The effects of vegetation on the hydraulic residence time of stormwater ponds

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ABSTRACT

Storm water ponds treat polluted run-off from urban areas, highways and agricultural land. Vegetation plays a key role in water treatment, but further understanding is required to identify how vegetation density and spatial distribution within a pond affect the residence time, an important parameter with respect to water treatment. This paper presents results from a preliminary study where the residence time distribution and discharge of a water treatment pond were measured at two stages within the vegetation’s seasonal growth cycle, representing the minimum and maximum states of the vegetation’s density. The results show clear and significant differences between the residence time distribution for the two cases, and highlight the need for further work on the topic.

Keywords: Residence times; Residence time distribution; Storm water ponds; Vegetation

1. INTRODUCTION

Stormwater ponds are used to reduce the negative environmental impact of run-off from urban areas, highways and agricultural land, through detention and water treatment (SEPA, 2003). Vegetation plays a key role in water treatment by providing the appropriate biological environment for the degradation of pollutants (Hansson et al., 2005). However, water treatment is also a function of the pond’s residence time, as contaminated water needs to reside in the pond for a sufficient time to be treated effectively. Uniform vegetation can increase the residence time of a pond by reducing the pond’s mean velocity. However, the effects on the residence time of more complex vegetation patterns and varying densities, such as those created naturally by the vegetation’s variation throughout the seasonal growth cycle, are less well understood.

Current estimates of pond residence times rely on the ‘nominal residence time’ (pond volume/discharge) which is the pond’s residence time assuming plug flow. However, a large amount of work has shown this parameter to provide a poor estimate of the pond’s residence time, as the flow fields in real stormwater ponds are often more complex (Wörman & Kronniö 2005, Jenkins & Greenway 2005, Min and Wise 2009, Shilton et al. 2008, Persson et al. 1999). The effects of geometric short circuiting (for example, when the outlet is placed adjacent to the inlet) are generally well understood. However, the effect of vegetation on the pond’s flow field and corresponding residence time is less well understood. Vegetation patches can create preferential flow paths within the pond, leading to short-circuiting which creates a reduced effective volume of the pond, and thus a residence time lower than the nominal residence time. The degree to which preferential flow paths are created around vegetation patches is affected by the vegetation’s density and type, and thus is a function of the seasonal growth and succession cycle, as the density of vegetation patches changes as vegetation grows though the year.

This paper presents results from a preliminary study to investigate the effects of vegetation density on the residence time of a large agricultural pond in Southern Sweden. Tracer experiments were conducted at two times throughout the year. One set of tests in March/April, a point of minimum vegetation density just before the start of the growth season, and a set of tests in November, at the end of the growth season when vegetation density is near the maximum level from the previous season’s growth. In addition, for the set of tests conducted in March/April, two contrasting discharges were investigated to highlight the effect of discharge upon the ponds residence time distribution.

2. EXPERIMENTAL SETUP

The experimental test program was conducted on a water treatment pond designed to treat run-off from agricultural land in Lyby, Southern Sweden. The system consists a sediment trap and two ponds in series, with tests conducted on the lower pond in the system, as shown in Figure 1.

Figure 1. Treatment pond in Lyby, Southern Sweden (Taken late 2001 just after construction, prior to any vegetation growth).
Three tests were conducted, in March 2008, November 2008 and April 2009. For each test, the residence time distribution and discharge of the pond were measured. In addition, a vegetation survey was conducted during Spring 2009.

The Residence Time Distribution (RTD) was measured by injecting a florescent dye, Rhodamine WT, into the pond’s inlet and measuring the dye concentration at the outlet as a function of time from injection. The concentration was measured using a Turner Designs ‘SCUFA’ fluorometer, which recorded a time series of the cross-sectional mean concentration of dye at the pond outlet. In addition to the residence time distribution measured at the pond outlet, a further 3 fluorometers were installed within the pond for the test conducted in November 2008. One fluorometer was installed in the pond’s Upper-Zone and two fluorometers were installed in the Lower-zone (See Figure 2 and 3).

The discharge was measured using a calibrated V-notch weir. Figure 4 shows the pond’s outlet weir, containing the outlet fluorometer.

A depth and vegetation survey was carried out on the pond in March 2009. Figure 5 shows results the relative depth and shape of the pond from the depth survey. The pond is 2.8 meters deep at the deepest point (shown in blue).

Figure 2 shows the distribution of the vegetation through the pond and Figure 6 shows the types of vegetation present in the pond.
a) Watercress (*Rorippa nasturtium-aquaticum* L.)

b) Cattail (*Typha latifolia* L.)

c) Broad-leaf pondweed (*Potamogeton natans* L.)

Figure 6. Example of main species of vegetation present in pond.

The three tests were conducted to investigate 2 main variables, vegetation density and discharge. Tests conducted in March 2008 and November 2008 compare conditions under which discharge is similar, but vegetation is at minimum and maximum level of density respectively. Tests conducted on March 2008 and April 2009 compare conditions under which vegetation levels are similar (at minimum level) but the discharge was contrasting, as summarised in Table 1.

<table>
<thead>
<tr>
<th>Test</th>
<th>Date (m/y)</th>
<th>Vegetation Configuration</th>
<th>Discharge (l/s)</th>
<th>Nominal Residence Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3/08</td>
<td>Min. level of emergent.</td>
<td>9.0</td>
<td>64</td>
</tr>
<tr>
<td>2</td>
<td>11/08</td>
<td>Fully vegetated.</td>
<td>11.5</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>4/09</td>
<td>Min. Level of emergent with some submerged.</td>
<td>1.6</td>
<td>351</td>
</tr>
</tbody>
</table>

3. RESULTS, ANALYSIS AND DISCUSSION

Figures 7-9 show the residence time distributions for the three tests conducted.

Tests 1 and 3 were conducted at similar times in the year (March 08 and April 09) but at contrasting discharges, (Test 1, Q = 9 l/s. Test 3, Q = 1.6 l/s). For Test 1, all vegetation had died leaving just the stems of emergent vegetation. Test 3 was a similar scenario, but with the addition of small levels of submerged vegetation, i.e. Test 1 can be considered the minimum density of vegetation and Test 3 can be considered near the minimum density with the addition of a small amount of growth, being 1 month into the growth cycle. For Test 1 (Figure 7) it took approximately 160 hours for the dye to completely exit the system, compared to 650 hours for Test 3 (Figure 9). The mean residence time for Test 1 was approximately 43 hours compared to approximately 202 hours for Test 3. This variation is due to the difference in the discharge between the two tests, as a higher discharge will correspond to a higher mean velocity in the pond, which will move the dye through the pond quicker. However, despite difference in magnitude of residence times, the residence time distribution for both traces follows a similar trend.

The similarity in trends can be highlighted by considering the profile in dimensionless form with the time non-dimensionlised with respect to discharge and pond volume, and with the concentration non-dimensionlised with respect to peak concentration, as shown in Figure 10. It can be seen that once the time base is non-dimensioned with respect to a discharge term, the distributions of Test 1 and Test 3 are similar, with the exception of slightly higher levels of noise on Test 1. The residence time distributions of Test 1 and 3 consist of a quickly rising leading edge followed by a long exponentially decaying trailing edge. This type of residence time distribution has been described by Danckwerts (1953) as ‘complete mixing’. In the original context, Danckwerts was describing a chemical reactor system that was well mixed, which in this case can be considered analogous to a pond with low levels of vegetation, where the tracer becomes well mixed in the pond and then gradually released through the outlet. It can also be noted that for both tests, the mean
Figure 7. Residence time distribution for Test 1 (March 08, minimum level of vegetation, Q = 9 l/s).

Figure 8. Residence time distribution for Test 2 (November 08, maximum level of vegetation, Q = 11.5 l/s).

Figure 9. Residence time distribution for Test 3 (April 08, slightly above minimum level of vegetation, Q = 1.6 l/s).

Figure 10. Comparison between dimensionless residence time distributions for Tests 1-3, where t is time, Q is discharge and v is pond volume.

The residence time is approximately 2/3 of the nominal residence time, indicating that even for the minimal vegetation case, some degree of short-circuiting is still occurring, and thus the nominal residence time is still a poor estimation of the ponds mean residence time.

Test 2 was conducted at a time in the year considered to be at the vegetation’s maximum density (November 08), at a similar discharge to Test 1 (Q = 11.5 l/s). From Figure 8 and 10 it can be seen that a clear change in the residence time distribution occurs between Test 2, the maximum vegetation case, and Test 1 and 3, the minimum vegetation cases. For the peak vegetation case, the residence time distribution can be split into two distinct sections, an initial part consisting of a quickly rising then falling leading and trailing edge, followed by exponentially decaying tail after the sharp peak on the trailing edge. This type of residence time distribution has been described by Danckwerts (1953) as ‘dead-water’. In the original context, Danckwerts was describing a system where the majority of a tracer was passing straight through, but with some residual trace being caught in ‘dead zones’. In this context, this type of distribution shows that a portion of the dye is moving quickly through the pond, as it follows a preferential flow path created by dense vegetation patches, and the residual dye mixing in the main pond volume, thus taking longer to exit. The profile in Figure 8 suggests that short-circuiting is occurring in the system.

This observation can be further supported by comparing Test 1 and Test 2, which were conducted at similar discharge. Whilst it takes a similar amount of time for all the dye to exit the system for each test (150 hours for Test 1 and 120 hours for Test 2), the difference in the profiles of the residence time distributions means that for the first 25% of the dye to exit the system it takes 52 hour for Test 1, compared to less than half that time, 23.8 hours, for Test 2.

Figure 11 shows the dye passing through a small section of the pond, and demonstrates the preferential flow path phenomenon, where the dye can be seen to take a path around a patch of floating vegetation.
Figure 11. Dye moving through the pond, demonstrating preferential flow path around vegetation patch.

A further observation that can be made between the residence time distributions of Tests 1 and 3 and Test 2 is that a delay in first arrival occurs for Test 2. For Tests 1 and 3, despite the fact that it takes several days for all the tracer to exit the system, the first portions of tracer exits the system relatively quickly (for Test 1, first arrival is 30 minutes of a 150 hour test. For Test 3, first arrival is 200 minutes of a 700 hour test). However, for Test 2, a delay of approximately 10 hours occurs before first arrival. Whilst it is not possible to provide a conclusive explanation of this phenomenon with the available data, it could be suggested that the complex flow field in the pond created by the patches of dense vegetation shown in Figure 2, could lead to an off-set of first arrival time. If the dye followed a complex preferential flow path, the length of the path, if meandering around vegetation, might lead to the delay in first arrival. However, the fact that the majority of the tracer was transported through the preferential flow path rather than utilising the entire pond volume would still lead the short-circuiting effect seen in the residence time distribution in Figure 8.

It can also be noted that mean residence time for Test 2 is approximately 80% of the nominal residence time. This figure again shows short-circuiting, but interestingly is closer to the nominal residence time than for the minimal vegetation cases. It is considered that this is due to the fact that the mean residence time for Test 2 is artificially high due to the offset of the first arrival time. If the first arrival was similar to Test 1 and 3, the residence time distribution for Test 2 would give a nominal residence time smaller than for Test 1 and 3, as the centroid of Test 2 is closer to first arrival then for Test 1 and 3, and thus would lead to a further divergence from the nominal residence time.

Figures 12-14 show the Cumulative Residence Time Distribution (CRTD) for each of the tests, which is the integrated form of the resident time distribution. The cumulative residence time distributions provide a clear display of time frame for a percentage of the dyes total mass to exit the system, which can be useful when considering related parameters for a systems residence time. Two examples of these parameters are the $t_{16}$ and $t_{50}$ times, i.e. the time for 16% and 50% of the dye to pass through the system. These times were selected on the basis that their ratio, $t_{16}/t_{50}$, has been suggested by Ta and Brignal (1998) as a parameter to quantify short-circuiting, where a low value of this ratio has was considered to demonstrate short-circuiting. The $t_{16}$ and $t_{50}$ time are presented on the cumulative residence time distributions in Figures 12-14 and their ratio, the short-circuiting parameter, is presented in Table 2.

Figure 12. Cumulative Residence time distribution for Test 1 (March 08, minimum level of vegetation, Q = 9 l/s).

Figure 13. Cumulative Residence time distribution for Test 2 (November 08, maximum level of vegetation, Q = 11.5 l/s).

Figure 14. Cumulative Residence time distribution for Test 3 (April 08, slightly above minimum level of vegetation, Q = 1.6 l/s).

Stovin et al. (2008) presented results and discussion which suggest that systems for which short-circuiting is occurring can also give a high value for the short-circuiting parameter, thus questioning the assertion that a low value for the parameter always demonstrates short-
For the present study, it can be seen that the short-circuiting parameter is relatively larger for Test 2, the case where the most short-circuiting is considered to be occurring, supporting the observations of Stovin et al. (2008). This is due to the fact that for Test 2, the majority of the mass of the dye is passing through the system relatively quickly; hence the time difference between 16% and 50% exiting the system is smaller than for Test 1 and 3. This leads to a higher value for the parameter compared to Test 1 and 3, where the more evenly spread residence time distribution leads to a larger difference between time for 16% and 50% of the dye to pass through the system, and hence a smaller value for the short-circuiting parameter. Stovin et al. (2008) suggest that a more usefully parameter for quantifying short-circuiting is the ratio of the $t_{50}$ time to the nominal residence time ($t_{50}/t_n$), where a low value demonstrates short circuiting. From Table 2 it can be seen that the values of this parameter for the present study are low for all tests by Stovin et al. (2008) definition, indicating that short-circuiting is occurring in all cases. However, there is not a large difference between Test 2, the high density case where the most short-circuiting is considered to be occurring, and Test 1 and 3, the low density cases where less short-circuiting is occurring. This is again considered to be due to the off-set in first arrival for Test 2.

Table 2. Summary of test series.

<table>
<thead>
<tr>
<th>Test</th>
<th>Mean Residence time ($t_{20}$) (hours)</th>
<th>Short Circuiting Parameter ($t_{50}/t_n$) (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43</td>
<td>0.42</td>
</tr>
<tr>
<td>2</td>
<td>39.5</td>
<td>0.67</td>
</tr>
<tr>
<td>3</td>
<td>202</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Further insight into Test 2, the case where the flow field is complex due to the dense vegetation, can be gained by considering the results from the instruments located within the pond.

Figure 15 shows the residence time distribution from the instrument within the pond’s Upper-zone, and Figure 16 and 17 show the residence time distributions from the two instruments within the pond’s Lower-zone.

Figure 15 shows a complex and unconventional residence time distribution within the pond’s Upper-zone, which cannot easily be interpreted through conventional solute transport theory. It can be noted from Figure 2 that the instrument used to measure this distribution was placed near several patches of vegetation, and thus could possibly be significantly affected by the complex flow field created by the surrounding vegetation, leading to the unconventional residence time distribution.

Figures 16 and 17 are the results from the Lower-zone, and show an intermediate residence time distribution between the Upper-zone and the outlet instruments. The residence time distribution is more conventional, but still shows irregular characteristics, such as the large spikes on the tails of the distributions occurring at approximately 40 hours.
The spatial variation of the dye plume in the transverse direction, further suggesting that solute transport through highly vegetated ponds is not a simple 1D problem.

From all the tests considered it can be seen that for Tests 1 and 3, where vegetation is minimal, the residence time distribution conforms to a fairly standard rising limb/exponential tail type distribution. As such, the system can be understood though simple approximations such as the ‘complete mixing’ distribution proposed by Danckwerts (1953) for a well-mixed reservoir.

However, for Test 2, where high levels of vegetation are present, the residence time distribution is more complex. Here some portion of the distribution represents parts of the system that are short-circuiting due to the presence of vegetation and preferential flow paths associated with complex flow fields. It is unclear why a delay in first arrival time occurs compared to the minimum vegetated cases, however, it may be that this phenomenon is again due to the complex flow field created by the vegetation. In addition, data collected in Upper and Lower zones of the pond further suggests that the flow field is complex and 3D, and cannot be easily approximated through a simple set of 1D assumption.

The results presented in this paper demonstrate that when vegetation is present at a significant density and associated distribution patterns, a full understanding of the 3D flow field inside the pond created by the vegetation is required to understand and model mixing processes. It is clear that good pond design needs to rely on modelling approaches that can incorporate the effects of the 3D flow field created by the vegetation, as opposed to simple parameters such as the nominal residence time.

A possible methodology to enable this is through 3D Computation Fluid Dynamics (CFD) modelling of vegetated ponds. A possible methodological approach to produce an appropriate, validated CFD model for this purpose is discussed further in Section 5.

4. CONCLUSIONS

Results are presented from 3 tracer tests on an agricultural water treatment pond in Lyby, Southern Sweden. Tests were conducted to compare a case of minimal and maximum vegetation in the pond at a similar discharge, and at a high and a low discharge for minimum vegetation.

The tests conducted at contrasting discharges for minimal vegetation levels showed that whilst it took considerably longer for the tracer to exit the system for the lower discharge case, the distribution of the residence times was essentially the same.

The tests conducted at contrasting levels of vegetation show that for the minimal vegetation case, the pond behaves in an analogous manner to a well-mixed reservoir, with a residence time distribution with a rising limb and exponentially decaying trailing edge. However, for the high vegetation case, the residence time distribution shows two main parts; an initial peak followed by a long tail. It is proposed that this profile demonstrates short-circuiting in the system, with the initial peak showing dye following a preferential flow path. Further aspects of the residence time distribution for the high vegetation case such as an off-set of first arrival time, cannot be conclusively explained with the available data. However, it is considered to be an effect of the complex flow field created in the pond by the vegetation patches and the ponds geometry.

Further results for the highly vegetated case, where the residence time distribution was measured within the pond, suggest even more un-conventional residence time distributions prior to the outlet, with transverse variation in the profile also demonstrated. These results further support the conclusion that for highly vegetated ponds the flow field created by the vegetation is complex and 3D.

The data presented demonstrated the need for 3D modelling to better understand and predict the mixing processes occurring due to the complex flow fields created by natural vegetation patterns in water treatment ponds.

5. FURTHER WORK

Further work will attempt to establish a 3D CFD model for the flow fields and corresponding mixing processes within vegetated stormwater ponds, which have been shown to be necessary by this preliminary study.

The CFD model will utilise a coarse cell size (approximately 150 mm cube) to simulate the hydraulics and mixing processes of ponds, where each cell will have a local longitudinal, transverse and vertical mixing coefficient and bulk porosity (simulating the vegetation within the cell).

The assumed parameters (longitudinal mixing coefficient, transverse mixing coefficient and bulk porosity) will be validated against a comprehensive and detailed set of new laboratory data. The laboratory data will be obtained by conducting tracer and hydraulic tests on sample vegetation sections taken from donor water treatment ponds at several times (at least four – i.e. once per season) through the seasonal growth cycle. Emergent, submerged and floating vegetation will all be tested for these parameters.

The code will be further validated against a more compressive set of tracer tests conducted in several real stormwater ponds, at several times through the seasonal growth cycle.

The final validated code can then be used with a variety of vegetation densities and distribution to establish the sensitivity of the residence time distribution to different vegetation patterns through the seasonal growth cycle. The code can be used as a predictive tool to increase understanding of solute transport in vegetated ponds, and to inform the future design of real world stormwater ponds.

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