Residence time in coastal canopies

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Residence time in coastal canopies

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Master of Engineering (Hydraulic Structures), 2010
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This thesis is presented for the degree of

Doctor of Philosophy

The University of Western Australia
(School of Civil, Environmental and Mining Engineering)
and Edith Cowan University
(School of Science)
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 correspond-
ing 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 .............................................

Date: 5/07/2017

..................................................
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Contents

Abstract iii
Declaration v
Acknowledgements vii
Contents ix
List of Tables xiii
List of Figures xiv
Statement of candidate contribution and publications xxv

1 Introduction 1
  1.1 Significance of the research ................................. 1
  1.2 Hydrodynamics of oscillatory canopy flows .................... 2
  1.3 The importance of canopy flexibility ........................... 4
  1.4 Research aims ................................................. 5
    1.4.1 Characterisation of vertical mixing in coastal canopies .... 5
    1.4.2 The impact of flexibility on flow, turbulence and vertical mixing 6
    1.4.3 Characterisation of wave-driven mean current ............... 6
    1.4.4 Residence time in aquatic canopies in wave-dominated flows ... 6
  1.5 Outline .................................................. 6

2 Vertical mixing in coastal canopies 9
  2.1 Abstract .................................................. 9
  2.2 Introduction ............................................... 9
  2.3 Methods .................................................. 12
    2.3.1 Wave flume ........................................ 12
    2.3.2 Model vegetation canopy ............................ 14
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3.3 Theoretical model for vertical mixing</td>
<td>16</td>
</tr>
<tr>
<td>2.3.4 Dye injection and concentration measurement</td>
<td>17</td>
</tr>
<tr>
<td>2.3.5 Estimation of diffusivity</td>
<td>18</td>
</tr>
<tr>
<td>2.3.6 Velocity measurements</td>
<td>20</td>
</tr>
<tr>
<td>2.4 Results</td>
<td>21</td>
</tr>
<tr>
<td>2.4.1 Velocity structure</td>
<td>21</td>
</tr>
<tr>
<td>2.4.2 Estimation of velocity difference across the top of the canopy</td>
<td>22</td>
</tr>
<tr>
<td>2.4.3 Vertical turbulent diffusivity</td>
<td>23</td>
</tr>
<tr>
<td>2.4.4 Shear-layer-induced mixing</td>
<td>24</td>
</tr>
<tr>
<td>2.4.5 Wake-induced mixing</td>
<td>25</td>
</tr>
<tr>
<td>2.4.6 Total vertical mixing</td>
<td>26</td>
</tr>
<tr>
<td>2.5 Discussion</td>
<td>27</td>
</tr>
<tr>
<td>2.5.1 The impact of wake mixing on the assumption of a vertically-</td>
<td>27</td>
</tr>
<tr>
<td>uniform diffusivity</td>
<td></td>
</tr>
<tr>
<td>2.5.2 The impact of oscillatory flow on vertical mixing</td>
<td>29</td>
</tr>
<tr>
<td>2.5.3 Residence time in coastal canopies</td>
<td>30</td>
</tr>
<tr>
<td>2.5.4 Impact of canopy flexibility and morphology:</td>
<td>33</td>
</tr>
<tr>
<td>2.6 Conclusion</td>
<td>34</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Abstract</td>
<td>35</td>
</tr>
<tr>
<td>3.2 Introduction</td>
<td>35</td>
</tr>
<tr>
<td>3.2.1 Hydrodynamics of oscillatory canopy flows</td>
<td>37</td>
</tr>
<tr>
<td>3.3 Methods</td>
<td>38</td>
</tr>
<tr>
<td>3.3.1 Design of flexible model vegetation</td>
<td>38</td>
</tr>
<tr>
<td>3.3.2 Construction of rigid and flexible canopies</td>
<td>41</td>
</tr>
<tr>
<td>3.3.3 Experimental setup</td>
<td>43</td>
</tr>
<tr>
<td>3.3.4 Velocity and turbulence measurements</td>
<td>44</td>
</tr>
<tr>
<td>3.3.5 Model for vertical mixing</td>
<td>47</td>
</tr>
<tr>
<td>3.4 Results</td>
<td>50</td>
</tr>
<tr>
<td>3.4.1 Effective canopy height (l_c)</td>
<td>50</td>
</tr>
<tr>
<td>3.4.2 Oscillatory flow structure</td>
<td>51</td>
</tr>
<tr>
<td>3.4.3 Turbulence structure</td>
<td>53</td>
</tr>
<tr>
<td>3.4.4 Turbulent scales</td>
<td>56</td>
</tr>
</tbody>
</table>
3.4.5 The impact of flexibility on vertical mixing ........................................ 58
3.5 Discussion ......................................................................................... 59
3.6 Conclusion ....................................................................................... 60

4 The wave-driven current in coastal canopies ......................................... 63
  4.1 Abstract .......................................................................................... 63
  4.2 Introduction ...................................................................................... 63
  4.3 Model development .......................................................................... 67
  4.4 Methods ........................................................................................... 69
    4.4.1 Experimental setup ................................................................. 69
    4.4.2 Model vegetation ................................................................. 70
    4.4.3 Velocity measurements .......................................................... 73
    4.4.4 Vertical orbital excursion ........................................................ 75
  4.5 Results ............................................................................................ 76
    4.5.1 Variation of $u$ ...................................................................... 77
    4.5.2 Prediction of wave-driven mean current ............................... 78
    4.5.3 Advection flux ........................................................................ 80
    4.5.4 Implications for predicting residence time in real canopies ....... 84
  4.6 Conclusion ....................................................................................... 85

5 Residence time in aquatic canopies in wave-dominated flows ............... 87
  5.1 Model development .......................................................................... 87
    5.1.1 Vertical mixing ....................................................................... 87
    5.1.2 Horizontal advection ............................................................ 88
    5.1.3 Residence time in coastal canopies ......................................... 89
    5.1.4 Variation of vertical mixing, horizontal flushing and Peclet num-
         ber with wave and canopy characteristics .............................. 90
    5.1.5 The limit of $Pe \ll 1$ ............................................................... 92
    5.1.6 The limit of $Pe \gg 1$ ............................................................... 92
  5.2 Future work ..................................................................................... 95
    5.2.1 Residence time in the limit of $Pe \sim O(1)$ ......................... 95
    5.2.2 Residence time of particulate materials ............................... 95
    5.2.3 Residence time in natural systems ........................................... 96

6 Conclusions ......................................................................................... 97
Bibliography
List of Tables

2.1 The four canopy densities employed in this study. . . . . . . . . . . . . . 14
2.2 The nineteen wave conditions to which each canopy was exposed. . . . . 15
3.1 Typical values for Posidonia australis leaves collected from two different sites (Cockburn Sound and Shoalwater Bay) in Western Australia. . . . . 40
3.2 Wave conditions to which the canopies were exposed. . . . . . . . . . . . 43
3.3 List of test cases examined in this study. . . . . . . . . . . . . . . . . . . 44
4.1 Canopy densities employed in this study. . . . . . . . . . . . . . . . . . . 73
4.2 Wave conditions employed in this study and the observed values of $\bar{u}_{\text{max}}$ near the top of the canopy. . . . . . . . . . . . . . . . . . . . . . . . . . . . 75
5.1 Typical wave and canopy conditions in a Posidonia australis meadow (Cambridge and Kuo 1979; Ghisalberti and Schlosser 2013). . . 91
List of Figures

1.1 Canopy-induced shear and the subsequent vortex generation in wave-dominated flows. (a) Vertical profiles of RMS velocities for identical waves ($U_{\text{rms}} = 17$ 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, $U_{\text{rms}}$, the above-canopy RMS velocity, $U_{\infty \text{rms}}$, and the velocity attenuation, $\Delta U$, 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).

2.1 The experimental setup, dye injection system and the model canopy. (a) Schematic view of the experimental configuration in the wave flume (not to scale) (b) The dye injection tubing extended wall-to-wall (at the top of a $\lambda_P = 3\%$ canopy) and the vertical arrangement of the five Cyclops 7 fluorometers (c) A close-up of the two-line injection system (in a canopy with $\lambda_P = 5\%$). The height of the central fluorometer (3) was exactly the same as that of the center of the injection tubing so as to measure the maximum concentration of the injected dye.

2.2 The vertical growth of the dye cloud for run 3-VL ($T = 8$ s, $H = 7$ cm) from $t = 0$ (the moment of injection) to $t = 8T$. Concentration values are time-averaged over exactly one wave cycle (indicated by markers). For all Gaussian fits (indicated by the lines), $R^2 > 0.97$, indicating that concentration distributions show excellent agreement with the model presented in Equation (2.6).

2.3 The growth of concentration distribution variance with time after injection for run 3-VL (the same run as in Figure 2.2.)
2.4 A time series of velocity in the direction of wave propagation \( u \) above the canopy in run 6-M. (a) The raw velocity signal containing the mean, oscillatory and turbulent components (Equation 2.12) (b) All velocity data from 50 wave cycles as a function of phase \( \phi \) (c) The phase-averaged oscillatory velocity \(<u(\phi)>\).

2.5 The impact of canopy density on the in-canopy oscillatory velocity. For identical waves (with \( T = 8 \) s), vertical profiles of \( U_{rms} \) for a dense canopy \( (\lambda_p = 10\%, \text{ black markers}) \), a sparse canopy \( (\lambda_p = 1\%, \text{ grey markers}) \) and a bare bed (white markers) are shown. Values of the in-canopy \( (U_{rms}^c) \) and above-canopy \( (U_{rms}^\infty) \) RMS velocities are indicated for the dense canopy.

2.6 The velocity attenuation ratio \( (\alpha) \) as a function of the dimensionless particle excursion length \( (U_{rms}^\infty / S) \) over a wide range of canopy density (here represented, as in Lowe et al. (2005a), by the ratio of the stem-to-stem spacing to the stem diameter, \( S/d \)). Here, \( U_{rms}^\infty \) is the RMS particle excursion far above the canopy (equal to \( A_\infty/\sqrt{2} \) for linear waves). Good agreement is observed between the measured values of \( \alpha \) (circles) and those predicted by the theoretical model of Lowe et al. (2005a) (solid lines); the average discrepancy is less than 5%.

2.7 The collapse of vertical diffusivity \( (D_{t,z}) \) data as a function of \( (\Delta UL_D) \) across the range of canopy density (indicated in the legend). The dashed line represents the trend at high \( (\Delta UL_D) \). Vertical bars represent the standard deviation of diffusivity estimates from the 3 to 8 replications in each run. In some cases, this variation is smaller than the marker size.

2.8 The importance of shear-layer-driven mixing at high \( KC \), as indicated by the collapse of diffusivity data when plotted against \( (\Delta UL_D) \) for \( KC > 18 \). Canopy density is indicated in the legend. The slope of the line of best-fit \( (0.082) \) provides the scaling factor \( \alpha_1 \).

2.9 The importance of wake-driven mixing in oscillatory canopy flows. When \( KC < 5 \), the diffusivity behaves as predicted by a steady flow model of wake-driven mixing (Equation (2.16)) across a range of canopy density (indicated in the legend). The slope of the line of best-fit \( (1.1) \) provides the scaling factor \( \alpha_2 \).
2.10 Mixing in oscillatory canopy flows as a combination of shear-layer- and wake-driven mixing processes. The triangle markers represent diffusivity data in the intermediate regime \(5 < KC < 18\), with circles representing the limiting regimes of shear-layer- and wake-dominance \((KC > 18\) and \(KC < 5\), respectively). There is a strong linear relationship between diffusivity and the sum of shear-layer-driven \((\text{Equation (2.15)})\) and wake-driven \((\text{Equation (2.17)})\) formulations over the entire range of canopy density and \(KC\) values examined here. The slope of the line of best-fit \((0.53)\) provides the scaling factor \(\beta\) in Equation (2.18).

2.11 The ratio of in-canopy \(\langle D_{t,z} \rangle_c\) to above-canopy diffusivity \(\langle D_{t,z} \rangle_\infty\) as a function of \(KC\). This ratio always exceeds 1 for \(KC < 5\), indicative of the impact of wakes on the rate of vertical mixing. This ratio decreases with \(KC\) such that \(\langle D_{t,z} \rangle_c/\langle D_{t,z} \rangle_\infty \approx 1\) for \(KC > 18\).

2.12 Comparison of observed vertical turbulent diffusivities in steady (data from runs A, C, D, E, F, G, H and I, \((\text{Ghisalberti and Nepf 2005})\)) and wave-dominated flows (present study) with the same above-canopy RMS velocity and identical canopies. Mixing in wave-dominated flows occurs at less than half the rate of that in the corresponding steady flow over the same canopy.

2.13 The variation of the characteristic canopy residence time \(T_{res}\) with wave height \((H)\) and canopy density \((\lambda_P)\). There is a simple decrease of residence time with increasing wave height. The variation with canopy density is more complex; the residence time depends heavily on canopy density \((\lambda_P)\) only if the canopy is sparse. In general, there is a trend of increasing residence time with canopy density for typical values of \(\lambda_P\).

2.14 The decrease of residence time with increasing wave period \((T)\). This decrease is sharper in sparser canopies, as can be seen by contrasting the dashed \((\lambda_P = 1\%)\) and solid \((\lambda_P = 5\%)\) lines.

3.1 The behavior of model seagrass leaves (under the wave crest) with \(B \approx 7\) to 50 in comparison with a real \(Posidonia australis\) leaf. The model blade with \(B \approx 12\) exhibited the most realistic motion.
3.2 Comparison of the real and model blade under different wave phases. The real plant is on the left-hand side in all photos. Figures 3.2a to 3.2c display the behavior of the model seagrass blade where the fluid motion is from left to right (in the direction of wave propagation), while 3.2d to 3.2f display the blade behavior when the fluid motion is from right to left (in the offshore direction).

3.3 Vertical variation of frontal area in the (a) real *Posidonia australis* (collected from Shoalwater Bay, Western Australia) and (b) model plant. The lower region of the canopy has a greater frontal area than the upper region so for (c) model plants, the average of the upper and lower frontal areas, $a_{beff}$, was used in calculation.

3.4 Schematic view of the experimental configuration in the wave flume (not to scale). Beaches of slope 1:10 were constructed at both ends of the flume to minimize wave reflection. Velocity measurements were taken by an Acoustic Doppler Velocimeter (ADV) in the geometric center of the canopy.

3.5 A typical velocity profile taken in run 18-FM showing raw and filtered data. Black circles represent $U_{rms}$ values of raw data and gray circles represent $U_{rms}$ values of filtered data (data with correlation > 70%). The shaded gray area represents the range of canopy height under the maximum pronation in the direction of wave propagation.

3.6 Photographs showing the dye injection system in a typical (a) rigid ($ad = 0.063$) and (b) flexible ($ab_{eff} = 0.064$) canopy. Five fluorometers were arranged vertically to monitor the evolution of concentration profiles over the water depth. The dye injection was done within and near the shear layer (where mixing is expected to be greatest); i.e., at the top of the rigid canopies and at the bed for flexible canopies.
3.7 Vertical growth of the dye cloud for two runs with comparable rate of spread of the dye sheet; i.e. (a) injection at the bed in run 6-FM ($T = 8$ s, $U_{\infty}^{rms} = 7.7$ cm/s) and (b) injection at the top of the canopy in run 2-RM ($T = 8$ s, $U_{\infty}^{rms} = 5.6$ cm/s) from $t = 0$ (the moment of injection) to $t = 6T$. Concentration values are time-averaged over exactly one wave cycle (indicated by markers). For all Gaussian fits (indicated by the lines), $R^2 > 0.9$, indicating an good agreement between the concentration distributions and the model presented in (3.11). 49

3.8 The growth of concentration distribution variance with time after injection for two comparable runs; i.e. (a) 6-FM and (b) 2-RM (the same runs as in Figure 3.7). The variance increases linearly with time until the dye cloud encounters the boundaries (i.e., water surface or/and bed) and stops growing. 50

3.9 The applicability of predictive models in (3.5) and (3.6) for effective canopy height. The predictive models suggested by Luhar and Nepf (2016) represent a good agreement with observations of this study for both (a) $L < 1$ and (b) $L > 1$. 51

3.10 Vertical velocity profiles of an identical wave (run 18, Table 3.3) over a sparse (gray markers) and a dense canopy (black markers) for both (a) rigid and (b) flexible canopies. While an increasing velocity attenuation with canopy density is observed in both systems, flexible canopies generate a weaker velocity attenuation compared to the rigid analogues. Values of in-canopy ($U_{c}^{rms}$) and above-canopy RMS velocities ($U_{\infty}^{rms}$) as well as $\Delta U$ are indicated for the dense canopies in both cases. The gray dashed lines indicate the maximum canopy height and the gray bands indicate the region of shear for dense canopies. The region of shear is centered around the canopy-water interface in rigid canopies and centered around the maximum pronation in flexible cases. 52

3.11 The velocity reduction observed within rigid ($\Delta U_R$) and flexible ($\Delta U_F$) canopies. There is a diminished attenuation in flexible canopies compared to rigid canopies with comparable canopy dimensionless frontal areas when subjected to the same wave conditions. 53
3.12 Vertical profiles of non-dimensional Reynolds stresses induced by an identical wave \( U_{rms}^\infty = 15 \text{ cm/s} \) and \( T = 5 \text{ s} \), Table 3.3) over (a) rigid and (b) flexible canopies with different densities (Table 3.2). The darkness of markers is proportional to canopy density. Reynold stresses peak near the center of the shear layer in both environments; indicating enhanced vertical mixing in this region. The magnitude of Reynolds stress increases with canopy density.

3.13 Phase-averaged statistics for an identical wave over comparable dense rigid and flexible canopies (runs 11-RH and 11-FH, Table 3.2 and Table 3.3). Dimensionless values of RMS velocities demonstrate a greater velocity reduction within the (a) rigid canopy compared to the (b) flexible analogue. An enhanced momentum transfer is observed near the center of the shear layer in both (c) rigid and (d) flexible canopies. The strength of \( TKE / (U_{rms}^\infty)^2 \) is significantly enhanced under the wave crest and trough in (e) rigid canopies whilst a more distributed pattern is observed throughout the entire wave cycle in (f) flexible canopies.

3.14 Power spectral densities of vertical turbulent velocity \( S_{w'w'} \) as a function of frequency \( f \) in rigid and flexible canopies with \( KC < 5 \) and \( KC > 5 \). While \( S_{w'w'} \) represents a negligible variation within the canopy \( (z = 16 \text{ cm} \) and \( z = 30 \text{ cm}) \) when (a) \( KC < 5 \) (runs 18-RL and 18-RH, respectively), it shows a greatly enhanced peak for lower frequencies when (c) \( KC > 5 \), supporting the generation of large scale shear-driven vortices when \( KC > 5 \). This is consistent with \( S_{w'w'} \) in flexible canopies with (b) \( KC < 5 \) and (d) \( KC > 5 \) (runs 18-FL and 18-FH, respectively). The noticeable augmentation of turbulent level compared to the above-canopy \( (z = 60 \text{ cm}) \) for higher frequencies \( (f > 0.04 \text{ Hz}) \) suggests the impact of wake turbulence in these frequency domains for both rigid and flexible canopies.

3.15 Values of vertical turbulent diffusivity, \( D_{t,z} \), observed within a flexible canopy plotted against \( D_{t,z} \) observed within a rigid canopy. \( D_{t,z} \) values are almost always lower within a flexible vegetation. Vertical and horizontal bars represent the standard deviation of diffusivity estimates from the 3 to 8 replications in each run for flexible and rigid canopies, respectively. In some cases, this variation is smaller than the marker size.
4.1 The impact of the wave-induced, shoreward mean current on a
dynamically-scaled flexible canopy in the laboratory. Images show the
canopy at its maximum pronation (a) in the direction of wave propaga-
tion, and (b) in the direction opposite to that of wave propagation. The
presence of the mean current creates an asymmetry in canopy posture,
with a greatly enhanced pronation in the direction of wave propagation. 65

4.2 The increase in attenuation of orbital velocity with density in submerged
canopies. Vertical profiles of RMS velocities for identical waves ($U_{\text{rms}}^\infty = 17 \text{ cm/s}$, Run 18 in Table 4.2) over a dense rigid canopy (10% by vol-
ume), a sparse rigid canopy (1% by volume) and a bare bed are presented.
Values of the in-canopy RMS velocity, $U_{\text{rms}}^c$, and the above-canopy RMS
velocity, $U_{\text{rms}}^\infty$, are indicated for the dense canopy. The gray dashed line
represents the top of the canopy. 66

4.3 Lagrangian and Eulerian views of the wave-induced drift over coastal
canopies. (a) The deviation of particle orbits from linear wave theory
(left) due to the canopy resistance. Fluid particles with a mean posi-
tion at the top of the canopy will have a greater velocity in the direction
of wave propagation ($U_1$) than in the offshore direction ($U_2$), generat-
ing a Lagrangian drift in the direction of wave propagation. (b) In spite
of a symmetric oscillation far above the canopy ($\bar{u} \approx 0$), fluid particles
within approximately one vertical orbital excursion (i.e. $\pm \xi T$) of the top
of the canopy move with the drift under a wave crest and against it under
a trough. This generates an asymmetric Eulerian velocity record, such
that $\bar{u} \neq 0$ near the canopy-water interface (shown for a typical wave with
$T = 5 \text{ s}$ and $U_{\text{rms}}^\infty = 19 \text{ cm/s}$; Run 16-RM, Table 4.2). 68

4.4 Schematic view of the experimental configuration in the wave tank (not
to scale). Beaches of slope 1:10 were constructed at both ends of the tank
to minimize wave reflection. Velocity measurements were taken by an
Acoustic Doppler Velocimeter (ADV) in the geometric center of the canopy. 70

4.5 Photographs showing the ADV probe measuring within the densest (a)
rigid and (b) flexible model canopies. 71
4.6 Vertical variation of dimensionless frontal area ($ab$) in the model *Posidonia australis* canopy. The lower region of the canopy has a greater frontal area than the upper region. The average of the upper and lower values, $ab_{eff}$, was used to characterize the flexible canopies.  

4.7 Vertical profiles of (a) $U_{rms}$ and (b) $\bar{u}$ in Run 18–FM estimated using raw and filtered data. The shaded areas represent the top of the canopy (with spatial variability) at the point of the maximum pronation in the direction of wave propagation. Gray dashed lines indicate the maximum blade height.  

4.8 Vertical profiles of mean velocity in the absence and presence of the canopy. The observed vertical profile of mean velocity in the absence of a canopy (gray solid line) is in good agreement with the prediction of Longuet-Higgins (1953). For the same wave ($U_{rms}^{\infty} = 19$ cm/s; Run 16, Table 4.2) in the presence of a canopy ($ad = 0.063$), the maximum current exceeds that in the absence of the canopy by an order of magnitude, typical of all the experimental runs conducted here.  

4.9 The impact of wave and canopy conditions on the mean current generated. (a) Identical rigid canopies ($ad = 0.063$, Table 4.1) subjected to different waves with $U_{rms}^{\infty}$ between 3 and 19 cm/s. The stronger the wave forcing, the greater the mean current. (b) Identical waves ($U_{rms}^{\infty} = 19$ cm/s) over different rigid canopies with $ad$ ranging from 0.016 (L) to 0.131 (H, Table 4.1). Importantly, stronger currents are generated by denser canopies. (c) The maximum value of $\bar{u}$ occurs near the canopy top for both rigid and flexible canopies, which is indicated by a dashed line for the rigid canopy and a gray band (representing the range of blade heights at maximum pronation) for the flexible canopy.  

4.10 Observed (vertical axis) and predicted (horizontal axis) values of the depth-averaged current speed in the canopy ($\bar{u}_c$) for two flexible canopy densities, $ab_{eff} = 0.064$ and 0.145 (FM and FH, Table 4.1). Grey dashed lines indicate $1:1$ agreement. (a) Predicted value of $\bar{u}_c$ from (4.1), taking $U_c \equiv U_b$ as the in-canopy oscillatory velocity amplitude (Equation (4.2)), and (b) using values of $U_c$ measured in these experiments. While Equation (4.1) provides reasonably accurate predictions of the mean currents in the experiments of Luhar et al. (2010) (abbreviated as LCIFN), it fails to do so in these experiments.
4.11 The direct proportionality ($R^2 = 0.80$) in rigid canopies between the maximum current speed ($u_{max}$) and the velocity differential experienced by particles that encounter the top of the canopy ($\delta U$). The dashed line represents the line of the best fit. This validates the hypothesis in (4.3), which underpins the model presented here for wave-generated currents. 80

4.12 The accuracy of the model developed here in predicting the maximum current, $u_{max}$. Observed $u_{max}$ values in both rigid and flexible canopies are in good agreement ($R^2 = 0.83$) with predicted values (from Equation (4.12)); the dashed line represents 1 : 1 agreement. Laboratory observations from Luhar et al. (2010) (only considering runs for which $A_{rms}^\infty /S < 1$) and field observations from Luhar et al. (2013) (abbreviated as LIOTN) are also well predicted by (4.12). 81

4.13 The collapse of vertical profiles of mean current speed on a normalized vertical scale ($z - h_c / \xi_T$) for rigid canopies with (a) $ad = 0.016$ (b) $ad = 0.063$ and (c) $ad = 0.131$. The darkness of the markers is proportional to the magnitude of $U_{rms}^\infty$ (as indicated by the colorbar). The dashed lines indicate the region within one vertical orbital excursion of the canopy top and the gray bands the range over which the total advective flux was evaluated. 82

4.14 The linear proportionality between the total flux in rigid canopies ($q_r$) and ($u_{max}$ $\xi_T$). The strong proportionality ($R^2 = 0.86$) validates the scaling relationship in (4.14) for rigid canopies. The slope of the line of best fit (dashed line) defines the scaling coefficient for rigid canopies, $\gamma (=1.2)$. 83

4.15 Profiles of $\bar{u}/u_{max}$ for the flexible canopy FH ($a_{eff} = 0.145$) when plotted on a normalized vertical scale ($z - h_c / \xi_T$). The darkness of markers is proportional to the magnitude of $U_{rms}^\infty$ (as indicated by the colorbar). 83

4.16 The linear proportionality between the total flux in flexible canopies ($q_f$) and ($u_{max}$ $\xi_T$). The strong proportionality ($R^2 = 0.80$) validates the scaling relationship in (4.14). The slope of the line of best fit (dashed line) defines the scaling coefficient for flexible canopies, $\gamma (=1.9)$. 84

5.1 Conceptual model showing the two important mechanisms controlling residence time in coastal canopies, i.e. (a) horizontal flushing (through wave-driven advection) and (b) vertical mixing. 89
5.2 Variation of (a) vertical mixing ($D_{t,z}$) and (b) horizontal flushing ($\pi_{\text{max}}$) with wave height ($H$) and canopy density (indicated as the dimensionless frontal area, $ad$). The darkness of lines is proportional to the magnitude of $H$ (indicated in colourbar). There is a simple increase of vertical mixing and horizontal flushing with increasing wave height. While $\pi_{\text{max}}$ increases simply with canopy density, the variation of $D_{t,z}$ with canopy density is more complex; vertical mixing depends heavily on canopy density only if the canopy is sparse. .............................................................. 92

5.3 Variation of $Pe$ with canopy density (indicated as $ad$) under different wave conditions. $Pe$ increases with $ad$ due to the enhanced advection in dense canopies (Equation (5.2)). The darkness of the markers is proportional to the canopy length (indicated in the colourbar). The Peclet number decreases with canopy length, such that vertical mixing controls exchange in long canopies. .............................................................. 93

5.4 Variation of canopy residence time with canopy density in the limit of $Pe \ll 1$ (based on Equations (5.4) and (5.1)). Despite a clear dependence of $T_{\text{mix}}$ on wave height, it becomes increasingly independent of $ad$ as canopy density increases. .............................................................. 93

5.5 $T_{\text{adv}}$ variation with $ad$ in the limit of $Pe \gg 1$. While a longer canopy leads to a greater $T_{\text{adv}}$, increasing canopy density reduces $T_{\text{adv}}$ due to the enhancement of $\pi_{\text{max}}$. .............................................................. 94
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.


**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.


*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 To-rum 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, $U_{\infty}^{rms}$. 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 $A_{\infty}$ is used as the characteristics length scale ($Re = U_{\infty}A_{\infty}/\nu$, with $U_{\infty}$ being the amplitude of oscillatory velocity far above the canopy and $\nu$ 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).
eller

Figure 1.1: Canopy-induced shear and the subsequent vortex generation in wave-dominated flows. (a) Vertical profiles of RMS velocities for identical waves ($U_{rms}^\infty = 17$ 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, $U_{rms}^c$, the above-canopy RMS velocity, $U_{rms}^\infty$, and the velocity attenuation, $\Delta U$, 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 $K_C > 5$ (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 remarkably 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 great 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
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 resus-
pension 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 ecolog-
ical, 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.


Mei, R. (1990), Particle dispersion in isotropic turbulence and unsteady particle dynamics at finite reynolds number.


