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Residence time in coastal canopies

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Abstract

Aquatic canopies provide important ecosystem services such as improved water quality, oxygen flux, sediment stabilisation and trapping and recycling of nutrients. The ecological health of coastal canopies and the significant ecosystem services they provide depends largely on the continuous exchange of dissolved and particulate materials across the canopy boundaries. In coastal environments, where flow is typically wave-dominated, vertical mixing is believed to be the dominant process controlling residence time and, therefore, exchange. However, experiments have shown that wave-driven flows over rough boundaries, such as canopies, generate strong onshore mean currents (75% of the orbital velocity far above the canopy) near the canopy top. Since these currents can significantly influence canopy residence time, it is imperative to understand how the two processes of vertical mixing and horizontal advection can influence water renewal and, ultimately, residence time in wave-dominated canopy flows. This thesis presents predictive formulations for (i) vertical mixing and (ii) horizontal flushing, the two key mechanisms dictating water renewal and ultimately residence time in these environments. It is also examined how embedding realism (in the form of flexibility and buoyancy) in the model vegetation can influence flow and turbulent structure as well as residence time. Finally, through consideration of a Peclet number *Pe* (the ratio of diffusive to advective time scales), a framework for quantitative prediction of residence time in these environments is presented.

It is found that two important mechanisms dominate vertical mixing under wave-dominated conditions: a shear layer that forms at the top of the canopy and wake turbulence generated by the stems. By allowing a coupled contribution of wake and shear layer mixing, a predictive formulation for the rate of vertical mixing in coastal canopies across a range of wave and canopy conditions is presented. Results also reveal that flexibility can significantly alter the hydrodynamics of the flow, shear layer characteristics and near-bed turbulent intensities. These differences ultimately lead to a significant reduction in the rate of vertical mixing in flexible canopies when compared to the rigid analogues such that vertical diffusivity in flexible vegetation was always lower than the corresponding rigid canopy (by up to 35%). A physical description of, and predictive formulation for, the mean current generated in wave-dominated flows over large benthic roughness (such as the canopies of seagrass, macroalgae and corals) is also presented. This model indicates that the magnitude of the wave-driven current increases with the above-canopy oscillatory velocity, the vertical orbital excursion at the top of the canopy and the canopy density. An extensive laboratory study, using both rigid and (dynamically-scaled) flexible model vegetation validated the accuracy of the proposed model. Results reveal that *Pe* depends heavily on wave and canopy properties and may vary significantly in real coastal canopies. Quantitative predictions for residence time in the limit of $Pe \ll 1$ (mixing-dominated exchange) and $Pe \gg 1$ (advection-dominated exchange) are presented. The results of this study can have significant implications for a range of environmental, ecological and biochemical studies as well as numerical simulations. In particular, it enables an enhanced predictive capability for the residence time of ecologically-significant materials such as nutrients, seeds, pollen as well as contaminants and dredging plumes. Additionally, the greatly improved understanding in the hydrodynamics of oscillatory canopy flows achieved through this study can serve as a foundation for the numerical modelling of these environments. Ultimately, the results of this study are a step towards an improving management and protection of coastal canopies and their associated ecological communities.

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

(i) incorporate without acknowledgment any material previously submitted for a degree or diploma in any institution of higher education;

(ii) contain any material previously published or written by another person except where due reference is made in the text; or

(iii) contain any defamatory material;

Signature [redacted]......

Date: 5/07/2017

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Statement of candidate contribution and publications

This dissertation is presented as a series of papers, some published and some under review, and consists of three self-contained articles (Chapters 2, 3 and 4, see below for publication status), and a fifth chapter synthesising the results of this study. Each paper concerns a key component when describing residence time in coastal canopies and has its own introduction, literature review, methodology, results and discussion. All papers are co-authored although I designed and conducted all laboratory investigations and the bulk of analysis and manuscript preparation.

M. Abdolahpour, M. Ghisalberti, P. Lavery and K. McMahon, Vertical mixing in coastal canopies, *Limnology and Oceanography*, 62(1), 26-42, 2017, doi : 10.1002/lno.103687. (**Chapter 2**)

Chapter 2, presents, for the first time, a formulation to predict rates of vertical mixing in vegetation canopies (e.g. seagrass, kelp, macroalgae) in coastal environments. The results of this study enables a significantly-enhanced predictive capability for the residence time of ecologically-significant species in these systems. I designed the study, the experimental setup, executed the laboratory work and undertook the data analysis and preparation of the manuscript. M. Ghisalberti provided significant advice on the data analysis approach, interpretation of the data as well as editorial feedback on the manuscript. P. Lavery and K. McMahon provided input into design of the experimental setup and assisted with interpretation of results for ecological implication.

M. Abdolahpour, M. Ghisalberti, K. McMahon and P. Lavery, The impact of flexibility on flow, turbulence and vertical mixing in coastal canopies, *Submitted to Limnology and Oceanography*. (**Chapter 3**)

Chapter 3, describes the impact of flexibility on flow, turbulence structure and mixing in coastal canopies. The subsequent publication that forms the basis for this chapter is primarily my own work. I designed the study, the experimental setup, executed the laboratory work and undertook the data analysis and preparation of the manuscript. M. Ghisalberti provided advice on the design of flexible model vegetation, interpretation of the data as well as editorial feedback on the manuscript. P. Lavery and K. McMahon provided input into the ecological implication of the results as well as editorial feedback on the manuscript.

M. Abdolahpour, M. Hambleton and M. Ghisalberti, The wave-driven current in coastal canopies, *Journal of Geophysical Research: Oceans*, 122, doi : 10.1002/2016JC012446. (**Chapter 4**)

Chapter 4, presents a predictive formulation for the wave-driven mean current generated over large benthic roughness. I designed the study and experimental framework, executed the laboratory work and undertook the data analysis and preparation of the manuscript. M. Hambleton assisted with data collection and analysis. M. Ghisalberti provided significant advice on the model development, interpretation of data as well as editorial feedback on the manuscript.

Chapter 5, is a synthesis of results obtained during this research (i.e. chapters 2 to 4) in which a framework for predictive quantifications of residence time in coastal canopies is presented. Data analysis, interpretation and discussion provided in this chapter is primarily my own work, although M. Ghisalberti, P. Lavery and K. McMahon have assisted with model development and interpretation, as well as drafting the document.

Part of my research has also been presented at three international conferences:
(i) at the 11th International Symposium on EcoHydraulics held in Melbourne, Australia in February 2016;
(ii) at the Ocean Sciences Meeting held in New Orleans, USA, in February 2016; and
(iii) at the 20th Australasian Fluid Mechanics Conference held in Perth, Australia in December 2016.

CHAPTER 1

Introduction

1.1 Significance of the research

Seagrasses meadows, which occupy 10% of world's shallow coastal environments, provide important ecological and economical services (*Green and Short* 2003). They are essential primary producers and form the foundation of shelter (*Fonseca et al.* 1992) and food (*Connolly et al.* 2005) for many aquatic organisms (*Gambi et al.* 1990; *Koch et al.* 2007). The total economic value of aquatic canopies, on the basis of nutrient cycling services alone, has been estimated at 3.8 trillion dollars per year (*Costanza et al.* 1997). Seagrass meadows increase biodiversity as the richness and abundance of marine species in seagrass beds is greater than in adjacent unvegetated areas (*Connolly* 1994; *Jenkins and Sutherland* 1997; *Irlandi and Peterson* 1991). By diminishing water velocity (*Kobayashi et al.* 1993; *Paul et al.* 2011; *Manca et al.* 2012), aquatic canopies, including seagrasses, reduce local resuspension (*Hansen and Reidenbach* 2011), promote sedimentation (*Gacia et al.* 1999), carbon burial (*Granata et al.* 2001) and increase the retention time of dissolved and particulate materials (*Fonseca and Cahalan* 1992; *Granata et al.* 2001) within the meadow. This modification of the environment, stabilises sediment and facilitates the ecosystem they provide. Note that while we focus here on seagrass meadows as the archetypal coastal canopies, the results of this study will be broadly applicable to a range of systems such as coral communities, kelp forests, mangroves and freshwater macrophytes.

The survival of submerged canopies, and the ecosystem services they provide, is strongly related to the rate and mechanism of water renewal in these environments. One example is the effect of vertical transport on the distribution of dissolved oxygen in the water column. As vascular plants, seagrasses require a continuous supply of oxygen for aerobic metabolism of both above ground and below ground tissues (*Larkum et al.* 2006). Seagrass leaves produce oxygen continuously during daylight and lose it to the water column through diffusion. If there is no flushing and replenishment of water, oxygen concentration within the seagrass meadow may reach toxic level, which has negative consequences on seagrass survival. However, if there is efficient exchange of water, there will be an enhanced oxygen concentration in the overlying water. Another example is the impact of rapid exchange on dispersal of seeds, pollen and spores. The dispersal of seeds is directly connected to the ability of a population to spread and migrate (*Kuparinen* 2006). Thus, by regulating the plant migration, water renewal plays a fundamental role in the population dynamics and conservation of plant species (*Cain et al.* 2000; *Kendrick et al.* 2012). In a similar way, rapid exchange has a tremendous effect on the concentration and residence time of nutrients and dissolved organic matters in the water column, vertical and horizontal transport of contaminants, sediments and dredging plumes (*Gacia et al.* 1999). Hence, to understand the extent to which these processes taking place, we need to understand the rate of water renewal and ultimately residence time in these environments, as a function of wave and canopy properties.

The vast majority of numerical, laboratory and field studies into the hydrodynamics of vegetated flows have focused on steady flow environments (*Nepf* 2012a;b) whereas many coastal canopies are subjected to oscillatory flows driven by surface waves. Our understanding of oscillatory canopy flows, however, remains limited. Previous research has focused primarily on the wave height attenuation of coastal canopies (*Dubi and Torum* 1996; *Bradley and Houser* 2009; *Zeller et al.* 2014) and the in-canopy flow structure (*Lowe et al.* 2005a; *Luhar et al.* 2010; *Pujol et al.* 2013a).

The oscillatory nature of wave-dominated flows profoundly influences the hydrodynamics and mass transport in marine environments (*Reidenbach et al.* 2007). For example, the in-canopy velocity (relative to the above-canopy velocity) is significantly enhanced under oscillatory flow conditions compared to the corresponding unidirectional flow (*Lowe et al.* 2005a). Surface waves enhance the rate of nutrient uptake by submerged canopies such as seagrasses (*Weitzman et al.* 2013; *Thomas and Cornelisen* 2003) and coral (*Falter et al.* 2004; *Reidenbach et al.* 2007) when compared to a unidirectional current of comparable magnitude. Thus, it can be inferred that the rate of mass transfer across the top of the canopy will vary greatly between unidirectional and oscillatory flows. This necessitates a specific investigation of oscillatory canopy flows which, in turn, will allow a more complete assessment of fluid exchange between coastal canopies and their surroundings.

1.2 Hydrodynamics of oscillatory canopy flows

The drag of submerged canopies creates a pronounced inflection point in the mean velocity profile (*Ghisalberti and Nepf* 2002), such that the shear layer across the top of the canopy is analogous to a mixing layer, rather than a boundary layer (*Raupach et al.* 1991; 1996; *Ghisalberti and Nepf* 2002). That is, the velocity within the canopy, U_c^{rms} (where the superscript 'rms' refers to the root-mean-square of the oscillatory velocity and the subscript 'c' to the in-canopy average), is attenuated from its value far above the canopy, U_∞^{rms}. This inflection point, which is enhanced with the canopy density (*Lowe et al.* 2005a; *Reidenbach et al.* 2007; *Pujol et al.* 2013a) (Figure 1.1a), is a necessary criterion for instability of an inviscid parallel flow (*Kundu and Cohen* 1990) and leads to the generation of Kelvin-Helmholtz-type vortices (referred to as KH-vortices hereafter) (*Brown and Roshko* 1974; *Winant and Browand* 1974) (Figure 1.1b).

In steady flows over submerged canopies, vertical transport is dominated by these coherent vortex structures (*Nepf and Ghisalberti* 2008). In wave-dominated flows, these large scale shear-driven vortices are generated only under certain conditions; namely, when the wave period is long enough to allow the shear-driven instability to be generated, and when the vortex instability is strong enough to overcome the stabilizing effects of viscosity; i.e. when $KC > 5$ and $Re > 1000$ (*Ghisalberti and Schlosser* 2013). Here Re is the Reynolds number in which the horizontal wave excursion A_∞ is used as the characteristics length scale ($Re = U_\infty A_\infty / \nu$, with U_∞ being the amplitude of oscillatory velocity far above the canopy and ν being the kinematic viscosity of the fluid) and KC is Keulegan-Carpenter number and can be viewed as the ratio of the timescale of flow oscillation to the timescale of shear formation. While, as in steady flows, the generation of these large scale vortices can profoundly impact vertical exchange of dissolved and particulate material, a real understanding of key processes controlling mixing and ultimately a predictive capability for the overall residence time in wave-dominated canopy-flows is still lacking.

In coastal canopy environments, the impact of advection on residence time is often neglected (*Abdolahpour et al.* 2017a). Although coastal systems are typically wave-dominated, this impact may not, necessarily be small. Indeed, aquatic canopies in oscillatory flows have been shown to generate a strong, shoreward mean current near the canopy-water interface (*Luhar et al.* 2010). This shoreward drift, which has been observed in both laboratory (*Lowe et al.* 2005a; *Luhar et al.* 2010) and field studies (*Luhar et al.* 2013), can significantly influence canopy residence time by introducing a second method of water renewal (other than vertical mixing across the top of the canopy).

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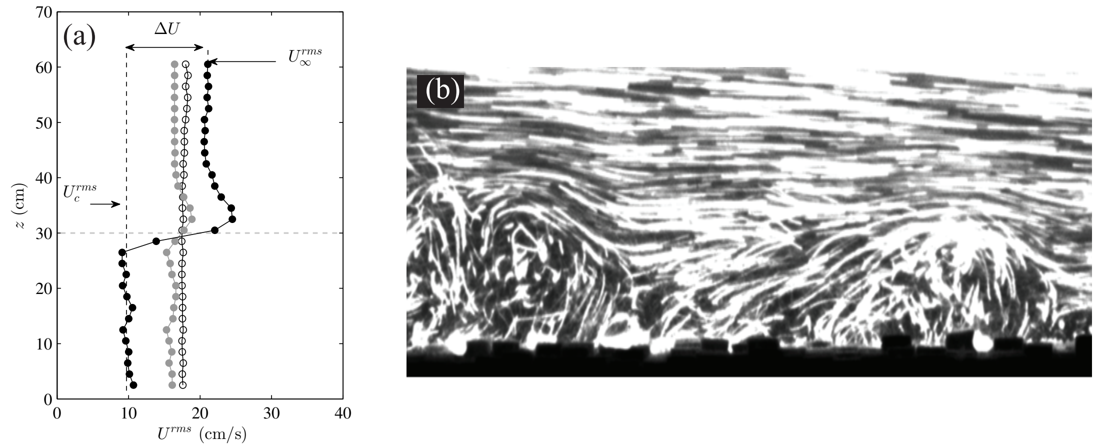

Figure 1.1: Canopy-induced shear and the subsequent vortex generation in wave-dominated flows. (a) Vertical profiles of RMS velocities for identical waves ($U_\infty^{rms} = 17$ cm/s) over a dense canopy (10% by volume, black circles), a sparse canopy (1% by volume, gray circles) and a bare bed (white circles) suggest an increasing velocity attenuation with canopy density (*Abdolahpour et al.* 2017a). Values of the in-canopy RMS velocity, U_c^{rms}, the above-canopy RMS velocity, U_∞^{rms}, and the velocity attenuation, ΔU, are indicated for the dense canopy. The gray dashed line indicates the top of the canopy. (b) Image showing the KH-vortices generated in an oscillatory canopy flow in the laboratory when $KC > 5$ (*Ghisalberti and Schlosser* 2013).

1.3 The importance of canopy flexibility

In spite of the growing interest in flow (*Pujol et al.* 2013a) and turbulence (*Reidenbach et al.* 2007; *Pujol et al.* 2013b) structure in wave-dominated flows over submerged canopies, and the improved understanding of mass (*Nishihara et al.* 2011; *Abdolahpour et al.* 2017a) and momentum (*Ghisalberti and Schlosser* 2013) transport in these environments, the majority of previous work has used rigid cylinders to simulate aquatic vegetation. This allowed the canopy geometry to be invariant and easily quantified. While these rigid elements are ideal to represent stem-like aquatic vegetation and hard corals, they may not successfully recreate situations where flexibility, buoyancy and configuration of flexible plants are important (*Koehl et al.* 2008; *Mass et al.* 2010).

In fact, flexibility enables plants to adapt their shape and posture in response to the flow, thus representing a time-varying roughness which oscillates over the wave cycle (*Luhar and Nepf* 2011; *Pan et al.* 2014; *Luhar and Nepf* 2016). The issue of time-varying roughness may result in a substantial drag reduction in these systems compared to rigid analogues (*Rominger* 2014). This issue may become more pronounced in coastal canopies where the generation of a strong current at the canopy top (*Luhar et al.* 2010; *Abdolahpour et al.* 2017b) can remarkedly modify the blade posture by introducing a more pronated canopy in the direction of wave propagation under the wave crest and a more upright canopy under the wave trough.

In addition to its physical significance, canopy flexibility can have important implications for chemical and biological processes. For example, the orientation of seagrass blades can greatly alter the light availability within the meadow such that an increase in bending height from 5 to 20 degrees, leads to 66% enhancement in canopy photosynthesis. But a further increase in the bending height, results in a slight reduction (10%) of photosynthesis due to sheltering impact of the canopy posture (*Zimmerman* 2003). The plant posture has shown significant impact on the rate of nutrient uptake, by controlling the viscous boundary layer at the seagrass blade (*Hurd* 2000). Thus, although inclusion of flexibility will add further complexity to the system, the issue of reconfiguration and time varying drag may have a non-negligible impact on important physical and biological processes.

1.4 Research aims

The overall objective of this research is to develop a framework for predictive quantification of residence time in coastal canopies. To achieve this overall aim, four main research objectives have been identified, each characterising an important component describing residence time, as described below:

1.4.1 Characterisation of vertical mixing in coastal canopies

The spatial extent over which meadows of submerged aquatic vegetation, such as seagrass, have an ecological and environmental influence is tightly limited by the exchange of water across canopy boundaries. Equally, the extent to which critical canopy process can occur may also be limited by exchange of water across the boundary. In coastal environments, the process of vertical mixing can govern this material exchange, particularly when mean currents are weak. This is investigated through an extensive laboratory study described in Chapter 2. A simple model of coastal canopies, an array of wooden dowels of variable packing density, subjected to waves with a wide and realistic range of height and period is used to mimic a simplified coastal canopy. This, as the first step, will allow the canopy geometry to be invariant and easily quantified. Later, in Chapter 3, the impact of flexibility, buoyancy and vertical variation in the canopy drag (which are typical of real canopies) on the results is examined.

1.4.2 The impact of flexibility on flow, turbulence and vertical mixing

While the rigid elements examined in Chapter 2 are ideal to represent stem-like aquatic vegetation and hard corals, they may not successfully recreate situations where flexibility, buoyancy and reconfiguration of the flexible plants are important. Many coastal canopies are flexible, taking advantage of reconfiguration to reduce drag and thus preventing uprooting during storm and other severe hydrodynamic conditions. The importance of creating flexible, buoyant seagrass canopies on flow and turbulent structures is investigated in Chapter 3. Finally, the impact of reconfiguration is investigated in the context of vertical mixing in these two canopy environments, rigid and flexible.

1.4.3 Characterisation of wave-driven mean current

Although coastal systems are typically wave-dominated, the impact of horizontal advection on residence time may not, however, necessarily be small. Indeed, aquatic canopies in oscillatory flows have been shown to generate a strong, shoreward mean current near the canopy-water interface (*Luhar et al.* 2010). This shoreward drift, which has been observed in both laboratory (*Lowe et al.* 2005a; *Luhar et al.* 2010) and field studies (*Luhar et al.* 2013), can significantly influence canopy residence time by introducing a second method of water renewal (other than vertical mixing across the top of the canopy). Chapter 4 presents a predictive formulation for, the wave-driven mean current at the canopy top. An extensive laboratory study, using both rigid and (dynamically-scaled) flexible model vegetation validates the accuracy of the proposed model. The validity of this model is also confirmed through available field measurements.

1.4.4 Residence time in aquatic canopies in wave-dominated flows

Finally, by synthesising the results obtained in the research described above, a framework for predicting residence time in coastal canopies is presented. This is done in chapter 5, through consideration of a Peclet number, which is the ratio of diffusive to advective time scales.

1.5 Outline

This thesis consists of six chapters, with the main body of work presented in Chapters 2 to 5, which correspond to three journal papers and a synthesis chapter. In order to retain chapters that are legible individually, some parts are repeated. Chapter 2 presents a predictive formulation for the rate of vertical mixing in wave-dominated canopy flows. In this chapter, submerged canopies were simplified by using rigid dowels. Chapter 3 describes how embedding realism to the model vegetation (in the form of flexibility and buoyancy) can impact hydrodynamics of the flow and ultimately residence time in vegetated flows. Chapter 4 presents a physical description of, and a predictive formulation for, the mean current generated at the canopy. Chapter 5 is a synthesis of the results obtained through chapters 2 to 4 in which a predictive framework for the residence time in coastal canopies is presented. Chapter 6 is a brief set of conclusions regarding the improved understanding of wave-dominated flows achieved through this research.

Chapters 2, 3, 4 & 5 have been omitted from this version of the thesis.

Chapter 2. Vertical mixing in coastal canopies

Chapter 3. The impact of flexibility on flow, turbulence and vertical mixing in coastal canopies

Chapter 4. The wave-driven current in coastal canopies

Chapter 5. Residence time in aquatic canopies in wave-dominated flows

Chapter 6
Conclusions

There are two mechanisms that control residence time in coastal canopies (1) vertical mixing and (2) horizontal flushing. By providing predictive formulations for each of these processes, this thesis presents an enhanced capability for quantitative predictions of residence time in coastal canopies. Below is a summary of the conclusions obtained in this study that specifically relate to the research questions initially presented in Chapter 1.

With respect to vertical mixing, an extensive laboratory study was conducted to obtain direct measurements of vertical turbulent diffusivity in wave-dominated canopy flows across a wide and realistic range of wave and canopy conditions (Chapter 2). Unlike in steady flows, where shear layer mixing is the dominant process controlling vertical mixing, vertical mixing in wave-dominate canopy flows was found to be a coupled contribution of both wake- and shear-driven mixing. Additionally, a direct comparison of vertical turbulent diffusivities between steady flows and comparable oscillatory flows revealed that vertical mixing in steady flows exceeded oscillatory flow values by a factor of $2-3$. This result may have significant ecological and environmental implications as it suggests a weaker vertical mixing of dissolved and particular material (such as nutrients, oxygen, pollen, sediments, seeds, etc.) in canopies exposed to oscillatory flows than those exposed to corresponding unidirectional flows.

Given the abundance of flexible buoyant canopies in real ecosystems, the impact of flexibility on flow and turbulent structure in coastal canopies was also investigated (Chapter 3). Results showed that there is a significant difference in flow and turbulence structure between flexible and rigid canopies. In particular, drag reduction caused by canopy reconfiguration leads to diminished velocity attenuation in flexible canopies. While this results in greatly enhanced in-canopy velocity, the shear-driven mixing is significantly reduced in these canopies. These differences lead to a significant reduction (up to 35%) in the rate of vertical mixing in flexible canopies compared to rigid canopies. The significant impact of flexibility (and plant reconfiguration) on flow and mixing can substantially influence important ecological and biological processes. For example, the higher in-canopy velocities observed in flexible canopies could alter nutrient uptake by plant tissue. In addition to higher wake mixing, the generation of near-bed shear layer vortices could enhance resuspension in these environments, with implications for near-bed processes such as particle retention and material flux across the sediment-water interface. Moreover, the weaker shear layer vortices and turbulent transport resulting from reconfiguration of the canopy will impact flux and exchange of dissolved (nutrient, oxygen and carbon dioxide) and particulate material (e.g., seeds, pollen and pollutants) across the canopy-water interface. Finally, the notable reduction in the rate of mixing in flexible canopies suggests a greater residence time in these environments. The ecological implications of this are complex, since some processes may be enhanced by longer residence times (e.g., particle settling) while others may be reduced (e.g., resupply of nutrients through flushing) with the net effect on ecosystem function difficult to predict. In any case, using simplified rigid elements will underestimate the residence time in real systems where flexibility is a salient feature of the canopy.

With respect to horizontal flushing, a physical description of and predictive formulation for the mean current generated in wave-dominated flows over large benthic roughnesses (such as the canopies of seagrass, macroalgae and corals) was presented (Chapter 4). It is found that the magnitude of the wave-driven current is directly proportional to both wave and canopy properties. Specifically wave-driven currents increase with the above-canopy oscillatory velocity, the vertical orbital excursion at the top of the canopy, and the canopy density. This formulation enables an enhanced predictive capability for the rate of horizontal flushing. The accuracy of this formulation was examined through a detailed experimental campaign involving both rigid and (dynamically-scaled) flexible canopy elements, as well as existing field data. These results enable an enhanced predictive capability for the rate of horizontal flushing.

Finally, by integrating the results obtained in this study (Chapters 2 through 4), a predictive framework for residence time in wave-dominated canopy flows was presented (Chapter 5). This was achieved through consideration of a Peclet number (Pe) which is the ratio of diffusive to advective time scales. The results reveal that Pe depends heavily on wave and canopy properties and may vary significantly in real coastal canopies. Quantitative predictions for residence time in the limit of $Pe \ll 1$ (mixing-dominated exchange) and $Pe \gg 1$ (advection-dominated exchange) are also presented. For Pe $O(1)$, both vertical mixing and horizontal advection equally contribute in controlling residence time. Characterisation of residence time within this limit is a fundamentally important question that remains to be answered.

The results of this study can have significant implications for a wide range of ecological, biochemical and environmental studies. For example, retention time of nutrients can have a tremendous impact on the health and propagation of coastal canopies (e.g. coral reefs, seagrass meadows, kelp forests and other aquatic vegetation) and, ultimately, on the ecosystem services that they provide. In a similar way, water renewal regulates distribution and abundance of plants across a landscape, the spread of existing populations and the potential for new population formation by a direct impact on the rate of seed and pollen dispersal. Moreover, coastal canopies are often sensitive to major turbidity and sediment deposition events (e.g. from dredging). The results of this study allow for an enhanced capability to understand and predict the concentration, exposure time and fate of dredging plumes in coastal canopies. Finally, the results obtained in this thesis can be embedded in process-based numerical models which, in turn, serve as a foundation for the improved management, protection and decision-making in coastal canopies.

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