HYDRAULICS EFFICIENCY OF CONSTRUCTED WETLANDS AND PONDS

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ABSTRACT

Constructed ponds and wetlands are widely used in urban design to serve a number of functions including stormwater management. The design of constructed wetlands for stormwater management involves a number of multi-disciplinary inputs. Fundamental to their sustainable operation are the proper control of the hydrologic regime of the wetland and optimal flow hydrodynamics within the wetland. Many of the problems encountered in constructed wetlands can be minimised or avoided by good engineering design principles. Poor wetland hydrodynamics are often identified as a major contributor to wetland management problems. Ponds and wetlands with a high hydraulic efficiency are expected to promote full utilisation of the available detention storage and near plug flow conditions. The shape and layout of urban ponds and wetlands are often varied to suit the landscape and to satisfy aesthetic requirements as an urban water feature. These can be achieved while maintaining an effective stormwater treatment outcome if steps are taken to ensure that the hydrodynamic behaviour of the system is not severely compromised. A consistent measure is required to allow the effects of design features to be evaluated against this criterion. This paper introduces a new measure for hydraulic efficiency that combines existing measures of flow uniformity and effective volume. Case studies are presented on the use of this measure to assess the effects of different pond and wetland shapes, locations of inlet and outlet, botanical layouts and basin morphology on the flow hydrodynamics.
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KEYWORDS

Detention period, flow hydrodynamics, ponds, stormwater, constructed wetlands

INTRODUCTION

Constructed wetlands and water pollution control ponds are becoming widely used for the treatment of stormwater and combined sewer overflows (CSO). These systems are surface flow detention systems which are often collectively referred to as constructed wetlands. However, it is useful to provide some distinction between ponds and wetlands as they do have significantly hydrologic and hydraulic characteristics and promote different water quality treatment processes. Ponds are generally small artificial bodies of open water with a small range of water level fluctuation. Emergent aquatic macrophytes are normally restricted to the margins because of water depth, although submerged plants may occur in the open water. Constructed wetlands are shallow detention systems, which regularly fill and drain and are typically extensively vegetated with emergent aquatic macrophytes.

The design of constructed wetlands and ponds requires multi-disciplinary input involving biological and ecological sciences, aquatic chemistry, engineering hydrology and flow hydraulics. In addition to stormwater quality improvements, constructed wetlands and ponds are often used in urban design as water features to

serve as part of the urban landform and to provide recreational amenities. Many such systems have been constructed, often with insufficient consideration to their requirement for proper hydrological and hydraulic design. Insufficient provision of storage volume and unsatisfactory hydrologic and hydrodynamic control are the main causal factors for poor performance of constructed wetlands and ponds as water pollution control facilities (Reed, 1995). These deficiencies have also resulted in many of these urban wetlands and ponds becoming a long-term liability to the community.

In relation to best practice in wetland design, Wong *et al.* (1998) suggest that three principal design components need to be addressed, ie.

1. hydrologic effectiveness;
2. hydraulic efficiency; and
3. facilitation and optimisation of water quality treatment processes.

Although each of the above processes are in some way inter-related, a systematic design procedure would address these three principal components in the above general order. The first design objective would be to facilitate an optimal rate of capture and detention of stormwater runoff by the wetland, ie. to optimise the hydrologic effectiveness of the wetland in accordance to the rainfall characteristics of the catchment (Wong and Somes, 1995). The second design objective is to ensure that stormwater inflow into the wetland is well distributed throughout the wetland by avoiding physical elements which may lead to the occurrence of short-circuits and poor utilisation of the available detention storage. A high system hydraulic efficiency can be achieved by proper definition of the shape and depth of the wetland or pond, and the locations and types of inflow and outflow structures. Special flow diversion features using vegetation, basin bathymetry design and other hydraulic measures may have to be introduced to facilitate even distribution of flow throughout the wetland or pond. Optimal hydrologic effectiveness and hydraulic efficiency provide the most appropriate conditions for promoting the necessary biological and chemical processes of stormwater treatment.

Constructed ponds and wetlands are often used in urban design as landscape amenities and landscape architects are prominent designers of these systems. The shape and layout of urban ponds and wetlands need to suit the landscape and satisfy aesthetic requirements as a urban water feature. These can be achieved while maintaining an effective stormwater treatment outcome if steps are taken to ensure that the hydrodynamic behaviour of the system is not severely compromised. A consistent and reliable measure of hydraulic efficiency is necessary to enable wetland and pond designs to be evaluated for their expected hydrodynamic performance. Desired variations in their geometric properties, bathymetry, vegetation layout, and locations and type of inlet and outlet structures to satisfy landscape design objectives need to be assessed and optimised to achieve the best possible hydrodynamic conditions in these systems. This paper describes a method for determining the hydraulic efficiency of a constructed wetland or pond. The method could be used as a tool to compare existing ponds and wetlands, or as a design tool to compare the efficiencies of different design alternatives prior to construction. The measure of hydraulic efficiency (λ) is tested against a wide range of hypothetical pond shapes and inlet/outlet locations and flow dynamics computed for a research wetland in the field. Depth integrated, modeling techniques were used to determine tracer responses for a number of combinations of pond and wetland design features and their hydraulic efficiencies evaluated.

BACKGROUND

The hydraulic efficiency of ponds and wetlands needs to reflect two basic features in the hydrodynamic performance of a stormwater detention system. The first is the ability to distribute the inflow evenly across the detention system and the second is the amount of mixing or re-circulation, ie. deviations from plug flow. Figure 1 shows a number of tracer responses in a detention system and is used to illustrate these two basic features. The figure shows three tracer concentration-time distributions in response to a spike tracer input and steady flow conditions. All three cases have similar mean detention periods but will have significantly different hydraulic efficiencies owing to their differences in the range of detention period experience by individual parcels of tracer entering the system.

Kadlec and Knight (1996) describe a distribution function of hydraulic residence time, referred to as the Retention Time Distribution (RTD) function to reflect the degree in which the hydraulic residence time varies. Under plug flow conditions, the concentration-time distribution is simply a spike with a very small standard deviation about the mean residence time as shown in Figure 1. This suggests that all individual parcels of tracer entering the wetland experience a similar period of detention. For continuously stirred flow condition, the concentration-time distribution takes the form of an exponential function where the effect of flow dilution in steady flow conditions progressively reduces the tracer concentration at the outflow.
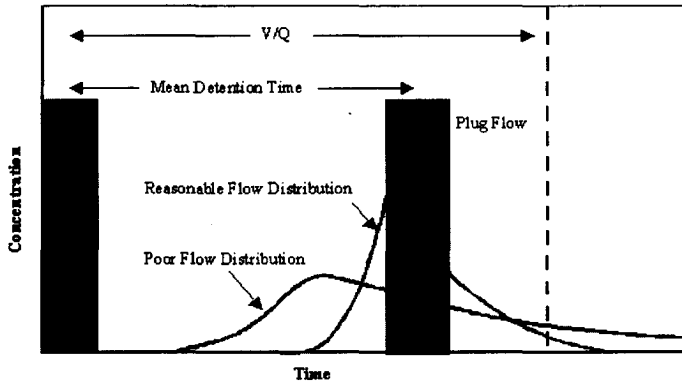

Figure 1   Illustration of Tracer Concentration-Time Distribution

Plug or continuously stirred flow conditions never occur in natural systems and the concentration-time distribution of natural wetland systems lies somewhere in between the distributions of plug flow and fully mixed flow conditions. According to Kadlec and Knight (1996), flow hydrodynamics within a wetland system may be modelled as a combination of plug flow (ie. a time delay before tracer outflow is observed) and a number of continuously stirred tanks reactors (CSTRs). A single CSTR will result in a pollutant hydraulic residence time distribution represented by an exponential function while plug-flow condition is the result of the number of CSTRs in series approaches infinity. The concentration-time distribution takes the form of a positively skewed distribution function with the tail of the distribution extending as flow condition for the entire detention system approaches fully mixed condition. The extent to which flow conditions depart from an idealised plug flow condition is reflected in the spread of the distribution function. Generally, an outflow concentration distribution with a large standard deviation suggest the presence of short-circuit flow paths and flow re-circulating zones. In some cases, the combined effect of short-circuit flow paths and re-circulating zones can result in the outflow concentration-time distribution exhibiting multiple peaks, or in other cases in a flat extended peak.

Tracer response curves for several surface flow wetlands were examined by Kadlec and Knight (1996) and found them all to be reasonably represented by 3 CSTRs in series in spite of their different shapes. Wind induced mixing was thought to be an important factor in reducing the number of CSTRs in series even in systems with large length to width ratios. However, closer examination of the observed tracer response curves clearly showed some of the more regularly shaped wetlands to have promoted better tracer residence time distributions and that it is possible to delineate systems with higher hydraulic efficiencies in the group examined by Kadlec and Knight (1996).

Figure 1 also shows that the mean detention periods of the three concentration-time distributions were less than the nominal detention period, computed as the ratio of the volume over the discharge (ie. V/Q). This is attributed to not all the available storage volume has been utilised in the detention of the tracer, ie. the effective volume is less than the nominal storage volume. A large difference between the observed mean detention period and the nominal detention period again suggests the presence of zones of stagnation (ie. ineffective detention zones) in the system.

It is evident that both near-plug flow and effective volume utilisation conditions are necessary to promote good hydraulic efficiency. Detention systems featuring near-plug flow conditions alone may not reflect good wetland design if the presence of a dominant short-circuit flow path results in the majority of the pollutant being rapidly transported to the outlet, albeit in a near-plug flow manner. While all parcels of pollutants experiences similar detention periods, these detention periods are significantly less that what would have been the case had all the storage volume been utilised in the detention of the pollutants. Similarly, systems that yield a mean detention period close to the nominal detention period (V/Q) but with a flat concentration-time distribution are also exhibiting poor hydraulic efficiency. In such cases, the individual parcel of pollutants experiences highly varied detention periods about the nominal detention period.

MEASURES OF FLOW HYDRODYNAMICS

Current measures of hydraulic efficiency are directed at one of the two features discussed above with none combining the two hydraulic performance criteria. Some common measures of the shape of the pollutant hydraulic residence time distribution involve the computation of the mean detention period and the variance (σ^2) or standard deviation of the hydraulic residence time distribution, eg.

$$\sigma^2 = \int_0^\infty (t - t_{mean})^2 E(t) dt \qquad (1)$$

where $E(t)$ is the pollutant hydraulic residence time distribution;
             t_{mean} is the mean detention time but is often assumed to be the same as the nominal
                        detention period ($t_n = V/Q$)

Others have used variations of the above, including the use of a dispersion number (D) as defined in the Wehner-Wilhelm equation to characterise the degree of non-ideal flow conditions within a detention system. A dispersion number of zero suggests plug flow conditions and the number approaches infinity for fully mixed conditions. There are a number of ways, in which the dispersion number can be computed, many of which utilise some measure of the variance of the hydraulic residence time distribution. For example, Levenspiel (1972) provided the following expression relating the dispersion number to the coefficient of variation (σ/t_{mean}) of the pollutant hydraulic residence time distribution, ie.

$$\left(\frac{\sigma}{t_{mean}} \right)^2 = 2D - 2D^2 \left(1 - e^{1/D} \right) \qquad (2)$$

According to Fogler (1992), the number of CSTRs in series is simply the inverse of the square of the coefficient of variation of the pollutant hydraulic residence time distribution, ie.

$$N = \left(\frac{\sigma}{t_n} \right)^{-2} \qquad (3)$$

The above measures require a quantification of the range of detention times within a wetland to allow calculation of the mean and standard deviation of the tracer response. The retention time distribution (RTD) is quantified by either field tracer study or numerical simulation of the passage of a conservative tracer through the wetland or pond. Many field tracer responses are characterised by positively skewed distributions with long tails and, as a result, the calculation of means and standard deviations of the RTD can vary significantly depending on the selected end point of the field measurement. In field studies, the end point is either defined by the detection limit of the tracer or a pre-specified minimum tracer recovery criterion, with unaccounted tracer assumed to be lost in the detention system. Numerical models can preserve the mass balance of the tracer input with the results often characterised by extremely long tails. It is

therefore necessary to arbitrarily select an endpoint, the position of which can affect the statistics of the distribution particularly the variance significantly.

To overcome these shortcomings, a number of methods have been developed to define the mean and standard deviation, ie.

$$t_{mean} = t_{50} \qquad (4)$$

and

$$\sigma \approx \frac{1}{2}\left(\frac{t_{84} - t_{16}}{t_{50}}\right) \qquad (5)$$

where t_{84}, t_{50} and t_{16} are the 84th, 50th and 16th percentiles of the hydraulic residence time distribution. Equation 5 assumes the tracer response is normally distributed, which is never the case in wetland and pond systems. Kadlec and Knight (1996) suggested an alternative equation to calculate the number of CSTRs in series. This was based on defining the difference in the time of the peak outflow concentration and the mean detention time, ie.

$$N = \frac{t_n}{t_n - t_p} \qquad (6)$$

Ta and Brignal (1998) utilised the ratio of the 16th percentile detention time over the 50th percentile detention time as a measure of the extent of short-circuiting (S) in a pond system, ie.

$$S = \frac{t_{16}}{t_{50}} \qquad (7)$$

None of the above measures explicitly account for any loss in effective detention volume and merely examine the shape of the pollutant hydraulic residence time distribution to determine the measure of flow hydrodynamic conditions in the wetland or pond. Thackston et al. (1987), on the other hand, utilised the ratio of the mean detention period over the nominal detention period to measure the effective volume ratio utilisation of detention systems, ie.

$$e = \frac{t_{mean}}{t_n} = \frac{V_{effective}}{V_{total}} \qquad (8)$$

HYDRAULIC EFFICIENCY (λ)

A review of measures adopted by others to define flow hydrodynamics in ponds and wetlands found them to inadequately described the two hydrodynamic criteria in the previous sections and illustrated in Figure 1. It is proposed that an alternative measure, based on the product of the effective volume ratio and a term involving the equivalent number of tanks in series, be formulated. The later factor describes the shape of the RTD, with N equal to 1 for continuously stirred flow and ∞ for plug flow. This new measure of hydrodynamic conditions in ponds and wetlands is referred to as the Hydraulic Efficiency (λ) and is expressed as follows:

$$\lambda = e\left(1 - \frac{1}{N}\right) = \left(\frac{t_{mean}}{t_n}\right)\left(1 - \frac{t_{mean} - t_p}{t_{mean}}\right) = \frac{t_p}{t_n} \qquad (9)$$

In the above expression, the first term defines the effective volume ratio of the detention system and the second term involves the term N, which is simply the number of CSTRs in series. Both terms have a range

of 0 to 1 providing equal weighting for effective volume and pollutant hydraulic residence time distribution. The resulting expression for hydraulic efficiency is simply the ratio of the time of the peak outflow concentration to the nominal detention period (V/Q). The measure can thus be readily derived from observed outflow pollutographs of wetland and pond systems and does not have the problems associated with defining the mean detention period (t_{mean}).

Two- and three-dimensional models can often provide valuable insights into the hydrodynamic behaviour of open water systems. Two-dimensional depth-averaged models are commonly applied to simulate flow patterns in shallow water bodies such as floodplains in flood investigations. Their appropriate use in modelling flow hydrodynamics in wetland and pond systems, which have significantly different flow characteristics from floodplain flow conditions during flood events, was investigated by Somes et al. (1996) and Bishop (1999). That study found two-dimensional depth-averaged models to be capable of reproducing observed flow pattern, defined by measured velocity vectors, in a research wetland provided careful attention is placed on modelling the diffusion process. Adamsson et al. (1999), compared the results obtained from a two-dimensional depth integrated model (MIKE 21), a three-dimensional model (Fluent) and a physical model and found both numerical models were able to reproduce the hydrodynamics of the physical model.

SIMULATIONS OF POND SHAPES AND INLET/OUTLET CONFIGURATIONS INFLUENCES

In a recent study, Persson (1999) investigated the influence of pond shape, inlet/outlet locations and inlet/outlet type on the hydrodynamics of these systems. In that study, 13 hypothetical ponds were investigated as shown in Figure 2. Each of these systems had approximately 2700 m^3 in volume and a depth of 1.5 m. A two-dimensional depth integrated hydraulic model, MIKE-21, was used to simulate the progress through the system of a spike of conservative trace injected at the inlet. The resulting RTDs were then used to compute various hydrodynamic measures such as the effective volume ratio and the amount of mixing. Table 1 lists the results of the simulation including the corresponding values of λ.

The cases considered may be categorised into the following three groups; (i) good hydraulic efficiency with $\lambda > 0.75$; (ii) satisfactory hydraulic efficiency with $0.5 < \lambda \leq 0.75$; and (iii) poor hydraulic efficiency where $\lambda \leq 0.5$. Table 2 lists the cases in these categories.

Table 1   Hydrodynamic Measures of Hypothetical Cases

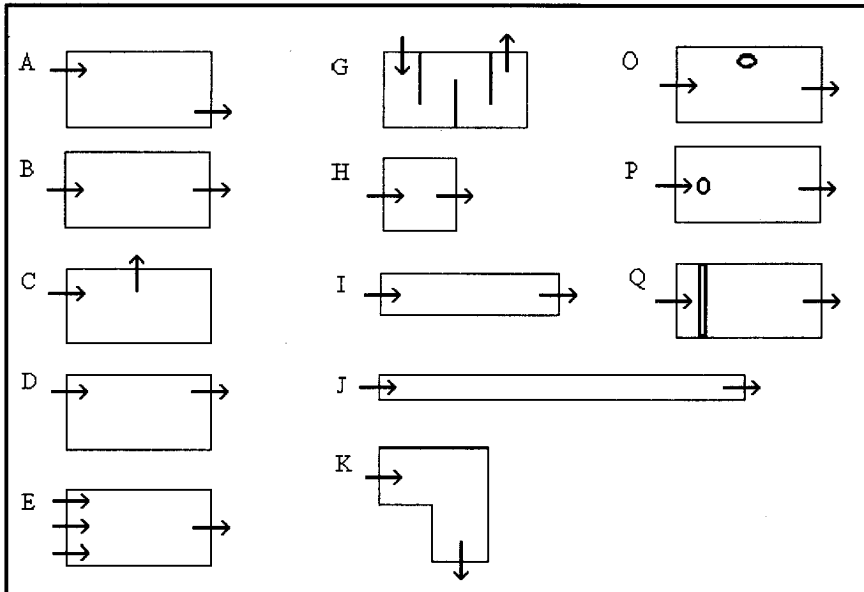| Case	S	e	1-1/N	$\lambda = \dfrac{t_p}{t_n}$
A	0.29	0.74	0.41	0.30
B	0.24	0.79	0.33	0.26
C	0.10	0.46	0.23	0.11
D	0.16	0.34	0.52	0.18
E	0.68	0.89	0.85	0.76
G	0.72	1.0	0.76	0.76
H	0.10	0.44	0.25	0.11
I	0.30	1.0	0.41	0.41
J	0.87	1.0	0.90	0.90
K	0.34	0.78	0.46	0.36
O	0.25	0.73	0.35	0.26
P	0.57	0.96	0.64	0.61
Q	0.50	0.93	0.64	0.59

Figure 2   The thirteen pond shapes and configurations investigated.

Table 2   Ranking of hypothetical ponds according to λ

Category	Cases
Poor Hydraulic Efficiency	A, B, C, D, I, H, K & O
Satisfactory Hydraulic Efficiency	P & Q
Good Hydraulic Efficiency	E, G, & J

Elongated pond shapes (Case J) or baffled systems (Case G) clearly provided very high hydraulic efficiency although care needs to be applied in designing elongated shapes to ensure that the increased flow velocity associated with the narrower cross section would not lead to resuspension and remobilisation of settled material. Case E, which spread inflow across the wetland, also provided a high hydraulic efficiency.

The simulations showed that designs involving a length to wide ratio of 4:1 or less, and with point inflow and outflow, (Cases A, B, D, H & I) will not promote good hydraulic efficiency unless steps are taken to evenly distribute the inflow across the width of the detention storage. The introduction of a small island in front of the inlet (Case P) was found to more than double the hydraulic efficiency (compared to Case B) of the system. The use of a submerged berm at the inlet, or a flow distribution inlet structure, was found to have a similar effect as for the case of a small island near the inlet with the distributed inlet providing a clear advantage. While no simulations were carried out for the case of a distributed outlet, it was suggested that a single outlet point would not affect the hydraulic efficiency significantly.

L-shaped ponds with an effective length to width ratio of 3:1 was found to yield unsatisfactory hydraulic efficiency with the result being only marginal better than the case of a rectangular-shaped pond with a 2:1 length to width ratio.

As expected, poor placement of the outlet (Case C) and length to width ratio (Case H) resulted in the lowest hydraulic efficiency. Similarly, the location of an island at the side of the system (Case O) does not improve flow distribution in the system.

SIMULATIONS OF WETLAND MORPHOLOGY AND VEGETATION INFLUENCES

Somes *et al.* (1998) undertook an investigation to examine available options to improve the hydraulic efficiency of a research wetland in South Gippsland, Australia. In that study, a 2-dimensional hydraulic model, MIKE-21, was used to simulate the effects of modifications to the wetland morphology and vegetation layout on the flow hydrodynamics. The existing wetland was constructed on an old creek line and this is reflected in its bathymetry, with a channel connecting the inlet and outlet. The bathymetry and original planting of the wetland have limited the distribution of emergent macrophytes to the fringes of the wetland. The model was calibrated against field measurement of flow velocities as reported by Somes *et al.* (1997). In examining possible modification options, 5 cases were simulated in addition to the existing base case. These were (i) fully vegetating the wetland; (ii) a series of aquatic benches (banded bathymetry) with fringing vegetation; (iii) a meandering low flow channel (labyrinth bathymetry) and full vegetation; (iv) aquatic benches (banded bathymetry and full vegetation); and (v) uniform depth and full vegetation.

Figure 4 plots the tracer responses for the simulations where the horizontal axis represents the time since the injection of the tracer and the vertical axis plots the outlet tracer concentration. The vertical line at 3:40 represents the theoretical exit time of a tracer slug if ideal flow conditions (V/Q) occurred in the wetland. The base case (Figure 4) indicates a significant proportion of the tracer exits well before the nominal detention time. Table 3 lists the six cases and their corresponding values of the two terms used to define the Hydraulic Efficiency (λ). The results clearly show that systems with fringing vegetation and natural bathymetry have low effective volume (0.4). The natural creek bed and fringing vegetation was found to have resulted in a preferential flow path along the central region of the wetland. Flow condition at this central region exhibited relatively low flow mixing (or a high degree of near-plug flow conditions) with an estimated number of CSTRs in series of 5.7. However, the combined effect of effective volume and flow mixing resulted in the λ value of 0.32, being the lowest of the cases considered.

The option of using a meandering low flow channel (labyrinth bathymetry) and full vegetation improved the effective volume but was found to have promoted two preferential flow paths as reflected in the presence of two peak concentrations in the outflow pollutograph. This has led to a lower number of CSTRs in series but the improvements to the effective volume was found to outweigh the increased mixing with a resulting λ value of 0.52.
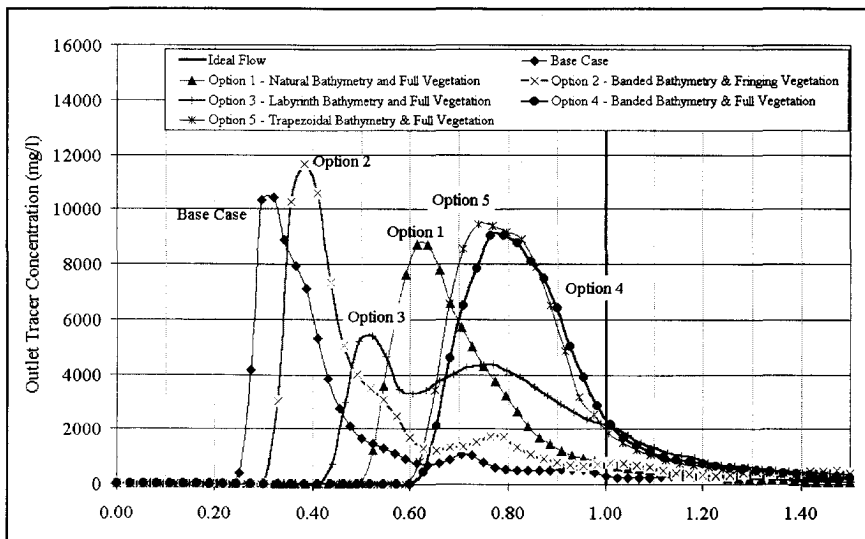

Figure 4   Tracer response from MIKE-21 Modelling – Monash University Research Wetland

The simulations found modification to the vegetation layout within the wetland to be most effective in improving flow hydrodynamic conditions. The option of full vegetation without associated morphological modifications was found to have doubled the base case hydraulic efficiency from 0.32 to 0.64. However, as discussed by Somes *et al.* (1996), maintaining a sustainable botanical structure is not a simple matter and requires particular attention to be given to the hydrologic regime control of the system and the matching of vegetation type to the wetness gradient.

Further improvements to the hydraulic efficiency for a fully vegetated system can be achieved with modification to the bathymetry to promote uniform flow conditions across the full cross section of the wetland by either using a series of submerged aquatic benches or to shape the basin bathymetry as trapezoidal cross sections to provide uniform flow depth throughout the system. As noted in Figure 4, the shapes of the outlet pollutographs for the banded bathymetry and uniform depth with full vegetation cases are similar and thus is expected to have similar hydraulic efficiencies. Both options gave high hydraulic efficiency values of approximately 0.75.

The derived values of the number of CSTRs in series (N) for the banded bathymetry and uniform depth fully vegetated cases examined were 23 and 12 respectively and highlight the importance in providing an upper and lower bound to the terms defining hydraulic efficiency. While the values of N are significantly different, the influence of N on the shape of the RTD is exponential and at large N values, the improvements are often marginal in spite of a large increase in N.

Table 3   Hydrodynamic Measures of Monash University Research Wetland

Case	$\dfrac{t_{50}}{t_n}$	N	λ
Base case	0.39	5.7	0.32
Full Vegetation	0.68	15	0.64
Banded Bathymetry &Fringing Vegetation	0.48	5.0	0.38
Labyrinth Bathymetry & Full Vegetation	0.77	3.1	0.52
Banded Bathymetry & Full Vegetation	0.83	23	0.76
Uniform Depth & Full Vegetation	0.80	12	0.74

CONCLUSION

A simple measure for defining the flow hydrodynamic characteristics of ponds and wetlands has been developed to allow the effect of variations in the design of these systems to be evaluated. The need to provide such measures stems from the recognition that ponds and wetlands are becoming widely adopted in urban design to provide functions beyond stormwater treatment. Their shape and layout will be varied depending on the landscape and the design features to meet aesthetic requirements. Insufficient considerations of the effects of these changes on flow hydrodynamics have been a major cause of poor performance of these systems. The Hydraulic Efficiency measure (λ) was found to provide a good balance in assessing the hydrodynamic performance of detention systems against the uniformity of flow and the effective utilisation of the available detention storage volume.

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