EFFECTS OF SEASONAL VARIATION OF VEGETATION ON HYDRAULIC RESIDENCE TIME DISTRIBUTIONS IN A STORMWATER POND

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ABSTRACT

Treatment system performance is often evaluated using Residence Time Distributions (RTDs), which will be different for different discharges. However, when normalised for discharge, the shape of the RTDs, for the same system, should be similar. In natural stromwater ponds, the change in vegetation cover throughout the year alters the system's effective bathymetry and flow field, as summer vegetation has a greater resistance than winter vegetation/free water. This will change the system RTD from summer and winter, which will impact on treatment performance. Fluorescent dye traces were conducted at a stormwater pond field site in Warwickshire, UK, in both summer and winter to evaluate the system RTD. The bathymetry of the site was surveyed and the vegetation distribution was analysed using aerial imagery in summer and winter. The results showed that the change in vegetation had an impact on the system hydraulics. The total vegetation surface coverage varied from ~60 % in summer to 40 % in winter. In terms of the RTDs, first arrival times and peak concentration times were similar for both summer and winter. However, the winter data showed less spread, and had a lower mean residence time than the summer data. The data suggests that the summer flow experienced more mixing, probably as a result of the increased vegetation coverage.

Keywords: Stormwater ponds, vegetation, residence time distribution, dye tracing.

1 INTRODUCTION

Storm water runoff typically contains and transports a wide range of pollutants, resulting in negative environmental effects with potential threats to ecosystems and health. Many runoff treatment ponds designed to moderate these impacts (Kadlec & Wallace, 2008; Shilton, 2005) are likely to be delivering sub-optimal levels of improvement in water quality due to poor understanding of flow patterns and the effects of vegetation. Pond performance (pollutant treatment efficiency) is directly related to hydraulic residence time, a function of the internal flow field, which in turn is controlled by the pond geometry and the distribution and type of vegetation present. A single hydraulic residence time is often a poor description of the pond, and instead it can be described using the residence time distribution (RTD). This is the probability distribution of the residence times of the influent. It gives the integration of all of the different flow paths through the system and is the simplest method to quantify the internal hydraulics of a system.

Vegetation can have both positive and negative effects on water quality treatment within stormwater ponds. It provides the appropriate environment for the support of biofilms and the colonisation by algae, enhancing treatment, yet variable spatial distribution influences the spread of the hydraulic residence time. If vegetation is spatially homogeneous it reduces velocity and aids sedimentation. With natural, diverse and heterogeneous vegetation, the plant density (porosity) impacts on the mean flow field, creating preferential flow paths. This is clearly illustrated in the photographs shown in Figure 1, taken during preliminary field studies shortly after the release of a fluorescent tracer (Hart et al., 2014). The tracer is still visible at this stage and is seen to flow around a small patch of low-density floating vegetation. The effect of this non-homogeneous vegetation patch reduces the mean residence time, the overall mixing and dilution within the pond. This paper presents new data illustrating the difference in cumulative residence time distributions (CRTDs) between winter and summer vegetation coverage in a stormwater pond.

2 PREVIOUS STUDIES

Previous work has been performed in laboratory situations using artificial vegetation (rigid cylinders) to investigate resistance, turbulence and diffusion (Nepf, 2012). Tanino and Nepf (2008) showed that, in a random array of cylinders simulating emergent vegetation, the major contribution to lateral dispersion switched from turbulent diffusion between the cylinders at low solid volume ratios, to the effect of tortuous flow paths at higher solid volume ratios. Shucksmith et al. (2010) employed real vegetation uniformly distributed across the full channel width to quantify the effects of porosity and growth cycle on flow resistance and longitudinal dispersion processes. The effects of real vegetation, including the solid volume fraction (porosity), heterogeneity (plant mosaic) and the effects of velocity, within a vegetation patch (permeability) and the shear caused by the patch, need to be quantified with respect to the physical plant properties and related to the annual growth cycle (winter dormancy, spring growth and summer maximum foliage) to permit realistic modelling of the physical processes.


a) 20 mins after injection b) 80 mins after injection

Figure 1 Aerial images illustrating the effects of vegetation on flow field, Lyby pond, Sweden

Modelling the presence of vegetation is necessary to predict velocities and other mean flow-field effects (Nepf, 1999; Tsavdaris et al*.,* 2013, Marjoribanks et al*.,* 2017), while solute transport modelling in vegetated systems is necessary to predict mixing and treatment processes (Sonnenwald et al., 2019). White and Nepf (2003) suggested that longitudinal dispersion in emergent vegetation is primarily due to vortex trapping and stem-scale secondary wake dispersion. Nepf et al. (1997) and Nepf (1999) proposed a model to estimate transverse dispersion within emergent vegetation due to two processes: energy dissipation from the stem drag force and the individual flow paths imposed by the tortuosity caused by the physical obstruction of the stems. Sonnenwald et al (2017b) conducted laboratory tracer studies to quantify both transverse and longitudinal dispersion within emergent vegetation simultaneously. Experimental dispersion data were collected for two densities of artificial vegetation and three types of real vegetation. Photographs showing the difference between the winter and summer Typha conditions are shown in Figure 2. The variation of the dispersion coefficients with longitudinal velocity for this vegetation is shown in Figure 3, illustrating the difference between winter and summer, which for the transverse dispersion coefficients, D_y, is a factor of three.


a) Winter b) Summer

Figure 2 Laboratory studies to quantify mixing within Typha
from Sonnenwald et al. (2017b)

Computational Fluid Dynamics (CFD) simulations have been used to study flow fields within ponds of different shapes (Persson et al., 1999) and containing vegetation (Tsavdaris et al., 2013). Persson *et al* (1999) reported results from a CFD study on the hydraulic performance of ponds of various layouts and extended the study (Persson & Wittgren, 2003) to the impact of effective volume and dispersion on pollutant removal efficiency. Pettersson (1999) conducted a study of stormwater ponds for pollution reduction, undertaking field studies to determine pollutant removal efficiency and CFD modelling of the internal flow field. His conclusion suggests that to accurately describe the effects of vegetation on preferential flow paths, transient storage zones and mixing within a natural stormwater pond, 3D representation would be essential. Shilton *et al.* (2008) describe a study which compared CFD simulations against tracer data for a field waste stabilization pond without vegetation. The comparison of the CFD results with the full-sized pond data showed a higher peak concentration and a time lag compared to that of the field studies. Sonnenwald et al (2017a) combined the characterization of mixing within vegetation with CFD modelling approaches to predict residence time distributions for vegetated stormwater treatment ponds. The results showed that the presence of vegetation resulted in residence times closer to plug flow, indicating significant improvements in stormwater treatment capability. The CFD modelling suggests that it is more important to include vegetation in the correct location than it is to accurately characterise it. Estimates of hydraulic efficiency suggest typical ponds with clear water need to be designed to be between 50 % and 100 % larger than their nominal residence times (t_n=vol/Q_{mean}) would suggest to obtain the design residence time.

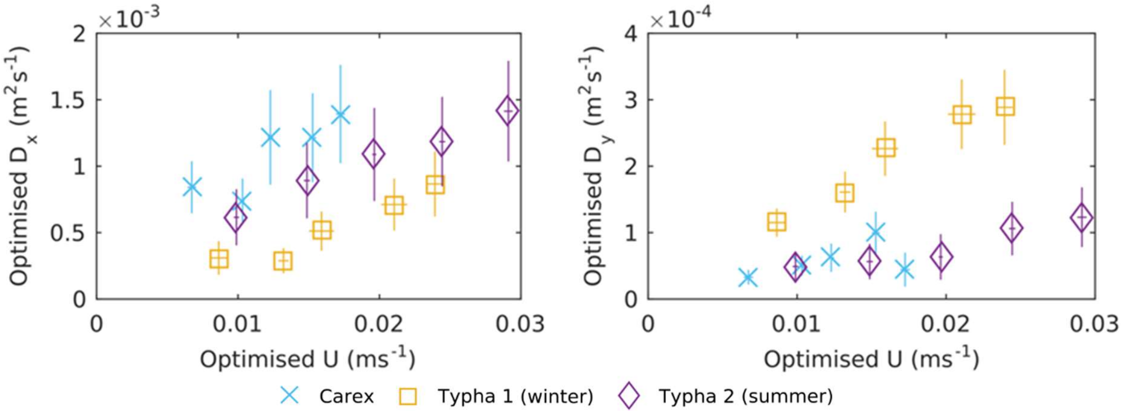

Figure 3 Dispersion coefficients obtained from real vegetation laboratory tests
Sonnenwald et al (2017b)

3 DATA COLLECTION - LONGBRIDGE STORMWATER POND

This paper presents new data from tracer tests that have been conducted at different times of year, under different discharge and growth conditions, with different natural vegetation distributions. The tests measured the discharge, the hydraulics (using dye tracing techniques) and the vegetation distributions (using aerial photography).

The investigated pond was located at the Longbridge Highways Depot, Warwickshire, UK, where it was constructed as a settling basin for stormwater from the adjacent roundabout (see Figure 4). The pond is over 25 years old and, since construction, has experienced extensive sediment build up and plant growth. The pond has only one inlet and one outlet (Figure 5), and has partial vegetation cover which changes seasonally. The pond is served with constant base flow from the stream at the inlet. This discharge was approximately 20 l/s in summer. The maximum discharge measured was in excess of 100 l/s. Various properties of the vegetation were evaluated, such as the location within the pond, the type and the density/form at different locations.

3.1 Survey Data

A topographic survey was conducted in April 2016, with the vegetation in its winter die-back state to improve lines of sight and access to the site. Around 1000 data points were recorded with a horizontal resolution of better than 1 m. The pond is a roughly triangular shape, Figure 5. The straight line distance between inlet and outlet is 40 m, although due to the topography and the extent of the plan growth, the main flow path is likely to be at least 60 m. The mean depth is 0.543 m and volume is 513 m^3. Figure 5 shows the transect X-X across which a number of fluorometers were positioned.

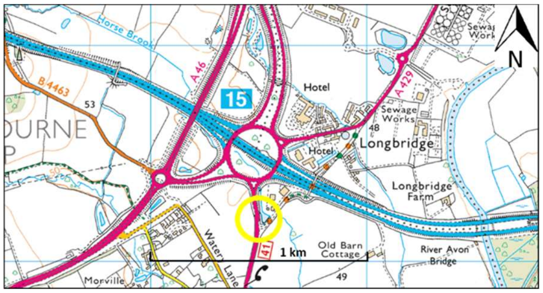

Figure 4 Pond Location
OS Grid Ref: SP 26526 62205

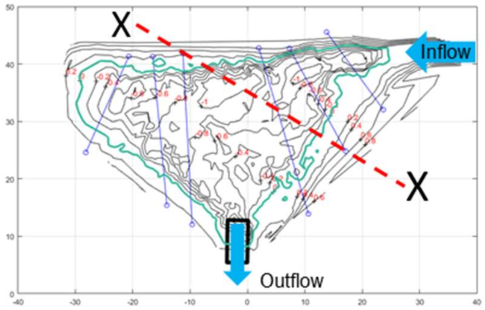

Figure 5 Contour plot of pond
(all dimensions in metres)

3.2 Vegetation distribution

Vegetation distributions were found using aerial photography captured with a drone, Figure 6. During the summer survey of July 2017, random quadrats were used to gather more information about the vegetation, such as density and species. A 300 x 300 mm quadrat was used at 10 random locations within the pond. Due to the difficulty of taking measurements from within a boat on the pond, the vegetation within the quadrat was cut and taken back to the lab for analysis. Once in the lab, the stem diameters and species of each stem were recorded. This also allowed for the density of vegetation in the quadrat to be calculated. From the July 2016 field survey the stem density was found to be 446 ± 228 stems/m^2 and solid volume fraction 1.17 ± 0.74 %.

Summer vegetation distribution (August 2015) Winter vegetation distribution (March 2015)

Figure 6 Images of summer and winter vegetation distribution at Longbridge Pond, UK
Top: aerial, bottom from outlet

3.3 Discharge measurements

At the outlet of the pond, the water entered a concrete forebay area and then went over a 300 mm thick concrete weir, shown in the lower pictures in Figure 6. The weir was 3 m wide and water at a depth of just over 20 mm flowed over it during base flow conditions. The assumption was made that the outlet weir could be treated as a broad-crested weir. As the flowrate over a broad-crested weir is a function only of height above the weir, depth sensors were used to determine the discharge. Three ISCO depth meters were used. Two were located at the outlet, one close to the weir, the other a little further upstream. The third was located near the inlet. Figure 7 shows the layout of sensor locations at the weir.

3.4 Dye Measurements

Dye tracing is the easiest means of measuring the RTD of a system. It can be achieved using either pulse or continuous injections. However, for large systems, the amount of dye required to conduct a continuous injection is impractical. Pulse injections of the fluorescent dye, Rhodamine WT were used in these tests. The dye was allowed to flow naturally through the system. The concentration of the dye was then measured at the outlet at 10 s intervals. The outlet concentration was measured using two different fluorometers, a Turner Designs Cyclops 7 fluorometer and a Turner Designs SCUFA. Both instruments were placed close to the water surface, next to the weir at the outlet of the pond, see Figure 7. Special care was taken to orient the instruments such that air bubbles did not get trapped near the light sensors, as this would interfere with the results. The fluorometers were pre-calibrated in the laboratory. Calibrating the instruments allowed comparison between the two instruments and allowed a mass balance check to be performed on the data. To gain insight into the flow field within the pond, six additional fluorometers were placed across a study transect to record temporal concentration distributions both within the vegetation and the open water. Figure 8 shows the location of the sensors across transect X-X in the pond.

Figure 7 Location of instruments at pond outlet

4 ANALYSIS

Concentration values were calculated from the raw data with the use of the laboratory calibration data. Even after calibration, the collected data often has an offset due the differences between the water used for calibration and the water present in the pond. The data recorded before the dye has been injected/arrived at the probe, was assumed to be at this background level. Due to variation in first arrival time at different discharges and at different sensor locations, background data was selected manually and was removed from the entire dataset.

Table 1. Summary of the key data from the traces.
(shading indicates the single winter trace)

Date	Time	Dye Inj.(ml)	Discharge ± SD (l/s)	Start Time (mins)	Peak Time (mins)	End Time (mins)	Mass Balance (%)
23/06/16	13:40	100	25.1 ± 0.6	66.5	148.0	1984.0	84
01/07/16	13:35	50	29.8 ± 1.5	74.0	124.0	1016.0	79
07/07/16	11:11	50	20.6 ± 0.6	87.0	167.5	1642.0	125
12/07/16	11:04	50	21.0 ± 3.4	106.0	173.0	1480.0	107
26/09/16	16:40	50	15.3 ± 2.4	101.0	152.5	2622.0	129
28/09/16	19:00	50	13.1 ± 0.4	100.5	156.5	2319.5	136
06/03/17	13:07	50	70.7 ± 13.6	35.0	51.0	278.0	117

Robust methods for finding the start, peak and end times of often noisy and non-smooth distributions, are difficult to find. In this analysis the concentration threshold was determined as 1.5 times the standard deviation of the background selection, i.e. a value related to the sensor noise. This method is robust as it is primarily a function of the sensor rather than system and as such should be the same or similar for different tests. Taking such a small multiple of the standard deviation is problematic for noisy data, as it is quite likely that the noise may pass this threshold before the dye has actually arrived. To mitigate for this problem, the data was smoothed with a five point moving average and this smoothed data was used to find the salient points. Even with the smoothing, false alerts were still common, so the final accepted values for start and end times stipulated that the next 10 points were also above/below the threshold. Once the start and end times of the trace had been identified, it was helpful for further analysis for the background data before and after the trace to be removed. A summary of the key trace data is presented in Table 1.

An example of the raw data from the instruments positioned along the study transect is shown in Figure 9. This clearly illustrates one of the major challenges of performing in-situ concentration measurements, namely interference from vegetation and noise. However, despite these problems, the data shows the difference in first arrival times between the instruments located in the clear flow (numbers 2, 3 & 4) and the instrument located within the vegetation, instrument 6. On this date, the difference is around 100 minutes.

The final stage in the process was to combine dye and discharge data to obtain the mass/volume flux of the injected dye. The mass flux is defined as the product of instantaneous concentration and discharge values and can only be derived at the outlet to the pond. A mass balance check was conducted for each of the tests. Table 1 gives a summary of the mass balance analysis.

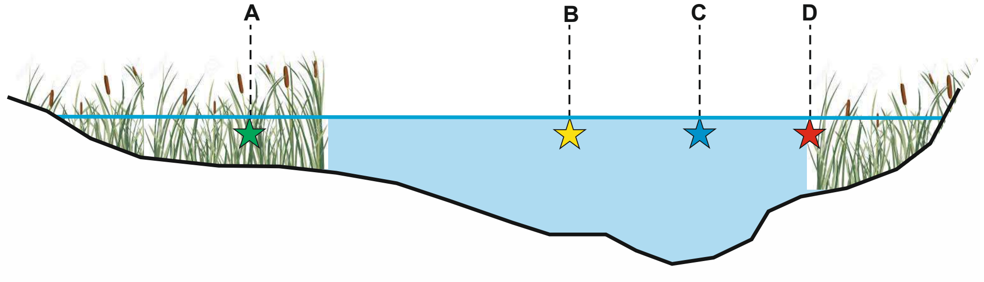

Figure 8 Schematic showing location of sensors across monitoring transect

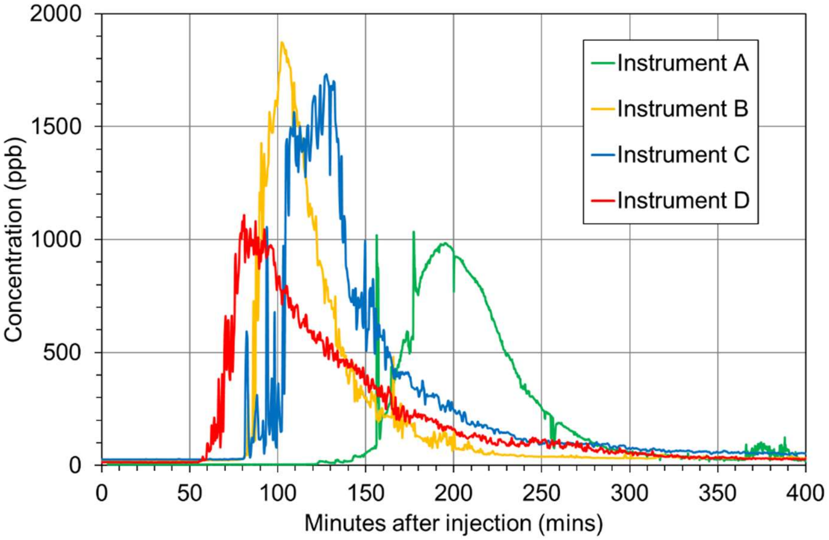

Figure 9 Example of temporal concentration distributions across measurement transect

Normalised residence time distributions and cumulative residence time distributions (CRTDs), shown in Figure 10, were calculated from the mass flux data by normalising the mass flux with the injected mass (M_{out}/M_{in}) and normalising the time axis with the nominal residence time (t/t_n). When the RTD is normalized this way, it is possible to compare different traces. Various metrics were calculated from the normalised RTD. t_m is the non-dimensional time of the centroid of the trace. t_{10}, t_{50} and t_{90} are the non-dimensional times for 10, 50 and 90 % of the dye to reach the outlet. t_p is the non-dimensional time of the peak trace value. Results of this analysis are summarised in Table 2.

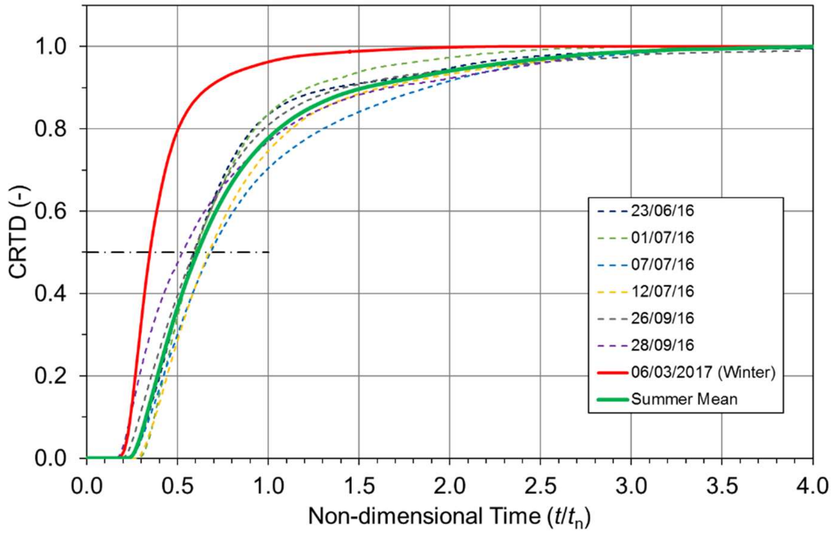

Figure 10 Measured Cumulative Residence Time Distributions at Longbridge Pond, UK.

5 DISCUSSION

The mass balance results are poor. This may be due to issues with the assumed calibration equation of the outlet weir, which was not designed as a gauging weir. Incorrect discharge data would give misleading results. However, data from the second series of traces suggests another explanation. In this set of tests, outlet dye data was also collected from the side of the weir, and often these appear to have resulted in lower than 100 % mass recovery, when sensors placed in the centre of the weir give over 100 %. This shows that the dye in not cross-sectionally well mixed in the forebay before the water flows over the weir. However, for the results presented here, an average concentration was used. Due to issues attaining mass balance for the different traces, the CRTDs for each of the traces tend to different values. This does not have a significant effect when calculating CRTD metrics, but is problematic for visually comparing different traces. The CRTDs were rescaled by taking the value relative to the final value, i.e. forcing a mass balance. This allowed the shapes of different CRTDs to be compared, and they are shown in Figure 10.

Table 2 Residence Time Distribution metrics

Date	Mean Discharge (l/s)	t_n (mins)	t_m	t_{10}	t_{50}	t_{90}	t_p
23/06/16	25.1	340.5	0.76	0.33	0.59	1.34	0.43
01/07/16	29.8	287.1	0.77	0.38	0.62	1.34	0.46
07/07/16	20.6	414.5	1.01	0.34	0.68	2.62	0.40
12/07/16	21.0	408.0	0.83	0.39	0.71	1.41	0.42
26/09/16	15.3	557.1	0.81	0.30	0.62	1.55	0.27
28/09/16	13.1	652.6	0.75	0.24	0.51	1.62	0.24
06/03/17	70.7	120.9	0.42	0.24	0.35	0.67	0.30

Figure 10 shows the comparative plots of the different traces, with 06/03/17 being the winter result and the others being for different stages during summer. What is clear from this plot is the stark difference of the band of summer results compared to the winter result. This data suggests that in winter, without the additional mixing produced by the presence of vegetation in the system, the flow moves rapidly and directly to the outlet, with little dispersion. Furthermore, the winter results appear to show a significant increase in the volume of dead water compared to summer, as the mean residence time is much lower.

For the summer traces, t_{50}, has a value of between 0.5 and 0.7 for most of the data collected. For the winter trace, 06/03/17, this value is much lower, at 0.35. In fact, most or all of the dye has gone through the system before the nominal residence time.

The fact that the winter residence times were lower is in some ways surprising. Despite a lower vegetation coverage, it is clear that the bulk of the flow travelled through a short-circuiting route and did not experience the full volume. This may be due to the design of this pond: in summer, a large patch of vegetation emerges from the northern bank, blocking the shortest route between inlet and outlet; in winter, this vegetation dies back and this more direct flow path is opened up.

It is expected that for other systems seasonal changes in vegetation would impact on the system RTD. The vegetation type, spatial distribution and seasonal variations need to be considered when assessing the residence time distributions for stormwater ponds.

6 CONCLUSIONS

The results showed that the change in vegetation had an impact on the system hydraulics. The total vegetation surface coverage varied from ~60 % in summer to 40 % in winter. In terms of the residence time distributions, first arrival times and peak concentration times were similar for both summer and winter vegetation conditions. However, the winter data showed less spread, and had a lower mean residence time than the summer data. The data suggests that the summer flow experienced more mixing, probably as a result of the increased vegetation coverage.

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