

Modelling the Hydraulic Characteristics of Artificial Wetlands

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Abstract: Free water surface wetlands are widely adopted for the treatment of both waste water and urban stormwater. The treatment of contaminants that occur in these wetland systems rely on physical, chemical and biological processes. The efficiency of these processes is affected by the residence time of water as it passes through these wetland systems. Flow conditions through a free water surface wetland system are rarely similar to plug flow, and generally the residence time is characterized by a distribution of values. This paper describes the development of a zones of diminished mixing (ZDM) model of flow through a free water surface wetland. The model has been applied to a set of hypothetical rectangular wetlands, in which response curves for a conservative contaminant tracer have been previously determined using a two-dimensional numerical flow model. The ZDM model has been fitted to the tracer response curves previously developed. The study indicates that the ZDM model parameters are functions of the length to width (L/W) ratio of the wetland, and are affected by the size of the recirculation zones that characterize the flow characteristics of these wetland systems.

Keywords: *Free water surface wetlands, Hydraulic residence time, Hydraulic Efficiency, Zones of Diminished Mixing*

1. INTRODUCTION

Free water surface wetlands have become an important part of urban stormwater management systems. These wetlands are characterised by shallow perennial or ephemeral water bodies with emergent vegetation. The treatment of stormwater as it flows through these wetland systems relies on the physical, chemical and biological processes that take place within the wetland. In the design of these systems, an understanding of the hydraulic residence time within the wetland system is a fundamental requirement. In natural and constructed wetland systems the hydraulic residence time is affected by the shape and bathymetry of the wetland and by the vegetation type and distribution. The uneven variation of these parameters throughout the wetland produces two-dimensional flow characteristics and the hydraulic residence time of a particular block of water depends on the path taken by the water as it flows through the system.

The physical, chemical and biological treatment processes that occur within a constructed wetland system rely on the flow of the water through the system to facilitate these treatment processes. Therefore, the hydraulic characteristics within the system have a significant influence on the efficiency of the wetland as a treatment device. Researchers have noted that many wetland

management problems can be attributed to poor hydrodynamic characteristics within the wetland system. Therefore, the design of these treatment systems requires efficient computational models of the flow characteristics within the wetland.

This paper describes a study to investigate the use of an efficient computational procedure to model the mixing and dispersion characteristics of flow through a wetland. The procedure uses a conceptual model of the flow characteristics comprising plug flow with dispersion plus a zone of diminished mixing. A modification of the Muskingum flood routing algorithm is used to model the advection and dispersion processes through the main flow path. The computational algorithm is compared with the results of a numerical study on the two-dimensional flow characteristics of constructed wetlands. The model of wetland flow characteristics developed in this study, will allow urban stormwater designers to gain a better understanding of the water quality treatment processes occurring within the system.

2. FLOW CHARACTERISTICS OF FREE WATER SURFACE WETLANDS

The physical, chemical and biological treatment processes that occur within an constructed wetland system rely on the flow of the water through the system to facilitate these treatment

processes. Therefore, the hydraulic characteristics within the system have a significant influence on the efficiency of the wetland as a treatment device. As noted by Persson et al., (1999), many wetland management problems can be attributed to poor hydrodynamic characteristics within the wetland system.

Under ideal conditions, plug flow characteristics can be assumed within the wetland system. This essentially means that all of the water that enters the wetland stays together as a single plug as it flows through and exits the system. The time that this plug of water stays in the system is referred to as the hydraulic residence time. A longer hydraulic residence time allows for more of the treatment processes to be completed. The hydraulic residence time under ideal plug flow conditions can be defined by Equation 1.

$$T_n = \frac{VOL}{Q} \quad (1)$$

Where:

- T_n Nominal hydraulic residence time;
- VOL Wetland volume;
- Q Flow rate through wetland.

However, in real wetland systems the water does not stay together as a single plug as it flows through the system. The spatial variability of the flow characteristics within a wetland system means that the hydraulic residence time of water flowing through the system is described by a distribution, rather than a single value.

Features such as recirculation zones represent volumes of water that are relatively ineffective in the treatment process. This ineffective volume results from the limited mixing that takes place between the water flowing through the system and the water within the recirculation zones.

Persson et al. (1999) defined the hydraulic efficiency λ of a wetland as the ratio of the time taken for a conservative tracer to reach a peak at the outlet to the nominal retention time. Persson et al. (1999) state that the hydraulic efficiency provides a good measure of the effective volume within the system, as well as the pollutant residence time distribution. Its most significant advantage is that it can be determined directly from a conservative tracer response curve, overcoming the problems associated with defining the mean residence time from tracer response curves with long receding limbs.

The hydraulic efficiency is defined by:

$$\lambda = \frac{T_p}{T_n} \quad (2)$$

Where:

- T_p Time for a conservative tracer to reach a peak at the outlet;
- T_n Nominal hydraulic residence time;

Persson et al. (1999) investigated the effect of wetland shape on the hydraulic efficiency λ and found that wetlands with large values of L/W produced higher values of λ . The study undertaken by Persson et al. (1999) used a two-dimensional flow model to investigate a range of wetland shapes and configurations. The flow conditions more closely approached plug flow as the wetland length to width ratio L/W increased.

Jenkins (2003) used a similar numerical modelling approach to Persson et al. (1999), and demonstrated that the recirculation zones at the inlet and mixing zones within the basin have a significant effect on the flow characteristics. Water entering the basin or wetland has limited ability to mix with water within the recirculation zones. Also, zones of limited mixing within the basin reduce the volume of water that is effective in the treatment process. The resulting short circuiting causes different flow characteristics to those described by ideal plug flow conditions.

3. MODELLING FLOW THROUGH WETLANDS

3.1. The Zones of Diminished Mixing Model

The successful design of constructed wetland systems requires accurate modelling of the flow characteristics within the system. In particular, it is important that the hydraulic residence time distribution is accurately reproduced. This will facilitate the modelling of the various chemical, biological and physical treatment processes that take place. The effectiveness of these treatment processes depends on the time each contaminant spends within the wetland system.

The assumption of plug flow within the system is generally a poor representation of the flow characteristics in most wetlands. To overcome the limitations imposed by the assumption of plug flow, models comprising a series of continuously stirred tank reactors (CSTR) are often employed. An example of this approach is described by Fletcher et al (2001). However, Werner and Kadlec (2000) have noted that the use of CSTR models often fails to replicate the sharp rise and

long flat tails of residence time distributions observed from tracer tests in wetlands.

Werner and Kadlec (2000) describe the use of a Zones of Diminished Mixing (ZDM) model that aims to overcome the short-comings observed in the use of the CSTR approach. The ZDM modelling approach assumes that water flows through the wetland along a main flow path from the inlet to the outlet. Along this flow path, it is also assumed that there are an infinite number of micro zones of diminished mixing. These ZDM's are not strictly dead zones. As the water flows along the main flow path, there is limited interaction with these diminished mixing zones. Werner and Kadlec (2000) model flow through the main flow path using a plug flow with dispersion model.

The model developed in this study uses the same conceptual main flow path with ZDM's approach as described by Werner and Kadlec (2000). The wetland is conceptually sub-divided into a series of computational elements, which are all of equal volume. Each computational element is itself sub-divided into a main flow path cell plus an adjacent ZDM cell. Rainfall into each element has not been included in the model. Figure 1 shows the details for computational element i .

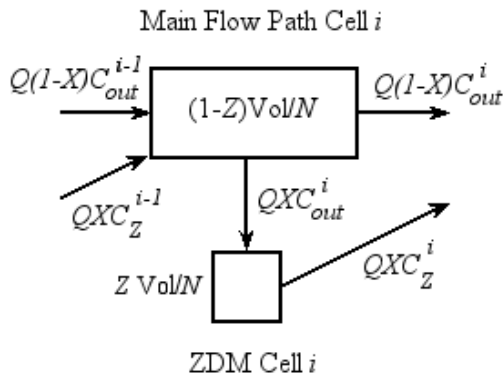


Figure 1. Arrangement of Computational Elements in the Model.

The volume of each computational element i , is defined as being equal to Vol/N , where Vol is the total volume of the wetland and N is the number of computational elements. In this study the number of cells has been set to $N=100$. The number of computational cells was selected so that the resulting time step provided a reasonable definition of the tracer response from the wetland. Z is defined as the proportion of the wetland volume in each ZDM cell. The proportion of the total flow that passes through each ZDM cell is defined as X .

All of the stormwater entering each computational element first flows through the main flow path cell. The outflow from this cell is sub-divided, with a portion, X , flowing into the ZDM cell. The outflow from the ZDM cell is mixed with the flow leaving the main flow path cell and flows to the next computational element downstream.

As with the model described by Werner and Kadlec (2000), each ZDM cell is modelled as a continuously stirred tank reactor. However, the flow through the main flow path cell is modelled using a modified Muskingum Cunge method. The adopted algorithm allows for contaminant routing using a relatively simple algorithm that models both the advective and dispersive components of the flow through the main flow path of the wetland.

3.2. Modified Muskingum Cunge Method

The passage of a stormwater wave through the main flow path section of the wetland is computed using a modification of the Muskingum Cunge method of routing. The method is used to compute the outflow pollutograph from that entering the main flow path section of the wetland. The Muskingum Cunge method is based on the continuity of mass equation. A thorough discussion of the Muskingum Cunge method for flood routing in rivers can be found in Raudkivi (1979) and Bedient and Huber (1992).

With reference to Figure 2 below, the continuity of contaminant mass equation for unsteady flow through the main flow path cell can be written in differential form as:

$$M_{in} - M_{out} = \frac{dB}{dt} \quad (3)$$

Where:

- M_{in} Mass flow rate of contaminant entering the main flow path cell,
- M_{out} Mass flow rate of contaminant leaving the main flow path cell,
- B Mass of contaminant in storage within the main flow path cell, and
- t Time.

Equation 3 can be rewritten in finite difference form as:

$$\frac{1}{2}(M_{in}^n + M_{in}^{n+1}) - \frac{1}{2}(M_{out}^n + M_{out}^{n+1}) = \frac{\Delta Z}{\Delta t} = \frac{1}{\Delta t}(B^{n+1} - B^n) \quad (4)$$

In equation 4, the superscripts n and $n+1$ denote the values of the variable at the beginning and end of the time step respectively.

It is assumed here that the mass of contaminants in storage within the main flow path cell can be expressed as a function of the mass inflow and mass outflow rates by:

$$B = K_i M_{out} + K_i \theta (M_{in} - M_{out}) \quad (5)$$

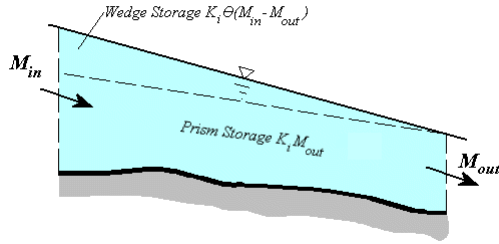


Figure 2. A main flow path cell showing contaminant mass storages.

The mass flow rate of contaminants is given by:

$$M = QC \quad (6)$$

Where:

C Concentration of contaminant in the stormwater.

Substituting equations 5 and 6 into equation 4 and rearranging gives the following expression:

$$C_{out}^{n+1} = \frac{\begin{pmatrix} A_1 Q_{in}^{n+1} C_{in}^{n+1} \\ + A_2 Q_{in}^n C_{in}^n \\ + A_3 Q_{out}^n C_{out}^n \end{pmatrix}}{Q_{out}^{n+1}} \quad (7)$$

$$\text{where: } A_1 = \frac{\Delta t - 2 K_i \theta}{2 K_i (1 - \theta) + \Delta t} \quad (7a)$$

$$A_2 = \frac{\Delta t + 2 K_i \theta}{2 K_i (1 - \theta) + \Delta t} \quad (7b)$$

$$A_3 = \frac{2 K_i (1 - \theta) - \Delta t}{2 K_i (1 - \theta) + \Delta t} \quad (7c)$$

In the equations above, K_i is the prism storage parameter and has the units of time. It is approximately equal to the travel time of the contaminant plug through the main flow path cell, i . Under ideal plug flow conditions, K_i can be approximated by dividing the volume of the main flow path cell by the flow rate through the wetland, Q .

The parameter θ is a dimensionless weighting factor that has a value between 0 and 0.5, and represents the relative weighting of the inflow and outflow when approximating the mass of the contaminant in storage within the main flow path cell. Linsley et al (1992) note that when adopting the Muskingum Method for flood propagation in natural channels, the value of θ is generally between 0.1 and 0.3. When $\theta = 0$, the volume of the contaminant in storage is purely a function of the outflow alone. A value of 0.5 indicates that the inflow and outflow have equal weighting in determining the volume in storage.

The parameter θ affects the attenuation of the pollutant wave as it travels through the main flow path, with the attenuation increasing as the value of θ decreases. A value of $\theta = 0.5$ produces no attenuation and the contaminant wave is purely translated by a time value equal to K_i .

When adopting the Modified Muskingum Method with short time steps, ie: where $\Delta t < K_i$, negative values of outflow concentration can occur on the rising limb of the pollutograph. Bedient and Huber (1992) and Raudkivi (1979) note that Cunge (1969) has shown that the use of the Muskingum Method is equivalent to the finite difference form of the kinematic wave equation. The negative values on the rising limb of the pollutograph are avoided in the Modified Muskingum Method adopted in this study by automatically setting the time step equal to the value of K_i adopted for the main flow path cell.

The benefit of this approach in contaminant routing is that the relatively simple algorithm is able to model both the advective and dispersive components of the flow through the main flow path of the wetland. However, as noted by Bedient and Huber (1992), the amount of attenuation produced by the method is affected by the time step adopted. Although this limits the universality of the θ parameter for different model arrangements, similar effects are produced by numerical diffusion in other more complex numerical algorithms.

4. EFFECT OF LENGTH TO WIDTH RATIO

Persson et al. (1999) and Jenkins (2003) have shown that the length to width ratio of a wetland has a significant influence on the flow characteristics through the system. In particular, it was shown that the recirculation zones at the inlet, and internal mixing zones act to reduce the effective volume of the wetland. Jenkins (2003) also showed that the hydraulic efficiency λ , within a rectangular wetland system can be described by the following relationship:

$$\lambda = 0.926 \left[1 - \exp\left(-0.231 \frac{L}{W}\right) \right] \quad (8)$$

In the study described by Jenkins (2003), a two-dimensional, depth-averaged numerical flow model was used to study the steady flow characteristics of rectangular wetlands. Nine different wetland configurations were modelled, with length to width ratios ranging between 0.357 and 35.7. A conservative contaminant tracer was injected at the inlet to each wetland, and the resulting tracer response curve was measured at the outlet.

The Zones of Diminished Mixing (ZDM) algorithm described in the previous section has been applied to the wetland configurations described by Jenkins (2003). In each case the ZDM model has been applied using $N=100$ computational elements. Setting the time step equal to the travel time through each element, K_i , resulted in time steps ranging between 0.135 and 2.763 minutes. This provides a significant improvement in computational time compared with the two-dimensional model study, which used a 2 second time step, with 7000 computational cells.

The ZDM model was developed using a MS© Excel spreadsheet. The model uses three parameters, which include:

- Z The proportion of the wetland volume contained within the ZDM,
- X The proportion of the flow entering the ZDM, and
- θ The dimensionless Muskingum weighting parameter.

Each of the model parameters for each wetland configuration was optimized using the Excel Solver routine. For some of the model configurations, the optimisation routine was sensitive to the initial parameters chosen. It is clear from this study that more research needs to be undertaken in the application of a more robust parameter optimisation algorithm.

The optimum parameters for the model, for each of the wetland configurations are given in Table 1. Figure 3 shows an example of the model tracer response curve, in comparison to that determined by Jenkins (2003) for a model wetland with a length to width ratio (L/W) of 2.80. The ZDM model response curve is also compared with that produced by a series of 5 CSTR's. Other CSTR options were investigated, however, the ZDM model gave a superior fit to all of the tracer response curves tested. The Muskingum prism storage parameter K_i , was held constant for each

computational element, and was determined by dividing the main flow path cell volume by the flow rate, ie $(1 - Z)Vol/(QN)$.

Table 1. Optimum ZDM model parameters determined from fitting to tracer response curves from Jenkins (2003).

L/W	Z	X	θ	ΣK_i (mins)
0.357	95.4%	0.74%	0.0	13.50
0.700	90.7%	0.72%	0.0	27.11
1.43	78.5%	0.78%	0.0	62.64
2.23	61.7%	0.83%	0.0	111.6
2.80	53.1%	0.82%	0.0	136.7
4.38	35.8%	0.51%	0.022	187.44
8.93	20.2%	0.53%	0.29	232.7
17.5	9.58%	0.21%	0.33	263.7
35.7	5.26%	0.38%	0.42	276.3

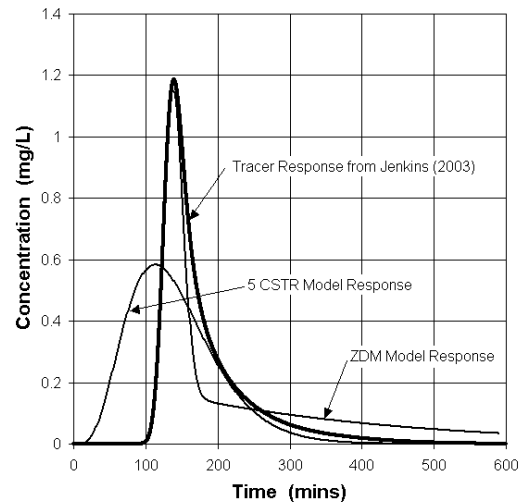


Figure 3. A comparison of tracer response from ZDM model and Jenkins (2003).

Table 1 indicates that the Muskingum prism storage parameter for the total wetland ΣK_i , increases as the length to width ratio increases. ΣK_i is approximately equal to the travel time of the contaminant plug through the wetland. Dividing ΣK_i by the nominal hydraulic residence time for the wetland T_n should approximate the hydraulic efficiency of the wetland, λ .

Figure 4 shows a comparison of the ratio of $\Sigma K_i/T_n$ from the ZDM model and the hydraulic efficiency versus L/W relationship developed by Jenkins (2003). This indicates that the relationship presented in equation 8 provides a

good estimate of K_i to adopt when using the ZDM model. Furthermore, the model parameter Z , the proportion of the wetland volume contained within the ZDM, is related to the size of the recirculation zones at the inlet to the wetlands. As noted by Jenkins (2003), the size of recirculation zones become smaller as the length to width ratio increases.

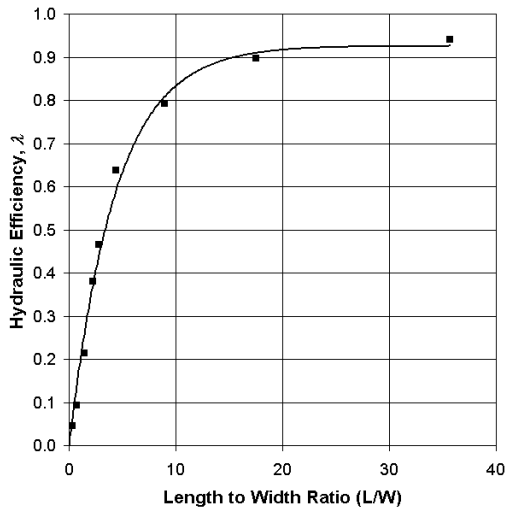


Figure 4. Hydraulic efficiency versus length to width ratio, after Jenkins (2003).

Table 1 shows that the proportion of the flow entering the ZDM, X , reaches a maximum for a length to width ratio of $L/W = 2.23$. Jenkins (2003) noted a similar effect for the variance of the tracer response curves from the two-dimensional model study. For length to width ratios less than this value, the downstream end of the wetland intercepted the recirculation zones originating at the wetland inlet. However, for length to width ratios greater than this value, the recirculation zones were shorter than the length of the wetland. This result suggests that the size of the recirculation zones in the wetland affects the amount of flow that enters the ZDM.

The dimensionless Muskingum weighting parameter θ , represents the amount of dispersion of the main plug of contaminant as it flows through the system. A value of $\theta = 0$ represents the maximum amount of dispersion possible from the model, whilst $\theta = 0.5$ represents no dispersion. As expected, the value of θ approaches 0.5 as L/W increases, and the flow conditions start to approach plug flow.

5. CONCLUSIONS

A Zones of Diminished Mixing (ZDM) model has been developed to model the flow of a conservative tracer through a surface water flow wetland. The model uses a variation of the

Muskingum method to model the flow of the contaminant plug through the main flow path of the wetland. The ZDM model has been fitted to tracer response curves derived by Jenkins (2003), using a two-dimensional numerical flow model, for a set of rectangular wetlands. It appears from the study that each of the ZDM model parameters are related to the flow characteristics observed in the two-dimensional numerical model wetlands, which themselves are related to the length to width (L/W) ratio of the wetland. The relationship previously derived by Jenkins (2003) between the hydraulic efficiency λ , and L/W ratio for the wetland provides a good estimate of the Muskingum prism storage parameter K_i required for the ZDM model.

6. ACKNOWLEDGEMENTS

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