Vortex instabilities in environmental flows over porous media

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Abstract

A large proportion of coastal regions are occupied with some form of vegetation, among the most common are seagrasses. The dynamic nature of coastal regions means they are subject to various flows. Their importance is evident by their enormous production which is said to rival the most productive terrestrial ecosystems on earth, along with a number of other ecological functions they provide to the marine ecosystem. Additionally, it is known that hydrodynamics plays a vital role in allowing them to provide their functions by controlling the vertical exchange of constituents in the flow. Shallow reef systems made up of porous media such as limestone are another prominent feature of coastlines.

The development of 2 new experimental techniques known as particle image velocimetry (PIV) and particle tracking velocimetry (PTV) in recent years has allowed for the development of incredibly detailed velocity fields in fluid flow. They are far more advanced than previously used techniques such as point probes as they provide instantaneous velocities that cover the entire water column, meaning vital flow statistics can be gained throughout the flow.

This study uses the PTV method to investigate unidirectional flow over rough and smooth limestone, and a model vegetative canopy in an experimental flume. It was determined that the presence of vegetation dramatically alters the flow by creating an inflection point in the mean velocity profile which causes the flow to become unstable. It is the instabilities which causes large coherent vortices to form. It was also determined that the mean position of the centre of the vortices lies in a region above the canopy and the vortices only penetrate a certain distance into the canopy. Additionally, similar coherent motions were shown to form over the rough limestone, albeit intermittently and of smaller size. It was determined that due to these coherent motions dominating vertical transport the vertical exchange was larger over the rough limestone in comparison to the smooth where no coherent motions were found.
Acknowledgements

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1 Introduction

Obstructed shear flows are commonplace in coastal regions. A large proportion of coastal areas are occupied with some form of vegetation whether it is a reef system occupied by various species of *macroalgae* or a sandy substrate occupied by seagrass meadows. Coastal waters are very dynamic regions, consequently they are often subject to various environmental flows. A seagrass meadow presents a region of high drag to incident flows and the physical structure of a seagrass meadow has been shown to significantly modify the flow environment (Raupach et al., 1996; Ikeda and Kanazawa, 1996; Ghisalberti and Nepf, 2002). Furthermore, flow fields above seagrass have been found to previously be dominated by organized vortices that dominate vertical transport (Ghisalberti & Nepf 2005).

Seagrasses are angiosperms restricted to the marine environments. Most species grow on soft bottom sediments sub-tidally (Hemminga & Duarte 2000). They are found in waters up to 30m deep littoral fringes off all continents with the exception of Antarctica (den Hartog 1970). Seagrasses at present are said to cover about 0.1–0.2% of the global ocean (Duarte 2002) with this figure currently experiencing worldwide decline and present losses are expected to accelerate (Duarte 2002). This decline is thought to be primarily because of human disturbances such as direct physical damage and the deterioration of water quality (Hemminga & Duarte 2000). This raises concerns that the ecological functions seagrasses provide to the marine ecosystem will be reduced. For example, seagrass loss has been shown to result in significant loss of coastal biodiversity. This leads to the modification of food webs and loss of harvestable resources (Hemminga & Duarte 2000). This highlights the need for more knowledge of the processes that affect seagrasses in order to provide a better means of revegetation and protection.

Coastal waters are a resource of vast natural and economic value. Humans depend upon the ocean for food, health, recreation and livelihood. Vegetation and reef systems are a major component of coastal regions and offer a number of functions that maintain their quality. In particular, seagrasses rank amongst the most valuable ecosystems in the
biosphere due to the importance of the services they provide (Costanza et al. 1997). They form highly productive ecosystems, they also have the ability to stabilize sediments; improve water quality; cause wave attenuation and provide habitats for microbes, invertebrates and, vertebrates. Reef systems also represent a region of high diversity.

Despite only making up less than 0.02% of the angiosperm throughout the world seagrasses are said to rival the most productive biomes on earth (Duarte & Chiscano 1999). Seagrasses store a large fraction their production and as a result they are responsible for about 15% of the carbon storage in the ocean (Duarte & Chiscano 1999). In an age where carbon levels in the earth’s atmosphere are rising rapidly and with global warming at the forefront of major world issues, the maintenance of such an invaluable sink for CO₂ is imperative.

Seagrasses also have the potential to influence erosion due to there sediment trapping abilities (Duarte 2002). The slowing of in canopy currents means seagrass meadows act as a depositional environment. In addition, seagrasses along with reef systems create a physical barrier that lines the shore which dampens ocean waves thereby reducing coastal erosion.

Deteriorating water quality is a direct result of pollution from the discharge of waste water associated with populated areas and agricultural runoffs. Widespread eutrophication has resulted from discharging excessive nutrient deposits in the form of urban wastewater and runoff from agricultural regions. This has led to the global deterioration in the quality of coastal waters (Vidal et al. 1999). Models have been developed that have related water quality to seagrass cover. It is said that by the direct uptake of nutrients and heavy metals (Kadlec and Knight 1996), the capturing of suspended sediment (Palmer el al. 2004) and the production of oxygen, ocean water quality can improve. With coastal populations only projected to increase in most regions pollution is expected to rise therefore understanding these processes becomes an important tool in maintaining a high standard of water quality in coastal regions.
Benthic communities are dependent on water motion for every aspect of their survival. Mean currents import dissolved and particulate matter from the surrounding ocean, while hydrodynamics control the rate of vertical transport necessary to maintain high rates in exchange of nutrients, larvae, dissolved gases, and other constituents with the overlying water column (Reidenbach et al. 2006). Hydrodynamics are therefore important in determining the uptake of dissolved gases, nutrients and organic carbon by the seagrass community necessary to perform their vital ecological functions such as improving water quality in the marine ecosystem. In addition, many coral-reef organisms have limited or no mobility and thus depend on water motion for their basic functions, (Kiflawi and Genin 1997). As a result quantifying flow properties becomes important.

The development of 2 new experimental techniques known as particle image velocimetry (PIV) and particle racking velocimetry (PTV) in recent years has allowed for the development of incredibly detailed flow fields. They’re far more advanced than previously used techniques such as point probes as they provide instantaneous velocities that cover the entire water column. This presents opportunities to analyze environmental flows in greater detail than was previously possible.

Despite the impact of vegetation on hydrodynamics and the ecosystem as a whole, the structure of vegetated aquatic flows is not completely understood. This study entails investigating unidirectional flow over 3 common substrates in the coastal region; rough and smooth limestone, and a model vegetative canopy with the aim to gain an idea of the extent of vertical transport of constituents in the flow to the benthic. The PTV method was chosen for use as it presented such benefits as cost and accessibility over PIV.
2 Literature Review

2.1 Flow above aquatic vegetation

In the present day the importance of vegetation such as seagrass to the marine environment is widely acknowledged. This has led to studies in recent years multiplying. A number of studies have concluded that vegetation significantly modifies the flow environment with respect to surrounding unvegetated waters and which makes for a convincing argument when all grouped together. Reductions of flow speeds on the seagrass beds are reduced at all heights relative to un-vegetated areas (Reidenbach et al. 1996). Speeds within the vegetative canopy are even further reduced relative to the unimpeded flow (Leonard and Reed 2002). Furthermore recent studies have shown how submerged vegetation varies both the mean and turbulent structure of the flow (Ikeda and Kanazawa, 1996; Ghisalberti and Nepf, 2004) and lastly, vegetation significantly affects vertical transport relative to a bare bed by increasing vertical diffusivity above the canopy and to decrease it within(Ghisalberti and Nepf 2005). The extent in which the flow is altered is also thought to be dependent upon canopy morphology and the physical structure of the individuals (Leonard & Reed 2002). As a whole studies on flow in and above aquatic vegetation canopies are still very limited and the structure of vortices in flow in aquatic vegetation is not yet fully understood.

2.2 Mixing layers in canopies

A mixing layer is a form of shear flow that can be thought of as one where shear does not arise from boundary conditions (Ghisalberti and Nepf 2002). It is characterized by a confined region of shear that that separates two co-flowing streams of approximately constant velocity that differ to one another. They are characterized by a strong inflection in the mean velocity profile, in contrast with boundary layer flow. It is recognized that shear flow becomes unstable and large coherent vortices form via Kelvin-Helmholtz (K-H) instabilities if the vertical profile of the flow velocity has an inflection point (Raupach et al. 1996; Ikeda and Kanazawa 1996; Ghisalberti and Nepf 2002) It’s these instabilities that cause coherent vortices to form and propagate downstream.
Flow in aquatic canopies is now thought act as a mixing layer rather than an extension of bed stress. When flow encounters drag from the vegetative canopy, flow is redirected over the top of the canopy resulting in lower lying flow decelerating within the canopy while flow above accelerates relative to unimpeded flow. These conditions produce an inflection point in the mean velocity profile that resembles the hyperbolic shape characterized in mixing layers. Figure 2.1 shows a measured mean velocity profile for data taken from Ghisalberti and Nepf (2002) with a trace of a hyperbolic profile fitted to the data. It clearly displays the similarities between the two. It is also evident that the inflection point is located in close proximity to the top of the canopy.

Figure 2.1 Measured mean velocity profile of an aquatic flow with flexible vegetation. (Ghisalberti and Nepf 2004)
As shown in figure 2.2 in unobstructed shear layer the vortices grow continually downstream, predominantly through vortex pairing (Winant and Browand, 1974). This is not the case for canopy obstructed shear flow where they grow to and maintain a finite thickness in a short distance. Ghisalberti and Nepf (2004) used both experiments and modeling to effectively show that vortex growth in obstructed shear flow is ended when the production of turbulent kinetic energy at the shear layer is balanced by dissipation within the canopy. Although there was strong agreement between the modeling and experiments it was suggested that field application of the model was limited.

Figure 2.2 Coherent vortices in an unobstructed shear flow (Raupach et al. 1996)

There was a time when canopy flows were considered extensions of a bed stress and were regarded as perturbed boundary layers. It wasn’t until (Raupach et al. 1996) argued that active turbulence near the top of a terrestrial canopy is in fact much closer to a mixing layer to the point where it has now become recognized universally. They based their argument on the increased correlation between horizontal and vertical turbulent fluctuations, and the structure of momentum transfer. Of the most significance however was a presence of a strong inflection point in the time averaged velocity profile which resembles the hyperbolic tangent of a pure mixing layer. This is an obvious feature of mixing layers that first prompted the comparison between them and canopy flows. It’s the inflection point that is said to render them susceptible to Kelvin-Helmholtz instabilities which generate large coherent vortices, They argued will great aplomb that the instability
processes that result from this inflection are similar to those in a mixing layer, and determine much of the coherent eddy structure near the top of a vegetation canopy. Table 2.1 clearly shows how statistically similar a mixing layer and canopy flow are while the surface layer (boundary layer flow) display significant differences.

<table>
<thead>
<tr>
<th>Property</th>
<th>Surface layer</th>
<th>Mixing layer</th>
<th>Canopy (z = h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U'(z)$ inflection</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\sigma_u / u_*$</td>
<td>2.5</td>
<td>1.7</td>
<td>1.8</td>
</tr>
<tr>
<td>$\sigma_w / u_*$</td>
<td>1.25</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>$r_{uw} = \overline{uw} / (\sigma_u \sigma_w)$</td>
<td>-0.32</td>
<td>-0.44</td>
<td>-0.5</td>
</tr>
<tr>
<td>$Pr^{-1} = \overline{K_H / K_M}$</td>
<td>1.1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$</td>
<td>Sk_u</td>
<td>,</td>
<td>Sk_w</td>
</tr>
<tr>
<td>$u, w$</td>
<td>$\propto z - d$</td>
<td>$\propto \delta_w$</td>
<td>$\propto h - d$</td>
</tr>
<tr>
<td>TKE budget</td>
<td>Small $T$:</td>
<td>Large $T$:</td>
<td>Large $T$:</td>
</tr>
<tr>
<td>$0 \approx P - \epsilon$</td>
<td>$0 = P + T - \epsilon$</td>
<td>$0 = P + T - \epsilon$</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1 Comparison of statistical flow properties for a surface layer, an unobstructed mixing layer; and canopy flow (Raupach et al. 1996)

A similar process was undertaken in by Ghisalberti and Nepf (2002). In this paper the findings of Raupach et al. (1996) for terrestrial vegetation were applied to determine if aquatic flows through submerged vegetation act in a similar manner. They concluded that shallow aquatic flows with submerged vegetation may also be patterned on a mixing layer rather than a boundary layer again due to a presence of a strong inflection point in the mean velocity profile which give way to K-H instabilities. They also concluded that coherent vortices cause vertical transport of streamwise momentum to be much more efficient than in boundary layers and they dominate vertical transport in a mixing layer.

### 2.3 Structure of vortices

Studies of KH vortices in aquatic flows in recent years have expanded however the structure of organized vortices is still not completely understood. One of the first investigations to investigate flow over vegetation was (Inoue 1963). This particular study
came to the conclusion that the wavy motion of grass seen to travel downwind is a result of eddies generated at the top of the canopy of the vegetation. Further studies have since transpired of similar note. Ghisalberti and Nepf (2002) concluded the wavy motion in flows over aquatic vegetation otherwise known as a monami is caused by the downstream advection of vortices. There findings were strongly supported by the strong agreement of predicted K-H (Kelvin-Helmholtz) frequency, mean monami frequency and peak frequency for the streamwise velocity spectra.

Improved technology has now vastly improved investigation into vortices. Ikeda and Kanazawa (1996) employed a similar technique to the one proposed in this study known as particle image velocimetry (PIV) along with flow visualization techniques to develop a detailed flow field in aquatic vegetation in order to describe the structure of vortices. The vortices were found to be elliptical in shape, inclined downwards to the front with the vortex centre located slightly above the canopy and moves horizontally downstream. This shape is shown in Figure 2.3 which used streak lines in a vortex. The PIV method was instrumental in the findings as velocity fields were able to be generated above the canopy to clearly illustrate the structure of the vortices.
A number of further studies have looked at the structure of vortices in canopy flows. Through the entrainment of surrounding fluid the vortices grow to form 3-dimensional structures with the lateral scale of the vortex of similar magnitude to the longitudinal scale (Ikeda and Kanazawa 1996). They are the most coherent of turbulent motions due to their low frequency (Ghisalberti and Nepf 2002) where a coherent motion can be defined as “a three-dimensional region of the flow in which velocity exhibits significant correlation with itself or with another variable over a range of space and/or time that is significantly larger than the smallest local scales of the flow” (Robinson 1991).

Vegetation encounters vortices continuously as in time as vortices are sustained by the shear at the top of the canopy and progress downstream. This creates oscillations in streamwise velocities in the flow field (Ghisalberti and Nepf 2006). A number of studies have employed spectral analysis to determine the frequency of these oscillations. Figure
2.4 taken from Ghisalberti and Nepf (2006) shows the smoothed spectra of vertical velocity in four regions of the flow. Evident are peaks in the spectral density at frequency 0.04 within the shear layer but not outside it. This demonstrated clearly that flow within a shear layer is periodic as a result of vortices, while vortices don’t produce oscillations outside the shear layer. Furthermore, their vortex frequency is expected to be proportional to their advection speed and inversely proportional to their size (Ghisalberti and Nepf 2002).

![Smoothed spectra of vertical velocity in four regions of the flow](image)

**Figure 2.4** Smoothed spectra of vertical velocity in four regions of the flow (Ghisalberti and Nepf 2006)

### 2.4 Vertical exchange in canopies

The dramatic altering of flow dynamics by aquatic vegetation can significantly affect the fate and transport of sediment nutrients, contaminants, dissolved oxygen and fauna (Fonsea and Kenworthy 1987). Replenishment of constituents to the canopy from the overlying flow is vital for vegetation to play their role in the marine ecosystem thus quantifying the vertical exchange becomes crucial. Mixing layers are characterized by rapid vertical exchange and mixing can be considered to be much more efficient than a
boundary layer (Ghisalberti and Nepf 2004). Ghisalberti and Nepf (2005) used dye injections experiments in flow in model vegetation to characterize vertical transport in aquatic vegetative flow. Using flow visualization and digital imaging to capture the dye injections they came to the conclusion that due to the strong periodicity of the concentration of the dye within the canopy, vertical transport is dominated by coherent vortices.

In vegetative mixing layer vortices reach a finite size that does not extend to the bed (Ghisalberti and Nepf 2002). This causes the segregation of the canopy into a region of rapid exchange in the upper canopy where vertical exchange is dominated by vortices and a lower region called the wake zone where transport is limited to small-scale turbulence generated from stem wakes thus water renewal is more limited (Nepf and Vivoni 2000). Figure 2.5 shows the zones of exchange in a vegetative mixing layer of thickness $t_{ml}$. The canopy of height $h$ is separated into the exchange zone which extends from the top of the canopy to the distance the mixing layer penetrates into the canopy with the wake zone located below. The penetration depth is said to vary inversely with canopy density and drag (Ghisalberti and Nepf 2004). Vertical exchange in the wake zone has been found to be typically an order of magnitude slower than that in the exchange zone (Ghisalberti and Nepf 2005).
Turbulence intensity and Reynolds stress’s are a maximum near the top of the canopy and they are transported up by ejections and downward by sweeps (Ikeda and Kanazawa 1996). In all the experiments conducted by Ghisalberti and Nepf (2006) sweeps were shown to dominate ejections within the canopy as shown in figure 2.6 resulting in approximately 80% of the total downward momentum transport across the top of the canopy occurs in just 30% of the time. It was also shown that this relationship was reversed above the canopy. Figure 2.6 demonstrates how Reynolds stresses and instantaneous velocities were used to successfully to support their argument.

Figure 2.5 Zones of exchange in a vegetative mixing layer (Murphy et al. 2007).
2.5 Flow over smooth and rough surfaces

Environmental flows in coastal environments have previously been studied over relatively smooth surfaces (Gross and Nowell 1983; Sanford and Lien 1999; Stacey et al. 1999). As a general rule all these studies found that the flow structure above the surfaces represents a turbulent boundary layer with velocity profiles varying logarithmically and turbulent kinetic energy decreasing hyperbolically away from the boundary. Figure 2.7 shows a typical velocity profile for a turbulent boundary layer. In classical turbulence

Figure 2.6 Reynolds stress’s and velocity vectors showing a strong sweep at the front of the vortex and followed by a weaker ejection at the rear within the exchange zone of a canopy (Ghisalberti and Nepf 2006).
theory, the turbulent boundary layer is considered to consist of an inner and outer layer which only interacts in a limited sense. As a result surface geometry was first thought to only affect the velocity distribution within the inner layer where the inner layer is only a few roughness heights away from the wall (Rotta JC 1962).

![Diagram](image)

**Figure 2.7** Velocity profiles for boundary layer theory under laminar and turbulent conditions.

Krogstad and Antonia (1999) investigated the influence surface roughness has on a turbulent boundary layer. This was done using a comparison of measurements for two surfaces varying in roughness and a smooth surface. They were able to conclude that surface roughness significantly affects the turbulent characteristics of the flow by showing that the turbulent energy production and the turbulent diffusion are significantly different between the surfaces. They also found the mean velocity profile for the rougher surfaces appears similar to the smoother surface, were found to resemble a boundary layer and albeit with much higher levels of shear, turbulence, and mixing.

Reidenbach *et al.* (2006) investigated flow structure over a coral reef by measuring velocities and turbulence. It was concluded that existing turbulent boundary layer flow theory can be applied to flows over the rough surfaces in coral reefs. It was also suggested that flow over reefs was far more influenced by the effects of topography.
rather than local roughness and that over complex roughness like that of a coral reef, shear-layer vortices might predominate, such as have been found for seagrass beds (Cornelisen and Thomas 2004).

It's also been shown that shear-layer structures are also common within a boundary layer, especially near the wall as embedded tornado-like vortices of a variety of strengths are known to exist within boundary layers (Robinson 1991). While their formation is usually explained by local shear-layer instabilities it remains up for debate. It has been suggested that instantaneously inflectional velocity profiles common near the wall and may "roll up" into vortices (Robinson 1991). Figure 2.8 taken from Black (1968) shows that vortex strength and size is expected to be random in boundary layers, however no concrete evidence was produced to support this theory.

![Diagram of vortex system](image)

**Figure 2.8** The variation of vortex strength and shape within a boundary layer (Black 1968).

Furthermore, it has also been shown that the dominance of sweeps over ejections that has been found for canopy flows also occurs in boundary layers (Raupach 1981). Additionally, vortex structure are thought to be the central elements in the transport of momentum between the inner and outer layers making them important to the vertical
transport of constituents in the flow. Despite their importance, vortex structures in boundary layer flow remain largely ambiguous.
3 Approach

3.1 Lab set-up

3.1.1 Flume set-up

The experiments for this study were conducted in a laboratory flume with dimensions 20 m long x 60 cm wide x 40 cm deep located in the hydraulics laboratory at the University of Western Australia. Figure 3.1 displays the flume. A pump was used to circulate water from one end of the flume to the other to simulate unidirectional flow such as flows found in sheltered embayment when tidal currents are the main source of water movement.

![Figure 3.1 Photo of the flume](photo)

Three different substrates were used in this study to represent common substrates in the marine ecosystem and all were subject to similar flow rates and a constant flow depth of 33 cm. The region chosen for studying was within the last 1 m of each substrate section to allow for fully developed flow. A flow straightener was also employed to eliminate large scale turbulence and secondary currents.
3.1.2 Substrates

Firstly, individual limestone blocks of dimensions 50cm long by 30cm wide by 3cm deep were laid in a 5m continuous section to simulate smooth and rough porous surfaces such as a limestone reef system. Each block was smoothed on one side using a grouter to represent the smooth surface while roughness on the other side of the block was promoted by cutting grooves to represent the rough surface (see fig 3.2). The grooves create a roughness scale of the order of approximately < 1cm.

![Figure 3.2 Photo of rough limestone surface](image)

The experimental vegetative canopy was comprised of wooden, circular cylinders each with a diameter of 6.4mm and height of 90mm, each cylinder was placed into holes drilled into Plexiglas boards. The ratio of the height of the canopy to flow depth (h/H) was opted to be > 2 to ensure that the shear layer growth was not restricted (Nepf and Vivoni 2000).
Four boards were used to create a model canopy of length 4m. Although variations in canopy morphology and the physical structure of individual plants control fine scale hydrodynamics, and influence particle advection, and particle settling (Lightbody and Nepf 2006), the model canopy can still be considered an idealized form of aquatic vegetation such as seagrass, therefore valuable knowledge can still be gained. The cylinders were randomly placed due to the general lack of ordered array within vegetation such as a seagrass meadow at a packing density of 533 per m². If the range of dimensionless plant densities for dense canopies is $ad = 0.016-0.051$ (Chandler et al 1996) this packing densities this packing densities falls within this range at $ad = 0.017$.

### 3.2 Particle tracking velocimetry

#### 3.2.1 Background

The development of 2 new experimental techniques known as particle image velocimetry (PIV) and particle tracking velocimetry (PTV) in recent years has allowed for the development of incredibly detailed information on fluid flow. They’re far more advanced than previously used techniques such as point probes as they provide instantaneous velocities that cover the entire water column. This presents opportunities to analyze in great detail various environmental flows. Although PIV has been the more popular of the two techniques the PTV method was chosen to be used in this study as it presented such benefits as cost and accessibility over PIV. Additionally, Cowen and Monismith (1997) proposed that PTV offers significant advantages in accuracy over traditional PIV methods.

In short, PTV involves capturing illuminated particles seeded in the flow using digital video images and processing video frames in order to track each particle between frames. This is where the difference between the methods lie as PIV uses the cross-correlation of the intensity fields in two consecutive frames (Nokes 2007). Flow fields can then be gained by tracking particles between frames over a known time step. This was done using the computer program *fluidstream* which employs a sophisticated algorithm to ‘best match’ particles between frames. Particle tracking velocimetry (PTV) will be used to
obtain flow fields above each substrate. It involves the 4 steps of image capturing, image processing, particle tracking and velocity field generation.

### 3.2.2 Image capturing

#### 3.2.2.1 Particle selection

Particle selection is vital as to gain an accurate representation of the flow they must replicate the velocity of the fluid particles surrounding (Raffel et al. 1998). A white material used in the rubber manufacturing process called Pliolite resin was used to seed the flow. It has become the standard particle used as it has a specific gravity relative to water of 1.03, is unreactive and spherical in shape.

A broad range of particle densities can be processed using the PTV method although in sparsely seeded flows, particles are more easily tracked between frames (Nokes 2007). As a general rule 2000 particles in the illuminated region at any given time was determined to be a desired amount. To satisfy this value approximately 50 grams of Pliolite was used to seed the entire flume.

Pliolite comes in range of sizes, from a few microns to hundreds of microns therefore sieving was required to obtain a uniform size range to obtain best results. Introducing very small particles to the flow can be difficult as surface tension can have an effect while larger particles have faster settling velocities. The size range that was used was 150µm to 212µm. The response time of particles to accelerations in the flow and settling velocities was deemed to be negligible in this size range.

#### 3.2.2.2 Lighting

A light box with high intensity light from a halogen light source was used to illuminate seeded particles in a 30 cm x 30 cm x 0.5 cm section of the flow shown in figure 3.3. The light box was placed 10cm above the waters surface parallel to the flow. The area of illumination must be free of foreign light as when the particle identification stage takes place it will be mistaken for particles in the flow. This will create errors in the data. Foreign light was eliminated by covering approximately 3 metres either side of the region
in question with black plastic sheeting ensuring there were no gaps. This sheeting can be seen in figure 3.4. Light reflection off the substrates was also found to have an effect on the reliability of the data by creating a lot of noise in the lower region of the flow through the incorrect identification of particles. The substrates were coated with a flat black paint to minimize the reflection of light off them, although this had a profound impact figure 3.3 shows all reflection was unable to be eliminated.

![Figure 3.3](image)

**Figure 3.3** Photo of the illuminated region

### 3.2.2.3 Image capturing

A high resolution (992 by 992 pixels) digital camera was used to capture the seeded particles in a sequence of video frames shooting at a rate of 30 frames per second. 2 minute runs were employed for each flow rate creating a total of 3600 frames for each sequence. This duration was deemed sufficient for meaningful turbulent averages to be obtained. The camera was situated approximately 1.5m metres away from the flume and 350mm by 350mm window filmed. Figure 1 shows the setup of the camera.
3.2.3 Image processing

Images sequences were processed using a computer program called *fluidstream* to identify particles within each frame. For each particle its location, intensity and size must be obtained. This is not a trivial process and requires algorithms designed to minimize incorrect particle identifications that may arise from such things as varying intensities in the light sheet and varying particle size (and thus brightness) (Nokes 2007). There are 3 algorithms within *fluidstream* that may be used, all with their strengths and weaknesses. This study used the Gaussian absolute algorithm which uses variations in the intensity within a particle to determine the particle’s location. It searches for pixels of intensities which are of a local maximum and exceed a set threshold. It then fits a Gaussian distribution to it and if the intensity of the adjacent pixels exceed the distribution, the pixels are determined to be part of the particle provided they are not a local maximum itself, in which case another particle would be identified (Nokes 2007). In each frame once identified the particles are assigned a unique number starting at 0, its position (in

*Figure 3.4* Photo of camera positioning and set up
mm), size (radius in mm) and intensity (an integer value between 0 and 255). Figure 3.5 displays the resulting field from the particle identification process (note particles have been removed in regions in the flow where incorrect particle identification has occurred such as above the substrate and near the surface due to light reflection.

![Particle identifications in the flow using Gaussian’s absolute algorithm.](image)

**Figure 3.5** Particle identifications in the flow using Gaussian’s absolute algorithm.

### 3.2.4 Particle tracking

The centre of PTV analysis is the tracking of particles between frames and this is the most complex aspect. The computer program *Fluidstream* again employs algorithms to determine the best match particles between frames. Challenges may arise as between frames a particle may leave the light sheet, become obscured by another particle or the particle identification process may not identify it (Nokes 2007). Consequently particles can be incorrectly matched or not matched at all therefore it is essential that algorithms are used to optimize the matching of particles to ensure reliability in the data.
To dramatically reduce the number of particles that can potentially be matched to between frames, a search window is employed. As a result a search window can significantly improve process times. It can be defined as a rectangular region in which only particles within it in the following frame can be matched to the particle in the previous (Nokes 2007). The size of the search window must be optimized using trade offs between the process times and accuracy. This is because generally the larger the window the higher the accuracy of particle matching while the process times increase. The size of the search window employed was 40mm by 40mm with the particle being matched situated in the centre in the first frame.

*Fluidstream* offers a large range of algorithms which calculate the costs for each of the potential matches of the particles between frames within the search window. The idea is that the correct match has substantially less cost than all other possible matches. A value known as the maximum matching cost is used to discount any incorrect matches. If the cost of a match exceeds this value it is deemed unreasonable and consequently only correctly matched particles are left (Nokes 2007).

This study employed the adjacency and local velocity algorithms to correctly match particles. The adjacency algorithm relies on matching particle patterns between frames. The degree in which the patterns match determines the cost (Nokes 2007). The local velocity algorithm uses an estimation of the velocity in the search window centered on a particle to predict it position in the next frame. The cost is proportional to the distance between the predicted position and its predetermined position in the next frame (Nokes 2007). As this algorithm requires matches in the subsequent frame it was performed after the adjacency algorithm. This process results in matches subsequently changing due to optimization.

A cleanup process is lastly employed to access the validity of the matches found. This is done using the local velocity algorithm with a low maximum matching cost and in the cases where it is exceeded the matches are simply removed while no more are created (Nokes 2007). In Figure 3.6 the blue lines display the particle matches for three
consecutive frames over the rough limestone. Each particle keeps track of the particles it is matched to in the previous frames. As shown not all particles can be matched within the window.

![Image of particle matches](image)

**Figure 3.6** Particle matches for 3 consecutive frames in the flow over the rough limestone.

### 3.2.5 Velocity field calculation

Once the particle matching process was completed the velocity of each particle, in each frame was calculated. Provided that the particle has a match in the previous or subsequent frame its velocity can be estimated by using the displacement of the particle between frames that are a known time step apart (Nokes 2007). Because velocities can only be determined at each particle location, the known velocities are at random locations in each frame. To gain the velocity field of the flow, each individual particle velocity must be interpolated onto a regular grid and the particle velocities within the each grid are used to
determine a velocity value for the node of the grid (Nokes 2007). For all velocity fields the grid size used was 10cm by 10cm, therefore 1296 nodes are located within the 350mm by 350mm window of the flow. Figure 3.7 shows an instantaneous velocity field for flow above the rough limestone. At each node a velocity vector is evident except within the grids where particles have not been matched.

![Instantaneous velocity field in the flow above the rough limestone.](image)

**Figure 3.7** Instantaneous velocity field in the flow above the rough limestone.

Once the velocity field is created *Fluidstream* has the ability to generate instantaneous and time averaged flow parameters such as velocity, turbulent stress, and turbulent kinetic energy at each grid point. This allows for detailed analysis of the flow.
4 Results

4.1 Mean velocity profiles

Figure 4.1 Mean horizontal velocity profile $u(\text{height})$ for the model canopy (dowels), rough and smooth limestone.

Profiles of the mean longitudinal velocity ($u(\text{height})$) for the rough and smooth limestone and the model canopy are shown in figure 4.1. It’s worth noting that the profiles don’t extend fully to the bottom interface or to the surface due to noise in the PTV data at these locations which can largely be explained by light reflection contributing to incorrect particle identification in the flow. These problems are evident in the velocity profiles near the surface where unexpected sharp declines in the rough and smooth profiles occur. Data from this region will be discounted from the analysis. In addition, data from 10mm directly above the porous limestone surface (height = 30-40mm) and 40mm at the bottom of the model canopy (height = 0-40mm) was discounted by deleting identified particles in the regions. Essentially a very important part of the flow is excluded from analysis.
It also must be noted that the flow rates over all 3 substrates vary slightly as they influences many properties of flow. Averaging the horizontal velocities for the regions of flow left, give rough estimations of -44, -40 and -33mm/s for the flow rates over the rough and smooth limestone and model canopy respectively. The variations in velocity are visually evident between the smooth and rough limestone’s as at all height the velocities in the rough exceed the smooth.

It can be said the smooth and rough profiles show marked similarities in shape. Both adhere to the “law of wall” for turbulent boundary layers with a region near the boundary where the velocity varies logarithmetically before reaching a more constant velocity near the surface. The similarities between rough and smooth velocity profiles have also been by found by Reidenbach et al. (1996). This suggests that the velocity profile shape is largely unaffected by roughness. By estimating the boundary layers as the region of strong gradient it is shown that the boundary layer thickness extends to a similar height in both cases. Despite the similarities in the mean velocity profile it is inadequate to suggest that roughness has no effect on the overall structure of the flow as surface geometry has been shown to significantly affect the turbulent characteristics of the flow (Krogstad and Antonia 1999), therefore further flow properties need to be analyzed.

The model canopy produces a distinctly different profile to that of the limestone surfaces. Its most important feature is the inflection point in the profile located near the top of the canopy (height = 90mm). Furthermore reductions in velocities are evident in the flow within the canopy (height < 90mm) as a result of drag from the. By extrapolating the profile into the region of no data (height < 40mm) it can be assumed that in-canopy flow becomes relatively uniform. Above the canopy (height > 90mm) the profile reverts to a relatively logarithmic profile (Nepf and Vivoni 2000) similar to those found over the rough and smooth limestone, however the region of strong gradient is less steep and extends to the surface. Therefore it can be concluded that the model canopy has a profound influence on the mean velocity profiles of flows with respect to ordinary boundary layer flow and the complete profile is markedly similar to a mixing layer profile rather than a boundary layer.
4.2 Spectral analysis

Figure 4.2 Spectra of vertical velocity in various points of the flow on a log scale for (a) model canopy, (b) rough limestone and (c) smooth limestone.
Frequency spectra are the main avenue for investigating the structure of turbulence. Turbulence in surface boundary layer is comprised of a variety of eddies ranging in sizes which contribute to variations in the streamwise velocities. Spectral information provides a way of examining the contribution of different frequencies to the observed velocity variations. The idea is to examine oscillations in the streamwise velocity to determine the frequencies of perturbations embedded in the flow from coherent structures. Given momentum transport in flows is dominated by large coherent vortices when they exist, there structure is far more relevant to vertical transport than fine scale turbulence.

Typically, in canopy flow oscillations in streamwise velocities result from continuous stream of coherent vortices progressing downstream (Ghisalberti and Nepf 2006). In Section 4.1 it has already been established that vortices will develop within the model canopy due to the presence of an inflection point in the mean velocity profile near the top of the canopy. Additionally, embedded tornados like vortices with a variety of strengths are known to exist in the boundary layers (Robinson 1991). Spectral analysis is a vital tool in determining the frequency of such motions.

Figure 4.1(a), (b) and (c) shows the spectra of the streamwise vertical velocities in various points above the bottom (y) for the model canopy, rough and smooth limestone respectively. Figure 4.1(a) shows distinct peaks in the spectra for all points. This was to be expected as all points were located within the region of strong gradient presented in section 4.1 meaning all points lie within the shear layer. While points at y = 80, 90 and 150mm all display a common peak frequency (fp ≈ 0.11Hz), y = 110mm shows only a minor difference (fp ≈ 0.14Hz). The similarities in all these values support the notion that the location of the spectral peaks does not vary strongly with height in the upper canopy and just above the canopy (Ghisalberti and Nepf 2006). Additionally the frequencies match vortex frequencies of 0.11Hz previously found (Ghisalberti and Nepf 2002). It can therefore be concluded that the peak frequencies determined from the spectra correspond to the oscillations in the streamwise vertical velocities from coherent vortices. It’s also worth noting that spectral densities are reduced for points y = 80, 150mm with respect to
y = 90, 110mm. This indicates that there less coherency in the flow in the canopy and away from the top of the canopy.

Figure 4.2(b) also displays distinct peaks in the spectra for velocities over the rough limestone, with peak frequencies of similar magnitude for all points measured. A peak frequency of (fp ≈ 0.11Hz) was both recorded for y = 60 and 130mm, furthermore it was found to be of a similar magnitude at y = 50 (fp ≈ 0.09Hz). As most of the contributing coherent motions in a turbulent boundary layer may be characterized as vortex or shear (Robinson 1991) it can be argued the peak frequencies to correspond to the vortex frequencies. The similarities in peak frequencies at various positions in the flow suggest that coherent motions exist not only in the regions of strong gradient in the boundary layer (y = 50 and 60mm) but also in the regions of lower gradient in the outer proportions of the boundary layers (y = 130mm). Furthermore the peak frequencies are of strong agreement with the frequencies for the model canopy with all falling within a range of 0.09-0.14Hz. It is worth noting that the spectral density value is of an order of magnitude lower than the model canopy which suggests that there are fewer coherent motions over the rough surface. This could be explained by the dependence on local conditions for vortex generation causing random variations in the vortex strengths and intermittency (Robinson 1991).

The spectrum for the smooth limestone shows clear dissimilarities to the rough and model canopy. Figure 4.2(c) shows that the spectra density decays with increased frequency with no clear peaks for all points in the flow. This indicates that turbulent motions in the flow were purely random with no coherent motions in the flow. It can therefore be concluded that no vortex structures exist in the flow over the smooth limestone.
4.3 Turbulent kinetic energy

One measure of the turbulent kinetic energy (TKE) of the flow is the intensity of the turbulence (Tennekes and Lumley 1972), therefore by calculating the TKE in the flow we can quantify the amount of turbulence. Figure 4.3 shows the 2-D vertical profile of the mean TKE per unit mass in the flows over the three substrates.

At the top of the vegetative canopy a strong velocity shear and increased turbulent intensities have been found as a result of drag (Gambi et al 1990). Figure 4.3 shows the TKE is a relative constant maximum above the canopy in the region (height = 100 – 170mm). As the turbulence is dominated by vortices near the canopy this was to be expected and was previously found by Ikeda and Kanazawa (1996) This region corresponds to the lower region of the shear layer and is above the inflection point in the mean velocity profile. At heights above this region the TKE decays linearly while below the same can be said. The region of a constant maximum followed by regions of decay indicates that the vortices have greater strength throughout a region above the canopy. As this region is found above the canopy and the TKE decays noticeably from it to the...
canopy at (height = 90mm) it can be stated that the vortex centre is located away from the top of the canopy where the TKE is maximum. Below the canopy the linear decay of TKE continues until (height = 50mm) where it appears to become relatively constant. The turbulence at this height is significantly less than above the canopy which can be explained by the reduction in velocities.

For flow over the limestone substrates a significantly different profile is evident to the model canopy. Firstly, both the smooth and rough profiles decayed away from the boundary and become relatively constant above (height = 100mm). This is to be expected as a low gradient was found in the velocity profile for (height > 100mm). In addition, the near-wall region is the source for nearly all of the turbulent kinetic-energy production in a boundary layer (Klebanoff 1954). This makes it the most important region of the flow in terms of turbulence; unfortunately data in this region is absent. Additionally, turbulence intensities for a large part of the flow (height > 100mm) are significantly less than for the model canopy. This would be primarily due to the increased magnitude of the shear stresses for the model canopy. It could also be argued that the higher turbulent intensities for the rough limestone compared with the smooth would have not only been a product of a slightly higher flow rate but also from increased shear stresses due to the increase roughness scale. Furthermore the coherent motions that were found over the rough limestone but not over the smooth are thought by many to be the central elements in the turbulence-production cycle (Robinson 1991) could have also contributed to the increase.
4.4 Turbulent shear stress

![Graph showing turbulent stress profile for smooth and rough limestone and model canopy.](image)

**Figure 4.4** Turbulent stress profile for the smooth and rough limestone and model canopy.

The time averaged turbulent shear stress per unit mass profiles for the rough and smooth limestone and model canopy are shown in figure 4.4 where the turbulent shear stress is calculated using the negative correlation between the fluctuating velocity components. Effectively it is a measure of the vertical momentum transport, therefore it can give valuable incite into vertical transport in flows.

For the flow over the model canopy the turbulent shear stress were largest near the top of the canopy as found by Finnigan (2000). The stresses were largest in the (height = 100 to 200mm) region. This corresponds to much the same region that the TKE was a maximum. The location directly above the canopy of this region indicates that the vertical exchange of momentum is dominated by coherent vortices which were found to exist in section 4.2. A local minimum is observed at (height ≈ 130mm) which could possibly correspond to the average position of the vortex centre on the basis of the symmetry the
profile shows above and below this height, however further investigations would need to be made to confirm this theory. Above the region of maximum stress (height > 200mm) a relatively linear decline in the stress to zero at near the surface occurs as the influence of the vortices reduces with height in the water column.

Below the region of maximum stress, most momentum is absorbed near the canopy top as found by Amiro (1990). This is evident through the rapid reduction in the profile towards zero between (height = 100mm to 50mm). As shown previously the velocities and TKE are reduced within the canopy with respect to above leading to a reduction in the turbulent diffusivity within the canopy (Raupach and Thom 1981).

As to be expected the profile is significantly different for the limestone surfaces. Figure 4.4 shows that the mixing of momentum is considerably larger for the model canopy due to the development of large coherent structures which dominate vertical transport. Although these structures were also shown to develop over the rough limestone there contribution to the vertical transport is reduced with respect to the model canopy. This can largely be explained by there intermittent generation and smaller size over the rough limestone.

Although the shapes of the profiles are relatively similar for the smooth and rough limestone with both being characterized by a linear decline with height in the water column to zero at the outer edge of the boundary layer, the magnitude is higher for the rough. This can be explained by a slightly higher flow rate and the formation of coherent motions above the rough but not the smooth which are thought by many to be the central elements transport of momentum between the inner and outer layers (Robinson 1991). It has previously been found that turbulent shear stresses are constant in the near-wall region (Tennekes and Lumley 1972). There is slight evidence of this occurring around (height = 50mm), however due to the lack of data within this region it can not be stated with any confidence.
### 4.5 Vertical length scales

![Graph showing vertical length scales](image)

**Figure 4.5** Vertical length scales for various heights in the water column for the rough limestone and model canopy.

The autocorrelation function measures how well correlated future velocities are with the current value (Raupach *et al* 1996). This means that the it is expected to be well correlated with its original velocity for short times, while tending to zero for large. The length over which the velocities are well correlated corresponds to the size of the largest eddies (Raupach *et al* 1996). By taking the integral of the autocorrelation function for streamwise vertical velocities, an effective means of estimating the largest vertical turbulent length scales in the flow results when multiplied with the streamwise horizontal velocity and the frequency the velocities are sampled at. These length scales are important as they draw energy from the mean flow and then dictate the rate of dissipation of this energy. They are also represent the size of the dominant eddies of the coherent motions responsible for vertical transport (Raupach *et al* 1996).
Figures 4.5 shows the vertical length scale determined for both the model canopy and rough limestone for various points where coherent motions were found to exist. It should be noted that over the smooth limestone no correlation was found between original and future velocities, therefore no vertical length scales were derived.

The vertical length scale in flow over the model canopy displays a clear peak at (height = 110mm) which also corresponds to a point in the region of highest TKE and turbulent shear stress in the flow. If the vertical length scale found in the flow corresponds to how well correlated future velocities are with the current value it can be said that the coherency in the turbulent motions is greatest in this region of the flow. As the largest length scales should occur within the vortex centre a peak at (height = 110mm) means that the mean vortex centre should be found in close proximity to it. Clear declines are evident in the length scales away from this region, higher in the shear layer (height = 150mm) as well as below (height = 100mm). It may be said that the declines correspond to the displacement from the mean vortex centre. At the top of the model canopy (height = 90mm) the length scale is of similar magnitude to height/3 as previously stated (Raupach et al 1996). This length scale decreases in the canopy as evident at (height = 80mm) this was to be expected as within the canopy as the influence of vortices is reduced.

In general vertical length scales shows obvious reductions at all heights in the flow over the rough limestone when compared with the model canopy except for (heights < 90mm) where length scales are reduced within the canopy. The overall reductions can be accounted for by the differences in the order of magnitude of the roughness scales between the two substrates creating larger turbulent eddies that result in higher vertical transport for the model canopy. Although a slight increase is evident at (height = 60mm) in general, the length scales over the rough limestone decline away from the surface interface. This is evident in the region (height ≥ 50mm). This is due to vortices being formed at the wall boundary.
5 Discussion

The following section contains a discussion of the results. Section 5.1 discusses the altering of flow by vegetation. Section 5.2 discusses the penetration of vortices into the canopy. In section 5.3, the mean position of the centre of the vortex was estimated. Section 5.4 discusses the affect of surface roughness on flow and finally in section 5.5, the structure of vortices above different orders of roughness scales is discussed.

5.1 The altering of flow by vegetation.

In all the flow properties presented there are significant differences between the model canopy and the two limestone substrates. As a result the presence of vegetation was shown to alter flow properties dramatically. Firstly, significant differences were evident in the mean velocity profiles, with flow over both the smooth and rough limestone resembling typical boundary layer flow, while the model canopy resembled a mixing layer profile. Due to the reduction in flow velocities within the canopy leading to the redirection of the flow above, an inflection point was found to exist near the top of the canopy which is considered to be the most important characteristic of a mixing layer. This is because it is recognized that shear flow becomes unstable and large coherent vortices form via Kelvin-Helmholtz (K-H) instabilities if the vertical profile of the flow velocity has an inflection point (Raupach et al. 1996; Ikeda and Kanazawa 1996; Ghisalberti and Nepf 2002).

The formation of these large coherent structures in the canopy flow contributed to dramatically altering the TKE and turbulent stress profiles in the flow. With respect to the boundary layer flows, TKE and turbulent shear stresses were significantly more for flow near the top and above the canopy while at lower regions of the flow within the canopy the turbulence was reduced as a result of the reduction in velocities. Overall, turbulence and the vertical momentum transport in the flow above and near the top of the model canopy was as much as an order of magnitude larger than the limestone surfaces corresponding to a significant increase in vertical transport.
5.2 The penetration of vortices into the canopy

The depth of penetration of turbulent shear stress into the canopy is a measure of the depth that vortices penetrate the canopy (Ghisalberti and Nepf 2002). If the vortex penetration distance corresponds to the point at which turbulent shear stress becomes negligible the vortices in the flow can be assumed to penetrate 40mm into the canopy. This separates the canopy into an exchange zone (height = 50 to 90mm) where vertical transport is dominated by vortices and a wake zone (height = 0 to 50mm), limited to small-scale turbulence generated in stem wakes (Ghisalberti and Nepf 2006). Therefore as previously found in dense canopies by Ghisalberti and Nepf (2005), it can be stated that the vortices do not extend all the way to the bed and vertical transport in the wake zone is an order of magnitude lower than the exchange zone. As a result, conditions within the canopy support rapid sedimentation and promote particle retention by reducing bed stresses. This creates a depositional environment where pollutants such as heavy metals can be removed from the water column, thereby increasing water quality.

5.3 Mean position of the centre of the vortex

When looking at all the flow properties for the model canopy as a whole there is overwhelming evidence that the mean position of the vortex centre exists above the canopy at approximately some position within (height = 100 to 150mm). This is because a clear pattern emerges of peaks in the vertical length scale, turbulent shear stress and TKE occurring within this region. In addition each peak displays clear declines both above towards the surface and below to the canopy. As it is reasonable to assume approximate vortex symmetry about its centre the declines can be thought to correspond to displacement from the mean vortex centre. The declines also show that the strength and influence of the vortices declines away from their centre.
5.4 The affect of surface roughness

Although strong similarities exist in the mean velocity profiles between flows over the smooth and rough limestones, further analysis of flow properties show considerable differences. Through spectral analysis coherent motions were found to exist in flow over the rough surfaces but not the smooth. This can be explained as in flows over rough surfaces, instantaneous inflectional velocity profiles are common near the wall and may "roll up" into vortices (Robinson 1991). It therefore can be argued that roughness play a vital role in forming instantaneous inflectional velocity profiles that create instabilities in the flow which produce vortices.

Although similarities exists between the smooth and rough with the decay of both the TKE and turbulent stress profiles away from the surfaces, the turbulence and turbulent shear stresses are slightly higher in the flow over the rough. This increase can be explained by the presence of coherent motions over the rough limestones which are thought by many to be the central elements in the turbulence-production cycle and also in the transport of momentum between the inner and outer layers (Robinson 1991).

Replenishment of food sources to reef organisms depends upon turbulent mixing near the reef (Genin et al 2002) and vertical transport. Due to the increased levels of turbulence and momentum transport over the rough limestone it has been found that food replenishment to benthic organisms will be greater inflows over rougher reefs. This means that food availability is a function of the roughness of the reef.

5.5 The structure of vortices above different orders of roughness scales

Despite the model canopy’s roughness scale being an order of magnitude larger than the rough limestone, through spectral analysis it was determined that peaks frequencies corresponding to the coherent motions in the flows were similar for both. With a large degree of uncertainty it can be suggested that the frequency of the coherent motions were
not dependent on the order of roughness scale, however this statement would require further analysis to have any substance.

It was also found that the spectral densities for the rough limestone were an order of magnitude lower than the model canopy. This discrepancy can be explained by the dependence on local conditions at the surface of the rough limestone to produce instantaneous inflectional velocities for the formation of vortices to occur. This results in an intermittent generation of vortices rather than a constant stream which is found in canopy flows.

Furthermore it can be argued that the scale of the vortices for the two substrates vary an order of magnitude. From the mean velocity profile for the canopy flow, the mixing layer thickness is shown to extend near the surface. As mixing layer thickness is strongly linked to the size of the vortices, the size of the vortices can be considered to take up a large proportion of the water column. In contrast vortices are known only to exist within a small proportion of the boundary layer. Using the point (height = 130mm) it can safely be assumed that the size of the vortices are an order of magnitude larger in the canopy flow. The reason for this is that although coherent motions were found to exist via spectra analysis at this point, a glance at the vertical length scale shows that they are of very small magnitude. This notion is further supported by the reduction in the vertical length scales determined at all other points (height = 50, 60 and 90) for the rough limestone with respect to above the model canopy.

It has been stated that vortices have previously been found to dominate vertical transport. The regions of maximum TKE and turbulent shear stresses that exist within the shear layer above the canopy further support this notion. Due to the reduced size and intermittent nature of the vortices over the rough limestone, the vertical transport as a result of vortices over the rough surface can be thought to be much less than the model canopy. In addition, vertical length scales, TKE and turbulent shear stresses which all correspond to the magnitude of vertical transport in the flow are of significantly less over the rough surface.
6 Conclusions

With the use of the recently developed PTV method the hydrodynamics above common substrates in the marine environment were studied for unidirectional flow over rough and smooth limestone and a model vegetative canopy in a laboratory flume. As hydrodynamics is important to support the variety of ecological functions valuable information was gained.

It was determined that the presence of vegetation dramatically alters the flow by creating an inflection point in the mean velocity profile. The presence of this inflection point resulted in the flow becoming unstable forming large coherent structures called vortices. It was these structures that dominated vertical transport within a shear layer, where the shear layer extended from the surface to the distance the vortices penetrated into the canopy. Furthermore beneath the penetration distance conditions were deemed to result in a depositional environment due to a reduction in flow velocities and turbulence. It was also determined that the mean position of the centre of the vortices lied in a region above the canopy in where turbulent shear stress, TKE and vertical length scales were of a maximum.

Despite mean velocity profiles over the rough and smooth limestone being similar in shape, further analysis showed that the roughness had significant influence on turbulent motion. Similar instabilities to those found for the vegetative flow were shown to form coherent motions over the rough limestone albeit intermittently and of smaller size. The presence of these motions was determined to result in vertical transport being larger in the flow over the rough limestone compared to smooth.
7 Recommendations

The importance of hydrodynamics to aquatic vegetation and the importance of vegetation to the marine ecosystem due to the ecological functions they provide are talked about within this study. The findings of this study should be taken into account when determining the best means of revegetation and protection to reduce the current rate of decline seagrasses throughout the world.

This study showed that the PTV method is a valuable tool in analyzing environmental flows and it is recommended that it be used frequently in the further studies of similar note. It is recommended however, that the methods presented in this study be further refined to produce better results. As the major contributor to the loss of valuable data in the near-wall region over the limestone substrates was found to be from light reflection off particles that had settled on the substrates, it is recommended that salt be added to all flows to make the particles neutrally buoyant. It is also recommended that camera quality be improved to allow for the study of faster flow rates.

It is recommended that further investigations be made to the scale of roughness to determine whether the frequencies of coherent motions are independent on the magnitude of roughness. Oscillatory flow also needs to be investigated as most coastal regions are influenced by wave action.
References


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