



## A brief review of pond residence time studies

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**ABSTRACT.** Vegetation has a significant effect on the purifying processes in storm-water ponds. As pond hydrodynamics are also strongly affected by vegetation, it is necessary to understand flow and mixing processes in vegetated ponds for effective treatment design. In this paper the Residence Time Distribution (RTD) and related indices are discussed, and selected recent field and laboratory studies on vegetated ponds are reviewed. Selected RANS CFD (Reynolds-averaged Navier–Stokes Computational Fluid Dynamics) studies, which investigate pond geometry, are outlined. Those studies which investigate the effects of vegetation are divided into two types, first those which consider it as bed roughness or a retarding force, and second, those which consider it as a flow zone. The conclusions from the first approach are that it is sufficient to predict average hydraulic features for flood studies but insufficient for investigating mixing effects of vegetation. Recent publications have suggested that the second approach, i.e. considering vegetation as a porous media, may be more suitable. However, the most recent study highlighted certain limitations, as well as providing some preliminary suggestions for overcoming them. This discussion reinforces the need for further comprehensive research into this, and alternative, approaches.

**KEYWORDS.** Pond; Vegetation; RTD; CFD; Tracer Study.

### INTRODUCTION

Storm-water runoff typically contains a wide range of pollutants that can potentially impose negative impacts on the environment. Ponds, often supplemented with wetland plantings, are installed to treat storm-water. These ponds have short retention times, typically just a few days, and provide peak attenuation and enhancement of storm-water quality [18]. Well-designed storm-water ponds moderate negative environmental impacts and reduce the level of pollutants to below the regulatory limit. Vegetation provides the appropriate environment for bacteria, and so enhances the treatment. The flow path, dead zones and shear layers that form in ponds, i.e. the hydrodynamics, are also highly affected by vegetation. To design a pond for effective treatment requires an understanding of flow patterns through vegetated and open parts, as well as the interaction between them.

A considerable number of studies have been done on quantifying and understanding the hydrodynamics of ponds with and without considering the effects of vegetation. These studies are predominantly based on the application of 2D and 3D Reynolds-averaged Navier-Stokes (RANS) Computational Fluid Dynamics (CFD) models, with some laboratory and field

monitoring programmes. The aim of this paper is to review the most significant achievements related to residence time studies in irregular shaped ponds and wetlands; constructed wetlands are not considered in this study.

## THE RESIDENCE TIME DISTRIBUTION (RTD) AND RELATED METRICS

A convenient way to investigate the hydrodynamic behaviour of a pond, wetland or any tank with inlet and outlet is to study the time that the fluid spends in it. The Residence Time Distribution (RTD) shows the distribution of travel times in response to an instantaneous injection; the area under the curve equals unity by definition. The curve of dye concentration at the outlet versus time is identical to a frequency distribution of residence time [1]. Typical types of RTDs and Cumulative RTDs are shown in Fig. 1.

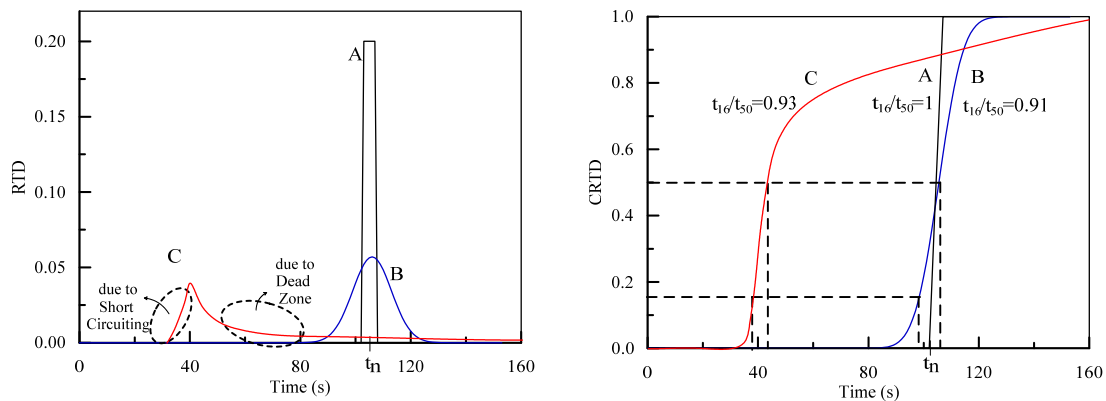


Figure 1: Typical RTDs, & CRTDs, A) plug flow, B) Gaussian spread and C) arbitrary mixing.

Several parameters have been defined to quantify pond performance. The Nominal Residence Time ( $t_n$ ) [18, 1] is calculated as the ratio of pond volume to inlet discharge, assuming that flow moves through the pond as plug flow, i.e. all the inlet flow is distributed evenly over the width of the pond and all the flow travels at a similar velocity (Fig. 1, case A). However, the assumption of plug flow is not valid in most real situations, because as mentioned by Thackston et al. [1] “the concept of plug flow assumes that there is no mixing or diffusion as the wastewater moves through the pond”. Unsteady flow rates, wind, inlet and outlet geometry effects and shear stresses due to boundary roughness at the sides and bottom, all act to cause dispersion in natural ponds. Dispersion causes a proportion of water to exit earlier than  $t_n$  and some to exit later, deviating from plug flow. The spread of the base of the RTD is a manifestation of dispersion, Fig. 1. cases B and C. Spread or dispersion can be quantified by the standard deviation.

One factor which causes deviation from plug flow is the presence of dead zones (also known as stagnation and recirculation zones). Thackston et al. [1] explained that any flow entering dead zones would be recirculated due to recirculation currents and have less than average velocities towards the outlet and hence a longer residence time. Although a high percentage of suspended solids may be removed in these locations, they have an adverse effect on treatment efficiency as their volume is unavailable to the mean flow and hence the mean residence time for most of the inflow decreases. Dead zones usually occur in hydraulically rough areas, corners, behind baffles or obstructions.

The reverse of the dead zone is short-circuiting, which has no precise technical definition [1] but which causes a significant part of flow to exit much earlier than  $t_{mean}$  or  $t_n$ . Ta and Brignal [3] used the ratio of  $t_{16}$  over  $t_{50}$  as a measure of short-circuiting ( $S=t_{16}/t_{50}$ ), where smaller values of  $S$  suggest less occurrence of short-circuiting. But, as is discussed by Stovin et al. [4], in the case of plug flow  $S$  would be equal to one despite the fact that there can be no short-circuiting in this condition (Fig. 1). Persson [5] suggested using  $t_{mean}$  instead of  $t_{50}$  in this formula, whereas Stovin et al. [4] proposed  $t_{50}/t_n$ . Case C in Fig. 1 demonstrates the effects of both short-circuiting (first arrival times  $\ll t_n$ ) and dead zones (a long tail on the RTD with some residence times well in excess of  $t_n$ ).

All the above mentioned features of imperfect hydrodynamic behaviour [6] cause the actual travel time to deviate from the nominal travel time. To quantify the degree of imperfection of flow, several authors have tried to provide an efficiency index which in essence compares the actual and the nominal travel times, e.g. Thackston et al. [1] defined  $t_{mean}/t_n$  as the hydraulic efficiency where Persson et al. [2] named this ratio as the effective volume and developed another index for the hydraulic efficiency as the ratio of  $t_p$  (time of peak concentration occurrence) over  $t_n$ .



The aim of the current research project is to use CFD to accurately characterise the RTDs of real storm-water ponds, and – in particular – to focus on properly representing the effects of vegetation. The following review highlights the key CFD studies relating to pond residence times, most of which have focused on pond geometry and neglected vegetation. As the development of a CFD-based modelling methodology that includes vegetation effects needs to be underpinned by a good understanding of the physical processes, relevant field and laboratory studies are briefly introduced; in particular, those that might provide suitable data for model development and validation are highlighted. The CFD studies to be discussed here are RANS models; other CFD approaches such as lattice Boltzmann and Large Eddy Simulation may also be relevant, but do not appear to have been practically implemented in pond studies to date.

## FIELD AND LABORATORY STUDIES

A tracer study on a 7 ha vegetated maturation pond was done by Espinoza and Rengel (cited by Alvarado et al.) [7, 8]. The latter developed a 3D CFD RANS model with  $k-\epsilon$  closure in ANSYS Fluent 6.3, using the former's field data for validation. The maturation pond was part of the largest wastewater facility in Ecuador. The total surface area of the system was 45 ha with a nominal residence time of 12 days. In the tracer study the RTD was produced by injecting a pulse of Rhodamine WT and the fluorescence concentration was measured for 30 days. It was seen that the majority of the tracer left the pond in the first 30 minutes, making a short circuit between the inlet and the outlet, which were both placed on the same side of the pond. A minor but visible quantity of tracer remained in the corner closest to the inlet pipe, indicating a stagnant zone. There were two peaks in the tracer record at the 2nd and the 4th hour of recording. An unsteady CFD model using the transient flow equation (species transport model) was run to simulate the first three days of the field tracer study. The main short-circuiting effects were reproduced well. However, there was no effort to model the vegetation and this may account for some discrepancies between the CFD and experimental data.

Tsavdaris et al. [9] studied a vegetated pond receiving road runoff with an area of  $51 \times 26$  m<sup>2</sup> and the capacity of 304 m<sup>3</sup> comprising two basins with a raised berm between them. The basins were planted with two types of emergent plants: (i) *Phragmites australis* (P.A) and (ii) *Typha latifolia* (T.L). Seven storm events were monitored with the highest  $Q=0.064$  m<sup>3</sup>/s. Vegetation cover was measured in 0.5 m<sup>2</sup> quadrats and plant diameters of 0.01 and 0.035 m were measured for (P.A) and (T.L) respectively. A laboratory study in a  $6 \times 0.29$  m flume with a slope of 0.004 with two discharges of 0.0077 and 0.0174 m<sup>3</sup>/s was also done. Emergent vegetation was simulated using stiff bamboo sticks with identical diameters to those observed and surveyed in the field study. They used the lab data to validate a CFD model (explained later under Tsavdaris et al. [10]) which used porous media to model the vegetation.

Shucksmith [11] investigated flow within emergent and submerged *Carex* grown for a period of 7 and 26 weeks in a  $14.48 \times 0.6$  laboratory channel with a slope of 0.00123. Tracer studies were done at 5 flow rates ranging from 0.00919 to 0.02942 m<sup>3</sup>/s. The compiled data from this study was used subsequently by other researchers to validate CFD models. Hart et al. [12] is another source of potentially-useful experimental and field data.

## GEOMETRY EFFECTS IN CFD STUDIES

Several 2D CFD modelling studies have been done to investigate different pond geometries. In these studies the vegetation was typically not considered, indeed the ponds were modelled as empty tanks. As an example, Persson et al. [2] provided a reasonably comprehensive review of geometry effects. They assessed the hydraulic efficiency of 13 pond geometries, with 2D models using Mike 21, a RANS CFD model with  $k-\epsilon$  turbulence closure. They found that elongated and baffled systems provided very high hydraulic efficiency, i.e. close to plug flow. They also demonstrated the significant effect of a subsurface berm or an island which could improve the hydraulic performance by decreasing short-circuiting [5].

## MODELLING VEGETATION IN CFD STUDIES

In order to take in to account the effect of vegetation on the flow field, different approaches can be found in the literature. Some have simply defined a roughness factor and others have used more complicated models, which are going to be discussed in this section.

### *Vegetation as a Boundary Condition*

Some researchers have considered vegetation only as a bed roughness effect and tried to model it by assigning very high friction factors like Manning's  $n$ . Manning equation is a 1D open channel steady uniform flow equation, determining average hydraulic characteristics of flow based on an estimated friction factor, Eq. (1).

$$v = \frac{1}{n} R_b^{2/3} s^{1/2} \quad (1)$$

in which,  $n$  is Manning's factor,  $v$  is the average velocity,  $R_b$  is the hydraulic radius and  $s$  is the slope of the channel. It appears that the first efforts to estimate the value of  $n$  for vegetated channels were reported by Chow [19], assigning values between 0.005 to 0.1 for low to very high density of vegetation.

Somes et al. [13] gathered vegetation distribution, basin bathymetry, and measurements of flow velocities of the Monash University Research Wetland (MURW), an irregular constructed wetland with emergent macrophytes on its fringes. Tracer studies were not done due to recirculating of water from the outflow. A 2D Mike 21 model was used and different values of Manning's  $n$  (from 0.05 to 1.0) were allocated to each vegetation type. The  $n$  values were calibrated by visually comparing the measured and recorded flow vectors and the flow patterns they formed. Testing different friction values they concluded that the model was relatively insensitive to changes in friction, and this was attributed to the fact that the low velocities create small friction forces. In fact they assumed both submerged and emergent vegetation could be represented using different bed roughness values. This approach could be sufficient for specific purposes such as flood studies to predict the flow depth, but in order to predict mixing processes it is necessary to investigate the flow behaviour within the vegetation. It should be mentioned that the field part of this study may represent the most comprehensive study done to date to map a pond's internal flow field.

### *Vegetation as an Obstacle*

Another approach to model the effect of vegetation is to consider it as an obstacle which exerts a retarding drag force on flow. There are some studies trying to find drag coefficient or to define a mathematical model based on drag coefficient to represent the effect of vegetation as a block in front of flow. Kadlec [14] assessed a number of proposed relations for taking to account the effect of vegetation and concluded that for emergent vegetation, open channel equations such as Manning's should not be used because they apply to situations where bottom drag is controlling. Instead he proposed to use drag force to represent the effect of emergent vegetation where vegetated drag controls. Although this study clarified the important effects of vegetation on flow field, the proposed 'solid block' approach does not help in terms of clarifying mixing effects within the vegetation.

### *Vegetation as a Flow Zone*

Flow behaviour within the vegetated parts is considerably different from its behaviour through open parts, in such a way that cannot be expressed only by friction or retarding force. Features such as residence time, short-circuiting, dead zone and also all the mixing coefficients cannot be estimated unless the vegetation can be modelled as a different flow zone from open parts of the pond. A new approach has emerged in recent years, which considers the vegetation as a porous media. The porous media concept allows for flow movement within the vegetation and the resulting mixing effects may potentially be modelled and investigated.

Saggiori [15], using 2D and 3D k- $\epsilon$  RANS CFD models in ANSYS Fluent 12, modelled vegetation as a "Porous Zone". In this approach an additional source term is added to the Navier-Stokes equation Eq. (2). This additional source is a force representing the effects of porosity in the flow direction. This force is computed by Eq. (3), consisting of viscous and inertial parts, where  $\rho$  is density,  $\mu$  is dynamic viscosity,  $u$  is velocity in the  $x$  direction and  $\alpha$  and  $C_2$  are estimated based on Eq. (4) and Eq. (5) respectively (Ergun [16]).

$$\frac{\partial \rho u u}{\partial x} + \frac{\partial \rho v u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + F_x \quad (2)$$

$$F_x = -\left( \frac{\mu}{\alpha} u + C_2 \left( \frac{1}{2} \rho u |u| \right) \right) \quad (3)$$

$$\alpha = \frac{d^2}{150} \frac{\phi^3}{(1-\phi)^2} \quad (4)$$



$$C_2 = \frac{3.5(1-\phi)}{d\phi^3} \quad (5)$$

These models were validated with experimental data from Shucksmith [11] and showed that the porous media approach resulted in velocity profiles which were consistent with experimental ones, see Fig.2. In addition, simulated RTDs, representing preliminary concentration profile predictions, showed promising comparability with the laboratory measurements.

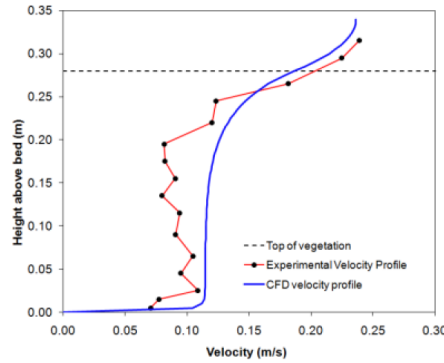


Figure 2: Comparison between experimental data and CFD data, 26 weeks;  $Q=29.5$  l/s (from Saggiori [15])

Tsavidaris et al. [10] used two strategies for the CFD modelling of vegetation in ponds, (i) directly replicating individual vegetation elements within the computational domain, and (ii) using porous media. By comparing the velocity profiles resulting from laboratory study and modelled in ANSYS Fluent 12.1, they concluded that the first approach was much more accurate than the porous configurations in predicting turbulent flow within the vegetation. However, it should be noted that the direct representation of individual vegetation elements is too computationally expensive to scale up for application to real pond systems. Tracer studies were not done in this research.

Sonnenwald et al. [17] undertook a sensitivity analysis of the porous media approach using ANSYS Fluent 14.5. They showed that the results were highly sensitive to  $C_2$  and insensitive to  $1/\alpha$ . CFD model was validated using Shucksmith's [11] laboratory data. Comparing particle tracking results with experimental solute traces showed that using the Ergun equation to estimate  $1/\alpha$  and  $C_2$  may not be suitable, instead estimating  $C_2$  by balancing gravity and drag forces was suggested. They explained that turbulence around vegetation is generated by two factors: (i) the shear layer at the boundary between the vegetated and open flow; and (ii) by wake effects of water passing the stems. By assessing the submerged vegetation model, they concluded the shear layer part (which is a result of velocity difference) was correctly modelled but the wake effect was not. This was attributed to the lack of a source of turbulence within the porous zone. Their suggestion was to manually set the  $k$  and  $\epsilon$  values for the porous zone to simulate the additional turbulence. They stated that it might be possible to empirically estimate these values based on vegetation characteristics.

## DISCUSSION

Velocities produced in real ponds are usually much smaller than those considered in most of the laboratory investigations. This can make the conclusions unrepresentative of what is exactly happening in the ponds. Also, in most of the CFD modelling research,  $k-\epsilon$  models are used in order to model the produced turbulence within the vegetation; these models assume that the Reynolds stress is the same in all the three dimensions. This assumption may not be true for some conditions, particularly for vegetation. In addition, a porous media approach may not be appropriate to model all different vegetation patterns, as there are many different vegetation patterns grown in ponds and also they tend to change from one season to another.

The present research is at a very early stage. Many relevant literature sources have not been discussed here. In addition, it is acknowledged that alternative model frameworks, such as lattice Boltzmann (which can potentially provide detailed information about flow behaviours e.g. wake effects associated with vegetative flows), need to be considered in the next phase of this study.



## CONCLUSIONS

An RTD describes and quantifies flow patterns and mixing processes within vegetated ponds. Most ponds do not have ideal plug flow; instead they are characterised by complex mixing processes, for example dead zones and short-circuiting. A range of field, lab and CFD studies, from simple 2D ones to comprehensive investigations of flow within the vegetation, were reviewed. Among different approaches for modelling vegetated ponds, using porous media has been introduced as the most appropriate approach to date. This approach makes it possible to predict RTD indices and hydrodynamic flow features including velocity profiles. However, further investigation is needed to produce a general model which can completely represent the turbulence generation and other hydrodynamic characteristics of flow within the vegetation.

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