Computational Flow Dynamics
Analysis of Nutrient Uptake and Flow Baffling by Submerged Macrophytes and Implications for Urban Drain Management

Ashley Wallace
November 2007
I present this dissertation as partial fulfilment of the requirements for the degree of Bachelor of Engineering (Environmental) in the School of Environmental Systems Engineering. I declare this constitutes my own original work unless otherwise stated in the text.

I would like to thank my supervisors Marco Ghisalberti and Anya Waite for their assistance in forming my thesis and preparing this dissertation. Marco was invaluable in the formation and troubleshooting of the model and the analysis of its results.

I would also like to thank Tom Atkinson of SERCUL for his enthusiastic assistance with profiling the modelled macrophyte species. More thanks go to José Romero, Halinka Lamparski and Phoebe Mack of GHD for providing assistance in the field and office. Finally, thanks to Matthew Zed for allowing me liberal use of his personal computer.

Ashley Wallace
26 November 2007
Abstract

The Water Corporation seeks to improve water quality in its network of urban open drains while maintaining their function. It has been suggested that planting the drainage network with a macrophyte species is an appropriate solution. This project assessed the effectiveness of macrophytes in removing nutrients from the water column and the extent to which they affect a drain’s ability to transmit water.

A software based fluid dynamics model (Shear Stress Transport, within ANSYS CFX) was utilised to describe flow around macrophyte strands. Three plant species were chosen for modelling, given the suitability of their growth characteristics to the environment presented by open drains: Baumea juncea, Baumea articulata and Potamogeton crispus.

The model inferred nutrient uptake to the macrophytes by the rate of release of the volumetric variable Nutrient from their surface. Their influence on channel velocity was estimated by measuring the force applied by the fluid motion to the plant bodies.

The model found that for flow velocities like those expected within the drain network (<10 cm/s), Potamogeton crispus is the most suitable species for planting. For the resulting loss in flow velocity, the model predicts Potamogeton crispus will remove the most nutrients from the water column.

A set of figures was produced which, given an initial velocity, the prediction of the percentage reduction in channel velocity a certain planting density would yield. It is expected that the Water Corporation will dictate an allowable loss of drainage capacity and from these figures subsequent planting densities and approximated uptake rates may be found.
Contents

ABSTRACT .................................................................................................................................................................. V
CONTENTS............................................................................................................................................................... VII
TABLES................................................................................................................................................................ IX
FIGURES ................................................................................................................................................................ X

1. INTRODUCTION ........................................................................................................................................ 1

2. LITERATURE REVIEW .............................................................................................................................. 3
   2.1 Site ............................................................................................................................................................ 3
   2.2 Macrophyte communities ...................................................................................................................... 3
      2.2.1 Nutrient removal processes ............................................................................................................. 4
      2.2.2 Macrophyte-epiphyte dynamics ..................................................................................................... 4
   2.3 Plant-water interactions .......................................................................................................................... 5
      2.3.1 Reaction kinetics ............................................................................................................................... 5
      2.3.2 Mass transfer ........................................................................................................................................ 5
      2.3.3 Plant influences on flow .................................................................................................................... 6
   2.4 Turbulence ............................................................................................................................................... 6
      2.4.1 Mean turbulence ............................................................................................................................... 7
      2.4.2 Statistical representation of turbulence ............................................................................................. 8
      2.4.3 Navier-Stokes ..................................................................................................................................... 8
      2.4.4 Reynolds averaging and Reynolds stress .......................................................................................... 8
      2.4.5 Turbulent kinetic energy ................................................................................................................... 9
      2.4.6 Turbulent dissipation ......................................................................................................................... 9
   2.5 External incompressible viscous flows .................................................................................................. 10
      2.5.1 Boundary layers ............................................................................................................................... 10
      2.5.2 Body force and drag .......................................................................................................................... 12
      2.5.3 Channel flow ....................................................................................................................................... 13
   2.6 Computational Flow Dynamics ............................................................................................................. 13
      2.6.1 k-Epsilon .......................................................................................................................................... 14
      2.6.2 k-Omega and the Shear Stress Transport model ................................................................................ 15

3. METHODS .................................................................................................................................................... 17
   3.1 Plant selection and characterisation ....................................................................................................... 17
   3.2 Geometry creation ................................................................................................................................... 22
      3.2.1 Test geometry .................................................................................................................................... 22
      3.2.2 Plant geometries .............................................................................................................................. 23
      3.2.3 Control volume .................................................................................................................................. 25
   3.3 Mesh generation ....................................................................................................................................... 26
      3.3.1 CFX-Mesh ....................................................................................................................................... 28
      3.3.2 Mesh generation ............................................................................................................................... 29
   3.4 Model run definition ............................................................................................................................... 32
      3.4.1 Modelled parameters ........................................................................................................................ 32
3.4.2 Boundary conditions ................................................................. 33
3.4.3 Solution methods ................................................................. 33
3.5 Model output analysis ................................................................. 35
3.5.1 Nutrient uptake ................................................................. 35
3.5.2 Flow baffling ................................................................. 36

4. RESULTS .......................................................................................... 39
4.1 Nutrient uptake ................................................................. 39
4.1.1 Baumea juncea ................................................................. 39
4.1.2 Baumea articulata ................................................................. 40
4.1.3 Potamogeton crispus ................................................................. 40
4.2 Turbulence ................................................................. 41
4.2.1 Turbulence structures ................................................................. 41
4.2.2 Drag area ................................................................. 45
4.3 Planting density analysis ................................................................. 46
4.3.1 Baumea juncea ................................................................. 46
4.3.2 Baumea articulata ................................................................. 47
4.3.3 Potamogeton crispus ................................................................. 47
4.4 Nutrient removal and loss of channel velocity ................................................................. 48

5. DISCUSSION .................................................................................. 51
5.1 Summary of findings ................................................................. 51
5.2 Analysis of results ................................................................. 51
5.2.1 Turbulence generation ................................................................. 51
5.2.2 Flow fields ................................................................. 52
5.2.3 Nutrient flux and loss of channel velocity ................................................................. 52
5.3 Model features ................................................................. 53
5.3.1 Nutrient uptake ................................................................. 53
5.3.2 Species selection ................................................................. 54
5.3.3 Plant geometries ................................................................. 54
5.3.4 Boundary conditions ................................................................. 55
5.3.5 Community structure ................................................................. 56
5.4 Future work ................................................................. 57

6. RECOMMENDATIONS .................................................................... 59
7. REFERENCES .................................................................................. 61

APPENDIX I: MESHING STATISTICS ................................................................. 65
APPENDIX II: FLUX-VELOCITY PLOTS ................................................................. 67
Tables

Table 1. Common macrophyte species of the Swan-Canning catchment (Personal communication: Phoebe Mack, 2007) ........................................................................................................ 18
Table 2. Calculated drag area values ........................................................................................................ 45
Figures

Figure 1. Typical boundary layer (adapted from Fox, McDonald & Pritchard 2004) ............ 11
Figure 2. a) Drag coefficient as a function of Reynolds number for a smooth cylinder and a smooth sphere b) Typical flow patterns for flow past a circular cylinder for Reynolds number indicated in (a) (Kundu 1990) ................................................................. 13
Figure 3. Created geometry for Rod, with control volume outline .................................... 22
Figure 4. a) Baumea juncea (Western Australian Herbarium 2007) b) Created geometry for Baumea juncea ......................................................................................................................... 23
Figure 5. a) An example of emergent Baumea articulata (New South Wales Government 2007) b) created geometry for Baumea articulata.............................................................. 24
Figure 6. a) Detailed view of a Potamogeton crispus leaf (Martin 2002) b) Created leaf geometry ........................................................................................................................................ 24
Figure 7. a) Potamogeton crispus in the water column (Schloesser 1986) b) Sketch of Potamogeton crispus (USDA 2007) c) Created geometry for Potamogeton crispus ........ 25
Figure 8. Examples of structured (left) and unstructured (right) meshes (Bern & Plassmann 1999) .......................................................................................................................... 27
Figure 9. Delaunay triangulation method (Liu & Joe 1994) ...................................................... 27
Figure 10. The five types of bad tetrahedra (Bern & Plassmann 1999) .............................. 28
Figure 11. Angular resolution method for surface mesh generation (ANSYS Inc. 2007) .... 29
Figure 12. Created surface mesh for Baumea juncea ........................................................ 30
Figure 13. Created surface mesh for Baumea articulata ..................................................... 31
Figure 14. Created surface mesh for Potamogeton crispus ................................................ 32
Figure 15. Example placement of Nutrient sampling plane shown in a velocity field ....... 36
Figure 16. Calculated flux of Nutrient from Baumea juncea under different flow velocities 39
Figure 17. Calculated flux of Nutrient from Baumea articulata under different flow velocities ................................................................................................................................. 40
Figure 18. Calculated flux of Nutrient from Potamogeton crispus under different flow velocities ................................................................................................................................. 40
Figure 19. Turbulent wake generated by Baumea juncea, inlet velocity 5 cm/s ............... 41
Figure 20. Turbulent wake generated by Baumea juncea, inlet velocity 13 cm/s ............ 42
Figure 21. Turbulent wake generated by Baumea articulata, inlet velocity 5 cm/s ........... 42
Figure 22. Turbulent wake generated by Baumea articulata, inlet velocity 13 cm/s ........ 43
Figure 23. Turbulent wake generated Potamogeton crispus, inlet velocity 5 cm/s,........... 44
Figure 24. Turbulent wake generated by Potamogeton crispus, inlet velocity 13 cm/s ..... 44
Figure 25. Baumea juncea velocity and nutrient transport by planting density ............... 46
Figure 26. Baumea articulata velocity and nutrient transport by planting density .......... 47
Figure 27. Potamogeton crispus velocity and nutrient flux by planting density .............. 47
Figure 28. For inlet velocity 2 cm/s, a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity ................................................................. 48
Figure 29. For inlet velocity 21 cm/s, a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m$^2$ and resultant percentage reduction in channel velocity ................................................................. 49

Figure 30. Velocity flow field for Baumea articulata, inlet velocity 5 cm/s ......................... 52
1. Introduction

Poor water quality in urban waterways is an issue of national importance. Open drains are major contributors to urban water bodies as they are responsible for transmitting stormwater away from developed areas. This stormwater is often high in nutrients and contaminants such as heavy metals. Although nutrients such as nitrogen and phosphorus are essential to the function of marine ecosystems, overloading (known as eutrophication) is ultimately detrimental.

This project suggests a new method of controlling water quality in urban drains. It is proposed that macrophyte beds may be planted within the drains, reducing nutrient concentrations in the water they transmit. This is an environmentally sustainable method of improving water quality, and would also increase amenity around both the drain and receiving water body.

The planting of drains has previously gone untried by the Water Corporation, as by convention open drains are kept free of vegetation due to its baffling effect on stormwater flows. It is therefore necessary to balance nutrient removal against any loss of hydraulic capacity in the drain.

This project attempts to quantify both nutrient uptake and flow baffling by submerged macrophytes by use of a computational model. Computational fluid dynamics (CFD) allows the numerical simulation of fluid flows around the plants, from which inferences about nutrient transfer and flow baffling may be made.

Chapter 2 presents a review of relevant literature, describing the methods by which macrophytes draw nutrients from their environment, and the principles of open channel flow.

Chapter 3 describes the methods by which the model was created and the analysis techniques applied to its output. The model results are shown in Chapter 4.

Discussion of the model results and recommendations for the Water Corporation are contained in Chapters 5 and 6.
2. Literature Review

2.1 Site

Currently, the Swan River is under stress from “urban, industrial and agricultural runoff, industrial wastewater and groundwater contamination” (Government of Western Australia 2004). The combined influence of these inputs has resulted in the eutrophication of the Swan River. Symptoms of this include toxic algal blooms and fish kills (Thompson & Hosja 1996). Additionally, eutrophication lowers the recreational value of the Swan River and reduces amenity.

The Central Belmont Catchment, within the City of Belmont, has been identified as a major contributor of nutrients to the Swan River (Swan River Trust 1999). Within the catchment, the Central Belmont Main Drain is responsible for transporting the majority of stormwater to the Swan River. During winter, heavy flows both dilute nutrient concentrations in the drains and flush the Swan River estuary (Peters & Donohue 2001). However, during summer nutrient rich groundwater is the most significant water source in the drains, and they then transmit a significant nutrient load to the Swan River.

The drain has average Total Nitrogen and Total Phosphorus values of 1.01 mg/L and 0.16 mg/L respectively (Environmental Design (ENDP3601) Class 2006), which are only slightly above Swan-Canning Cleanup Program guidelines of 1 mg/L and 0.1 mg/L (Swan River Trust 1999). However, during summer peaks of >2 mg/L Total N and >0.5 mg/L Total P are often reached (Environmental Design (ENDP3601) Class 2006). Within Belmont a drainage section 50 m long has been set aside to trial the planting of macrophyte communities as a tool to reduce in-channel nutrient concentrations, the focus of this study.

2.2 Macrophyte communities

Macrophytes have long been noted for their ability to remove nutrients from the water column by assimilation and sedimentation processes (Howard-Williams 1981; Cattaneo & Kalff 1980). As a direct result of this, and as part of the growing field of ecological engineering, in the early 1980s macrophytes were introduced as a wastewater treatment and water polishing method (Brix & Schierup 1989; Gu et al. 2001).
Several different macrophyte aquatic treatment systems have been previously constructed, including free-floating systems, submerged wetlands and emergent wetlands (Gumbricht 1993). The effectiveness (and appropriateness) of each system is dependant on local conditions. The open drains which are the focus of this study provide submersive, free flowing conditions which are appropriate for a submerged macrophyte system.

### 2.2.1 Nutrient removal processes

Macrophytes aid in nutrient removal by both biotic and abiotic processes. Biotic processes include assimilation by vegetation, plankton, periphyton and micro-organisms, while abiotic processes include sedimentation, adsorption to sediments/soils, precipitation and sediment/water column exchange processes (Reddy et al. 1999).

Aquatic vascular plants are able to acquire nitrogen and phosphorus from the water column via uptake across shoot and leaf surfaces, and from the sediments through their roots (Viaroli et al. 1996). Carignan (1982) explored the relative rates of phosphorus uptake from sediment pore water and the water column, and found that for a relative concentration of soluble reactive phosphorus of 3.3:1.0, uptake from the two sources was roughly the same. At ratios lower than this, the water column was found to be the principle source. Thus, for the conditions found in this study (high water column nutrient concentrations) any planted macrophytes would uptake a significant proportion of nutrients from the water column.

### 2.2.2 Macrophyte-epiphyte dynamics

Rooney and Kalff (2003) confirmed the importance of the water column as a nutrient source for submerged macrophytes. However, they demonstrated that while the presence of their experimental macrophyte bed significantly reduced nutrient concentrations in the water column, nutrient loading by the macrophyte bed itself was negligible when compared to the production of epiphytic organisms attached to the plant surfaces.

This result has been confirmed many times over (Cattaneo & Kalff 1980; Howard-Williams 1981; Pelton, Levine & Braner 1998; Wade et al. 2001): macrophyte blades are regularly covered by epiphytic organisms and these organisms cycle nutrients at far higher rates than the macrophytes themselves. The rate of epiphytic nutrient uptake is therefore pivotal in the rate of nutrient removal of a macrophyte bed and, significantly for this study, the epiphytes uptake nutrients purely from the water column (Cornelisen & Thomas 2004).
2.3 Plant-water interactions

The rates at which submerged vegetation exchange nutrients, gases and waste with the water column are controlled by processes occurring at the plant-water interface. Two main processes dictate the rate of nutrient exchange across this boundary: mass transfer across the thin water layer adjacent to the boundary, and the reaction kinetics at the active surface (Sanford & Crawford 2000). Commonly in macrophyte communities the demand for nutrients is greater than the rate of physical transfer, and thus nutrient uptake is mass transfer controlled (Cornelisen & Thomas 2002). This is the basis upon which the conducted modelling work is built.

2.3.1 Reaction kinetics

If low enough, nutrient uptake from the water column by submerged organisms is controlled by concentration of the nutrient. Under these circumstances the rate of uptake may be described most simplest by (Hemond & Fechner-Levy 2000):

\[ R = kC_0 \]

Where \( R \) is the reaction rate, \( k \) is the reaction constant and \( C_0 \) is the initial concentration of the reactant. Here the reaction rate is dependant on concentration, but does will not saturate at high concentrations i.e. the rate is unbounded. Commonly in ecological problems the reaction rate is limited to some upper bound (e.g. Atkinson & Davies 1974), in which case the reaction rate may be given as (Hemond & Fechner-Levy 2000):

\[ R = \frac{V_m C_0}{K_m + C_0} \]

Where \( V_m \) is the maximum uptake rate and \( K_m \) is the concentration at which the uptake rate is half its maximum. This equation is known as Monod kinetics.

In the case of submerged macrophytes, the reaction rate is generally controlled by \( C_0 \) and not by \( V_m \), meaning nutrient uptake is limited by mass transfer (Larned, Nikora & Biggs 2004; Pasciak & Gavis 1974; Riber & Wetzel 1987).

2.3.2 Mass transfer

Mass transfer describes the rate at which the water column can supply the surface of the active organism with the required reactant. The main restraint on mass transfer is a boundary layer adjacent to the active surface of the vegetation (Larned, Nikora & Biggs 2004; Pasciak & Gavis 1974; Riber & Wetzel 1987).
The boundary layer is formed as vegetation uptakes nutrients and a concentration gradient between the plant and the ambient water forms (see Section 2.5.1 for further explanation of the boundary layer concept).

The diffusive boundary layer acts to retard the physical transfer of nutrients to the vegetation (Pasciak & Gavis 1974). Diffusion rates across the layer are influenced by its thickness, and the steepness of the gradient. In turn, these properties are governed by water velocity, chemical concentration and surface roughness and topography (Jousse, Jongen & Agterof 2005; Reidenbach et al. 2006; Thomas, Cornelisen & Zande 2000).

### 2.3.3 Plant influences on flow

Flow properties can impact on nutrient uptake rates, for example it has been shown an oscillatory flow has a positive influence on uptake when compared to unidirectional flow (Hurd 1999; Lowe et al. 2005) and higher water velocities also generally yield higher uptake rates (Cornelisen & Thomas 2002; Sand-Jensen & Pedersen 1999; Nishihara & Ackerman 2006).

However, it is mainly the plants’ own properties that dictate their uptake rates. In streams, flow fields are strongly modified by the presence of submerged plants. This can occurs on a large scale involving entire stream reaches, and on a small scale involving individual plant strands (Helmouth, Sebens & Daniel 1997; Reidenbach et al. 2006). Specifically, plant morphology and surface roughness alter local hydrodynamic conditions (Stevens & Hurd 1997). By increasing drag and turbulence intensity, which then disturbs any present boundary layer, a plant may increase mass transport to itself as well as any adjacent downstream vegetation (Nepf 1999).

### 2.4 Turbulence

Flows involving viscous fluids may be classified as either laminar or turbulent. Fluid particles experiencing laminar flow move in smooth layers (laminas), while those under turbulent flow experience random three-dimensional velocity fluctuations as they move (Fox, McDonald & Pritchard 2004).

The apparently random three-dimensional fluctuations in motion exhibited by turbulent flows are primarily the result of eddies. Eddies are irregular whirls of random fluid motion, and are the dominant process responsible for mixing within turbulent flows. In a fully developed turbulent flow, a continuous spectrum of eddies exist. Energy cascades from larger eddies to successively smaller ones, until the kinetic energy of eddies at the
smallest permissible length scale is dissipated by viscosity into heat (Rubin & Atkinson 2001).

Often, the Reynolds number is used to distinguish between laminar and turbulent flow. Laminar flows exhibit low Reynolds numbers while turbulent exhibit high Reynolds numbers. Reynolds number is defined below (Equation 3), where \( u \) is the characteristic velocity of the flow, \( l \) the characteristic length (channel width or rod diameter, for example) and \( \nu \) the kinematic viscosity of the fluid in motion (Rubin & Atkinson 2001).

\[
\text{Equation 3} \quad \text{Re} = \frac{u \cdot l}{\nu}
\]

In environmental flows, turbulence is responsible for the majority of mixing and energy dissipation. Under a laminar regime, mixing is limited to only molecular diffusion, a relatively slow procedure occurring in the order of \( 10^{-6} \) to \( 10^{-8} \) m\(^2\)s\(^{-1}\) (Rubin & Atkinson 2001). In turbulent flows, mixing occurs by a combination of molecular diffusion, turbulent diffusion and shear. Also, while laminar flows dissipate only small amounts of energy, turbulent flows are strongly dissipative and decay rapidly without a continuous energy source.

Thus, by increasing turbulence in the surrounding flow, a submerged plant may increase the rate of nutrient transfer to itself by increasing local mixing rates. Additionally, the increased turbulence results in the dissipation of energy, slowing the flow.

### 2.4.1 Mean turbulence

Turbulent flow may be considered as the combination of a time-averaged mean component and a fluctuating component such that the velocity \( u \) at any time may be given by:

\[
\text{Equation 4} \quad u = \overline{u} + u'
\]

Where \( \overline{u} \) is the time-average of \( u \), described by:

\[
\text{Equation 5} \quad \overline{u} = \frac{1}{T} \int_{0}^{T} u \, dt
\]

Where \( T \) is the time period for the average. As a consequence of the above:

\[
\text{Equation 6} \quad \int_{0}^{T} u' \, dt = 0
\]
2.4.2 Statistical representation of turbulence

Turbulent fluctuations are considered as realisations of a random process. Due to this, it is sometimes more convenient to describe turbulence in a terms of the statistical properties of the flow field.

The displacement of a particle \( x \) at time \( t \) may be considered as a random variable with a normal distribution. The statistical properties of \( x \) such as the mean, variance and correlation coefficients may be found by repeated sampling. For example, after \( N \) sampling events the ensemble average of fluid velocity \( \bar{u} \) is given by:

\[
\bar{u} = \frac{1}{N} \sum_{i=1}^{N} u_i
\]

2.4.3 Navier-Stokes

The motion of all fluids, turbulent or not, are bound by the governing dynamical equations for a fluid. The Navier-Stokes equations state that the changes in momentum in infinitesimal fluid volumes are the sum of changes in pressure, gravity and dissipative viscous forces. In an inertial frame of reference (i.e. one which is neither accelerating nor rotating) the general form of the Navier-Stokes equations is (Fox, McDonald & Pritchard 2004):

\[
\rho \left[ \frac{\partial x_i}{\partial t} + (x_j \cdot \nabla) x_j \right] = -\nabla p + \nabla T + \rho g_i
\]

Where \( \rho \) is fluid density, \( x_i \) is the \( i \)th component of fluid velocity, \( p \) is static pressure, \( g_i \) is the influence of gravity in the direction of the fluid velocity component and \( T \) represents the viscous stresses.

Apart from cases exhibiting the most simplified geometries and boundary conditions, solutions of the Navier-Stokes equations are generally very difficult to find. Solutions to the equation set give the velocity of a fluid at a particular place in space and time, and are known as flow fields. Once the flow field is known other quantities such as flow rate and drag force (explored below) may be found.

2.4.4 Reynolds averaging and Reynolds stress

The separation of turbulent flows into mean and fluctuating components (Section 2.4.1) is also known as Reynolds decomposition or Reynolds averaging. When applied to the Navier-Stokes equations, the result is (Rubin & Atkinson 2001):
Equation 9
\[
\rho \frac{\partial \overline{u}_i}{\partial t} + \frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} = \rho \overline{f}_i + \frac{\partial}{\partial x_j} \left[ -p\overline{\delta}_j + \mu \left( \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) - \rho \overline{u}_i \overline{u}_j \right]
\]

Where an overbar indicates a time-averaged value. The non-linear term \( \rho \overline{u}_i \overline{u}_j \) is known as the Reynolds stress, a stress tensor quantifying the random turbulent fluctuations in the fluid momentum. Reynolds stresses have a similar effect to viscous stresses, however their physical basis is the fluctuating flow field instead of fluid viscosity.

### 2.4.5 Turbulent kinetic energy

Turbulent kinetic energy (TKE) is a quantitative measure of turbulence intensity. Assuming, as described in Section 2.4.1, a flow may be separated into mean and turbulent parts, the kinetic energy of the flow is then the sum of the kinetic energy in each part. For a three dimensional flow, the kinetic energy possessed by the mean flow is given by Equation 10, and the kinetic energy for the turbulent part (i.e. the TKE) is given by Equation 11 (Rubin & Atkinson 2001).

**Equation 10**
\[
MKE = \frac{1}{2} \left( \overline{u}^2 + \overline{v}^2 + \overline{w}^2 \right)
\]

**Equation 11**
\[
TKE = \frac{1}{2} \left( \overline{u}'^2 + \overline{v}'^2 + \overline{w}'^2 \right)
\]

The general form of the TKE conservation equation, derived from the Navier-Stokes equations, can be seen below where TKE is represented by \( K \) (Rubin & Atkinson 2001).

**Equation 12**
\[
\frac{DK}{Dt} = \frac{\rho \overline{u}_i}{\rho_0} g_i - \frac{\partial}{\partial x_j} \left( \frac{\rho \overline{u}_i}{\rho_0} - v^2 \frac{\partial K}{\partial x_j} + \frac{1}{2} \overline{u}_i \overline{u}_j \right) \overline{u}_j - \overline{u}_i \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} - v \left( \frac{\partial \overline{u}_i}{\partial x_j} \right)^2
\]

The first term on the right hand side accounts for gravity or buoyancy work, the second term is known as flux divergence and refers to the redistribution of mean kinetic energy by pressure and shear stresses, the third term is the rate of work of the Reynold stresses to convert mean kinetic energy to TKE, known as shear production, and the final term accounts for the dissipation of mean kinetic energy into heat.

### 2.4.6 Turbulent dissipation

The final term in Equation 12 is known as turbulent dissipation, and sometimes abbreviated as \( \varepsilon \). It represents the rate of dissipation of turbulent energy per unit mass. The formal equation for the rate of change of \( \varepsilon \), obtained again from the Navier-Stokes equations is (Rubin & Atkinson 2001):
\[
\frac{D\varepsilon}{Dt} = -2\nu \left( \frac{1}{\rho_0} \frac{\partial}{\partial x_k} \left( \frac{\partial u_i}{\partial x_j} \frac{\partial p}{\partial x_j} \right) + \frac{1}{2} \frac{\partial}{\partial x_k} \left[ \frac{\partial u_j}{\partial x_i} \left( \frac{\partial u_i}{\partial x_j} \right)^2 \right] + \frac{\partial u_j}{\partial x_i} \frac{\partial u_i}{\partial x_k} \frac{\partial u_k}{\partial x_j} \right) \\
+ \nu \left( \frac{\partial^2 \varepsilon}{\partial x_i \partial x_k} \right)
\]

Equation 13

Turbulent dissipation is a common tool in Computational Flow Dynamics (see Section 2.6). When combined with TKE, it forms the basis for many attempts at second-order closure of turbulence modelling problems.

### 2.5 External incompressible viscous flows

#### 2.5.1 Boundary layers

The boundary layer concept was first introduced by Ludwig Prandtl in 1904 (Fox, McDonald & Pritchard 2004). He suggested that in order to satisfy the conditions imposed by viscous flow, it is necessary during analysis to separate the flow into two parts: a thin boundary layer close to solid boundaries, and the rest of the flow. Inside the boundary layer, both viscous and inertia forces are important, while outside viscous forces may be neglected (inviscid flow).

The formation of a boundary layer is a direct consequence of a “No-Slip” condition at the surface of a solid body with which the flow is interacting. This condition requires that the flow velocity at any point on the surface is zero. Assuming a constant pressure and velocity above the layer, a velocity gradient will form between the stationary body surface and the inviscid flow above: the boundary layer. This is illustrated below, in Figure 1.
There are several techniques used to describe the thickness of a present boundary layer. The disturbance thickness \( \delta \) is one such method, which is defined as the distance from the body surface at which the velocity is within 1 % of the free-stream velocity i.e. \( u \approx 0.99U \) (Rubin & Atkinson 2001).

Two other common definitions are displacement thickness (\( \delta^* \)) and momentum thickness (\( \theta \)). These are based on the idea that a boundary layer acts to retard fluid and so mass and momentum flux are less than they would be in the absence of a boundary layer. They both refer to the distance from the body surface a plate would need to be placed in order to reduce either the mass or momentum flux by the same amount as the boundary layer. They are expressed in Equation 14 and Equation 15 below, where \( u \) is the velocity inside the boundary layer, and \( U \) is the free-stream velocity (Fox, McDonald & Pritchard 2004). It is important to note that in all cases the size of the boundary layer is inversely proportional to free-stream velocity.

**Equation 14**

\[
\delta^* = \int_0^\infty \left(1 - \frac{u}{U}\right)dy \approx \int_0^{\delta} \left(1 - \frac{u}{U}\right)dy
\]

**Equation 15**

\[
\theta = \int_0^\infty u \left(1 - \frac{u}{U}\right)dy \approx \int_0^{\theta} u \left(1 - \frac{u}{U}\right)dy
\]

**Mass transfer**

The formation of a velocity gradient within the layer is a result of the diffusion of momentum from the wall into the flow. By similar methods, boundary layers relating to
mass transfer may form. The basic differential equation for mass diffusion in one dimension is (Rubin & Atkinson 2001):

\[
\frac{\partial C}{\partial t} = k_m \frac{\partial^2 C}{\partial y^2}
\]

Where \( C \) is mass concentration and \( k_m \) is mass diffusivity. For a two-dimensional case of a flat plate of concentration \( C_0 \) diffusing into a semi-infinite domain of initial concentration zero, it may be said (Rubin & Atkinson 2001):

\[
\frac{C}{C_0} = f\left(\frac{y}{\delta}\right)
\]

Where again \( \delta \) is boundary layer thickness. By substitution and integration a formula for boundary-layer thickness emerges:

\[
\delta^2 = -k_m \int_0^\infty f \, d \frac{y}{\delta}
\]

### 2.5.2 Body force and drag

Whenever there is relative motion between a solid body and a surrounding viscous fluid, the body will experience a net force \( F \). The magnitude of this force is primarily dependant on the surrounding fluid velocity and the body’s shape and size. The net force may be resolved into the drag force \( F_D \), the component of the force parallel to the direction of fluid motion, and the lift force \( F_L \) (if present), the component of the force perpendicular to the direction of motion (Fox, McDonald & Pritchard 2004).

The drag equation, shown below in Equation 19, relates the drag force experienced by a body to its drag area \( C_D A_f \) (Fox, McDonald & Pritchard 2004).

\[
F_D = \frac{1}{2} \rho C_D A_f U^2
\]

Drag area is the product of the drag coefficient \( C_D \), a dimensionless quantity characterising the amount of drag caused by a particular body under fluid flow and \( A_f \), the area presented by the body that is perpendicular to the direction of fluid motion. Provided the Reynolds number of the flow is high enough to create a turbulent wake, the drag coefficient of a particular body is constant under changing velocity. This point is illustrated in Figure 2, which shows the drag coefficient of a smooth cylinder as a function of Reynolds number.
Figure 2. a) Drag coefficient as a function of Reynolds number for a smooth cylinder and a smooth sphere b) Typical flow patterns for flow past a circular cylinder for Reynolds number indicated in (a) (Kundu 1990)

2.5.3 Channel flow

The open surface drains which are the subject of this study are examples of common channel flow. The net forces acting on fluids held within a channel are shear stress along the channel boundary and gravity. Assuming an otherwise lossless channel (e.g. neglecting wall friction terms), velocity down a channel is given by the product of gravity and the channel slope. If a solid body possessing drag coefficient $C_D$ is introduced to the channel, the resultant balance between drag forces and acceleration due to gravity may be expressed by (Rubin & Atkinson 2001):

\[
\frac{1}{2} C_D a U^2 = g_s S
\]

Where $a$ is the surface area presented by the submerged body per unit channel volume.

2.6 Computational Flow Dynamics

Computational Flow Dynamics (CFD) is the use of computer-based models to describe and predict environmental fluid flows. It was popularised during the 1970s, when technological breakthroughs allowed the solution of equation sets describing fluid flows that were previously too laborious to work through.
The main challenge presented within CFD is the accurate description of turbulence (Spalart 2000). Nearly all engineering problems are turbulent and thus require a turbulence model. In general, mathematical models of turbulence are created by augmenting the governing (Navier-Stokes) equations for fluid motion with additional differential terms designed to represent how turbulence is created and dissipated, and the influences it exerts within the fluid flow.

Most popular turbulence models use only two equations in addition to the Navier-Stokes equations. The first is generally a term for turbulent kinetic energy, commonly abbreviated to $k$ (see Section 2.4.5). The second term may involve the dissipation of turbulent energy or measure fluctuations in vorticity, or some combination of the two. Generally, the first equation determines the energy in the turbulence while the second equation determines the scale of turbulence (either length scale or time scale). The emergence of two-equation turbulent models was predicted by Kolmogorov (1942), who first characterised turbulence by its fluctuation energy, which is only a factor of two-thirds different to $k$ used today, and frequency, which when multiplied by fluctuation energy is proportional to turbulent dissipation (see Section 2.4.6) (Spalding 1991).

### 2.6.1 k-Epsilon

The k-Epsilon ($k-\varepsilon$) model was first proposed by Harlow and Nakayama (1968), and is derived and described at length in Launder and Spalding (1974). It is one of the most common two-equation models, including transported variables $k$, the turbulent kinetic energy, and $\varepsilon$, turbulent dissipation. Energy within the turbulence is determined by $k$, while $\varepsilon$ controls the scale of the turbulence.

The model may be derived directly from the incompressible Navier-Stokes equations. For turbulent energy $k$:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho \varepsilon
\]

Where $\sigma_k = 1$ is a model constant, and $P_k$ is turbulence production due to viscous and buoyancy forces.
For turbulent dissipation $\varepsilon$:

Equation 22

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right]$$

$$+ C_{1e} \frac{\varepsilon}{k} \left( P_k + C_{3e} P_b \right) - C_{2e} \rho \frac{\varepsilon^2}{k}$$

Where typically $C_{1e} = 1.44$, $C_{2e} = 1.44$, $C_{3e} = 0.09$ and $\sigma_\varepsilon = 1.0$.

Turbulent velocity $\mu_t$ is modelled as:

Equation 23

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

The model works well for turbulent flows, however further terms must be introduced for near-wall areas where viscous forces dominate (i.e. boundary layers) (Tutar & Hold 2001).

### 2.6.2 k-Omega and the Shear Stress Transport model

The k-Omega ($k - \omega$) model, like the $k - \varepsilon$ model, includes two additional equations to characterise turbulence. These are $k$, the turbulent kinetic energy, and $\omega$, specific dissipation. Within $k - \omega$ models turbulent kinetic energy is calculated by:

Equation 24

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho ku_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_k \mu_t \right) \frac{\partial k}{\partial x_j} \right] + P_k - \beta^* \rho \omega^2$$

Where the model constants are $\beta^* = 0.09$ and $\sigma_k = 2$. Similar to the $k - \varepsilon$ treatment, $P_k$ is turbulence production due to viscous and buoyancy forces.

Specific dissipation is calculated by:

Equation 25

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_\omega \mu_t \right) \frac{\partial \omega}{\partial x_j} \right] + \alpha \frac{\omega}{\tau} P_k - \beta \rho \omega^2$$

Where the model constants are $\beta = 0.075$, $\sigma_\omega = 2$ and $\alpha = \frac{3}{\tau}$.

The Shear Stress Transport (SST) model is an example of a two-equation k-Omega model. It was first proposed by Menter (1994) as a reaction to the perceived failings of the k-Epsilon model, which is unable to properly recreate the behaviour of turbulent boundary layers up to the point of separation.
$k \sim \omega$ models have proved to be substantially more accurate than $k \sim \varepsilon$ models in near-all (boundary) layers. However, it has been shown that the $\omega$ equation is overly sensitive to $\omega$ in the free-stream (Menter, Kuntz & Langtry 2003). The SST model overcomes this by a zonal formulation, which determines near-wall areas to be evaluated using $k \sim \omega$ methods and free-stream areas for evaluation by $k \sim \varepsilon$ methods.
3. Methods

This project sets out to analyse, by way of a CFD model, the ability of several submerged macrophytes to uptake nutrients from the water column. Ancillary to this data, the model output will include the forces applied by the water to the plant body, which assuming mass-transfer limited conditions will allow the formulation of a relationship between nutrient uptake and allowed channel velocity.

There were four phases involved in this project: the selection of plants for modelling, the recreation of the geometry of the chosen plants and their underwater domain within the computer-based model, the division of the model into a series of discrete sub-domains within which the governing flow equations may be solved and the definition of model input parameters such as flow velocity and nutrient diffusivity. These four phases are outlined in Sections 3.1 to 3.4 below.

ANSYS, Inc. created the software package ANSYS Workbench which allows the completion of the latter three outlined phases, along with resolution of the final created problem. This project utilises ANSYS Workbench for all computer-based modelling tasks.

3.1 Plant selection and characterisation

GHD, under instruction of the Water Corporation, have carried out preliminary work at the Paterson Road site. Phosphorus and nitrogen have been monitored under high and low flow conditions. In association with South East Regional Centre for Urban Landcare (SERCUL), the Water and Rivers Commission and the West Australian Herbarium, GHD prepared a list of macrophyte species common to the Canning River catchment. Phoebe Mack (GHD) conducted an assessment of their suitability to drainage planting. Her results are summarized in Table 1, overleaf, describing the growth characteristics and preferred environments of selected macrophytes.

From this table, three plants were selected for modelling: Baumea juncea, Baumea articulata and Potamogeton crispus. While GHD nominated eight species for their planting trials, this project was limited to three species by time and computational constraints. The methods outlined in Sections 3.2 to 3.5 infer nutrient uptake and flow baffling from plant morphology, so species were selected for modelling that would provide a range of morphologies. The appearance of the modelled species is further detailed in Section 3.2, below.
<table>
<thead>
<tr>
<th>Species (Common name)</th>
<th>Description</th>
<th>Nature of growth</th>
<th>Species acceptance or rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Potamogeton crispus</strong> (Curly Pondweed or Water Ribbon)</td>
<td>• Rhizomatous&lt;br&gt;• Submerged aquatic perennial herb&lt;br&gt;• Leaves narrow ovate, margins crisped&lt;br&gt;• Flower green-brown (July-May)&lt;br&gt;• Flat branch stems 1-3 m long, leaves 10 cm wide</td>
<td>• Grows rapidly and prolific in waterways of the region, likely to become present without deliberate planting&lt;br&gt;• Grows in slowly flowing freshwater up to 2.5 m, also tolerant of slightly saline water common in drains&lt;br&gt;• Growth from Oct- Dec. Annual dieback in January&lt;br&gt;• Also easier to harvest as floating so may rake or boom&lt;br&gt;• Preferred soil type: mud</td>
<td>Yes, selected for planting due to:&lt;br&gt;• High nutrient uptake capacity&lt;br&gt;• Ease with which harvesting may occur&lt;br&gt;• Is already present in waterway</td>
</tr>
<tr>
<td><strong>Potamogeton pectinatus</strong> (Fennel Pondweed)</td>
<td>• Rhizomatous&lt;br&gt;• Submerged aquatic perennial herb&lt;br&gt;• Linear leaves&lt;br&gt;• Flowers green-yellow from Oct-Jan</td>
<td>• Grows in fresh or saline waters including lakes, creek, rivers and streams&lt;br&gt;• Tolerates water to 3 m</td>
<td>Not selected:&lt;br&gt;• One pondweed species considered sufficient</td>
</tr>
<tr>
<td><strong>Potamogeton ochreatus</strong> (Blunt Pondweed)</td>
<td>• Rhizomatous&lt;br&gt;• Submerged aquatic perennial herb&lt;br&gt;• Linear leaves&lt;br&gt;• Flowers green-brown from Sep-Mar</td>
<td>• Grows in freshwater dams, lakes, swamps and rivers&lt;br&gt;• Preferred soil type: Mud or gravel substrate</td>
<td>Not selected:&lt;br&gt;• One pondweed species considered sufficient</td>
</tr>
<tr>
<td><strong>Potamogeton drummondii</strong></td>
<td>• Rhizomatous&lt;br&gt;• Emergent aquatic perennial herb&lt;br&gt;• Broad leaves&lt;br&gt;• Flowers green from Oct-Feb</td>
<td>• Grows in freshwater lakes, rivers, swamps and dams</td>
<td>Not selected:&lt;br&gt;• One pondweed species considered sufficient</td>
</tr>
<tr>
<td><strong>Juncus kraussii</strong> (Sea Rush)</td>
<td>• Rhizomatous&lt;br&gt;• Perennial herb&lt;br&gt;• Flowers brown-red from Oct-Jan</td>
<td>• Likes flood plain&lt;br&gt;• Easy to grow and attain&lt;br&gt;• Growth 0.3 – 1.2 m high&lt;br&gt;• Preferred soil type: White or grey sand,</td>
<td>Yes, selected for planting due to:&lt;br&gt;• Ease of growth&lt;br&gt;• Appropriate soil type&lt;br&gt;• Appropriate water depth</td>
</tr>
<tr>
<td>Plant Name</td>
<td>Plant Characteristics</td>
<td>Habitat Requirements</td>
<td>Selection Notes</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>---------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Juncus pallidus (Pale Rush)</td>
<td>Rhizomatous, Robust perennial herb, Flowers green from Oct-Dec</td>
<td>Does not like to be inundated and can tolerate dryness, Grows 0.5-2 m high, Preferred soil type: Clay, Grows in swamps, watercourses</td>
<td>Not selected: Preferred soil type not compatible to site conditions</td>
</tr>
<tr>
<td>Eleocharis acuta (Common Spikerush)</td>
<td>Rhizomatous, Perennial, grass-like or herb (sedge), Flowers brown from Sep-Dec</td>
<td>Grows to 0.7 m, Excellent grower, commonly spreads in between other sedges, Dies back annually with risk of not growing back, Prefers to dry out over summer, Preferred soil type: Brown sandy clay peat, Grows in swamps, clay pans</td>
<td>Not selected due to: Annual dieback characteristic, Inappropriate preferred soil type</td>
</tr>
<tr>
<td>Ottelia ovalifolia (Swamp Lilly)</td>
<td>Tufted aquatic perennial or annual with submerged and floating leaves and flowers, Submerged leaves strap-like; floating leaves with lamina elliptic to 16 cm long, 3-6 cm wide, petiole to 1 m long, Chasmogamous flowers emergent; green and white with maroon base from Oct-May, Cleistogamous flowers submerged with reduced perianth segments</td>
<td>Grows in stationary and slowly flowing freshwater to 1 m, Usually prefers water with high nutrient levels indicative of high nutrient uptake capacity</td>
<td>Yes, selected for planting: Currently prolific in SAT waterway, thus will be harvested and transplanted</td>
</tr>
<tr>
<td>Typha domingensis (Bulrush or Narrow-leaved Cumbungi)</td>
<td>Rhizomatous, Monoeicous emergent perennial herb, Flowers brown May-Sep</td>
<td>Although native, is commonly unpopular as can easily hybrid to alien weed Typha orientalis, Grows through low flow period and dies off annually, thus if not harvested</td>
<td>Yes, selected for planting due to: Ease of growth, Appropriate soil type, Appropriate water depth, Very high nutrient uptake</td>
</tr>
</tbody>
</table>
| **Baumea vaginalis** (Sheath Twigrush) | **Rhizomatous**  
| Robust, tufted perennial, grass-like or herb (sedge)  
| Flowers brown from Oct-Nov | Grows 0.6 – 1.5 m high, to 1.5 m wide  
| Preferred soil type: Dark brown sand  
| Grows in winter-wet depressions along watercourses | Not selected:  
| Less common than other Baumea species |
| **Baumea juncea** (Bare Twigrush) | **Rhizomatous**  
| Colonising perennial, grass-like or herb (sedge)  
| Flowers brown-grey from Oct-Mar | Grows 0.2-1.2 m  
| Preferred soil type: Dark grey sand, waterlogged soils  
| Grows in both dry and inundated conditions and can cope with fluctuations | Yes, selected for planting as is:  
| Ideal size  
| Able to handle water level fluctuations |
| **Baumea rubiginosa** | **Rhizomatous**  
| Colonising perennial, grass-like or herb (sedge)  
| Flowers brown from Aug-Mar | Grows to 4 m high and 2 m wide  
| Grows in streams and swamps | Not selected:  
| Grows too high |
| **Baumea articulata** (Jointed Rush) | **Rhizomatous**  
| Robust perennial, grass-like or herb (sedge)  
| Flowers red-brown from Jan-Dec, pendulous | Growth 1-2.6 m  
| Tolerates water to 0.7 m  
| Presented aggressive growth in previous projects, can overrun other species  
| Preferred soil type: wet or waterlogged, black sand  
| Grows in seasonal swamps, and along borders of lakes | Yes, selected for planting:  
| Ideal water depth tolerance  
| Aggressive growth indicative of high nutrient-stripping capabilities |
| **Schoenoplectus validus** (Lake Club-rush) | **Rhizomatous**  
| Robust perennial, grass-like or herb (sedge) | Grows 0.8-2 m  
| Prolific growth rates which can overrun other species, however high nutrient uptake capacity  
| Preferred soil type: Silt and sand  
| Grows in fresh or brackish water, swamps and estuaries | Not selected:  
| Observed to overrun species in past projects |
| Ficinia nodosa (Knotted Club-rush) | • Caespitose rhizomatous  
• Erect, perennial herb (sedge)  
• Flowers brown-cream from Oct-Jan | • Tolerant of drying  
• Grows to 1 m high and 0.8 m wide  
• Preferred soil type: Bare white calcareous, dark sandy clay, granite and limestone  
• Grows in coastal dunes, flats, seasonally wet swampland and on the shores of salt lakes | Yes selected for planting:  
• Tolerates drying and seasonally wet areas  
• Ideal for floodplain bank top |
| Patersonia occidentalis (Purple Flag) | • Rhizomatous  
• Tufted perennial herb  
• Flowers blue-purple from Sep-Jan | • Grows 0.25-0.7 m high  
• Preferred soil type: Grey, yellow or white sand, lateritic gravel, granite or sandy clay | Yes, selected for planting:  
• Tolerates drying and seasonally wet areas  
• Ideal for floodplain bank top |
3.2 Geometry creation

Once an appropriate set of species was found, representative geometries were created within DesignModeler, the Computer Aided Design-based software included within the ANSYS Workbench package. Computational restrictions required that each species be limited a single specimen, and so geometries were created to represent major morphological features, such as branch diameter and leaf shape. One limitation is that DesignModeler requires all created bodies to be completely rigid, unable to react to motion in the water column. While the form of rush species such as Baumea juncea and Baumea articulata would generally not be greatly influenced by water motion, soft tissue species such as Potamogeton crispus tend to move with the flow of water. This is explored further in Section 5.3.

3.2.1 Test geometry

In order to test the sensitivity of model input parameters, a simple geometry which would take a relatively small amount of time to resolve was created. A smooth rod 60 mm high with a diameter of 4 mm was created within a control volume of dimensions 60 x 100 x 200 mm.

![Created geometry for Rod, with control volume outline](image)

**Figure 3.** Created geometry for Rod, with control volume outline
3.2.2 Plant geometries

*Baumea juncea*

Baumea juncea grows to between 0.2 and 1.2 m (Western Australian Herbarium 2007). Due to its growth characteristics (colonising perennial), the geometry was created to represent a fully-grown specimen. Branch diameter was set constant at 20 mm, and a thick area was created at the base of the geometry to represent root mass. An example of Baumea juncea and the created geometry are shown below in Figure 4.

![Baumea juncea geometry](image)

**Figure 4.** a) Baumea juncea (Western Australian Herbarium 2007) b) Created geometry for Baumea juncea

*Baumea articulata*

Baumea articulata is similar in appearance to Baumea juncea, however its stems are generally thinner and more tightly packed. Baumea articulata stems were created with a diameter of 6 mm, reflecting the 4 – 10 mm range found in the field. The created geometry appears alongside an example of Baumea articulata below in Figure 5.
**Potamogeton crispus**

The geometric modelling of *Potamogeton crispus* occurred in two phases: creation of a leaf structure and creation of a stem structure. The leaf was created with a flat spine 4 mm in width. Care was taken to represent the curved tissue at the edges the leaf; the surface was interpolated from the spine outwards to a pattern of alternating semi-circles of radius 4 mm. Filets were also taken from the four vertices. The final leaf, illustrated below in Figure 6, is 1 mm thick and at its largest points measures 20 x 80 mm.

**Figure 5.** a) An example of emergent *Baumea articulata* (New South Wales Government 2007) b) created geometry for *Baumea articulata*

**Figure 6.** a) Detailed view of a *Potamogeton crispus* leaf (Martin 2002) b) Created leaf geometry
In creating the stem section of the Potamogeton crispus geometry an attempt was made to reflect the form an average specimen would take when submerged. The stem, 10 mm in diameter, branches loosely in several areas and tends in the direction of the flow as it moves away from the channel floor. Leaves were then attached to the stem in a manner representing their submerged alignment. Figure 7 illustrates these features.

![Figure 7. a) Potamogeton crispus in the water column (Schloesser 1986) b) Sketch of Potamogeton crispus (USDA 2007) c) Created geometry for Potamogeton crispus](image)

**3.2.3 Control volume**

The plant geometries were placed in a control volume of height 500 mm, representing an average channel water depth. Spalart (2000) suggested that in order to properly capture the influence of an object on a flow, the model domain should extend either side of the modelled object a distance at least twice its diameter. This rule was taken as a minimum. In extending the domain along the line of fluid motion a conservative approach was taken: upstream a similar approach to cross stream dimensions was taken, while the downstream an area more than large enough to resolve the expected downstream wake was created. The size of the model domains relative to the plant geometries is illustrated below in Section 3.3.2.

The model domain was not created to emulate the exact dimensions of a typical surface drain. Instead, it was made to reflect the conditions a single specimen may encounter within a channel. That is, the top and bottom of the domain were created an appropriate distance apart to reflect average water depth, but cross and along stream dimensions were created large enough so that flow around the plant would not be influence by them.
3.3 Mesh generation

Numerical solutions for the partial differential equations governing fluid flow and heat transfer are generally very hard to find, except in the most simple of cases. For this reason it is necessary to divide the nominated flow domain in many smaller sub-domains, where it may be possible to numerically solve discretised governing equations. Sub-domains are known individually as elements or cells, and collectively as the domain mesh or grid.

When dividing the flow domain it is important to ensure solution continuity between sub-domains such that the entire solution gives an accurate description of fluid flow. The process of finding an appropriate mesh for a given flow domain is not an exact art, and many algorithms have been suggested. These may be classified into two categories: structured meshes and unstructured meshes, examples of which may be seen below in Figure 8.

A structured mesh is one in which all interior vertices are topologically alike. It can be expressed as a two- or three-dimensional array, which limits cells to quadrilaterals in two dimensions and hexahedra in three. A structured surface mesh usually takes the appearance of cross-hatch (see Figure 8 below). The main advantages of structured meshes are simplicity and efficiency. Compared to unstructured meshes, they possess reduced mesh file sizes as neighbour connectivity may be defined implicitly.

Unstructured meshes are characterized by irregular connectivity, having arbitrarily varying local neighbourhoods. Thus, cell geometry is limited only by the solver's abilities. As a consequence of this, the position of cells may require explicit definition, which results in larger mesh file sizes. Unstructured meshes do well with complex geometries, providing a similar quality grid to structured methods however with a much reduced number of cells. Other advantages include rapid grading from small to large cells, and easy refinement and derefinement. Unstructured meshes generally use (but are not limited to) triangles and tetrahedra for two and three dimensional domains.
The creation of an unstructured mesh occurs in two parts: the placement of mesh vertices and triangulation. The placement phase generally places vertices along domain boundaries (or surfaces) before filling the interior. This may be done to a user-defined resolution.

Mesh vertices are subsequently joined in the triangulation phase. The most common method to achieve this is known as Delaunay triangulation (de Berg et al. 1997). In two dimensions, if there exists a point set $S = \{s_1, s_2, \ldots, s_n\}$ the Delaunay triangulation of the set $DT(S)$ is defined by the empty circle condition. That is, a triangle $s_i, s_j, s_k$ appears in $DT(S)$ only if its circumcircle encloses no other points of $S$. This is illustrated below in Figure 9.
In two dimensions, two cases may arise in which a created triangle may be considered bad: when the triangle contains an angle close to 0°, or an angle close to 180°. And, no failure of the first kind implies no failures of the second. The three-dimensional case is more difficult, however; Figure 10 below illustrates the five possible types of failure. These are characterised by the individual or combined presence of small solid angles and small dihedral (inter-plane) angles. Liu and Joe (1994) showed a variety of methods for the control of tetrahedral quality, of which the most successful is the limitation of internal solid angles, which then prevents small dihedral angles.

![Figure 10. The five types of bad tetrahedra (Bern & Plassmann 1999)](image)

The most common failure in three-dimensional mesh generation is the creation of sliver elements. This arises from Delaunay triangulation, as a sliver does not have an unusually large circumsphere compared to its edge lengths. It is difficult to include methods for reducing sliver creation within the generation algorithm and so a sliver removal routine is generally included in mesh post-processing.

### 3.3.1 CFX-Mesh

CFX-Mesh, the meshing program within the ANSYS Workbench package, utilises several variations on these basic ideas in creating its meshes. Its angular resolution function allows the mesh edge length on nominated faces to vary according to local curvature. This improves mesh quality by creating smaller edges where the face is highly curved and larger edges in flatter areas where a lower resolution is acceptable. As shown in Figure 11 below, angle \( \phi \) is nominated between 0° and 90°; a smaller \( \phi \) results in more nodes being placed on the surface. Minimum and maximum edge lengths may also be nominated to prevent over- and under-refinement.
CFX-Mesh makes available several geometry and surface mesh checking routines which test the domain for possible errors before the volume mesh is generated. The geometry is first checked for short edges, areas where a face edge is smaller than the required mesh size spacing in the region. Short edges result in an uneven mesh, with many more elements than are required. To remove short edges, an edge length is set below which the mesher ignores the edge and collapses the two ends to a point.

When creating a surface mesh, CFX-Mesh places at least three vertices on each face and edge of the modelled body. As a result, if there are many short edges or narrow faces in the geometry then the created mesh may again be unnecessarily fine. To overcome this, it is possible to merge faces and edges into larger virtual faces and edges.

Once vertices for the boundaries have been defined and checked, the domain is filled by way of an advancing front. Here the cells themselves are placed, rather than only the vertices. This allows for greater control of the cell shape especially in near-boundary areas, an area of interest in this project.

The mesh generator starts with the triangulated domain boundary, and iteratively places a layer of tetrahedra over that face. Then, while attempting to fill clefts left in the previous layer, the generator continues to build layers outwards, filling the domain. For each tetrahedron, three vertices will always be taken from the existing face, while the fourth is either specially created or will again be an existing vertex. When determining the location for a created vertex, the generator considers the resultant aspect ratio (the maximum to minimum width ratio within an element) and length functions and tests for possible collisions with other cells.

### 3.3.2 Mesh generation

It is difficult to represent the created three-dimensional mesh in a two-dimensional figure. Instead, examples of the created surface meshes for each geometry are
presented below along with meshing statistics. The surface mesh spacing offers an indication of the spacing of the volume mesh.

Generally the meshing settings suggested by CFX-Mesh, representing the coarsest recommended mesh size, were deemed appropriate. It was however necessary to reduce the mesh edge length on the face of the plant body to ensure a fine enough mesh to properly recreate the boundary layers forming around the bodies.

**Baumea juncea**

In creating the mesh for *Baumea juncea*, the settings recommended by CFX-Mesh were used across all faces of the model domain except for the plant body. Here, a refined mesh was used, with a minimum edge length of 1 mm. Figure 12 shows sections of the generated surface mesh.

![Figure 12. Created surface mesh for Baumea juncea](image)

**Baumea articulata**

Again, suggested settings were used for body and face spacing. On first attempt at creating a mesh for the domain the mesher failed, due to the large amount of detail in the *Baumea articulata* geometry. It was thus necessary to use an alternate meshing...
method on the plant surface. Instead of the default angular resolution method, the volume spacing option was used, where the only limit placed upon the mesh is a maximum spacing, taken as the default maximum body spacing.

The resultant mesh is shown in Figure 13. Of the three modelled species, Baumea articulata had by far the largest number of elements in its generated mesh.

**Figure 13. Created surface mesh for Baumea articulata**

**Potamogeton crispus**

In generating the surface mesh for Potamogeton crispus, a very small minimum edge length was chosen so the mesher may accurately cover the fine detail in the plant leaves. Automatic mesh generation trials with larger minimum edge lengths returned surface meshes deemed by CFX-Mesh to be invalid. Accordingly, the maximum edge length at the plant surface was also reduced, however all other parameters were left at their default values. Figure 14 shows a region of the generated surface mesh for the Potamogeton crispus model.
3.4 Model run definition

3.4.1 Modelled parameters

*Nutrient*

An additional variable, Nutrient, was introduced to represent the transport of nutrients within the model domain. Nutrient was nominated to be a non-reacting volumetric variable defined by an amount per unit volume of fluid and assigned concentration units, kgm\(^{-3}\). It was assigned a kinematic diffusivity of \(10^{-8}\) m\(^3\)s\(^{-1}\), a value close to the diffusivity of both nitrogen and phosphorus under expected conditions.

As ANSYS CFX allows only for the transport of additional variables away from bodies, this project will model the reverse of the physical situation: nutrient uptake by the modelled plants will be estimated by the transport of the additional variable Nutrient away from the plant surface. The plant surface will be held at a concentration of 1 kgm\(^{-3}\), while the incoming flow will be given an initial concentration of 0 kgm\(^{-3}\).
Flow velocity

As channel flow data is not available, and in order to make this project more widely applicable, several different water velocities were used. The modelled velocities varied between 1 and 34 cm/s according to the Fibonacci sequence. This provides a concentration of points around expected channel velocities, in the order of 5 cm/s.

3.4.2 Boundary conditions

It was necessary to define several different boundary conditions over the model domains. The domain inlet was given a set velocity perpendicular to its face, while the outlet was given a fixed, equal pressure relative to the inlet.

A no-slip condition was applied to the surface of the plants. This condition holds stationary any fluid in contact with the surface, accounting for frictional effects. A similar condition was applied to the top and bottom of the domain, the appropriateness of which is discussed in Section 5.3.

The sides of the domain were given a free-slip condition. This allows fluid to move in and out of the domain, without its velocity being retarded by wall friction effects.

3.4.3 Solution methods

Fluid model

The Shear Stress Transport (SST) model, as outlined in Section 2.6.2, was chosen as the fluid model for this project. Early trials with a k-Epsilon model failed, as the method could not accurately recreate the diffusive boundary layer surrounding the plant surface and therefore gave zero values for Nutrient transfer. However the SST model’s adjusted wall-function approach gave acceptable patterns of Nutrient transfer during trials on the test geometry.

Additional variable transport

The general form of the transport equation used by ANSYS CFX for additional variables is shown below in Equation 26, where \( \rho \) is the mixture density, \( \Phi \) is the conserved quantity of the additional variable per unit volume (concentration), \( \phi \) is the conserved quantity per unit mass, \( S_\phi \) is the volumetric source term and \( D_\phi \) is the variable’s kinematic diffusivity.

\[
\frac{\partial (\rho \phi)}{\partial t} + \nabla \cdot (\rho U \phi) = \nabla \cdot (\rho D_\phi \nabla \phi) + S_\phi
\]
For turbulent flow, ANSYS CFX uses a Reynolds averaged form of the equation, shown in Equation 27 where $Sc_t$ is the turbulent Schmidt number and $\mu_t$ is the turbulence viscosity.

\[
\frac{\partial (\rho \phi)}{\partial t} + \nabla \cdot (\rho U \phi) = \nabla \cdot \left( \left( \rho D_{\phi} + \frac{\mu_t}{Sc_t} \right) \nabla \phi \right) + S_{\phi}
\]

**Solver control**

The fluid model was instructed to find a steady-state solution. While the physical situation may include eddies and other varying structures in the downstream wake, this project is concerned only with averaged values for transported variables.

ANSYS CFX uses an iterative Incomplete Lower Upper factorisation for solving the discrete system of linearised equations put forward by the fluid model. This process starts with the general matrix form shown in Equation 28, where $[A]$ is the coefficient matrix, $[\phi]$ is the solution vector and $[b]$ the right hand side.

\[
[A][\phi] = [b]
\]

If the first approximate solution is given by $\phi^n$, then subsequent solutions $\phi^{n+1}$ are obtained by adding the correction term $\phi'$ to the solution $\phi$. The solution of $A \phi'$ is known as the residual, given below in Equation 29.

\[
\phi^n = b - A \phi^n
\]

The residual is a measure of the local imbalance of each conservative control volume equation. As such, ANSYS CFX uses the normalised residual level to judge whether a solution has been converged upon. RMS values of the residuals of fluid momentum equations are used, along with any additional variables. The residual level for turbulence transport equations are however not used as part of the convergence criteria. For this project, the RMS residual target was left at its default value of $10^{-4}$. 
3.5 Model output analysis

3.5.1 Nutrient uptake

To quantify the transport of Nutrient away from the plant bodies, a plane was placed perpendicular to the channel flow direction, downstream from the plant body in the solved domain. Nutrient flux from the plant body was then found by integrating the point product of the velocity and Nutrient concentration across the face. Equation 30 is an algebraic representation of this procedure.

\[ \phi = \int uC_n \, dx \, dy \]

Nutrient flux, represented by \( \phi \), is the amount of variable Nutrient transported from the plant body per unit time and has units kg/s. Equation 30 was achieved within CFX-Post, the solution analysis program within ANSYS Workbench, by the following function:

Nutrient flux = areaInt(Velocity * Nutrient)@PlaneXY

The function areaInt integrates a variable over a specified two-dimensional location, in this case the sampling plane PlaneXY.

Care was taken to place the sampling plane far enough downstream such that the effect of any upstream velocities within the wake were minimised. This is illustrated below in Figure 15. Velocity vectors for a plane placed midway up the test geometry are shown.
This analysis was carried out for each modelled flow rate, giving the function $\phi = f(u)$. Then, assuming equal transfer rates for all plants within a community, nutrient flux for a community under a constant velocity may be given by $\phi = f(n)$.

### 3.5.2 Flow baffling

To describe the influence of a modelled plant on the surrounding flow, the force imparted by the motion of the fluid on the plant body was quantified. This was done in CFX-Post using the `sum` (summation) function:

```plaintext
Body force = sum(ForceZ)@PlantBody
```

As shown in Section 2.5.2, $F_D$ may be related to drag coefficient $C_D$ by the following Equation 31.

**Equation 31**

$$C_D A_f = \frac{F_D}{\frac{1}{2} \rho U^2}$$

Where $A_f$ is the frontal area presented by the body and $U$ is fluid velocity. The drag coefficient of each plant should be similar for each modelled velocity (see Section 2.5.2), and so a final averaged drag area $C_D A_f$ may be found for each plant.

---

*CFD Analysis of Submerged Macrophytes and Implications for Urban Drain Management*
As shown in Section 2.5.3, flow through a channel past a blunt body may be described by:

**Equation 32**

\[
\frac{1}{2} C_D a U^2 = gS
\]

Where \( S \) is the channel slope, and \( a \) is frontal area per unit volume, described by Equation 33. For this project, a channel slope of \( 10^{-5} \) was used, representative of an average drainage channel slope (Fox, McDonald & Pritchard 2004).

**Equation 33**

\[
a = \frac{A_f n}{h}
\]

Where \( n \) is the number of plants in the community and \( h \) is the plant height. By substituting this definition into Equation 32 and rearranging, a formula for allowed channel velocity as a function of plant density \( n \) may be found.

**Equation 34**

\[
U = f(n) = \left( \frac{2ghS}{C_D A_f n} \right)^{\frac{1}{2}}
\]
4. Results

4.1 Nutrient uptake

Figure 16, Figure 17 and Figure 18 below show the relationships between inlet channel velocity and flux of Nutrient from a single modelled specimen of Baumea juncea, Baumea articulata and Potamogeton crispus, respectively. It may be observed that a generally linear relationship exists between the two variables.

4.1.1 Baumea juncea

![Graph showing the relationship between velocity and flux for Baumea juncea.](image)

**Figure 16.** Calculated flux of Nutrient from Baumea juncea under different flow velocities
4.1.2 *Baumea articulata*

![Graph showing the calculated flux of nutrient from *Baumea articulata* under different flow velocities.](image)

**Figure 17.** Calculated flux of nutrient from *Baumea articulata* under different flow velocities

4.1.3 *Potamogeton crispus*

![Graph showing the calculated flux of nutrient from *Potamogeton crispus* under different flow velocities.](image)

**Figure 18.** Calculated flux of nutrient from *Potamogeton crispus* under different flow velocities
4.2 Turbulence

4.2.1 Turbulence structures

To illustrate the model’s correct handling of turbulence, the following figures showing the turbulent wake structures created by the plant geometries were produced. Turbulence kinetic energy ($k$) is shown, indicating the intensity of the generated turbulence. It can be seen that as inlet velocity increases so too does turbulence intensity.

The figures were generated by creating a plane parallel to the channel floor, midway up the water column ($y = 250$ mm). The channel inlet is to the left.

*Baumea juncea*

Figure 19. Turbulent wake generated by *Baumea juncea*, inlet velocity 5 cm/s
Figure 20. Turbulent wake generated by Baumea juncea, inlet velocity 13 cm/s

Baumea articulata

Figure 21. Turbulent wake generated by Baumea articulata, inlet velocity 5 cm/s
Figure 22. Turbulent wake generated by Baumea articulata, inlet velocity 13 cm/s
**Potamogeton crispus**

Illustrations of the turbulent wakes generated by Potamogeton crispus were created in the XY plane, as there is little detail to be shown in the ZX plane. The created plane was positioned 50 mm downstream of the base of the specimen.

**Figure 23.** Turbulent wake generated Potamogeton crispus, inlet velocity 5 cm/s,  

**Figure 24.** Turbulent wake generated by Potamogeton crispus, inlet velocity 13 cm/s
4.2.2 Drag area

Table 2 shows the calculated drag areas for each modelled species under experimental channel velocities.

Table 2. Calculated drag area values

<table>
<thead>
<tr>
<th>Velocity</th>
<th>Baumea juncea $C_D A_f$</th>
<th>Baumea articulata $C_D A_f$</th>
<th>Potamogeton crispus $C_D A_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 ms$^{-1}$</td>
<td>$1.05 \times 10^{-1}$ m$^2$</td>
<td>$1.42 \times 10^{-1}$ m$^2$</td>
<td>$2.50 \times 10^{-2}$ m$^2$</td>
</tr>
<tr>
<td>0.02 ms$^{-1}$</td>
<td>$9.40 \times 10^{-2}$ m$^2$</td>
<td>$1.28 \times 10^{-1}$ m$^2$</td>
<td>$2.28 \times 10^{-2}$ m$^2$</td>
</tr>
<tr>
<td>0.03 ms$^{-1}$</td>
<td>$8.83 \times 10^{-2}$ m$^2$</td>
<td>$1.24 \times 10^{-1}$ m$^2$</td>
<td>$2.18 \times 10^{-2}$ m$^2$</td>
</tr>
<tr>
<td>0.05 ms$^{-1}$</td>
<td>$8.06 \times 10^{-2}$ m$^2$</td>
<td>$1.21 \times 10^{-1}$ m$^2$</td>
<td>$2.09 \times 10^{-2}$ m$^2$</td>
</tr>
<tr>
<td>0.08 ms$^{-1}$</td>
<td>$7.30 \times 10^{-2}$ m$^2$</td>
<td>$1.21 \times 10^{-1}$ m$^2$</td>
<td>$2.03 \times 10^{-2}$ m$^2$</td>
</tr>
<tr>
<td>0.13 ms$^{-1}$</td>
<td>$6.45 \times 10^{-2}$ m$^2$</td>
<td>$1.43 \times 10^{-1}$ m$^2$</td>
<td>$2.00 \times 10^{-2}$ m$^2$</td>
</tr>
<tr>
<td>0.21 ms$^{-1}$</td>
<td>$5.71 \times 10^{-2}$ m$^2$</td>
<td>$1.22 \times 10^{-1}$ m$^2$</td>
<td>$1.99 \times 10^{-2}$ m$^2$</td>
</tr>
<tr>
<td>0.34 ms$^{-1}$</td>
<td>$5.21 \times 10^{-2}$ m$^2$</td>
<td>$1.22 \times 10^{-1}$ m$^2$</td>
<td>$1.98 \times 10^{-2}$ m$^2$</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>$7.68 \times 10^{-2}$ m$^2$</td>
<td>$1.28 \times 10^{-1}$ m$^2$</td>
<td>$2.13 \times 10^{-2}$ m$^2$</td>
</tr>
</tbody>
</table>
4.3 Planting density analysis

Shown below are the relationships between planting density $n$ specimens/m$^2$ and resultant channel velocity and Nutrient flux. It can be seen that channel velocity follows a pattern of exponential decay with increasing planting density, while flux of Nutrient increases in a natural logarithmic manner. A channel inlet velocity of 5 cm/s was used.

4.3.1 Baumea juncea

![Graph showing the relationship between planting density and nutrient transport for Baumea juncea](image)

Figure 25. Baumea juncea velocity and nutrient transport by planting density
4.3.2 Baumea articulata

Figure 26. Baumea articulata velocity and nutrient transport by planting density

4.3.3 Potamogeton crispus

Figure 27. Potamogeton crispus velocity and nutrient flux by planting density
4.4 Nutrient removal and loss of channel velocity

By analysis of data presented in Sections 4.1 to 4.3 the following Figure 28 and Figure 28 were prepared, showing the rate of Nutrient flux achieved by planting each species to a density allowing a specified reduction in channel velocity. Also shown is the required planting density in number of specimens per square metre. See Appendix I for flux-velocity plots for all modelled inlet channel velocities.

![Figure 28](image-url)

**Figure 28.** For inlet velocity 2 cm/s, a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity.
Figure 29. For inlet velocity 21 cm/s, a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity
5. Discussion

5.1 Summary of findings

Three plant species, *Baumea juncea*, *Baumea articulata* and *Potamogeton crispus*, were modelled under a variety of flow velocities. Their response to the flow was measured by way of release of the volumetric variable Nutrient from their surface and the drag force applied by their bodies to the flow.

For all species, the release of Nutrient was found to vary linearly with increasing velocity (Section 4.1). For a given velocity, *Baumea juncea* released the most Nutrient per specimen, followed by *Baumea articulata* and finally *Potamogeton crispus*, which released several orders of magnitude less Nutrient.

Similarly, modelled flows exerted the greatest forces on the *Baumea juncea* specimen, followed by *Baumea articulata* and *Potamogeton crispus* (see Section 4.2).

As shown in Sections 4.3 and 4.4, for low inlet flow velocities (< 10 cm/s), *Potamogeton crispus* released the most Nutrient by reduction in flow velocity. *Baumea juncea* released slightly less, followed by *Baumea articulata*. For higher inlet velocities, *Baumea juncea* released the most Nutrient by reduction in flow velocity followed by *Potamogeton crispus* and *Baumea articulata*.

5.2 Analysis of results

5.2.1 Turbulence generation

Figure 19 to Figure 24 show the difference between the turbulent wakes generated under different flow conditions. Turbulence increases with increasing flow velocity, shown by an increase in the size and intensity of the generated wake. This agrees with expected results, as Section 2.4.5 shows turbulence intensity to be proportional to the square of velocity.

It can be observed that the size and intensity of the created turbulent wake is directly proportional to the surface area which the plant body presents perpendicular to the direction of the flow, represented in this case partly by the drag area (see Table 2). This again agrees with predicted results as discussed in Section 2.5.2.
5.2.2 Flow fields

As discussed in Section 2.4, a principle result of turbulence generation is the dissipation of flow kinetic energy, or velocity. Figure 30 below shows the velocity field for modelled Baumea articulata under an inlet velocity of 5 cm/s. Velocity can be seen to decrease sharply in the areas of high turbulent kinetic energy (see Figure 21 and Figure 22), an outcome consistent with predicted results. An increased velocity is shown to the sides of the plant body as mass is conserved and the model accounts for the lower velocity closer to the plant. This pattern was repeated for other modelled geometries.

![Velocity field for Baumea articulata](image)

**Figure 30.** Velocity flow field for Baumea articulata, inlet velocity 5 cm/s

5.2.3 Nutrient flux and loss of channel velocity

Nutrient flux was shown to vary linearly with increasing velocity. When flux is compared to resultant loss of channel velocity, it becomes apparent that the rate of Nutrient flux is a function of plant geometry.

Relative to the other modelled species, Potamogeton crispus presents the smallest area perpendicular to flow direction, and possesses the lowest drag area. However, its complex leaves give the plant a large surface area overall. The results suggest that Nutrient release is therefore proportional to plant surface area as well as turbulence.
intensity. This agrees with the commonsense idea that an increase in the area able to release Nutrient will subsequently increase the amount of Nutrient released.

It is possible then that Potamogeton crispus has developed the characteristics required to maximise nutrient flux from the water column: minimise any surrounding loss of channel velocity by presenting a small area to the direction of flow, and increasing the ratio of surface area to volume. See Section 5.3.3 for further discussion of plant morphology.

5.3 Model features

5.3.1 Nutrient uptake

This study modelled the release of a volumetric variable Nutrient from the surface of the macrophyte bodies. This situation is analogous to the uptake of nutrients by the plant surfaces, as the same processes which act to retard the release of Nutrient similarly act to retard the uptake of nutrients.

**Quantity**

The model is only able to predict a relative, not specific rate of nutrient uptake. The figures which it produces for Nutrient release are only representative of the rate a species may uptake nutrients comparatively to another. They show the link between plant morphology and relative rates of nutrient uptakes.

It may be possible to link the modelled Nutrient release rates to actual nutrient uptake rates by, for example, experiments determining more representative and dynamic molecular diffusion rates. This however was outside the scope of this project.

Therefore, the model is unable to provide an expected reduction in nutrient concentrations within the surface drains. It is however able to recommend the species which for a given channel velocity most reduce nutrient concentrations.

**Hydrodynamic limitation**

The most significant assumption made by this model about the uptake of nutrients is that it occurs only through the surface of the plants, and not through their roots. Literature has shown this to be the case when nutrient concentration in the water column is similar to that in the pore space (Carignan 1982) however this model was not able to test those results.
It is expected that the ratio of root to body nutrient uptake is not constant across modelled species. The species with harder tissues (Baumea juncea and Baumea articulata) may rely more heavily on uptake from the sediment pore space, while the softer tissued species Potamogeton crispus may be more reliant upon uptake from the water column. This is illustrated by the way the Baumea species may grow to heights significantly greater than the water depth, while Potamogeton crispus is entirely submerged.

As discussed in Section 2.2.2, a significant proportion of the nutrient cycling that occurs within macrophyte beds can be attributed to attached epiphytes. Thus, the interactions between the surface of the plants and the water column are most important when considering the net effect of a macrophyte bed on in-stream nutrient concentrations.

It cannot be expected that the water column is the sole source of nutrients for the plants. However, as it is a significant source for macrophytes (and their associated epiphytes) under expected conditions, this limitation should not drastically alter the relevance of the results.

### 5.3.2 Species selection

Due to time and computational restraints only three of the eight species selected for a planting trial by GHD were chosen for modelling, which limits the applicability of the results.

However, the only basis the model used for distinguishing between uptake rates for each species was differences in their geometry. The species not chosen for modelling were not significantly different in their appearance to the modelled species, and so the creation of additional plant geometries would not necessarily have yielded a wider set of similarly high-quality results.

### 5.3.3 Plant geometries

Plant geometries were created to be representative of a species, reflecting their major morphological traits. Significantly, however, the model was unable to recreate the flexibility of the plants. It is difficult to quantify or even characterise the effect of this limitation on model results. The species with firmer tissue (Baumea juncea and Baumea articulata), would be less affected, however the leaves and stems of Potamogeton crispus are very flexible.
The flexibility of *Potamogeton crispus* would cause it to align itself with the direction of the flow. This would result in a reduced body force when compared to a rigid body under the same velocity. Thus by the drag equation (Equation 19) for a constant drag area the flexible body would permit a higher flow velocity than the rigid body.

However, as discussed in Sections 2.3 and 2.5.1, the rate at which a plant can uptake nutrients from the water column is positively related to the amount of turbulence in the surrounding flow. And, if the body force is lower for a flexible specimen, then so too is the intensity of generated turbulence. Thus in the context of this study the benefits to channel hydraulic capacity of flexible plant bodies are somewhat offset by a reduced nutrient uptake capacity. The extent to which each process occurs is however difficult to quantify.

5.3.4 Boundary conditions

*Nutrient release*
In the physical world it is unlikely that nutrient uptake rates are constant across plant leaves and stems, however the model was unable to specify different Nutrient properties for different areas of the plant geometries.

This should not be a problem for *Baumea* species as their morphology is rather constant, being a series of near-vertical rods. However *Potamogeton crispus* has both leaves and stems, which could not be expected to uptake nutrients evenly.

*Channel surface*
It is difficult within ANSYS Workbench to create a model domain which mimics the fluid dynamic of an open channel. Within the program a solid domain of constant dimensions is required. However within an open drain only three solid boundaries exist; the water surface is free to rise and fall.

When an obstacle such as an aquatic plant is introduced to the channel the created drag slows the fluid flow. For a given flow rate, to satisfy conservation of mass requirements the flow area i.e. channel depth must then increase. The introduction of a solid-wall boundary at the channel surface may then artificially increase velocity around the plant body also increasing turbulence and therefore Nutrient release.

The impact of this was somewhat lessened by the introduction of free-slip boundaries at the domain sides allowing fluid to pass out of the domain, analogous to an increase in
flow area. However the influence of a non-dynamic water depth on flow velocities is still unknown.

The no-slip condition applied at the top of the domain introduces a frictional element which is not present in the physical situation. The interactions at the solid-fluid boundary of the model domain would not necessarily be indicative of the water-air interactions in the field. It is likely that rather than holding the water stationary, the air would apply some velocity to the underlying fluid. However, the model could be considered an averaged case where the surrounding atmosphere is stationary. The no-slip condition introduces additional drag to the model, however as the same condition is applied across all modelled species it is not expected to skew the results.

**Channel floor**

A no-slip condition was also applied at the channel floor, disallowing the passage of fluid. As discussed in Section 2.1, the main water source for the drains over the period of interest is in fact groundwater seeping through the channel walls. However this occurs at a rate significantly slower than the motion of along channel flows and may thus be disregarded.

Instead, it was made to reflect the conditions a single specimen may encounter within a channel. That is, the top and bottom of the domain were created an appropriate distance apart to reflect average water depth, but cross and along stream dimensions were created large enough so that flow around the plant would not be influence by them.

**5.3.5 Community structure**

The model assumes that per specimen uptake is constant regardless of planting density. As discussed in Section 2.3, the rate of nutrient uptake is positively affected by turbulence intensity. Figure 19 to Figure 24 show an increase in turbulence downstream from plant bodies. Thus, the uptake rate for a single specimen in otherwise low-turbulence conditions would not be indicative of the uptake rate of a specimen within a larger community.

It could be expected that uptake rates for a plant within a community would be greater than those for a single plant due to the increased turbulence intensity. The impact of this on modelled uptake rates could not be expected to be constant across species; the results of this study show that uptake rates are dependant on geometry as well as created drag (see Figure 28). It is unknown whether this exaggerates or understates the differences between species.
Also, it has been shown that if community spacing is sufficiently small, the generated turbulence will reduce the bulk drag coefficient for the community (Nepf 1999). The result of this effect for dense communities is a higher allowed channel velocity for a similar rate of nutrient transfer.

### 5.4 Future work

While a useful tool for differentiating between species, as a predictor of actual nutrient uptake rates the model may be considered incomplete. There are two areas where the model needs expansion before it may be considered complete: the dynamic rates at which the plants uptake nutrients from their surfaces needs to be explored, possibly by closer modelling of the near-surface region, as well as the dynamic ratio between pore space and water column uptake.

A field of current research upon whose work this model may be expanded is that relating community spacing and structure to nutrient uptake rates (e.g. Helmuth, Sebens & Daniel 1997; Nepf 1999). As discussed above, one possible source of inaccuracy is the model’s treatment of individual plant uptake, something that is expected to vary according to plant spacing.
6. Recommendations

The conducted research aimed to determine a species for planting in a system of open surface drains which would reduce nutrient concentrations within the water while minimising the resulting loss of hydraulic capacity. The produced model, despite several limitations, produced high quality results consistent with predicted outcomes.

The model found that for flow velocities like those expected (< 10 cm/s), Potamogeton crispus is the most suitable species for planting. For the resulting loss in flow velocity, the model predicts Potamogeton crispus will remove the most nutrients from the water column.

Potamogeton crispus is also the most practical choice. It exhibits fast growth during summer, the period over which nutrient concentration is of concern, and dies back over winter allowing maximum drain hydraulic capacity. To ensure that decaying organic matter does not re-release nutrients into the drain or receiving body it may be easily harvested after the growth period.

A set of figures was produced (see Appendix II) which allows the drain manager to predict, given an initial velocity, the percentage reduction in channel velocity a certain planting density would yield. It is expected that the Water Corporation will dictate an allowable loss of drainage capacity, and from these figures subsequent planting densities may be found along with approximated uptake rates.
7. References


Atkinson, B. & Davies, I. J. 1974, 'The overall reaction rate of substrate uptake (reaction) by microbial films part I: A biological rate equation', *Chemical Engineering Research and Design*, vol. 52a, pp. 248-259.


Environmental Design (ENDP3601) Class 2006, *Detailed design for the central Belmont catchment restoration*, University of Western Australia (School of Environmental Systems Engineering).


USDA 2007, 'United States Department of Agriculture PLANTS Profile: Potamogeton crispus'.


Appendix I: Meshing statistics

Baumea juncea

Table 1. Automatic mesh generation input parameters for Baumea juncea

<table>
<thead>
<tr>
<th>Location</th>
<th>Meshing option</th>
<th>Mesh resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default body</td>
<td></td>
<td>Maximum spacing: 20 mm</td>
</tr>
<tr>
<td>Default face</td>
<td>Angular resolution</td>
<td>Angular resolution: 30°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimum edge length: 3.3 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum edge length: 20 mm</td>
</tr>
<tr>
<td>Plant surface</td>
<td>Angular resolution</td>
<td>Angular resolution: 18°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimum edge length: 1 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum edge length: 10 mm</td>
</tr>
</tbody>
</table>

Table 2. Generated mesh statistics for Baumea juncea

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>543,791</td>
</tr>
<tr>
<td>Number of tetrahedra</td>
<td>2,127,186</td>
</tr>
<tr>
<td>Number of elements</td>
<td>2,439,280</td>
</tr>
</tbody>
</table>

Baumea articulata

Table 3. Automatic mesh generation input parameters for Baumea articulata

<table>
<thead>
<tr>
<th>Location</th>
<th>Meshing option</th>
<th>Mesh resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default body</td>
<td></td>
<td>Maximum spacing: 28 mm</td>
</tr>
<tr>
<td>Default face</td>
<td>Angular resolution</td>
<td>Angular resolution: 30°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimum edge length: 1.4 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum edge length: 28 mm</td>
</tr>
<tr>
<td>Plant surface</td>
<td>Volume spacing</td>
<td>Radius of influence: 0 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Expansion factor: 1.2</td>
</tr>
</tbody>
</table>

Table 4. Generated mesh statistics for Baumea articulata

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>804,452</td>
</tr>
<tr>
<td>Number of tetrahedra</td>
<td>4,531,879</td>
</tr>
<tr>
<td>Number of elements</td>
<td>4,531,879</td>
</tr>
</tbody>
</table>
**Potamogeton crispus**

**Table 5.** Automatic mesh generation input parameters for Potamogeton crispus

<table>
<thead>
<tr>
<th>Location</th>
<th>Meshing option</th>
<th>Mesh resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default body</td>
<td>Angular resolution</td>
<td>Maximum spacing: 38 mm</td>
</tr>
<tr>
<td>Default face</td>
<td>Angular resolution</td>
<td>Angular resolution: 30°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimum edge length: 1.9 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum edge length: 38 mm</td>
</tr>
<tr>
<td>Plant surface</td>
<td>Angular resolution</td>
<td>Angular resolution: 18°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimum edge length: 0.01 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum edge length: 3 mm</td>
</tr>
</tbody>
</table>

**Table 6.** Generated mesh statistics for Potamogeton crispus

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>566,298</td>
</tr>
<tr>
<td>Number of tetrahedra</td>
<td>3,171,722</td>
</tr>
<tr>
<td>Number of elements</td>
<td>3,171,722</td>
</tr>
</tbody>
</table>
Appendix II: Flux-velocity plots

Figure 1. Inlet channel velocity 1 cm/s: a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity
Figure 2. Inlet channel velocity 2 cm/s: a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity.

Figure 3. Inlet channel velocity 3 cm/s: a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity.
Figure 4. Inlet channel velocity 5 cm/s: a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity

Figure 5. Inlet channel velocity 8 cm/s: a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity
Figure 6. Inlet channel velocity 13 cm/s: a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity

Figure 7. Inlet channel velocity 21 cm/s: a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity
Figure 8. Inlet channel velocity 34 cm/s: a) Nutrient flux for each modelled species as a function of reduction in channel velocity b) Planting density in specimens/m² and resultant percentage reduction in channel velocity