Field Study on Flow Structures Within Aquatic Vegetation under Combined Current and Wind-driven Wave Conditions

(Running title: Flow Structures Impacted by Vegetation)

Yinghao Zhang[1,2], Xijun Lai[2*], Jingxu Ma[1], Qian Zhang[1], Ru Yu[1], Xin Yao[1], Huanguang Deng[1]

[1]School of Environment and Planning, Liaocheng University, Liaocheng, 252059, China
[2]Key Laboratory of Watershed Geography Sciences, Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences, Nanjing, 210008, China

* Corresponding author at: 73 East Beijing Road, Nanjing, 210008, China.
E-mail Address: xjlai@niglas.ac.cn (X. Lai).

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Abstract

Field measurements were conducted to study the influence of aquatic vegetation on flow structures in floodplains with the hydrodynamic conditions dominated by combined current and wind-driven wave. Wave and turbulent flow velocity components were decomposed from the time series of instantaneous velocity and analyzed separately. With the ratio of wave excursion to stem spacing less than 0.5, the interaction between wave and vegetation was weak in present study, leading to the vertical distributions of time-averaged velocity (U_{horiz}) and turbulent kinetic energy (*TKE*) with the presence of vegetation similar with the vegetated flow structures under pure current conditions. For emergent vegetations, U_{horiz} and *TKE* distributed uniformly through the entire water column or increased slightly from bed to water surface. Similar distributions were present in the lower part of submerged vegetations. Within the upper part of submerged vegetations, U_{horiz} and *TKE* increased rapidly toward water surface and *TKE* reached its maximum near the top of vegetation. With small E_w/S the wave orbital velocity (U_w) within vegetation was not attenuated when compared with the U_w above vegetation, and U_w through the entire water column can be predicted by the linear wave theory. However, wind-driven waves made the turbulence generated near the top of canopy penetrate a deeper depth into vegetation than predictions under pure current conditions.

Keywords: aquatic vegetation; turbulence; wave; current; Poyang Lake

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 costal 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 by conducting flume experiments (e.g., **Ghisalberti & Nepf, 2002, 2004, 2006; Jarvela, 2005; Okamoto & Nezu 2009; Tanino & Nepf, 2008a, b; Yang, Kerger, & Nepf, 2015; Zhang, Lai, & Jiang, 2016**), field measurements (e.g., **Cameron et al., 2013; Leonard & Croft, 2006; Leonard & Luther, 1995; Lightbody & Nepf, 2006; Neumeier & Amos, 2006; Zhang et al., 2020**), and numerical investigations (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 influenced by AV in detail, and identified the canopy- and stem-scale turbulences 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, Casamitjana, Serra, & Colomer, 2010; 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 larger than 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 (China), a shallow lake connected to Yangtze River. Affected by the upstream water inflow and surface wind, 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

Field experiments were performed in floodplains located in the southwest part of Poyang Lake (Fig. 1a). Poyang Lake, the largest freshwater lake in China, is located in the south bank of middle reach of Yangtze River (28°24′ ~ 29°46′N, 115°49′ ~ 116°46′E). It has a drainage basin area of 162,225 km^2, 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 floodplain and inundated all year round. In the higher elevation, the floodplain is inundated seasonally (i.e., inundated and exposed in flood and dry seasons, respectively) and some emergent aquatic vegetations (e.g., *Carex cinerascens*, *Artemisia selengensis*, and reeds) grow.

Two floodplains formed in Ganjiang River were selected and named sites A and B from upstream to downstream the Ganjiang River, respectively (Fig. 1b). As one of the main tributaries, Ganjiang River has steady flow direction from its upstream basin (south) to the lake (north) (shown by the black arrows in Fig. 1b, 1c, and 1d). In addition, the water surface was also influenced by wind, leading to the hydrodynamic conditions of our study sites were dominated by combined currents and waves. For each site, five cases (Fig. 1c and 1d) selected for velocity measurements were distributed vertically to the flow direction. All cases were located in the higher elevation with seasonal inundation, 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 for 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 similar 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 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, and an average of 12 blades are grown 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. 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 the top to the bottom of stem. *P. arundinacea* has rigid stem with a mean diameter of 0.5 cm. The blades of *P. arundinacea* are lanceolate, and on average, each blade has the length of 15 cm and the maximum width of 1.8 cm. 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 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 positions in sites A and B were exposed to air. For each case, the stem density was estimated by randomly choosing three 1 m × 1 m quadrats within a 5-m radius of the velocity measurement position. 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. 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 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:

$$u_e = U_e + u_{we} + u_e' \tag{1}$$

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:

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

in which T_d is the time duration for each measurement point, and similar for U_n and U_u. As 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:

$$U_{horiz} = \sqrt{U_e^2 + U_n^2} \tag{3}$$

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 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, Fast Fourier Transform (FFT) of the 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

$= \sqrt{\left(R\left(F_{ue}\right)\right)^2 + \left(I\left(F_{ue}\right)\right)^2}$) and phase angle ($\varphi$) of the signal within 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 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 $P_w = \int_{f_l}^{f_h} A_w df / \int_0^F A_s df$ (with F (= 16 Hz in present study) 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, Inverse Fast Fourier Transform (IFFT) of F_t and F_w is computed to reconstruct the time series of turbulent ($u_e'(t)$) 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 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) velocities after decomposition.

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

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

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

$$U_{w_{horiz}} = \sqrt{U_{we}^2 + U_{wn}^2} \tag{5}$$

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**)

$$U_{w_{horiz}} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} \left(a_w \omega \frac{\cosh(kz)}{\sinh(kh)} \cos(kx - \omega t)\right)^2 d\varphi} = \frac{1}{\sqrt{2}} a_w \omega \frac{\cosh(kz)}{\sinh(kh)} \tag{6}$$

and

$$U_{w_{vert}}=\sqrt{\frac{1}{2\pi}\int_0^{2\pi}\left(a_w\,\omega\,\frac{\sinh(kz)}{\sinh(kh)}\sin(kx-\omega t)\right)^2 d\varphi}=\frac{1}{\sqrt{2}}a_w\,\omega\,\frac{\sinh(kz)}{\sinh(kh)} \qquad (7)$$

respectively, in which a_w is the wave amplitude near the water surface, ω (= $2\pi/T$ with T the wave period) is the wave radian frequency, k (= $2\pi/\lambda$ with λ the wave length) is the wave number, h is the water depth, and z is the vertical coordinate. The instantaneous turbulent fluctuations (σ_e, σ_n, σ_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:

$$TKE=\frac{1}{2}\left(\sigma_e^2+\sigma_n^2+\sigma_u^2\right) \qquad (8)$$

The horizontal and vertical TKE can then be expressed as TKE_{horiz} = $(\sigma_e^2+\sigma_n^2)/2$ 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 linear wave theory, the wave length (λ) can be estimated using the relationship of ω^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 with the time-averaged velocity profile under pure-current conditions (e.g., **Zhang, Lai, & Jiang, 2016**). Percentages of wave portion on the 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 ~ 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 (λ = 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).

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 with vegetation under emergent (i.e., cases A1, A2, B1, B3, and B4) and submerged (i.e., cases A3, A4, A5, B2, and B5) conditions were considered separately.

For cases A1, A2, and B1, the height of vegetation was larger than the water depth (i.e., $h_v > h$). Restricted by the setup of ADV measurements (i.e., the sampling volume is located at 15 cm downward the probe tip) and the fluctuation of water surface, the highest positions for velocity measurement were only at half or lower 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). However, U_{horiz} increased gradually with increasing z for cases B3 and B4 (Fig. 5h and 5i), for which the vegetation was just emergent with $h_v \approx h$. According to **Lightbody & Nepf (2006)**, the mean velocity within emergent vegetation varied inversely with 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 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 sprouted 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). This velocity distribution was very similar to observations by **Nepf & Vivoni (2000)**, and 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” (δ_e), 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 $\delta_e = 0.23/(C_D a)$. C_D was the vegetative drag coefficient and a relatively constant value of $C_D = 1.1$ for $ad \leq 0.01$ (**Nepf, 1999**). With $ad = 0.003 \sim 0.013$ for all cases in present study, $C_D = 1.1$ was used, and the prediction gave $\delta_e = 34.8$, 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 U_{horiz} 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 of 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 interactions, 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. In present study, the measured U_{w_horiz} and U_{w_vert} (symbols in Fig. 6) agreed with the predictions (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. 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. Therefore, with weak wave-plant interaction (E_w/S < 0.5) the wave orbital velocity within vegetation can be predicted by linear wave theory under combined wave-current conditions.

As AV can efficiently inhibit the wave amplitude (e.g., **Bradley & Houser, 2009; Luhar, Infantes, & Nepf, 2017**), the presence of AV decrease the wave orbital velocity by attenuating wave amplitude, 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, attenuation 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 vegetated 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 the canopy interface, and then decreased toward the water surface (e.g., Figs. 7c, 7d, 7e, and 7j).

Within the emergent vegetation and the 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 (= $U_{horiz}d/v$ with v 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 u_{wmax} measured at $z = h_v/2$, the KC of all cases ranged 2 ~ 24 (Table 1), suggesting that 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, for submerged cases the *TKE* distributions near the top of vegetation 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*) were analyzed separately. With E_w/S (= 0.03 ~ 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 with 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. Similar distributions were present for *TKE*. Although wake turbulence by wave-plant interactions was expected to occur in some cases in present study, the *TKE* within canopy was comparable for all cases as the E_w/S was small. Near the top of submerged vegetation, U_{horiz} increased rapidly with increasing distance to the bottom, and shear turbulence was expected to be generated and penetrated downward into the canopy. The measured penetration depths were compared with predictions by a model proposed under pure-current condition, and the measured was less than the prediction, indicating that the presence of wind-driven waves increased the penetration depth of shear turbulence. Besides, the generation of shear turbulence made *TKE* reach its maximum near the vegetation interface and decrease toward both bed and water surface. In present study, 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 with weak wave-plant interaction. Therefore, the wave orbital velocity within vegetation can be predicted by linear wave theory under combined wave-current conditions when the E_w/S was small (i.e., E_w/S < 0.5).

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Tables:

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

Case[a]	Vegetation type	m[b] (m^{-2})	d[c] (cm)	h_v[d] (m)	h[e] (m)	a_w[f] (cm)	T[g] (s)	λ[h] (m)	k[i] (m^{-1})	u_{wmax}[j] (cm/s)	E_w[k] (cm)	KC[l]	E_w/S[m]	Re_d[n]
S0	-	-		-	2.20	1.75	2.0	6.1	1.03	4.0	1.27	-	-	-
A1	*A. selengensis*	480	0.5	0.90	0.65	0.45	1.1	1.8	3.41	1.5	0.26	3.3	0.06	90.3
A2	*A. selengensis*	420	0.5	1.00	0.90	0.42	1.6	3.6	1.72	2.5	0.64	8.0	0.13	47.5
A3	*P. arundinacea*	120	0.5	0.65	1.15	0.46	1.4	3.0	2.09	2.0	0.45	5.6	0.05	15.6
A4	*C. cinerascens*	1260	0.3	0.20	0.80	1.88	1.1	1.9	3.36	2.3	0.40	8.4	0.12	3.7
A5	*P. arundinacea*	520	0.5	1.00	1.80	3.66	1.1	1.9	3.33	1.0	0.18	2.2	0.04	14.2
B1	*P. arundinacea*	240	0.5	1.30	0.67	0.76	2.0	4.5	1.38	6.0	1.91	24.0	0.30	22.7
B2	*P. arundinacea*	280	0.5	0.60	1.66	1.41	1.7	4.4	1.42	2.0	0.54	6.8	0.08	26.8
B3	*P. arundinacea*	280	0.5	0.60	0.60	0.35	1.0	1.5	4.09	1.8	0.29	3.6	0.05	50.2
B4	*P. arundinacea*	320	0.5	0.90	0.90	1.06	1.0	1.6	4.03	5.5	0.88	11.0	0.16	41.3
B5	*P. arundinacea*	300	0.5	0.70	1.00	0.40	1.0	1.6	4.03	1.3	0.21	2.6	0.03	33.1

[a]S0 was the bare bed case. A1 ~ A5 and B1 ~ B5 were cases with the influence of AV and located in sites A and B (Fig. 1b), respectively.

[b]Stem density (stems per unit area). Please note that several stems are grown for each individual plant of *A. selengensis* and *P. arundinacea. C. cinerascens* was composed of basal blades, so that its stem density in present study referred to the numbers of blade per unit area.

[c]Stem diameter. For *C. cinerascens* this table gave the value of mean blade width.

[d, e]Height of vegetation (h_v) and water depth (h).

[f]Wave amplitude calculated by fitting eq. (6) to measured horizontal wave velocity (U_{w_horiz}) at the highest three measurement points.

[g]Wave period calculated as $T = 1/f_p$ with f_p the peak frequency of the wave domain in the power spectral density of instantaneous vertical velocity.

[h, i]Wave length ($\lambda = 2\pi/k$) and wave number (k) estimated by linear wave theory, i.e., $\omega^2 = (kg)\tanh(kh)$, with ω ($= 2\pi/T$) the wave radian frequency, g the gravitational acceleration, and h the water depth.

[j]Maximum velocity in wave cycle.

[k]Wave excursion (radius of wave orbital motion) estimated by $E_w = u_{wmax}T/(2\pi)$.

[l]*Keulegan-Carpenter* number estimated as $KC = u_{wmax}T/d$.

[m]Ratio of wave excursion (E_w) to stem spacing (S) with $S = m^{-1/2}$.

[n]Stem Reynolds number estimated by $Re_d = U_{horiz}d/v$ (with $v = 10^{-6}$ the water kinematic viscosity) within the vegetation.

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 southwest 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.