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The influence of multi-scale spatial heterogeneity of aquatic vegetation on turbulence, mixing, and dispersion in coastal environments

A thesis
submitted in fulfilment
of the requirements for the Degree
of
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Abstract

Aquatic vegetation is a common feature of coastal, estuarine, and riparian environments. Aquatic vegetation provides many ecosystem and habitat services such as acting as a buffer zone to capture sediment, particulate matter, and pollutants, thus preventing these materials from entering the open ocean. Vegetation can also dissipate hydrodynamic energy and mitigate against physical hazards. However, to quantify and predict these effects across a range of forcing regimes and environments necessitates a detailed understanding of flow-vegetation interactions. Therefore in recent decades, many laboratory and numerical studies have focussed on elucidating physical processes such as turbulence generation, mixing, and dispersion in aquatic vegetated flows. However, such laboratory and numerical studies typically simplify vegetation geometries, often by representing canopies as regular arrangements of uniform cylinders, or by applying uniform time-invariant hydrodynamic forcing, which does not always capture real-world conditions. This thesis assesses the impact of spatial heterogeneity of aquatic vegetation across different spatial scales ranging from the vegetation stem-scale ($\mathcal{O}(0.01\text{ m})$) to the larger-scales observed in multi-patch arrays of vegetation ($\mathcal{O}(10\text{ m})$). We develop generalized theoretical models that incorporate multi-scale heterogeneity observed in the real-world aquatic vegetation.

Field measurements and model predictions of turbulent kinetic energy in canopies of sparse vegetation under tidal flows

In the second chapter, we conducted field experiments measuring high resolution velocity data in a sparse canopy of pneumatophores coexisting with a very

sparse stand of young mangrove saplings to study the small-scale turbulence ($\mathcal{O}(0.01 - 0.1\text{ m})$). There was no significant wave activity observed for the duration of the experiments making the dataset well suited for testing existing models developed from laboratory experiments under uniform currents. The measured turbulent kinetic energy (TKE) was compared with existing models which assume the eddy length scales to be on the order of the stem-diameter. In these cases the models significantly under-predicted the TKE in the real world setting. However, by modifying predictions to include the measured eddy length scales (around 15-times larger than stem diameter), the model was found to perform well, with percentage errors in predicted TKE of around 67%.

The generation of the larger eddies was attributed to the presence of the saplings. This result therefore highlights the importance of characterizing the correct length scales in spatially heterogeneous vegetation canopies.

The influence of patchy vegetation on tidal flows: Field dye measurements of intra- and inter-patch mixing, residence times, and dispersion parameters

In the third chapter, we explored medium- and large-scale ($\mathcal{O}(> 1\text{ m})$) flow and mixing processes in multi-patch vegetation systems. We deployed a randomly arranged patch array of 20 identical patches on an intertidal flat and measured flow behaviours and tracer dispersion across 3 densities (which were kept the same in every patch), for different submergence levels. High-resolution spatial and temporal dye intensities obtained from UAV based dye imagery in combination with Rhodamine WT dye releases were used to estimate longitudinal and transverse dispersion coefficients. The dispersion coefficients were strongly dependent on submergence ratios with a clear inverse proportionality between dispersion coefficients and submergence levels. The intermediate density patches showed slightly greater dispersion compared to denser patches, which was attributed to the variability in the flow path of the dye clouds be-

tween different releases.

Furthermore, local behaviours of the tracers were studied using the temporal variance and dye residence times at every location (video pixel). The values of both the local parameters increased from upstream to downstream inside the array with some particularly large values within close proximity of individual patches. The dye residences showed no dependence on submergence levels as the vegetation-induced dispersion compensated for the reduced bare-bed dispersion at low submergence levels. Finally, a general model for predicting dispersion coefficient as a function of submergence ratio is proposed and validated with field measurements.

The impact of the spatial distribution of patches on dispersion in submerged aquatic vegetation for varying vegetation densities and submergence ratios

The third chapter only considered a single patch arrangement, a relative patch diameter of $\Lambda = 100$, and constant system dimensions of 6×6 m. Therefore, in the fourth chapter we conducted numerical simulations of 8 different patch arrangements using Horizontal Large Eddy Simulation (HLES) in Deflt3D combined with the in-built rigid vegetation model. A few additional simulations were also undertaken to study the impact of system dimensions and relative patch diameter on dispersion coefficients.

The results showed significant variability in dispersion coefficients between the different patch arrangements. The results confirmed the inverse relationship between dispersion coefficients and submergence levels in the field and also showed the impact of vegetation density with higher densities producing larger dispersion values. However, for greater submergence levels ($S_r > 2$) the impact of both the vegetation densities and patch arrangements were negligible. The results from different relative patch diameters also implied that

the frontal area density is a better parameter to characterize patch regimes instead of the solid volume fraction. Furthermore, the results from the longer patch arrays (12×12 m) showed that the dispersion coefficients reduced with increase in vegetation densities beyond a certain density, which is the opposite trend to that observed in the shorter patch arrays. Finally, a general dispersion model for predicting dispersion coefficients based on frontal area density and submergence levels is proposed for patchy aquatic vegetation.

The results from the thesis have helped to elucidate the importance of characterizing spatial heterogeneity of aquatic vegetation across different scales to understand the scale-dependent physical processes. Furthermore, significant contributions were made by developing the existing and newer models for predicting turbulence and dispersion in aquatic vegetation systems which can be used to understand and manage coastal and wetland aquatic systems.

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Chapter 1

Introduction

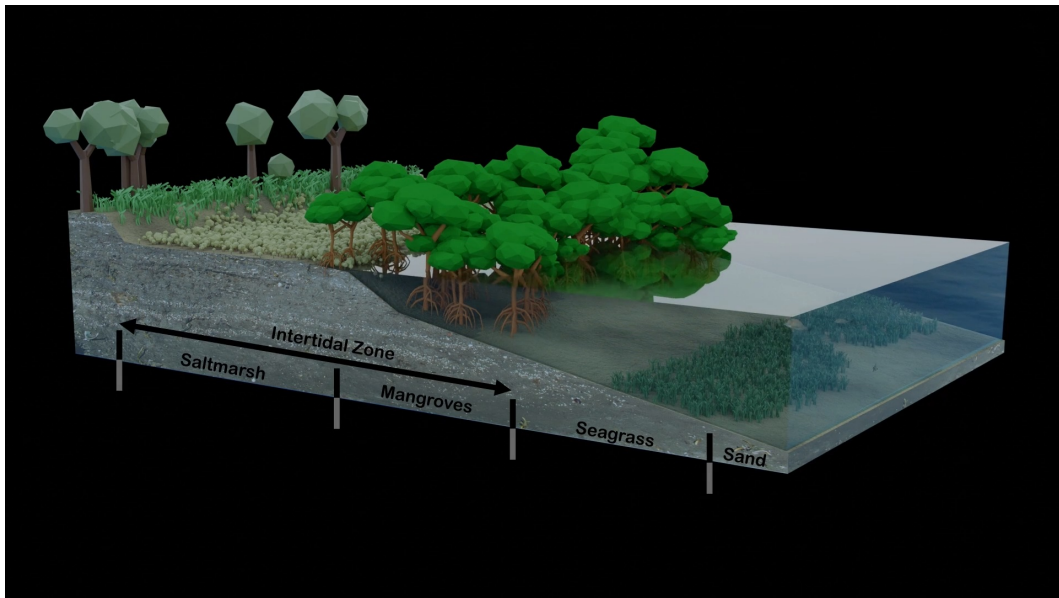


Figure 1.1: Examples of different types of coastal aquatic vegetation from the subtidal to the intertidal. (Figure taken from CSIRO, 2025).

Hydrodynamics and sediment transport in coastal, estuarine, and riverine environments are often characterized by the presence of aquatic vegetation. Coastal aquatic vegetation can be broadly classified into mangroves, salt marshes, seagrasses, and macroalgae such as seaweed and kelp. Mangroves are salt-tolerant trees which grow in estuaries, open coasts, and along river-banks in the fluvial-to-marine transition zone. These trees have aerial root structures which spread over a wide area from the tree trunk. In *Avicennia* mangroves, the roots form as pencil-like structures called pneumatophores that protrude

above the sediment. Other mangrove species can possess different aerial root systems such as prop (stilt) roots, knee roots, and plank (buttress) roots. Salt marshes are plants that thrive in the intertidal zone while being flooded and drained on a regular basis. Depending on the location, seagrasses can live both in the intertidal (predominant in New Zealand) and deeply submerged regions. The three types often occur in different zones from the coast characterized by local salinity and water depth (Figure 1.1). The interactions between water flows and vegetation structures influence the physical, chemical and biological processes and characteristics in aquatic regions.

Aquatic vegetation provides multiple ecosystem services. These buffer zones between land and water are often regions of high biodiversity and constitute valuable habitat for fish and animals (van Katwijk et al., 2016; Barbier et al., 2011). These ecosystems act as a natural water filtering system, enhancing nutrient cycling (Li et al., 2026), and capturing terrestrial runoff which would otherwise end up in the oceans (Temmerman et al., 2013; Lin and Dushoff, 2004). Aquatic vegetation, and mangroves in particular, trap and store large amounts of blue carbon helping to mitigate against climate change (Breithaupt et al., 2012; Fourqurean et al., 2012). Moreover, many communities around the world use vegetated regions as a resources for food, medicine and raw building materials (Saenger, 2002).

In addition to the ecological services provided, the ability of aquatic vegetation to extract energy from, and slow flows, gives rise to a number of physical services. The presence of vegetation has been shown to stabilize flood banks (Barbier et al., 2011; Pollen and Simon, 2005), dissipate waves and currents (Vettori et al., 2025; Mazda et al., 2006), and even protect coastlines during extreme events (Montgomery et al., 2019; Temmerman et al., 2023). By altering the hydrodynamic regime, aquatic vegetation also influences sediment resuspension, deposition, and transport. In some cases, these ecosystems are

able to mitigate erosion risk (Morris et al., 2018; Borsje et al., 2011), with a few examples of accretion at a sufficient rate to keep pace with sea level rise (Gijssman et al., 2021; Bouma et al., 2014).

The rise in sea levels due to global warming and the increase in the frequency of extreme events pose a serious threat to coastal areas (Hulme, 2014). In recent decades, aquatic vegetation has been increasingly proposed as a nature-based soft-engineering solution (NbS) to mitigate coastal hazards (Gijssman et al., 2021; Morris et al., 2018; Temmerman et al., 2013). However, to design and predict the efficacy of these approaches necessitates a deeper understanding of the hydrodynamics, morphodynamics, mixing, and other physical processes in vegetated flows.

1.1 Key parameters for patchy aquatic vegetation

This section presents the key parameters required to characterise physical processes in patchy aquatic systems. The geometry of a system of vegetation patches can be defined using system length (L), width (W), patch density ($\Phi_p = n_{patches}/LW$) in which $n_{patches}$ are the number of patches in the system per m^2 , h is the vegetation height, and H is the water depth (Figure 1.2A).

The proportion of volume occupied by the solid canopy or a single patch of diameter (D), also called the solid volume fraction, is denoted by $\phi = (\pi/4)n(d)^2$, in which d is the vegetation diameter, and n is number of stems per m^2 . The plant area in the plane perpendicular to the flow per unit volume is defined as frontal area density and is denoted by a . If there are n stems with a spacing of ΔS between them (Figure 1.1B), the relationship between n and ΔS is $n = 1/\Delta S^2$. Then, the volume fraction can be expressed as

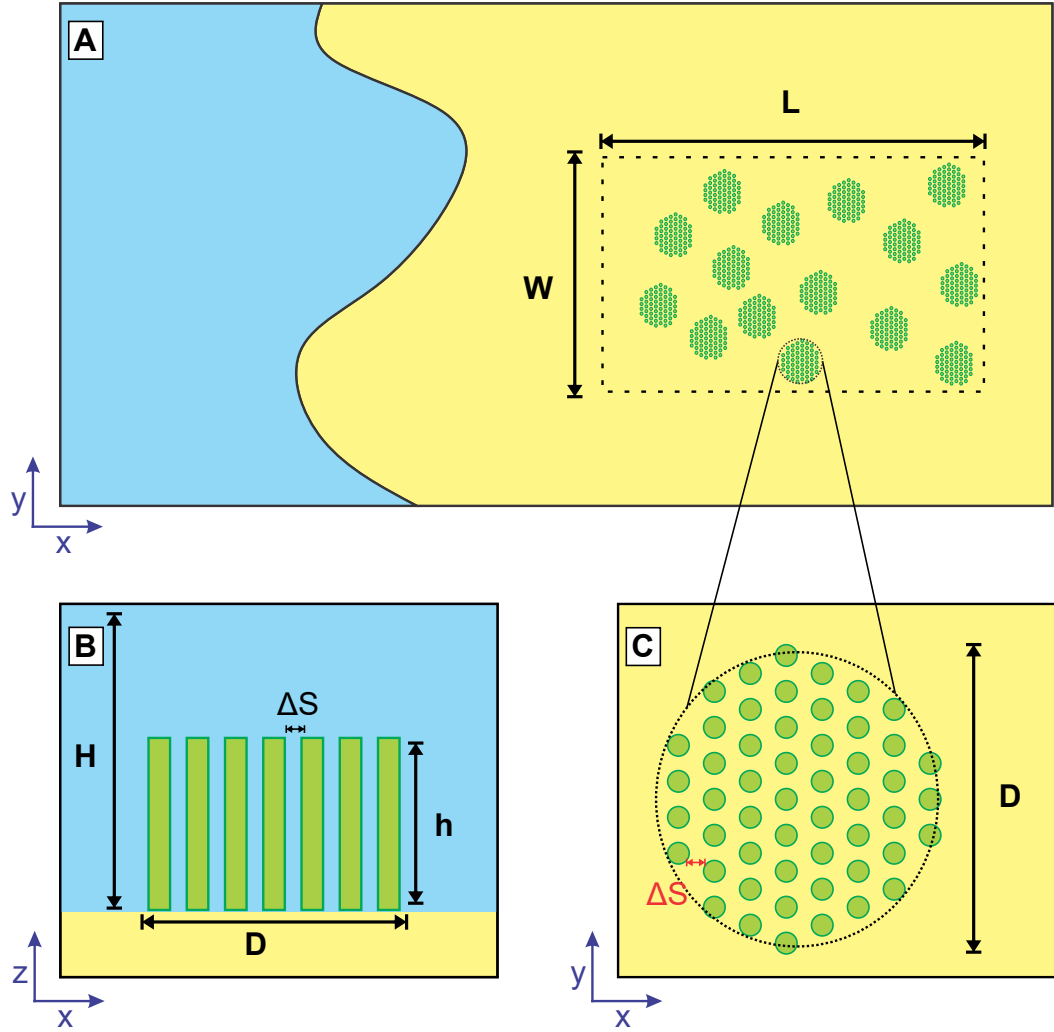


Figure 1.2: Definition of vegetation parameters for patches of uniform vegetation. A) System view of patch system. B) Side view of a single patch. C) Top view of a single patch.

$\phi = (\pi/4)(d/\Delta S)^2$ and the frontal area density becomes $a = nd = d/\Delta S^2$. Furthermore, canopies are classified as emergent canopies ($H/h = 1$), deeply submerged canopies ($H/h \geq 10$), and transitional canopies ($1 < H/h < 10$) using the ratio of canopy height to water depth (H/h), called the submergence ratio (Nepf, 2004).

Finally, non-dimensional numbers are commonly used in the field of fluid mechanics to characterize and identify flow regimes. For studying vegetated aquatic flows, the Reynolds number (Re), the Keulegan–Carpenter number (KC), and Strouhal number (St), are some important non-dimensional numbers. Reynolds number is defined as $Re = \rho u L / \mu$ in which ρ is the density of water, μ is dynamic viscosity of water, u and L are the characteristic flow speed and length respectively. The channel-averaged velocity and stem diameter (d) often used as characteristic parameters for Re. The Keulegan–Carpenter number is defined as $KC = uT/D$ in which T is period of oscillatory flows, and D is the characteristic diameter. The Strouhal number is $St = fL/u$ in which f is the vortex shedding frequency.

1.2 Drag and flow modification in continuous vegetation canopies

Early investigations of vegetated aquatic flows typically focused on flow modification and drag generated by continuous canopies of rigid homogeneous vegetation. Whereas open-channel flows (bare-bed) are mainly driven by pressure gradients and/or gravitational potential (bed slope), aquatic vegetation canopies generate additional drag and turbulent stresses (Nepf, 1999). The logarithmic velocity profiles observed in the bare-bed flows are modified within the canopy due to the additional drag (Nepf, 2004; Nepf and Vivoni, 2000) (Figure 1.3). The characteristic eddies in open channels scale with the water depth,

however, in vegetation canopies these eddies are attenuated into smaller stem-scale and canopy-scale eddies by flow-vegetation interactions (Nepf, 2012a; Finnigan, 2000). Submerged canopies further modify the classical logarithmic velocity profile with an inflection point developing at the top of the canopy where a mixing layer is generated (Nepf, 2012b,a). The complexities multiply for multi-layer vegetation canopies (vegetation of different heights in the same canopy) due to the formation of multiple inflection points and mixing layers (Anjum and Tanaka, 2020). In submerged canopies of uniform vegetation, the vertical exchange of momentum dominates the lateral exchange of momentum, but in mixed layer canopies lateral exchange of momentum is stronger (Anjum and Tanaka, 2020; Liu et al., 2010).

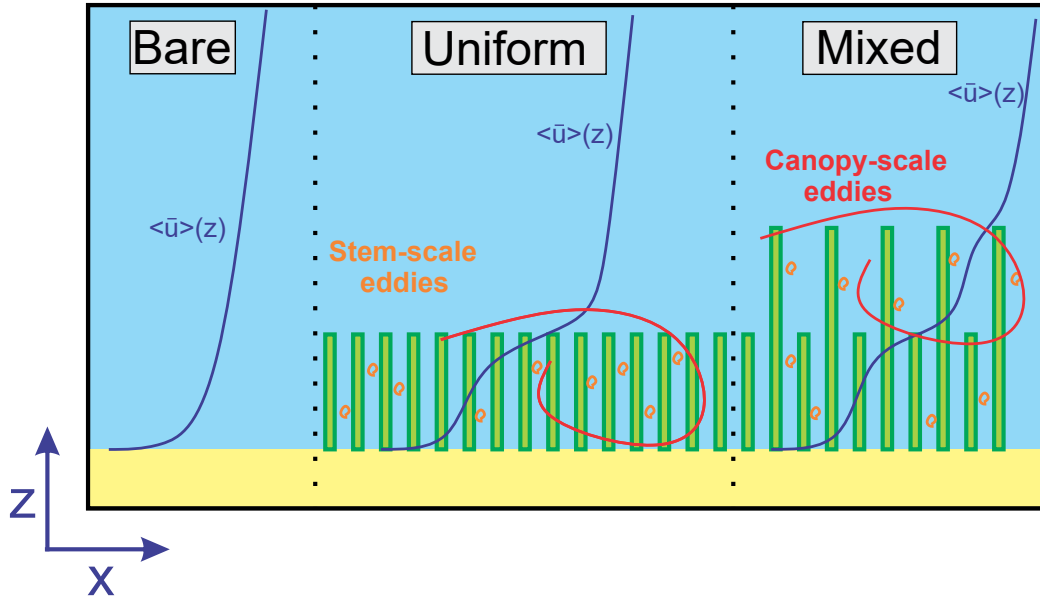


Figure 1.3: Flows in vegetation canopies represented for bare-bed, uniform height and mixed height vegetation (green bars) in which the blue lines are the mean velocity profiles, the orange twirls are stem-scale eddies, and the red twirls are canopy-scale eddies.

Additional complexities are introduced for flexible vegetation and/or in environments with wave forcing. Therefore, further work on drag in vegetation involved oscillatory flows and flexible vegetation. For oscillatory flows in rigid

canopies, Augustin et al. (2009) showed that vegetation drag correlates with Reynolds number (Re) for emergent vegetation, and Keulegan–Carpenter number (KC) for submerged vegetation. Blackmar et al. (2014) conducted experiments on oscillatory flows in mixed-layer rigid vegetation and found that drag correlates well with a linear combination of Re , and KC numbers. Flexible vegetation reconfigures in aquatic flows by bending reducing both the height and effective frontal area of the canopy which in turn results in reduced drag (Luhar and Nepf, 2011; Albayrak et al., 2012). The vegetation drag force ($F_d \propto U^2$) is usually propositional to the square of mean flow speeds (U); however, in case of extreme vegetation bending $F_d \propto U^{2+\gamma}$, where γ is referred to as the Vogel exponent (Vogel and Beety, 1994; Albayrak et al., 2012). In uniform flows, flexible vegetation undergoes dynamic reconfiguration due to canopy-scale vortices in a phenomenon termed as monami (Ghisalberti and Nepf, 2006). Zeller et al. (2014) modeled the canopy drag for oscillatory flows in flexible vegetation using a modified KC number.

Incipient motion and transport of sediment in open channels has been extensively researched in the last century resulting in the development of bed-shear stress (τ) based models (Ancy, 2020a,b) for predicting sedimentation in aquatic flows. As aquatic vegetation significantly alters near-bed flows, sediment transport in these regions is subsequently impacted (Yager and Schmeeckle, 2013; Conde-Frias et al., 2023). Recent laboratory flume studies on uniform vegetated aquatic flows have revealed that incipient sediment motion occurs at lower than expected bed-shear stress (τ) but at a consistent critical turbulent kinetic energy (TKE) by measuring near-bed TKE (Yang and Nepf, 2019; Tinoco and Coco, 2016; Liu et al., 2021). This observation has led to the acceptance of TKE as a better predictor of incipient motion of sediment than τ . Additionally, the τ -based models for predicting sedimentation can be modified to TKE-based models by recasting bed-shear stress into TKE using the relation $TKE = \tau / (0.19\rho)$ (Soulsby, 1983). The modified

TKE-based equations are observed to perform better in predicting sedimentation (Zhao and Nepf, 2021; Yang and Nepf, 2019). The TKE-based models are developed assuming that the local dissipation of TKE is equal to the local production of TKE. However, the assumption is only valid within continuous canopies beyond a flow adjustment length from the leading edge of the canopy (Chen et al., 2013).

The flow modification in the presence of aquatic vegetation results in significantly more variability of mixing and deposition of particles than in unvegetated regions. Early studies showed that dispersion in flows with continuous emergent vegetation is controlled by the vegetation density highlighting the impact of aquatic vegetation in mixing (Sonnenwald et al., 2019; White and Nepf, 2008; Lightbody and Nepf, 2006). Studies in submerged vegetation canopies have demonstrated that key parameter influencing dispersion varies with canopy length: for longer canopies, the dispersion coefficient is controlled by the water depth, while for shorter canopies the dispersion is controlled by the length of the vegetated region (Ghisalberti and Nepf, 2009; Nepf et al., 2007). While previous models have assumed a two layer canopy model for submerged canopies, Shucksmith et al. (2011) further developed the theoretical by including more layers, and were able to predict observed longitudinal dispersion coefficients with errors to 20%.

1.3 Flow and sediment transport in regions with patchy vegetation

While this early work has provided substantial understanding of the underlying dynamics and processes for predominantly uniform and homogeneous vegetation, in natural systems, vegetation can encompass multiple different characteristics and have a spatially variable distribution. In pioneer fringing

zones, variable growth can lead to discontinuous discrete patches, which can interact with each other depending on their relative proximity (Schoelynck et al., 2018; Kondziolka and Nepf, 2014; Cannon et al., 2021). For isolated patches, studies have investigated and generalized flow patterns around and behind the obstacles. Flows through a vegetation patch experience ‘bleeding’ in horizontal (from the trailing edge and the sides) and vertical directions, and the complex interactions between the three bleeding flows create multiple shear layers behind the patch (Taddei et al., 2016; Nicolai et al., 2020). Liu et al. (2021) and Nicolle and Eames (2011) identified three flow regimes based on the solid volume fraction: very dense patches act like a solid cylinder, medium density patches act like porous cylinders (with bleed flow and wakes), and very sparse patches act like a set of interacting stems. Vandenbruwaene et al. (2011) identified that the shape of the patches has minimal impacts with the flow patterns next to a square patch and a circular patch being comparable. Flow decelerates in front of a patch with some slowly flow bleeding through the patch itself, while lateral flows are accelerated (Rominger and Nepf, 2011). Behind an intermediate density patch the existence of bleed flow pushes the onset of the von Karman vortex street downstream by a length L_{xy} (see Figure 1.4A). Additionally, in submerged patches a vertical recirculation zone extends for a distance L_{xz} behind the patch (Liu et al., 2018; Rominger and Nepf, 2011) (see Figure 1.4B). These two key lengthscales determine sediment deposition patterns behind an isolated patch: for narrow patches (height/width < 0.75), L_{xy} is the lengthscale that controls the length of the deposition area, while for wider patches (height/width > 0.75), L_{xz} controls the length of deposition region behind the patch (Hu et al., 2018).

Several later studies have also examined the flow interactions between two circular patches. Interacting patches of identical size and densities (in several different spatial arrangements) have demonstrated extended deposition regions behind the patches, with up to 3.8 times the area observed for a single patch

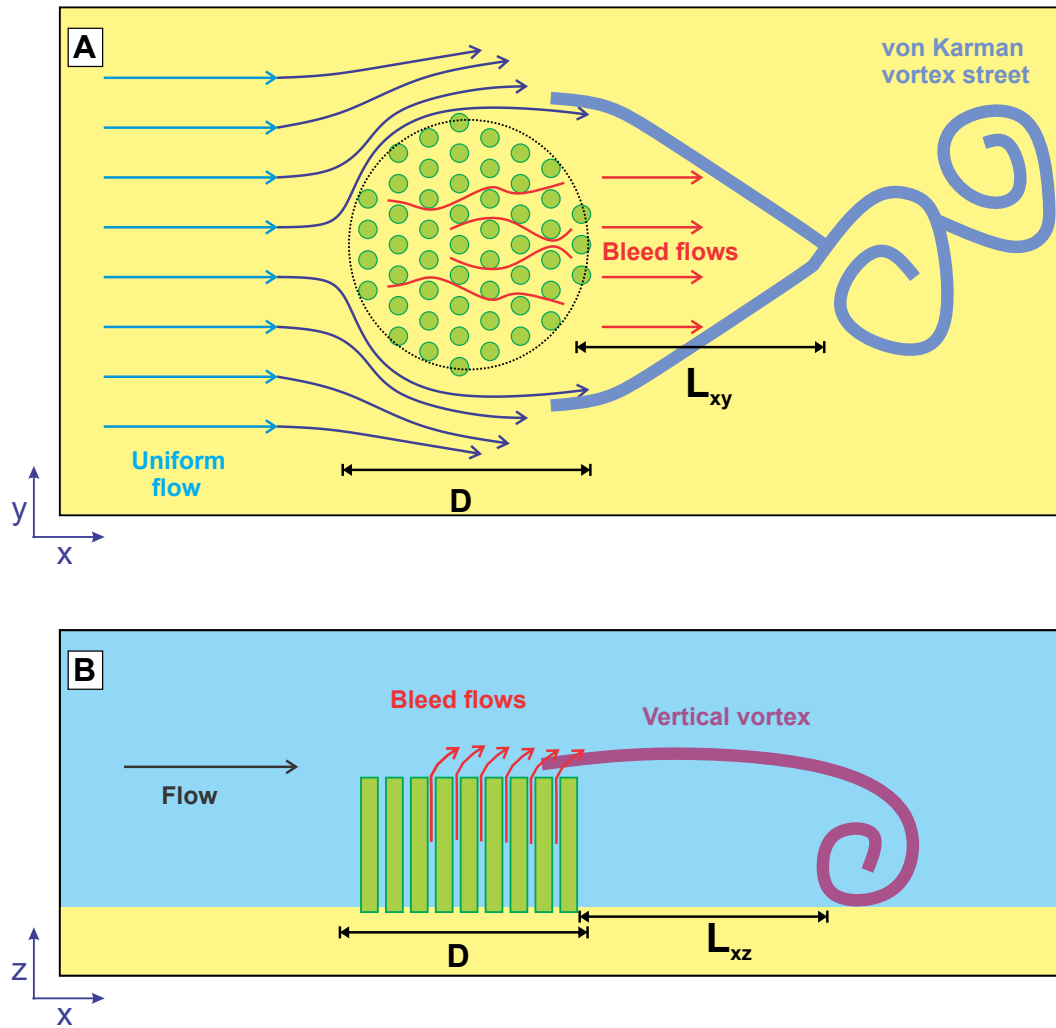


Figure 1.4: Flows in an isolated vegetation patch. A) Top view, and B) Side view of a single vegetation patch.

(Meire et al., 2014; De Lima et al., 2015). Kitsikoudis et al. (2020) investigated the dynamics of two interacting patches of different densities, and found that when the nonidentical patches are in a staggered arrangement, the wake and deposition are controlled by the vegetation density of the downstream patch.

The dynamics of systems with multiple (> 2) patches are much less studied. However, a few recent investigations have started to explore the complex dynamics of multi-patch systems. Investigations on the effect of vegetation patch systems on hydraulic resistance showed that the hydraulic resistance coefficients depended on relative submergence and frontal area (blockage) of the submerged vegetation (Savio et al., 2023). Park and Nepf (2025) have developed methods to predict TKE in submerged patchy vegetation systems as a function of frontal area density and have highlighted the importance of spatial configuration in patchy systems. Additional studies focused on modeling the stability and growth of the patches in patch systems (Calvani et al., 2022; Carbonari et al., 2022; Yamasaki et al., 2019). While most studies focused on patches of vegetation on a bare-bed, the inverse problem (patchy gaps in a field of continuous vegetation) has also received attention (Da Silva et al., 2024, 2026). Finally, more recent work has focused on mixing and dispersion in patchy vegetated systems (Park and Hwang, 2019; Dang et al., 2023). Park and Hwang (2019) investigated the impact of patch arrangements on hydraulic parameters. They found significant variability in observations across different patch arrangements and discussed the implications of such variability on mixing and dispersion but did not estimate any dispersion coefficients. Dang et al. (2023) estimated dispersion coefficients based on the velocity profile in numerical simulations of randomly evolving vegetation in a river and found a positive correlation between the amount of vegetation cover and dispersion coefficients. However, studies linking the medium-scale flow processes to larger system-scale dispersion are lacking. In particular, a useful contribution would be to derive a general expression to estimate/predict dispersion coefficients

using system geometry, vegetation characteristics, and mean flow parameters.

1.4 Research questions

Most of the above advances in our current understanding of flows and mixing in aquatic vegetation systems were achieved from laboratory and numerical studies. These approaches typically employed simplified flows (uniform currents and simple waves), and regular arrangements of simplified geometry of vegetation (use of smooth wooden dowels in regular/staggered layouts, often with uniform diameters and heights) (Tinoco et al., 2020). A wider exploration of flow processes is therefore needed before results can be extrapolated to real-world conditions. Recent results from Yoshikai et al. (2025) highlight for example that the use of flumes in laboratory studies can lead to different flow behaviour to that observed in the field, owing to the restriction of lateral flow diversion.

The overall aim of this thesis is to explore the effect of spatial heterogeneity of vegetation on flow-vegetation interactions. In particular, I focus on mangroves to examine the following research questions:

1. How does heterogeneous vegetation (composed of multiple length-scales) influence flows and the generation of turbulence? How do the flow structures generated by different sized vegetation (pneumatophores and trees) interact? How close are the current laboratory-based models for estimating turbulent kinetic energy (TKE) in representing the multi-scale flow dynamics in the real aquatic vegetation canopies?
2. How does the presence of multiple vegetation patches affect medium- and large-scale flow dynamics? How do vegetation densities and submergence levels change these flow-vegetation interactions?
3. Can we find generalized flow patterns and predict dispersion coefficients for different spatial configurations of multiple patches?

1.5 Approach used in this thesis

1.5.1 Field Experiments

The field experiments for answering research questions 1 and 2 are conducted on an intertidal flat located in the Purangi estuary, New Zealand (-36.84° N, 175.76° E). The intertidal flat is mostly barren with rough sand (median particle diameter of $180\text{ }\mu\text{m}$) with the southern tip inhabited by a small stand of a young *Avicennia marina* mangroves. The Purangi estuary has a tidal range of 1.5-2 m which periodically floods and drains the intertidal flat with maximum water depths on the flats reaching up to 1 m at the high tide. The tidal flow directions on the flat and lack of vegetation in the northern parts provide an excellent opportunity to deploy artificial vegetation systems and explore the effects on flow for real-world forcing conditions.

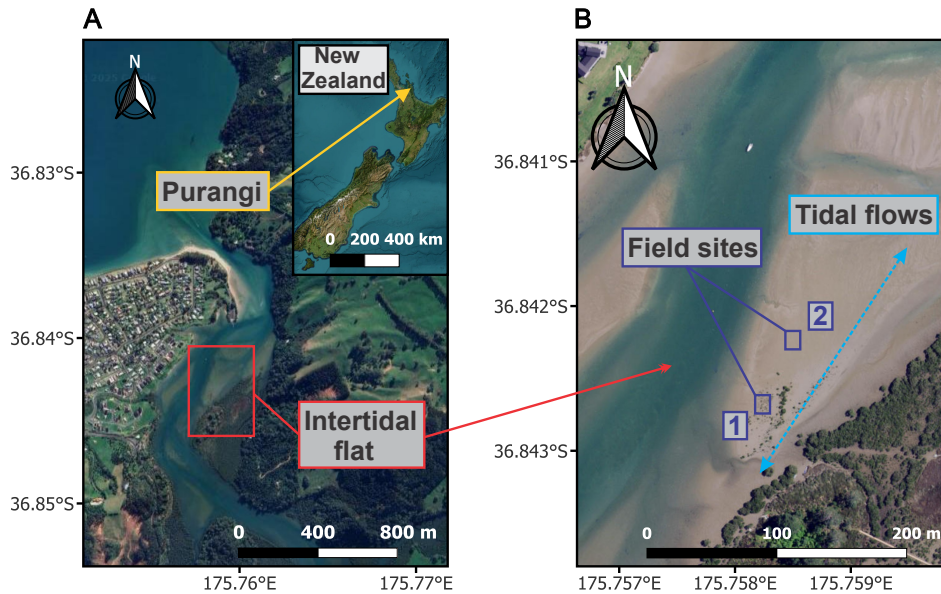


Figure 1.5: Field sites.

Measuring velocities, pressure and other parameters

While details are given in the respective chapters, here I provide a brief overview of instrumentation used in this thesis. To acquire flow data, Acoustic Doppler Current Profilers (ADCPs) such as Nortek Aquadopps, Signature, and Velocimeters (ADV) such as Vectrino profilers, and Vectors are deployed to measure three dimensional (3D) velocities, and pressure data for the duration of the experiments. The instruments measure either a point or over a vertical profile a set distance from the sensor head termed as the blanking distance. Conductivity Temperature and Depth sensors widely known as CTDs measure salinity, temperature and pressures of water at particular location. A summary of measurement resolutions, and profiling methods for all instruments is provided in Table 1.1. The high resolution velocity timeseries are despiked using the phase-space thresholding method by Goring and Nikora (2002). Significant wave heights were estimated from the water-depth time series data from the CTD pressure sensor using Green and Coco (2007).

High-quality vegetation geometric parameters were estimated using structure-from-motion techniques and the sector-slice algorithm of Liénard et al. (2016) for 1-m² quadrats. The photogrammetric estimates were validated using hand-measured values. Additionally, sediment samples collected at the field site are processed using a laser particle sizer (Malvern Mastersizer 3000) to estimate particle statistics at the field site.

UAV imagery and dye releases

Previous laboratory experiments have also used tracer release and image processing to provide spatially resolved flows Shin et al. (2020); Hamidifar et al. (2015); Hu et al. (2018), and more recently such approaches have also been transferred to field studies to capture large-scale flow behaviours (Říha et al., 2023; Peeters and Hofmann, 2015; Pinton et al., 2020) and dispersion Jo-

Table 1.1: Sampling resolutions of equipment deployed as part of the experiments undertaken for this thesis.

Instrument	Type	Vertical resolution	Temporal resolution	Blanking distance
Aquadop	ADCP	25 mm	8 Hz	54 mm
Signature	ADCP	20 mm	8 Hz	10 mm
Vector	ADV	point	32 Hz	150 mm
Vectrino Profiler	ADV	1 mm	50 Hz	40 mm
RBR concerto	CTD	point	6 Hz	-
RBR duet	CTD	point	16 Hz	-

hansen et al. (2022); Legleiter et al. (2022); Peeters and Hofmann (2015) in riverine, estuarine and coastal environments. The success of these works have underscored the potential of UAV-based dye tracer measurements to help to understand flows in patchy aquatic vegetation systems.

In the work presented in this thesis Rhodamine WT was released in the field using a dye diffuser. The subsequent spreading and movement of the dye clouds were recorded with a 4k-resolution RGB camera (Zemuse XT2), attached to a DJI Matrice 300 drone flying at a constant barometric altitude (≈ 20 m) for each release. The camera is set to record looking straight down. The recorded images were first corrected to align each frame with ground control points placed at the field site and rotated to align with the principal axes of the flows. This process provides images of dye intensity in space (x, y) at each time step (t) . Following Johansen et al. (2022) and Clark et al. (2014), dye intensity (I) was estimated as:

$$I(x, y, t) = R(x, y, t)^2 / (B(x, y, t) \times G(x, y, t)), \quad (1.1)$$

in which R , G , and B are respectively the values of the red, green, and blue color channels. I is used as a proxy for dye concentration in this manuscript.

1.5.2 Numerical modeling

Field experiments provide real world measurements, but typically are limited to a subset of geometric and flow characteristics. For example, hydrodynamic data from field are often measured at a single point or a small profile with intrusive equipment. The dye releases serve as an effective platform to study flow behaviours but are limited to two dimensions (2D) and only provide semi-quantitative measures of concentrations. However, numerical simulations can provide much finer spatial and temporal measurements of exact physical parameters. The flow conditions and geometries of the vegetation can also be modified between simulations to cover wide parameter space and improve our general understanding of the physical processes.

The 3D Horizontal Large Eddy Simulation (HLES) in Delft 3D (Deltares, 2026) combined with a 3D rigid vegetation model (Uittenbogaard, 2003) is used to study the flow behaviours of patchy aquatic vegetation systems. 3D HLES is well suited for simulating systems in which the horizontal scales of eddies are much larger than vertical eddies (Vossen, 2000), such as found in patch-scale and system-scale turbulence in the patchy aquatic vegetation systems. The numerical model results were validated with the results from the field experiments conducted at field site 2 (Figure 1.5B).

1.6 Thesis outline

Each of the following three chapters was intended as a stand-alone document for submission to an international, peer-reviewed journal. Chapter 2 focuses on small-scale (stem scale) flow characteristics while chapters 3, and 4 focus on medium (inter-patch) and large (system-wide) scale flow characteristics.

- Chapter 2 investigates the efficacy of laboratory-based formulations for

turbulent kinetic energy (TKE) in aquatic vegetation canopies in a real environment using field measurements of TKE inside a small stand of *Avicennia marina* mangroves. The work highlights the importance of identifying dominant vegetation and flow length-scales, which can change with submergence levels. This work was published in *Limnology and Oceanography Letters* in 2026, with me as the first author.

- Chapter 3 investigates bulk and local behaviour of tracers in a randomly arranged artificial system of vegetation patches created on an intertidal flat. UAV imagery of over 45 Rhodamine WT dye releases with high spatial and temporal resolution was collected over several tidal cycles. For each dye release, bulk dispersion coefficients, local residence times, and temporal variance are computed and compared. A model for estimating dispersion coefficients using submergence ratio is proposed and validated. This work is intended for submission to *Journal of Geophysical Research: Oceans* with me as the first author.
- Chapter 4 builds on the previous chapter by expanding the parameter space using numerical simulations. Additional vegetation densities and patch arrangements are simulated to further test and improve the model proposed in chapter 3. A more complete model for estimating dispersion coefficients using frontal area and submergence levels is proposed and validated. This work is intended for submission to *Water Resources Research* with me as the first author.
- Chapter 5 summarizes the main findings of this thesis and ends with suggestions for future work.

Chapter 2

Field measurements and model
predictions of turbulent kinetic
energy in canopies of sparse
vegetation under tidal flows

Contribution of authors

Chapter 2 duplicates a paper “Field measurements and model predictions of turbulent kinetic energy in canopies of sparse vegetation under tidal flows” by Vinay Nelli (60%), Julia C. Mullarney (15%), Rémi Chassagne (15%), William Nardin (5%), and Rafael O Tinoco (5%), in which the percentage of contribution from each author is in the brackets and was published in *Limnology and Oceanography Letters* in 2026. The majority of text and figures are identical to the published version with the exception of a few changes and some supplementary information as suggested by the examiners of this thesis. Data were collected for this study in the field by myself, Julia C. Mullarney, Rémi Chassagne, and Ben Roche. I wrote scripts to load, quality control, and analyze all of the hydrodynamic data. My co-authors edited my drafts along with providing helpful comments, direction, and editorial help responding to reviewers’ comments.

Abstract

The presence of vegetation in aquatic environments alters hydrodynamics and sediment resuspension. A recent paradigm has suggested that turbulent kinetic energy (TKE) serves as a better predictor of sediment transport in aquatic canopies than bed shear stress. This observation has led to the development of formulations to predict TKE for vegetated flows in the laboratory. However, model validation from natural heterogeneous field environments is lacking. Here, we explore the application of laboratory-based formulas in a real environment, characterised by multiple vegetation length scales. We measured turbulence within a sparse canopy of mangrove pneumatophores and saplings during an experimental period with negligible wind-wave activity. The existing formulations for TKE performed well in the field, but only when using the measured values for horizontal eddy length scales. These length scales accounted for the generation of additional turbulence from the surrounding sapling canopy, leading to notably larger TKE values than in similar laboratory experiments.

2.1 Introduction

Aquatic vegetation provides habitat for different species (Costanza et al., 1997; van Katwijk et al., 2016), stabilizes riverbanks (Barbier et al., 2011; Pollen and Simon, 2005) and attenuates waves and storm surges in coastal regions (Vetori et al., 2025; Temmerman et al., 2023; Montgomery et al., 2019; Hu et al., 2025). The effectiveness of aquatic vegetation in mitigating coastal hazards has led to the use of some species being promoted as a soft engineering so-

lution against coastal erosion. However, at present, accurate and long-term predictions of the efficacy of such approaches are limited, as the processes controlling the movement and resuspension of sediment in these environments are still not fully constrained (Nepf, 2012b,a). Studies of sediment transport in regions with aquatic vegetation have shown that the presence of vegetation significantly alters the near-bed flow (Yager and Schmeeckle, 2013; Yang et al., 2015; Conde-Frias et al., 2023). Moreover, a recent shift in the sediment transport paradigm argues that traditional approaches for bare-bed flows based on shear stress predictors are inaccurate for vegetated environments, and that turbulent kinetic energy (TKE) is a better predictor of sediment motion (Yang et al., 2016; Tinoco and Coco, 2018).

While recent laboratory (Yang et al., 2015; Chen et al., 2020; Liu et al., 2021) and numerical (Etminan et al., 2018; Anjum and Tanaka, 2020; King et al., 2012) studies have shown that TKE can be accurately predicted in vegetated channels, these works use a myriad of simplifications which induce bias in the results (Tinoco et al., 2020). Horstman et al. (2018) conducted laboratory experiments with smooth cylindrical dowels and real vegetation, and concluded that dowels poorly mimic pneumatophores. Field studies in natural environments with complex non-stationary hydrodynamics, varying submergence levels, asymmetric tidal flow, and heterogeneous vegetation remain rare. Recent data from mangrove canopies show the direct dependence of bed-level changes on TKE and a positive relationship between TKE intensity and vegetation density (Norris et al., 2019, 2021); emphasizing the need for an accurate TKE prediction model, which is applicable to complex natural environments.

Here, we report high-resolution (temporal and spatial) field measurements of velocity and turbulence within a sparse canopy of *Avicennia marina* mangrove roots. The measurements of TKE are then compared to predictions from laboratory-derived models over changing water depths and velocities observed during a tidal period.

2.1.1 Models to predict TKE in pneumatophore canopies

The TKE in vegetated aquatic environments is commonly approximated as the sum of two independent terms: a bed-generated, and a vegetation-generated component. This section will provide insights into the formulation of the contributions and introduce the combined TKE formulation.

Bed shear stress in open channels is related to the mean flow speed as $\tau = \rho C_f U^2$ (Schlichting, 1979; Williams, 1995), in which τ is the bed shear stress, U is the depth-averaged flow speed, ρ is the density of water, and C_f is the bed friction factor. The shear stress equation can then be recast in terms of TKE using the relation $k_{\text{bed}} = \tau / (0.19\rho)$ (Soulsby, 1983), yielding an expression for bed-generated TKE as

$$k_{\text{bed}} = \frac{C_f}{0.19} U^2. \quad (2.1)$$

Vegetation-generated TKE (k_{veg}), produced at the scale of the root diameter, can be estimated assuming a local balance between turbulence production in stem wakes and viscous dissipation as (Tanino and Nepf, 2008),

$$k_{\text{veg}} = \delta \left(C_D \frac{\phi}{(1 - \phi)\pi/2} \frac{l_t}{d} \right)^{2/3} U^2, \quad (2.2)$$

in which C_D is the form drag coefficient for individual stems, $\phi = n\pi d^2/4$ is the solid volume fraction for arrays of cylindrical elements, n is the number of stems per m^2 , d is the stem diameter, l_t is the characteristic eddy length-scale and δ is an empirical scale coefficient. Large eddy simulations (Etminan et al., 2018) have been conducted for various staggered arrays of vegetation, revealing that form drag can be accurately predicted as

$$C_D = 0.9\zeta^2 \left[1 + 10 \left(\frac{\zeta U d}{\nu} \right)^{-2/3} \right], \quad (2.3)$$

in which ν is the kinematic viscosity of water, and the coefficient $\zeta = \frac{1-\phi}{1-\sqrt{2\phi/\pi}}$ is the ratio of average velocity in the smallest cross-section (maximum constriction) to the mean velocity of the flow. Combining expressions (2.1) and (2.2) for bed- and vegetation-generated turbulence, we obtain the present model for predicting total TKE, k_t^{pred} , in pneumatophore canopies

$$k_t^{\text{pred}} = \begin{cases} \underbrace{\frac{C_f}{0.19} U^2}_{k_{\text{bed}}} + \underbrace{\delta \left[\left(C_D \frac{\phi}{(1-\phi)\pi/2} \frac{l_t}{d} \right)^{2/3} U^2 \right]}_{k_{\text{veg}}}, & \text{Near-bed} \\ \underbrace{\delta \left[\left(C_D \frac{\phi}{(1-\phi)\pi/2} \frac{l_t}{d} \right)^{2/3} U^2 \right]}_{k_{\text{veg}}}, & \text{In the canopy.} \end{cases} \quad (2.4)$$

The distinction between near-bed and in-canopy TKE is defined later in the manuscript within the context of this study. This TKE formulation has been recently validated by many laboratory experiments (Yang and Nepf, 2018; Zhao and Nepf, 2021; Liu et al., 2021, among others), and large eddy simulations (Etminan et al., 2018). In the present work, we test this formulation with field observations.

2.2 Field site and instrumentation

The data presented in this study were collected in Purangi estuary, New Zealand (-36.84° N, 175.76° E) over six full tidal cycles from 8 to 12 September 2022. Measurements were taken inside and around a small stand of *Avicennia marina* mangroves (Figure 2.1). At the measurement location (red square in Figure 2.1), the vegetation consisted primarily of pneumatophore roots and sparsely populated juvenile mangroves (“saplings”) of average cross-sectional span of ≈ 0.1 m diameter, ≈ 0.2 m height with leaves, and a density of 3-5 saplings per m^2 . Adjacent to the site was a line of medium-size mangrove trees of an average cross-sectional span of 1-2 m diameter, and 1-1.5 m height (green ellipse, Figure 2.1B). The flood and ebb flow directions were aligned with the orientation of the mangrove trees (Figure A.1) and speeds were slow

enough to assume that the mangrove trees have no effect on the study site. The measurement location was situated about halfway along the length of the canopy in both the flow directions and therefore we assume measured flows were fully developed (Chen et al., 2013). The pneumatophores and saplings did not move under the currents and thus can be treated as rigid vegetation. Furthermore, the frontal area density at the site ($ah < 0.035$) was low enough to assume canopy-scale shear layer vortices were not generated.

Near-bed velocities and pressure over bare-bed (purple circle, Figure 2.1B) were measured by a downwards-looking Acoustic Doppler Current Profiler (2 MHz Nortek Aquadopp, ADCP) operating in pulse-coherent mode. The instrument was positioned 0.21 m above the bed and collected data at a rate of 8 Hz, with 25 mm vertical resolution and a blanking distance of 54 mm. A conductivity-temperature-depth sensor (CTD, RBR Concerto) was positioned inside the pneumatophore canopy to measure local water depth, temperature, and salinity.

Three profiling Acoustic Doppler Velocimeters (ADV - 10 MHz Nortek Vectrino Profilers) were deployed to measure flow velocities within and above the sparse pneumatophore canopy. The ADVs recorded 3 components of velocity over a vertical profile of 30 mm with 1-mm spatial resolution at a rate of 50 Hz. The centre ADV was positioned to capture flows close to the bed (0 to 30 mm height above bed) for the full duration of the experiment, while the other two ADVs were moved in between tides in both horizontal and vertical directions to capture measurements at three different heights above the bed (0 to 30, 70 to 100 and 96 to 126 mm) and two horizontal positions. Instrument positions are summarised in Table A.1.

Sediment grain size was determined from surface grab samples using a particle size Analyzer (Malvern Mastersizer 3000). Pneumatophores characteris-

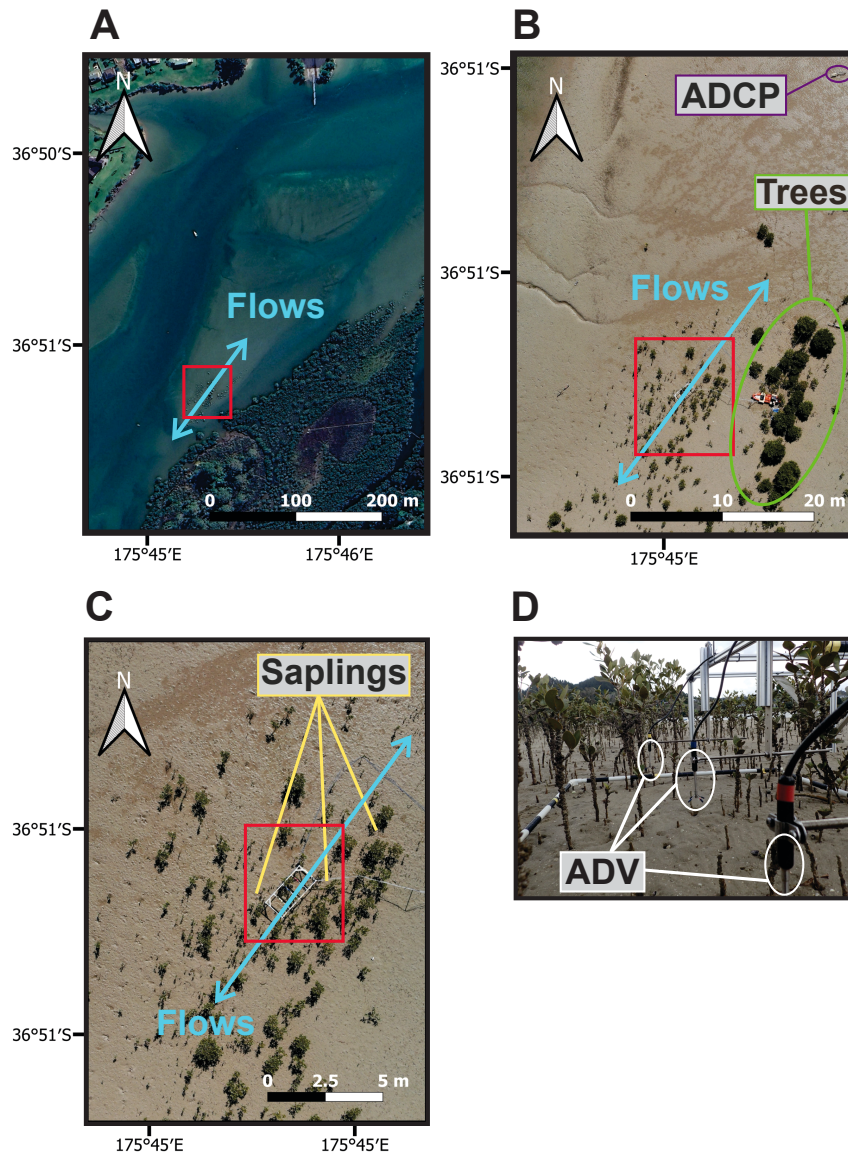


Figure 2.1: Field deployment A) Satellite image of the Purangi Estuary with the field site shown in the red square, and principal flow axis shown in blue, B) Geo-rectified drone image of the field site showing the locations of the profiling ADVs (red square), ADCP (purple circle), and mangrove trees (green), C) Geo-rectified close-up drone image of the field site showing the locations of the profiling ADVs (red square), and example mangrove saplings (yellow), D) Photograph of the Vectrino Profilers (white circle), and surrounding sapling canopy (plants with leaves).

tics were estimated in 1-m² quadrats placed below the ADVs using structure-from-motion techniques and the sector-slice algorithm of Liénard et al. (2016), applied to over 100 images. This analysis provided estimates of the pneumatophore parameters, stem diameter (d), number of stems per square meter (n), frontal area density $a = nd$, and solid volume fraction $\phi = \pi nd^2/4$ as a function of height above the bed.

2.2.1 Data quality control and processing

The data from the ADCP over the duration of experiments (6 tides) was used to determine the bare-bed friction factor $C_f = \tau/(\rho U^2)$ using the open channel flow approximation (Schlichting, 1979), and observed bed shear stress $\tau = C_2 0.5 \rho \overline{w'^2}$, where $C_2 = 0.9$. w' are the turbulent velocity fluctuations in the vertical direction, and the overbar represents a temporal average (Biron et al., 2004; Kim et al., 2000). The ADCP was downward-looking at 210 mm from bed level. The velocity fluctuations used in estimation of C_f are from the bin closest to the bed level at 31 mm, close to the suggested measurement height of 0.1 of water depth by (Biron et al., 2004) for estimating shear stress from turbulence measurements.

Low-quality velocity data from the ADVs (correlations $< 70\%$, and signal-to-noise ratios, $\text{SNR} < 10 \text{ dB}$) were removed, with gaps filled by linear interpolation. Velocities from cells from below the identified bed level were removed. The tidal flow was observed to have a principal axis with mean flow direction (to) during flood of 250° and 50° during the ebb (Figure S1). Therefore, velocities were rotated with positive u into the flood direction (250° SW), v perpendicular to the flood direction (340°), and w is the vertical velocity (positive upwards). Finally, the data were despiked using the phase-space thresholding method (Goring and Nikora, 2002). Doppler noise values estimated from the filtered time-series were much smaller than the estimated TKE values (Figure A.1).

For each instrument, TKE was calculated over 3-min windows with a 1.5-min overlap:

$$k_t^{(\text{meas})} = \langle \overline{(u'^2 + v'^2 + w'^2)/2} \rangle, \quad (2.5)$$

in which u' , v' , and w' are the fluctuations from the mean over each window, the overbar represents a temporal average and the angle brackets denote an average over all vertical bins.

In (2.1) and (2.2), the two contributions of the total TKE were modelled based on the depth-averaged (channel-averaged) velocity. In our experiments we have used the velocity averaged over the short (30 mm) ADV profile, noting (Xu and Nepf, 2020) measured TKE in two canopies made with real plant morphologies and found similar results when using either depth-averaged velocities, or velocities averaged over the canopy height.

The observed bed-generated turbulence $k_{\text{bed}}^{(\text{estim})}$ was estimated using the mean horizontal speed $U = \langle \sqrt{u^2 + v^2} \rangle$ in Equation 2.1. The vegetation-generated turbulence was then estimated as,

$$k_{\text{veg}}^{(\text{meas})} = \begin{cases} k_t^{(\text{meas})} - k_{\text{bed}}^{(\text{estim})}, & \text{Profiler at bed} \\ k_t^{(\text{meas})}, & \text{Profiler away from bed} \end{cases} \quad (2.6)$$

The ADVs were moved between 3 different heights above bed with the closest profile to bed in the range of 0 to ~ 30 mm. Therefore, we define measurement heights below 30 mm as close to the bed. The parameter δ required for predicting vegetation-generated TKE k_{veg} (2.2) is then computed by fitting against the observed vegetation-generated TKE, i.e.

$$\delta = \begin{cases} \frac{k_t^{(\text{meas})} - k_{\text{bed}}^{(\text{estim})}}{\left(C_D \frac{\phi}{(1-\phi)\pi/2} \frac{l_t}{d}\right)^{2/3} U^2}. & \text{Profiler at bed} \\ \frac{k_t^{(\text{meas})}}{\left(C_D \frac{\phi}{(1-\phi)\pi/2} \frac{l_t}{d}\right)^{2/3} U^2}. & \text{Profiler away from bed} \end{cases} \quad (2.7)$$

The errors in prediction were estimated using MAPE (Mean Absolute Percentage Error) defined as

$$\text{MAPE} = \sum (100 * |(k_t^{(\text{meas})} - k_t)| / k_t^{(\text{meas})}) / N, \quad (2.8)$$

where Σ denotes the sum, and N is the number of data points.

The size of dominant eddies is characterized by the integral length scale l_t . The horizontal integral length scales can be computed using the autocorrelation of velocity fluctuations (Kundu et al., 2016) as

$$l_{t,x} = U \int_0^{\xi_0} \rho_{uu} d\xi, \quad \rho_{uu}(\xi) = \frac{\overline{u'(t)u'(t+\xi)}}{\overline{u'^2}}, \quad (2.9)$$

in which U is the mean horizontal flow speed, ξ_0 is the first zero-crossing of the autocorrelation function of velocity fluctuations, ξ is the time lag, and ρ_{uu} is the autocorrelation function of the fluctuating velocity component u' .

2.3 Results

2.3.1 A new field measurement data set

The site was sandy with a median grain size of $180\ \mu\text{m}$ and showed no sediment resuspension for the duration of the experiment. Further, the region of interest was also covered with many shells contributing to additional bed roughness. The bed friction factor for the bare-bed region was estimated from the ADCP data as $C_f = 0.0041 \pm 0.00032$ (Figure 2.2A) with a P-value < 0.01 . The critical velocity and TKE for incipient motion based on the median grain size and bed friction factor were estimated (using (Soulsby and Whitehouse, 1997)) as $0.19\ \text{m/s}$ and $8 \times 10^{-4}\ \text{m}^2\text{s}^{-2}$, respectively. These values are greater than those observed for the majority of the observations, so sediment resuspension was expected to be negligible (Figures 4B and C).

The pneumatophores were sparsely distributed with a mean height of $100\ \text{mm}$ (Figure 2.2) within the 1-m^2 quadrats with the profiling ADVs situated at the center of the quadrat. The depth-averaged stem diameters (Figure 2.2C) and solid-volume fraction (Figure 2.2E) for each quadrat were $d = 10.96\ \text{mm}$,

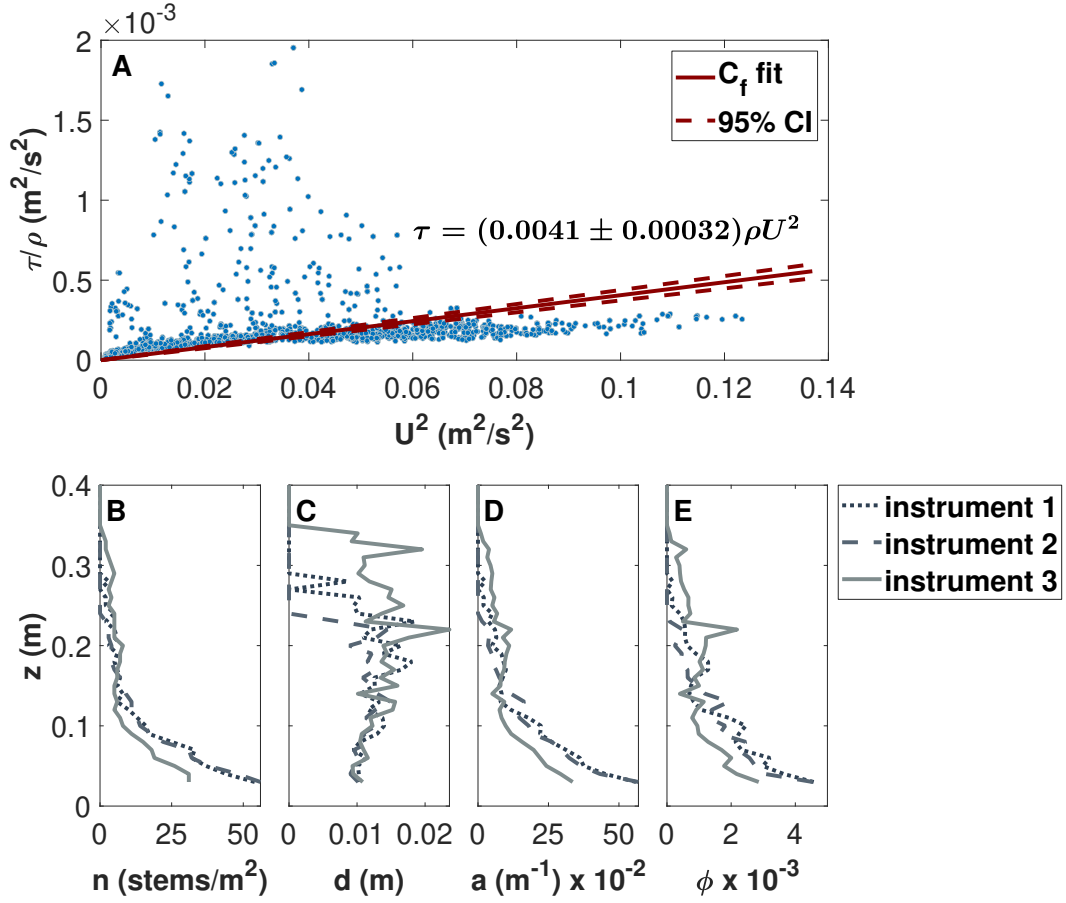


Figure 2.2: A) Bare-bed shear stress estimates from the ADCP measurements as a function of the square of depth-averaged flow speed U . Vegetation parameters from underneath the three ADVs determined from the photogrammetric analysis: B) number of stems per square meter, C) mean diameter, D) frontal area per unit volume, E) solid volume fraction.

10.36 mm, and 10.57 mm, and $\phi = 0.0029$, 0.0026, and 0.0017, respectively. The corresponding frontal areas per bed area for each ADV quadrat were $ah = 0.0339$, 0.0321, and 0.0206 (Figure 2.2D). The estimated pneumatophore diameters compare well with the measured values at the field site under each instrument (Figure A.4).

The velocity and pressure data from various instruments (ADV, ADCP, and CTD) revealed negligible wave activity over the duration of the experiments (Figure A.2). Significant wave heights were estimated from the water-depth time series data from the CTD sensor (Figure A.3) for 5-minute windows (Green and Coco, 2007). Wave heights were predominantly less than 20 mm (98.4 % of the record) with maximum values reaching 30 mm. Moreover, times with wave heights of >20 mm coincided with low SNR values and are discarded during estimating of TKE. The discarded noisy data were a continuous block of data collected at the end of the last tide under rain and windy conditions. Therefore, the data provides a unique set of field data with minimal wave influence for testing the TKE formulations derived under unidirectional flow conditions.

Over the 6 measured tidal cycles, the maximum water depth was between 0.54 m to 0.82 m providing a range of vegetation submergence levels (Figure 2.3A). Flow speeds (Figure 2.3B) reached a maximum value during the middle of the flood tide, subsequently decreased until the peak water depth was reached, and then increased almost monotonically over the ebb tide. The measured TKE at the three different profile heights using (2.5) showed a trend similar to the mean flow speed (Figure 2.3C), indicating a correlation between flow speeds and TKE values. Figure 2.3D, shows that the total TKE generally increased with flow speed, and TKE values from the instruments above the denser quadrats (ADV 1 and 2) were slightly larger than above the most sparse quadrat (ADV 3).

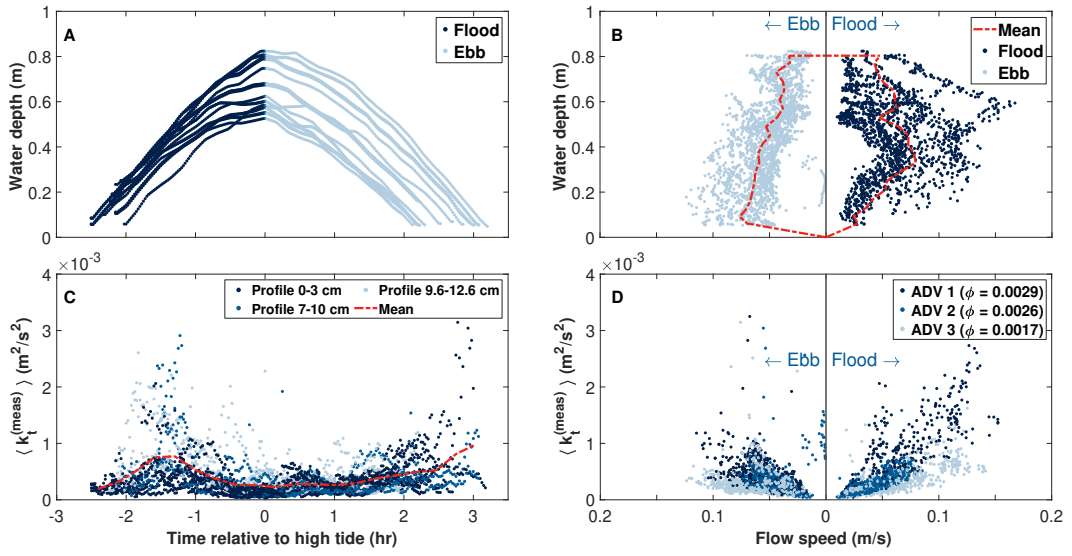


Figure 2.3: A) Water depths (dark and light lines show flood and ebb phases of the tide, respectively) plotted against relative time to high tide (defined at the maximum water depth) B) Tidal stage diagram showing water depth vs measured flow speed (dashed line is the mean flow speed), C) Observed TKE (dashed line is the mean observed TKE) plotted against relative time to high tide (defined at the maximum water depth), and D) Observed TKE vs measured flow speed from each ADV.

2.3.2 Evaluation of the vegetation-generated turbulence model

Figure 2.4A shows the median value (across all tides and ADVs) of horizontal integral length scales at each water depth $l_{t,x}$ estimated using Equation 2.9. For very shallow water depths (< 0.15 m), horizontal length scales $l_{t,x}$ are small (< 0.1 m), five to ten times the vegetation typical diameter. Length scales increase substantially as water depths increase, and stabilize to values between 0.1 and 0.17 m for water depths greater than 0.2 m.

The turbulence estimates from the theoretical model are compared against the field measurements. First, the parameter δ of the vegetation-generated turbulence model was obtained by fitting Equation 2.7 on aggregated data from all tides and three instruments. Our data yielded a value of the fitting parameter $\delta = 0.52 \pm 0.028$.

The performance of the model is shown in Figure 2.4B, which shows the predicted and measured TKE (3-min averages). The data from all tides and the three ADVs were combined by sorting into increasing measured TKE values, and then averaged into bins of 100 data points. For TKE values lower than $5 \times 10^{-4} \text{ m}^2\text{s}^{-2}$, the model was in very good agreement within uncertainties, although slightly under-predicts the measured values. However, for larger TKE values, the model under-predicts the observations. The overall Mean Absolute Percentage Error (MAPE) for all the measured TKE values (3-min averages) is 67%. The MAPE observed TKE values over $5 \times 10^{-4} \text{ m}^2\text{s}^{-2}$ is 72%, and MAPE for observed TKE values under $1 \times 10^{-4} \text{ m}^2\text{s}^{-2}$ is 65%.

Figure 2.4C shows water depth against flow speed, with points colored by observed vegetation-generated turbulence ($k_{\text{veg}}^{(\text{meas})}$) from Equation 2.6. No

clear relationship between TKE and water depth can be discerned; however, larger values of $k_{\text{veg}}^{(\text{meas})}$ consistently correspond to faster flow speeds (Figure 2.4C). Figure 2.4D compares the observed dimensionless vegetation-generated TKE ($\sqrt{k_{\text{veg}}}/U$) values from the field with laboratory observations (Yang and Nepf, 2019; Horstman et al., 2018; Liu et al., 2021; Zhao and Nepf, 2021) and theoretical values calculated assuming integral length scales are equal to the stem diameter (dashed line), and assuming integral length scales are equal to 15 times the stem diameter (solid line) as observed in the experiment.

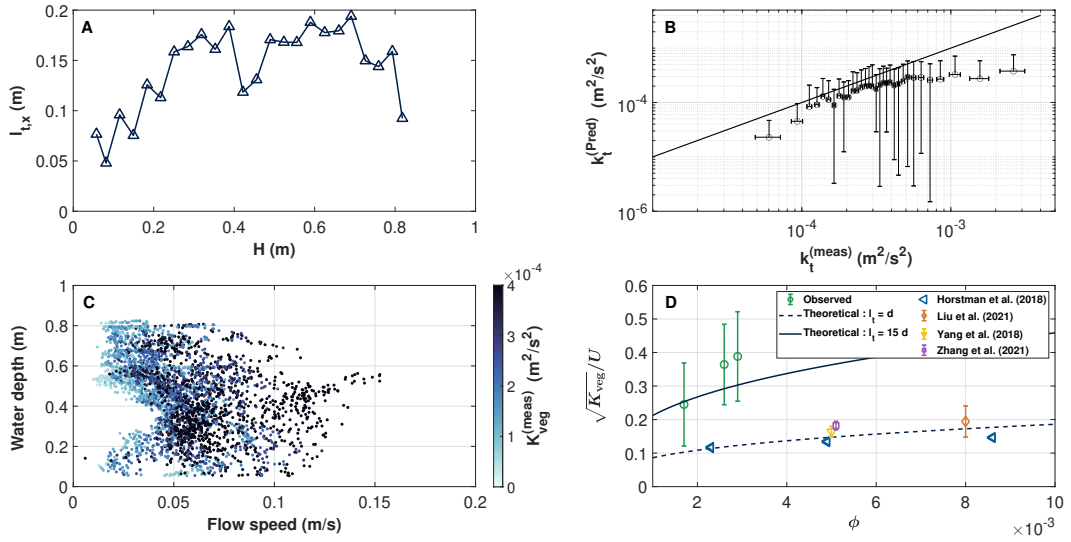


Figure 2.4: A) Median horizontal integral length scales $l_{t,x}$ (triangle) estimated from the primary horizontal (u) component of the velocity (2.9) at different water depths (across all tides and ADVs), B) Predicted TKE estimated using Eq. (2.4) against measured TKE (2.5)) over all tides sorted by measured values and averaged over bins of 100 points in which the error bars indicate the standard deviation of the values, C) Water depth against flow speed where the points are colored with observed vegetation generated turbulence from Equation 2.6, and D) Dimensionless vegetation-generated TKE, $\sqrt{k_{\text{veg}}}/U$, compared with theoretical values for the current field study and recent laboratory experiments (Yang and Nepf, 2019; Horstman et al., 2018; Liu et al., 2021; Zhao and Nepf, 2021). Error bars represent standard deviation.

2.4 Discussion

2.4.1 Comparison with laboratory experiments

The pneumatophores in the field site were sparse, with smaller volume fractions $\phi = 0.0017 - 0.0029$, than used in laboratory experiments ($\phi = 0.005 - 0.05$), and an order of magnitude sparser than in the majority of previous work (Yang and Nepf, 2019; Liu et al., 2021; Zhao and Nepf, 2021). Despite the sparseness of vegetation, the TKE model (Equation 2.5) performs reasonably well for low turbulence conditions, with a MAPE between predicted and measured TKE of 62%. The bulk scaling parameter is here computed as $\delta = 0.52 \pm 0.028$, similar to the values found in laboratory experiments by (Zhao and Nepf, 2021) ($\delta = 0.52 \pm 0.07$), and (Yang and Nepf, 2019) ($\delta = 0.4 \pm 0.3$). The results of this study demonstrate that the TKE model, validated under laboratory channel conditions, can be effectively applied to estimate TKE in real-world field conditions.

One striking difference of the present work is the observed value of integral length-scale l_t . Arguing that the scale of largest eddies is typically the stem diameter, or inter-stem distance when vegetation density is very large, the integral length-scale is usually defined as $l_t = \min\{d, s_n\}$ in which s_n is the average spacing between pneumatophores (Tanino and Nepf, 2008; Etminan et al., 2018), with $l_t \sim d$ typically applied. Our observations reveal the length scales can reach up to 15-times the stem diameter (Figure 2.4A), indicating that the stem diameter alone should *not* be used to estimate the turbulent length-scale under real-world conditions with heterogeneous vegetation characterized by multiple length scales.

Necessity of incorporating largest length scales

The value of the integral length-scale indicates turbulence production at scales larger than stem diameter. Since wave activity was absent during the field measurement periods, waves can be excluded as an additional source of turbulence. In addition, ah of at least 0.1 is needed for canopy shear layer vortices to appear (Nepf et al., 2007; Nepf, 2012b). At the field site, the ah value is in the range 0.02 – 0.034. Therefore, shear layer vortices are not expected to be generated by the pneumatophore canopy. The field site is also populated by mangrove saplings of average cross-sectional span of ~ 0.1 m diameter, and ~ 0.2 m height with leaves (Figure 2.3B), which is similar to the observed integral length scales at water depths larger than $H > 0.2$ m. At lower water depth, the sapling branches and leaves are emergent, and the integral length scales are closer to the average stem diameter even though it remains larger. This observation suggests that the presence of the saplings, even though very sparse and barely affecting the spatially averaged vegetation characteristics (i.e. the frontal area per unit volume a and volume fraction ϕ), introduces another scale of turbulence, which is advected inside the canopy and towards the measuring instruments.

The spatial heterogeneity of vegetation observed in the field has strong implications in terms of turbulence intensity compared to laboratory conditions (Figure 2.4D). Laboratory experiments with real pneumatophore canopies and similar hydrodynamics conditions as in our field experiment (Horstman et al., 2018) found normalized TKE values of $\sqrt{k_t}/U \sim 0.12$ for a pneumatophore canopy of $\phi = 0.005$, water depths of up to 0.3 m (submergence ratios of 1.9 to 4.7), and for flow speeds of 0.10, and 0.15 m/s (blue triangles in Figure 2.4D). For these similar flow conditions and the slightly lower vegetation densities from the current field site, we find normalised TKE values ($\sqrt{k_t}/U$) between 0.22 to 0.36 on average across the three quadrats (green circles in Figure 2.4D),

i.e. more than twice values recorded in laboratory settings, with the additional turbulence being attributed to production from the nearby saplings. The difference between the laboratory and field conditions is well captured by the vegetation-induced TKE law (equation (2.2)) through the dependence on the integral length-scale. Assuming $l_t \sim d$ in Equation 2.4, as in laboratory conditions, would lead to severe underestimation of the vegetation-generated TKE (Figure 2.4D) since the measured integral length-scale varies from $l_t \sim 5d$ at low water depth to $l_t \sim 17d$ for $H > 20$ cm (Figure 2.4A).

2.4.2 Spatial heterogeneity and sediment transport implications

In order to predict turbulence intensity in natural configurations with heterogeneous vegetation, it is therefore crucial to estimate precisely the integral length-scale, which might be challenging. Our measurements indicate that spatial heterogeneity in vegetation affects the integral length-scale. However, it is not clear from the present results, over which spatial extent it would be necessary to parameterize the spatial heterogeneity. Our measurements revealed similar flow characteristics between the three instruments; which is not surprising instrument locations were similar in terms of distance into the vegetated region and proximity to nearby saplings. Additionally, given the sparsity of the pneumatophores at the field site ($\phi \sim 0.002 - 0.003$), we don't expect the pneumatophores to interact with or significantly attenuate the sapling-generated turbulence. However, for denser root canopies such as in tropical systems, externally generated turbulence would be expected to be either attenuated or transferred from sapling to stem scale through the spectral shortcut mechanism (Finnigan, 2000). The assumption of $l_t \sim d$ would still apply and the interior of the canopy would be isolated from the turbulence generated outside.

One of the main motivations for developing TKE prediction models is to

predict sediment transport. In the presence of vegetation, it has been observed that TKE is a reliable predictor of incipient motion (Yang et al., 2016; Tinoco and Coco, 2018), sediment transport (Yang and Nepf, 2018, 2019) and resuspension (Tinoco and Coco, 2014; Xu and Nepf, 2020). Recent approaches in formulating bedload transport in vegetated flows have adapted τ -based formulations to k_t -based formulations. Therefore, the vegetation-generated TKE law could be implemented in numerical models (e.g. depth-averaged models) to predict sediment transport, providing a significant change for large-scale modelling of coastal geomorphic evolution. The results of the present study suggest that current laboratory-derived formulations can be used to predict of the efficacy of aquatic vegetation as a nature-based solution for protection against coastal hazards, so long as the existence of multiple vegetation length scales are considered and parameterized appropriately.

Chapter 3

The influence of patchy
vegetation on tidal flows: Field
dye measurements of intra- and
inter-patch mixing, residence
times, and dispersion
parameters

Contribution of authors

Chapter 3 duplicates a paper “The influence of patchy vegetation on tidal flows: Field dye measurements of intra- and inter-patch mixing, residence times, and dispersion parameters” by Vinay Nelli (60%), Julia C. Mullarney (12%), Rémi Chassagne (9%), Masaya Yoshikai (9%), William Nardin (5%), and Rafael O Tinoco (5%), in which the percentage of contribution from each author is in the brackets and is intended to be submitted to *Journal of Geophysical Research: Oceans* in 2026. Data were collected for this study in the field by myself, Julia C. Mullarney, Masaya Yoshikai, Ben Roche, Katherine Rowe, and Deonie Castle. I wrote scripts to load, quality control, and analyze all of the hydrodynamic and drone data. My co-authors edited my drafts along with providing helpful comments, direction, and editorial help responding to examiners’ comments.

Abstract

In nature, submerged aquatic vegetation can grow in a fragmented manner especially in pioneer fringing zones, creating a mosaic of vegetation patches interspersed with bare sediment. Such patchiness induces significant heterogeneity in vegetation-generated resistance and turbulence, altering system-scale dispersion. We present measurements of flows patterns and dye-dispersion from field experiments using an array of randomly arranged artificial vegetation patches on an intertidal sandflat. In particular, we explore the dependencies on vegetation density and submergence levels using drone-videos of Rhodamine WT dye releases at high spatial and temporal resolution. Both longitudinal and transverse dimensionless dispersion coefficients were greater than bare-bed values and decreased with submergence ratios. Longitudinal coefficients were around three times greater than transverse coefficients. While there was significant scatter, intermediate and dense patch densities exhibited larger dispersion coefficients than the array composed of sparse patches. The bulk longitudinal coefficients estimated from the field observations matched a theoretically derived relationship well. Dye intensity time series revealed significant local spatial heterogeneity across the array with dye residence times and variability depending on proximity to patches. However, residence times generally increased with both distance into the array and vegetation densities, owing to longer duration of trapping of dye within patches. Conversely, dye residence times are found to be relatively independent of submergence levels as the vegetation-induced dispersion compensated for the reduced bare-bed dispersion at low submergence levels.

3.1 Introduction

Aquatic vegetation provides many ecosystem services such as offering habitat for different species, stabilizing riverbanks, and attenuating waves and storm surges in coastal regions (Barbier et al., 2011; van Katwijk et al., 2016; Temmerman et al., 2023). However, the provision of such services is strongly

dependent on the extent and spatial distribution of the vegetation coverage. In pioneer fringing zones, vegetation often grows in non-uniform patterns as systems of individual or several interacting patches (Kondziolka and Nepf, 2014; Schoelynck et al., 2018). While much early work examining flow-vegetation interactions has focused on continuous (and often homogeneous) vegetation areas (Nepf, 2012a,b; Mullarney and Henderson, 2018), detailed quantification of how larger-scale patchiness affects flows, mixing, and sediment transport remains incomplete (Tinoco et al., 2020).

In uniform configurations, vegetation is known to reduce flow speed while producing turbulence at the scale of plant elements (Tanino and Nepf, 2008; Nelli et al., 2026). Laboratory experiments with uniform vegetation have demonstrated that both sediment resuspension (Tinoco and Coco, 2014) and bedload transport (Yang and Nepf, 2018) scale more strongly with turbulence than with bed shear stress - a shift in the traditional paradigm of sediment transport. Understanding turbulence dynamics within and around vegetated zones is therefore critical for predicting morphodynamic evolution and the long-term stability of these ecosystems.

The flow dynamics around individual circular patches have been relatively well documented. Numerical simulations (Nicolle and Eames, 2011; Liu et al., 2021) revealed different flow regimes based on vegetation density. At low density $\phi < 0.05$, the patch effect is negligible and turbulence is primarily driven by stem-scale structures. At intermediate density $0.05 < \phi < 0.15$, patch-like behavior emerges, characterized by wake formation and patch-scale turbulent structures. At large density $\phi > 0.15$, the flow resembles that around a solid cylinder. Many studies have described the wake formation, particularly focusing on how bleed flow influences wake position and length (Bouma et al., 2007; Chen et al., 2012; Follett and Nepf, 2012), and on the feedback on sediment deposition and habitat (Licci et al., 2019).

Studies with more than two vegetation patches investigated the stability and growth of the patches (Calvani et al., 2022; Carbonari et al., 2022;

Yamasaki et al., 2019), hydraulic resistance (Savio et al., 2023), or turbulent kinetic energy (Park and Nepf, 2025) of the patch systems. However studies on such configurations remain scarce, partly because the involved scales ($\mathcal{O}(10)\text{m}$) are difficult to represent in laboratory experiments with typical flume widths of 1-2 m and in numerical simulations for which large-scale models are still lacking. Therefore, this study aims to explore the interactions between multiple vegetation patches under natural, unbounded flow conditions on an intertidal sand-flat.

The mixing of nutrients and suspended sediment in the flow is governed by turbulence dispersion, which is highly influenced by the presence of vegetation (Lightbody and Nepf, 2006; White and Nepf, 2008; Sonnenwald et al., 2019). In submerged vegetation canopies, laboratory experiments (Nepf et al., 2007; Ghisalberti and Nepf, 2009) have shown that the turbulent dispersion coefficient is controlled by canopy geometry, such as canopy length and density, and flow conditions, including water depth and flow speed. The wake interactions in a multi-patch system are therefore expected to significantly influence turbulent dispersion (Park and Hwang, 2019), but it is not yet clear how vegetation density and submergence ratio affect turbulent dispersion, especially in natural flow conditions.

This article introduces a novel turbulent dispersion experiment with an array of multiple vegetation patches. A system of 20 artificial patches of vegetation mimics were randomly placed in a natural sand-flat, providing well-constrained vegetation characteristics. The dynamic intertidal conditions enabled exploration of a broad range of submergence ratios. To characterize turbulent dispersion within the patch system, we conducted dye tracer releases and analyzed the results using UAV-based drone imagery, a method widely used to study large-scale flow behavior (Peeters and Hofmann, 2015; Pinton et al., 2020; Říha et al., 2023) and dispersion in riverine, estuarine and coastal environments (Peeters and Hofmann, 2015; Johansen et al., 2022; Legleiter et al., 2022).

3.1.1 Dispersion in patchy vegetation

We can derive an expression for estimating dispersion coefficients in patchy aquatic vegetation systems following Taylor's shear dispersion (Fischer, 1979) and recent results from Park and Nepf (2025). The longitudinal shear dispersion (D_x) in a vegetation patch system can be written as (Fischer, 1979; Lightbody, 2004):

$$D_x = \frac{\Delta U^2 h_v^2}{K_z}, \quad (3.1)$$

in which ΔU is the velocity difference between flows inside the vegetation patch system and flows above the vegetation layer, and K_z is a factor dependent on diffusion. Park and Nepf (2025) show that for rigid canopies the average velocity within the canopy (U_c) is:

$$U_c = U_0 S_r^q, \quad (3.2)$$

in which, U_0 is the unobstructed channel-averaged velocity, $S_r = H/h_v$ is the submergence ratio, and q is a function of frontal area a . The above-canopy velocity (U_a) can be derived from the continuity equation for two layer flows as follows (Park and Nepf, 2025; Chen et al., 2013):

$$U_0 H = U_a (H - h_v) + U_c (1 - \phi) h_v, \quad (3.3)$$

$$U_0 S_r = U_a (S_r - 1) + U_c (1 - \phi), \quad (3.4)$$

$$U_a = \frac{(U_0 S_r - U_c (1 - \phi))}{(S_r - 1)}, \quad (3.5)$$

Substituting Eq. 3.2 into Eq. 3.6 and assuming $1 - \phi \approx 1$

$$U_a = U_0 \frac{S_r - S_r^q}{S_r - 1}, \quad (3.6)$$

ΔU can be estimated as,

$$\Delta U = U_a - U_c, \quad (3.7)$$

$$= U_0 \left(\frac{S_r - S_r^q}{S_r - 1} - S_r^q \right), \quad (3.8)$$

$$= U_0 S_r \left(\frac{1 - S_r^q}{S_r - 1} \right). \quad (3.9)$$

using Eq. 3.1 and Eq. 3.9, the relation between dimensionless longitudinal dispersion (D_x^*) and submergence ratio (assuming that the dispersion is primarily caused by canopy shear) can be written as:

$$D_x^* \propto S_r \times \left(\frac{1 - S_r^q}{S_r - 1} \right)^2. \quad (3.10)$$

3.2 Materials and Methods

3.2.1 Experiment Setup

The field experiments (Figure 3.1) were conducted on intertidal sandflat in the Purangi estuary, New Zealand (-36.84° N, 175.76° E) over three full tidal cycles from 10 May to 12 May 2024. The field site is situated near — but unaffected by — a small strand of mangroves, allowing the observed flows to closely mimic those of natural mangrove systems. Twenty circular patches of diameter $d_p = 0.5$ m, made of $d_v = 5$ mm diameter and $h_v = 0.2$ m wooden dowels were built to represent an array of patches. The vegetation mimics in each patch were arranged in a staggered array. The positions of patches were determined using a Matlab script choosing 20 random locations in 6 m×6 m square area. The same solid volume fraction (ϕ) was used in each of the 20 patches, defined as $\phi = n \frac{\pi}{4} d_v^2$, with n the number of stems per square meter. Three different vegetation densities were used: hereafter we refer to dense, intermediate and sparse vegetation densities with $n = 1600, 400$, and 100 stems per m², respectively. These densities are selected to represent observations

from natural mangroves (Yoshikai et al., 2022; Vovides et al., 2016). Changes in densities were made between tides (see Figure 3.2A).

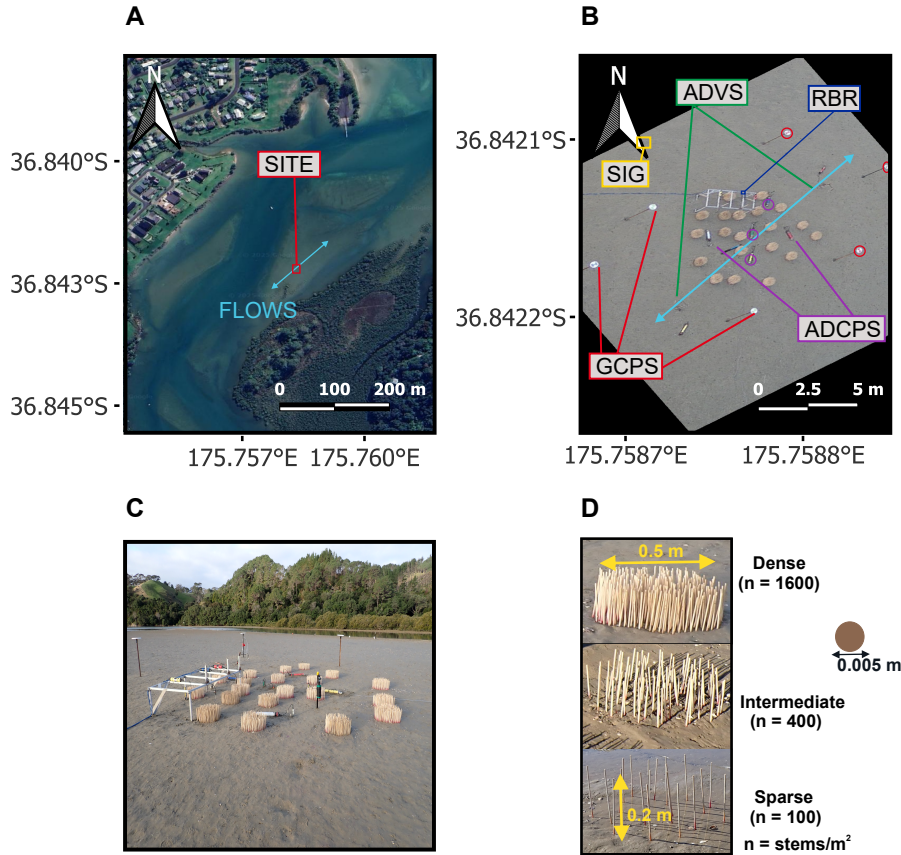


Figure 3.1: A) Satellite image of Purangi Estuary with the field site shown in the red square, and principal flow axis shown in blue. B) Geo-rectified drone image of the field site showing the locations of the patch array and placements of instruments, and ground control points (GCPs). We note only data from the signature ADCP, pressure sensor, central Aquadopp ADCP are presented in this paper. C) Side-view of the field deployment at low tide. D) Close-up pictures of the three different patch densities used in the field experiment.

An Acoustic Doppler Current Profiler (ADCP, 2 Mhz Nortek Aquadopp) was deployed in the centre of the patch array to obtain a profile of three components of velocities at 8 Hz with 25-mm vertical resolution (Figure 3.1B). Similarly a second upward-looking ADCP (Nortek Signature 1000, SIG) was positioned at the side of the patch array (~ 8 m perpendicular to flow centre-line) to measure unobstructed flow conditions. A pressure logger (RBR duet)

was deployed to measure water depths within the patch system placed 70 mm above bed. Additional instrumentation consisting of two acoustic doppler velocimeters, ADVs and four upward-looking ADCPs, and a frame (above water) are shown in the image in Figure 3.1B, but data from these instruments are not presented here.

Over the experimental duration, we conducted 45 Rhodamine WT dye releases (Figure 3.2A). Dye was released approximately 5 m upstream of the patch array in the flow direction, so the dye cloud encroached on the centre of the patch array in either direction (noting that different spatial arrangements were therefore encountered between ebb and flood releases). The average dye concentration was 3.5 kg/m^3 released through a 1 m-wide dye diffuser with four outlets ports spaced 0.25 m apart, at a height above bed equal to 0.2 m ($= h_v$). The release and subsequent spreading of the dye clouds were recorded with a 4k-resolution RGB camera (Zenmuse XT2), attached to a DJI Matrice 300 drone flying at a constant barometric altitude for each release. The camera is set to record nadir at a frame rate of 30 frames per second. The lens is a prime lens with the focus at 8 mm, and an FOV of $57.12^\circ \times 42.44^\circ$ which is rectilinear and does not require any corrections for lens deformation in post processing. The camera altitudes were between 19-25 m resulting in a Ground Sampling Distance (GSD) of $\sim 0.005 \text{ m}$. The drone videos were recorded at 30 frames per second and were stopped once dye had passed through the patch array and out of frame (typically within 3 min of release). Six Ground Control Points (GCPs) were placed around the patch system for geo-rectifying the drone captures. Two GCPs were placed in the flood and ebb flow directions 6 m away from the center of the patch system. The four remaining GCPs were placed 5 m away from center of the patch system in the four cardinal directions (North, East, West, and South).

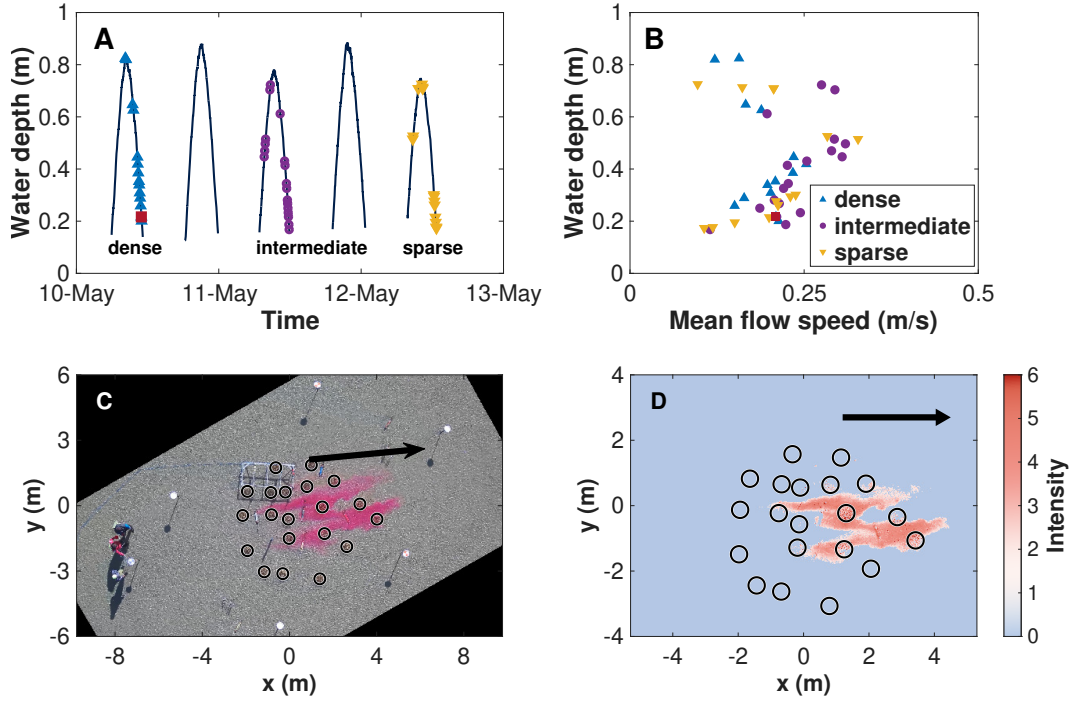


Figure 3.2: A) Water level at the field site. Symbols show dye release times for patches with dense (blue triangles), intermediate (purple circles), and sparse (yellow downward triangles) densities. The release shown in panels C,D is shown by the red square. B) Depth-averaged flow speeds observed during the dye releases plotted against water depth. C) Example of a geo-rectified frame in earth coordinates (North is upward) with the black circles highlighting the patches, and the black arrow representing the flow directions. D) Dye intensities extracted from the frame rotated to align with the flow direction with the colorbar representing the dye intensity, the black circles highlighting the patches, and the black arrow shows the flow direction.

3.2.2 Data Processing

For each dye release, the water depth was estimated by averaging the pressure time series obtained from the RBR duet over the duration of the release. The depth-averaged mean flow speeds for each release were obtained from the ADCP located in the center of the patch (Figure 3.2B). The drone videos for each release were processed using Matlab scripts as follows. First, the drone videos were geo-rectified using the ground control points into directions aligned with East and North directions, respectively (Figure 3.2C). The rectified drone videos were rotated into the flow directions to align the x-axis with the principal flow direction. To extract dye intensity information, a hue-threshold filter (Hue > 0.87 , i.e., red band) was used to isolate the pink dye in the frame, and a noise cleaning filter was used to remove blobs with an area smaller than 10,000 pixels ($\sim 0.25 \text{ m}^2$). This process provides images of dye intensity in space (x, y) at each time step (t) corrected (rotated) to align with the flow directions (Figure 3.2D). Following Johansen et al. (2022) and Clark et al. (2014), dye intensity (I) was estimated as:

$$I(x, y, t) = R(x, y, t)^2 / (B(x, y, t) \times G(x, y, t)), \quad (3.11)$$

in which R , G , and B are respectively the values of the red, green, and blue color channels. I is used as a proxy for dye concentration in this manuscript.

3.2.2.1 Bulk dispersion analysis

The bulk dispersion coefficient in the patch array is obtained from the time derivative of the spatial variance of the dye cloud intensity. For longitudinal dispersion, first, the transverse average dye intensity at each x-position at a single timestamp is computed as,

$$I_m(x, t) = \frac{1}{W} \int_0^W I(x, y, t) dy, \quad (3.12)$$

in which W is the width of the frame. The j^{th} moment in dye intensity at each time t is defined as,

$$M_j(t) = \int_0^L x^j I_m(x, t) dx, \quad (3.13)$$

in which L is the length of the frame. The longitudinal spatial variance ($\sigma_x^2(t)$) is obtained from the moments as,

$$\sigma_x^2(t) = \frac{M_2(t)}{M_0(t)} - \left(\frac{M_1(t)}{M_0(t)} \right)^2. \quad (3.14)$$

Finally, the longitudinal bulk dispersion coefficient (D_x) is computed as (Peeters and Hofmann, 2015; Okubo, 1971),

$$D_x = \frac{1}{2} \frac{\partial(\sigma_x^2(t) - \sigma_x^2(t_0))}{\partial(t - t_0)}, \quad (3.15)$$

in which t_0 is the time at which the dye enters the patch system. The spatial variance time series is filtered with a Savitzky–Golay Filter of order 1 and a window size of 4seconds. Similarly, the process can be applied in the y -direction to obtain the transverse spatial variances ($\sigma_y^2(t)$) and the transverse bulk dispersion coefficient (D_y). Finally, we fit an exponential relationship for the non-dimensional dispersion coefficients ($D^* = D/(UH)$) of the form:

$$D^* = A \times S_r \times \left(\frac{1 - S_r^{-1.73}}{S_r - 1} \right)^2, \quad (3.16)$$

in which A is a fitting coefficient, $S_r = H/h_v$ is the submergence ratio, and h_v is the height of the vegetation. The derivation of Eq. (??) is shown in section 3.1.1. Note, the value $q = -1.73$ is suggested by Park and Nepf (2025) for dense canopies.

3.2.2.2 Spatially varying parameters

Dye residence time and time variance of the dye intensity time series were computed at every point (pixel) to understand the local characteristics of the patch system. Dye residence time $T_{\text{res}}(x, y)$ is defined as the duration for which the dye intensity at the location (x,y) exceeds a threshold of 2 to exclude noise. Temporal variance $\sigma_t^2(x, y)$ of the dye intensity at location (x,y) is estimated in a similar manner as for spatial variance as shown in Eqs. 3.13-3.14:

$$\sigma_t^2(x, y) = \frac{TM_2(t)}{TM_0(t)} - \left(\frac{TM_1(t)}{TM_0(t)} \right)^2, \quad (3.17)$$

in which the j^{th} order temporal moment (TM_j) of dye intensity is defined as:

$$TM_j = \int_0^T t^j I(x, y, t) dt. \quad (3.18)$$

The residence times and temporal variance variables are non-dimensionalized using the characteristic advective time scale $t_* = L/U$, in which U is the depth-averaged horizontal flow speed and $L = 6$ m is the length of the patch system.

3.3 Results

A sequence of drone images showing dye movement through the patch array after release (at $t = 0$ s) is shown in Figure 3.3, for the densest vegetation configuration ($n = 1600$ stems/m²), and near-emergent vegetation ($S_r = 1.08$) in which submergence ratio $S_r = H/h_v$ in which H is the water depth, and h_v is the height of the vegetation canopy. Upstream of the patch array, the dye cloud expands slowly as it is advected in the along-flow direction. Once the dye cloud enters the patch system, the cloud elongates substantially, particularly in the along-flow direction, owing to the trapping within, and slow release of dye from, the individual patches. The dye cloud also expands in the

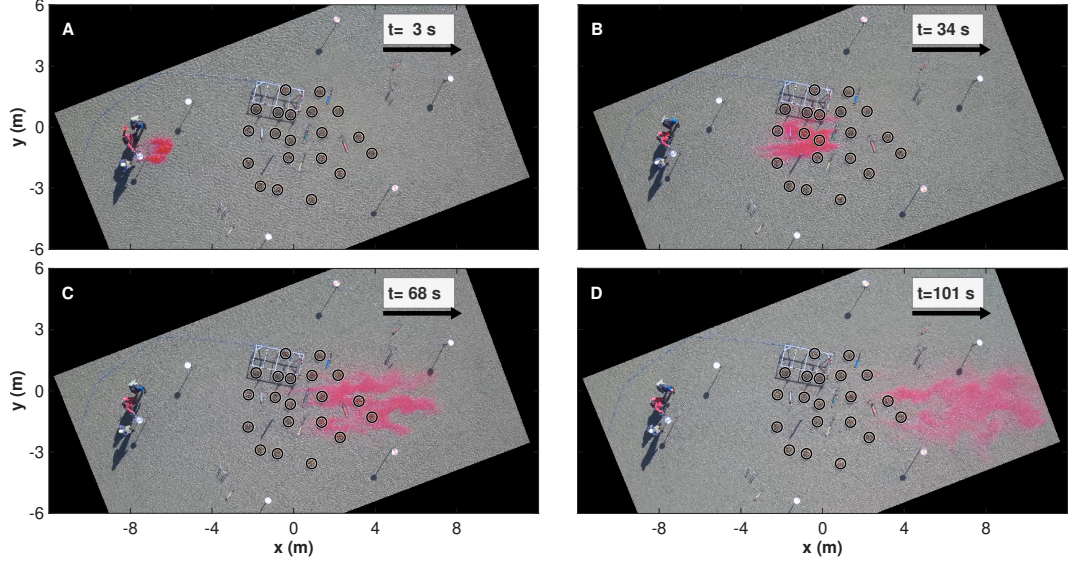


Figure 3.3: Sequence of geo-rectified drone images of the dye tracer cloud released into a near-emergent dense patch system ($n = 1600 \text{ stems/m}^2$, and $S_r = 1.08$) with the timestamp denoted in the white box top right of each subplot (release occurs at $t = 0 \text{ s}$). The black circles indicate the patches, and black arrows show the flow direction.

lateral direction due to both deflection around the patches and shear instabilities forming in the patch wakes.

Figures 3.4A and B show the longitudinal and transverse variance. The dispersion coefficients are obtained from the linear fit of the filtered variance signal between the entrance and exit time (dashed lines in Figures 3.4A and B). Figures 3.4C and D show, for all patch densities and submergence ratios, the dispersion coefficients, non-dimensionalised with time- and depth-averaged horizontal flow speed (U) and the water depth (H) measured during the dye release. While there is considerable scatter in the results, at lower submergence ratios (< 2.5), dispersion coefficients were found to depend on patch density with larger values observed for the intermediate and dense patch arrays. For larger submergence ratios (> 2.5), the dispersion coefficients across the three patch densities are almost identical. A few large values of dispersion coefficients in the fully emergent ($S_r < 1$) sparse vegetation case were removed

from the analysis as these were owing to the dye sticking to the bed surface. The calculated longitudinal non-dimensional dispersion coefficients D_x^* (Figure 3.4C) were between 0.5-2, unsurprisingly larger than the range observed for transverse coefficients D_y^* (Figure 3.4D), which ranged between 0.1-0.5. The fits based on Equation (3.16) yielded coefficients estimated for the dense, medium, and sparse patch systems of 0.65 ± 0.13 , 0.7 ± 0.22 , and 0.58 ± 0.18 , for longitudinal coefficients and 0.17 ± 0.04 , 0.19 ± 0.04 , and 0.12 ± 0.04 , for transverse coefficients, respectively. The mean percentage error for longitudinal dispersion across all points is 39%. The mean percentage error for all transverse fits is 68%.

We examine the dependence of dye intensity on position into the patch array. Figure 3.5 panels A, C, and E show, for the densest vegetation configuration, snapshots of the dye cloud spreading through the array for different submergence levels. Panels B, D, and F show time series of dye intensities at different positions into the array. The concentration profiles in deeply submerged case (Figure 3.5B) reveal skewed normal dye intensity profiles, corresponding to dye intensities rapidly increasing as the cloud reaches a position, but the right-hand tails are extended as dye gets trapped both within patches and in eddies and wakes behind patches. As the dye spreads further into the patch, peak dye intensities gradually decrease from upstream to downstream profiles, and each profile becomes increasingly asymmetric with distance into the array. For the intermediate and near-emergent submergence levels (Figure 3.5D and F), the dye traverses the patch more rapidly due to increased flow speeds. Peak dye intensities are lower, and decline from upstream to downstream profiles with a more pronounced rate of decline compared to the deep submergence case, suggesting enhanced mixing. For intermediate submergence levels, profiles are more asymmetric with longer tails indicating more trapping within the patches and secondary dye releases of the trapped dye compared to the deeply submerged case. For the near-emergent submergence level (Figure

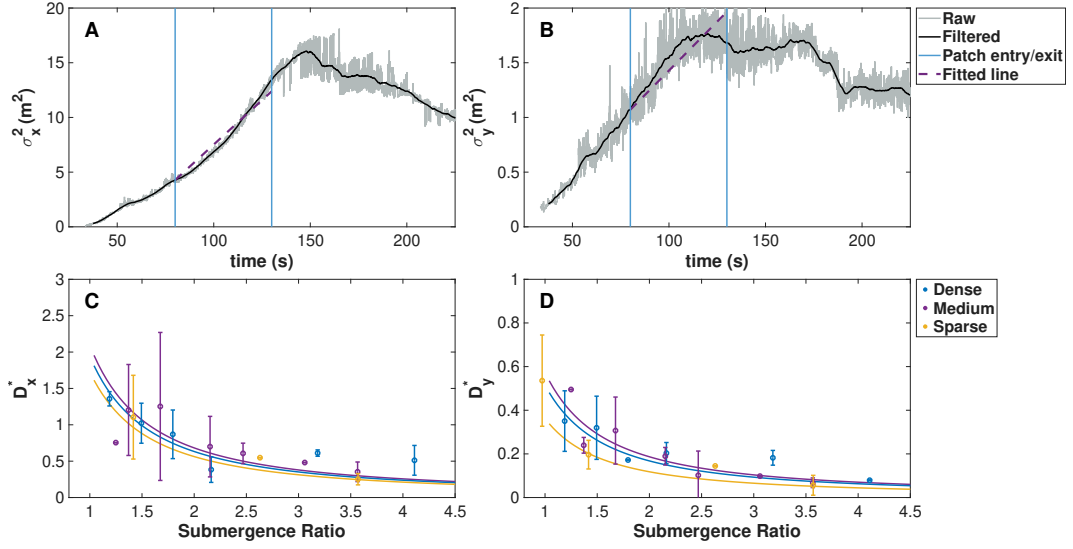


Figure 3.4: Time series of the spatial variance of dye intensity in the A) longitudinal, and B) transverse directions estimated using Eq. 3.14 for $n = 1600 \text{ stems/m}^2$, and $S_r = 4.12$. Gray lines show raw data, black lines are the filtered series; vertical blue lines indicate the initial times of dye entry and dye exit into the patch system, respectively, and the purple dashed line is the fit used to estimate dispersion coefficients using Eq. 3.15. C) Longitudinal and D) transverse non-dimensional dispersion coefficients estimated using Eq. 3.15, Solid lines are using Eq. ??, the circles are the mean values of the binned dispersion coefficients, and error bars in panels C and D are the standard deviation of binned dispersion coefficients.

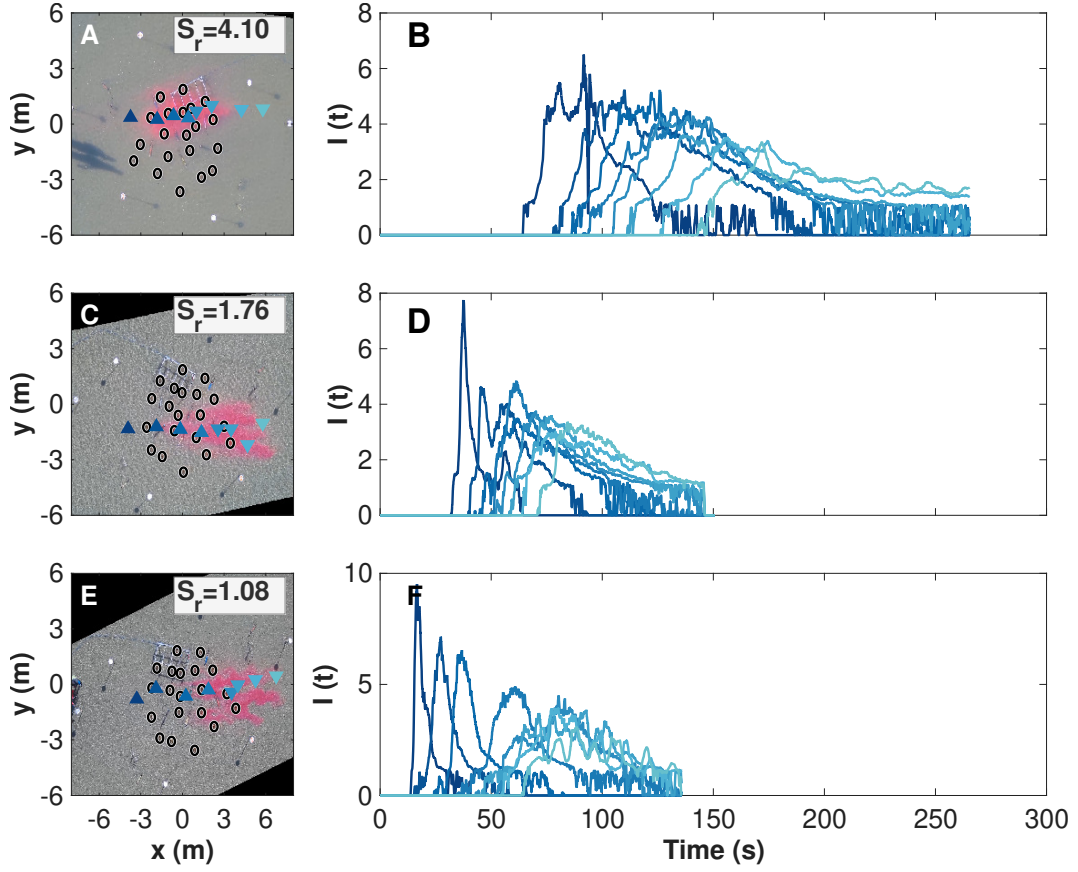


Figure 3.5: Dye intensity time series observed in the dense patch system ($n = 1600 \text{ stems/m}^2$): A,C,E) Snapshot of a dye release with the the upward triangle representing selected upstream points and downward triangle representing the selected downstream points, the submergence ratio denoted in the white box at the top right of each subplot, and the black circles highlighting the patches. B,D,F) Dye intensity time series plots at the selected locations (0.5-s moving average) in which the color intensity reduces from upstream points to downstream points.

3.5F), the profiles from directly behind downstream patches at the start of the array ($x \sim -3\text{ m}$) are close to symmetric indicating less trapping of dye inside the patches and more lateral deflection around patches with weak oscillatory behaviour (see the dye cloud oscillating in Figure 3.5E; also supported by Figure 3.4D, showing the increase in D_y^* with the decrease in S_r). Points further into and downstream of the patch array, exhibit an oscillatory profile due to vortex shedding from the patches.

For intermediate and sparse patch density configurations, similar but weaker spatial patterns in dye intensities are observed (Figures S1,S2). However, profiles are less asymmetric owing to much weaker within and behind patch trapping of dye by the smaller vegetation densities, so dye passes through the system more quickly. The associated changes in peak intensities with distance into the patch array are also smaller. Moreover, for the near-emergent submergence levels, the dye profiles do not exhibit oscillations as there is minimal vortex shedding and wake formation.

Examples of the spatial patterns of dimensionless residence times and temporal variances of dye intensities are shown in Figure 3.6 at three difference submergence levels for the dense patch system. For the deeply submerged case (Figure 3.6A), the residence times show consistent values along the path of the dye cloud with the edges of the dye cloud having lower values. For the intermediate submerged case (Figure 3.6C), the residence times are lower in front of the system with the values increasing as the dye cloud enters the patch system and the values behind the patch system are about twice as much as the values in front of the patch. For the near-emergent case (Figure 3.6E), a similar trend to the intermediate submergence case is observed but the residence times only start increasing in the downstream half of the patch system. The spatial patterns of residence times for the intermediate and sparse patch densities were similar (Figures S3 and S4).

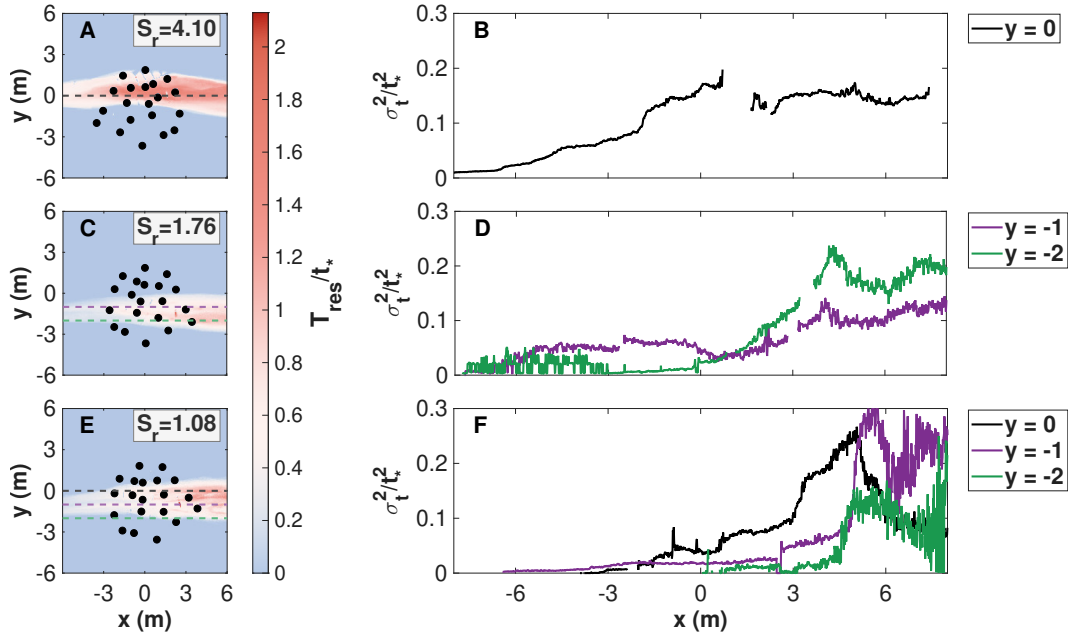


Figure 3.6: Spatial parameters estimated for the dense patch system ($n = 1600 \text{ stems/m}^2$): A,C,D) non-dimensional residence times of a dye release with the dashed lined representing transects used for temporal variance, the submergence ratio denoted in the white box at the top right of each subplot, and the black circles highlighting the patches. B,E,F) non-dimensional spatial variance estimated for the transects represented in the left subplot. The values inside the patches are excluded from the plots as these points cannot be resolved.

Figure 3.6B,E,F, show the dimensionless temporal variances from deeply submerged case to the near-emergent case for the transects denoted in Figure 3.6A,C,D, respectively. For the deeply submerged case (Figure 3.6B), the temporal variance increases as the cloud passes through the patch system with values dropping a little and staying constant in the downstream of the patch system. For the intermediate submerged case (Figure 3.6D), the transects show that the arrangement of the patches is crucial. In the patch system, the $y = -2$ transect does not encounter patches until the cloud passes the center of the patch system and the temporal values only start increasing after the cloud encounter any patches. Contrastingly, the temporal variances in the $y = -1$ transect increases in the first half of the patch system, decreases in the middle of the patch and increases again as it leaves the downstream half of the system reflecting the transect encountering patches at different points to the $y = -2$ transect. The spatial patterns of temporal variances for the intermediate and sparse patch densities were similar (Figures B3 and B4) for the deeply and intermediate submergence levels. The near-emergent case (Figure 3.6F) showed similar trends to the intermediate system (Figure 3.6D) as the dye cloud passes the patch system with strong oscillatory behaviour behind the patch system due to the shedding of the von-karman vortices. The intermediate density patch system (Figure B3F) shows similar trends in the near-emergent case with the absence of the strong oscillatory behaviour. The sparse density patch system (Figure B3F) shows lower values of dimensionless temporal variance than the denser patch systems with the temporal variance in the patch system influenced by the path of the dye cloud linked to the points at which the cloud encounter the patches.

Results are summarised in Figure 3.7, which shows the average values of dimensionless residence times and temporal variances of dye intensities along the path of the dye cloud (x -direction) for different submergence ratios with the clouds being released in the left side and traveling towards the right side.

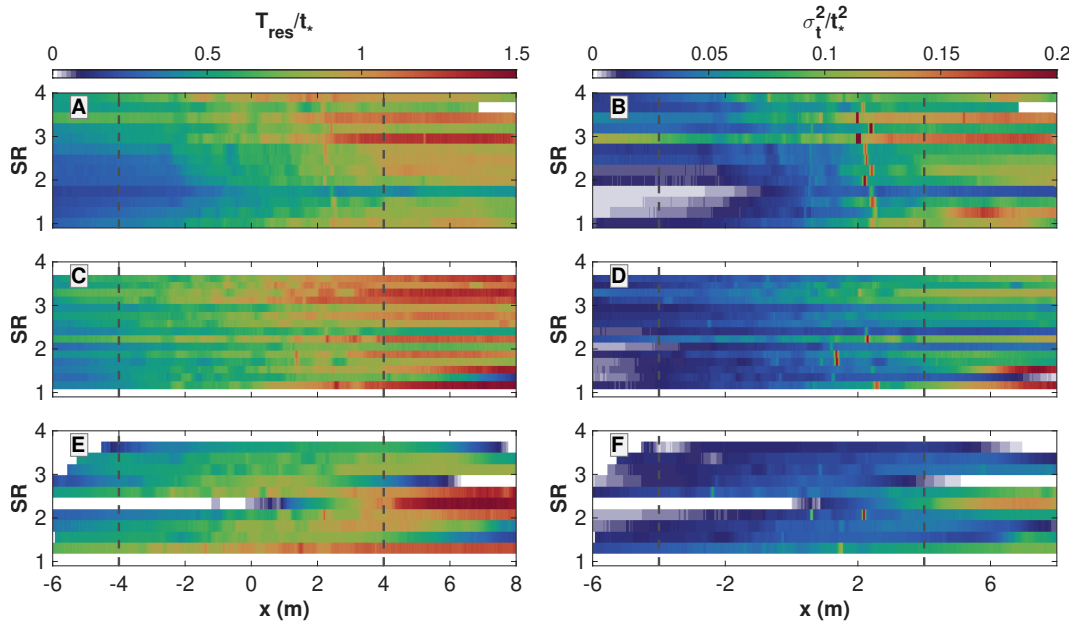


Figure 3.7: Average dimensionless residence times (A,C,E) and temporal variances of dye intensity (B,D,F) along the path of the dye cloud plotted against submergence ratio. The vertical black dashed lines show the extent of the patch system, and the dye is traveling from left to right (-ve x to +ve x). Results for the dense (A,B), intermediate (C,D), and sparse (E,F) patch cases.

The residence times show similar values across the submergence ratios with the values in the downstream being elevated compared to the upstream values for intermediate-low submergence cases. The dense and intermediate density systems shows elevated temporal variance in the downstream across submergence levels while the sparse densities show such behavior only for intermediate and low submergence cases.

3.4 Discussion

Our experiments demonstrated that both submergence ratio (S_r) and the vegetation density (n stems/m²) play a role in determining the impact of patch systems on mixing and dispersion. For submergence ratios of over about 2.5 ($S_r > 2.5$), the patch system led to minimal horizontal flow diversion; while, for $S_r < 2.5$, the patch system diverts the flow horizontally depending on the vegetation density and submergence ratio. This result is consistent with that from Ortiz et al. (2013) who showed that, for patches of similar vegetation density, submerged patches tend to deflect flow over and above the top of the vegetation, whereas emergent patches induced horizontal flow diversion. Moreover, Park and Nepf (2025) compared wake and shear turbulent kinetic energy (TKE) production and showed that wake production of patches decreases as S_r increases, falling significantly lower than shear production at $S_r = 2$, with the total TKE production rapidly decreasing as S_r increases further.

For emergent to intermediate submergence levels ($S_r < 2$), the density of the patches exerts a strong control on the extent and characteristics of the flow deformation. Liu et al. (2021) and Nicolle and Eames (2011) found that, for $\phi > 0.15$, the patches start to behave as a solid cylinder, while for $0.05 < \phi < 0.15$, the patches show bleed flows with weak wake formations; and, finally, for low densities, the patches do not form any clear wakes, with

stems acting as isolated cylinders. While our observations show similar flow regimes, the transitions between regimes occur at different values of ϕ despite our densest patches ($\phi = 0.0314$) being well under the limits proposed by Liu et al. (2021) and Nicolle and Eames (2011). Moreover, we observed some trapping and slow secondary release of dye within patches for the most dense cases, although most dye was diverted around the patches. These differences suggest that the frontal area density, controlled by relative patch diameter, the ratio of patch diameter to stem diameter ($\Lambda = d_p/d_v$) may be a better indicator of the flow regimes in individual patches. In our study ($\Lambda = 100$), the relative patch diameter is around five times that used in the previous studies ($\Lambda \approx 21$) and the frontal area density impacting flow is therefore five times greater for the same solid volume fraction. However, if we define the flow regimes using the non-dimensional patch frontal area (ad_p) (with $ad_p < 1$ as the sparse regime, $1 < ad_p < 3.5$ as the intermediate regime, and $ad_p > 3.5$ as the dense regime) our observed transitions between the different flow regimes match the observations from Liu et al. (2021) and Nicolle and Eames (2011).

3.4.1 Comparison with classical dispersion formulations

Classical formulations for dispersion above bare beds (based on Elder’s formula) give $D_{bare} = 5.9u_*H$ (Fischer, 1979) which can be written as $D_{bare} = 5.9\sqrt{C_f}UH$, in which u_* is the friction velocity, and C_f is the bed friction coefficient. For the measured sediment size at our field site (Yoshikai et al., 2025), $C_f \approx 0.003$ yielding the non-dimensional bare-bed dispersion of $D_{bare}^* = \frac{D_{bare}}{UH} \approx 0.32$. In the presence of vegetation, the longitudinal non-dimensional dispersion coefficient is elevated for lower submergence levels and decreases nonlinearly with submergence levels (Figure 3.4C). For even the sparsest vegetation density in our experiments, the dimensionless longitudinal dispersion was always greater than the estimated bare-bed dispersion. However, this was not the case for transverse dispersion coefficients, which are

smaller than the estimated bare-bed dispersion for greater submergence levels.

The residence times for bare-bed flows are expected to increase with submergence levels due to linear increase in dispersion. However, in our experiments with vegetation patches, the measured residence times (Figure 3.7A,C,E) show only a very slight dependence on submergence levels. The lack of dispersion by the bare-bed is compensated by vegetation-generated dispersion at lower submergence levels. The weak dependence of residence times on submergence levels has implications for sediment transport and micro-plastic deposition in patchy aquatic vegetation systems, suggesting for example, that hot spots of particle deposition are more likely to be dependent on patch configurations than submergence levels.

3.4.2 Observed flow behaviours

In a typical dye release (Figure 3.8A) as observed in the experiment, the dye cloud expands uniformly until reaching the patch system. In very deep waters or for very sparse vegetation densities, the dye cloud continues expanding uniformly with slight change in the rate of expansion. Once the cloud enters the array of vegetation patches, the behaviour is governed by both the water level and patch vegetation densities. In shallow- to intermediate-depth waters (smaller submergence ratios) with medium to high vegetation densities, the lateral expansion (perpendicular to the flow) is slowed by the patch system with the cloud forming into an ellipse. Longitudinal expansion (into the flow) of the cloud is complex due the deformation from the patch dynamics and, the dye is also trapped and released by the individual patches causing additional elongation of the cloud in the longitudinal direction. While interactions of the cloud with upstream patches influence the dye reaching a patch, the behaviour as the cloud impinges on an individual patch can be schematized as shown in Figure 3.8B). The released dye is rapidly advected through the

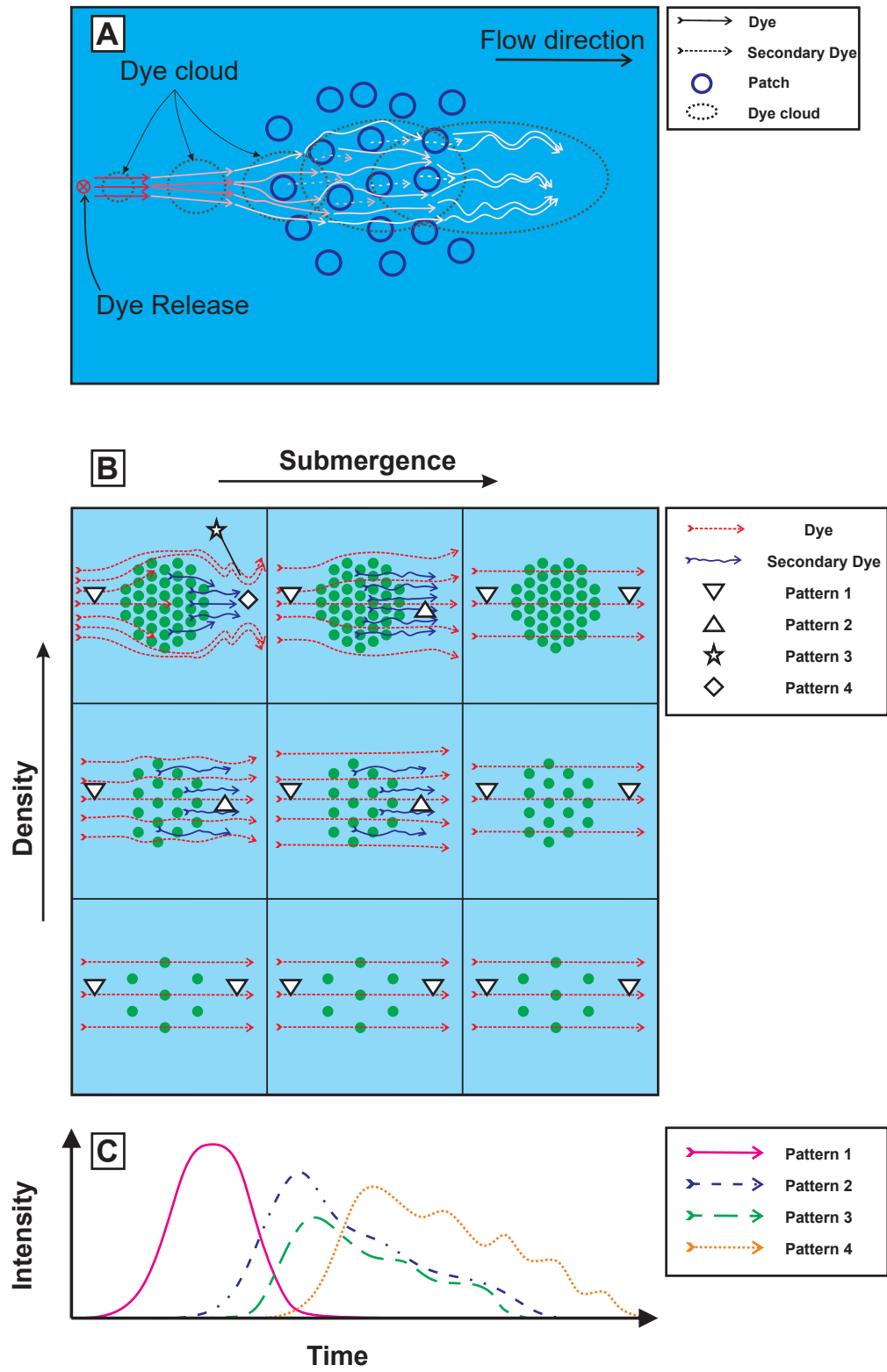


Figure 3.8: A) Schematic of dye movement and dispersion through the patch system: The red circle with an X represents the point of dye release with a diffuser. The solid arrows of the path followed by the released dye, and the dashed arrows represent the secondary releases of trapped dye by the patches, and the color intensity of the arrows represent the concentrations of the dye. B) Generalized tracer patterns for a single patch of vegetation at different densities and submergence levels. Dashed red lines indicate paths of the released dye, curvy purple lines show the secondary dye releases of the trapped dye, and the symbols denote locations selected to showcase different regimes or patterns in the time series of dye intensities. C) Examples of the different regimes of time series of dye intensities (depth-averaged concentrations) corresponding to the locations denoted in B.

patch if vegetation in patch is really sparse or the patch is deeply submerged ($S_r > 2$). If the vegetation density in the patch is intermediate to dense, and the patch submerged at an intermediate level ($1.5 < S_r < 2$), the majority of the released dye bleeds through the patch with some lateral deformation of the dye path due to edge effects. Additionally, some dye gets trapped and slowly released defined here as secondary dye releases. In near-emergent submergence levels ($S_r < 1.5$), intermediate density patches have a similar behaviour to the one in intermediate submergence levels albeit with stronger flow deformations and intense secondary dye mechanisms. The high density patches create a preferential path diverting the flow around patch to downstream at low submergence levels with only a small amount of dye being trapped and slowly released as secondary dye. Furthermore, the high density patches create a von Karman vortex street further deforming the dye path downstream of the patch.

3.4.3 Limitations of field studies and future considerations

The analysis of the dye cloud demonstrated the dependence of the path taken by the dye cloud on both the bulk and local results. The flow direction of the dye cloud is different between dye releases due to the natural turning of tide, albeit holding a reasonably consistent direction within the period of a dye release. In Figure 3.4C,D, the bulk results show considerable variability in values for similar submergence levels and densities highlighting the variability caused by the path of the cloud in the bulk dispersion. The value $q = -1.73$ is suggested by Park and Nepf (2025) for a dense canopy which nonetheless matches the observations from the current study with smaller densities (Figure 3.4C). However, the dependence of the fitting coefficient D_x^* on vegetation densities and patch configurations remains a subject for future work. At low submergence ratios (from $S_r \approx 1$ -1.5), an isolated patch would experience a reduction in within-patch flow speeds (impacting bleed flows) with an increase in submergence ratio, which would result in larger dispersion coefficients (Yoshikai et al., 2026). However, such behaviour is not observed in our results, which may be owing to the medium-scale interactions between multiple patches.

The local parameters (residence times and temporal variance) show elevated values right behind and in the near wake of individual patches highlighting the upstream effects on local dye behaviour at any point. The observations imply that further work resolving the dependence on patch distributions would provide a useful contribution - especially given that laboratory experiments often use regular staggered vegetation arrangements (Tinoco et al., 2020), and field experiments in engineered wetlands show creation of preferential flow paths (Lightbody et al., 2008). Moreover, the measured dye intensities are two-dimensional which omit the vertical distribution of the dye and impact of vertical flow structures. Lastly, intensities are limited to a precision of 8-bits

i.e. the values are integers from 0-255 so the concentration values show low dynamic resolution.

Finally, the current study uses rigid vegetation of a constant patch diameter, vegetation stem diameter, vegetation height, and aspect ($AR = 0.4$), in which the aspect ratio (AR) is defined as the ratio of patch height to the patch width. However, the aspect ratio of the patch determines whether the horizontal or vertical eddies are dominant in the wake of the patch, and the distance at which the dominant wakes form behind the patch system (Liu et al., 2018; Hu et al., 2018; Chen et al., 2013). For wide patches ($AR < 0.75$), the vertical eddies dominate wake of the patch, and for narrower patches ($AR > 0.75$) the wake is dominated by lateral eddies. Furthermore, Nepf et al. (2007) and Ghisalberti and Nepf (2009) show the ratio of the length of the patch to patch height controls the dominant process of dye removal within the patches: longer canopies ($L > 20h$) are flushed by vertical exchange while shorter canopies are flushed by advection. Additionally, the use of a single patch diameter also fixes the relative patch diameter (Λ), resulting in different frontal areas (blockage) for similar vegetation densities.

Furthermore, flows in intertidal systems are cyclic in nature switching directions between flood and ebb tides. Therefore, dispersed and deposited tracers (such as suspended sediments) can undergo resuspension and re-enter the system during the opposite flow phase, with additional complexities introduced due to settling lag and tidal asymmetries (Hunt et al., 2015; de Ruiter et al., 2019). Hence, our results cannot be directly applied to the long-term geomorphic evolution of inter-tidal multi-patch systems, which would require numerical simulations of tidal flow cycles.

3.5 Conclusions

We conducted novel field-based dye tracer experiments using UAV imagery in patchy aquatic vegetation to quantify system-scale dispersion. The measured data is of high temporal and spatial resolution facilitating the understanding of local behaviors in a multi-patch system. A relationship for bulk dispersion (system-scale) based on the submergence ratio is derived. Bulk dispersion is found to be dependent on the path of the dye cloud (patch configuration) and within-patch vegetation densities. Spatial analysis of dye clouds indicates that dye residence times and variability in dye intensity increase with distance into the patch. However, the increase in submergence levels had minimal impact on residence times suggesting that, for low submergence levels, the elevated vegetation-generated dispersion compensates for the lack of bare-bed dispersion. Furthermore, the same solid volume fraction can present different frontal areas depending on the ratio of the patch diameter to vegetation stem diameter, thus indicating that the solid volume fraction is a poor indicator for identifying the lower limit of vegetation density at which patch-like behavior emerges in individual patches.

The use of UAV-based observations enabled measurements over large spatial extents but was not able to capture the full three-dimensional transport dynamics. Future studies should combine laboratory experiments and numerical simulations to explore a wider range of patch arrangements and resolve vertical and longitudinal transport processes, providing a more complete understanding of dispersion in patchy vegetation systems. Despite these limitations, by parameterizing submergence ratio and patch density, we provide a practical framework for predicting transport in patchy vegetation systems, with applications in cases such as microplastic dispersion, sediment deposition, and the understanding and management of vegetation across diverse aquatic environments.

Chapter 4

The impact of the spatial
distribution of patches on
dispersion in submerged aquatic
vegetation for varying
vegetation densities and
submergence ratios

Contribution of authors

Chapter 4 duplicates a paper “The impact of the spatial distribution of patches on dispersion in submerged aquatic vegetation for varying vegetation densities and submergence ratios” by Vinay Nelli (60%), Julia C. Mullarney (12%), Rémi Chassagne (9%), Masaya Yoshikai (9%), William Nardin (5%), and Rafael O Tinoco (5%), in which the percentage of contribution from each author is in the brackets and is intended to be submitted to *Water Resources Research* in 2026. I developed the numerical model using Delft3D and wrote MATLAB scripts to process and analyse the model data. My co-authors edited my drafts along with providing helpful comments, direction, and valuable feedback throughout the drafting process.

Abstract

Submerged aquatic vegetation (SAV) is known to act as a buffer zone by filtering nutrients and controlling the spread of sediments, microplastics and other pollutants into the open ocean. SAV is often found in patches in nature, but dispersion processes through systems of patchy aquatic vegetation are not well quantified. Here, we develop a theoretical model for predicting dispersion coefficients in a system of patches in a 6 m by 6 m area based on submergence levels (S_r) and within-patch vegetation density. We test the proposed expressions for dispersion coefficients against results from numerical model simulations using Horizontal Large Eddy Simulation (HLES), and also with data from field experiments. Results show that both the density of vegetation and the arrangement of patches had a significant effect on dispersion coefficients for lower submergence levels ($S_r < 2$) but showed no significant impact at greater submergence levels ($S_r > 2$). Despite the variability in coefficients between the 8 different spatial arrangements, the proposed model successfully predicted mean dispersion coefficients. Some additional simulations were undertaken to understand the impact of relative patch diameter of the patches and the system dimensions of the patch array. The simulations with varying relative patch diameter suggested that frontal area density is a better predictor for the flow regime in patches, than the solid volume fraction because it is possible to have different frontal areas while retaining the same solid volume fraction. Results also revealed that in longer patch systems, the dispersion coefficients decreased with vegetation density beyond a certain density in contrast to trends observed in shorter patch systems, thus emphasizing that it is necessary to incorporate the system dimensions into any prediction models for dispersion coefficients.

4.1 Introduction

Submerged aquatic vegetation (SAV) is a prominent feature in many freshwater and coastal aquatic systems. SAV provide many services such as providing habitat (van Katwijk et al., 2016; Barbier et al., 2011), regulating water qual-

ity and cycling nutrients (Van Der Heide et al., 2007; Moore, 2004). SAV can also partially mitigate global warming due to green house gases by acting as a carbon sink (Fourqurean et al., 2012; Duarte et al., 2013; Nellemann et al., 2009). Most of the services provided by SAV are related to mixing and dispersion within the SAV. Therefore, many studies on dispersion in SAV focused predominantly on continuous canopies in which the dispersion is shown to be increase as a function of vegetation density within the canopy (Sonnenwald et al., 2019; De Serio et al., 2018; White and Nepf, 2008; Lightbody et al., 2008).

In nature, SAV is often found in patchy environments with bare sediment filling the gaps (Schoelynck et al., 2018; Kondziolka and Nepf, 2014). Early laboratory studies investigated the impact of canopy dimensions (length and height) on dispersion in a single patch and showed that dispersion is controlled by the length of the canopy; for longer canopies the dispersion is controlled by the water depth, and for shorter canopies the dispersion is controlled by the length of the patch (Ghisalberti and Nepf, 2009; Nepf et al., 2007). Nepf et al. (2007) first developed a model for predicting dispersion coefficients assuming a two-layer flow model and validated the model using laboratory experiments. The two-layer flow model oversimplifies the vertical flow structures and therefore, Shucksmith et al. (2011) developed the model into an n-layer model (multiple vertical layers), which was able to predict longitudinal dispersion coefficients with errors between predicted and observed values of <20%.

Mixing and dispersion in patchy and patchy vegetated systems has gained attention in recent studies (Park and Hwang, 2019; Dang et al., 2023). Park and Hwang (2019) conducted laboratory experiments across different patch arrangements and found that patch arrangements have a significant impact on hydraulic parameters (drag and mean velocities), which in turn impacts dispersion; however, they did not estimate any dispersion coefficients. Savio

et al. (2023) found hydraulic resistance coefficients to be dependent on relative submergence and area blockage factors of the vegetation. Numerical simulations by Dang et al. (2023) found a positive correlation between the amount of vegetation cover and velocity based dispersion coefficients in randomly evolving vegetation in a river. However, the earlier studies did not investigate the medium-scale flow processes (interactions between patches within the system of patches) and moreover, a general expression consolidating the impact of various parameters such as system geometry, vegetation characteristics, and mean flow parameters on dispersion coefficients is yet to be derived.

In chapter 3, I investigated the large- and medium-scale mixing and residence of tracers advected through a system of multiple vegetation patches (represented by mimics) on an intertidal sandflat. Dispersion coefficients were found to be inversely proportional to the submergence levels. There was substantial variability in the estimated dispersion coefficients between different releases. This variability was attributed to the paths of the dye cloud changing over the tide, and thus also altering the effective patch arrangement encountered by the dye cloud, thus underscoring the role of patch arrangements. The intermediate vegetation densities produced slightly larger dispersion coefficients than the dense vegetation, possibly also owing to the variations in dye release and paths. A theoretical model for predicting dispersion coefficients in the system of patches was proposed and results matched field observations reasonably well. However, the field experiments covered a limited parameter space - with only two spatial arrangements of patches examined (a single arrangement but for both ebb and flood tides). Furthermore, the observed velocities were dependent on the water depths and therefore, the dispersion coefficients were non-dimensionalised to remove the dependence of flow speeds on water depths. Additionally, the transition between different flow regimes were observed at lower solid volume fraction of $\phi = 0.0079$ compared to the threshold suggested by numerical studies ($\phi > 0.05$). We hypothesise that this

discrepancy between our results and previous results is due to the use of a higher relative patch diameter of $\Lambda = 100$ compared to the value $\Lambda = 20$ used in the numerical studies (Nicolle and Eames, 2011; Liu et al., 2021).

The present study aims to test this hypothesis and also to develop and test a generalized model for predicting dispersion in rigid multi-patch systems (such as mangrove pneumatophores) of different spatial arrangements and within-patch vegetation densities. The study employs a 3D Horizontal Large Eddy Simulation (HLES) model using the Delft3D-FLOW software package (Deltares, 2026) combined with the inbuilt rigid vegetation model (Uittenboogaard, 2003). Da Silva et al. (2026) have validated the depth-averaged model for spatially patchy vegetation by reproducing the experiments by Vandenberghe et al. (2011). Therefore, we expect the more vertically resolved HLES models to perform well in representing the flow behaviour in patchy vegetation. Finally, we examine the impacts of relative patch diameter of the patches and the system dimensions of the patch array on the bulk dispersion coefficients.

4.1.1 Dispersion in patchy vegetation

In chapter 3, I derived the relationship between dimensionless longitudinal shear dispersion ($D_x^* = D_x/(US_r h_v)$) and submergence ratio ($S_r = H/h_v$) in which H is the water depth, h_v is the vegetation height, and U is the depth-averaged flow speed. Following classical Taylor's shear dispersion (Fischer, 1979; Lightbody, 2004):

$$D_x = \frac{\Delta U^2 h_v^2}{K_z}, \quad (4.1)$$

$$D_x \propto \Delta U^2, \quad (4.2)$$

in which ΔU is the velocity difference between the average velocity inside the vegetation patch system and the average velocity above the vegetation layer, and K_z is a factor dependent on diffusion. As in Chapter 3, following (Park and Nepf, 2025; Chen et al., 2013), we use,

$$\Delta U = U_0 S_r \left(\frac{1 - S_r^q}{S_r - 1} \right). \quad (4.3)$$

Combining Eq. 4.2 and Eq. 4.3 yields

$$D_x^* \propto S_r \cdot \left(\frac{1 - S_r^q}{S_r - 1} \right)^2, \quad (4.4)$$

in which, q is a function of frontal area a . Park and Nepf (2025) empirically show that $q = -0.08a - 0.27$, hence

$$D_x^* = \Psi S_r \cdot \left(\frac{1 - S_r^{(-0.08a - 0.27)}}{S_r - 1} \right)^2, \quad (4.5)$$

in which we have defined the scaling factor Ψ , which is expected to be dependent on the spatial distribution of patches and within patch vegetation density.

4.2 Methods

4.2.1 Model setup

The numerical analysis in this chapter is conducted using a domain-decomposed 3D Horizontal Large Eddy Simulation (HLES) model developed in the Delft3D-FLOW software package (see Figure 4.1). The HLES model provides a very efficient framework for simulating systems in which the horizontal scales of eddies are much larger than vertical eddies (Vossen, 2000). Therefore, the HLES models are suited for simulating the patch- and system-scale vortices generated by vegetation patches, noting that the size of the vertical eddies is limited by the shallow water depths.

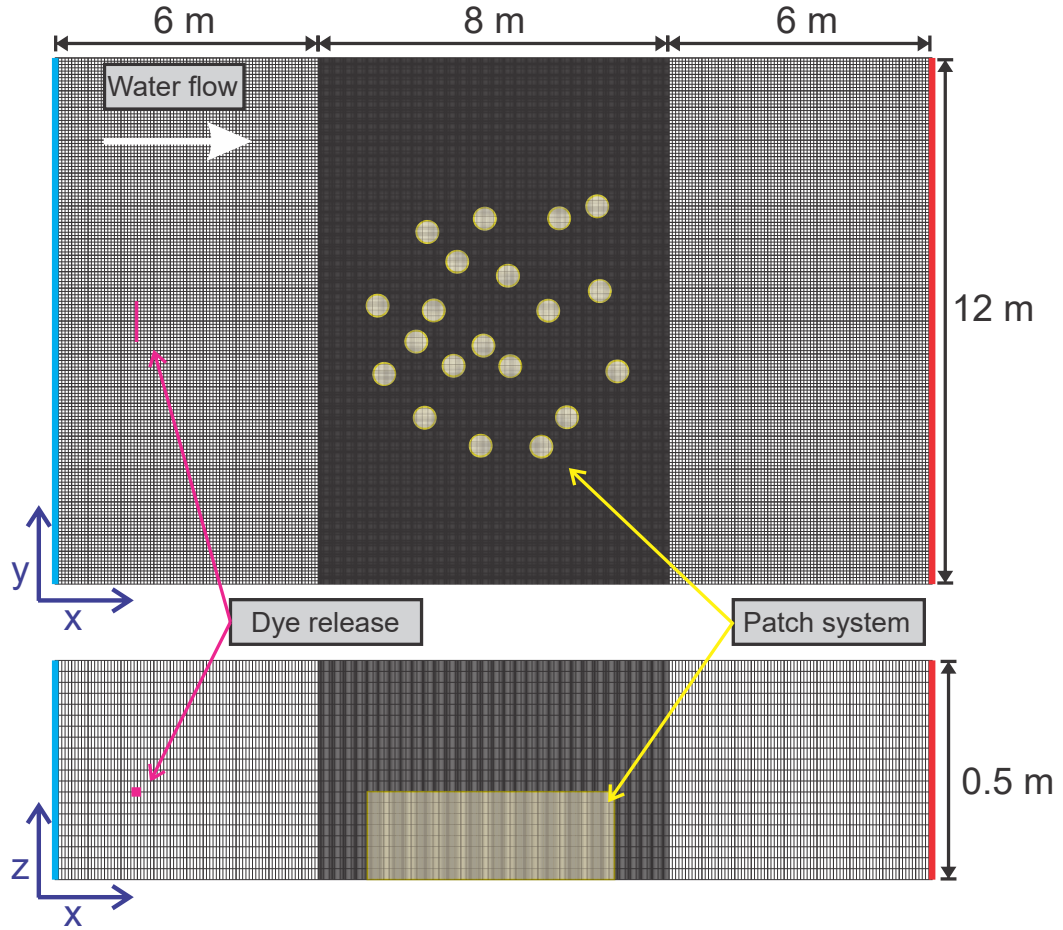


Figure 4.1: An example of the computational domain implemented in this study for a simulation in which the water depth is 0.5 m and for a single patch arrangement. The yellow zones denote the patch system, the pink spots denote the dye release points, the white arrow denotes the flow direction and the blue and red edges are the upstream and downstream boundaries, respectively. The top image shows the plan view, while the bottom plot shows the cross section view of the domain.

The computational model is a three part domain-decomposed model with a fine mesh in the middle zone of dimensions 8×12 m and coarser upstream and downstream meshes of dimensions 6×12 m in the $x - y$ plane. The fine and coarse meshes are composed of square grid cells in the horizontal with sides of lengths 0.025 m, and 0.075 m, respectively. The vertical cell size is the same in each of the three domains with vertical layer depths of 0.025 m. Hence, the number of layers varied between 8 and 32 for the simulated water depths between 0.2 m and 0.8 m. The upstream and downstream boundary conditions are set to have a constant elevation such that a constant uniform horizontal flow speed of 0.15 m/s is reached in bare-bed conditions (consistent with the speeds observed in the field, Chapter 3) is reached within the domain. The lateral boundaries are set as free-slip walls. The model was run from rest until a steady state is reached with a time step of 0.06 s.

A uniform standard Chèzy coefficient of $65 \text{ m}^{1/2}/\text{s}$ was applied throughout the domain at the bed, while a free surface condition was applied at the water surface. The relaxation time in the HLES model was set to 100.02 s which is 6 times the expected vortex shedding frequency by a single patch. The vertical eddy viscosity and diffusivity were both set to $1 \times 10^{-6} \text{ m}^2/\text{s}$, respectively. The sensitivity analysis of cell sizes and other parameters essential for model definition are presented in Section C.1.

Vegetation patches were created with vegetation stems of 0.005 m in diameter (d_v), and varying densities of $n = 100, 200, 400, 800$, and 1600 stems/m^2 . Patches were 0.5 m in diameter (D_p) and 0.2 m in height (h_v) resulting in a relative patch diameter $\Lambda = D_p/d_v = 100$. As with the field experiments, the vegetation density was the same inside all patches for a single dye release simulation. The vegetation is modeled using the in built 3D rigid vegetation model of Delft3D-FLOW which models the vegetation as additional drag force

(F_D) (Deltares, 2026):

$$F_D(z) = \frac{1}{2}\rho_0 C_D a(z) |u(z)| u(z), \quad (4.6)$$

in which z is height from the bed, ρ_0 is density of water, $a(z) = n(z) \cdot d(z)$ is the frontal area density, $u(z)$ the horizontal flow velocity, and $C_D = 1$ the cylindrical resistance coefficient (Uittenbogaard, 2003). Four submergence levels ($S_r = 1, 1.25, 1.5, 2, 3$, and 4) were simulated.

Eight different spatial arrangements of 20 patches were constructed (Figure 4.2). The first two patterns correspond to the flood and ebb configurations used in the field experiments in Chapter 3 (Figures 4.2A,B), with positions inside a $6\text{ m} \times 6\text{ m}$ square area which were randomly generated using a Matlab script. Figures 4.2C,D and Figures 4.2E,F show the flood and ebb configurations for two additional randomly generated systems. The final two spatial arrangements were for regular staggered patches with loose and tight packing (Figures 4.2G,H).

In each simulation, dye was released after the model reached a stable state. The dye is released 8 m in front of the patch system along a 1 m line at 0.2 m from the bedlevel for 12 s to replicate the dye diffuser used in the field experiments in Chapter 3. In total over 208 simulations were performed to investigate the dependence of dispersion on patch arrangements (Table 4.1).

Eight additional simulations were undertaken to explore the influence of relative patch diameter Λ , while retaining the same solid volume fraction (ϕ). In these cases, the patch arrangements A and B were used with $d_v = 0.025\text{ m}$, while retaining a solid volume fraction of $\phi = \pi n d_v^2 / 4 = 0.0314$ resulting in $n = 64\text{ stems/m}^2\text{s}$, corresponding to $\Lambda = 20$ (Table 4.1). A further 4 simulations for emergent ($S_r = 1$), dense ($n = 1600\text{ stems/m}^2\text{s}$) patches in a longer

and wider patch systems are also undertaken. The spatial arrangement of patches in these cases are shown in section C.2.

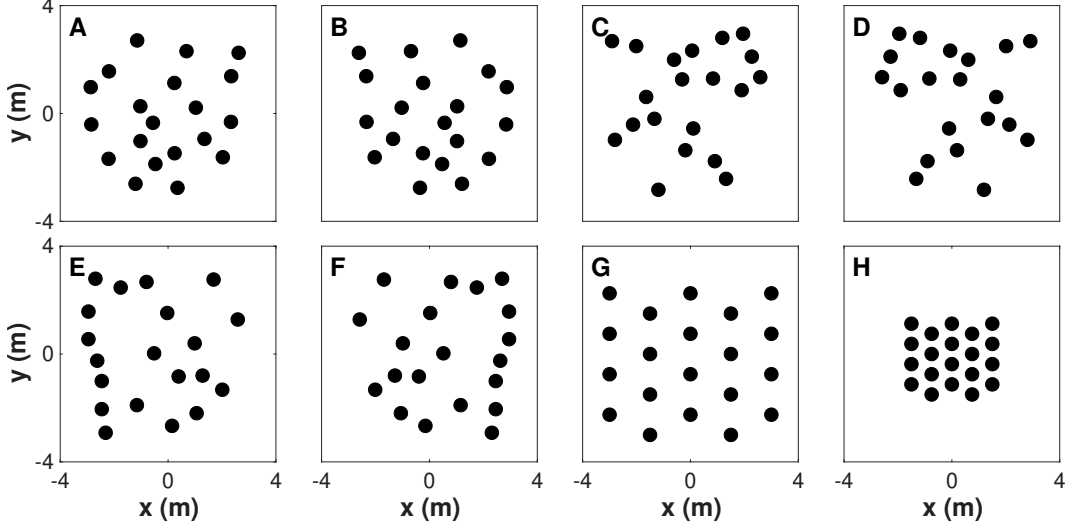


Figure 4.2: Patch arrangements simulated in this study. Panels A and B correspond to the patch arrangement used in the field experiment during ebb and flood tides, respectively, in which the flows move from left to right. Panels C and D, and E and F are two further randomly generated arrangements and reversed. G and H are regular staggered arrangements with loose and tight packing.

4.2.2 Data analysis

The bulk dispersion coefficients in the patch array are obtained from the time derivative of the spatial variance of the dye cloud intensity in a similar manner to Chapter 3. For longitudinal dispersion, first, the transverse-averaged dye concentration C at each x -position at a single timestamp is computed as,

$$C_m(x, t) = \frac{1}{W} \int_0^W \frac{1}{H} \int_0^H C(x, y, z, t) dz dy, \quad (4.7)$$

in which W is the width of the whole domain, and H is the height of the whole domain. The j^{th} moment in dye intensity at each time t is defined as,

$$M_j(t) = \int_0^L x^j C_m(x, t) dx, \quad (4.8)$$

		Submergence levels					
		1.00	1.25	1.50	2.00	3.00	4.00
n stems per m ²	100	✓	✓	✓	✓	✓	✓
	200	✓	✓	✓	✓		
	250	○					
	300	○	○	○	○		
	400	✓, ×	✓	✓	✓	✓	✓
	600	○	○	○	○		
	800	✓	✓	✓	✓		
	1600	✓, ×, Δ	✓, Δ	✓, Δ	✓, Δ	✓	✓

Table 4.1: Description of simulations run as part of the study. ○ are simulations run for pattern A only, and ✓ are run for patterns A-H, Δ denote the simulations with $\Lambda = 20$ which are run for only patterns A-B, and × shows conditions for the longer domain patterns I-J (Section C.2).

in which L is the length of the whole domain. The longitudinal spatial variance of the dye cloud ($\sigma_x^2(t)$) is obtained from the moments as,

$$\sigma_x^2(t) = \frac{M_2(t)}{M_0(t)} - \left(\frac{M_1(t)}{M_0(t)} \right)^2. \quad (4.9)$$

Finally, the longitudinal bulk dispersion coefficient (D_x) is computed as (Peeters and Hofmann, 2015; Okubo, 1971),

$$D_x = \frac{1}{2} \frac{\partial(\sigma_x^2(t) - \sigma_x^2(t_0))}{\partial(t - t_0)}, \quad (4.10)$$

Similarly, the process can be applied in the y-direction to obtain the transverse spatial variance of the dye clouds ($\sigma_y^2(t)$) and the transverse bulk dispersion coefficient (D_y).

4.3 Results

4.3.1 Comparison with field observations

Here we want to compare the behaviours of the dye cloud from the computational model to ensure results are consistent with the observations from the

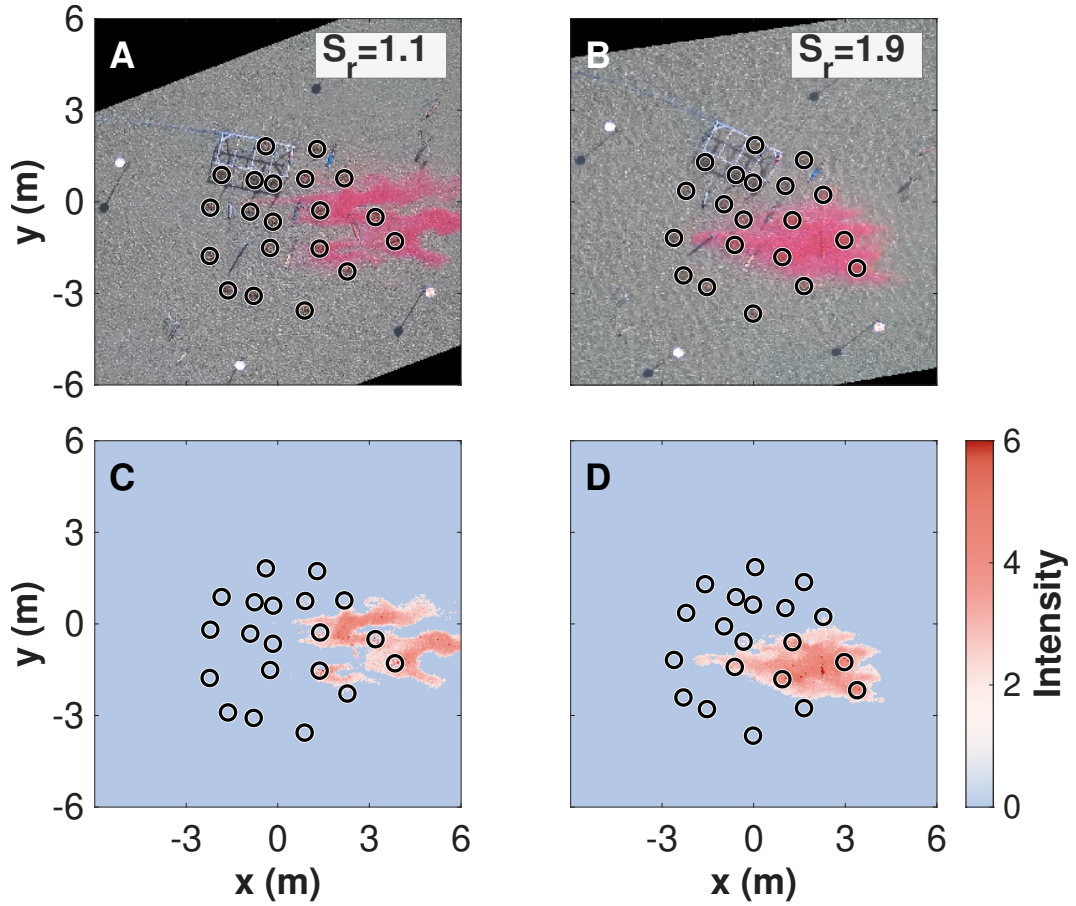


Figure 4.3: Examples of field observations of dye releases. Panels A) and B) show snapshots in time for $n = 1600 \text{ stems/m}^2$, and $S_r = 1.1$, and $n = 1600 \text{ stems/m}^2$, and $S_r = 1.9$, respectively and panels C) and D) show the corresponding processed dye intensities, in which the x -axis is aligned with the flow direction with the flows going from left to right.

field experiments presented in Chapter 3. However, it is important to note that field experiments and numerical simulations cannot be directly quantitatively compared to each other. The field measurements use dye intensity (I) as proxy for depth-averaged concentration. However, the dye intensity is only a semi-quantitative proxy i.e. only the surface reflectance is captured in the imagery and further the values are very discrete in nature due to the RGB channels only providing 8-bit integer values from 0-255. The spatial variance of the dye clouds required to estimate dispersion coefficients use the same moments based formulations (Eq. 4.9-4.10) with the only difference as the dye intensity being used for field-based studies and dye concentration being used for numerical studies. Therefore, discrepancies between magnitudes and precision of dye intensities in the field and dye concentrations in the numerical simulations will extend to magnitudes of spatial variance of the dye clouds as well. Moreover, in the field experiments, the path of the dye cloud is different between each case i.e. the effective patch arrangement was slightly different between each release due to the slight changes in tidal flow directions.

Figures 4.3A and B are the field observations showing raw RGB snapshots of dye releases for the densest vegetation ($n = 1600 \text{ stems/m}^2$) and submergence levels $S_r = 1.1$ and 1.9 , respectively. Figures 4.3C and D show the corresponding estimated dye intensities (I) following the same method from Chapter 3:

$$I(x, y, t) = R(x, y, t)^2 / (B(x, y, t) \times G(x, y, t)), \quad (4.11)$$

in which R , G , and B are respectively the values of the red, green, and blue color channels and a threshold of 2 is applied to remove noise. Figure 4.4 shows the corresponding results from the numerical simulations of depth-averaged velocity and concentration snapshots. The figures show similar flow features: For the emergent patch system ($S_r = 1$, Figure 4.4A,C), the dye cloud follows preferential path around the patches and forms a combination of Kelvin Helmholtz and von Karman vortices behind the patch system. For the immediately submerged patch system ($S_r = 2$, Figure 4.4B,D), the dye cloud goes

over the canopy and von Karman vortices are absent (also noted in the field observations). Furthermore, the depth-averaged velocities are slower within the patch system for the emergent case compared with the intermediately submerged case (Figure 4.4C,D).

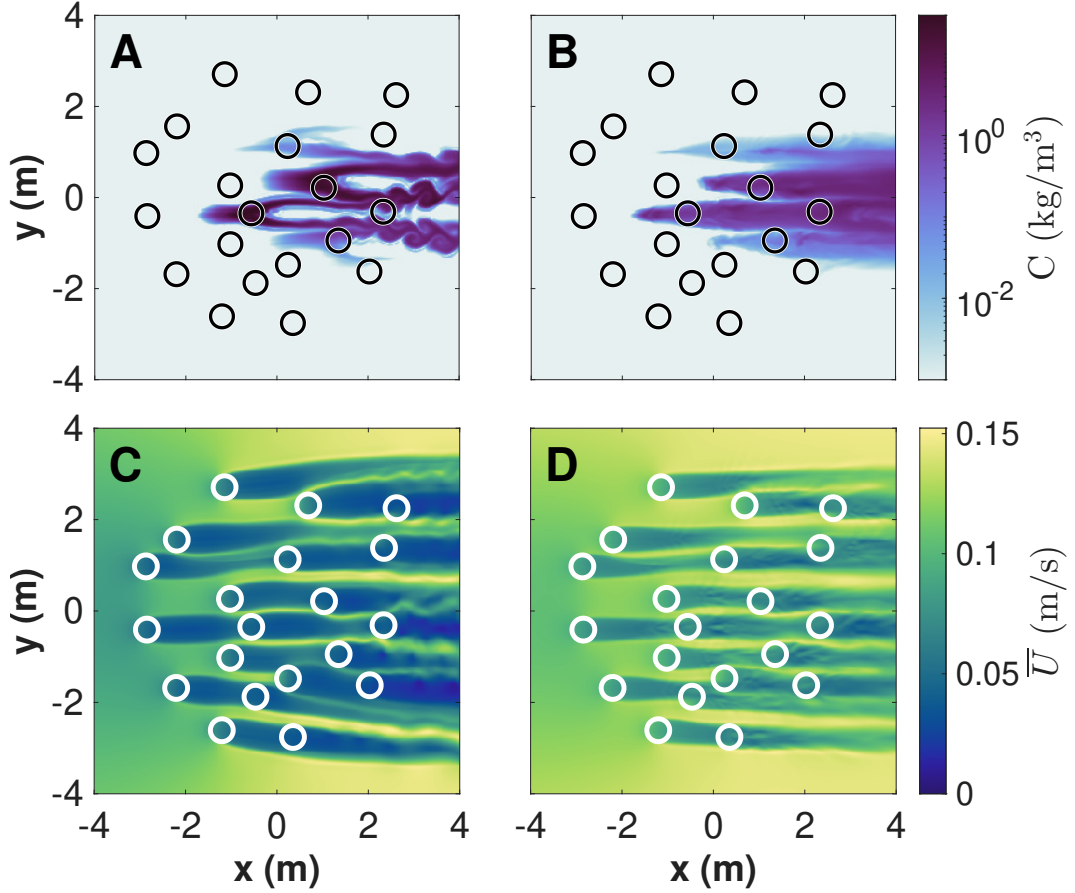


Figure 4.4: Examples of modeled depth-averaged concentrations and horizontal flow speeds for Pattern A (Figure 4.2A). A) A snapshot of depth-averaged concentration for $n = 1600$ stems/m², and $S_r = 1$, B) A snapshot of depth-averaged concentration for $n = 1600$ stems/m², and $S_r = 2$, C) A snapshot of depth-averaged horizontal flow speed for $n = 1600$ stems/m², and $S_r = 1$, and D) A snapshot of depth-averaged horizontal flow speed for $n = 1600$ stems/m², and $S_r = 2$.

Figures 4.5A and B show times series of the longitudinal and transverse spatial variance of the dye cloud observed in the field experiments plotted against advective time ($t^* = t/(H/U)$) across different submergence levels, while Figures 4.5C and D show the equivalent results from the numerical model

using Eq. 4.9 for pattern A (Figure 4.2A) and the densest vegetation ($n = 1600 \text{ stems/m}^2$) across similar submergence levels. The modelled spatial transverse variances (~ 0.2) are significantly lower than the estimated value from the field dye releases (~ 2). However, both the longitudinal and transverse spatial variance of the dye clouds from the simulations show similar trends to the field observations with the spatial variance of the dye cloud in both longitudinal and transverse directions increasing slightly until the dye cloud reaches the patch system ($t < \sim 100 \text{ s}$), at which point, variances increase linearly as the dye clouds passes through the patch system until reaching a peak. The drop in the spatial variance of the dye clouds starts as the leading edge of the dye cloud starts leaving the computational domain and the variances drop to zero as all the dye leaves the computational domain. While the numerical model results show a clean trend in which maximum variances decrease with submergence level, this trend is not visible in the field observations, likely owing to the variation in the paths of the incoming dye cloud in reality. The time series are also shorter in the field observations (Figure 4.5A,B) as the observed domain is effectively smaller i.e. the numerical simulations simulate a longer field than recorded by the drone. Figures 4.5E and F show the longitudinal and transverse spatial variance of the dye cloud time series estimated from the numerical model using Eq. 4.9 for an emergent ($S_r = 1$) pattern A (Figure 4.2A) across different vegetation densities. The spatial variance of the dye clouds increase more steeply with wider curves for higher density than in the sparser patch systems, which is consistent with the (much) slower flow speeds and trapping of dye within denser patch systems observed in Chapter 3.

4.3.2 Dispersion coefficients

The longitudinal and transverse dispersion coefficients are obtained using Eq. 4.10 and non-dimensionalised using the depth-averaged flow speed (U) and water depth (H). Figure 4.6 shows the dimensionless longitudinal dispersion

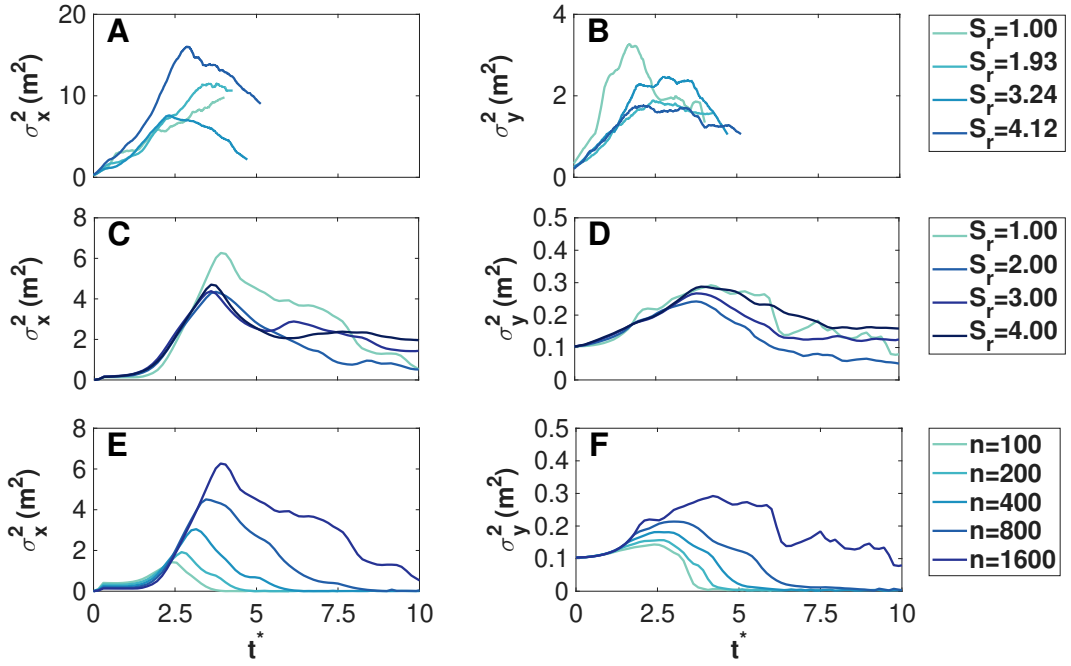


Figure 4.5: Examples of time-series of longitudinal and transverse spatial variance of the dye clouds for one spatial distribution of patches (pattern A, Figure 4.2A). Time series of A) longitudinal and B) transverse spatial variance of the dye clouds calculated from the field data for different submergence levels and $n = 1600 \text{ stems/m}^2$. C,D) The corresponding numerical model results for panels A and B. Numerical model results showing time series of E) longitudinal, and F) transverse spatial variance of the dye clouds for different vegetation densities (in stems/m²) and $S_r = 1$.

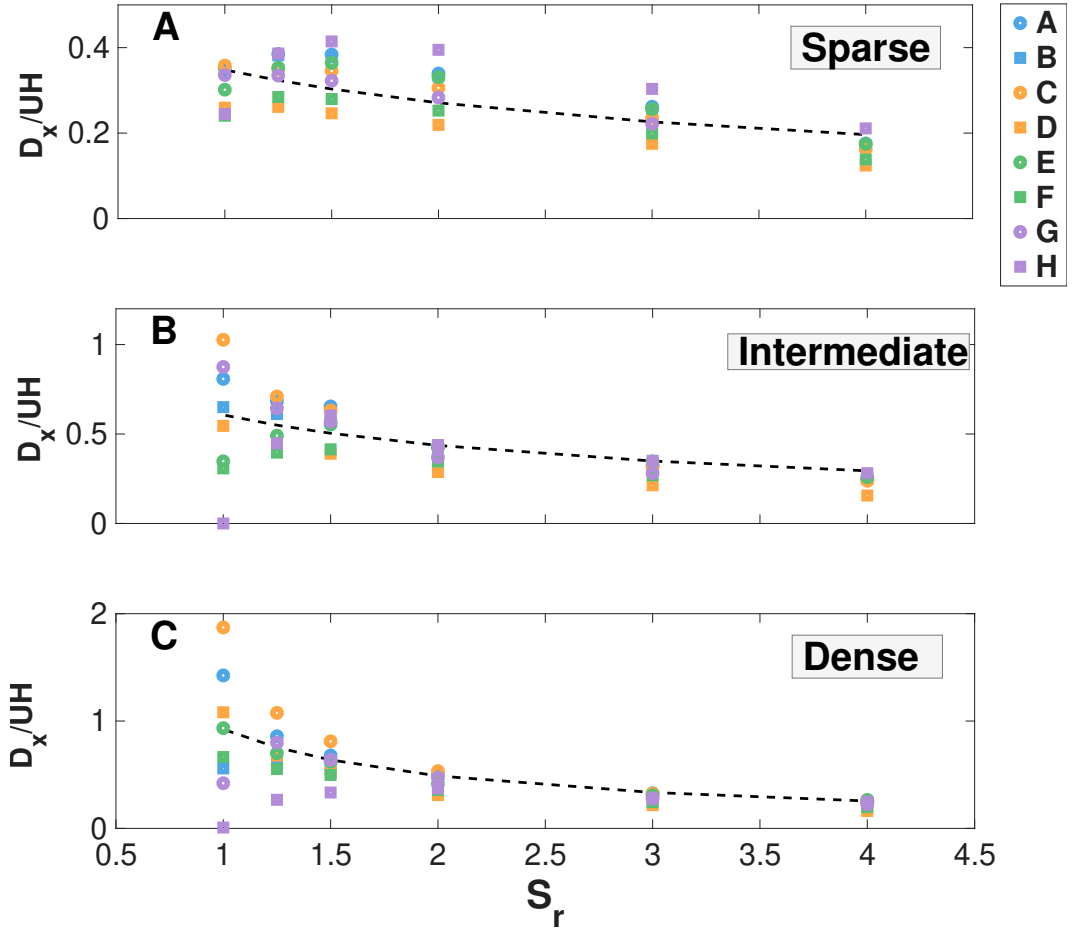


Figure 4.6: Longitudinal dispersion coefficients for selected densities (patterns A-G) across all spatial arrangements of patches. A) Sparse ($n = 100 \text{ stems/m}^2$), B) Intermediate ($n = 400 \text{ stems/m}^2$), and C) Dense ($n = 1600 \text{ stems/m}^2$). The black dashed lines are the fits generated using Eq. 4.5. Symbols correspond to the different spatial arrangements of patches shown in Figure 4.2.

coefficients across all patterns and submergence levels for three vegetation densities ($n = 100, 400$, and 1600 stems/m²). The values and trends of modeled dispersion coefficients corresponding to the field arrangements of patches (Figure 4.2A-B) are similar to those obtained from the field data presented in Chapter 3 ($0 < D_x^* < 2.5$).

For greater submergence levels ($S_r > 2$), the dispersion coefficients exhibited almost no dependence on either the spatial arrangement of patches, and only a minimal negative dependence on submergence ratios. Conversely, for intermediate-low submergence levels ($S_r < 2$) and intermediate-dense patch systems ($n \geq 400$), dispersion coefficients varied substantially across the different patch arrangements. However, for the random patch arrangements (Figure 4.2A-F), the ordering of the dispersion coefficients between the different spatial patterns remained the same across submergence levels (Figure 4.6C), i.e. certain arrangements of patches generated more dispersion over all water depths. In a few cases, when the submergence level is increased from emergent ($S_r = 1$) to just submerged ($S_r = 1.25$) the dispersion coefficients also exhibit a slight local increase before decreasing again with submergence level; however, this effect was not consistent across all patch arrangements or vegetation densities.

The black dashed lines in Figure 4.6 are fits for the relationship between dispersion coefficients as a function of submergence ratio using (4.5), for each vegetation density and across all spatial arrangement except for tight staggered regular pattern (Figure 4.2H). For higher submergence levels ($S_r \geq 2$), fitted values match those calculated from model results well, while for intermediate to low submergence levels ($S_r < 2$), the predicted dispersion is close to the mean of the dispersion observed in the model simulations. The estimated scaling factors are $\Psi = 3.65 \pm 0.34$, 3.3 ± 0.34 , and 1.12 ± 0.09 for $n = 100, 400$, and 1600 stems/m², respectively. The mean percentage errors for longitudinal

dispersion are 108, 34, and 23% for $n = 100$, 400, and 1600 stems/m², respectively. For $n = 100$ stems/m², the mean percentage error is 84% for $S_r > 1$ and 202% for $S_r = 1$ which is due to the estimated scaling factor over estimating dispersion values in the emergent patch system ($S_r = 1$).

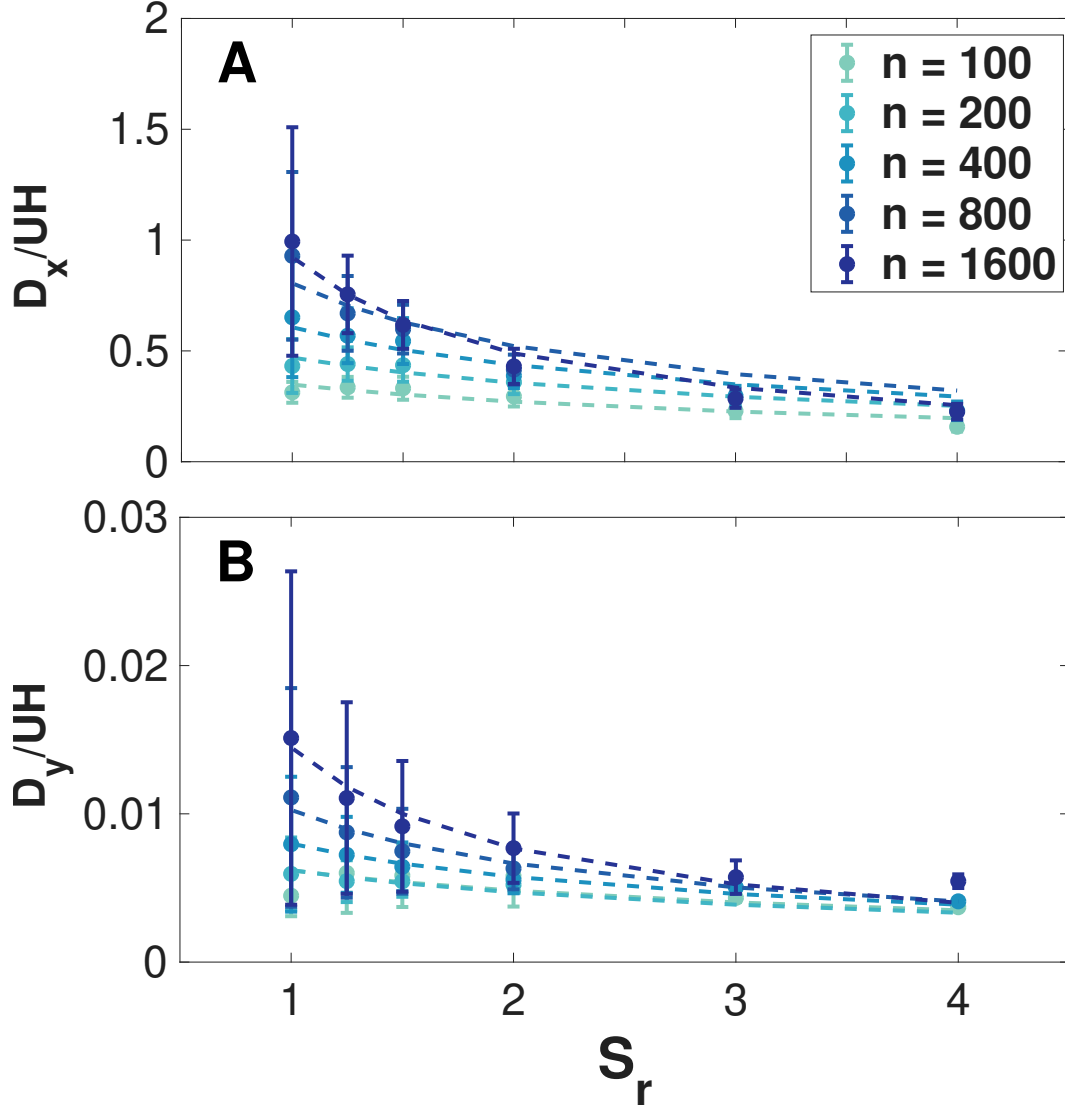


Figure 4.7: A) Longitudinal, and B) transverse dispersion coefficients from numerical model results for different densities across all patterns A-G. The circles with the errorbars represent the estimated values in which the errorbars are the standard deviation of observations from patterns A-G. The dashed lines show the predicted values using Eq. 4.5. n is the vegetation density in the patches in stems/m².

Figures 4.7A and B show the theoretical predicted longitudinal and transverse dispersion coefficients (dashed lines) compared to numerical model re-

sults across all vegetation densities and patch arrangements. As in the field results, transverse dispersion coefficients (0.03-0.05) were smaller than longitudinal coefficients (0.5-1.5), but a notable difference is that the numerical values of transverse dispersion from the simulations were two orders of magnitude smaller compared to one in the field results. The results also show a similar dependence on submergence levels to the field data - in that dispersion coefficients decrease with submergence ratio, and the dependence is much stronger for lower submergence levels ($S_r < 2$). Additionally, a clearer dependence on vegetation density emerges than in the field results: Greater vegetation densities correspond to larger dispersion coefficients, but at larger submergence ratios ($S_r > 2$), the dependence of vegetation density is significantly reduced. In all cases, the theoretical expressions (Eq. 4.5) are used to predict the mean dispersion coefficients across patch arrangements A-G and the expressions perform reasonably well.

4.3.3 Effect of relative patch diameter

This section investigates the effect of the relative patch diameter, the ratio of the patch to stem diameter $\Lambda = D/d_v$. In these cases vegetation volume fraction is unchanged between simulations but a is altered which changes Λ and flow blockage.

Figures 4.8A and B show an example of the simulated depth-averaged horizontal flow speeds through one spatial arrangement of vegetation patches (pattern A), one submergence ratio ($S_r = 1$, emergent vegetation), fixed volume fraction ($\phi = 0.0314$), but for different relative patch diameters, $\Lambda = 100$ and 20, respectively. For $\Lambda = 20$ (Figure 4.8B) the frontal area is substantially reduced, leading to much smaller vegetation drag and approximately ~ 2 times faster flow speeds within the patch system compared to the case with $\Lambda = 100$. Conversely, for $\Lambda = 100$ (Figure 4.8A), the flow diversion around

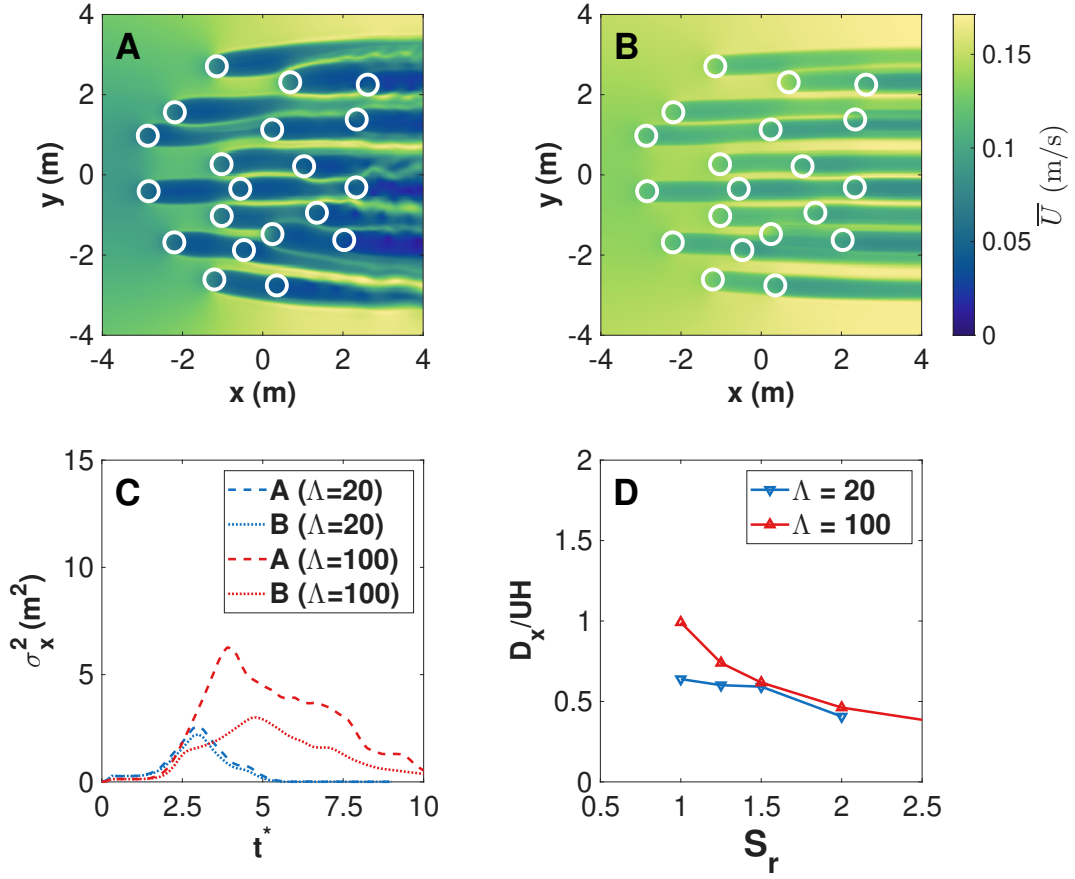


Figure 4.8: Effect of relative patch diameter. Snapshot of horizontal depth-averaged flow speeds for emergent vegetation ($S_r = 1$) for scenarios with A) $\phi = 0.16$ and $\Lambda = 100$, and B) $\phi = 0.16$, $\Lambda = 20$. White circles represent the vegetation patches. C) Time series of longitudinal spatial variance of the dye clouds for patterns A and B (Figure 4.2A-B), $\phi = 0.16$, $S_r = 1$ in which the blue and red triangles represent $\Lambda = 20$ and 100, respectively. D) Mean longitudinal dispersion coefficients for patterns A and B (Figure 4.2A-B) against submergence ratio, $\phi = 0.16$ in which the blue and red triangles represent $\Lambda = 20$ and 100, respectively.

the individual patches is more pronounced inducing stronger velocity spatial gradients and the formation of Von-Karman vortices.

Figure 4.8C shows the comparison of time series of the longitudinal spatial variance of the dye cloud for patterns A and B (Figure 4.2A-B), and the same solid volume fraction $\phi = 0.0314$, $S_r = 1$, and $\Lambda = 20$ and 100 . The evolution of spatial variance of the dye cloud directly correlates with frontal area density with the greater dispersion observed in the system with the most blockage. For $\Lambda = 100$ (more flow blockage), substantial differences in flows arise between patterns (compare red lines in Figure 4.8C) again highlighting the variability in flow behaviour due to patch arrangements. Figure 4.8D shows the mean longitudinal dispersion coefficients for the different spatial arrangements of patches (A and B, Figure 4.2A-B) and the same solid volume fraction $\phi = 0.0314$, across submergence levels. For larger submergence ratios ($S_r > 2$) the relative patch diameter has minimal effect on dispersion, but for lower submergence levels ($S_r < 2$) the dispersion coefficients are dependent on relative patch diameter, with larger coefficients for larger diameters.

4.4 Discussion

4.4.1 Performance of the HLES simulations

The numerical model is able to reproduce behaviour of the dye cloud observed during the field experiments (Chapter 3), i.e. the HLES model closely reproduces the observed turbulent flow structures within the system and behind the patches (Figures 4.3-4.4). However, the estimated values for other parameters from the numerical models cannot be directly and quantitatively compared with field experiments for a few reasons. First, the values of simulated concentrations are very precise compared to Rhodamine dye intensities which provide only a semi-quantitative measurement of dye concentration. Additionally, the

field experiments show a lot of variability in the results due to the changes in the direction of release because of the variations in flow directions. Furthermore, the HLES model used in the current study simulates drag forces and turbulence without resolving individual stems which may result in an underestimation of mechanical diffusion. However, mechanical diffusion in vegetated systems is often much lower than turbulent diffusion (Nepf, 1999) making the HLES model suitable for simulating dispersion in vegetated systems.

The values obtained for the longitudinal dispersion coefficient using the HLES simulations are within the observed range of values in Chapter 3 ($0 < D_x^* < 2.5$) which implies the rate of change in spatial variance of the dye clouds is consistent between the HLES simulations and real world observations. However, the modelled transverse dispersion coefficients (~ 0.2) are significantly lower than the estimated value from the field dye releases (~ 2). The discrepancies in transverse dispersion are due to the dye intensity being a poor proxy for concentration values in the field. The field proxies of concentration are saturated (so low concentrations with very low to medium concentrations produce a similar dye intensity). Consequently, the dye cloud appears more dispersed than the underlying concentrations in the field. This effect is evident from the numerical concentration data, which must be plotted on a logarithmic scale to reveal the full spatial extent of the plume (Figure 4.4). Nonetheless, HLES methods can reasonably simulate dispersion in patchy submerged aquatic vegetation systems (Figure 4.5) in the longitudinal direction.

4.4.2 Performance of the proposed dispersion model

The proposed model predicts the dependence of the dispersion coefficients plotted on submergence ratios across all patch arrangements (Figure 4.7) for both transverse and longitudinal dispersion. Figure 4.9A shows the obtained scaling parameters for each density for the dispersion model in which longitudinal and transverse dispersion coefficients required different scaling parameters.

The fitted scaling parameters show a clear dependence on frontal area density (a) (see Figure 4.9A). The relationship between Ψ and a can be written as:

$$\Psi = C_0 - C_1 \ln(a), \quad (4.12)$$

in which C_0 and C_1 are fitting coefficients. For the longitudinal scaling factor (Ψ_x), C_0 and C_1 are 3.5 ± 0.88 and 0.94 ± 0.73 , respectively. For the transverse scaling factor (Ψ_y), C_0 and C_1 are 0.05 ± 0.003 and 0.02 ± 0.002 , respectively. Therefore a complete model for estimating dispersion coefficients in patched aquatic vegetation based on frontal area density and submergence ratio can be written as:

$$D_x^* = (3.5 - 0.94 \ln(a)) \cdot S_r \cdot \left(\frac{1 - S_r^{(-0.08a-0.27)}}{S_r - 1} \right)^2, \quad (4.13)$$

$$D_y^* = (0.05 - 0.02 \ln(a)) \cdot S_r \cdot \left(\frac{1 - S_r^{(-0.08a-0.27)}}{S_r - 1} \right)^2. \quad (4.14)$$

Figure 4.9B shows the mean percentage errors obtained for patterns A-G using the proposed dispersion model across all submergence levels and densities. The model performs slightly better in predicting longitudinal dispersion with errors less than 40% ($n \geq 400$ stems/m²) compared to transverse dispersion with minimum errors larger than 50%. It is important to note that the method developed (Eq. 4.5) is based on theories for longitudinal dispersion in bare-beds. However, the dispersion model also performs reasonably well in predicting transverse dispersion using the modified scaling parameters Ψ_y .

During the field experiments presented in chapter 3, strong patch-like behaviour was observed at a $\phi = 0.0314$ which is lower than the widely accepted limit for patch-like behaviour (Nicolle and Eames, 2011; Liu et al., 2021). Consequently, these observations led to the conclusion that frontal area density is a better indicator for identifying patch-flow regimes. Figure 4.8 confirmed the

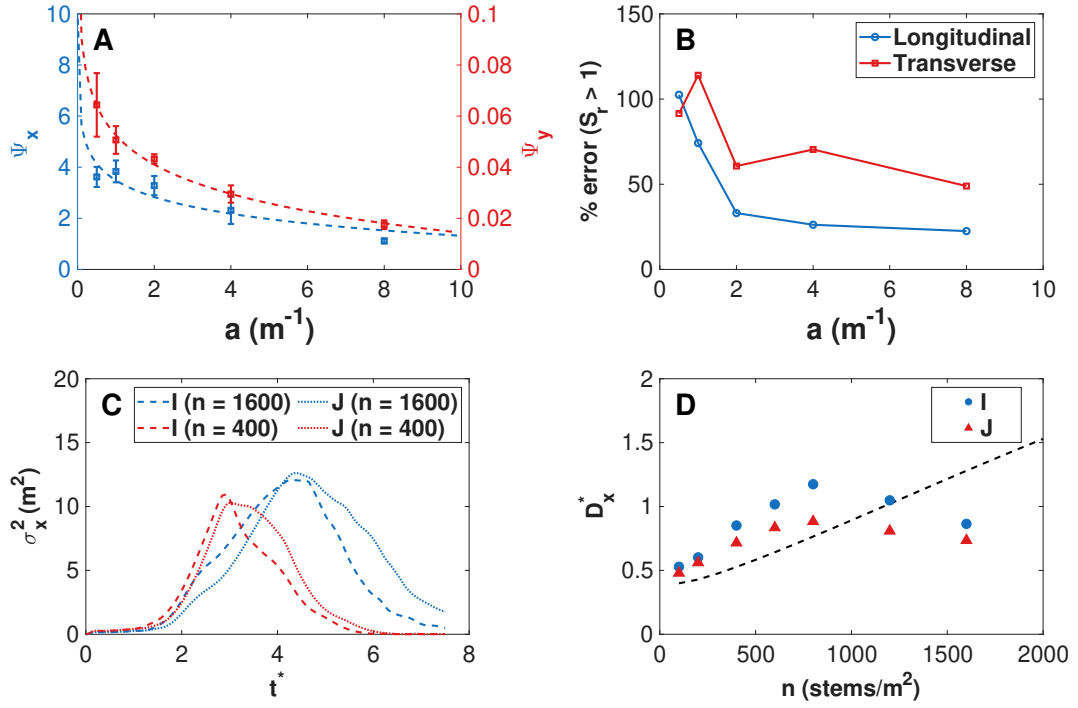


Figure 4.9: Performance of the dispersion model. A) Longitudinal and transverse scaling parameters across different densities in which the errorbars are 90% confidence intervals, and the dashed lines are fits from Eq. 4.12. B) Errors in predicted longitudinal and transverse dispersions across various densities. C) Longitudinal spatial variance of the dye cloud time series for patterns I-J shown in section C.2. D) Comparison of the estimated dispersion coefficients for longer domains and the proposed dispersion model (black dashed line).

same solid volume fraction can present different frontal areas based on the relative patch diameter causing different levels of flow blockage. Therefore, it is imperative that flow regimes and by extension, parameters such as dispersion coefficients be represented using frontal area density instead of solid volume fraction. Furthermore, the impact of patch diameter is not significant for greater submergence levels ($S_r > 2$) as dispersion coefficients from different vegetation densities start to converge.

Figure 4.9C-D shows results from simulations with larger arrays of patches (randomly arranged patterns I-J, Section C.2). In these simulations, array dimensions are twice that in patterns A-H (12×12 m). Figure 4.9C shows time series of the longitudinal spatial variance of the dye cloud time for two vegetation densities ($n = 400$, and 1600 stems per m^2). The temporal trend of the evolution of spatial variance of the dye cloud is consistent with observations from shorter patch systems (Figure 4.5E) with a slight difference where the slope of sparser patch system ($n = 400$) is steeper than the slope of denser patch system ($n = 1600$). The difference in trends is expected as the overall horizontal flow speeds are significantly slower in the denser canopy i.e. the dye cloud moves and evolves slower in the denser patch system compared to a sparser patch system.

Figure 4.9D shows the dispersion coefficient estimated using Eq. 4.10 compared with proposed dispersion model (Eq. 4.13) in the black dashed line. In these cases, fits are poor and the trend is not captured. The dispersion in the longer systems decreases with vegetation density after a threshold in contrast to the observations from shorter patch systems. Shorter patch systems composed of more dense vegetation allow the development of preferential flow paths, characterised by significantly faster flow. In these cases, the large difference in flow speeds between dye ejected into these faster flow streams and caught within patches leads to significant stretching of the dye cloud lon-

gitudinally and hence larger dispersion coefficients. However, in longer patch systems of dense vegetation, overall speeds are slowed such that the relative differences in flow speeds between preferential flow paths and patches is smaller. Therefore, in longer patch systems the dispersion coefficients exhibit a negative dependence on vegetation density beyond a certain density.

We hypothesize that for long patch systems, the dispersion coefficients will increase with density from 0 (bare-bed) up to a specific threshold density, at which point the flow speeds within the patch system reduce drastically making the effective dispersion of the dye cloud lower. Xu et al. (2022) found similar trends in sediment deposition with the net deposition (ND) initially increasing with increasing vegetation densities, but the trend reverses with any further increase in vegetation density.

4.4.3 Future considerations and implications

The results showed a great variability of dispersion in different patch arrangements. However, this study employs patch systems of constant dimensions (length and width) and $\phi_p = 1.67$ patches/m² is which $\phi_p = n_p/(LW)$ is the patch volume fraction, $L = 6$ m and $W = 6$ m are length and width of the patch system, respectively. Further studies should extend the dispersion models over a wider parameter space in ϕ_p and the system dimensions (L and W).

The current model uses an expression for shear velocity in patchy vegetation from Park and Nepf (2025), which is derived using the two-layer (two box) canopy flow model proposed by Nepf et al. (2007). The two-layer model oversimplifies the vertical flows and does not resolve complex structures such as Kelvin-Helmholtz vortices within the canopy, and therefore does not capture the penetration of vertical vortices into the patch system. Shucksmith et al. (2011) further adapted the model for continuous submerged canopies by in-

corporating more layers, and predictions of longitudinal dispersion coefficients were improved (errors within 20%). Future studies should attempt a similar adaptation of the current two-layer dispersion model for patchy vegetation proposed in this study, to further resolve the complex vertical flow structures.

Finally, our study presents a framework for developing a generalized dispersion model for patchy aquatic vegetation systems using a two-layer model. While the current model is only validated for a patch system density of $\phi_p = 1.67$ patches per m^2 using field observations of dye cloud spreading (Chapter 3), the numerical simulations show potential for the model to be extendable to different ϕ_p values.

4.5 Conclusions

We developed a new theoretical model to predict dispersion coefficients in a system of patches based on submergence levels and frontal area density of the patches. We have tested our model on results from 3D HLES simulations, which were found to be capable of simulating flows in patchy aquatic vegetation (based on comparisons with field observations). Predictions of dispersion coefficients from the theoretical model matched numerical results from the short patch array well, although values were sensitive to the spatial arrangement of patches. The model can thus be used to predict the dispersion of various particles such as microplastics, and suspended sediment in short patchy aquatic vegetation systems. However, future work should focus on extension to longer domains, as these appear to be governed by different dynamics.

Chapter 5

General conclusions

5.1 Review of major concepts

The research presented in this thesis aimed to enhance our understanding of the impact of spatial heterogeneity of aquatic vegetation on physical processes across different scales, from the vegetation stem-scale ($\mathcal{O}(0.1)m$) to the larger scale of an array of multiple vegetation patches ($\mathcal{O}(10)m$). In Chapter 1, the aims of the thesis were divided into three research questions, and the conclusions regarding each of the research questions are reiterated below:

1. How does heterogeneous vegetation (composed of multiple length-scales) influence flows and the generation of turbulence? How do the flows structures generated by different sized vegetation (pneumatophores and trees) interact? How close are the current laboratory-based models for estimating turbulent kinetic energy (TKE) in representing the multi-scale flow dynamics in the real aquatic vegetation canopies?

Chapter 2 tested the efficacy of the existing models to predict turbulent kinetic energy (TKE) in real world conditions. These existing models have been found to perform well in predicting vegetation-generated TKE in homogeneous canopies of varying densities in laboratory experiments (Horstman et al., 2018; Yang and Nepf, 2019; Liu et al., 2021). One key point is that

these theoretical models to estimate TKE make the (sometimes implicit) assumption that the dominant horizontal eddy length-scales scale are equal to the size of pneumatophore stems (Yang and Nepf, 2019; Zhao and Nepf, 2021). The assumption is justified by the spectral short circuiting mechanism which states turbulent structures larger than the scale of the stems are broken into smaller scales (Finnigan, 2000) (Figure 5.1).

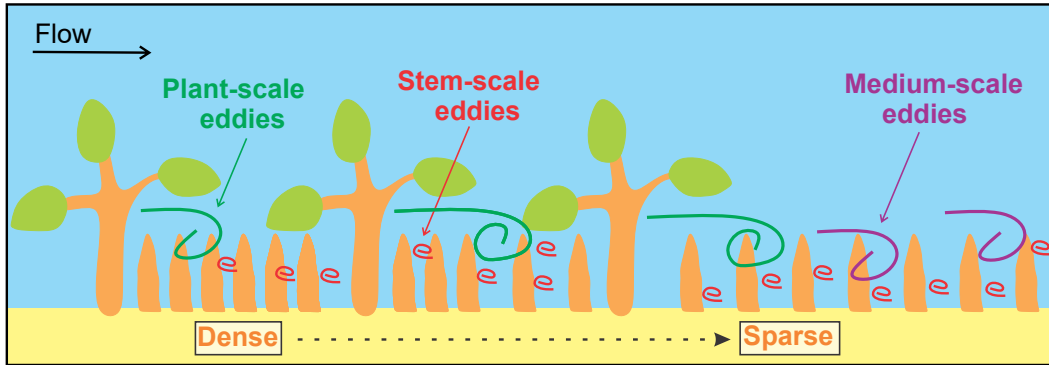


Figure 5.1: Turbulence in spatially heterogeneous vegetation canopies with saplings (small trees) and pneumatophores (orange roots). The flow direction is from left to right, the red twirls represent stem-scale eddies, the green twirls show sapling-generated eddies, and the purple twirls are medium-scale eddies generated by shear at the top of the vegetation canopy.

Our field measurements were taken in a very sparse pneumatophore canopy with $\phi < 0.003$, corresponding to the lower end values in laboratory experiments. The field site was also populated by small saplings of density 3-5 trees per m^2 . The lack of significant wave activity for the duration of the experiments provided a valuable data set to test the laboratory-derived model under uniform flows in natural conditions. When the stem diameter was used as the dominant eddy length-scale in the field the models severely underpredicted the measured TKE; however, when models were applied using the eddy length-scales estimated from the measured velocity data (around 15 times stem diameter), the predictions of TKE were reasonable with mean percentage errors of 67%. These results emphasize that in heterogeneous sparse canopies,

it is crucial to correctly characterize and parameterize the horizontal eddy length-scales to accurately predict TKE.

2. How does the presence of multiple vegetation patches affect medium- and large-scale flow dynamics? How do vegetation densities and submergence levels change these flow-vegetation interactions?

While Chapter 2 considered smaller scale spatial heterogeneity in a pneumatophore canopy with saplings, other larger scales of variability can be introduced through the distribution of uniform vegetation (such as patches). The study of larger-scale variability is important as most aquatic vegetation is found in patchy arrangements.

Chapter 3 presented one of the first attempts to parameterize horizontal dispersion coefficients in patchy aquatic vegetation systems. UAV-based high-resolution (spatial and temporal) imagery of Rhodamine WT dye releases were used to study flow behaviour and dispersion through an artificial vegetation patch system. Data were collected for three different within-patch vegetation densities and a range of submergence levels. Furthermore, only two randomly arranged patch arrangements are considered in this study (through flood and ebb flows impinging on a single arrangement).

The high-resolution spatial and temporal dye intensity values were used to estimate longitudinal and transverse dispersion coefficients. For greater submergence levels, the vegetation density within the patches exhibited minimal impact on dispersion, but in lower submergence levels the dispersion coefficient is positively impacted by vegetation densities. Additionally, the residence times showed a slight dependence on vegetation densities, but were not influenced by submergence levels.

An expression for estimating dispersion coefficient as a function of submergence levels is derived. The expression follows classical Taylor shear dispersion model (Fischer, 1979), modified to incorporate effects of two-layer vegetation canopy flow model (following Nepf et al., 2007), and patchy vegetation systems (using Park and Nepf, 2025). While there was substantial variability in the dispersion coefficients derived from observations owing to the dye impinging on different sections of the array at different stages in the tides, the model nonetheless performed well, with reasonable agreement between predictions and observed dispersion coefficients.

3. Can we find generalized flow patterns and predict dispersion coefficients for different spatial configurations of multiple patches?

The results from Chapter 3 showed that dispersion coefficients were quite sensitive to the paths the dye took through the patch array (as dye impinged on different regions depending on the tidal flow direction). Hence, Chapter 4 builds on the observations from the field experiments in Chapter 3 by assessing the influence of spatial distribution of patches. Numerical simulations with a combination of 3D Horizontal Large Eddy Simulation (HLES) (Vossen, 2000) and the rigid vegetation model (Uittenbogaard, 2003) in Delft3d (Deltares, 2026) are used to simulate 8 different patch arrangements (random and regularly staggered) and 6 different vegetation densities across a range of submergence levels. The results from the numerical model were validated with the field data from Chapter 3.

The HLES models performed well in reproducing the observed patterns in the field experiments. The patch arrangements showed significant variability in dispersion coefficients for lower submergence levels ($S_r < 2$) but showed no significant variability for higher submergence levels ($S_r > 2$) which is consistent from the field observations. Similarly, denser vegetation produced larger dispersion coefficients compared to sparser vegetation for lower submergence

levels ($S_r < 2$) but the impact of vegetation density on dispersion coefficients was not significant for greater submergence levels ($S_r > 2$).

The two-layer dispersion model proposed in Chapter 3 is further developed into a more complete model for estimating dispersion coefficients using both the submergence ratio and frontal area density is derived in the chapter. The proposed model performed well with errors less than 50% in longitudinal dispersion coefficients across 7 different random patch arrangements.

Furthermore, a few additional simulations were undertaken to study the impact of system dimensions and relative patch diameter. The simulations using different relative patch diameters highlighted that the frontal area density is a better indicator of patch flow regimes compared to the solid volume fraction. Further, the simulations in longer patch systems demonstrated a converse dependence between vegetation density and dispersion coefficients i.e. the dispersion coefficients reduced when vegetation density was increased beyond a certain density..

5.2 Recommendations for future work

Chapter 2 revealed the dynamical role played by vegetation of different characteristics. In this case the TKE generated by the larger saplings was able to propagate into the sparse canopy of the smaller pneumatophores. This result showcases that which is likely a different flow regime to that in tropical mangroves. The tropics are characterised by larger trees and denser pneumatophores, so in these cases spectral short-circuiting will likely occur with the larger-scale tree-generated eddies unable to propagate into the interior of the denser pneumatophore canopy. However, the balance between these different turbulence regimes remains unconstrained. Future work could focus on

laboratory experiments (or numerical simulations) with vegetation of mixed densities and characteristics to more carefully identify the controls on and transitions between these regimes.

The model for predicting dispersion in patchy aquatic systems developed in this thesis (Chapters 3 and 4) is only tested and validated on single patch density of $\phi_p = 1.67$ patches per m^2 and constant system dimensions of 6×6 m. Future studies should extend the model parameters to include patch density (ϕ_p). Additionally, the model assumes that all the patches in the vegetation system have the same vegetation density (homogeneous patch systems). However, Kitsikoudis et al. (2020) showed that, when patches of two different densities are placed along the flow path (one behind another), the wake and deposition are controlled by the vegetation density of the downstream patch. Therefore, it is important to identify how we can parameterize heterogeneous patch systems and predict dispersion coefficients in such systems.

The current dispersion model is developed from classical Taylor shear dispersion model (Fischer, 1979) and using a two layer model for flow behaviours in patchy aquatic vegetation systems (Park and Nepf, 2025; Nepf et al., 2007). However, the two-layer model does not fully resolve the complex vertical turbulent structures and the mixing layer at the top of the canopy. For predicting dispersion in continuous vegetation canopies, Shucksmith et al. (2011) extended the two-layer model to include n-layers (multiple layers) and found that the accuracy of predictions of the dispersion coefficients significantly improves with errors less than 20%. Therefore, developing a n-layer dispersion model in patchy aquatic vegetation systems might achieve higher accuracy in predicting dispersion and mixing processes. Furthermore, the proposed dispersion model in the thesis only predicts depth-averaged dispersion whereas an n-layer model could be used to identify and predict dispersion and mixing in different parts of the column. A more complex model could also be used to explore the relative contributions to mixing from vertical and horizontal

eddies. Additionally, real-world vegetation systems have a depth-varying density profile i.e. the flow blockage varies across the water depth and multi-layer models can better resolve the complex geometries compared with simpler two-layer models.

The current dispersion model could also be applied to flexible vegetation systems by using the modified submergence ratio and diameter estimated after reconfiguration (flexible vegetation bends increasing submergence ratio and patch diameters). However, flexible vegetation undergoes dynamic reconfiguration due to canopy-scale vortices in a phenomenon termed as monami (Ghisalberti and Nepf, 2006) which might also induce a cyclic behaviour in the values of dispersion coefficients. Finally, the current dispersion model was developed for uniform flow conditions and could be extended to account for the additional dispersion induced by wave action. However, incorporating wave effects is challenging because the resulting dispersion depends on the interactions between waves and currents, including their relative magnitudes and directions. Future work should also investigate the development of a unified, scale-independent dispersion model by identifying the governing dimensionless parameters that control dispersion across different spatial scales.

5.3 Summary

This thesis explored the impact of spatial heterogeneity across multiple vegetation scales on the physical processes in vegetated aquatic flows. Theoretical models for predicting mixing and turbulence in vegetated aquatic flows are developed and validated using real world field data. The developed theoretical models can be further parameterized and used in large-scale numerical simulations to understand vegetated wetland and coastal dynamics in order to better manage and possibly restore aquatic vegetation systems. Importantly, the observations from this thesis using relatively small scale field observations,

highlighted the importance of complimenting our understanding of flow processes obtained from laboratory experiments using real world data.

Appendices

Chapter A

Chapter 2 supplementary information

A.1 Principal flow directions at the field site

Mean flow directions were determined over the tidal cycle from 10-minute segments (Figure A.1). The measurements revealed the flows directions are predominantly along an axis pointing towards 250° SW during the flood phase and towards 50° NE during the flood phase of the tidal cycle. The data used in Figure A.1 is obtained from instrument 1 during tide 2 by averaging over 10-minute intervals with an overlap of 5-minutes.

A.2 Lack of wave activity at the field site

Studying the power spectra for velocity and current profilers in the field showed that the field site has no significant wave influence during the period of the experiments (Figure A.2). The power spectral density (PSD) of vertical velocities was calculated for the middle bin of VP2 from tides 1, 3, and 5. PSDs were calculated for 10-min time segments using a 5-min moving Hanning windows with a 70% overlap, and three examples are shown in Figure . The PSD indicated that the wave activity during the experiments is minimal. Addition-

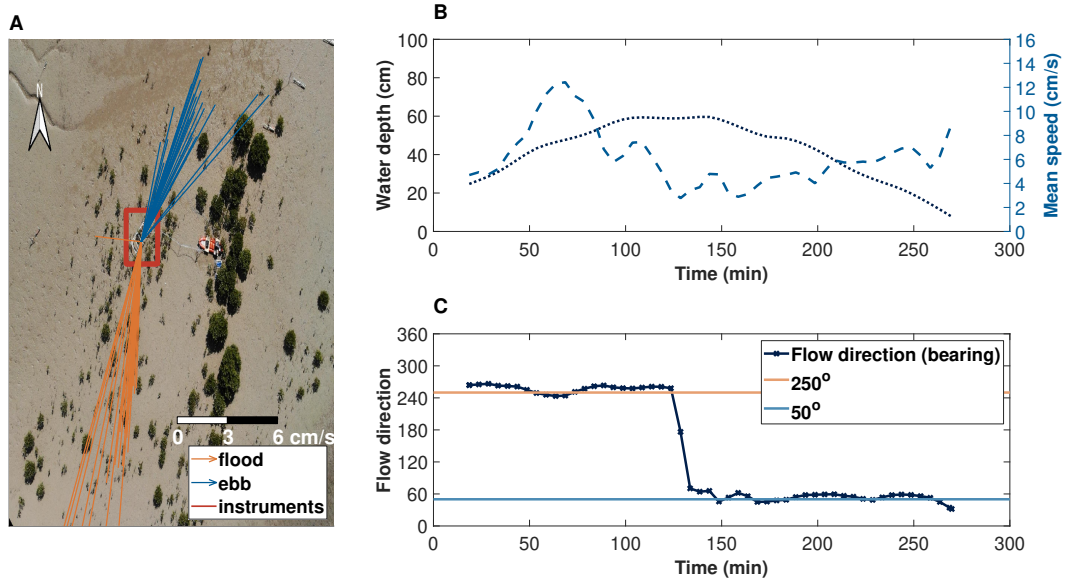


Figure A.1: A) Drone image of the site overlain by vectors representing the flow direction for the tidal period. Flood tide flows are shown in orange and ebb tide currents are in blue. The length of vectors is representative of mean flow speed. Instruments' location indicated within the red square. B) Water depth (dotted line) and mean flow speed (dashed line) plotted over a tidal period. C) Flow direction (compass bearings relative to true north) plotted over a tidal period with orange line representing the mean flood direction and blue line representing the mean ebb direction.

ally, significant wave heights are estimated for 5-minute windows using wave spectra (Green and Coco, 2007) with frequency cutoffs set to 1 Hz and 1/30 Hz, from the water-depth time series data from the CTD at the study site (Figure A.3). The significant wave heights are found to be predominantly less than 20 mm suggesting weak wave activity. Furthermore, time intervals with wave heights larger than 20 mm coincided with bad data with low SNR values and are discarded during estimating of TKE.

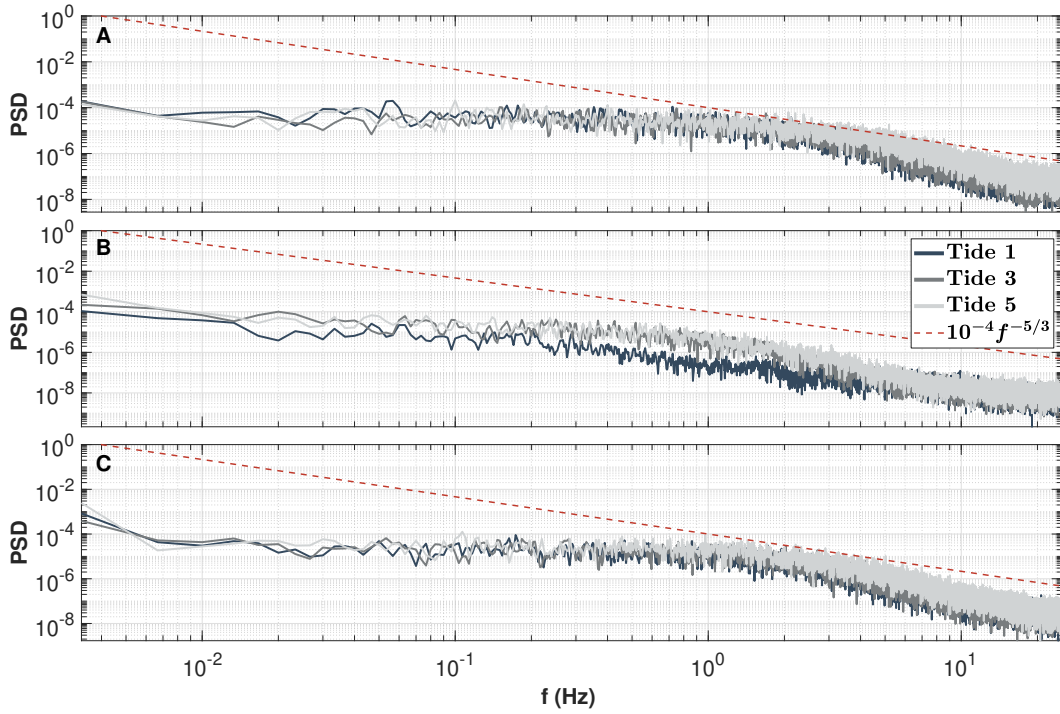


Figure A.2: Example power Spectral Density (PSD) of 10-min time segments of the middle bin vertical velocity of instrument 2 time series for tides 1, 3, and 5 where the red dashed line represents the $-5/3$ slope. A) In the first hour of tide, B) around the middle of the tide, and C) in the last hour of tide.

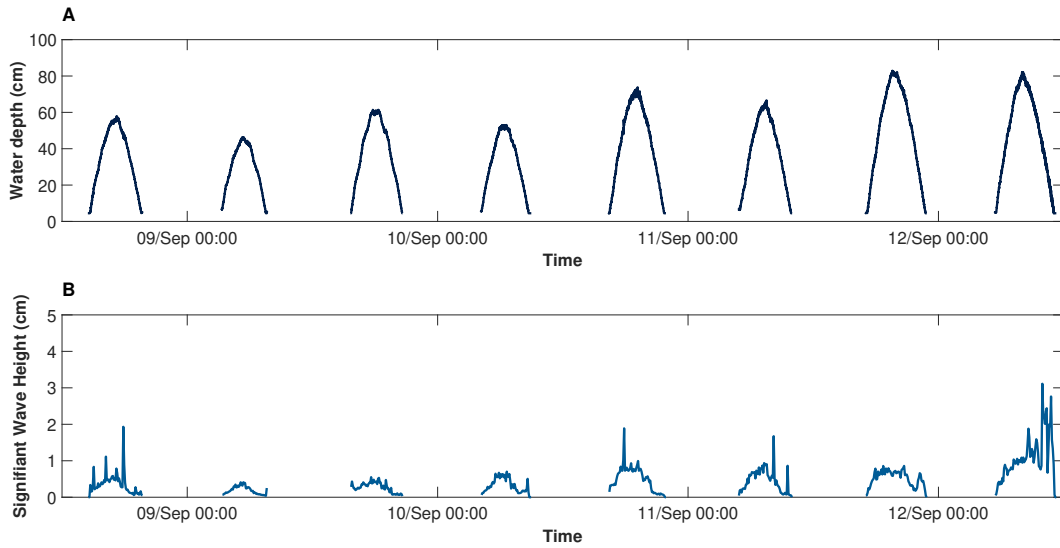


Figure A.3: Time series of values estimated from the pressure sensor of the CTD. A) Water depth, and B) Significant wave heights estimated over 5-minute time intervals.

A.3 Comparison of the measured vegetation parameters and the modeled values

Pneumatophore diameters are measured under each ADV for selected pneumatophores (two pneumatophore from each corner and the middle of a quadrat and 10 more randomly selected in each quadrat to a total of 60) at three different heights (near the base, middle, and near the top). Comparing the field measurements (Figure A.4A) to the results from the photogrammetric method (Figure A.4B), we find the hand measurements are generally consistent with, but slightly underestimate, the values obtained from structure-from-motion (noting also that only a small subset of roots were measured by hand). The comparisons align with the findings by Liénard et al. (2016) who concluded that hand measurements do not resolve (and typically underestimate) complex in-situ characteristics such as the presence of barnacles on pneumatophores which are resolved by the photogrammetric analysis. Furthermore, the photogrammetric method does not resolve really short pneumatophores (heights <30 mm).

A.4 Doppler noise estimation

The Doppler noise (Blanckaert and Lemmin, 2006) is estimated as

$$\text{Noise} = (\overline{w_1^2} + \overline{w_2^2} - \overline{w_1 w_2})/2, \quad (\text{A.1})$$

after removing bad data (low correlation and SNR), and despiking (Goring and Nikora, 2002) (Figure A.5). The Doppler noise is less than $10^{-5} \text{ m}^2/\text{s}^2$ which is far less than observed values TKEs highlighting minimal Doppler noise in estimated TKEs. However, we recommend using the updated despiking method by Parsheh et al. (2010) in future experiments to further minimize

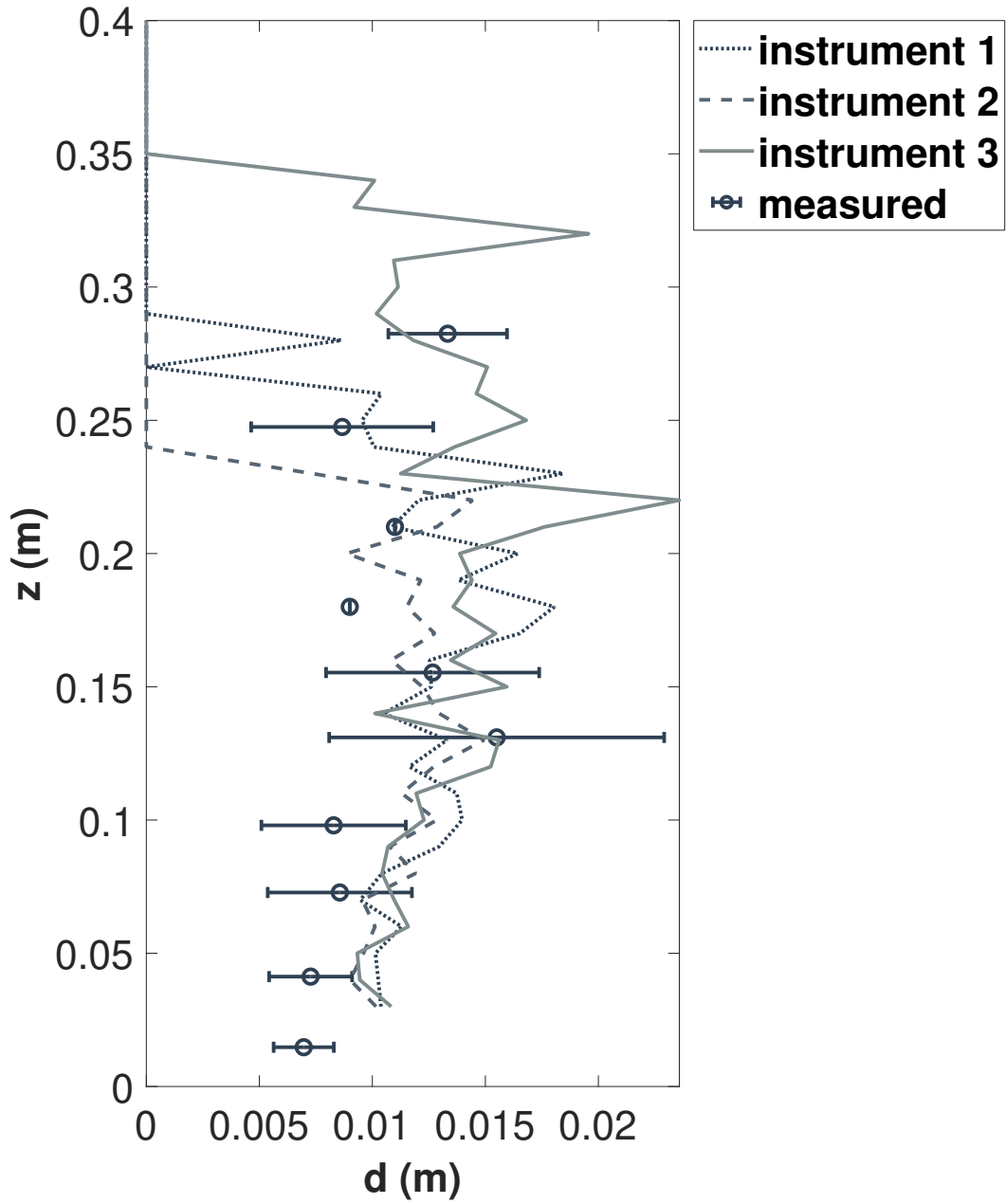


Figure A.4: Hand measurements of pneumatophore diameters at the field site (circles show means, and bars are one standard deviation) compared to mean diameters under each ADV determined from the photogrammetric analysis (lines). For hand measurements, a subset of 60 pneumatophores were measured. Short pneumatophores (heights < 30 mm are not resolved by the photogrammetric analysis.

noise.

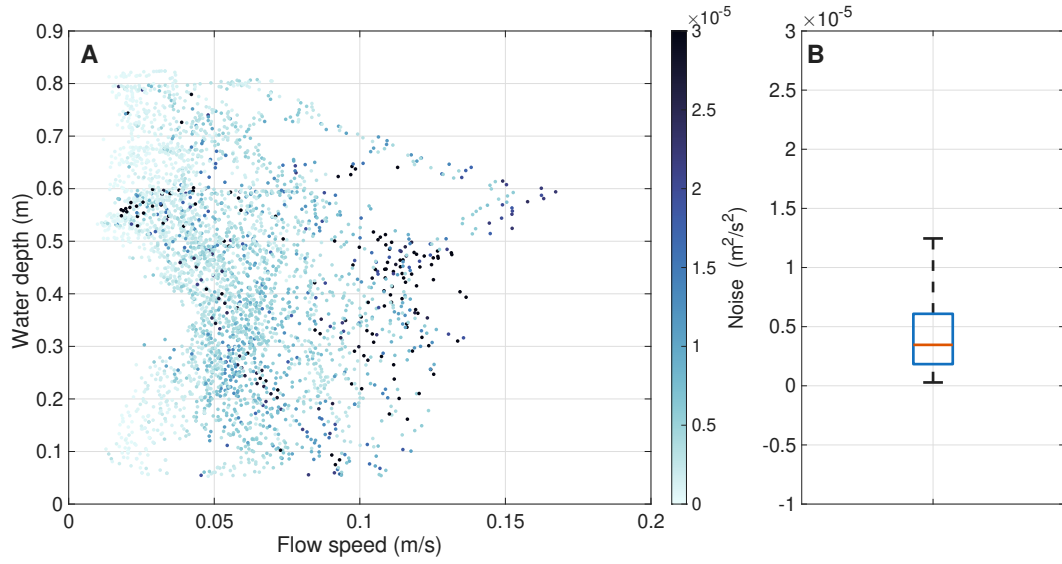


Figure A.5: Doppler noise estimated using vertical velocity fluctuations. A) Water depth against flow speed where the points are colored with estimated Doppler noise using Equation A.1, and B) Boxplot of observed Doppler noise.

A.5 Summary of experimental parameters and instrument positions for each tidal cycle

Table A.1: Summary of experimental parameters and instrument positions for each tidal cycle

Tide	Duration (minutes)	Tide height(m)	Profile range from bed level ^a (cm)		
			instrument 1	instrument 2	instrument 3
1	285	0.54	0-2.6	0-2.9	0-2.8
2	284	0.61	7-10	0-2.8	7-10
3	303	0.70	9.6-12.6	0-2.9	9.6-12.6
4	279	0.59	9.6-12.6	0-2.9	9.6-12.6
5	333	0.82	7-10	0-2.8	7-10
6	313	0.81	0-2.6	0-2.3	0-2.8

^aThe vertical profile measured from by Vectrino Profilers relative to the bed at each tide is listed.

Chapter B

Chapter 3 supplementary information

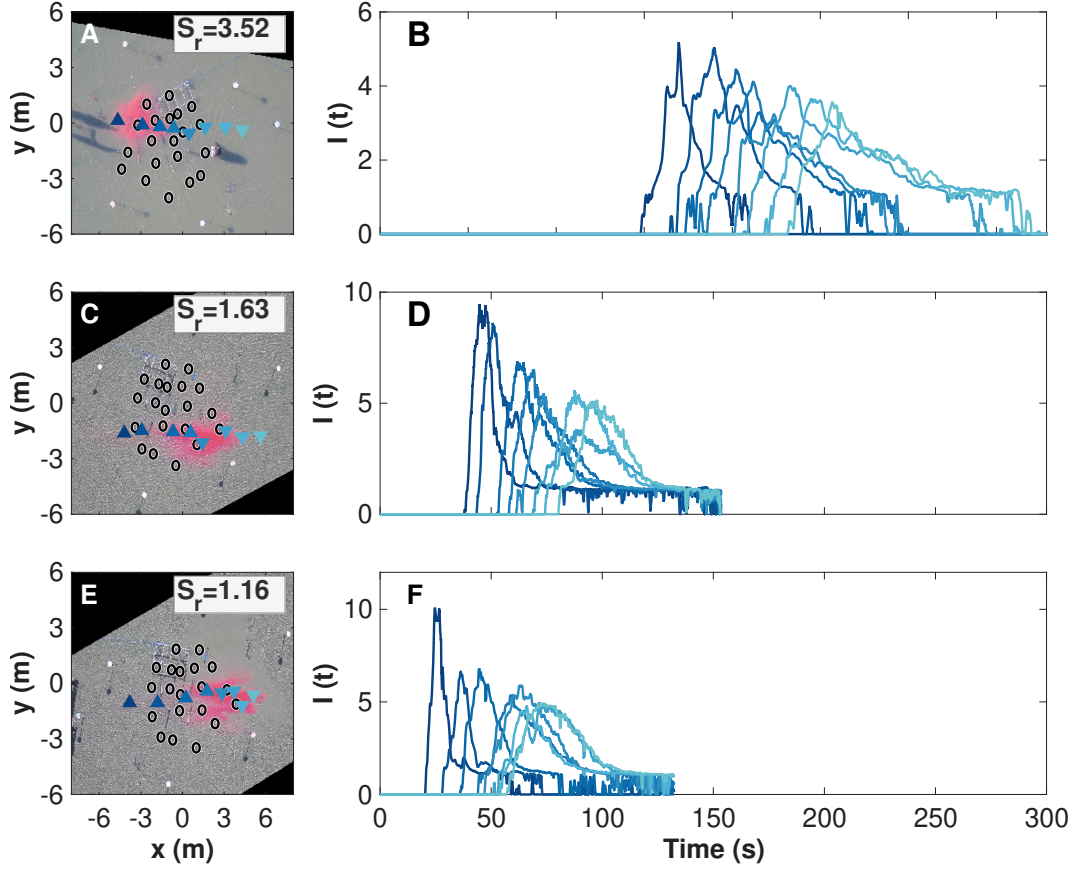


Figure B.1: Dye intensity time series observed in the intermediate patch system ($n = 400 \text{ stems/m}^2$): A,C,E) Snapshot of a dye release with the the upward triangle representing selected upstream points and downward triangle representing the selected downstream points, the submergence ratio denoted in the white box at the top right of each subplot, and the black circles highlighting the patches. B,D,F) Dye intensity time series plots at the selected locations (0.5-s moving average) in which the color intensity reduces from upstream points to downstream points.

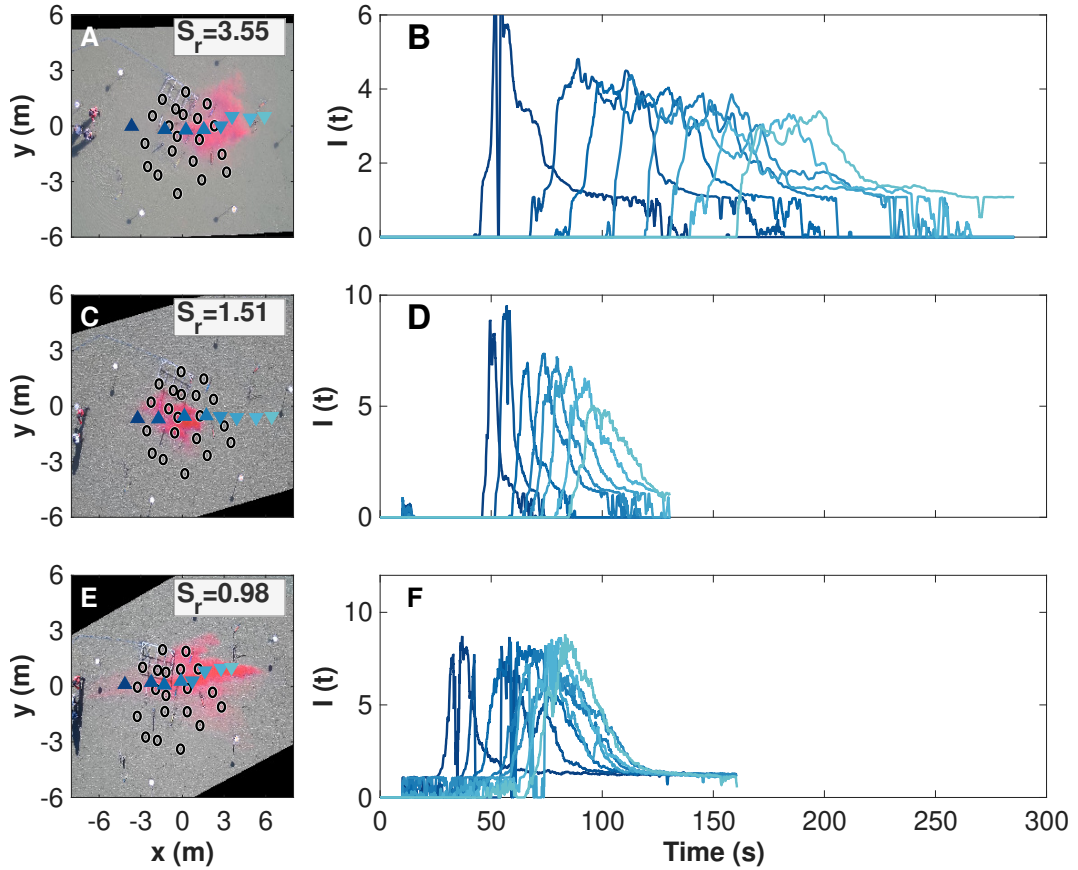


Figure B.2: Dye intensity time series observed in the sparse patch system ($n = 100 \text{ stems/m}^2$): A,C,E) Snapshot of a dye release with the the upward triangle representing selected upstream points and downward triangle representing the selected downstream points, the submergence ratio denoted in the white box at the top right of each subplot, and the black circles highlighting the patches. B,D,F) Dye intensity time series plots at the selected locations (0.5-s moving average) in which the color intensity reduces from upstream points to downstream points.

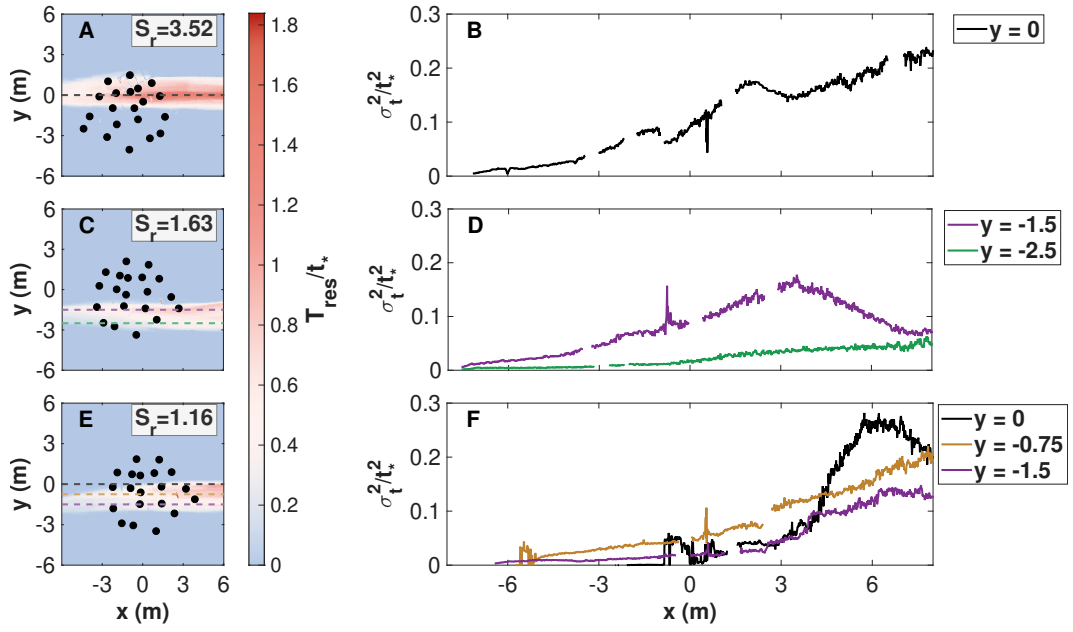


Figure B.3: Spatial parameters estimated for the intermediate patch system ($n = 400 \text{ stems/m}^2$): A,C,D) non-dimensional residence times of a dye release with the dashed lined representing transects used for temporal variance, the submergence ratio denoted in the white box at the top right of each subplot, and the black circles highlighting the patches. B,E,F) non-dimensional spatial variance estimated for the transects represented in the left subplot. The values inside the patches are excluded from the plots as these points cannot be resolved.

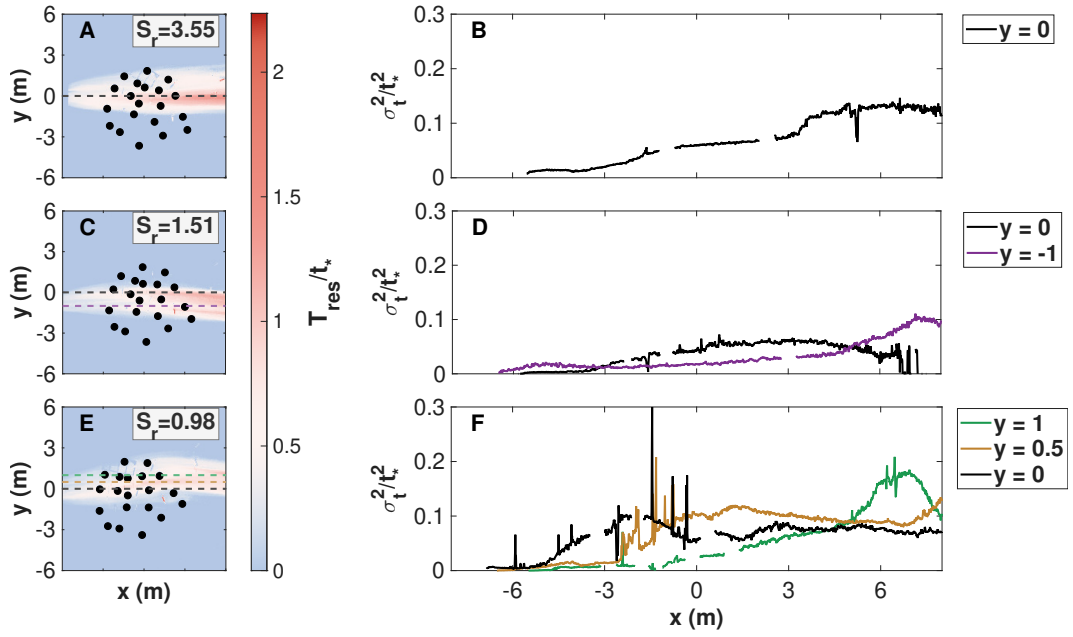


Figure B.4: Spatial parameters estimated for the sparse patch system ($n = 100$ stems/ m^2): A,C,D) non-dimensional residence times of a dye release with the dashed lined representing transects used for temporal variance, the submergence ratio denoted in the white box at the top right of each subplot, and the black circles highlighting the patches. B,E,F) non-dimensional spatial variance estimated for the transects represented in the left subplot. The values inside the patches are excluded from the plots as these points cannot be resolved.

Chapter C

Chapter 4 supplementary information

C.1 Sensitivity analyses

Delft3d simulations with the three-dimensional Horizontal Large Eddy Simulation (3D HLES) approach were chosen for undertaking the numerical study of the patch systems. To identify the optimal simulation parameters for the simulation, sensitivity analyses were undertaken for each parameter using a simplified computational domain containing a single patch.

C.1.1 Grid convergence

The grid convergence, vertical layers and vertical background viscosity and diffusivity sensitivity analysis are discussed in this section. Grid convergence analysis is undertaken to find the coarsest grid size where the numerical errors can no longer be mitigated by making the numerical grid finer. A 5×5 m numerical grid with a water depth of 0.5 m divided into 20 layers. A 1-m submerged pneumatophore patch with a density of 1600 stems/m² and a vegetation height of 0.2 m is placed in the center of the grid.

Grid cell sizes of 0.1, 0.075, 0.05, and 0.025 m are used for the analysis.

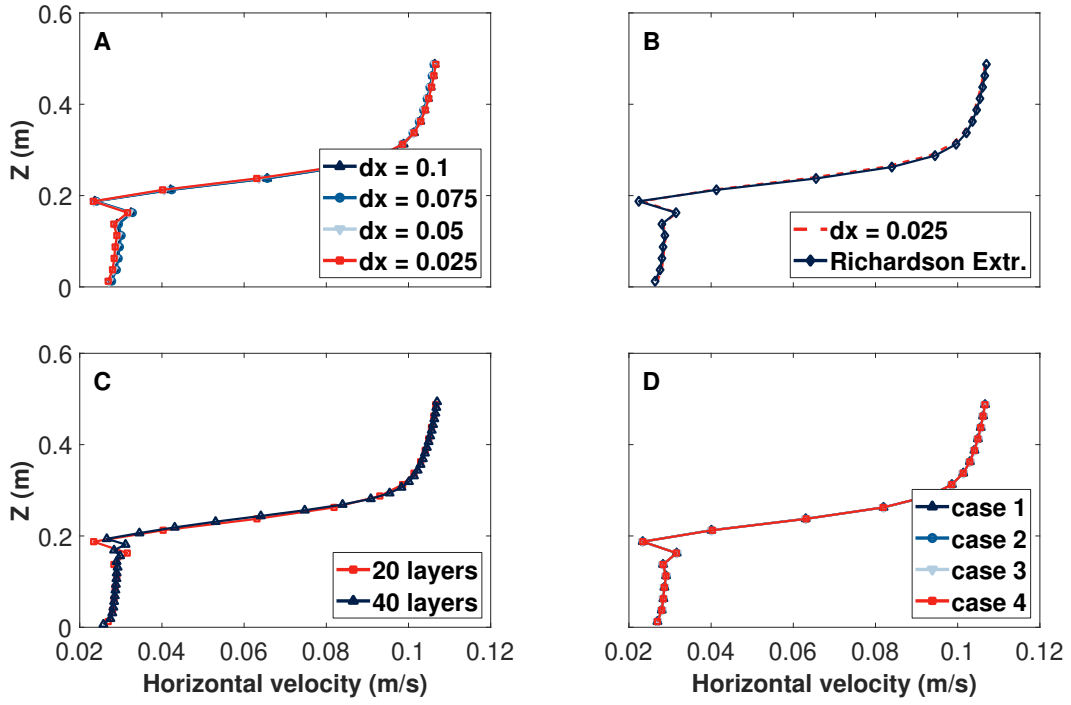


Figure C.1: Grid convergence and sensitivity analyses. A) Vertical profile of horizontal velocity at the center of the patch for $dx = 0.1$, 0.075 , 0.05 , & 0.025 m, B) Comparison of results from the finest ($dx = 0.025$ m) with Richardson extrapolated values from the coarsest grids, C) Vertical resolution analysis with 20 and 40 layers and B) Grid sensitivity to background viscosity and diffusivity values, cases 1 to 4 correspond to 0.25×10^{-6} , 0.5×10^{-6} , 1×10^{-6} , and $2 \times 10^{-6} \text{ m}^2/\text{s}$, respectively.

Background vertical viscosity and diffusivity values are set to $1 \times 10^{-6} \text{ m}^2/\text{s}$. Figure C.1A shows that velocities converge going from the coarsest grid to the finest grid. Furthermore, velocities from the 0.025 m grid cells are consistent with the Richardson extrapolated values (Figure C.1B) (Celik et al., 2008). Finally, the vertical cell size is tested by doubling the number of vertical layers from 20 layers ($\Delta Z = 0.025$ m) to 40 layers ($\Delta Z = 0.0125$ m). The results are close to identical and so a vertical resolution of $\Delta Z = 0.025$ m is selected for numerical simulations (see Figure C.1C).

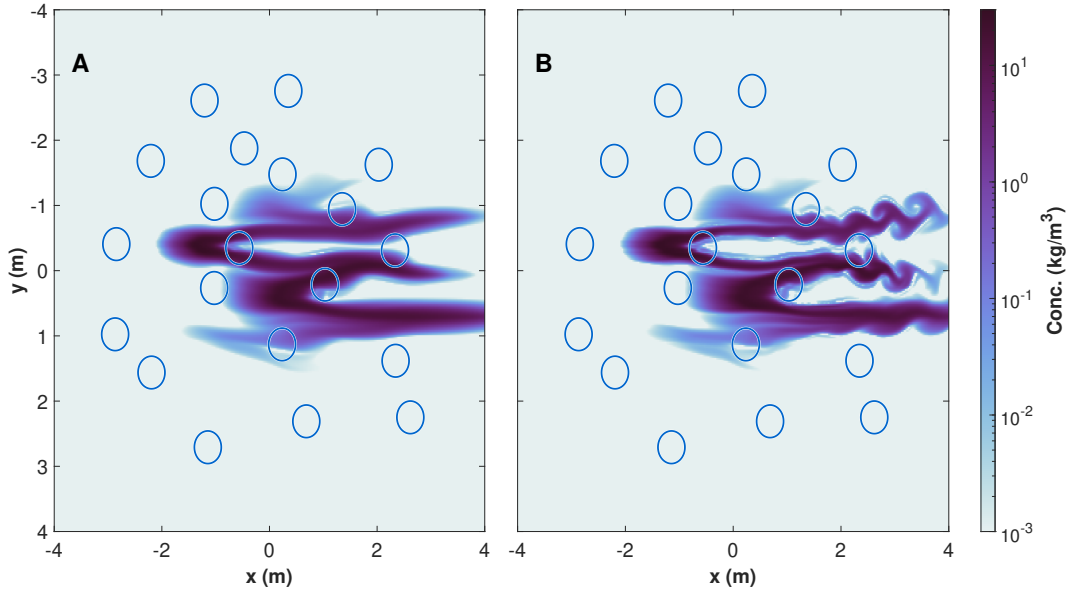


Figure C.2: Effect of relaxation time on an emergent canopy. A) Relaxation time = 0 s, and B) Relaxation time = 100.2 s.

C.1.2 Sensitivity analysis of tunable parameters

3D HLES in Delft3d requires the selection of the background vertical diffusivity and viscosity. The values are used internally as the minimum diffusivity/viscosity due to turbulence in the vertical direction, in addition to the molecular values i.e. $\nu_{total} = \nu_{mol} + \min(\nu_{3D}, \nu_{back})$ in which ν_{total} , ν_{mol} , ν_{3D} , and ν_{back} are the total, molecular, estimated, and background values, respectively. The model is found to be not sensitive to the background vertical diffusivity and viscosity values (see Figure C.1D).

3D HLES by default does not simulate Shear dispersion due to the default value of the “Relaxation time” parameter which is set to -1. It is recommended in the manual to set the relaxation time to be set between 2-6 times of the expected eddy time-scales. Eddy time scales (T) for a patch size of L, and flow speed of U can be estimated as $T = L/(USt)$ in which St is the Strouhal number. For 0.5 m patch diameter, 0.15 m/s flow speed, and a typical Strouhal number of 0.2, the eddy time scales are expected to be 16.67 seconds. In our testing of 2, 4, and 6 times of eddy timescales produced identical results. So, the relaxation time is set to 100.02 seconds (see Figure C.2).

C.2 Effect of system dimensions on dispersion

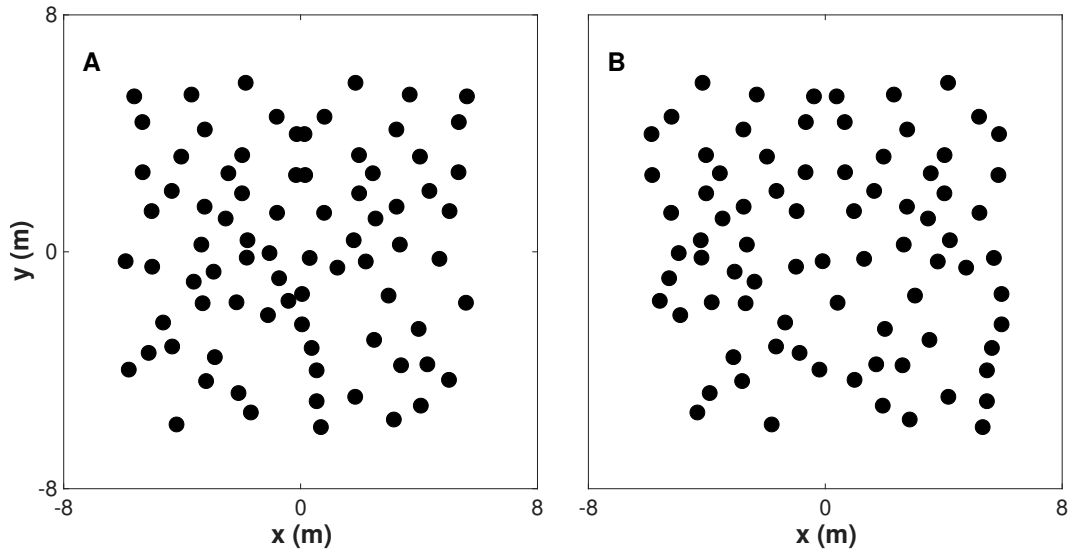


Figure C.3: Patch arrangements used in this study for understanding longer patch systems. A) Patch arrangement I, and B) patch arrangement J.

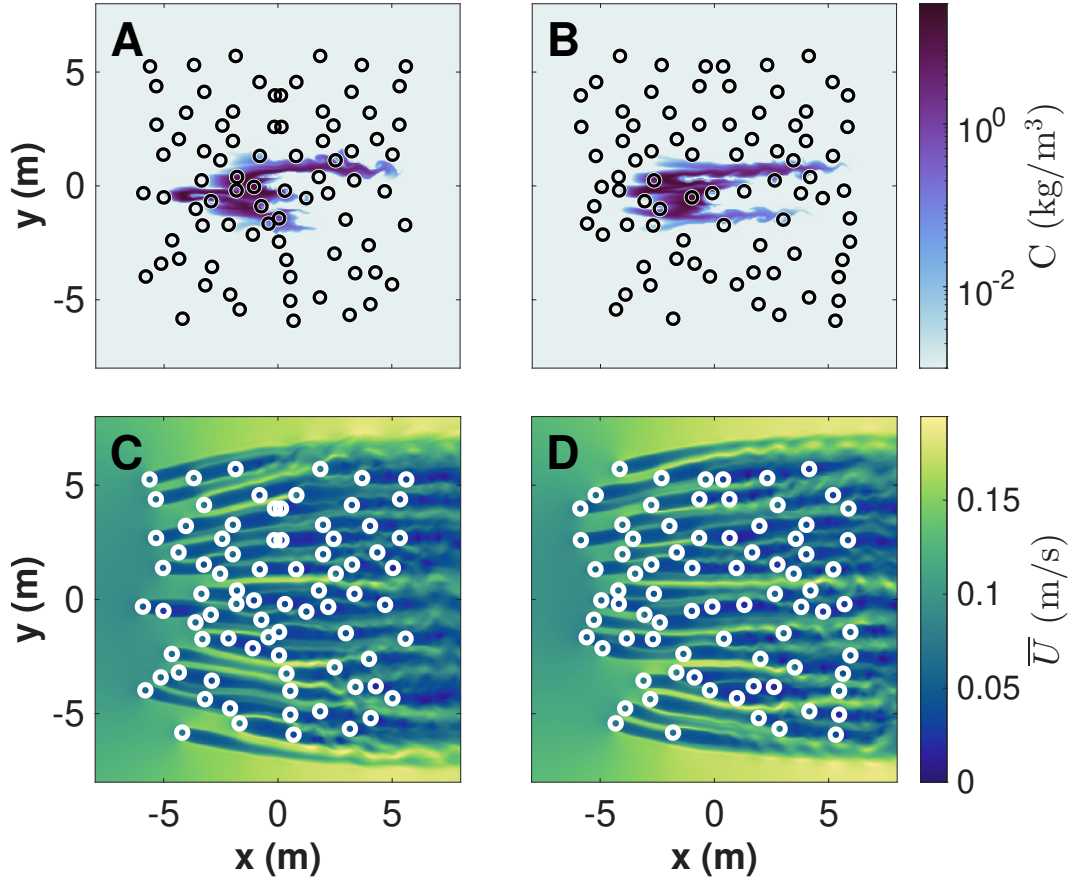


Figure C.4: Examples of modeled depth-averaged concentrations and horizontal flow speeds for the larger patch arrangements shown in Figure C.3, with $n=1600$ stems/m² in all panels. A-B) Snapshot of depth-averaged concentrations for $S_r = 1$. C-D) Snapshots of depth-averaged horizontal flow speeds for $S_r = 1$.

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