A validated CFD model for estimating residence times in vegetated stormwater ponds

Un modèle CFD validé pour estimer les temps de séjour dans les bassins de stockage des eaux pluviales végétalisés

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RÉSUMÉ

Des données expérimentales sur la dispersion dans la végétation naturelle typique des bassins ont déjà été recueillies en laboratoire. Cette caractérisation du mélange a été combinée à des approches de modélisation de la mécanique des fluides numérique (CFD) déjà proposées pour prédire les distributions du temps de séjour (RTD) des bassins de stockage des eaux pluviales végétalisés. Dans cet article, les résultats de la simulation sont validés à l'aide de traces de soluté obtenues dans un bassin de stockage d'eaux pluviales en activité. Compte tenu du degré d'incertitude associé à la géométrie du bassin et de la végétation, les temps de parcours médians et de première arrivée simulés correspondent étroitement aux données observées. Inversement, les simulations effectuées sans tenir compte de la présence de la végétation montrent des niveaux plus élevés de flux en court-circuit. L'approche de modélisation de la CFD comprend une méthode d'estimation du C_D basée sur les caractéristiques physiques de la végétation, ce qui permet de prévoir plus précisément la RTD par rapport aux directives précédemment disponibles sur le C_D.

ABSTRACT

Experimental data characterising dispersion within typical natural pond vegetation has previously been collected in a laboratory setting. This mixing characterisation has been combined with previously proposed Computational Fluid Dynamics (CFD) modelling approaches to predict Residence Time Distributions (RTDs) for vegetated stormwater ponds. In this paper, the simulation results are validated using solute traces obtained from an operational stormwater pond. Considering the level of uncertainty associated with the pond and vegetation geometry, the simulated first arrival and median travel times closely match the observed data. Conversely, simulations undertaken without accounting for the presence of vegetation show higher levels of short-circuiting flows. The CFD modelling approach includes a method for estimating C_D based on the physical characteristics of the vegetation; this is shown to provide a more accurate prediction of the RTD compared with previously available guidance on C_D.

KEYWORDS

Computational Fluid Dynamics (CFD), Drag coefficient, Pond, Residence Time Distribution (RTD), Vegetation

1 INTRODUCTION

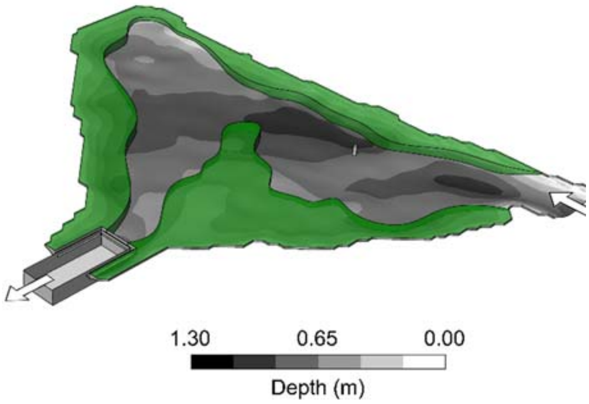
Vegetation is typically present within stormwater ponds. Vegetation has an important role to play in promoting the settlement of sediments and the biological removal of various stormwater pollutants. However, vegetation can also promote short-circuiting and potentially reduce the efficiency of treatment processes, such as sedimentation, that are linked to the residence time. The aim of this paper is to validate a CFD-based modelling approach to estimating the solute transport and mixing characteristics associated with a real, vegetated, stormwater management pond.

2 METHOD

2.1 Field Site & Dye Tracing

The pond (Figure 1a) is owned and operated by Highways England, and is located at Longbridge, UK, where it was constructed as a settling basin for stormwater from the adjacent M40 Junction 15 roundabout. The pond is at least 25 years old and has experienced extensive sediment build up and plant growth since its construction. The pond has one inlet (top right) and one outlet (bottom). Its surface area is approximately 750 m^2 with a 650 m^3 volume; the low-flow residence time is around 8 hrs. Flow rates range from a base flow of approximately 20 l/s to storm flows in excess of 100 l/s.

a) Aerial photograph (scale approximate)



b) CFD model with contours of depth (excluding outlet basin), green shaded area indicates vegetation

Figure 1 – The Longbridge pond

Tracer tests were undertaken on several occasions during 2016. Two traces conducted in the summer at 21 l/s and 25 l/s have been selected here.

2.2 CFD Modelling

Several researchers have applied Computational Fluid Dynamics (CFD) to predict pond hydrodynamic process, and the associated Residence Time Distributions (RTDs). Early outputs typically focused on simplified 2D models that did not account for vegetation (e.g. Persson *et al.*, 1999). However, vegetation is typically present in stormwater ponds, and its impacts on the flow field cannot be ignored. Vegetation may be taken into consideration within CFD models by explicitly modelling each individual stem in the domain. Unfortunately, the explicit modelling of stems is computationally expensive, as it requires mesh cell sizes to be of the order of the scale of the vegetation (mm) compared with the domain (tens of meters), resulting in a large number of cells.

The application of a drag force as a momentum sink within CFD models provides an alternative to the stem-scale approach (Tsavdaris *et al.*, 2014), with stem drag represented by C_D, the drag coefficient. However, this bulk scale approach removes stem-scale processes from the model that are essential for correctly representing mixing within the vegetation. It is possible to approximate those stem-scale processes using a fixed diffusion coefficient (e.g. Sonnenwald *et al.*, 2018a). However, a more elegant approach has subsequently been proposed (Sonnenwald et al, submitted) in which the magnitude of the in-vegetation mixing coefficient is determined both from the physical characteristics of the vegetation and from the local flow and turbulence processes. Following the approach outlined by King *et al.* (2012), the standard k-ε turbulence closure model has been modified to include turbulent kinetic energy (TKE), production within the vegetation, and to capture the energy transfer from shear-scale to vegetation-scale

TKE at the vegetation/clear flow shear interface. Values for the drag coefficient and the mixing coefficients are estimated for each cell based on the vegetation characteristics and local flow conditions. The framework has been implemented within a commercial CFD code – ANSYS Fluent 18.2 – via a set of user-defined-functions.

Based on a field topographic survey and aerial photography (Fig. 1a), the Longbridge pond was represented in CFD using a ~4 million cell model. The modelled pond volume was 600 m^3; this is slightly lower than the real pond due to model simplifications, including the removal of shallow pond margins. The vegetation varies seasonally, and the model was set-up to reproduce the summer conditions associated with the selected tracer tests, when the vegetation is most lush and extensive. The modelled vegetation was defined as summer *Typha latifolia* (Sonnenwald *et al.*, 2017), with a stem diameter (d) of 0.019 m, frontal facing area of 3.2 m^2/m^3, solid volume fraction (ϕ) of 0.049, and stem edge-to-edge spacing of 0.029 m. C_D was calculated as a function of d, ϕ, and velocity, based on Sonnenwald *et al.,* (2018b). Simulations were also undertaken with no vegetation and with the *Typha latifolia* vegetation, but assuming C_D = 1.0; this value is typically assumed in the absence of better information. The free surface was simulated with a zero shear fixed-lid approximation. The inlet velocity was set to 0.006 m/s for a steady flow equivalent to 22 l/s.

3 RESULTS

Figure 2 shows the simulated flow field at the pond surface. It is evident that there is considerable short-circuiting of the flow, with a clear direct route from inlet to outlet bypassing much of the vegetation. Recirculation cells are evident in the open water to either side of the main flow path.

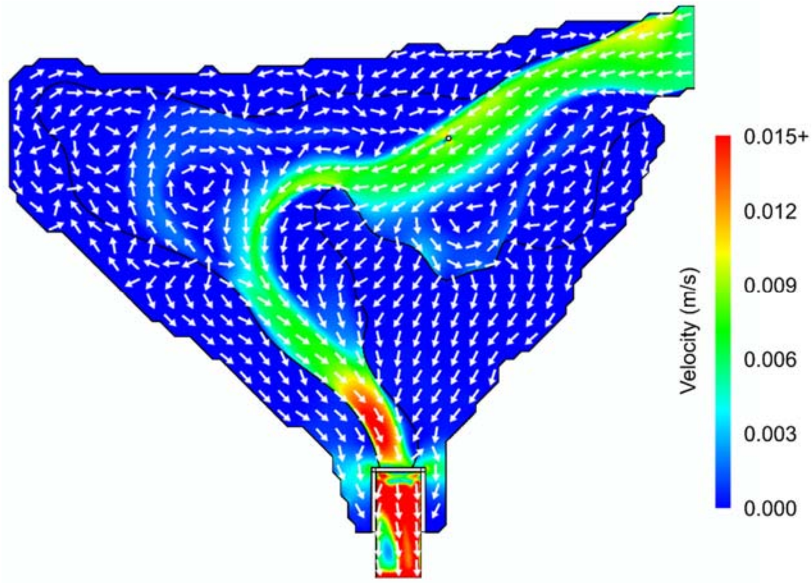


Figure 2 – Surface velocity contours with vectors indicating flow direction

Figure 3 compares the Cumulative RTDs (CRTDs) from the three simulations with the two observed traces. The x-axis is normalised time, λ, which is actual time divided by the nominal travel time (pond volume divided by flowrate = 7.6 hours). For plug flow, the CRTD would be represented by a vertical line at λ = 1.0; in this case, however, all the CRTDs indicate short-circuiting, with median normalised travel times of around $\lambda \approx 0.5$. This confirms that a substantial portion of the pond volume is bypassed by the flow. The long tails of the distributions are due to the small fraction of tracer that experiences transient storage in dead zones.

It may be seen that – with the exception of the no vegetation case – the simulated CRTDs match the observed data reasonably well. The model with no vegetation overestimates short-circuiting effects, with a median normalised residence time ($\lambda \approx 0.3$) that is significantly lower than the observed trace data ($\lambda \approx 0.5$). The inclusion of vegetation leads to a much closer match between the simulated and observed CRTDs. Comparison of the first arrival times indicates that the model incorporating a refined estimate of C_D (in this case ≈ 2.0, varying with velocity) performs better than a model that assumes C_D = 1.0. In the latter case, the first arrival time is 20-30% later, i.e. short-circuiting is underestimated.

It should be noted that complete mass-recovery has been assumed for the experimental CRTDs presented in Figure 3. However, it is possible that lower rates of recovery were achieved in practice, due to low sensitivity of the instruments at the end of the trace and/or incomplete mixing at the outlet. It is therefore possible that the experimental CRTDs in Figure 3 level off at mass-fraction below 1.0, potentially improving the goodness-of-fit of the CFD generated CRTDs.

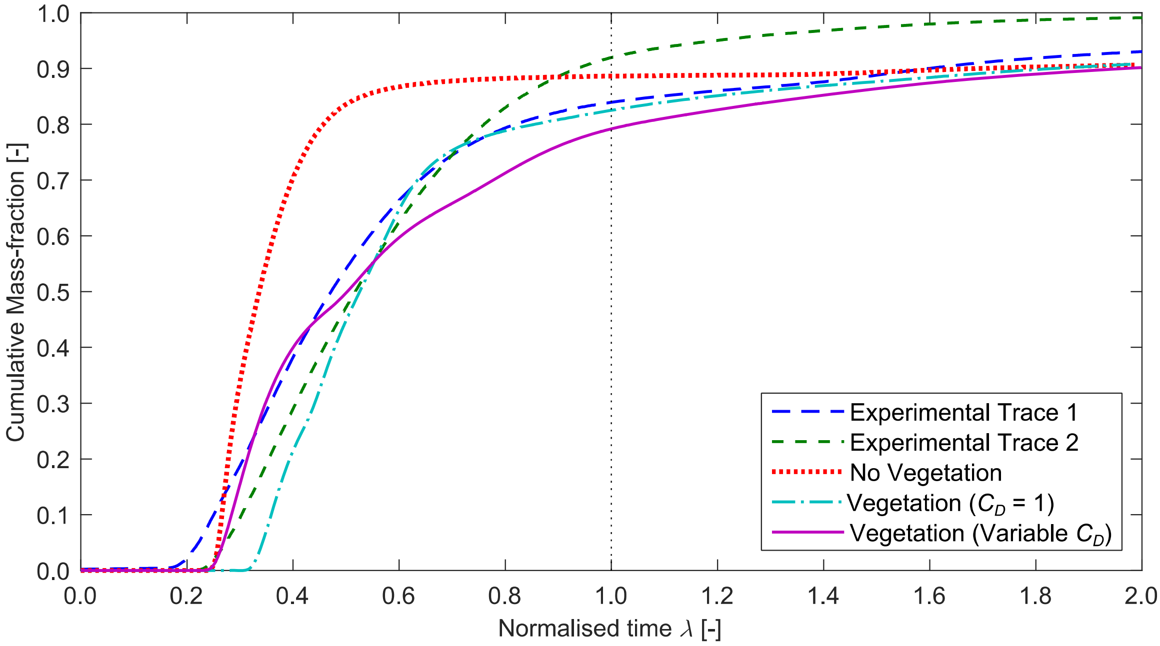


Figure 3 – Measured and simulated CRTDs, vertical dotted line indicates t_n

4 CONCLUSIONS

- It is feasible to capture the effects of vegetation on pond flow field and mixing processes via commercial CFD modelling tools combined with the user-defined functions outlined here.
- A comparison of modelled and measured solute traces suggests that the residence time distributions are reproduced well in the model.
- Failure to incorporate vegetation effects leads to poor estimation of mixing processes.
- Estimation of C_D based on Sonnenwald *et al.* (2018b) provides a better match to the observed data than a simplified value of 1.0.

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