The Hydraulic Efficiency of Simple Stormwater Ponds

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Abstract

This paper investigates the hydrodynamic characteristics of nine stormwater pond configurations. These ponds represent an extension of earlier work by Persson (1999) who proposed the thirteen pond configurations currently used as a guide in the hydrodynamic component of the Cooperative Research Centre for Catchment Hydrology (CRCCH) Model for Urban Stormwater Improvement Conceptualisation (MUSIC). The hydrodynamic behaviour of each pond has been studied using two-dimensional depth averaged flow simulations (MIKE 21). The hydraulic efficiency of each configuration is also evaluated. The configurations studied in this paper are intended to aid in the conceptual design of stormwater treatment systems such as ponds and wetlands. Outcomes confirm that configurations with the greatest length to width ratio result in the highest hydraulic efficiency. This study also demonstrates that correct positioning of design elements such as islands can significantly enhance the hydraulic characteristics of a pond.

1. Introduction

Stormwater runoff from urban areas is known to contribute large quantities of pollutants into receiving waters. Constructed stormwater treatment ponds are often used to mitigate this impact. The pollutant removal capacity of these systems is known to be dependant on mixing quality (German *et al.*, 2004). Despite this, current design methods typically fail to adequately consider this issue. In particular, the hydrodynamic basis for commercial modelling tools such as MUSIC (CRC Catchment Hydrology) and MEDLI (Queensland Department of Natural Resources and Mines, Queensland Department of Primary Industries and Fisheries and CRC for Waste Management and Pollution Control) often rely on the assumption of ideal flow such as complete mixing or plug flow. However this is rarely achieved in practice.

Hydrological and hydraulic design considerations are the major factors influencing the water quality improvement potential of stormwater treatment ponds and wetlands (Persson, 1999). As such, the need for proper consideration of these elements cannot be underestimated (Adamsson, 2004; Persson, 1999). The objective of this study is to investigate the relationship between pond geometry and hydrodynamic behaviour.

1.1. Background

The influence of inlet/outlet configuration and length to width ratios on the performance of wetlands and ponds have been investigated by a number of authors (eg Kadlec and Knight 1996; Persson, 2000; German *et al.*, 2004; Persson *et al.*, 2003). To improve the distribution of flow into a pond or wetland, the use of design elements such as submerged berms or strategically placed deep zones or islands are often recommended. For example, deep zones placed perpendicular to the flow path have been found to increase the hydraulic efficiency of wetlands (Kadlec & Knight, 1996). Thackston *et al.* (1987) showed that length to width ratio (L/W) is most important factor affecting hydraulic efficiency as did Mangelson & Watters (1972). In addition to this, Comings *et al.* (2000) also found that extended residence time enhances pond efficiency.

Persson (1999) also examined the hydraulic efficiency of ponds with different configurations and proposed a measure, hydraulic efficiency, (λ), as follows;

$$\lambda = \frac{t_p}{t_n} \quad \text{and} \quad t_n = \frac{V}{Q} \qquad \text{Equation 1}$$

Where t_p is the time when the peak concentration passes the outlet (for a pulse test) and the nominal residence time (t_n) is calculated by dividing the system volume (V) by the constant flow rate (Q). Here hydraulic efficiency ranges between 0 and 1, with 1 representing the best performance and 0 being the poorest. The classification of hydrodynamic behaviour according to hydraulic efficiency, (λ) is presented in Table 1.

Table 1 – Interpretation of Hydraulic Efficiency (Persson, 1999)

Good hydraulic efficiency	$0.7 < \lambda$
Satisfactory hydraulic efficiency	$0.5 < \lambda < 0.7$
Poor hydraulic efficiency	$\lambda < 0.5$

The behaviour of flow through a pond can also be described using a tanks-in-series model. Here a system is represented by a number of well mixed tanks-in-series. Hydraulic efficiency (λ) can be used to determine the number of tanks-in-series (N) according to Equation 2 (Persson *et al.*, 1999). As N increases, flow tends towards plug flow.

$$N \sim \frac{1}{1-\lambda} \qquad \text{Equation 2}$$

Another useful measure for evaluating the hydrodynamic performance of ponds was proposed by Ta & Brignal (1998) who developed a measure of the extent of short circuiting in a system (refer Equation 3). Here, a low value of S indicates short-circuiting.

$$S = \frac{t_{16}}{t_{50}} \qquad \text{Equation 3}$$

Where:

t_{16} is the time taken for 16% of inert tracer to exit a system (for a pulse test)

t_{50} is the time for 50% of the tracer to exit a system (for a pulse test)

Persson (1999) also undertook a series of two-dimensional modelling (Mike 21) to derive hydraulic efficiency for the pond configurations shown in Figure 1. The configurations shown in Figure 1 have been extensively quoted in the literature, and are given as a guide for the commonly used in the MUSIC software. Subsequent investigations by German *et al.* (2004) and Jansons *et al.* (2005) investigated the hydraulic efficiency of additional box and oval shaped ponds, as shown in Figure 2.

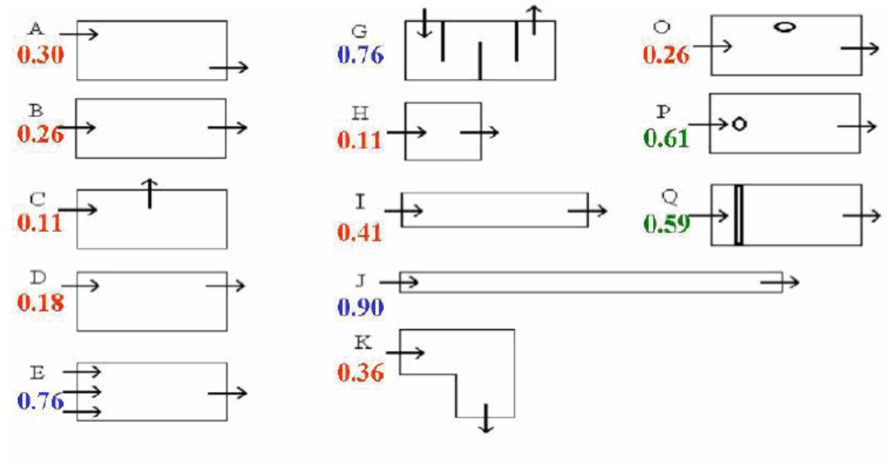

Figure 1: Hydraulic Efficiency (λ) of theoretical pond configurations (adapted from Persson *et al.*, 1999).

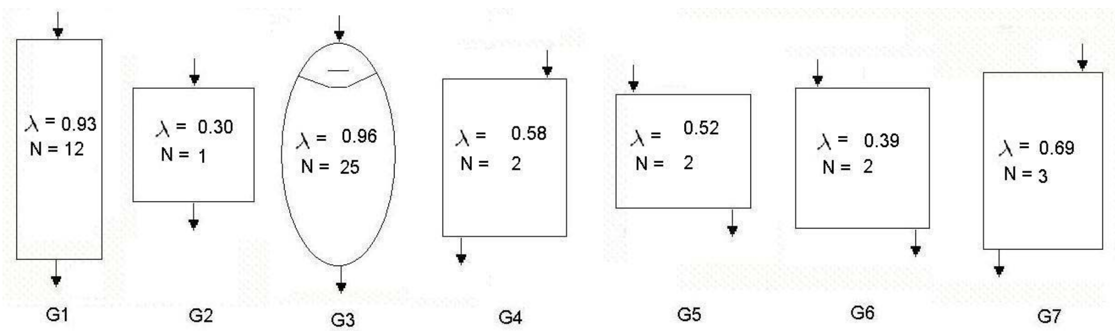

Figure 2: Hydraulic Efficiency (λ) and the number of tanks-in-series (N) best representing theoretical pond configurations (Jansons *et al.*, 2005). Pond G3 has a submerged berm at the inlet.

2. Study Approach

A series of nine simple pond configurations were simulated (refer to Figure 3). A description of these ponds is presented in Table 2. The designs are intended to reflect more realistic pond shapes than those studied by Persson (1999) and Jansons *et al.* (2005).

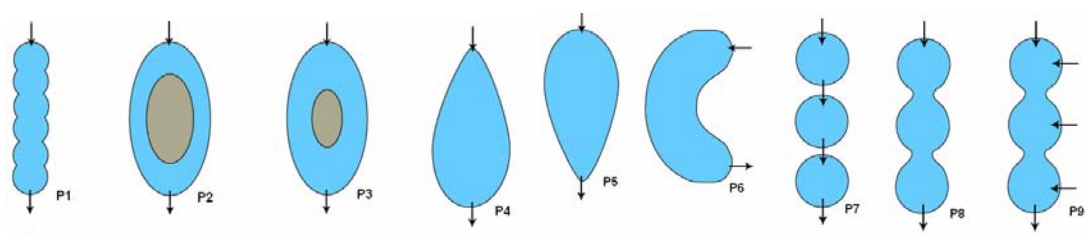

Figure 3: The simple pond configurations studied. The ponds have varying length to width ratios and inlet and outlet locations. All ponds have a depth of 1.5m, constant flow rate of 300 L/s and a surface area of approximately 18,000 m^2.

Table 2: Description of the ponds shown in Figure 3.

Pond	Description
P1	This pond has a high length to width ratio. Comparisons will be made between pond P1 and its box shaped equivalent to ascertain the effects of landscaping the edges of a pond.
P2 & P3	Islands are also a very typical feature in a constructed stormwater treatment pond. Ponds P2 and P3 will be compared to assess the performance of different shaped islands.
P4 & P5	Teardrop shaped ponds will give a complex flow pattern that is not easily predicted. The hydrodynamics will be assessed and the effect of the inlet/outlet position will be investigated.
P6	Kidney shaped ponds are fairly prevalent in reality. It will be important for designers to observe the flow patterns within a pond of this shape.
P7, P8 & P9	The effect of modelling multiple cell ponds as a single water body or separate water bodies connected by pumped flow will be assessed. Long ponds also commonly have multiple inlets at intervals along their length. The effects of multiple inlets will be determined.

The intention of this research is to reveal the flow pattern in some common pond shapes. This is only a first step towards a wider range of configurations intended to be modeled, however the few configurations included in this study were chosen on the basis of their prevalence in reality.

2.1 Modelling Approach

A two-dimensional hydraulic model (MIKE 21) is used to assess the flow pattern for each pond configuration. MIKE 21 (DHI, 2006) is a two-dimensional depth averaged model commonly used to study stormwater ponds (eg. Adamsson, 2004; Persson, 2000; and German *et al.,* 2004). The input parameters of the model include bathymetry, boundary conditions, resistance, viscosity and time step. In this study the bathymetry of each pond was created using a 2m grid.

3. Results

Tracer simulations were carried out using Mike 21 AD (advection dispersion) module for a constant flow of 300 L/s and a conservative tracer added as a pulse input at the inlet. The resultant RTD curves were used to calculate the hydraulic efficiency (λ), the number of tanks-in series (N) and the index of short-circuiting (S) for each pond.

The results of the numerical modelling are shown in the following velocity vector plots (Figure 4). It should be noted that for clarity, the plots have been rescaled and made coarser. An interpretation of these results is presented in Table 3. Hydrodynamic indicators are listed in Table 4. These results are the subject of discussion in Section 4.

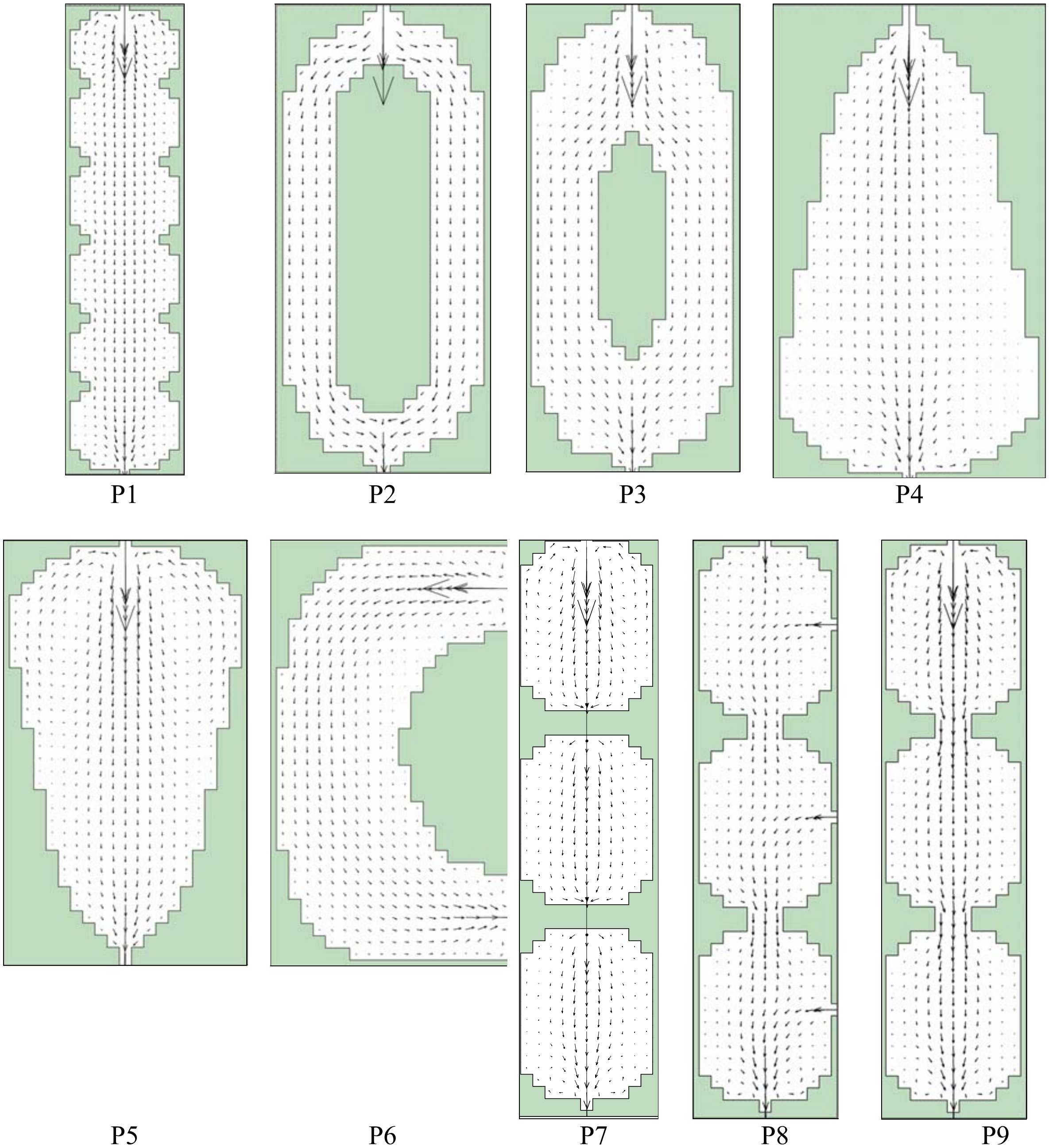

Figure 4**:** Mike 21 generated velocity vector plots for ponds P1 to P9 under steady flow conditions (300 L/s).

Table 3 – Interpretation of the simulation results presented in Figure 4

Pond	Comments
P1	A reasonable proportion of the volume is being used effectively in pond P1, although, irregular edges (such as those that may result from landscaping) have resulted in slight zones of stagnation. This pond is on the border for good to medium hydraulic efficiency as shown in Table 4.
P2	The larger island in pond P2 creates a quite hydraulically efficient pond, as flow is evenly spread either side of the island. A high value of hydraulic efficiency is observed and limited short-circuiting (see Table 4).
P3	The smaller island here is less successful at enhancing flow than the larger island of pond P2. In this pond small eddies are formed at the inlet which creates zones of stagnation. However, this pond has a higher hydraulic efficiency than most other ponds investigated.
P4	Pond P4 contains a main flow path along the centre of the pond and large regions of stagnation at the edge of the pond. Subsequently, this pond has a poor hydraulic efficiency.
P5	Reversing the direction of flow from pond P4 results in a reduction in hydraulic efficiency. Large circulation patterns are evident near the inlet (i.e. in the widest section of the pond). There is also slightly more short-circuiting occurring in pond P5 than in pond P4.
P6	The kidney shape of this pond is shown to be relatively effective at distributing the flow evenly. Regions of stagnation are observed around the inner side of the curve, but the overall flow is fairly consistent. This configuration resulted in a medium hydraulic efficiency (refer Table 4).
P7	Pond P7 has poor hydraulic performance due to the large degree of circulation that occurs in each separate pool. The degree of flow between the ponds is highly dependent on the amount of flow through the pumps connecting each pool. It should be noted that the pumping rate is equal to the influent rate.
P8	As with ponds P1, P7 and P9, regions of stagnation are evident along the edges of this pond, resulting in a poor hydraulic performance.
P9	The distributed inflows along the length of this pond have resulted in a substantial decline in hydraulic efficiency (compare pond P8 with pond P9).

Table 4 Hydraulic efficiency, index of short-circuiting and the number of tanks-in-series for ponds P1 to P9.

Pond	**Hydraulic Efficiency (λ)**	**Index of Short-circuiting (S)**	**Tanks in Series (N)***	**Hydraulic Efficiency Interpretation+**
P1	0.49	0.84	2	Satisfactory
P2	0.87	0.89	8	Good
P3	0.72	0.88	4	Satisfactory
P4	0.44	0.75	2	Satisfactory
P5	0.37	0.68	2	Satisfactory
P6	0.65	0.75	3	Good
P7	0.36	0.70	2	Poor
P8	0.38	0.77	2	Poor
P9	0.11	0.31	1	Poor

* The number of tanks-in-series was obtained using Equation 2.
\+ Interpretation of mixing quality according to hydraulic efficiency as defined in Table 1.

4. Discussion

Where it is not possible to obtain high length to width ratio, Adamsson (2004) suggested the use of islands to remedy potential short-circuiting effects. In this way, the proper use of islands can not only enhance aesthetics, but also improve the hydraulic performance of a pond. For example, the linear flow paths created either side of pond P2 resulted in a high length to width ratio, increased hydraulic efficiency and less short-circuiting than for a pond of similar shape without an island. Figure 4 indicates that the positioning of the island in pond P2 successfully distributes flow and results in the highest hydraulic efficiency (λ = 0.87) of the nine configurations studied. In this way, short-circuiting is reduced (S=0.89) and the plug flow tendency of the flow is increased (N~8). Overall, pond P2 reveals that when used correctly, the inclusion of an island can significantly enhance flow. However, the smaller island in pond P3 was less effective at distributing flow. This suggests that the size of the island is an important factor in the resultant hydrodynamic characteristics.

The importance of correct inlet/outlet positioning is demonstrated by ponds P4 and P5. These ponds show that alternating the direction of flow by modifying the inlet and outlet positions has a significant impact on hydraulic efficiency. Inspection of Figure 4 shows that ponds P4, P5 and P8 result in significant regions of stagnation. Furthermore, as shown in Table 4, this causes poor hydraulic efficiency (λ=0.44, 0.37 and 0.38, respectively).

The kidney shaped pond, P6 is also shown to be a relatively effective layout for enhancing hydraulic efficiency, although, small regions of stagnation can be observed on the inside of the bend. Moreover, the geometry of this pond is likely to make it susceptible to scouring.

Multiple inlets have been reported to improve performance (Moreno 1990), however, the distributed inlets of pond P9 do not reflect this trend as the inlets are placed along the length of the pond rather than dispersed across the width of the inlet. The positioning of inlets close to outlets is also not recommended as this can lead to short-circuiting and poor pollutant removal.

5. Conclusion

This paper has assessed the hydrodynamic characteristics of nine simple pond configurations using two-dimensional modelling (Mike 21) and hydraulic indicators (λ and S). This study confirmed that configurations with the greatest length to width ratio result in the highest hydraulic efficiency. This study also showed that:

1. Correct positioning of design elements such as islands can significantly enhance the hydraulic characteristics of a pond.
2. Teardrop and kidney shaped ponds are likely to result in a higher hydraulic efficiency than most rectangular shaped ponds with the same surface area.
3. Distributed inflows along the length of a pond can result in a substantial decline in hydraulic efficiency.

This study represents an extension of Persson's (1999) work and the outcomes may be used to aid in the conceptual design of stormwater treatment systems. In particular, it is anticipated that this information may assist in the modelling of stormwater treatment ponds and wetlands using the commercial modelling package MUSIC (CRC Catchment Hydrology).

6. Further Work

The work presented in this paper is undergoing continual extension. An additional fifteen pond configurations, based on existing stormwater ponds in the Melbourne area, are currently undergoing hydraulic and kinetic modelling. Also currently under investigation is a refined tanks-in-series based model (suitable for inclusion into MUSIC) that allows for the representation of stagnation which is a common problem in wetlands and stormwater treatment ponds.

7. Acknowledgements

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