Surface wetlands for the treatment of pathogens in stormwater: three case studies at Lake Macquarie, NSW, Australia

H. Méndez, P. M. Geary and R. H. Dunstan

ABSTRACT

The treatment of stormwater using surface constructed wetlands has become common in the last decades. However, the use of constructed wetlands for stormwater management has not been thoroughly evaluated in their capacity to treat microbial loads. The case studies presented in this paper are situated at Lake Macquarie, a large estuarine lagoon located approximately 150 km north of Sydney, Australia. To protect the lake ecosystem from the impact of increasing urban development, the local Council constructed numerous stormwater quality improvement devices (SQIDs) at selected locations. The SQIDs typically consisted of trash racks, gross pollutant traps and surface constructed wetlands. To evaluate the effectiveness of three of these devices in reducing faecal contamination, water samples were collected for faecal coliforms (FC) during and following rainfall at inlets and outlets of the structures. Results indicated one of the SQIDs as the most efficient for bacterial reduction, while the other two provided low or non reduction of FC. Results also illustrated dependence of bacteria reduction on flow conditions. Comparison of devices suggested that hydraulic residence times and other design parameters strongly influenced the capacity of each device to reduce FC counts during different weather conditions.

Key words | constructed wetlands, faecal bacteria, pathogens, stormwater

INTRODUCTION

The evaluation of constructed wetland systems have been extensively made in regards to their performance in reducing different contaminants from wastewaters such as nutrients (nitrogen and phosphorus), heavy metals and other organic compounds. However, there have been relatively few reports that include microbial treatment evaluation, and these have been mainly for those systems that deal with municipal waste. Moreover, the majority of the research available in relation to the reduction of bacteria in constructed wetlands has been conducted on sub-surface (SSF) wetlands for wastewater treatment, probably because these type of systems are more common in Europe, particularly in the UK (Perkins & Hunter 2000). In other countries some investigations have been reported as well. For instance, Kadlec & Knight (1996) summarised several studies conducted in the USA that aimed to evaluate the performance of constructed wetlands (surface and sub-surface) in reducing faecal bacteria indicators from municipal wastewater.

Surface flow (SF) systems have been used for the treatment of primary, secondary and tertiary wastewater effluents. Karathanasis et al. (2003) and Ravva et al. (2006) in the USA, for example, have shown bacterial evaluation of SF systems for the treatment of domestic wastewater and dairy effluents, respectively. In Australia, Greenway (2005) reported high percentage removals of FC from three
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SF wetlands that treated sewage secondary effluents, and Maynard et al. (1999) in the UK and Macintyre et al. (2006) in Canada, presented investigations of faecal bacteria indicators in SF wetlands for the treatment of tertiary treated effluents. In the literature there have been relatively few reports that involved studies of faecal bacteria in SF wetlands for the treatment of stormwater. Papers by Stenström & Carlander (2001) in Sweden, and Davies & Bavor (2000) in Australia, have paid attention to the reduction of bacteria in constructed wetlands for stormwater treatment. Moreover, none of those reports have involved extended monitoring and sampling under different weather conditions. There is lack of data that shows how SF constructed wetlands could contribute to the reduction of faecal bacteria in stormwater.

The case studies in this paper are situated at Lake Macquarie, a large estuarine lagoon located centrally along the NSW coast, approximately 150 km north of Sydney, Australia. The lake and its catchment are extremely important to the local and regional community as a source of recreational fishing, recreational boating, swimming habitat and tourism. In the past few decades, urban development around the lake has increased, leading to concerns about the health of the lake ecosystem. In response to this concern, Lake Macquarie City Council implemented a program that involved the construction of a significant number of stormwater quality improvement devices (SQIDs), which in some cases, incorporated small surface constructed wetlands that feed runoff directly to the lake. These devices were designed primarily for sediment and nutrient control that are transported by stormwater into Lake Macquarie waters. While the performance of a number of these devices has previously been evaluated for the treatment of nitrogen and phosphorus (Geary et al. 2003), their performance with respect to microbiological quality has only been undertaken over the last few years (Méndez et al. 2005).

The aim of this paper is to evaluate the capability of three SQIDs which incorporate surface flow constructed wetlands in reducing faecal bacteria indicators under different weather conditions, and as a consequence, under different flow conditions. These results contribute to an understanding of the mechanisms of bacterial reduction using these types of devices.

METHODS

Site descriptions

Research was conducted at three different SQIDs around Lake Macquarie, NSW, Australia, in the specific suburbs of Bolton Point (1), Blackalls Park (2) and Toronto West (3) as shown in Figure 1.

The characteristics of each site, including the catchment area, land usage and estimated hydraulic residence time (HRT) have been summarized in Table 1.

The predominant vegetation in the surface flow constructed wetlands at each of the SQIDs was Spiny mudgrass (Schoenoplectus mucronatus), Common Spikerush (Eleocharis acuta) and Jointed Twigrush (Baumea rubiginosa) for Bolton Point (BP) and Toronto West (TW), whilst Narrow Cumbungi (Typha domingensis) was the predominant vegetation at Blackalls Park (BPK).

Rainfall data used in this project was provided by Pasminco Weather Station, which is located at Boolaroo, north of Lake Macquarie (see Figure 1), 6.3 km from BP, 7.2 km from BPK and 8.1 km from TW. This weather station has been recording information since January 2000. During the period of 2000–2007 the recorded mean annual precipitation at this site was 852.5 mm.

Design of experiments

To evaluate the performance of these types of stormwater treatment devices in relation to the removal of
microorganisms, a monitoring program started in October 2004 for a period of two years at each of the three previously mentioned sites. The monitoring program involved sample collection during dry and wet weather conditions. Discrete and continuous wet weather samples were collected during and/or after rainfall events. The depth of water at the inlet culverts and flow velocity were measured on each sampling occasion and hydraulic residence time estimated using the design volume. Flow velocities were measured using a stream current meter FLO-MATE, model 2000 from Marsh-McBirney, Inc.

All samples were collected at the two inflow and outflow points of each of the SQIDs. Samples were collected by wading into the water towards the centre of the flow where the water was turbulent and mixed, or at the mouth of the pipes where applicable. When possible, all three SQIDs were sampled for the same event. A total of 18 rain event and 4 dry weather sample sets per site were included in the data analysis.

Water samples which were tested for thermotolerant coliforms (faecal coliforms, FC) were collected in pre-sterilised 125 mL screw top polypropylene bottles and analysed within the next 6–8 hours. The FC concentrations were determined by membrane filtration following standard methods (APHA 1998), using m-FC agar as nutrient media, and incubating at 44.5 (± 0.5)°C over 24 (± 2) hours.

All statistical analyses were carried out with STATISTICA V6.1. Analyses involved normality tests for each variable, and simple and multiple correlations. FC counts which presented as a non-normal distribution were fitted into a Log-normal distribution. For the purpose of comparing tests and graphs, the logarithm transformed FC data were used. Differences between means were evaluated at the 99% level of confidence (p < 0.01).

### RESULTS

To evaluate the performance of the SQIDs, all the discrete samples collected during the two years of monitoring program were analysed. The data shown in Figures 2, 3 and 4 summarise faecal coliforms detected at each of the SQID sites. In each figure is shown the variation between bacterial counts in wet weather and dry conditions at each

<table>
<thead>
<tr>
<th>Features</th>
<th>Bolton point (BP)</th>
<th>Blackalls park (BPK)</th>
<th>Toronto west (TW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment area (ha)</td>
<td>14.06</td>
<td>25.04</td>
<td>17.13</td>
</tr>
<tr>
<td>Catchment land usage</td>
<td>60% Urban</td>
<td>90% Urban</td>
<td>70% Urban</td>
</tr>
<tr>
<td>Average annual rainfall (mm)</td>
<td>852.5</td>
<td>852.5</td>
<td>852.5</td>
</tr>
<tr>
<td>Year of construction† (SQID)</td>
<td>2003</td>
<td>2001</td>
<td>2003</td>
</tr>
<tr>
<td>Surface area (m²)</td>
<td>630</td>
<td>285</td>
<td>945</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>473</td>
<td>228</td>
<td>803</td>
</tr>
<tr>
<td>Hydraulic residence time (HRT)‡</td>
<td>8 min–7.5 h</td>
<td>10 min–1.5 d</td>
<td>40 min–11 d</td>
</tr>
<tr>
<td>Length:width ratio</td>
<td>2:1</td>
<td>12:1</td>
<td>10:1</td>
</tr>
<tr>
<td>Inlet zone</td>
<td>GPT‡</td>
<td>GPT‡</td>
<td>GPT‡</td>
</tr>
<tr>
<td>Outlet zone</td>
<td>Spillway</td>
<td>Spillway</td>
<td>Water level control structure</td>
</tr>
</tbody>
</table>

*Information provided by Lake Macquarie City Council, 2005.
†HRT estimations based on tracer studies and flow measurement during and after sample collection under different weather conditions.
‡Gross pollutant trap.
of the inlets and outlets. It is evident that during dry conditions, bacterial counts were significantly lower (2 to 3 orders of magnitude) and the variance was much higher, compared with those observed during wet weather conditions.

Comparison between inlets and outlets in Figures 2, 3 and 4 also suggests that the three different SQIDs displayed variable capacities of reducing FC. BP and BPK SQIDs (Figure 2 and 3 respectively) did not show any reduction in the coliform counts, in fact, a statistical increase was detected based on standard errors. In contrast, Figure 4 at the Toronto West (TW) site showed reduction of bacteria during both dry and wet weather. Although, results for TW were not significantly different at the 99% confidence interval, a statistical difference was shown when the confidence interval was dropped to 97%.

On the other hand, during dry weather conditions the performance of each SQID in reducing FC was highly variable. While at the TW site, mean ± standard error of FC from the inlets to the outlet showed a reduction in numbers, inlets and outlets at BP and BPK showed very close mean and variance values, indicating no distinguishable difference between these two water sampling locations. However, the confidence intervals in the three cases were wide enough and did not allow a statistical differentiation between inlets and outlets under dry conditions.

The percentage removal of FC was calculated for each SQID during three specific rainfall events which occurred in 2006, based on their FC event mean concentrations (EMC). Results are summarised in Table 2. The percentage removals in this table were calculated using a traditional yield equation using outlet and inlet FC EMCs. The percentage removal values in Table 2 indicate that BP and BPK SQIDs had poor performance in reducing FC bacteria during the two first rain events. In the third rain event, where all three SQIDs were evaluated, the TW SQID had a much better performance in FC reduction compared to the other two devices during/after the event. Results using the event mean concentration approach (from a continuous sampling method during rain events) were consistent with the outcomes from the discrete sampling approach.
An additional evaluation was performed on the data generated during the continuous sampling approach on the specific rainfall episodes. Analysis of FC concentrations and simultaneous flow measurements illustrated the dependence of bacteria reduction on the flow conditions within the device (data not shown). Data collected during the first two rainfall events showed that FC levels at outlets from BP and BPK peaked at the same time that flow conditions were decreasing. Those results revealed that these devices did not provide treatment during rain episodes. Also, results from the third continuous sampling event indicated that BPK improved its capacity for treatment while lowering the flow, whilst the TW site provided reduction of FC during higher and lower flow conditions. The BP SQID, on the other hand, appeared to have provided no treatment of faecal bacteria in any case.

**DISCUSSION**

In comparing the performance of these structures with respect to bacterial removal, it is necessary to consider the different morphological parameters that might have influenced these results. Firstly, although the catchment areas were very similar for each of the SQIDs, and similar rainfall intensities and storm volumes were monitored, the TW SQID had the largest volume in proportion to the catchment area. Consequently, when heavy rainfall occurred, TW was able to hold the largest amount of water without overflowing the structure; therefore it had the longest residence time. In contrast, BP and BPK were more likely to overflow during heavy rain events.

The direct consequence of overflow in these structures was that the numbers of FC detected in the outlets were the same or even higher than at the inlets. The BPK wetland had a designed overflow side channel along the whole wetland (reed bed) area which allowed stormwater to pass through without treatment when the flow was very high. The underdesign of stormwater wetlands results in reduced performance associated with a reduced hydraulic residence time. Often the design storm and hydraulic calculations for these devices are based on mean annual rainfall as there may be limited availability of the rainfall data for the target area. If hydraulic analysis is to be based on monthly data to include events with a larger return period, then larger volumes would be required and better treatment would be achieved (Koob et al. 1999).

Improved HRT can also be achieved using and/or changing other morphologic features in the SQIDs. For instance, including the use of a large aspect ratio (length: width) will reduce short circuiting of flow (an optimum ratio should be no less than 3:1; DLWC 1998). This, however, may not always be possible as the topography, shape and size of the available land may be frequently limiting factors in design. In the case of BP, the aspect ratio was around 2:1 and the main inlet was directly in front of the outlet. This design promoted the rapid passage of water straight through the wetland during heavy rainfall. The opposite case is shown in TW, in which the large aspect ratio definitely helped in its improved performance relative to the other wetland designs.

The shape of a wetland with the intention of increasing the HRT is clearly a central factor in a good design, although as mentioned above, it may not always be possible to achieve if land is not available. Kay & McDonald (1980) reported that the distance from inlet to outlet played a key role in the purification processes of contaminated water occurring in wetlands. A sinusoidal shape similar to the TW wetland

<table>
<thead>
<tr>
<th>Event Date/Rainfall</th>
<th>Location</th>
<th>EMC Inlet (cfu/100 mL)</th>
<th>EMC Outlet (cfu/100 mL)</th>
<th>% Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>18/July/2006 (21.9 mm)</td>
<td>BP</td>
<td>14,688</td>
<td>11,875</td>
<td>19.9</td>
</tr>
<tr>
<td>07/Sept/2006 (44.9 mm)</td>
<td>BPK</td>
<td>28,125</td>
<td>21,875</td>
<td>22.7</td>
</tr>
<tr>
<td>11–14/Sept/2006 (20.1 mm)</td>
<td>BP</td>
<td>1,505</td>
<td>4,020</td>
<td>260.6</td>
</tr>
<tr>
<td></td>
<td>BPK</td>
<td>2,432</td>
<td>11,734</td>
<td>36.9</td>
</tr>
<tr>
<td></td>
<td>TW</td>
<td>266,595</td>
<td>6,164</td>
<td>97.9</td>
</tr>
</tbody>
</table>

*Event mean concentration.
increases the hydraulic flow pathway so the travelling distance is longer while reducing the flow velocity. Therefore, the detention time can be further maximized.

In general, the mechanisms for reductions in bacterial numbers through wetlands are not well understood (Stenström & Carlander 2001). However, predation and ultraviolet (UV) radiation are possibly the most relevant factors affecting the survival rate of bacteria (Sinton et al. 1994; Burkhardt et al. 2000). Open water areas in a constructed wetland allow for the maximum exposure of bacteria to radiation helping the die-off process.

The location of the open water within a wetland could be also significant. Open water areas at the front of the pond usually receive the water following initial detention and sedimentation in most good designs. While the larger particles settle in the sedimentation pond, the finest particles are still in suspension when they reach the open water area. High turbidity after a rain event decreases UV penetration, thus the survival of bacteria may be longer. In the case of TW, there were two open water areas in between the wetland (reed bed) area. When inflowing water reaches the second open water area, the sedimentation process might be advanced in addition to a much slower water velocity. As a result, the exposure of radiation could be more effective, so the mortality rate of bacteria is increased.

According to Koob et al. (1999), the successful design of a wetland for stormwater treatment involves its capacity to keep enough moisture during dry weather periods to support the growth of vegetation. This might be possible to achieve if the hydrological calculations included discrete rainfall data rather than mean annual rainfall. However, the maintenance of a large area of open water during dry weather periods needs to be carefully evaluated. In this regard, TW SQID possessed a flow control structure that allowed for a faster discharge of excess water during high flow conditions, but it also helped to control the flow during moderate and small rain events and kept a low permanent flow during dry weather periods. Theoretically, low flow conditions in the SQIDs would extend the HRT avoiding stagnant conditions, which is important for the open water areas during dry weather periods as they may experience an increase in faecal bacterial numbers due to the presence of wildlife such as birds.

**CONCLUSION**

Three stormwater quality improvement devices (SQIDs) were evaluated for their ability to reduce thermotolerant coliforms (faecal coliforms, FC). One out of the three structures was shown to be better able to treat and remove FC bacteria from stormwater. The hydraulic residence times (HRT) and other design parameters of these SQIDs appeared to strongly influence the capacity of each device to reduce FC counts from the inlet to the outlet during dry periods and in rain events.

 Constructed wetlands, which are now incorporated in water sensitive designs for new urban development, are a feasible option for the treatment of stormwaters. However, the stochastic nature of the variables involved in the stormwater hydrology, makes it difficult to accurately design a wetland that would provide for an overall acceptable performance in terms of the bacteriological aspect of water quality improvement, particularly during rain events with a large return period.

**REFERENCES**


Department of Land and Water Conservation 1998 The Constructed Wetlands Manual, Volume 2; Published by the DLWC.: Sydney, New South Wales, Australia.


Kadlec, R. H. & Knight, R. L. 1996 Treatment Wetlands. CRC Press, Inc., Boca Raton, USA.


