Hydrodynamic Effects of Surface Piercing Plants

by

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S.B. Ocean Engineering
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Submitted to the Department of Civil and Environmental Engineering
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Submitted to the Department of Civil and Environmental Engineering on June 29, 1994 in partial fulfillment of the requirements for the Degree of Master of Science in Civil and Environmental Engineering

Abstract

Under a variety of circumstances creeks and rivers overtop their banks and inundate the surrounding land and flora. The inundated flora become arrays of flow obstructions, dramatically changing the characteristics of the local flow. This thesis describes a laboratory study of the effects of flow obstructions on the velocity and turbulence profiles within the obstructions. The flow in three plant densities was modeled with a pump driven current and wooden dowels in a laboratory flume. It was found that the major effect of increasing plant density was to significantly increase the horizontal and vertical turbulence. This is due predominantly to wake interaction, and the overall increase in the number of wakes producing strong lateral shears. In addition, pressure forced vertical velocities were measured just upstream and downstream of individual array elements, and these vertical velocities are swept into the main flow as the turbulence levels increase. The increased turbulence mixes momentum downward, and compresses the boundary layer to approximately 0.5 cm, which is 1/16 of the boundary layer thickness in the approaching free-stream.

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# Table of Contents

Abstract 2

Acknowledgments 3

Table of Contents 4

List of Figures 6

List of Tables 7

1 Introduction 8

2 Experimental Facilities and Methods 15

2.1 Flume and Current 15

2.2 Model Plants 17

2.2.1 Wake Theory 18

2.3 Measurement and Analysis 25

2.3.1 Velocity Measurement 25

2.3.2 Positioning 28

2.3.3 Velocity Analysis 30

2.3.4 Error Analysis 33

3 Results and Discussion 52

3.1 Single Dowel Phenomenon 52

3.1.1 Observations 52

3.1.2 Theory 54

3.2 Low Density Results 56
3.3 Medium Density Results
3.4 High Density Results
3.5 Comparison of Densities
3.6 Proposed Explanation

4 Conclusions and Recommendations
4.1 Conclusions
4.2 Recommendations for Further Study

References
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flume Setup 37</td>
</tr>
<tr>
<td>2</td>
<td>Wake Profiles at U = 3 cm/s 38</td>
</tr>
<tr>
<td>3</td>
<td>Wake Profiles at U = 12 cm/s 39</td>
</tr>
<tr>
<td>4</td>
<td>Determination of C₁ from Centerline of Experimental Data 40</td>
</tr>
<tr>
<td>5</td>
<td>High Density Arrangement 41</td>
</tr>
<tr>
<td>6</td>
<td>Medium Density Arrangement 42</td>
</tr>
<tr>
<td>7</td>
<td>Low Density Arrangement 43</td>
</tr>
<tr>
<td>8</td>
<td>Beam Convergence 44</td>
</tr>
<tr>
<td>9</td>
<td>Medium Density Mass Balance Estimate of Velocity Inside Dowels 45</td>
</tr>
<tr>
<td>10</td>
<td>High Density Mass Balance Estimate of Velocity Inside Dowels 46</td>
</tr>
<tr>
<td>11</td>
<td>Laser System 47</td>
</tr>
<tr>
<td>12</td>
<td>Fringe Theory 48</td>
</tr>
<tr>
<td>13</td>
<td>Positioning Systems 49</td>
</tr>
<tr>
<td>14</td>
<td>Analysis of Flow Areas 50</td>
</tr>
<tr>
<td>15</td>
<td>Vertical Velocity Profile, No Dowels 82</td>
</tr>
<tr>
<td>16</td>
<td>Lateral Velocity Profile, No Dowels 83</td>
</tr>
<tr>
<td>17</td>
<td>Observed Flow 84</td>
</tr>
<tr>
<td>18</td>
<td>Single Dowel Measurements - Velocity 85</td>
</tr>
<tr>
<td>19</td>
<td>Single Dowel Measurements - RMS Velocity 86</td>
</tr>
<tr>
<td>20</td>
<td>Varying Density Measurements - Velocity 87</td>
</tr>
<tr>
<td>21</td>
<td>Varying Density Measurements - RMS Velocity 88</td>
</tr>
<tr>
<td>22</td>
<td>Horseshoe Vortex 89</td>
</tr>
<tr>
<td>23</td>
<td>Coefficient of Pressure Variation 90</td>
</tr>
<tr>
<td>24</td>
<td>Vertical Velocity Forcing 91</td>
</tr>
<tr>
<td>25</td>
<td>Low Density Lateral Profiles 92</td>
</tr>
<tr>
<td>26</td>
<td>Low Density Vertical Profiles 93</td>
</tr>
<tr>
<td>27</td>
<td>Low Density Vertical Profiles - Positions 2 and 4 94</td>
</tr>
<tr>
<td>28</td>
<td>Low Density Vertical Profiles - Positions 1, 3 and 5 95</td>
</tr>
<tr>
<td>29</td>
<td>Range of U* Estimates for Each Position - Low Density 96</td>
</tr>
<tr>
<td>30</td>
<td>Positions with Shedding Peaks 97</td>
</tr>
<tr>
<td>31</td>
<td>Medium Density Lateral Profiles - Longitudinal Velocity 98</td>
</tr>
<tr>
<td>32</td>
<td>Medium Density Lateral Profiles - Vertical Velocity 99</td>
</tr>
</tbody>
</table>
Figure | Page
--- | ---
33 Medium Density Vertical Profiles - Velocity | 100
34 Medium Density Vertical Profiles - Turbulence Intensity | 101
35 Medium Density Vertical Profiles - Positions 1, 2 and 4 - Velocity | 102
36 Medium Density Vertical Profiles - Positions 1, 2 and 4 - Turbulence Intensity | 103
37 Medium Density Vertical Profiles - Positions 3 and 5 - Velocity | 104
38 Medium Density Vertical Profiles - Positions 3 and 5 - Turbulence Intensity | 105
39 Range of U* Estimates for Each Position - Medium Density | 106
40 High Density Lateral Profiles - Longitudinal Velocity | 107
41 High Density Lateral Profiles - Vertical Velocity | 108
42 High Density Vertical Profiles - Velocity | 109
43 High Density Vertical Profiles - Turbulence Intensity | 110
44 Range of U* Estimates for Each Position - High Density | 111
45 Comparison of Lateral Profiles - Velocity | 112
46 Comparison of Lateral Profiles - Turbulence Intensity | 113
47 Comparison of Vertical Profiles - Velocity | 114
48 Comparison of Vertical Profiles - Turbulence Intensity | 115
49 Comparison of U* Estimates | 116
50 Comparison Across Densities - Position 4 - Velocity | 117
51 Comparison Across Densities - Position 4 - Turbulence Intensity | 118

List of Tables

Table | Page
--- | ---
1 Comparison of Area Estimation Methods | 33
2 Velocity Distribution | 51
3 Estimated Errors | 36
1 Introduction

Under a variety of circumstances creeks and rivers overtop their banks and inundate the surrounding land and flora. Tidal marshes and river flood plains are two regions where this is likely to happen. In tidal marshes, diurnal flooding tides cause creeks to overflow into marshes dominated by grasses, such as *Spartina alterniflora*. In riverine situations, storms and spring runoff may cause flooding on a much less regular basis. The inundated grasses of the marsh and the trees on the riverine flood plains become arrays of flow obstructions which dramatically effect local flow structure.

The aim of this laboratory study was to explore some of the changes in the local flow produced by the flow obstructions in a controlled environment. Specifically, the effects of plant density on velocity and turbulence structure were examined. Horizontal and vertical flow components were measured in three densities of model plant arrays. It is hoped that the results may be used to parameterize the effects of plant density in regions of flooded flora in future modeling efforts.
The fate and transport of nutrients and pollutants are frequently modeled in attempts to predict and understand their impact on the ecosystem. The accuracy of these models is dependent on the parameters used to represent dispersion and mixing in the flow. Areas of submerged plants pose a particular problem for modelers, because little work has been done to characterize flow in these areas. Local dispersion and mixing characteristics of mass, momentum and energy also affect the microenvironment experienced by aquatic plants. Nutrient uptake and gas exchange by plants are strongly affected by local turbulence levels, and the plants themselves are often the largest contributor to the turbulence. Anderson and Charters (1982) found that *Gelidium nudifrons*, an aquatic plant composed of closely spaced rodlike branches, suppresses ambient turbulence while generating microturbulence via wake vorticity from its individual branches. While the morphology of *S. alterniflora* differs substantially from that of *G. nudifrons*, we still expect similar turbulence production due to the presence of plants.

Field experiments in the atmospheric boundary layer have been conducted to explore the effects of obstructions in the boundary layers. Plate and Quraishi (1965) investigated the velocity distributions inside and above crops. Their research was performed both in the field and laboratory, where they used flexible plastic strips and wooden dowels to model the crops. Their laboratory results indicate that the flow within the roughness elements is considerably three dimensional. The three dimensional effects are determined by the spacing and arrangement of the roughness elements. Consistent with these observations, they found that the velocity profile inside a plant cover is strongly
dependent on the plant type, while the velocity profile above the plant cover is well represented by a logarithmic law.

In his study of momentum absorption by vegetation, Thom (1971) measured the wind profiles within and above an artificial crop, and the drag on individual elements of the crop. His results indicated that the drag on an individual crop element in the array could be calculated from the coefficient of drag on an isolated element, and the wind profile within the array. However, the total drag, or momentum absorption, on the vegetated surface cannot be found by integrating over the entire surface because of a sheltering effect by the elements on one another. Thus, the wind profile measured between elements did not represent the profile experienced by an individual element, and an additional factor, constant for a given crop, was needed to parameterize total drag.

In 1992, Raupach explored the partition of drag between the roughness elements and the underlying substrate in a model plant array. Raupach defined an effective shelter area and volume for the roughness elements to address the effects that the bottom boundary has on the roughness element wake. He found that once the frontal area per unit ground area, $\lambda$, is greater than 0.03 to 0.1, the drag due to the surface is negligible. However, his results hold only for roughness elements with aspect ratios, $b/h$, close to 1, and do not consider surface piercing plants ($b/h >> 1$) as do the experiments presented here.
The experiments by Plate and Quraishi (1965), Thom (1971), and Raupach (1992) indicate a need for experiments which further detail the flow within roughness elements. Plate and Quraishi (1965) note the three dimensionality of the flow within arrays, but it is uncertain whether these three dimensional effects are caused by the interaction of the elements with the free stream above the elements; by the effects of the bottom; or by some other process. Flow obstructions which pierce the surface will eliminate any effects of the free stream above the elements, allowing us to examine the interactions between the obstructions and the bed. Raupach (1992) acknowledged the effects of the bottom on the wakes in defining an effective shelter area and volume. He also determined the partitioning of drag between the roughness elements and substrate. However, his results do not illustrate the effects of the bed on the velocity profile within the array, and are restricted to elements with aspect ratios close to 1. With elements with aspect ratios of 24, the experiments presented here can distinguish between the effects from the bed and the obstructions. Thom (1971) found that the velocity profile experienced by an individual element differed from that measured between adjacent elements, and needed an extra coefficient to account for this. By measuring the velocity profile at several locations within the obstruction array, it will be possible to obtain a bulk profile which more accurately represents the velocity experienced by individual elements.

Research in aquatic environments has been performed by Eckman (1983), and El-Hakim and Salama (1992). Eckman (1983) studied the effects of marsh grass on the benthic recruitment of animals. Measurements in the laboratory were taken so that the
mechanics of the flow around the model grass would be understood. Straws 0.6 cm in
diameter and 1-2 cm tall were used to model the aquatic vegetation. The results of this
study indicated that the presence of any plants enhances the recruitment of benthic animals
and particles through hydrodynamic effects such as increased bed stress and turbulence.

El-Hakim and Salama (1992) conducted experiments in a trapezoidal flume on the
effects of submerged grasses on the flow structure. They measured the velocity
distribution inside and above the model grasses. Branched, flexible plastic strips were
used to model the vegetation. As has been found in the atmospheric boundary layer, the
velocity profile within and above flexible roughness elements could not be modeled with a
single equation. Above the roughness elements a logarithmic law was found to be an
appropriate model of the velocity structure, while within the roughness elements a power
law was more appropriate. Our experiments will focus on a simpler flow, with rigid,
cylindrical, surface-piercing obstructions. By understanding the dynamics of this basic
arrangement we can put results from more complicated obstructions into context.

One effort to model flow in taller, simpler obstructions was undertaken by Burke
in his 1982 thesis. Burke’s aim was to model the vertical velocity variations within the
obstructions given the free surface variation and wind stress forcing. Field experiments in
tidally inundated marshes were performed to calibrate the model. In the field
experiments, the marsh grasses, such as _S. alterniflora_, often protruded through the free
surface. He found that the turbulent kinetic energy of the flow increased for low
vegetation density ($\lambda < 0.1$) but then decreased for further increases in density. In addition, Burke found that turbulence generated by plants dominates the flow for $\lambda > 0.1$.

As far as the author is aware, Burke’s is the only study which examines flow through obstructions which protrude through the entire water column, although this condition is common in tidal marshes and overrun river banks. This lack of basic understanding in this common environmental flow condition motivates the research described here. A simple case of rigid, uniform diameter model plants protruding through the surface was considered to be a good baseline for exploring the effects of obstructions on flow structure. The experiments presented in this thesis detail the velocity and turbulence structure of flow within arrays of these obstructions. It is hoped that these results will form the baseline for other studies which might explore flexible model plants, non-uniform arrays, and the interaction between the flow in the obstructed and unobstructed regions of flooded channels.

The goal of these experiments is to explore the effects of plant population density on velocity and turbulence intensity. Three plant densities in addition to the null case were selected. The criteria for the design of the three densities are described in Section 2.2. For all plant population densities the bulk flow was 6 cm/s, and five vertical profiles were measured. The locations of the vertical profiles were chosen so that a variety of flow conditions would be sampled at each density (see Section 2.2 and Figures 5-7). With knowledge of the flow conditions at several locations a bulk profile could be created by
averaging the data. Section 2.3.3 details the distribution of the profile locations at each density, and the methods used for the bulk averaging. The results will be discussed in Chapter 3. Chapter 4 presents the conclusions and recommendations for further study.
2 Experimental Facilities and Methods

2.1 Flume and Current

The experiments described in this thesis were conducted at the Parsons Laboratory at MIT, in a glass-walled flume measuring 38 cm wide, 60 cm deep and 24 m long, pictured in Figure 1. The coordinate axes are oriented such that the x-axis is parallel to the long axis of the flume with the positive direction pointing downstream. The y-axis is perpendicular to the long axis of the flume and is positive pointing away from the measurement system (into the page). The z-axis is parallel to gravity and is positive upwards from the dowel base.

A recirculating current was generated by a Weinman model 3G-181 pump. An Asahi diaphragm valve in the return piping was used to control the flow velocity in the flume. The linearity of this valve allowed flow rate adjustments with a resolution of 5 gpm, or velocity adjustment resolution of 0.5 cm/s, at the experimental water depth. A paddle wheel flow gauge was installed 2 m from the valve to monitor the flow rate.
The inlet pipe released water into the center of the flume approximately 1 m from the upstream end. A piece of rubberized coconut fiber 38 cm wide, 60 cm long and 5 cm thick was placed beneath the inlet to reduce the turbulence. Flow straighteners were placed in series 3.5 m downstream of the inlet. This distance was experimentally determined to produce the most uniform flow conditions in the test section. The flow straighteners were made of extruded plastic cylinders 1.9 cm in diameter with a wall thickness of 0.8 mm. Each of the two straighteners was 38 cm wide, 46 cm long and 15 cm tall. As the maximum eddy size scales on the flow width and depth, these dimensions were chosen to maximize the flow straighteners' effectiveness.

For these experiments, the flow straighteners were placed on a Plexiglas false bottom. As will be described in Section 2.2 the plants were modeled by wooden dowels which were fixed in place in a Plexiglas sheet. To remove any discontinuity in the bottom in the test section due to this dowel base, the entire test section was raised on 1.26 cm thick Plexiglas. Three pieces of 38 cm wide, 120 cm long, 1.26 cm thick Plexiglas were laid on the bottom and the three pieces were connected by 5 cm long, 0.6 cm diameter stainless steel rods inserted into holes drilled into the ends of the Plexiglas. This arrangement allowed the three pieces to be aligned both vertically and laterally in the flume.

The downstream edge of the flow straighteners was aligned with the downstream edge of the upstream piece of Plexiglas. This allowed the flow to enter the Plexiglas...
bottomed region before entering the flow straighteners. The middle piece of Plexiglas was left bare as a spacer between the flow straighteners and the dowel section. The downstream piece of Plexiglas had an array of 0.6 cm holes drilled in it to hold the dowels. The design of this piece will be described in Section 2.2.

2.2 Model Plants

*Spartina alterniflora* was modeled with 0.6 cm diameter hardwood dowels. The diameter was chosen based on actual stalk diameters listed in *Gray's Manual of Botany* (1950) and the *Manual of the Grasses of the United States* (1971). Each dowel was cut to 20 cm long so that it would extend through the entire water column.

The base was designed to be used for three densities of dowels. As the goal was to examine cases with varying degrees of wake interaction, the densities were chosen based on the following criteria:

1) In the low density arrangement, the wakes from the dowels should not interact.

2) In the high density arrangement there should be extensive wake interaction, with every dowel in 3 or more wakes and no region in the plant array unaffected by wakes.

3) The medium density arrangement should represent a middle ground between low and high density. Wakes should interact, but on a limited basis, and each dowel should be in 1 or 2 wakes.
4) At the high density, the flow should be fully blocked when looking downstream; i.e. it should not be possible to draw a straight streamline through the dowel arrangement.

5) Wake extent is determined by 85% recovery of the longitudinal velocity as determined by wake theory (presented in Section 2.2.1).

6) The dowels must not obstruct the laser beams of the LDV system.

2.2.1 Wake Theory

To meet the above criteria it was necessary to determine wake width and flow recovery as a function of distance behind a dowel. Lateral profiles of the longitudinal velocity were made at several locations both in front of and behind a single dowel placed in the flow. These profiles were made for two velocities, 3 and 12 cm/s, so that a comparison of the wakes could be made. These initial experiments were used to choose the testing velocity and dowel configuration for the model plants. Figures 2 and 3 show mean and rms velocity profiles. The velocities in each profile have been offset by their longitudinal position, in centimeters, relative to the dowel which is located at \( x = 0 \). For example, the bottom most profile was measured at 3.6 cm upstream of the dowel, and so it is offset by -3.6 cm/s. The solid line in Figures 2a and 3a is a comparison to wake theory.
\[ \frac{u_1}{u_\infty} = \frac{u_\infty - u}{u_\infty} = \frac{\sqrt{10}}{18 \beta} \left( \frac{x}{C_d d} \right)^{\frac{1}{2}} \left[ 1 - \left( \frac{y}{b} \right)^{\frac{3}{2}} \right]^2 \]  

(1)

where:

\[ C_1 = \frac{\sqrt{10} C_d d}{18 \beta} \]  

(2)

\[ b = \sqrt{10 \beta} \left( xC_d d \right)^{\frac{1}{2}} \]  

(3)

and \( d = \) dowel diameter; \( u_\infty = \) freestream velocity; \( u_1 = \) difference between the freestream and measured velocity, \( u; \) \( C_d = \) coefficient of drag = \( f(R=U u_\infty d \nu) \); \( y = \) lateral position (0 = centerline of dowel); \( \beta = \) proportionality constant between mixing length, \( l, \) and wake width, \( b; \) and \( x = \) distance behind dowel.

Equation 1 was evaluated at \( y = 0 \) to determine the centerline properties of the wake. \( C_D \) was found from the Reynolds number and a plot of \( C_D \) versus Reynolds number (Gerhart and Gross, 1985), to be 1.5 at \( u = 3 \) cm/s and 1.1 at \( u = 12 \) cm/s. The value of \( C_1 \) can be found by comparing the experimental data to Equation 1 written in terms of \( C_1: \)

\[ \frac{u_1}{u_\infty} = C_1 x^{-\frac{1}{2}} \]  

(4)

Figures 4a and b show this relationship for \( u = 3 \) and 12 cm/s. In these cases \( C_1 \) was found to be approximately 0.4 and 0.5, respectively. Equation 2 can then be solved for \( \beta. \)
The value of $\beta$ can then be plugged into Equation 3 to find the wake width $b$ as a function of $x$.

As expected, wake theory does not match these results exactly because the theory is valid for:

$$x > 50C_\alpha d.$$  \hspace{1cm} (5)

In these profiles, wake theory should apply for $x > 48$ cm for the 3 cm/s case and $x > 35$ cm for the 12 cm/s case. Although all of the measurements were taken within 20 cm of the dowel, the theory does converge to within 10\% of the measured profiles of $u$ by approximately $x \approx 6$ cm. Thus we will use wake theory to approximate the width of the wakes to design the dowels base, even in regions that do not meet the criteria of Equation 5.

Figures 5-7 show the dowel bases for the three chosen densities. The high density (Figure 5) was designed first, taking into account design criteria 2, 4 and 5. It is based on a repeating pattern of dowels where adjacent rows are offset by 1.2 cm to create full frontal blockage by the eighth row. The nominal spacing between dowels in a row is 3.2 cm, and between rows is 1.6 cm. The low and medium density arrangements were created by removing dowels in a regular pattern until the appropriate design criteria were met.

The lower right corner of each base plan depicts the approximate wake regions defined by theory and flow visualization. These regions are discussed in more detail in Section 2.3.3. The dowel arrangements have 1, 1.5 and 6\% of the base area covered by dowels in the
Low, medium and high densities, respectively. These base plans were modified in the actual experiments and these modifications will be discussed later in this section.

Longitudinal (u) and vertical (v) velocities were measured in five vertical profiles, as indicated in Figures 5-7. The measurement points in each profile were spaced at 1 cm in the vertical, except near the bottom where two extra points were inserted at approximately 0.2 and 0.5 cm to increase the resolution of the bottom boundary layer. Each point was measured for 100 seconds at a sampling rate between 100 and 500 Hz. The variations in the sampling rate will also be discussed in Section 2.3.3. Four additional traverses were added to explore a velocity minimum observed in the low density vertical profiles. The added profiles were lateral traverses at 0.6, 3 and 10 cm above the bottom at the same longitudinal position as the five vertical profiles, and one vertical traverse within 0.2 cm behind a dowel.

In order to accommodate the LDV system minor adjustments were made to the array near the measurement site. Figure 8 details the beam paths for each of the five measurement points. From this drawing it was decided that the dowels marked a-d would be left out of all three density arrangements, and dowels e and f would be shifted 0.48 cm as indicated. These adjustments had no effect on the low density case, and removed only one dowel from the medium density case. The effects of the removal of these four dowels from the high density case were judged to be small since the actual measurement points were further into the dowel array where the density was unaffected.
To maintain an approximately smooth bottom at all three densities, the empty holes were plugged with RTV silicone rubber. Initially, all holes were plugged so that a profile without any dowels could be made under the same bed conditions as the three densities. The testing proceeded from low to high density so that only the holes that were needed for a particular density were unplugged.

After the dowels for the medium density were added to the flow a lateral oscillation of the surface appeared. The oscillation grew steadily over 15 minutes and then reached a steady-state at which the water surface oscillated about a node in the center of the channel with an amplitude of approximately 1.5 cm. The seiching had a frequency equal to one half the Strouhal frequency associated with the dowels,

$$\omega_f = \frac{Sd}{u} \approx 1.9 \text{ Hz},$$

(6)

where S, the Strouhal number, approximately 0.2 for R = 381, (Gerhart and Gross, 1985). The seiche was caused by phase-locking of the vortex shedding behind the dowels. Vortices shed from a dowel in the leading row would impact downstream dowels and synchronize their shedding. The spacing of the dowels was such that eventually all of the dowels shed vortices at the same time on the same side. This sort of synchronized shedding has been documented before by Williamson (1985). In our experimental setup, the natural frequency of the channel is close to 1 Hz and so the phase-locked shedding forced an harmonic oscillation.
To reduce the amplitude of the oscillations, dowels were removed on both sides of the array to reduce the reinforcing reflection from the sidewalls. Figure 6 shows the array as it was tested (solid circles) superimposed on the array as it was designed. For measurement points deep in the array, it is unlikely that these changes had any effect at the measurement location. However, at the edges of the array there was a strong shear due to the water jetting through the unobstructed regions which may have affected the outermost points (1 and 2), see Figure 6.

The background velocity in the dowels ($u_2$ in Figure 9) was calculated using a mass balance estimate. Velocity measurements were taken across the channel just upstream of the dowel array, $u_o$, and in the gaps on either side, $u_1$ and $u_3$. Below Figure 9 are the equations used to estimate the intra-dowel velocity. Since the intra-dowel velocity was within 5% of that for the low density, no adjustments were made to the pumping rate.

After all the dowels were inserted for the high density case, a lateral seiche again developed to steady-state in 15 minutes. At this density there were two nodes in the seiche, each 1/4 of the tank width from the side. The amplitude was 0.7 cm and the frequency about 1 Hz.

This time removing dowels from both sides was not feasible because it would affect the flow conditions in the testing area too much. The high density conditions required high levels of wake overlap which would have been compromised by removing
the dowels on the near side of the flume. Instead, all of the dowels from one-third of the flume away from the measurement positions were removed, see Figure 5. Because the dowel array presented a formidable obstruction much of the flow was redirected down the unobstructed region. This produced a high velocity jet on the far side of the flume and reduced the flow rate through the dowels. In addition, a high velocity jet formed in the narrow region between the edge of the dowel array and the near side of the flume. The jet on the near side of the tank was effectively stopped by taping dowels to the side of the tank. This was confirmed by dye studies before and after the dowels were inserted. The jet on the far side of the tank could not be prevented, so the total pumping rate was adjusted to ensure the correct flow velocity through the dowels.

A mass balance was again used to estimate the intra-dowel velocity for the high density case. Velocity measurements were made upstream of the array and in the unobstructed region, as shown in Figure 10. The calculated velocity was compared to the velocity inferred from the movement of dye. The velocities compared closely, $U_{mb} = 3.3 \text{ cm/s}$ and $U_{dye} = 3.4 \text{ cm/s}$, and it was decided to use the dye estimate to set the velocity inside the dowel array. The pump valve was adjusted until the velocity estimated from the dye travel time was approximately 6 cm/s.
2.3 Measurement and Analysis

2.3.1 Velocity Measurement

The velocity measurements were taken with a Dantec Inc. laser Doppler velocimeter (LDV). The 300mW blue-green Argon-ion laser was supplied by Ion Laser Technology (ILT). For the medium and high density cases a 2D measurement system was used, and both $U$ (longitudinal) and $W$ (vertical) velocities were measured. For the low density and null cases a 1D system was available, so only $U$ velocities were measured.

As shown in Figure 11, the LDV system consists of a laser, a beam splitter and Bragg cell, a probe and a processor. The laser light is produced by the ILT system and aimed into the Dantec optics. The blue-green beam is first passed through a beam splitter (to produce two blue-green beams), and then through a Bragg cell which shifts one beam with respect to the other. Both the shifted and unshifted beams are then split into blue (488 nm) and green (514.5 nm) beams. The four beams are directed through fiber optic cable to the probe.

Optics in the probe focus the four beams into a measurement volume 76 μm in diameter and 0.64 mm in length. The blue pair define one measurement direction and the green a second, orthogonal, direction. The probe also collects backscattered light from particles passing through the measurement volume. This light is then transmitted via a fiber optic cable to a photoreceptor which detects the bursts of light and converts them
into voltages. The burst patterns are then sent to the Dantec 58N40 Flow Velocity Analyzer (FVA).

**Fringe Theory**

Laser Doppler velocimetry is based on the scattering of light by particles passing through the fringe pattern created by the intersection of coherent laser beams. The fringes are an interference pattern produced when two wave trains cross at an angle $\theta$, as shown in Figure 12. The fringe pattern consists of alternating lines of relative light and dark. The spacing of the fringes, $d_f$, is determined by the frequency of the light, $\lambda$, and the angle between the beams, $\theta$:

$$d_f = \frac{\lambda}{2 \sin \frac{\theta}{2}}.$$  \hspace{1cm} (7)

As a particle passes through these regions of light and dark it scatters light - more when moving through two "crests" and less when moving through two "troughs." The sequence of strong and weak scattered light detected by the photoreceptor is a "burst." The velocity of the particle is determined by the frequency within the bursts and the spacing of the fringes:

$$v_p = f_D d_f.$$  \hspace{1cm} (8)

where $f_D =$ frequency within the bursts in Hz, $d_f =$ fringe spacing, and $v_p =$ particle velocity.

In the situation just described there is ambiguity as to the direction of the moving particle. A particle moving in the $+x$ direction will produce the same velocity as one
moving in the \(-x\) direction. To resolve the direction of the particle’s motion one beam is phase-shifted by a Bragg cell. Now, when the two beams meet, the fringes are not stationary, but move at a velocity defined by:

\[
v_s = f_s d_f
\]  

This fringe velocity, \(v_s\), is much greater than the expected particle velocity ensuring that the resulting measured particle velocity is unambiguous. A particle moving with a velocity opposite to the motion of the fringes will now encounter these fringes at a higher frequency than a particle moving with a velocity in the same direction as the fringes.

**Sampling Control**

Each point was sampled for 100 s at sampling frequencies between 100 and 500 Hz. Each sample was triggered by a confirmed detection on the \(U\) velocity system. Since particles do not come at regular intervals the sampling rate varied. The sensitivity of the system to particle detection could be set by adjusting two variables. The high voltage setting determines the signal amplification and the validation setting determines the threshold value for a burst to be considered a particle. The combination of these two settings determines which particles are counted.

In all cases the sampling rate decreased as the measurement volume moved further into the tank. This is because the light traveled further through the water, and was scattered more on its trip back to the probe. A solution to this problem is to increase the high voltage. However, this causes the system to be biased towards larger particles and
affects the rms statistics accordingly. Therefore, the high voltage setting was held fixed throughout a traverse so that the results could be compared accurately.

An additional setting that was used to increase resolution was the band setting. It controlled the range of velocities which could be measured. The processor has a fixed number of bins, 200, to which a particle can be assigned. These 200 bins are spread evenly over the velocity range chosen. Thus, a range ten times as large has one-tenth the resolution. For all experiments the smallest band width, \(-0.13\) to \(+0.13\) m/s, was used.

2.3.2 Positioning

To make the necessary traverses the laser probe needed to be positioned accurately in all three dimensions. A hardwood lateral traverse was mounted on a photography tripod to provide accurate positioning in the \(y\) and \(z\) directions. A system of levels and rulers were used to locate the measurement volume, as shown in Figure 13.

Longitudinal

The initial step in positioning the measurement volume was to set the longitudinal, \(x\), position. This was accomplished by moving the tripod to the desired location and centering the beams in the gap between dowels. The distances from each side of the front edge of the traverse to the outside of the flume were measured and compared to assure that the beams were perpendicular to the tank. For the lateral traverses behind a single dowel, a ruler was taped horizontally onto the tank side. The dowel was set to a fixed and known location with respect to this ruler. The beams were set to focus at the desired
distance behind, or in front of, the dowel on the ruler. Once the distance was set the beams could be focused at the correct height and lateral position.

**Lateral**

Lateral positioning used the hardwood traverse, which was equipped with a ruler and pointer to locate the position of the probe with respect to the side of the flume. Zero was determined by pushing the probe lens up against the flume side, and reading the distance off of the traverse ruler. Probe position values were measured positive outward from the outside of the glass, while measurement volume position values were measured positive inward from the inside of the glass. Equation 10 was used to set the measurement volume to its desired location.

\[
y_{mv} = y_{max} - \frac{n_{water}}{n_{air}} \cdot y_{probe}
\]

Where \(y_{mv}\) = the measurement volume location within the flume, \(y_{probe}\) = the probe position as determined by the pointer and ruler on the traverse, \(y_{max}\) = the maximum distance into the tank that could be measured corresponding to \(y_{probe} = 0\), and \(n_{water}\) and \(n_{air}\) are the indices of refraction for water and air respectively. For lateral traverses, \(y_{probe}\) values were calculated from desired measurement volume locations, \(y_{mv}\). For vertical traverses the lateral position of the measurement volume, \(y_{mv}\), was set by eye at the base of the dowel array, by looking in from the top and centering the measurement volume behind the appropriate dowel. The actual value of \(y_{mv}\) was calculated by using the value of \(y_{probe}\) from the ruler in equation 10.
Vertical

Vertical positioning was accomplished with a level and a ruler taped vertically to the side of the tank (as shown in Figure 13). A height could be chosen, and then a level would be laid across the ruler at this height and made level. The tripod would be raised or lowered until the horizontal pair of beams were aligned with the edge of the level. To correct for any discrepancy between the height of the bottom and the ruler bottom, and second ruler was taped to a small block of Plexiglas and inserted into the flow at the measurement volume. With the beams focused on the ruler scale it was possible to determine the actual height of the measurement volume, and make any corrections. This calibration was generally performed once or twice over a vertical traverse.

2.3.3 Velocity Analysis

The velocity data were analyzed in several steps. First, the FLOware FVA uses a correlation technique to decipher the frequency information provided by the photoreceptor. FLOware calculated 100 second averages of velocity, rms velocity and turbulence (average/rms). All of the post-processing of the velocity record was performed in either Microsoft Excel or MATLAB.

Microsoft’s Excel was used to produce the normalized and bulk averaged profiles. All of the data from a given dowel density were normalized by the average velocity of the lateral traverse at $z = 10$ cm. This velocity was chosen to represent the free stream (outside of bottom the boundary layer) velocity within the dowels.
It was important to have a good technique with which to average the vertical profiles at each density because we were interested in the variations of the bulk properties of the flow. An unweighted average is inappropriate because it leads to bias in the bulk profiles; i.e. since only five profiles were measured, a profile in a region representing only a small fraction of the total area would have disproportionate influence in an unweighted average. To determine an appropriate weighting for each profile at each density it was necessary to determine the percentage of the total flow that a particular profile represented. Using wake theory as well as flow visualization in the dowel arrays, three wake regions were designated:

1) within one diameter of the dowel on the downstream side there is a region of backflow, representing a tiny fraction of the total base area (light grey, Figure 14),

2) entirely surrounding the dowel, but more extensively on the downstream side, is an area of velocity reduced by 70% or more (dark grey),

3) a much larger wake region representing areas in which the flow is 70-90% of the free stream velocity (medium grey).

In addition, the regions with effectively no wake were left white, and dowels are black.

The model wakes were copied onto each dowel in a small region of the dowel array plans. Lines were then drawn between single or groups of dowels to divide the plan into identical sections. Each of the four regions in a single parallelogram was then colored
appropriately. Since each parallelogram effectively represented the total base area (except for the errors introduced by the array boundaries) one needed only to calculate the percentage of each parallelogram covered by each color. To this end, the parallelogram was then further divided in a regular array of smaller, similar parallelograms. The total number of these parallelograms within each color was counted. This process is illustrated in the table at the bottom of Figure 14.

To determine the percentage of the flow area represented by each color, equation 11 was used:

$$\% A_{color} = \frac{N_{color}}{N_{total} - N_{dowel}}$$

(11)

where $N_{color} = \text{number of trapezoids of a given color}$, $N_{total} = \text{total number of trapezoids}$, $N_{dowel} = \text{number of trapezoids covered by dowels}$. The dowel area was subtracted out of the total area because it is not considered part of the total flow area. At the end of this step, the percentage of the total flow area in each wake region was known.

To check this process, the dowel area percentage, as calculated by the trapezoidal method, was compared to the theoretical dowel area percentage as calculated by equation 12, below:

$$\% A_{theoretical} = \frac{\pi r^2 n_{dowels}}{A_{total}}$$

(12)

Where $r = \text{dowel radius}$, $n_{dowels} = \text{number of dowels at a particular density}$, $A_{total} = \text{total area of dowels base} = 2204 \text{ cm}^2$. The results were good as shown below:
Table 1

<table>
<thead>
<tr>
<th>Density</th>
<th>( n_{\text{dowels}} )</th>
<th>( A_{\text{color}} )</th>
<th>( A_{\text{theoretical}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>34</td>
<td>0.8%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Medium</td>
<td>96</td>
<td>1.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>High</td>
<td>385</td>
<td>6.5%</td>
<td>5.5%</td>
</tr>
</tbody>
</table>

The next step was determining in which area each vertical profile lay. Table 2 shows the results of this analysis. The equations used to average the profiles at each density are shown at the bottom. In cases where more than one profile represented the same area, those profiles were averaged and then weighted. In cases where an area was not represented by a profile at all and represented a very small fraction (< 2\%) of the flow (such as light grey - backflow - in the low density arrangement) that fraction was neglected, and the total percentage was reduced accordingly.

The lateral profile average represents an unweighted average of the three profiles, although an appropriately weighted bulk average would be more accurate. The \( z = 10 \) cm profile may be used as an approximation for the bulk average because neither of the other two profiles represented a significant fraction of the total flow depth.

2.3.4 Error Analysis

All of the above described procedures were subject to error. For example it was discovered the plexiglas bottom did not lie level for the high density case - it was tipped at approximately 0.8°. This resulted in the dowels leaning about 2 mm in the lateral direction over their 15 cm height. When the lateral position of a vertical traverse was set it was
assumed that the position was fixed. Therefore, in some cases, the vertical traverses were not aligned to the dowel over the entire depth. Fortunately this was noticed relatively early and corrections were made on the remaining traverses. This error varied over the three densities, and could be easily corrected in the lateral traverses by centering the wake minima. It was most important in the high density vertical profiles in which the longitudinal velocities varied up to 6 cm/s over 0.5 cm of lateral movement. (see Section 3.2).

Additional lateral positioning errors were introduced through the hardwood traverse. It is estimated that these errors were approximately +/- 0.2 mm. Again, this error was compensated for by centering the wake minima when the lateral traverses were plotted. However, this correction was not possible for the vertical traverses.

Errors in the longitudinal positioning and squareness to the side were introduced by the tripod. As the tripod was raised or lowered in tended to twist. Realigning the beams to negate the twist was attempted, but this almost certainly resulted in some variability in the lateral position. This rotational error, $\psi$, is estimated at +/- 0.18°. The angular error introduces a positioning error of the order +/- 1 mm, and a velocity measurement error of +/- 0.15 mm/s. The positioning error introduces an additional velocity error which was most important when the velocities were changing rapidly in the longitudinal direction - such as in a region very close to a dowel.
Vertical positioning errors were introduced through three mechanisms. The first is the Plexiglas substrate being out of level as described above. A vertical position of \( z = 1 \) cm measured on the ruler taped to the side could be off by as much as 2 mm. This error was corrected for by using a second ruler inserted into the flow as described above. The second error is introduced through the actual positioning method - the ruler and a level. As much as +/- 0.5 mm of uncertainty was introduced from the inaccuracies of the method. The third mechanism is the traverse being laterally out of level. It was possible for the traverse to tip front to back causing the beams to angle up or down as they entered the flow. A level mounted on the traverse and a second placed atop the probe were used to reduce this angular error, \( \theta \), to approximately +/- 0.15\(^\circ\) which corresponds to a positioning error of +/- 1 mm. This third error is a constant value for the vertical traverses and was corrected for by calibrating the ruler on the glass with another inside the flume at the measurement location.

Additional errors were introduced through possible rotation of the probe about its long axis and through the Dantec Flow Velocity Analyzer. This type of angular error would cause a small part of the \( U \) velocity to be aliased into the \( V \) component, and vice-versa. This angle, \( \phi \), is estimated as +/- 0.5\(^\circ\), producing a maximum error of 0.5 mm/s for mean velocities of 6 cm/s. The processing error is approximately +/- 0.15 mm/s.

Table 3 summarizes the error information. The total velocity error is computed via equation 13:
\[ E_t = \sqrt{\sum_i \left( \frac{\partial u}{\partial x_i} E_{x_i} \right)^2} \]  \hspace{1cm} (13)

where \( E_t \) is the total error, \( E_{x_i} \) is the error associated with each direction \( x_i \) in positioning, and \( \frac{\partial u}{\partial x_i} \) is the variation of the velocity, \( u \), with position (Kline and McClintock, 1953).

<table>
<thead>
<tr>
<th>Direction</th>
<th>Error</th>
<th>Direction</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x )</td>
<td>+/- 0.5 mm</td>
<td>( x )</td>
<td>+/- 0.3 mm/s</td>
</tr>
<tr>
<td>( y )</td>
<td>+/- 1 mm</td>
<td>( y )</td>
<td>+/- 1.35 mm/s</td>
</tr>
<tr>
<td>( z )</td>
<td>+/- 1 mm</td>
<td>( z )</td>
<td>+/- 0.2 mm/s</td>
</tr>
<tr>
<td>( \theta )</td>
<td>+/- 0.15°</td>
<td>( \theta )</td>
<td>+/- 0.15 mm/s</td>
</tr>
<tr>
<td>( \phi )</td>
<td>+/- 0.5°</td>
<td>( \phi )</td>
<td>+/- 0.35 mm/s</td>
</tr>
<tr>
<td>( \psi )</td>
<td>+/- 0.18°</td>
<td>( \psi )</td>
<td>+/- 0.15 mm/s</td>
</tr>
<tr>
<td>DANTEC</td>
<td>+/- 0.15 mm/s</td>
<td>Total</td>
<td>+/- 1.4 mm/s</td>
</tr>
</tbody>
</table>

Table 3
Figure 1: Flume Setup
Figure 2: Wake Profiles at $U = 3$ cm/s
Comparison to Theory (−)

(a) $U$

(b) $U_{rms}$

Lateral Position (cm)

Velocity (cm/s)
Longitudinal Position (cm)

Lateral Position (cm)

RMS Velocity (cm/s)
Longitudinal Position (cm)

Symbols:
- $x = -3.6$
- $x = 1.1$
- $x = 2.2$
- $x = 3.9$
- $x = 6.6$

Solid line: Theory
Figure 3: Wake Profiles at $U = 12$ cm/s
Comparison to Theory (-)
Figure 4: Determination of $C_1$ from Centerline of Experimental Data

(a) $U = 3 \text{ cm/s}$
$C_1 = 0.38$

(b) $U = 12 \text{ cm/s}$
$C_1 = 0.5$
Figure 5: High Density Arrangement
Figure 6: Medium Density Arrangement
Figure 7: Low Density Arrangement
Figure 8: Beam Convergence
Figure 9: Medium Density Mass Balance Estimate of Velocity Inside Dowel Array

Equation used for calculating the velocity inside the dowel array:

\[ U_2 = \frac{U_o w_o - (U_1 w_1 + U_3 w_3)}{w_2} \]
Equations used for calculating the velocity inside the dowel array:

\[ U_{dowels} = \frac{\forall_{upstream} - \forall_{jet}}{w_{dowels}} \]

\[ \forall_{upstream} = \frac{1}{2}(U_1 + U_2)y_2 + U_3(y_4 - y_2) + \frac{1}{2}(U_4 + U_5)(y_5 - y_4) + \frac{1}{2}U_6(38 - y_3) \]

\[ \forall_{jet} = U_{j1}w_{j1} + U_{j2}w_{j2} \]
Figure 11: Laser System

- Power Supply
- Laser
- Beam Separator and Bragg cell
- Photomultipliers
- Processor
- Probe
- To Computer
Figure 12: Fringe Theory
Figure 13: Positioning Systems

LONGITUDINAL

LATERNAL

VERTICAL
Figure 14: Analysis of Flow Areas

<table>
<thead>
<tr>
<th>Color</th>
<th>Description</th>
<th>Number of Trapezoids</th>
<th>Percent of Total Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>Dowel</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Light Grey</td>
<td>Backflow</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Dark Grey</td>
<td>&lt;70% of freestream</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>Medium Grey</td>
<td>70-90% of freestream</td>
<td>15.5</td>
<td>26</td>
</tr>
<tr>
<td>White</td>
<td>No wakes</td>
<td>41</td>
<td>68</td>
</tr>
</tbody>
</table>
Table 2: Velocity Distribution

Location of Measurement Points

<table>
<thead>
<tr>
<th>Density</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>White</td>
<td>Dark</td>
<td>White</td>
</tr>
<tr>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>White</td>
<td>Dark</td>
<td>Medium</td>
</tr>
<tr>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Light</td>
<td>Dark</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Distribution Over Total Area (%)

<table>
<thead>
<tr>
<th>Density</th>
<th>Black</th>
<th>Light</th>
<th>Dark</th>
<th>Medium</th>
<th>White</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.8</td>
<td>1.2</td>
<td>4</td>
<td>26</td>
<td>68</td>
</tr>
<tr>
<td>Medium</td>
<td>1.4</td>
<td>2.7</td>
<td>11</td>
<td>46.6</td>
<td>38.3</td>
</tr>
<tr>
<td>High</td>
<td>6.5</td>
<td>11.2</td>
<td>49.4</td>
<td>32.9</td>
<td>----</td>
</tr>
</tbody>
</table>

Distribution Over Available Flow Area (%)

<table>
<thead>
<tr>
<th>Density</th>
<th>Black</th>
<th>Light</th>
<th>Dark</th>
<th>Medium</th>
<th>White</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>----</td>
<td>1.4</td>
<td>4.1</td>
<td>26</td>
<td>68.5</td>
</tr>
<tr>
<td>Medium</td>
<td>----</td>
<td>2.8</td>
<td>11.1</td>
<td>47.2</td>
<td>38.9</td>
</tr>
<tr>
<td>High</td>
<td>----</td>
<td>12</td>
<td>52.8</td>
<td>35.2</td>
<td>----</td>
</tr>
</tbody>
</table>

Equations Used to Calculate Weighted Average at Each Density

- **Low =** \( \frac{(4.1) P4 + (26) (P1 + P2) / 2 + (68.5) (P3 + P5) / 2}{4.1 + 26 + 68.5} \)

- **Medium =** \( \frac{(11.1) P4 + (47.2) (P1 + P2 + P5) / 3 + (38.9) P3)}{11.1 + 47.2 + 38.9} \)

- **High =** \( \frac{(12) P3 + (52.8) P4 + (35.2) (P1 + P2 + P5) / 3}{100} \)

**Key:**

- **Black** Dowel
- **Light Grey** Within 1 diameter downstream of a dowel
- **Dark Grey** Velocities to 70% of free stream
- **Medium Grey** Velocities 70 - 90% of free stream
- **White** Outside of any wake
3 Results and Discussion

Vertical and lateral profiles of velocity were taken in the test section before any dowels were inserted into the base. These profiles are shown in figures 15 and 16. The vertical profiles indicate a logarithmic boundary layer 7 cm thick. The lateral profile demonstrates uniformity across the center piece of the channel, with 9 cm thick sidewall boundary layers.

3.1 Single Dowel Phenomenon

3.1.1 Observations

Initial flow visualization studies in the low density arrangement demonstrated a somewhat unexpected result. The movement of the dye, shown in Figure 17, revealed a strong vertical velocity immediately behind the dowel. The dye was observed to rise 7 to 10 cm from the bottom. It became more diffuse as it rose as portions of it were swept downstream. Above $z = 10$ cm the dye was undetectable. It is unclear whether the dye
continued to rise or whether the vertical velocity did not extend above 10 cm. Attempts to increase the dye concentration at 7 to 10 cm were inconclusive because the injected dye had its own velocity which obscured the vertical velocity.

Further details of the flow structure were analyzed by changing the injection point of the dye (Figure 17). In particular, we noted a region of backflow (negative $U$) that extended about 1 diameter (0.6 cm) downstream of the dowel. Around the sides and front of the dowel there was a narrow, $O(0.2 \text{ cm})$ annulus free of dye. About even with the trailing edge of the dowel a thin stream of dye curled in and was sucked upwards in the velocity behind the dowel. This stream maintained its vorticity and coherence for several centimeters up from the bottom. The largest part of the dye was pushed away from the dowel region and swept downstream. With injection locations higher in the water column, vortex streets could be seen forming several diameters behind the dowel. These vorticities were absent in the bottom few centimeters. The vertical location of the transition between the regions in which there was and was not shedding, could not be determined through flow visualization.

A single dowel was isolated in the flume and vertical traverses were made 2 mm upstream, and 2 mm downstream of the dowel, and compared to a profile made with the dowel removed. Both longitudinal and vertical velocities were measured, and these results are shown in Figures 18 and 19. Upstream of the dowel the longitudinal velocity was significantly reduced with respect to the null case, but the turbulence intensity was nearly
identical. (This information was used in preparing the bulk averaging technique, Section 2.3.3) Downstream of the dowel the turbulence intensity was only slightly increased, while the mean velocity was reversed, indicating a backflow region. The vertical velocity measurements, Figure 19, depict the vertical flow originally observed with dye: upstream of the dowel there exists negative vertical velocity while downstream there exists positive vertical velocity. The positive velocity is up to 35% of the average longitudinal flow.

To gather information about this phenomenon at the three densities, a vertical traverse within 2 mm of the backside of the dowel was measured. These results are shown in Figures 20 and 21. The backflow velocity becomes stronger as the density is increased, changing from 5 to 20% of the average velocity. The streamwise turbulence intensity increased from nearly identical to the no-dowels case to over 40% of the average velocity at the high density. Inversely, the positive vertical velocity decreased as the density increased, changing from 30 to 10% of the flow. As the vertical mean velocity decreased the vertical turbulence intensity increased dramatically, more than doubling between the low and high densities.

3.1.2 Theory

The phenomena described above can be explained by recognizing the effects of a bottom boundary on the flow structure. Specifically, that the bottom imposes a no-slip condition which creates a non-uniform velocity profile. In the null case a log-layer profile is evident. In all other densities there is a narrow region, less than 1 cm thick, in which the
longitudinal velocity changes from 0 at the bed to the nearly uniform velocity of approximately 6 cm/s (normalized to approximately 1 in the graphs, see Figure 28).

This highly sheared region near the bottom creates lateral vorticity, \( \omega_y = \frac{\partial u}{\partial z} \). In unobstructed flow this vorticity can be thought of as a rotating cylinder whose axis is aligned with the \( y \)-axis. When a dowel is placed in the flow, aligned with the \( z \)-axis as in these experiments, the lateral vorticity gets bent around the dowel forming a horseshoe vortex, see Figure 22. At the very bottom of the upstream half of the dowel there is a radially outward velocity from the horseshoe vortex. This is what clears the dye from a region about 2 mm thick around the base.

The vertical velocities near the dowel are driven by vertical variations in pressure. Pressure gradients arise from differences in drag resulting from vertical variations in longitudinal velocity, \( U(z) \). At higher velocities, the pressure drop around the dowel is greater, resulting in higher form drag. The pressure drop is best described by the coefficient of pressure recovery, \( C_p \), shown in Figure 23. Using:

\[
C_p = \frac{P - P_\infty}{\frac{1}{2} \rho u^2_\infty} = \pm 1
\]

where \( u_\infty \) is the velocity at a particular vertical location in the free stream, \( \rho \) is the density of water, and \( P \) is the pressure on the dowel surface, and \( P_\infty \) is the free stream pressure, excluding hydrostatic, which is uniform over depth. On the upstream face, stagnation occurs such that \( P = \frac{1}{2} \rho u^2_\infty + p_\infty \), and \( C_p = 1 \). Thus, on the front of the dowel,
equation 14 can be re-written at both the top and the bottom as:

\[ p_t = \frac{1}{2} \rho u_{t,\infty}^2 C_p + p_\infty \quad \text{top} \quad (15a) \]

\[ p_b = \frac{1}{2} \rho u_{b,\infty}^2 C_p + p_\infty \quad \text{bottom} \quad (15b) \]

In these equations, \( p_\infty \) and \( \rho \) are constants throughout the water depth. So, on the upstream side of a dowel where \( C_p = 1 \) and \( u_{t,\infty} > u_{b,\infty} \), \( P_t > P_b \) and the flow will be driven downwards. On the downstream side \( C_p \approx -1 \). This value is based on observation within laminar wakes. For this value of \( C_p \), Equations 15a and 15b yield \( P_t < P_b \), and flow will be driven upwards along the back of the dowel. Figure 24 illustrates this effect.

In summary, the imposition of a no-slip condition produces a vertically sheared velocity profile. The combination of separated flow behind a bluff body and the sheared velocity profile produces pressure driven vertical velocities immediately up and downstream of the bluff body. The variations in pressure recovery lead to negative velocities upstream of a dowel and positive velocities downstream.

### 3.2 Low Density Results

As described in Section 2.1, three lateral and five vertical traverses were measured. The results of the lateral profiles for the low density arrangement are shown in Figure 25. The top half of the figure presents the normalized longitudinal velocity, \( U(\gamma)/U_{10} \), and the turbulence intensity, \( U_{\text{rms}}(\gamma)/U_{10} \). Recall that \( U_{10} \) is the laterally averaged velocity at \( z = 10 \) cm. The solid line is the average longitudinal velocity and the dashed line is the average
turbulence intensity. The bottom half of Figure 25 is a schematic of dowel location with respect to the measurement points. Flow direction is from the bottom of the page towards the top. The scales of both halves of Figure 25 are the same. The small circles in the plot of dowels location represent the measurement points shown in the velocity plot. The numbered plusses (+) represent the locations of the five vertical traverses.

The most important feature of the velocity plot is the 40-60% reduction of the velocity in the dowel wake, visible in all three profiles. The profile taken at $z = 0.6$ cm has both the smallest free stream velocity and the smallest reduction due to the wake. The other two profiles at $z = 3$ and 10 cm are very similar to each other, although the profile at $z = 3$ cm shows a greater reduction in the wake.

Other interesting features of Figure 25 are the increased turbulence intensity in the wake and the intensity maxima at the wake edges. Notice that the turbulence intensity peaks occur at the locations corresponding to the largest velocity gradient ($du/dy$), as would be expected. Although all three turbulence intensity profiles show these features, there are subtle differences between them. The $z = 0.6$ cm traverse shows the smallest variation, approximately 10% of $U_{10}$, across the wake region in a broad single peak. And while the $z = 3$ cm velocity profile shows a larger velocity gradient, it is the $z = 10$ cm profile which shows the highest turbulence intensity peaks.
Figure 26 presents the results from the vertical profiles measured at the five points shown in Figure 25. Figure 26a presents the normalized longitudinal velocity data, \( \frac{U(z)}{U_{10}} \), and Figure 26b presents the turbulence intensity data, \( \frac{U_{\text{rms}}(z)}{U_{10}} \). For comparison the no-dowels (Null) and weighted average (Avg) profiles are presented as the dotted and solid lines, respectively.

Figure 26a demonstrates that the overall reduction in the free stream velocity in the \( z = 0.6 \) cm lateral profile is due to its location in the boundary layer. The boundary layer extends to approximately \( z = 1 \) cm in all five profiles. Above \( z = 1 \) cm significant differences in the vertical structures exist between the five profiles. At positions 2 and 4 there is a large region of velocity deficit from approximately \( z = 1 \) to \( 7 \) cm, with a maximum deficit at \( z = 2 \) cm. At positions 1, 3 and 5 the profiles are nearly uniform from \( z = 1 \) cm to the water surface at \( z = 15 \) cm.

Position 4 (P4) is located 3 diameters (1.9 cm) directly downstream of the nearest dowel and corresponds to the wake center in the lateral profiles. Position 2 (P2) is located 11 diameters (7 cm) directly downstream of another dowel. The remaining three positions (1, 3 and 5) are at least 26 diameters (16.5 cm) downstream of the nearest dowel. This suggests that the velocity deficit region in the position 2 and 4 profiles is a function of dowel proximity. For further exploration of the velocity structure, the profiles of positions 2 and 4 have been isolated in Figure 27, and the profiles for positions 1, 3 and 5 have been isolated in Figure 28.
The vertical profiles may be broken into three flow regimes. The first is the near-bed regime which is characterized by the large velocity gradient due to the presence of the bed. The near-bed regime extends from the bed to approximately \( z = 1 \) cm. The second regime is the deficit regime which is defined by the vertical limits of the velocity deficit in profiles 2 and 4. At P4 the deficit regime extends from \( z = 1 \) to 12 cm, while at P2 its upper limit is at \( z = 6 \) cm. The third regime is the uniform profiles regime in which the velocity is nearly constant with height. Profiles 1, 3 and 5 only contain near-bed and uniform profile regions, whereas profiles 2 and 4 include all three regions.

The level of maximum velocity deficit in the P4 profile corresponds to the \( z = 3 \) cm lateral traverse, which had the largest velocity reduction in the wake region (see Figure 25). The \( z = 10 \) cm lateral traverse passes through the top of the velocity deficit regime of the P4 profile where the velocities are nearly uniform. Consistent with the relatively small deficit in the wake region of the \( z = 0.6 \) cm lateral traverse, the vertical profiles are all very similar at this height. This reflects the fact that at \( z = 0.6 \) cm, the bed effects dominate the dowel effects, making the profiles more spatially uniform near the bed than further up in the flow. The P4 velocity profile, however, does not reach the same near bed velocity maximum as the other profiles (0.8 vs. 0.95), suggesting that due to its proximity, the dowel has a large influence over this entire profile, even near the bed. This is further borne out by the fact that the turbulence intensity profile at P4, in Figure 27b, is dissimilar to the other four profiles. It shows a dramatic jump in turbulence intensity over the other four profiles throughout the water column. The P4 turbulence intensity profile is uniform.
over the entire water depth, showing no change near the bed or in the velocity deficit region. The turbulence intensity profile at P2 is quite similar to the bulk turbulence intensity profile. It shows a slight overall increase in the velocity deficit and uniform regions, and a pronounced increase in the near bed region. As both the P2 and the P4 turbulence intensity profiles illustrate no effects of the velocity deficit region, it appears that the deficit region does not increase the turbulence levels.

Figure 27 helps to define the region of dowel influence at the low density. At P4 (3 dia.) it is clear that the dowel dominates the turbulence intensity and velocity structure over the entire depth. A near-bed regime exists below $z = 1$ cm, but the magnitude of the velocity is determined by the dowel wake. By P2 (11 dia.) the bed dominates the lower 2 cm of the flow. The wake's influence is not seen until $z > 2$ cm. This result supports idea that there is a region near the bed in which the most important length scale is the distance from the bed, not the dowel size, and in which the bed generated turbulence dominates the turbulent kinetic energy.

The velocity and turbulence intensity profiles at positions 1, 3 and 5 are all very similar to one another, see Figure 28. This is not surprising since all three points are in nearly identical flow conditions; i.e. outside any significant wakes. The significant feature of these plot is the apparent downward mixing of longitudinal momentum. The uniform velocity layer, which begins at about $z = 7$ cm in the no-dowels case, has been extended downwards to about $z = 1$ cm. This causes a region of increased shear which is
manifested by increased turbulence intensity in the position 1 and 3 profiles. In addition, there is an overall increase in turbulence intensity in the low density arrangement.

In order to quantify the increased shear at the bed, $U^*$ was estimated by two methods. The first method uses:

$$\frac{(U^*)^2}{\nu} = \frac{\partial u}{\partial z}. \quad (16)$$

Because equation 16 is very sensitive to the value of $z$, and there is substantial uncertainty in $z$, $U^*$ was calculated with $z + \delta$ and $z - \delta$, where $\delta$ is the estimated error on $z$ (refer to Table 3). The values of $U^*$ were calculated for each of the five vertical profiles and the no-dowels profile. The results are shown in Figure 29.

The second method for estimating $U^*$ is based on the existence of a log layer:

$$\frac{U}{U^*} = \frac{1}{\kappa} \ln z \quad (17)$$

where $\kappa \approx 0.4$, the von Karman constant. The no-dowels profile and the bulk averaged profile were used with this equation to find the values represented by the solid points in Figure 29.

The significant feature of Figure 29 is the increase at all measurement points of $U^*$ (estimated with Equation 16) with respect to the no-dowels case. Comparing the Equation 17 estimates of $U^*$ to one another, the low density value is again higher than the no-dowels case. This indicates an increased stress at the bed which would affect the
deposition and suspension of sediments. In addition, the increase in turbulence intensity from the no-dowel profile to the low density bulk averaged profile indicates an increase in mixing and dispersion over the entire water column. It is likely that there would be enhanced resuspension of particles and that these particles would be mixed over the entire flow depth.

Recall that in Section 3.1.1 vortex streets were observed high in the water column but not near the bed. In order to explore the extent of the vortex shedding, spectral analyses were performed on some velocity records. In particular the vertical traverses at positions 4 and 5, and all three lateral traverses were analyzed. The results are shown in Figure 30.

Figure 30a presents the lateral profiles while Figure 30b presents the vertical profiles. The solid points are those which exhibited a peak in their velocity spectra at the Strouhal frequency, $S_f = 1.9$ Hz. The lateral traverses define a region in which shedding occurs. This region coincides with the wake region, although the wake centerline is free of spectral peaks at all depths. Notice that the $z = 0.6$ cm traverse has no points with spectral peaks, and the $z = 3$ cm traverse has peaks only at the two points on the edge of the wake.

The vertical profiles support these observations of the shedding domain. The P4 profile, which is in a wake, shows shedding peaks above $z = 5$ cm, while the P2 profile,
which is far from any wakes shows none. However, it seems likely that the P4 profile is not exactly centered in the wake because it does show spectral peaks, which are not present in the lateral traverses at the wake center.

Kovasznay (1949) studied wake profiles behind cylinders at the transition between vortex shedding and non-shedding regimes. In his experiments the flow velocity was varied between cases to produce small changes in Reynolds number. Lateral profiles of the wakes were measured with a hot-wire anemometer at various locations behind the cylinder. His results indicated that the critical Reynolds number, $R_{crit}$, for vortex shedding was 40. Small changes in Reynolds number around $R_{crit}$ produced large changes in wake characteristics due to the presence on absence of a vortex street.

In the absence of vortex shedding, the wake width grows linearly and the velocity deficit decreases linearly as the distance from the cylinder increases. This is in distinct contrast to the wake profile in the presence of vortex shedding. When vortex shedding occurs, the velocity deficit, which is approximately equal to the non-shedding case for $x/d < 4$, decays exponentially. The wake width, which is also approximately the same size as the non-shedding case for $x/d < 4$, grows logarithmically.

In the present experiments, it has been noted that vortex shedding does not occur for $z < 4$ cm in the P4 profile. This non-shedding region is contained within the velocity deficit regime, also observed in the P4 profile. It is likely that the velocity deficit is due to
the change in wake characteristics in the non-vortex shedding conditions; i.e. at a given
distance the velocity in a non-shedding wake will be smaller than the velocity in a shedding
wake. Consistent with this concept, the velocity in the P4 profile is seen to increase as the
measurement points move into the shedding region.

Interestingly, the Reynolds numbers for all points in the P4 profile are significantly
greater than $R_{cr} = 40$. The free-stream (shedding) Reynolds number based on the dowel
diameter and the bulk velocity profile is 380, while the Reynolds number in the non-
shedding region ranges from 250 at $z = 0.2$ cm to 360 at $z = 3$ cm. In the current
experiments the critical Reynolds number is between 360 and 380. It should be noted that
Kovasznay determined $R_{cr}$ in infinite depth flow, where no boundaries influenced the flow
at the measurement location. In our experiments, the bottom boundary has significant
influence over the region in which there is no vortex shedding. It is likely that the
influence of the bed causes the observed shift in the critical Reynolds number. It is also
possible that the horseshoe vortex, created by distorting boundary layer vorticity, disrupts
the formation of the vortex street.

Finally, notice that the bulk profiles for both velocity and turbulence intensity, in
Figure 26, represent positions 1, 3 and 5 quite well, but not positions 2 and 4. This
matching is due to the fact that positions 2 and 4 represent only small fractions of the total
flow area (see Table 2), and so have small weighting coefficients when the average is
computed. They do have enough effect to shift the velocity profile slightly lower and the
turbulence profile slightly higher. Also note that the bulk profile is uniform at $U/U_0 = 1$, thus demonstrating an appropriate choice of $U_0$ as a representative mean velocity.

3.3 Medium Density Results

Both longitudinal and vertical velocities were measured at the medium and high density arrangements. However, vertical velocities could only be measured between $z = 2$ and $13.5$ cm because the substrate (or surface) obstructed one of the laser beams outside this region. Figures 31 and 32 present the lateral profiles of longitudinal, $U(y)/U_0$, and vertical, $W(y)/U_0$, velocities at the three measurement heights. The lateral traverses were extended to include a second region of velocity deficit caused by a second wake.

Notice in Figure 31 that as in the low density traverses the $z = 0.6$ cm traverse shows the smallest velocities and the smallest change due to the wakes. An interesting note is that while the second wake is nearly as prominent in the velocity record, it barely registers in the turbulence intensity record. Also interesting is the significantly higher velocities seen between wakes in the $z = 10$ cm profile, than in the other two profiles.

The vertical velocities, Figure 32, could only be measured at the two upper traverses. At both heights there is a substantial increase in the turbulence intensity in the wake regions. The vertical velocities, however, show little effect from the wakes. At $z = 3$ cm there are small regions of slightly negative velocities just outside of the wakes, and slightly positive velocities inside of them. The difference is significant even accounting for
the possible errors. It is likely that the downward velocity produced on the upstream face of the dowel has been swept around the dowel and downstream, thus creating the negative vertical velocity that was measured. The horseshoe vortices may also contribute to the vertical velocities.

The vertical profiles of longitudinal velocity further illustrate changes in the flow within the dowels, and are shown in Figure 33. In particular, the bulk averaged profile is beginning to show a velocity deficit regime, seen only at positions 2 and 4 at the low density. All five individual profiles exhibit a velocity deficit regime, with the magnitude of this feature being directly linked to the distance between the measurement point and the nearest upstream dowel. At the medium density P1 is 5 diameters downstream of the nearest dowel, P2 is 11, P3 is 34, P4 is 3, and P5 is 26. In Figure 33a, the velocity profiles of P3 and P5 are above the bulk profile, while P1 has joined P2 and P4 below the bulk profile.

The bulk profile in Figure 33a shows a further depression of the uniform profile towards the bed. The highly sheared region has been reduced to 0.5 cm from 1 cm in the low density arrangement. In addition, the profiles all follow a similar shape in the near-bed region, supporting the idea that as the dowel density increases a larger fraction of the flow depth is dominated by the dowels, but that there remains a narrow region that is dominated by the bed. While the bed does not dominate the flow above \( z = 0.5 \) cm, it
does influence the flow there by regulating vortex shedding, as indicated by the velocity deficit region in all five profiles.

The profiles of vertical velocity, \( W(z)/U_{10} \), shown in Figure 33b show an unexpected positive bulk average. Recall that in Section 3.1.1 positive vertical velocities were measured immediately behind a dowel, and were thought to be associated with the backflow region within 1 diameter of a dowel. In this case, positive vertical velocities are measured throughout the flow depth. However, the bulk average profile is within the measurement error of zero, which is required to satisfy continuity.

Figure 34 presents the longitudinal, \( U_{ma}(z)/U_{10} \) and vertical \( W_{ma}(z)/U_{10} \) turbulence intensity profiles. In both plots the turbulence intensity increases as the distance from a dowel decreases. The profiles in order of decreasing distance are P3, P5, P2, P1, P4. Another notable feature of the turbulence intensity profiles is that they are all quite uniform with depth, especially \( W_{ma}(z)/U_{10} \). The \( U_{ma}(z)/U_{10} \) profiles are uniform at near their maximum value attained at the top of the near-bed regime. In addition, above \( z = 0.5 \) cm the \( U_{ma}(z)/U_{10} \) bulk profile looks nothing like the no-dowels profile, as it did in the bottom 2 cm in the low density arrangement. This is due to the fact that the dowels have more influence on the entire water column in the medium density.

Figures 35 through 38 display the vertical profiles broken into two groups of similar structure. At this density P1 has joined P2 and P4 in the group which displays a
significant velocity deficit regime (Figures 35 and 36). P3 and P5 are presented together as representative of profiles far from dowels, and show only slight velocity deficit regimes at $z = 2$ cm, (Figures 37 and 38).

As in the low density profiles, the P4 profile, being the closest to a dowel, shows the greatest effects of the wake - a very pronounced velocity deficit regime extending to $z = 10$ cm. The P1 velocity profile shows a small velocity deficit regime which extends to between $z = 2$ and 4 cm. From the top of the deficit regime the P1 profile increases linearly with height. It is possible that this linear increase is due to errors in the location of the measurement volume. As discussed in Section 2.3.4 the Plexiglas bed may have been out of level by 2 mm or more over 15 cm (0.8°). As the vertical traverses proceeded upwards they were parallel to the z-axis while the dowels were out of line. This would cause the measurement volume to drift out of line with the wake. An extra line, representing the bulk average without P1 (Avg 2), has been added to Figure 35a to demonstrate the effect of the drift in measurement volume location. Because there are two other profiles (P2 and P5) which represent the same area of the flow, the effect of P1 is minor. In light of this, the P1 profile has been left in the bulk average for all medium density profiles.

The profiles of vertical velocity, shown in Figure 35b, indicate that below 5 cm the velocities are positive (up to 5% of $U_{10}$), while above 5 cm they are less positive and more scattered. The turbulence intensity profiles, Figure 36, indicate that the profiles at P1, P2

68
and P4 have significantly higher levels of turbulence than does the average profile. All of the bulk averaged profiles are smaller in magnitude than these three profiles suggesting that the wake profile is not yet fully representative of the overall flow conditions.

Both positions 3 and 5 are far from dowels, and have higher velocities than the average profile as shown in Figure 37b. They show only modest velocity deficits at \( z = 2 \) cm, and uniform profiles 10 to 20% above the bulk average. The profiles of vertical velocity show the average falling in the middle of these two positions above 6 cm. Below 6 cm the P3 and P5 profiles have zero or slightly negative vertical velocities.

The P3 and P5 turbulence intensity records, Figure 38, reveal a relative maximum very close to the bed in the region of strong shear, and a uniform increase over the null case over the upper 14 cm. The fact that the bulk averaged profiles have moved further from these non-wake profiles suggests that they are becoming less representative of the overall flow, an idea borne out by Table 2. It is also significant that the P3 and P5 profiles are now uniform at approximately 18% of \( U_{10} \), where in the low density they were uniform near 15% of \( U_{10} \). This indicates that the turbulence intensity levels are being increased everywhere in the flow.

Figure 39 presents the results of the analysis of \( U^* \) for the medium density case. Recall that the \( U^* \) levels were approximately 0.25 to 0.6 in the low density plot (Figure 29) so there is no major difference between the low and medium density cases. Notice
that the highest estimate of $U^*$ for the no-dowels case corresponds to the lowest estimates of $U^*$ for the medium density.

3.4 High Density Results

The high density lateral profiles, Figures 40 and 41, illustrate the dramatic effects of the dowels. Two rows of dowels figure prominently in the lateral structure of the flow. In the profile of longitudinal velocity, $U(y)/U_{10}$, the nearest dowels create immense velocity deficits, and even backflow at $y = 11.5$ cm. The next row of dowels creates wake regions with 40\% reductions in longitudinal velocity. The flow between wakes in highly accelerated with peak velocities at 140\% of $U_{10}$. The lateral shears are very large with the biggest changes in velocity, approximately 1.7 times $U_{10}$, occurring over just 0.5 cm. The turbulence intensity results show a general increase over the medium density everywhere in the flow, with the highest values occurring at the edges of the wakes created by the nearest row of dowels.

The profiles of vertical velocity, $W(y)/U_{10}$, Figure 41, show regions of positive vertical velocity in the wakes of the nearest row of dowels, and nearly zero velocity elsewhere. The turbulence intensity is fairly uniform over depth and lateral position, except at the edges of wakes. This increase is particularly prominent between $y = 8.5$ and 9 cm.
Figures 42 and 43 present the vertical profiles of longitudinal, $U(z)/U_{10}$, and vertical, $W(z)/U_{10}$, velocity. At the high density, the positions of the profiles with respect to the nearest upstream dowel were as follows: P1: 5 diameters, P2: 3, P3: 0.4, P4: 3, P5: 5. It is important to note that P3 ended up close enough to a dowel to be in the backflow region. In Figure 42a, P3 shows a negative longitudinal velocity between -10 and -20% of $U_{10}$, or -0.6 to -1.2 cm/s. In Figure 42b, P3 shows positive vertical velocities of 5 to 10% of $U_{10}$, or 0.3 to 0.6 cm/s, and an increased vertical turbulence intensity. The positive vertical velocity measured at P3 is the one discussed in Section 3.1. The high density is the first time one of the profiles was located in the area subject to the pressure forcing. While the P3 profile represents only a 11% of the total flow area, it brings the average profile down to a normalized value of 1.

Interestingly, none of the five vertical profiles shows a velocity deficit regime. P1 and P4 remained at the same distance downstream of a dowel as they were at in the medium density arrangement, and P2 is now at the same distance as P4. Figure 43, the turbulence intensity plots, show that both the longitudinal and vertical turbulence levels have increased to nearly 40% of $U_{10}$. The combination of a lack of a velocity deficit regime at P1, P2 and P4, and the increased turbulence intensity, suggests that the level of mixing has increased to the point where vertical gradients of velocity are rapidly erased and persist only in the near-bed region where they are created by the no-slip condition. It appears that longitudinal momentum has been thoroughly mixed over the entire water column.
The P2 and P4 profiles also show a distinct longitudinal velocity maximum at the top of the near-bed regime. Notice that the near-bed regime has been further depressed from the medium density arrangement to < 0.5 cm. The P1 profile, when compared to the P2 and P4 profiles, illustrates the changes in the flow structure which occur over two diameters of longitudinal motion. At P1 (5 dia.), the profile is uniform at $U/U_{10} = 1.5$, where at P2 and P4 (both at 3 dia.) the profiles are uniform at 1.1. These values of $U/U_{10}$ may be compared to those at P1 and P4 at the medium density (Figure 33), where the values were 1 at P1 and 0.8 at P4. Recall that at the medium density both the P1 and P4 profiles had distinct velocity deficit regimes. Based on single dowel wake observations, we expect that profiles at this distance, 3 diameters, would show a velocity reduction due to the wake. In this case, they both show an increase over the average profile. Profiles measured between 1 and 3 diameters are may show the expected velocity reduction. Profiles at less than 1 diameter are in the backflow region.

A comparison between the profiles at P1 and P5 demonstrates the effect that the Plexiglas bed being out of level can have on a profile. The P5 profile exhibits a linear decrease in velocity with height, whereas the P1 profile does not. These profiles are in nearly identical conditions. In this case it is known that as the traverse proceeded upwards the measurement volume moved out of line and began entering a wake region. It is clear from Figure 40 that a 2-3 mm lateral movement over the water depth could produce the
observed profile. For this reason, the bulk profile for the high density was calculated neglecting the P5 profile.

The profiles of vertical velocity, \( \frac{W(z)}{U_{10}} \), show extensive scatter about the average profile. However the P3 profile has a positive vertical velocity and the P1 profile has a negative vertical velocity. The average profile is again within the measurement error of zero. The turbulence intensity profiles show little to distinguish them. The P3 profile shows the highest levels of both vertical and longitudinal turbulence intensity. It should be noted that at all densities the profile closest to a dowel recorded the highest levels of turbulence intensity. P1 is the furthest from a dowel (as is P5), and as was true for all densities, the profile furthest from a dowel shows the lowest levels of turbulence intensity.

Figure 44 presents the results from the \( U^* \) analysis at the high density. The value of \( U^* \) for P3 could not be computed because of the negative velocities measured at that location. Notice that \( U^* \) has increased further over the no-dowels profile. The range of \( U^* \) for the high density is 0.4 to 0.8, where it was 0.35 to 0.65 in the medium density and 0.25 to 0.6 in the low density.

3.5 Comparison of Densities

Figures 45-48 compare the bulk profiles from the lateral and vertical transects at all three densities. The major effect of the increasing density is to increase the turbulence intensity in both the longitudinal and vertical velocities (see Figures 46 and 48). The
biggest change occurs between the medium and high densities. This is not surprising since the plan area covered by dowels increases from 0.5% at low density to 1.4% at medium and jumps to 5.5% in the high density arrangement. An important result is that although the dowels themselves are 2D, they ilicit a 3D response in the flow. The explanation for these 3D effects is that the dowels are not in an infinite depth flow. The presence of the bottom produces 3D phenomenon as described in Section 3.1. The mechanism by which this a 3D phenomenon affects the bulk profiles will be discussed in Section 3.6.

The lateral profiles of average velocity, \( U_{\text{avg}}(y)/U_{10} \) and \( W_{\text{avg}}(y)/U_{10} \), shown in Figure 45, illustrate the effects of the dowels. The wake centered near \( y = 13 \) cm produces a velocity reduction of 0.45 at all three densities. However, in the high density profile, this reduction is taken from a higher background velocity. Between dowels, the high density longitudinal velocity is dramatically increased. This is due to the prevalence of wake regions which reduce the effective flow area. The flow is forced to accelerate and through the path of least resistance in the dowel and wake field. The longitudinal velocities in the low and medium densities are very similar to one another, and show only modest (0.1) acceleration of the flow between dowels.

The vertical velocities, shown in Figure 45b, are slightly positive in the wake regions at both the medium and high densities. Between wakes, the vertical velocities are slightly negative. This result is explained by the vertical velocity production described in Section 3.1. Positive vertical velocities are produced immediately behind dowels. Some
of this vertical velocity is transported away from the dowel, as was indicated by the decreasing dye concentration with height. Negative vertical velocities are produced immediately upstream of dowels. Some of this negative vertical velocity is transported out of the production region and into the main flow by lateral and longitudinal turbulent fluctuations. It is likely that the positive vertical velocities would stay mostly within the wake region, and the negative vertical velocities would stay outside of the wakes. Additional vertical velocities are induced by the horseshoe vortices which form around the dowels, and are swept into the flow.

The lateral profiles of turbulence intensity, $U_{ms.avg}(y)/U_{10}$ and $W_{ms.avg}(y)/U_{10}$, are shown in Figure 46. The most important feature of both of these plots is the large increase in turbulence intensity as the density increases. In both Figures 46a and b, the medium density turbulence intensity is about 25% of $U_{10}$, while the high density turbulence intensity is about 40% of $U_{10}$. At all three densities, the turbulence intensity is increased in the wake regions. Because the high density arrangement is completely dominated by wakes, it is not surprising that the turbulence intensity levels are highest at the high density. The extreme wake interaction causes increased mixing in all directions and means that every point is in a wake (as specified in the design criteria).

The vertical profiles of velocity, $U_{avg(z)}/U_{10}$ and $W_{avg(z)}/U_{10}$, shown in Figure 47, illustrate the changing bulk profile of the flow. As the dowel density increases, the uniform region mixes downwards. The biggest effect is seen between the null and low
density cases, in which the uniform profile is stretched down to \( z = 3 \) cm from \( z = 7 \) cm. This is a large change considering how few dowels were added (154 dowels/m\(^2\)). As the density increases beyond this, the boundary layer is depressed to 0.3 cm thick. The average velocity profiles are remarkably uniform with depth above \( z = 3 \) cm.

All three bulk profiles show a velocity deficit regime below \( z = 3 \) cm, which increases in magnitude with increasing dowel density. As described in Section 3.2, this velocity deficit is caused by the difference in wake structure due to the absence of vortex shedding. Wakes in which vortices are not shed have lower velocities at a given distance than in wakes in which vortices are shed. As the density of dowels increases, a larger fraction of the flow area is directly influenced by wakes, and profiles with a deficit region become representative of the overall flow conditions. The vertical velocities are very small, and are within the measurement error of zero, as expected from continuity. The spatial variations in vertical velocity, noted in Figure 45, have been averaged out.

The vertical profiles of turbulence intensity, \( \frac{U_{\text{rms.avg}}(z)}{U_{10}} \) and \( \frac{W_{\text{rms.avg}}(z)}{U_{10}} \) (Figure 48), show interesting changes between the four dowel densities (including the no-dowels case). In comparing the no-dowels profile to the low density, it is obvious that there is a 10 to 15% increase in turbulence intensity above \( z = 1 \) cm. More importantly, in the bottom centimeter of the flow, the low density profile overlays the no-dowels profile almost exactly. The turbulence intensity maximum is slightly (2%) greater in the low density profile. The similarity between these profiles below \( z = 1 \) cm suggests that the
proximity of the bed, rather than the dowels, has the most significant influence on the flow in this region. Above $z = 1$ cm, the low density profile is dominated by the dowel wakes. The no-dowels profile, however, is dominated by the bottom viscous effects to $z = 7$ cm.

The changes in profile structure between the low and medium density are more subtle, but are also very important. The medium density profile shows a 5% increase in turbulence intensity in the uniform profile regime. However, the turbulence intensity is now nearly uniform to $z < 0.5$ cm in the medium density. The medium density profile shows a decrease of less than 2% of $U_{10}$ at the top of the near-bed regime, and a near-bed maximum which is equal to the free stream turbulence intensity. The fact that the medium density profile no longer overlays the no-dowels profile suggests that the region of dowel influence has extended downwards to $z = 0.5$ cm. The near-bed regime has been compressed to less than one half centimeter. Although the increase in dowel density was moderate (0.5% in the low density to 1.4% in the medium density), the effects of the additional wakes is substantial.

More pronounced changes are expected in moving between the medium and high densities because the dowel density increases to 5.5% of the total plan area at the high density. Figure 48a shows a doubling in turbulence intensity from the medium to the high density profile. Interestingly, the turbulence intensity decreases with decreasing height, starting at $z = 2$ cm. Recall that in the no-dowels, low, and to some extent, medium densities, the turbulence intensity increases towards the bed from the uniform profile. At
the high density, the dowels dominate the turbulence, and the effect of the bed is to damp turbulence relative to the free.

The profiles of vertical turbulence intensity, $W_{nvec,avg}(z)/U_{10}$, are shown in Figure 48b. They show that the turbulence intensity nearly doubles between the medium and high densities. However, data could not be gathered below $z = 2$ cm, so nothing can be added to the analysis of the near-bed and velocity deficit regimes.

Figure 49 presents a comparison of the $U^*$ across all three densities. All locations, at all densities show a substantial increase in $U^*$ over the no-dowels case. The low and medium density estimates of $U^*$ are very similar to one another, while the high density values are higher. The magnitude of $U^*$ doubles between the no-dowels and maximum density cases, resulting in a four-fold increase in bottom stress, $\tau_b = \rho U^{*2}$.

Position 4 is unique in the vertical profiles because it remained at a fixed distance behind a dowel over the three densities. All of the other positions had dowels inserted closer to them than in the low density case. Thus position 4 provides an opportunity to look at the effects of changing density at a particular location. It is valuable because it shows the effects of a wake and represents between 25 and 50% of the flow area at all three densities. Figures 50 and 51 summarize the results at position 4. The remarkable result is how nearly identical the profiles are at the low and medium densities, for both the mean and turbulence intensity. Then, at the high density the velocity deficit between 1 and 5 cm is significantly diminished. This suggests that the integrity of P4's wake was
destroyed by the overall increase in turbulence intensity. The velocity deficit regime was also diminished by the increased mixing which transported higher momentum fluid into it.

3.6 Proposed Explanation

The 3D effects generated by the dowels can be explained by extending the theory put forth in Section 3.1. Dowel wakes are 2D only in infinite depth flow. As shown above, the presence of a bottom creates a variety of 3D effects. The increase in the bulk vertical turbulence intensity is produced through a combination of the previously described vertical effects and the 2D effects of increasing dowel density.

At the low density individual wakes do not interact and so the effect of each dowel is isolated (refer to Figure 45). The changes in velocity and turbulence intensity are associated with discrete wakes, and only localized mixing occurs. The positive vertical velocity produced behind a dowel is effectively trapped there. There is a flow upstream, towards the dowel, of 5 to 10% of $U_{10}$, and a turbulence intensity of the same magnitude (Figures 20 and 21). Only occasionally will parcels of water with significant vertical velocity be swept out of the backflow region by longitudinal turbulent fluctuations.

At the medium density, the lateral profile of vertical velocities, Figure 32, shows regions of upwelling in wakes and regions of downwelling outside of wakes. This suggests that the negative vertical velocities are being swept around the wakes by the bulk flow, although the horseshoe vortices may contribute as well. The vertical velocities and
turbulence intensities measured in front of the dowels are small compared to those measured behind, and probably do not contribute significantly to the bulk flow properties.

A more interesting bulk property at the medium density is the vertical turbulence intensity. Figure 34, vertical profiles, reveals a significant increase in intensity over the null case. The medium density turbulence intensity profile, in the backflow region (2 mm from the dowel) shown in Figure 21b, has the same magnitude as that found in the bulk profile. It is likely that the vertical turbulence is being swept out of the backflow region by the increasing longitudinal turbulence. Figures 20a and 21a show that at the medium density, the magnitude of the longitudinal turbulence intensity is larger than the mean backflow. This means that the turbulence can move parcels out of the backflow region quite easily.

Again at the high density, the vertical turbulence intensity measured in the backflow region is equal to the vertical turbulence intensity measured in the bulk profile. The magnitude of the longitudinal turbulence intensity at the high density is about twice the magnitude of the backflow. Also seen at the high density are regions of positive vertical velocity associated with the wakes, Figure 45.

In summary, pressure gradients behind a dowel produce positive vertical velocities. Increases in dowel density cause greater interaction between wakes, which increases the lateral and longitudinal turbulence intensity. As the magnitude of the longitudinal
turbulence intensity exceeds the magnitude of the backflow, the vertical velocity and turbulence can be swept into the bulk flow. The greater number of wakes also produces more lateral shear, which in turn produces more turbulence and more mixing. The major effects of increasing dowel density are to extend the uniform velocity profile downwards, to greatly increase the levels of turbulence and mixing in all directions in the entire flow area, and to increase the bed stress.
Figure 15: Vertical Velocity Profile, No Dowels
Figure 16: Lateral Velocity Profile, No Dowels
Figure 17: Observed Flow Pattern

Dye pattern at bed:

Dye pattern above $z = 7$ cm:

von Karman vortex street
Figure 18: Single Dowel Measurements

Velocity: Taken +/- 2mm from Dowel

(a) $U/U_{10}$

(b) $W/U_{10}$
Figure 19: Single Dowel Measurements
Turbulence Intensity: Taken +/- 2mm from Dowel

(a) $U_{rms}/U_{10}$

(b) $W_{rms}/U_{10}$
Figure 20: Varying Density Measurements
Velocity: Taken 2mm Downstream of Dowel

(a) $U/U_{10}$

(b) $W/U_{10}$

Symbols:
- No Dowel
- Single
- Medium
- High
**Figure 21: Varying Density Measurements**

Turbulence Intensity: Taken 2mm Downstream of Dowel

(a) $U_{rms}/U_{10}$

(b) $W_{rms}/U_{10}$

- **No Dowel**
- **Single**
- **Medium**
- **High**

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88
Figure 22: Horseshoe Vortex
Figure 23: Coefficient of Pressure Variation

\[ C_p = 1 - 4 \sin^2 \theta \]

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Figure 24: Vertical Velocity Forcing

\[ \begin{align*}
  \text{U} & \quad \text{u}_{t \infty} \quad \text{p}_{t \infty} \\
  & \quad \text{p}_t \\
  & \quad \text{p}_b \\
  & \quad \text{u}_{b \infty} \quad \text{p}_{b \infty} \\
  & \quad \text{p}_t \\
  & \quad \text{p}_b
\end{align*} \]
Figure 25: Low Density Lateral Profiles
Solid = U/U_{10}  Empty = U_{rms}/U_{10}

- 0.6: U
- 3: U
- 10: U
- Avg: U
- 0.6: rms
- 3: rms
- 10: rms
- Avg: rms
Figure 26: Low Density Vertical Profiles

(a) $U(z)/U_{10}$

(b) $U_{rms}(z)/U_{10}$

Normalized Velocity ($U/U_{10}$)

Turbulence Intensity ($U_{rms}/U_{10}$)
Figure 27: Low Density Vertical Profiles
Positions 2 and 4

(a) $U(z)/U_{10}$

(b) $U_{rms}(z)/U_{10}$
Figure 28: Low Density Vertical Profiles
Positions 1, 3 and 5

(a) $U(z)/U_{10}$

(b) $U_{rms}(z)/U_{10}$
Figure 29: Range of $U^*$ Estimates for Each Position
Low Density

$u^* = \sqrt{\frac{v}{du/dy}}$

Position Number

Low. Log
Null Log
Null
P1
P2
P3
P4
P5
Null
Null: Log
Low: Log
Figure 30: Positions with Shedding Peaks

Solid = Peaks, Empty = No Peak

(a) $U(y)/U_{10}$

(b) $U(z)/U_{10}$
Figure 31: Medium Density Lateral Profiles
Solid = $U/U_{10}$  Empty = $U_{rms}/U_{10}$

![Graph showing lateral profiles with normalized velocity compared to lateral position.](image)
Figure 32: Medium Density Lateral Profiles
Solid = W/U_{10}  Empty = W_{\text{rms}}/U_{10}
Figure 33: Medium Density Vertical Profiles

Longitudinal (a) and Vertical (b) Velocity

(a) $U(z)/U_{10}$

(b) $W(z)/U_{10}$
Figure 34: Medium Density Vertical Profiles
Longitudinal (a) and Vertical (b) Turbulence Intensity
Figure 35: Medium Density Vertical Profiles
Positions 1, 2 and 4: Longitudinal (a) and Vertical (b) Velocity

(a) $U(z)/U_{10}$

(b) $W(z)/U_{10}$
Figure 36: Medium Density Vertical Profiles
Positions 1, 2 and 4: Longitudinal (a) and Vertical (b) Turbulence Intensity

(a) $U_{rm}(z)/U_{10}$

(b) $W_{rms}(z)/U_{10}$
Figure 37: Medium Density Vertical Profiles
Positions 3 and 5: Longitudinal (a) and Vertical (b) Velocity

(a) $U(z)/U_{10}$

(b) $W(z)/U_{10}$
Figure 38: Medium Density Vertical Profiles
Positions 3 and 5: Longitudinal (a) and Vertical (b) Turbulence Intensity

(a) $U_{rms}(z)/U_{10}$

(b) $W_{rms}(z)/U_{10}$
Figure 39: Range of $U^*$ Estimates for Each Position
Medium Density

$u^* = (v \frac{du}{dz})^{1/2}$

Position Number

- P1
- P2
- P3
- P4
- P5
- Null
Figure 40: High Density Lateral Profiles

Solid = $U/U_{10}$  Empty = $U_{rms}/U_{10}$
Figure 41: High Density Lateral Profiles

Solid = $W/U_{10}$  Empty = $W_{rms}/U_{10}$
Figure 42: High Density Vertical Profiles
Longitudinal (a) and Vertical (b) Velocity

(a) $U(z)/U_{10}$

Normalized Velocity ($U/U_{10}$)

(b) $W(z)/U_{10}$

Normalized Velocity ($W/U_{10}$)
Figure 43: High Density Vertical Profiles
Longitudinal (a) and Vertical (b) Turbulence Intensity

(a) $U_{rms}(z) / U_{10}$

(b) $W_{rms}(z) / U_{10}$
Figure 44: Range of $U^*$ Estimates for Each Position

High Density

$u^* = (v \frac{du}{dz})^{1/2}$
Figure 45: Comparison of Lateral Profiles

Velocity

(a) $U(y)/U_{10}$

(b) $W(y)/U_{10}$
Figure 46: Comparison of Lateral Profiles

(a) $U_{rms}(y)/U_{10}$

(b) $W_{rms}(y)/U_{10}$
Figure 47: Comparison of Vertical Profiles

(a) \( U(z)/U_{10} \)

(b) \( W(z)/U_{10} \)
Figure 48: Comparison of Vertical Profiles

Turbulence Intensity

(a) $U_{rms}/U_{10}$

(b) $W_{rms}/U_{10}$

- **Null**
- **Low**
- **Medium**
- **High**
Figure 49: Comparison of U* Estimates
Every Measurement Position

- No Dowels
- Low
- Medium
- High

u*(z_min) and u*(z_max)
Figure 50: Comparison Across Densities

Position 4: Velocity

(a) $U/U_{10}$

- Height Above Bottom (cm)
- Normalized Velocity ($U/U_{10}$)

(b) $W/U_{10}$

- Height Above Bottom (cm)
- Normalized Velocity ($W/U_{10}$)
Figure 51: Comparison Across Densities
Position 4: Turbulence Intensity

(a) $U_{mv}/U_{10}$

(b) $W_{mv}/U_{10}$
4 Conclusions and Recommendations

4.1 Conclusions

The goal of this work was to explore the effects of plant density on the velocity and turbulence structure of the flow. The experiments have shed light on not only the changes in the flow structure, but on the production mechanisms behind these changes.

In response to the stated goals, the major conclusions of this research are that:

1) Increased plant density results in downward turbulent transport of momentum, which depresses the bottom boundary layer, (null = 7 cm, low = 1 cm, medium = 0.5 cm, high < 0.5 cm); and increases the shear stress at the bed as reflected in $U^*$. The velocity profiles become nearly uniform with depth over the entire region above this compacted boundary layer.
2) As plant density increases so do the levels of both horizontal and vertical turbulence. The level of vertical turbulence is similar in magnitude to the horizontal turbulence at all densities. In addition, the lateral shear introduced by wakes increases the production of turbulence. The increases in turbulence augment the downward transport of momentum.

3) Because the stagnation pressure (upstream) and the pressure recovery (downstream) at the dowel are functions of the oncoming velocity, the vertically sheared velocity profile produces a pressure gradient that drives vertical velocities. A negative vertical velocity is produced just upstream of a plant, and a positive one just downstream.

As the horizontal turbulence increases with wake interaction at higher plant densities the vertical momentum is carried into the main flow. Higher plant densities produce a smaller boundary layer, which confines this phenomenon to a smaller layer near the bottom. However the pressure gradient is increased due to the reduction of the distance over which the variation in pressure occurs.

4) The increase in turbulence due to plant density will have large effects on dispersion and mixing in nature. Nutrients and contaminants may mix thoroughly throughout the water column and stay suspended longer due to the increased turbulence. These changes in the environment will affect the nutrient and gas exchange by the
plants. In addition, in regions of high plant density the fate and transport of nutrients and pollutants will be significantly different from that predicted for open channels.

5) The velocity deficit regime, most prominent in the P4 profile at the low density, is caused by the difference in wake structure due to the absence of vortex shedding. Wakes in which vortices are shedding have higher velocities at a given downstream distance than those in which vortices are absent. Spectral analysis of individual profiles indicated that vortex shedding did not occur in the region $z < 4$ cm, which is a subset of the deficit regime.

6) Phase-locking, or synchronized vortex shedding, is an important phenomenon to be considered in laboratory experiments. Its nature the irregular spacing of plants will reduce the chances that the plants will become phase-locked.

4.2 Recommendations for Further Study

The results and conclusions of this study suggest several areas which deserve further exploration. It would be valuable to study the near-bed and non-vortex shedding regimes further. As was observed in the dye studies and spectral analysis, the flow in this regime behaved as if it were at a lower Reynolds number. It appears that the influence of the bed, shifts the critical Reynolds number at which shedding is initiated to a higher value. Spectral analysis of more profiles would help to define the region of vortex shedding more.
exactly. In addition, lateral traverses at approximately $z = 0.5, 4$ and $10$ cm, at several longitudinal positions behind a plant would be useful in visualizing the wake structure in the different shedding regimes.

Studies using a rough bottom, in which the roughness element size could be varied, would allow further analysis of the mechanism driving the vertical velocities. Because roughness elements would change the bottom boundary condition and the boundary layer profile, changes in the magnitude of the vertical velocity would be expected. This study could also examine the near-bed region. Roughness elements could prevent the observed smooth near-bed flow from existing, or could increase its size.

Other studies which use flexible plant models or vary the velocity would also be informative. Flexible plants have the ability to absorb and store energy, and so may change the flow conditions dramatically. Research by Anderson and Charters (1982) indicated that in some cases, plants may suppress any incoming turbulence. However, Geladium nudifrons, the plant used in their experiments, has a substantially different morphology. $G. $nudifrons is composed of many rodlike branches which are closely spaced, where Spartina alterniflora is more reedlike, with one main shoot.

Different velocities will change both the Reynolds and Strouhal numbers of the flow. The difference between laminar and turbulent flow entering the plant array may
produce significant changes. Changes in the shedding frequency may or may not have
effects other than to reduce phase-locking and resonance in flumes like ours.

Adding a third measurement direction would also help clarify what is going on
inside the plant arrays. Measurements of lateral velocity and turbulence would finish the
picture of mass, momentum and energy transport within plant arrays.
References


