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Feasibility of the porous zone approach to modelling vegetation in CFD

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Abstract Vegetation within stormwater ponds varies seasonly and its presence affects the flow field, which in turn affects the pond's Residence Time Distribution and its effectiveness at pollutant removal. Vegetated flows are complex and, as a result, no suitable tools exist for evaluating realistic stormwater pond designs. Recent research has suggested using a porous zone to represent vegetation within a CFD model, and this paper investigates the feasibility of this approach using ANSYS Fluent. One of the main benefits of using a porous zone is the ability to derive the relevant parameters from the known physical characteristics of stem diameter and porosity using the Ergun equation. A sensitivity analysis on the viscous resistance factor $1/\alpha$ and the inertial resistance factor C_2 has been undertaken by comparing model results to data collected from an experimental vegetated channel. Best fit values of C_2 were obtained for a range of flow conditions including emergent and submerged vegetation. Results show the CFD model to be insensitive to $1/\alpha$ but very sensitive to values of C_2. For submerged vegetation, values of C_2 derived from the Ergun equation are under-predictions of best-fit C_2 values as only the turbulence due to the shear layer is represented. The porous zone approach does not take into account turbulence generated from stem wakes such that no meaningful predictions for emergent vegetation were obtained. C_2 values calculated using a force balance show better agreement with best-fit C_2 values than those derived from the Ergun equation. Manually fixing values of k and ε within the porous zone of the model shows initial promise as a means of taking stem wakes into account.

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1 Introduction

Stormwater, the run-off from rainfall events, typically carries pollutants that negatively affect the environment. Engineered devices, commonly referred to as SuDS, or Sustainable Drainage Systems, are introduced to detain flows and help remove pollutants, protecting receiving waters. As they are engineered devices, they are designed and implemented with specific goals in mind. However, as semi-natural systems they are complex and in many cases robust tools to assess both their design and performance do not exist.

Stormwater treatment ponds, for example, contain both open water and vegetation in highly asymmetric configurations. Pond performance is typically assumed to depend on the nominal residence time, V/Q, where V is pond volume and Q is discharge (Persson, 2000). A Residence Time Distribution (RTD) (Levenspiel, 1972), describing the range of times water takes to travel through the pond, can be experimentally determined after construction and better reflects pond performance. An RTD closer to "plug flow", where all water remains in the pond for a similar time (i.e. the nominal residence time), is considered ideal for treatment (Holland et al, 2004).

Natural vegetation, which may vary by season and year, affects the flow field and makes assessing pond performance complex. The nominal residence time does not take vegetation into account and it is impractical to experimentally determine the RTD of every pond repeatedly as the vegetation grows or dies off. A more robust modelling approach capable of assessing pond performance that includes vegetation would therefore be of benefit.

1.1 Modelling vegetation

Modelling the impacts of vegetation on flow (and thereby mixing) is necessary to robustly estimate residence times. This is a problem not only in stormwater ponds, but also in channels (Souliotis and Prinos, 2011; Patil and Singh, 2011), wetlands (Kjellin et al, 2007; Huang et al, 2008), and coastal areas (Lightbody and Nepf, 2006). There are several parallel tracks of investigation being undertaken to understand and quantify the impacts of vegetation on flow, from the very theoretical (Nepf, 1999) to more practical engineering approaches (Kadlec, 1990).

Most approaches to modelling vegetation consist of estimating a coefficient of drag, C_D, obtained through experimental and/or theoretical means, e.g. Jadhav and Buchberger (1995); Nepf (1999); Tanino and Nepf (2008). More empirical approaches use Manning's n, e.g. Hoffmann (2004); Wu and He (2009). King et al (2012) propose a new $k-\varepsilon$ turbulence model for inclusion in a Computational Fluid Dynamics (CFD) model that takes the effects of vegetation into account. Alternatively, Stoesser et al (2010) directly simulated flow through vegetation stems using Large Eddy Simulation.

1.2 CFD Modelling of ponds

CFD has become established as a common tool for pond design and evaluation, e.g. Shilton (2000); Peterson et al (2000); Persson (2005); Shilton et al (2008); Khan et al (2012); Alvarado et al (2013). These studies have typically focused on pond shape or configuration, but have not taken into account the presence of vegetation.

Saggiori (2010), Tsavdaris et al (2013), Tsavdaris et al (2014), and Li (2014) have modelled vegetated ponds using the commercial CFD code ANSYS Fluent (ANSYS, Inc., 2012) by treating vegetated areas as a "Porous Zone". A CFD model solves a discretised form of the Navier-Stokes equations, which balance forces acting on a volume of water. Equation 1 shows the balance of forces acting in the x-direction, assuming a 2-D problem and excluding turbulence (Fluent Inc., 1998), where ρ is density, u is velocity in the x-direction, v is velocity in the y-direction, p is pressure, and τ is shear stress in the subscripted directions.

$$\frac{\partial \rho u u}{\partial x} + \frac{\partial \rho v u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + F_x \tag{1}$$

$$F_x = -\left(\frac{\mu}{\alpha} u + C_2 \left(\frac{1}{2} \rho u |u|\right)\right) \tag{2}$$

The effects of the porous zone are included as part of the additional source term F_x, shown in Equation 2, where μ is the fluid viscosity, $1/\alpha$ is a viscous resistance coefficient (based on Darcy's law), and C_2 is an inertial resistance coefficient. ANSYS suggests that the $1/\alpha$ and C_2 parameters may be calculated using Equations 3 and 4 respectively, which are derived from the Ergun equation (Ergun, 1952), where d is stem diameter and ϕ is porosity. This paper further investigates the porous zone approach to modelling vegetation in CFD.

$$\alpha = \frac{d^2}{150} \frac{\phi^3}{(1-\phi)^2} \tag{3}$$

$$C_2 = \frac{3.5}{d} \frac{(1-\phi)}{\phi^3} \tag{4}$$

2 Methodology

A preliminary 2D investigation of the porous zone approach to modelling vegetation in CFD has been carried out in 2 stages using ANSYS Fluent 14.5 (the double precision solver). The first stage consists of evaluating the sensitivity of the porous zone parameters ($1/\alpha$ and C_2). The second stage consists of fitting these parameters to different experimental conditions.

Experimental data collected by Shucksmith et al (2010) has been used for validation of the CFD model. They investigated longitudinal dispersion in a vegetated channel, emergent or submerged depending on flow rate. *Carex*, a common aquatic plant, was grown for a period of 26 weeks in a channel 14.48×0.6 m. 8 measurement sets (outlined in Table 1) were collected over this period as the vegetation grew, each consisting of vertical velocity profiles (at 5.6 m into the vegetation) and 5 repeat solute transport traces at 5 flow rates ranging between 9.19 and 29.42 ls^{-1}. These flow rates correspond to mean velocities of 0.099–0.264 ms^{-1} and stem Reynolds numbers of 1490–7083. The solute was injected onto the surface at the start of the vegetation and the traces were recorded at 3 locations within and above the vegetation at 7.36, 9.80, and 12.24 m downstream using fluorometers.

The CFD model geometry used is a simplified 2D representation of the channel centreline. 15 m of open water was added before the vegetation for flow establishment, the vegetation was changed to a 14.5 m length, and 0.5 m free water was added after the vegetation. The vegetation itself was modelled as a porous zone, with the $1/\alpha$ and C_2 parameters applied in the x-direction only. Boundary conditions were specified as a velocity-inlet, a pressure-outlet, symmetry boundary (fixed-lid approximation) at the surface, and a channel bed roughness height of 7e-4 m (representative of gravel).

A mesh independence study showed that a rectangular mesh with a cell size of 14.625 mm was a good balance of mesh independence, number of cells, and the log-law boundary layer treatment requirement of $30 < y^+ < 300$. According to the results of a discretisation settings and turbulence model sensitivity study, second order spatial discretisation, the PRESTO! pressure discretisation formulation (an interpolation scheme to calculate pressure on cell faces), the Standard Wall Functions (a log-law viscous sub-layer approximation), and the Realisable $k-\varepsilon$ turbulence model have been used. The inlet and outlet turbulence boundary conditions have been specified as a turbulent intensity of 5% and a turbulent length scale equivalent to the water depth. All models were run for sufficient iterations for their residuals to stabilise, indicating model convergence. The SIMPLE pressure-velocity coupling was used (an uncoupled solver).

Particle tracking was used to generate solute trace data comparable to the experimental dye injections. This approach has previously compared favourably with experimental results, e.g. Stovin et al (2008). 40,000 neutrally buoyant particles were injected just below the surface at the start of the vegetation and tracked using the Discrete Random Walk Model until leaving the outlet. As the particles crossed the three monitoring planes, the times at which they crossed and whether they crossed in the vegetation or water was recorded.

2.1 Sensitivity of $1/\alpha$ *and* C_2

A sensitivity analysis was carried out to explore the impact of the porous zone parameters $1/\alpha$ and C_2 on the modelled solute transport in the vegetated channel. Logarithmically spaced values were used: $1/\alpha$ = 0.60, 3.11, 16.10, 83.40, 431.80, 2236.60, 11584.20, and 60000 m^{-2}; and C_2 = 0.20, 0.54, 1.44, 3.86, 10.34, 27.79, 74.55, and 200 m^{-1}. The 64 combinations of these values are representative of d from 1 to 50 mm and ϕ from 0.900 to 0.999. The CFD model was configured to represent measurement set 3 with a 28.66 ls^{-1} flow rate, for a flow depth of 0.234 m, a vegetation depth of 0.160 m, and a mean velocity of 0.204 ms^{-1}. Measured values of $d = 0.02$ m and $\phi = 0.992$, giving $1/\alpha = 24.6$ m^{-2} and $C_2 = 1.41$ m^{-1}.

To compare the CFD solute traces with the experimental data, the latter has been pre-processed to subtract background concentration using a linear approximation based on the first and last 5 seconds of data. As the laboratory calibration data could not be found, the experimental traces were scaled according to the mass-balance of their CFD counterparts, assuming 100% conservation of mass. The start times of the experimental data were unavailable and so were approximated based on the CFD results.

2.2 Porous zone parameter fitting

Best fit porous zone model parameters for the experimental results have been generated. CFD models for all 8 vegetation measurement sets at all 5 flow rates (covering emergent and submerged vegetation) have been created. Results to be discussed show that the porous zone model in the scenarios examined is primarily sensitive to values of C_2 and so $1/\alpha$ has been fixed at a value of 1. Based on those same results, the range of values of C_2 was modified so that 10 values of C_2 = 0.20, 0.36, 0.65, 1.17, 2.11, 3.79, 6.84, 12.32, 22.20, 40.00 m^{-1} have been used. For each configuration, the solute traces generated using particle tracking have been compared to their corresponding experimental solute traces. This comparison was carried out using the R^2 correlation measure [Equation 5 (Nash and Sutcliffe, 1970)] after aligning the centroids of the traces. The value of C_2 with the highest R^2 is assumed to best represent the experimental data as R^2 values close to 1.0 indicate a better fit, while values below 0 indicate no fit.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(C_i - \hat{C}_i)^2}{\sum_{i=1}^{N}(C_i - \bar{C}_i)^2} \tag{5}$$

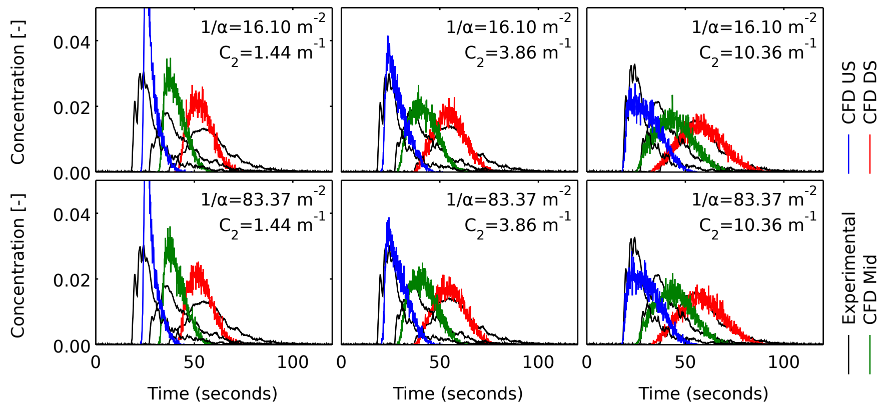

Fig. 1 Particle tracking solute traces recorded at 7.36 (US), 9.80 (Mid) and 12.24 m (DS) within the open water above the vegetation compared to experimental solute traces, showing variation in the CFD model with $1/\alpha$ and C_2 (measurement set 3 at 28.66 ls^{-1})

3 Results and discussion

8 values of $1/\alpha$ and 8 values of C_2 were used in 64 combinations to evaluate CFD model sensitivity to the porous zone parameters. A subset of these is presented in Fig. 1, which shows CFD model particle tracking solute traces recorded in the open water above the vegetation compared to the experimental results. The traces are significantly less sensitive to the $1/\alpha$ parameter than to C_2. Considering Equation 2, the viscous ($1/\alpha$) term is several orders of magnitude lower than the inertial (C_2) term for most combinations of $1/\alpha$ and C_2. However, as velocity approaches zero, the viscous term becomes more significant. Therefore, the insensitivity of the model to $1/\alpha$ may need to be revisited at lower velocities.

The model predictions are very sensitive to the C_2 parameter. Visual inspection suggests that $C_2 = 3.86$ m^{-1} produces a much better fit to experimental data than C_2 =1.44 m^{-1} (comparable to the value of 1.41 m^{-1} derived from the Ergun equation for this experimental configuration). Even small errors in estimating d or ϕ can therefore significantly influence the model. Given the inherent variability in measuring vegetation, this suggests that using the Ergun equation to estimate $1/\alpha$ and C_2 may not be robust.

Equation 6 is the standard stem drag formula, where a is frontal area. It is similar to the inertial loss term of Equation 2. This, combined with the sensitivity analysis presented above, suggests that the viscous loss term can be ignored, while maintaining the relevant model physics. This assumption allows the second stage of investigation to focus solely on C_2.

$$F_x = -\left(\frac{1}{2} C_D a \rho u^2\right) \tag{6}$$

3.1 The porous zone problem

A CFD model has been created with constant $1/\alpha = 1$ m^{-2} for each combination of 8 measurement sets, 5 flow rates, and 10 values of C_2, giving 400 models in total. Not all of these models ran as expected. Fig. 2 shows an example of poor model prediction, where the CFD-generated solute traces indicate plug flow. This is clearly not the case in the experimental results. The unexpected plug flow traces occur in all cases when the vegetation is emergent or only just submerged—only the fully submerged cases produce reasonable results. In all cases the velocity profiles match the experimental data. However, it is evident that the turbulence, which influences the particle tracking (i.e. mixing), is not being properly modelled.

Turbulence around vegetation can be thought of as being primarily generated by two mechanisms. When vegetation is submerged, water travels slower in the vegetation than the water above it due to resistance and as a result of this differential in velocity a shear layer forms, expressed as an asymptote in a velocity profile. This shear layer generates turbulence. Within the vegetation, the mean flow velocity is fairly uniform due to the drag of the stems acting on the water passing them. Although there is no velocity differential and no shear layer, turbulence is still generated as a result of the wake effect of water passing the stems.

When representing submerged vegetation via a porous zone, the flow is slowed in the porous zone and a shear layer forms at the porous zone/open water interface as a result of the velocity differential. However, nothing within the CFD model generates the within-vegetation wake effect, i.e. there is no source of turbulence within the porous zone. As such no mixing can take place when the vegetation is emergent, as observed. It is clear that the default porous media approach to vegetation modelling is inappropriate for reproducing mixing effects. Despite this, the CFD model appears to function well in the submerged vegetation cases when there is a sufficient depth of water above the vegetation for the shear layer to fully form, suggesting the mixing caused by a shear layer dominates.

Fig. 3 compares velocity and turbulent kinetic energy profiles for emergent and submerged vegetation, clearly showing the lack of turbulence within

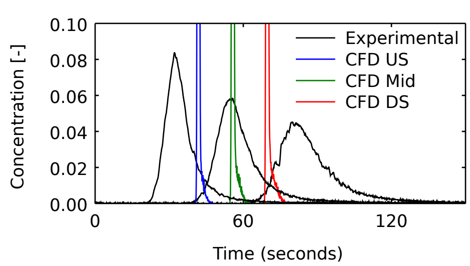

Fig. 2 Emergent vegetation particle tracking solute traces recorded at 7.36 (US), 9.80 (Mid) and 12.24 m (DS) compared to experimental solute traces for $C_2 = 1.71$ (measurement set 3 at 10.19 ls^{-1})

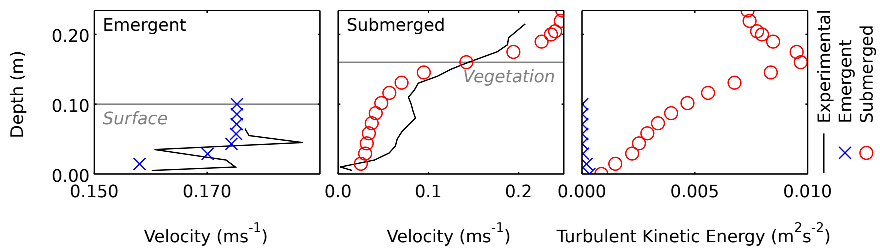

Fig. 3 Velocity and turbulent kinetic energy for emergent vegetation and submerged vegetation (measurement set 3 at 10.19 and 28.66 ls^{-1} respectively)

the emergent vegetation model. The experimental velocity profiles have been scaled according to the ratio of their area-weighted average to the mean velocity (Saggiori, 2010) to account for an experimental mass-balance error believed to be due to the existence of a preferential flow path around the vegetation at the side of the channel. This preferential path is also may account for some of the differences between the CFD generated and the experimental solute traces.

3.2 Best fit values of C_2 for submerged vegetation

As previously mentioned, the predicted solute traces for the submerged cases closely match the experimental data. Fig. 4 shows a subset of the submerged vegetation particle tracking data within the vegetation for measurement set 6 at 28.74 ls^{-1} flow. Visual inspection indicates that the best fit C_2 value is in the range of 6.84 to 12.32 for this experimental trial. Fig. 5 shows the range of best fit C_2 values determined by R^2 value at the maximum flow rate (25.22–29.42 ls^{-1}) for each dye injection trial at each measuring point. There is some variation within each measurement set, although for sets 3–8 the median values are consistently 6.84. The higher values for measurement set 1 may correspond to stiffer vegetation, causing increased mixing.

Table 1 shows the C_2 values for each measurement set derived from Equation 4. The calculated values consistently under-estimate the best-fit values. This may be in part due to the latter compensating for the lack of stem eddy mixing by artificially increasing the shear layer mixing. In turn the flow field will be affected, under-estimating flow in the vegetation and over-estimating it in the canopy, as seen in Fig. 3. The under-estimate also potentially indicates the Ergun equation is unsuitable for this application.

Tsavdaris et al (2013) used the porous zone approach to model the hydraulic effects of vegetation in a channel, but noted that it could not be used to predict turbulence. Without taking into account the turbulent effects of the vegetation stems, no CFD model utilising a porous zone will produce an accurate description of the treatment capability of a pond (e.g. an accurate RTD). Despite this, Tsavdaris et al (2014) used the porous zone approach to evaluate various pond designs, including those with emergent vegetation. They note increased turbulence around vegetation, which is the result of a porous zone interface, but their models do not account for turbulence within the vegetation. Their conclusions on large scale hydraulics do not appear to be directly affected by this, but their results imply a level of functionality of porous zone modelling that is not the case.

3.3 The porous zone solution?

Two problems have been identified with using porous zones. The first problem is the potential unreliability in estimating C_2. The second is the lack of turbulence generation within the porous zone to represent stem wake effects within vegetation. It is possible that relationship between C_2 and C_D could be developed (Zinke, 2010; King et al, 2012). Equation 7 provides an estimate of C_2 by balancing of gravity forces and drag forces, where g is the acceleration due to gravity, S is channel slope, and h is flow depth. Table 1 shows C_2 values derived with this equation, which provide reasonable agreement with the best fit values.

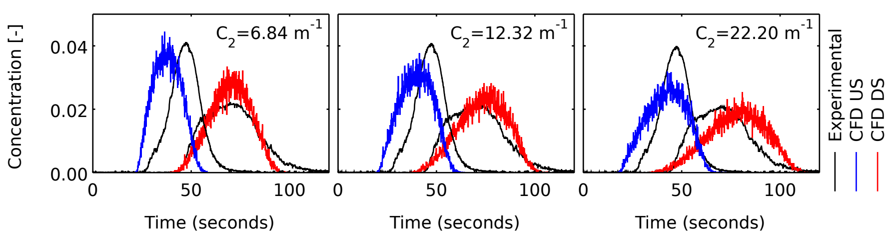

Fig. 4 Particle tracking solute traces recorded at 7.36 (US) and 12.24 m (DS) within the the vegetation compared to experimental solute traces, showing variation in the CFD model with C_2 (measurement set 6 at 28.74 ls^{-1})

Table 1 Outline of measurement sets, Ergun equation derived C_2 values, best fit C_2 values at 29 ls^{-1} flow rate, and C_2 values derived from a force balance

Measurement set	1	2	3	4	5	6	7	8
Age (weeks)	2	5	7	10	16	20	24	26
d (m)	0.010	0.015	0.020	0.030	0.040	0.045	0.050	0.055
ϕ	0.998	0.996	0.992	0.982	0.969	0.960	0.951	0.941
Ergun C_2 (m^{-1})	0.69	1.04	1.41	2.17	3.03	3.49	4.00	4.54
Best fit C_2 (m^{-1})	40.00	3.79	6.84	6.84	6.84	6.84	6.84	6.84
Force C_2 (m^{-1})	5.01	6.10	6.23	6.49	6.27	5.58	7.50	9.18

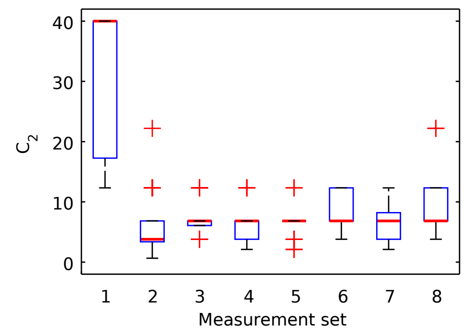

Fig. 5 A box plot comparing best fit C_2 values at the 29 ls^{-1} flow rate across measurement set for each possible R^2 comparison between CFD and experimental solute traces, where the thick line is the median, the box shows the 25th–75th percentile, the whiskers $\pm 2.7\sigma$, and the pluses values that fall outside the range of the whiskers

$$C_2 = \frac{2gS}{u^2 h} \tag{7}$$

It is possible to simulate additional turbulence within the vegetation. ANSYS Fluent allows the k and ε values of a porous zone to be manually set. Assuming that the vegetation is uniform and that the velocity distribution over the depth of the vegetation is uniform (two assumptions made for the application of the porous zone), the mixing effects of the stem wakes could be reproduced by choosing the correct k and ε values. Fig. 6 shows CFD generated solute traces corresponding to $k = 0.005$ and $\varepsilon = 0.0003$ for the same experimental configuration as Fig. 2, and shows more reasonable agreement with the experimental solute traces. These initial results are promising, but there are questions to be answered and potential limitations.

k and ε are complex parameters and suitable values should ideally be derived from the physical characteristics of the vegetation. The new $k - \varepsilon$ model proposed by King et al (2012) for vegetation may offer insight into how k and ε values may be determined empirically. Their results suggest this may be possible down to Reynolds number as low as 36. However, further work is required to implement and evaluate this approach.

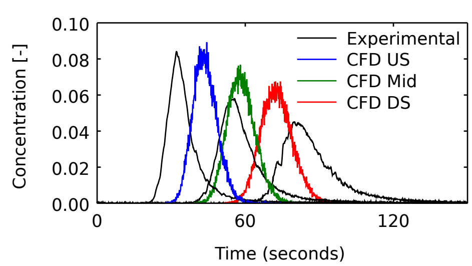

Fig. 6 Particle tracking solute traces recorded at 7.36 (US), 9.80 (Mid) and 12.24 m (DS) within the vegetation compared to experimental solute traces for $C_2 = 1.71$ with fixed $k = 0.005$ and $\varepsilon = 0.0003$ (measurement set 3 at 10.19 ls^{-1}, emergent vegetation)

4 Conclusions

This study showed CFD models of vegetation using a porous zone were insensitive to $1/\alpha$, but very sensitive to C_2. The porous zone approach could not reproduce solute transport data with emergent vegetation. This is attributed to the lack of a source of turbulence within the CFD model equivalent to that generated by stem wakes. As such, the default approach to modelling vegetation with a porous zone is inappropriate for reproducing mixing effects.

Best fit C_2 values for submerged vegetation show that C_2 values derived from the Ergun equation are under-estimates, and therefore the Ergun equation may not be an appropriate means of estimating porous zone parameters. The higher best fit values may be compensating for the missing mixing effects of the vegetation stems. Better estimates of C_2 may possibly be obtained by treating it similarly to a drag coefficient, i.e. C_D, and using a force balance to estimate it from experimental data. Values obtained using this approach show better agreement with the best fit values, although such an approach still fails to represent the within-vegetation generation of turbulence.

To better represent vegetation, the porous zone can be configured with fixed k and ε values, simulating the additional turbulence caused by stem wakes. This shows promising initial results and it may be possible to estimate suitable values based on vegetation characteristics. Therefore, although at present care must be taken when using the porous zone approach to modelling vegetation in CFD as it only reproduces the flow field, it may be feasible to use it to accurately represent the effects of vegetation on mixing in the future.

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