier coefficients of turbulence are determined by  $F_t = A_t [\cos(\varphi) + i \sin(\varphi)]$  assuming the phase angles are not altered. Setting  $A_w = 0$  outside wave frequency window, the Fourier coefficients of wave are determined by  $F_w = A_w [\cos(\varphi) + i \sin(\varphi)]$ . Fifth, the Inverse Fast Fourier Transform (IFFT) of  $F_t$  and  $F_w$  is computed to reconstruct the time series of turbulent ( $u_e'$ ) and wave ( $u_{we}(t)$ ) velocities, respectively. Similar procedures are employed for velocities in north and upward directions. The velocity record measured near the water surface (i.e.,  $z = 55 \text{ cm}$ ) of case A4 was used as an example to show the time series of turbulent (blue line in Fig. 3b) and wave (red line in Fig. 3b) velocity after decomposition.

The wave orbital velocity was defined as the root mean square (RMS) of the wave velocity time series, i.e.,

$$U_{we} = \sqrt{\frac{1}{T_d} \int_0^{T_d} (u_{we}(t) - u_{we})^2 dt} \quad (4)$$

in which  $u_{we}$  is the time-averaged value of  $u_{we}(t)$ , and similar for  $U_{wn}$  and  $U_{wu}$ . Considering the wave velocity in the east and north directions, the horizontal component of wave orbital velocity,  $U_{w\_horiz}$ , was defined as

$$U_{w\_horiz} = \sqrt{U_{we}^2 + U_{wn}^2} \quad (5)$$

The vertical wave orbital velocity  $U_{w\_vert} = U_{wu}$ . From linear wave theory for small amplitude, monochromatic waves, the horizontal and vertical wave orbital velocities were computed as (**Dean & Dalrymple, 1991**)

$$U_{w\_horiz} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} \left( a_w \omega \frac{\cosh(x\xi)}{\sinh(x\eta)} \cos(kx - \omega t) \right)^2 d\varphi} = \frac{1}{\sqrt{2}} a_w \omega \frac{\cosh(kz)}{\sinh(kh)} \quad (6)$$

and

$$U_{w\_vert} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} \left( a_w \omega \frac{\sinh(x\xi)}{\sinh(x\eta)} \sin(kx - \omega t) \right)^2 d\varphi} = \frac{1}{\sqrt{2}} a_w \omega \frac{\sinh(kz)}{\sinh(kh)} \quad (7)$$

respectively, in which  $a_w$  is the wave amplitude near the water surface,  $\omega (= 2\pi/T$  with  $T$  the wave period) is the wave radian frequency,  $k (= 2\pi/\lambda$  with  $\lambda$  the wave length) is the wave number,  $h$  is the water depth, and  $z$  is the vertical coordinate. The instantaneous turbulent fluctuations ( $\sigma_\epsilon, \sigma_\nu, \sigma_u$ ) were defined as the standard deviation of the reconstructed time series of turbulent velocity ( $u_e'(t), u_n'(t), u_u'(t)$ ), and the turbulent kinetic energy ( $TKE$ ) is expressed as:

$$TKE = \frac{1}{2} (\sigma_\epsilon^2 + \sigma_\nu^2 + \sigma_u^2) \quad (8)$$

The horizontal and vertical  $TKE$  can then be expressed as  $TKE_{horiz} = (\sigma_\epsilon^2 + \sigma_\nu^2)/2$  and  $TKE_{vert} = \sigma_u^2/2$ , respectively.

For each case, the wave amplitude,  $a_w$ , was estimated by fitting the measured  $U_{w\_horiz}$  to eq. (6) at the highest three measurement points. The peak frequency ( $f_p$ ) of the wave domain in the PSD of instantaneous velocity was used to determine the wave period, i.e.,  $T = 1/f_p$ . Based on the linear wave theory, the wave length ( $\lambda$ ) can be estimated using the relationship of  $\omega^2 = (kg) \tanh(kh)$  with  $g$  representing the gravitational acceleration. Wave parameters for each case are listed in Table 1.

## 4 Results and Discussion

### 4.1 Flow structures in bare bed

To set a base line, the condition without vegetation (i.e., case S0) was first considered. Under wave-current conditions, the vertical distribution of time-averaged horizontal velocity ( $U_{horiz}$ , grey circles shown in Fig.

4a) was characterized by a logarithmic profile and the time-averaged vertical velocity ( $U_{vert}$ , blue triangles in Fig. 4a) was vertically uniform near the value of zero. This was similar to the time-averaged velocity profile under pure-current conditions (e.g., **Zhang, Lai, & Jiang, 2016**). The percentages of wave portion on total energy in the PSD of instantaneous velocity (i.e.,  $P_w$ ) decreased gradually from the water surface to the bed (Fig. 4b), indicating that the influence of surface waves on water motion became weaker and weaker with decreasing  $z$ . However, with  $P_w$  of vertical velocity  $P_{w-u} > 10\%$  through the entire water column (blue circles in Fig. 4b), water motion over the full-depth was affected by wave energy. Under wind-driven waves with typical period  $T = 1 \sim 5$  s, the water orbital motions can penetrate down from water surface to bed when  $h < \lambda / 2$  (**Green & Coco, 2014**). For the case S0 in present study, the water depth was 2.2 m, smaller than half of the wave length ( $\lambda = 6.1$  m, Table 1). Besides,  $P_w$  of horizontal velocities (i.e.,  $P_{w-e}$  and  $P_{w-n}$ ) was smaller than  $P_{w-u}$  at the same vertical height (Fig. 4b) because of the small total energy of velocity caused by weaker hydrodynamics (especially the smaller flow velocity, Fig. 4a) in the vertical direction than the horizontal directions. The measured wave orbital velocity in both horizontal ( $U_{w-horiz}$ ) and vertical ( $U_{w-vert}$ ) directions decreased with decreasing  $z$  (Fig. 4c), and agreed (within 25%) with the predictions of linear wave theory by eqs. (6) and (7), respectively. Therefore, eqs. (6) and (7) were used to estimate the natural wave attenuation with water depth for the vegetated cases. The turbulent kinetic energy ( $TKE$ ) was dominated by the horizontal component and decreased gradually from the water surface to the bed (Fig. 4d), a trend that was also observed by **Pujol et al. (2010)** and **Zhang et al. (2018)**.

#### 4.2 Time-averaged velocity within vegetation

Compared with bare bed, vertical profiles of the time-averaged horizontal velocity ( $U_{horiz}$ ) were altered by the presence of AV. Velocity profiles can be divided into two categories based on the vegetation was under emergent (i.e., cases A1, A2, B1, B3, and B4) and submerged (i.e., cases A3, A4, A5, B2, and B5) conditions.

For the cases A1, A2, and B1, the vegetation height was larger than the water depth (i.e.,  $h_v > h$ ). Restricted by the setup of ADV measurements (with the sampling volume 15 cm downward the probe tip) and the fluctuation of water surface, the highest position for velocity measurement was only half or less than half of the canopy height. For these three cases, the measured  $U_{horiz}$  distributed uniformly through the water column (Fig. 5a, 5b, and 5f), whereas  $U_{horiz}$  increased gradually with increasing  $z$  for cases B3 and B4 (Fig. 5h and 5i), for which the vegetation was just emergent with  $h_v = h$ . According to **Lightbody & Nepf (2006)**, the mean velocity within emergent vegetation varied inversely with the canopy frontal area ( $a = md$  with  $m$  and  $d$  representing the stem density and stem diameter, respectively) under conditions with pure current. In present study, the dominant vegetations for the emergent cases were *P. arundinacea* and *A. selengensis* (Table 1). With blades uniformly distributed from top to bottom of the stem, the  $a$  of both *P. arundinacea* and *A. selengensis* was uniform through most part of the stem. Near the top of vegetation,  $a$  decreased with increasing  $z$  as fresh blades with small length and width always grew at the top. Therefore, the velocity profiles, with  $U_{horiz}$  uniformly distributed through the entire water column for cases A1, A2, B1 and  $U_{horiz}$  gradually increasing with increasing  $z$  for cases B3 and B4, were consistent with observations by **Lightbody & Nepf (2006)**.

The time-averaged velocity profiles can be separated at the top of canopy ( $z = h_v$ ) when the vegetation was under submerged condition (i.e.,  $h_v < h$ ). Within vegetation ( $z < h_v$ ),  $U_{horiz}$  was small and uniformly distributed in the lower part of vegetation, and increased with increasing  $z$  in the upper part of vegetation (e.g., cases A3 and B5 in Fig. 5c and 5j, respectively). The velocity distribution within canopy in present study was very similar to observations by **Nepf & Vivoni (2000)**. Regions in the lower and upper part of canopy corresponded to the “longitudinal exchange zone” and “vertical exchange zone”, respectively, in **Nepf & Vivoni (2000)**. Defined as the distance from the top of vegetation to the point within canopy at which  $U_{horiz}$  has decayed to 10% of its maximum value, the thickness of “vertical exchange zone” ( $\delta_\epsilon$ ), or the penetration depth called by **Nepf & Vivoni (2000)**, was 50, 10, 15, 25, and 20 cm for the submerged cases A3, A4, A5, B2, and B5, respectively. Under unidirectional current, a model was proposed by **Nepf et al. (2007)** to predict the penetration depth and it gave that  $\delta_\epsilon = 0.23 / (C_D a)$ .  $C_D$  was the vegetative drag coefficient and a relatively constant value of  $C_D = 1.1$  for  $ad \geq 0.01$  (**Nepf, 1999**). With  $ad =$

0.003 ~ 0.013 for all cases in present study,  $C_D = 1.1$  was used, and the prediction gave  $\delta_\epsilon = 34.8, 5.5, 8.0, 14.9,$  and  $13.9$  cm for cases A3, A4, A5, B2, and B5, respectively, smaller than the measured. As **Nepf et al. (2007)** model was built under unidirectional current condition, its underestimation indicated that the vertical exchange of momentum can penetrate a deeper depth within canopy when water motion was also affected by wind-induced waves.

In present study with the hydrodynamic environment dominated by combined wave and current, the vertical distributions of time-averaged velocity were more similar to that under unidirectional current than waves. Under pure wave conditions the presence of AV can alter the mean flow structure, and a significant mean current in the direction of wave propagation is generated within vegetation when the ratio of wave excursion ( $E_w = u_{wmax} T / (2\pi)$ , with  $u_{wmax}$  the maximum velocity in wave cycle) to stem spacing (distance between two adjacent stems,  $S = m^{-1/2}$ ) larger than one (**Luhar, Coutu, Infantes, Fox, & Nepf, 2010**). Using the velocity measured at the middle height within vegetation (i.e.,  $z = h/2$  and  $h_v/2$  for emergent and submerged cases, respectively),  $E_w / S = 0.03 \sim 0.3$ , indicating weak wave-plant interaction, for all cases in present study (Table 1). Therefore, under combined wave-current conditions the time-averaged velocity was determined by the magnitude of current when the  $E_w / S$  was small. However, the existence of waves enhanced the momentum transfer between the canopy and its overlying water column, leading to a larger penetration depth present within the canopy.

### 4.3 Wave orbital velocity within vegetation

Vertical profiles of the wave orbital velocity,  $U_w$ , for cases with vegetation were shown in Figure 6. Measurement points with  $P_{w-u} < 10\%$  (indicating the water motion was not affected by surface waves) were excluded from the velocity profiles. For all vegetated cases tested here, both the horizontal ( $U_{w\_horiz}$ , grey circles in Fig. 6) and vertical ( $U_{w\_vert}$ , blue triangles in Fig. 6) components of wave orbital velocity decreased from the water surface to the bed. To determine the extent to which reduction of wave velocity by the interaction with AV, linear wave theory (i.e., eqs. (6) and (7)) was used to estimate the natural attenuation of wave velocity with depth. For both the horizontal and vertical components of wave velocity, the measured  $U_{w\_horiz}$  and  $U_{w\_vert}$  (symbols in Fig. 6) agreed with the predictions (red and blue dashed curves in Fig. 6) through the entire water column, suggesting that the wave orbital velocity within vegetation was not attenuated compared with that above the vegetation or near the water surface in present study. As noted by **Low et al. (2005)**, the significance of wave orbital velocity reduction within vegetation, for which we can call the wave attenuation in vertical direction, can also be indicated by  $E_w / S$ , and this vertical attenuation by vegetation is significant for  $E_w / S > 1$ . With  $E_w / S = 0.03 \sim 0.3$  in present study, the wave orbital motion was not significantly altered by the interaction with vegetation. This finding is similar to laboratory measurements of flow structure within and above a model *Z. marina* meadow (**Luhar, Coutu, Infantes, Fox, & Nepf, 2010**) and field observations by **Hansen & Reidenbach (2013)** in coastal regions.

As AV can efficiently inhibit the wave amplitude (e.g., **Bradley & Houser, 2009; Luhar, Infantes, & Nepf, 2017**), the presence of AV can decrease the wave orbital velocity by attenuating wave amplitude (i.e., eqs. (6) and (7)) compared with bare bed, which we can refer as the attenuation of wave orbital velocity in horizontal direction. The extent to which reduction of wave amplitude was determined by the relative velocity between vegetation and water motion and the distance the wave propagated into the vegetation (e.g., **Luhar, Infantes, & Nepf, 2017; Mendez, Losada, & Losada, 1999; Mullarney & Henderson, 2010**). Therefore, the attenuation of wave orbital velocity in both the horizontal and the vertical directions should be considered to fully evaluate the impact of vegetation on wave orbital velocity by measuring the velocity in the vegetation region and its adjacent bare-bed region simultaneously.

### 4.4 Turbulent kinetic energy within vegetation

The presence of vegetation also altered the vertical distribution of turbulent kinetic energy ( $TKE$ ). For emergent conditions (i.e.,  $h_v > h$ ),  $TKE$  was uniformly distributed through the entire water column (i.e., cases A1, A2, and B1 shown in Figs. 7a, 7b, and 7f, respectively) or increased from bed to water surface

(i.e., cases B3 and B4 as shown in Figs. 7h and 7i, respectively). This distribution also occurred within the lower part of canopy (e.g., A3, A5, and B5 in Figs. 7c, 7e, and 7j, respectively) when the vegetation was under submerged conditions (i.e.,  $h_v < h$ ). Near the top of vegetation,  $TKE$  increased with increasing  $z$  and reached its maximum near canopy interface, and then decreased toward the water surface (e.g., Figs. 7c, 7d, 7e, and 7j).

Within the emergent vegetation and lower part of submerged vegetation with  $U_{horiz}$  small and uniformly distributed, stem wakes were the main source of turbulence (e.g., **Nepf & Vivoni, 2000; Zhang, Tang, & Nepf, 2018**). Under unidirectional currents, vortices shed behind stems when the stem Reynolds number  $Re_d (= U_{horiz}d / \nu$  with  $\nu$  the water kinematic viscosity)  $> 120$  (**Liu & Nepf, 2016**). For all cases tested here, the  $Re_d$  within the canopy varied between 3 and 90 (Table 1), indicating that no turbulence was generated by the interaction of vegetation and mean current. Stem vortices by wave-plant interaction are governed by the *Keulegan-Carpenter* number,  $KC (= u_{wmax}T / d)$ , and vortex shedding occurs near the stem for  $KC > 6$  (**Sumer, Christiansen, & Fredsoe, 1997**). Using the  $u_{wmax}$  measured at  $z = h_v / 2$ , the  $KC$  of all cases in present study ranged 2 ~ 24 (Table 1), suggesting that the stem turbulence was generated for some cases (e.g., B1 and B4). However, with weak wave-plant interaction (i.e.,  $E_w / S < 0.5$ ) in present study the stem-generated turbulence cannot enhance the turbulence level within canopy (**Zhang, Tang, & Nepf, 2018**), leading to the turbulence level within vegetation for cases with  $KC > 6$  was not elevated compared with cases with  $KC < 6$ . Besides, with weak wave-plant interaction the  $TKE$  distributions near the top of vegetation for submerged cases in present study were similar to that by pure currents (e.g., **Zhang, Lai, & Jiang, 2016; Zhang et al., 2020**). Recall that  $U_{horiz}$  increased with increasing  $z$  near the top of vegetation. This can lead to the generation of shear turbulence (**Nepf & Vivono, 2000**), making  $TKE$  reach its maximum near the canopy interface and decrease toward bottom and water surface. The presence of shear turbulence can also give explanation for the increased  $TKE$  toward water surface for the emergent cases B3 and B4 in which the  $U_{horiz}$  gradually increased with increasing  $z$  near the water surface (see Fig. 5h and 5i).

## 5 Conclusions

Field experiments were conducted in floodplains of Poyang Lake, China, to investigate the influence of AV on flow structures under combined current and wind-driven wave conditions. Spectral decomposition was used to decompose the wave and turbulent components from the instantaneous velocity series, and the vertical distributions of time-averaged velocity ( $U_{horiz}$ ), wave orbital velocity ( $U_w$ ) and turbulent kinetic energy ( $TKE$ ) with the presence of AV were analyzed separately. With  $E_w / S (= 0.03 \sim 0.3) < 0.5$  for all cases tested here the interaction between waves and vegetation was weak and the vertical profiles of  $U_{horiz}$  and  $TKE$  were more similar to that under pure-current conditions. Without significant wave-induced current generated within canopy,  $U_{horiz}$  distributed uniformly through the entire water column or increased gradually from bed to water surface for emergent vegetation and in the lower part of submerged vegetation. As  $Re_d$  varied between 3 and 90, no stem-generated turbulence was expected to produce within vegetation, leading to the  $TKE$  within canopy was comparable for all cases in present study. Near the top of submerged vegetation,  $U_{horiz}$  increased rapidly with increasing distance to the bottom, and shear turbulence was expected to be generated near the canopy interface, leading to  $TKE$  reaching its maximum near the vegetation interface and decrease toward both bed and water surface. With weak wave-plant interaction, the measured  $U_w$  for the vegetated cases agreed with predictions by linear wave theory through the entire water column, suggesting that the wave velocity was not attenuated by AV. Although the mean and turbulent flow structures within vegetation were not altered by waves with weak wave-plant interaction in present study, the shear turbulence generated at the top of vegetation penetrated a deeper depth within vegetation with the influence of waves than without.

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**Tables:**

**Table 1.**Vegetation and wave parameters for each experimental scenario.

Case <sup>a</sup>	Vegetation <sup>b</sup> type	(m <sup>2</sup> )	<i>d</i> <sup>c</sup> (cm)	<i>h<sub>v</sub></i> <sup>d</sup> (m)	<i>h</i> <sup>e</sup> (m)	<i>a<sub>w</sub></i> <sup>f</sup> (cm)	<i>T</i> <sup>g</sup> (s)	<i>λ</i> <sup>h</sup> (m)	<i>k</i> <sup>i</sup> (m <sup>-1</sup> )	<i>u<sub>wmax</sub></i> <sup>j</sup> (cm/s)	<i>E<sub>w</sub></i> <sup>k</sup> (cm)	<i>KC</i> <sup>l</sup>	<i>E<sub>w</sub>/u<sub>w</sub></i> <sup>m</sup>
S0	-	-	-	-	2.20	1.75	2.0	6.1	1.03	4.0	1.27	-	-
A1	<i>A. se-len-gen-sis</i>	480	0.5	0.90	0.65	0.45	1.1	1.8	3.41	1.5	0.26	3.3	0.06
A2	<i>A. se-len-gen-sis</i>	420	0.5	1.00	0.90	0.42	1.6	3.6	1.72	2.5	0.64	8.0	0.13

Case <sup>a</sup>	Vegetation <sup>b</sup> type	$m^b$ ( $m^{-2}$ )	$d^c$ (cm)	$h_v^d$ (m)	$h^e$ (m)	$a_w^f$ (cm)	$T^g$ (s)	$\lambda^h$ (m)	$k^i$ ( $m^{-1}$ )	$u_{wmax}^j$ (cm/s)	$E_w^k$ (cm)	$KC^l$	$E_w/u$
A3	<i>P. arundinacea</i>	120	0.5	0.65	1.15	0.46	1.4	3.0	2.09	2.0	0.45	5.6	0.05
A4	<i>C. cinerascens</i>	1260	0.3	0.20	0.80	1.88	1.1	1.9	3.36	2.3	0.40	8.4	0.12
A5	<i>P. arundinacea</i>	520	0.5	1.00	1.80	3.66	1.1	1.9	3.33	1.0	0.18	2.2	0.04
B1	<i>P. arundinacea</i>	240	0.5	1.30	0.67	0.76	2.0	4.5	1.38	6.0	1.91	24.0	0.30
B2	<i>P. arundinacea</i>	280	0.5	0.60	1.66	1.41	1.7	4.4	1.42	2.0	0.54	6.8	0.08
B3	<i>P. arundinacea</i>	280	0.5	0.60	0.60	0.35	1.0	1.5	4.09	1.8	0.29	3.6	0.05
B4	<i>P. arundinacea</i>	320	0.5	0.90	0.90	1.06	1.0	1.6	4.03	5.5	0.88	11.0	0.16
B5	<i>P. arundinacea</i>	300	0.5	0.70	1.00	0.40	1.0	1.6	4.03	1.3	0.21	2.6	0.03

Case <sup>a</sup>	Vegetation <sup>b</sup>		$d^c$	$h_v^d$	$h^e$	$a_w^f$	$T^g$ (s)	$\lambda^h$	$k^i$	$u_{wmax}^j$	$E_w^k$	$KC^l$	$E_w/u$
	type	(m <sup>-2</sup> )	(cm)	(m)	(m)	(cm)		(m)	(m <sup>-1</sup> )	(cm/s)	(cm)		
aS0	aS0	aS0	aS0	aS0	aS0	aS0	aS0	aS0	aS0	aS0	aS0	aS0	aS0
was	was	was	was	was	was	was	was	was	was	was	was	was	was
the	the	the	the	the	the	the	the	the	the	the	the	the	the
bare	bare	bare	bare	bare	bare	bare	bare	bare	bare	bare	bare	bare	bare
bed	bed	bed	bed	bed	bed	bed	bed	bed	bed	bed	bed	bed	bed
case.	case.	case.	case.	case.	case.	case.	case.	case.	case.	case.	case.	case.	case.
A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1	A1
~	~	~	~	~	~	~	~	~	~	~	~	~	~
A5	A5	A5	A5	A5	A5	A5	A5	A5	A5	A5	A5	A5	A5
and	and	and	and	and	and	and	and	and	and	and	and	and	and
B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1	B1
~	~	~	~	~	~	~	~	~	~	~	~	~	~
B5	B5	B5	B5	B5	B5	B5	B5	B5	B5	B5	B5	B5	B5
were	were	were	were	were	were	were	were	were	were	were	were	were	were
cases	cases	cases	cases	cases	cases	cases	cases	cases	cases	cases	cases	cases	cases
with	with	with	with	with	with	with	with	with	with	with	with	with	with
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in-	in-	in-	in-	in-	in-	in-	in-	in-	in-	in-	in-	in-	in-
flu-	flu-	flu-	flu-	flu-	flu-	flu-	flu-	flu-	flu-	flu-	flu-	flu-	flu-
ence	ence	ence	ence	ence	ence	ence	ence	ence	ence	ence	ence	ence	ence
of	of	of	of	of	of	of	of	of	of	of	of	of	of
AV	AV	AV	AV	AV	AV	AV	AV	AV	AV	AV	AV	AV	AV
and	and	and	and	and	and	and	and	and	and	and	and	and	and
lo-	lo-	lo-	lo-	lo-	lo-	lo-	lo-	lo-	lo-	lo-	lo-	lo-	lo-
cated	cated	cated	cated	cated	cated	cated	cated	cated	cated	cated	cated	cated	cated
in	in	in	in	in	in	in	in	in	in	in	in	in	in
sites	sites	sites	sites	sites	sites	sites	sites	sites	sites	sites	sites	sites	sites
A	A	A	A	A	A	A	A	A	A	A	A	A	A
and	and	and	and	and	and	and	and	and	and	and	and	and	and
B	B	B	B	B	B	B	B	B	B	B	B	B	B
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den-	den-	den-	den-	den-	den-	den-	den-	den-	den-	den-	den-	den-	den-
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eral	eral	eral	eral	eral	eral	eral	eral	eral	eral	eral	eral	eral	eral
stems	stems	stems	stems	stems	stems	stems	stems	stems	stems	stems	stems	stems	stems
are	are	are	are	are	are	are	are	are	are	are	are	are	are
grown	grown	grown	grown	grown	grown	grown	grown	grown	grown	grown	grown	grown	grown
for	for	for	for	for	for	for	for	for	for	for	for	for	for
each	each	each	each	each	each	each	each	each	each	each	each	each	each
in-	in-	in-	in-	in-	in-	in-	in-	in-	in-	in-	in-	in-	in-
di-	di-	di-	di-	di-	di-	di-	di-	di-	di-	di-	di-	di-	di-
vid-	vid-	vid-	vid-	vid-	vid-	vid-	vid-	vid-	vid-	vid-	vid-	vid-	vid-
ual	ual	ual	ual	ual	ual	ual	ual	ual	ual	ual	ual	ual	ual
plant	plant	plant	plant	plant	plant	plant	plant	plant	plant	plant	plant	plant	plant
of	of	of	of	of	of	of	of	of	of	of	of	of	of

Case <sup>a</sup>	Vegetation <sup>b</sup> type (m <sup>-2</sup> )	$d^c$ (cm)	$h_v^d$ (m)	$h^e$ (m)	$a_w^f$ (cm)	$T^g$ (s)	$\lambda^h$ (m)	$k^i$ (m <sup>-1</sup> )	$u_{wmax}^j$ (cm/s)	$E_w^k$ (cm)	$KC^l$	$E_w/...$
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### Figure Legends:

**Figure 1 .** (a) Poyang Lake is located at the south bank of Yangtze River. It receives inflows from five tributary rivers (i.e., Xiushui, Ganjiang, Fuhe, Xinjiang, and Raohe) and discharges into Yangtze River at Hukou. The study area (marked as black square) was located at the southeast of Poyang Lake. (b) Two sites, named A and B, were chosen at floodplains formed in Ganjiang River to measure the flow velocity. (c) and (d) Positions of all measurement cases in sites A and B. Black arrows show the flow direction.

**Figure 2 .** (a) Water level variation (in days) in Duchang Hydrological Station in the year of 2015. Velocity measurements were conducted from August 18 to August 24, which was marked as the red square in the figure. (b) Wind speed (maximum in hours) measured by Poyang Lake Wetland Observation Station, Chinese Academy of Sciences, located in Xingzi from Aug. 18 to 24. Blue arrows denote the direction toward which the wind is blowing, with northward up and eastward to the right.

**Figure 3 .** (a) Power spectral density (PSD) of the instantaneous velocity  $u_u$  measured near the water surface ( $z = 55$  cm with  $z = 0$  representing the bottom) of case A4. Grey circles show the domain of wave signal with its boundaries labeled as  $f_l$  and  $f_h$ . Outside the wave domain (marked as black line) is the spectra of turbulence. Red dashed line presents the best linear fit for the amplitude within the frequency range of  $f_L \sim f_l$  and  $f_h \sim f_H$ . (b) Time series of the instantaneous velocities demonstrating the decomposition of the original velocity (black line) into time-averaged (green line), wave (red line), and turbulent (blue line) velocities using the method of spectral decomposition.

**Figure 4 .** Vertical distributions of the time-averaged velocity ( $U$ ), wave energy percentage ( $P_w$ ), wave orbital velocity ( $U_w$ ), and turbulent kinetic energy ( $TKE$ ) for the bare-bed case S0. Dashed line in (b) presents  $P_w = 10\%$ . The red and blue dashed curves in (c) show the predictions of linear wave theory using eqs. (6) and (7), respectively.

**Figure 5.** Vertical distributions of the time-averaged horizontal velocity,  $U_{horiz}$ , for cases with vegetation. The upper five plots and lower five plots present velocity profiles measured in sites A and B, respectively. Blue and green dashed lines show the positions of water surface and the top of vegetation, respectively. The absence of green dashed lines in some plots indicated that the vegetation was under emergent conditions. Sketch of the vegetation was also present with the velocity profile for each case.

**Figure 6 .** Vertical distributions of wave velocity ( $U_w$ ) for vegetated cases. The horizontal ( $U_{w,horiz}$ ) and vertical ( $U_{w,vert}$ ) components were considered separately and marked as grey circles and blue triangles, respectively, in the figure. Measurement points with  $P_{w-u} < 10\%$  in the lower part of water column were excluded from each profile. For each plot, the red and blue dashed curves show the prediction of  $U_{w,horiz}$  and  $U_{w,vert}$  by eqs. (6) and (7) with the wave amplitude estimated by fitting eq. (6) to measured  $U_{w,horiz}$  at the highest three measurement points. Predictions of  $U_{w,horiz}$  and  $U_{w,vert}$  were overlap for cases A5 (e), B4 (i), and B5 (j). Please note that the scale of  $x$ -axis was different between cases.

**Figure 7 .** Vertical distribution of the turbulent kinetic energy ( $TKE$ ) for vegetated cases. Upper five plots and lower five plots present  $TKE$  profiles measured in sites A and B, respectively. The  $TKE$  for the measurement points with  $P_{w-u} < 10\%$  near the bed was calculated by eq. (8) using original instantaneous velocity. Blue and green dashed lines show the positions of water surface and the top of vegetation, respectively. Sketch of the vegetation for each case was present with the  $TKE$  profile.

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