
Ecological and hydrological assessment for a constructed stormwater wetland restoration

Évaluation écologique et hydrologique pour la restauration d'une zone humide artificielle de gestion des eaux pluviales

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RESUME

Bien que la végétation d'une zone humide artificielle de gestion des eaux pluviales joue un rôle important dans les procédés de traitements, sa densité et sa distribution dépendent de la bathymétrie et du régime hydrologique imposé de cette zone humide. Cet article décrit une évaluation écologique et hydrologique d'une ZUA sur une période de 5 années. Cette évaluation comprend l'utilisation d'un modèle hydrologique de simulation continue combiné à un modèle d'élévation numérique de la bathymétrie de la ZUA, ainsi qu'une série temporelle de cartes de végétation. L'analyse combinée spatiotemporelle révèle que la fréquence et la durée des inondations a affecté le devenir de la végétation dans toute la ZUA. Des stratégies de restauration ont également été étudiées pour améliorer la survie de la végétation dans la ZUA.

ABSTRACT

Although the vegetation within constructed stormwater wetlands plays an important role in the treatment processes taking place, its density and distribution depends on the wetland bathymetry and the imposed hydrologic regime. This paper describes an ecological and hydrological assessment of a constructed stormwater treatment wetland over a 5 year period. This assessment included the use of a continuous simulation hydrologic model combined with a Digital Elevation Model of the wetland bathymetry, plus a time series of vegetation maps. The combined spatial and temporal analysis indicates that both the frequency and duration of inundation has affected the fate of vegetation throughout the wetland. Restoration strategies have also been investigated to improve the survival of vegetation within the wetland.

KEYWORDS

Continuous simulation, Hydrological modelling, Hydroperiod, Macrophytes, Stormwater wetlands, Vegetation zonation.

1 INTRODUCTION

Constructed wetlands and retention ponds are two common stormwater treatment devices for both storage and water-quality improvement. In addition to providing stormwater treatment, wetlands and ponds can also improve aquatic biodiversity and provide a range of ancillary community benefits (Knight *et al.*, 2001, Wetzel, 2001). Wetlands and ponds incorporated into the urban landscape can be aesthetically pleasing and a focal point for passive recreation. Vegetation (usually emergent macrophytes) is the dominant feature of wetlands, whereas open water is the dominant feature of ponds, except for the shallow littoral margins. Submerged species may occur if there is sufficient light.

Vegetation plays an important role in the treatment processes in wetlands, including the filtration of particles, reduction in turbulence, stabilisation of sediments, nutrient uptake, microbial-rhizosphere interaction and the provision of increased surface area for biofilm/periphyton growth (Wong *et al.*, 1998, Greenway, 2004). These processes are also influenced by the hydraulic interaction between the vegetation and the water as it flows through the system (Jenkins & Greenway, 2005). The density and distribution of this vegetation within the macrophyte zone is dependent on the bathymetry of the wetland and the hydrologic regime imposed by the rainfall and runoff characteristics of the site. Mitsch and Gosselink (2000) state "Hydrology is probably the most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes".

Stormwater wetlands should support a zonation of wetland plants, each adapted to a specific hydroperiod (i.e. the extent of periodic or permanent inundation). Wong *et al.* (1998) recognise five wetland zones (ephemeral swamp, shallow marsh, marsh, deep marsh and open water) that can be incorporated into constructed wetlands, and suggest these should be arranged in series across the notional flow path. Hoban *et al.* (2006) show that the vegetation within stormwater wetlands with low hydrologic effectiveness can experience periods of extended inundation and depth. Vegetation in these systems must accommodate a greater range of depths and inundation duration than expected in a wetland with a higher hydrologic effectiveness. However, the bathymetry in these systems often limits the space available for vegetation habitat.

In this paper a stormwater wetland in Brisbane, Australia is used to investigate the way in which the hydrologic regime affects macrophyte establishment. It is shown that a five-year study of plant establishment and a continuous-simulation hydrologic model of the catchment, explain the fate of vegetation establishment in different parts of the wetland. The model incorporates an analysis of the frequency and duration of inundation over a two-year period. Using the model in a long-term simulation has allowed for the statistical prediction of the wetland hydroperiods. The hydrological model has also been used to investigate two restoration strategies that could be adopted to improve the survival of vegetation within the wetland.

2 METHODS

The Bridgewater Creek wetland is located in Brisbane, SE Queensland, where the climate is defined as subtropical with no dry season, using the modified Koeppen classification system, (Australian Bureau of Meteorology, 2006). The median annual rainfall is 1118 mm, with the wet part of the year occurring during the summer months. The wetland was constructed in 2001, with six interconnected ponds (Figure 1). Pond 1 is a sediment basin with an area of 1000 m² and a depth of 2 m. Ponds 2 to 6, with a combined area of 7000 m², were originally designed as "macrophyte zones" to include open water, deep marsh, shallow marsh and ephemeral zones. Water flows from pond 1 into pond 2 via an underground pipe, whereas surface water

flows progressively from pond 2 to pond 6. During large storm events, stormwater overflows from pond 1 into a “bypass” channel via an overflow weir. An overflow weir is also located at the downstream end of pond 6. The outlet structure comprises a riser with an invert level of approximately 4.0 m Australian Height Datum (AHD), while the reduced level (RL) of both overflow weirs is 5.01 m AHD.

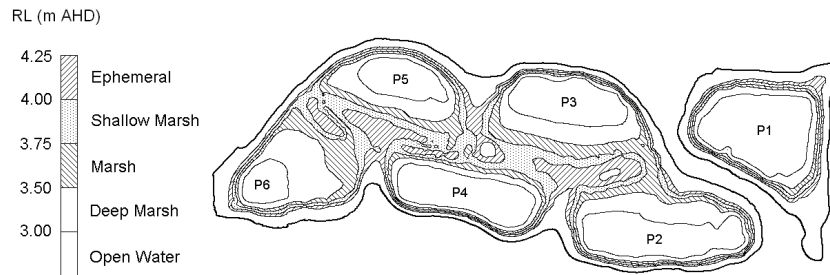


Figure 1. Location of wetland zones, based on the wetland bathymetry at November 2004

Vegetation establishment has been monitored since March 2002 using a series of permanent transects. Species presence were recorded in quadrats along each of the transects. A topographic survey of the wetland system was undertaken using a digital Topcon Total Station. 1,200 spot heights were recorded throughout all of the ponds, including the inlet pond 1, up to the top of the embankment surrounding the wetland system. A digital elevation model (DEM), with a grid resolution of 250 mm in both directions was then generated from the spot heights using a kriging algorithm. The vegetation zones based on the original plantings have been defined by the bathymetric contours derived from this DEM, as shown in Figure 1. The Ephemeral, Shallow Marsh, Marsh, Deep Marsh and Open Water areas cover 10%, 12%, 12%, 19% and 28% of the wetland area respectively. The wetland has a permanent pool volume of 5.2 megalitres (ML) and a detention volume of 7.1 ML, up to the level of the bypass weir. This permanent pool volume represents 42% of the total wetland storage, which is significantly larger than the 10 – 15% ratio recommended by Wong *et al.* (1998)

From August 2002 to February 2004, water levels were recorded at both the inlet to pond 2 and the outlet to pond 6. This period has been referred to in this study as the wetland establishment period. Although samples were taken generally at a daily frequency, there were many days during this period when no water level values were recorded. A hydrologic model of the continuous rainfall and runoff processes within the catchment and wetland system provides a way of filling in this missing water level information. The UrbSim model was used to investigate the inundation characteristics within the wetland during the establishment period using recorded rainfall data. The UrbSim catchment and wetland model was then run to simulate runoff from the wetland over a 50 year period to derive a long-term statistical estimate of the inundation frequency and duration characteristics of the wetland.

UrbSim is a program that has been designed to simulate the rainfall and runoff processes from an urban catchment, Jenkins and Newton (2005). The catchment area is subdivided into a network of sub-catchments, with the boundaries of each lying along the watershed boundaries that drain to the sub-catchment outlet. The rainfall and runoff processes are modelled using two separate steps. The first step is the generation of daily rainfall excess in each sub-catchment, using a hybrid metric-conceptual approach to represent the rainfall runoff processes (Wheater *et al.* 1993).

The second step is the conversion of this rainfall excess into runoff and the routing of this runoff to the sub-catchment outlet. The flow routing model solves the continuity of mass equation through conceptual storages within each sub-catchment at a sub-daily time step. Overland flow on the impervious and pervious parts of the sub-catchment are modelled separately, using an area weighted routing algorithm that is similar to that adopted in the WBNM rainfall runoff routing model, described by Boyd *et al.* (1995) and Boyd *et al.* (1987). Flow through the wetland is modelled using a level-pool routing algorithm with three-point Lagrange interpolation to solve the continuity of mass equation.

3 RESULTS AND DISCUSSION

3.1 Vegetation Survey

Within the first six months after construction of the wetland, there had been extensive loss of newly planted vegetation within the deep marsh, and the extent of open water had increased from 25% to 56%. Over the proceeding years the extent of open water further increased from 56% to 80% as plants failed to establish and spread in the marsh zones. Loss of plants in the ephemeral zone resulted in bare mud. After 12 months, all of the *Cyperus polystachys* had died in the shallow marsh. By 24 months, *Isolepis nodosa* and *Baumea rubiginosa* had disappeared. After 36 months, the only plants surviving and thriving were clumps of *Juncus kraussii* and *Juncus usitatus* that had been planted in the most elevated sections of the ephemeral zone. *Baumea articulata* and *Schoenoplectus validus*, originally planted in the deep marsh zone, only survived where they had spread into the shallow marsh zones.

Natural colonisation of *Potamogeton javanicus* was of particular interest. This species was first identified as isolated individuals in early 2004 and by November 2004 had completely colonised the original marsh zones (RL 3.25-4.00) in pond 6. By November 2005 it had spread into pond 4 and pond 5.

Bolboschoenus fluviatilis was the only species to successfully cope with increased water depth by spreading landward using its rhizomatous system. By May 2004, it had spread 1 m landward and crept up the embankment. Clumps of *Schoenoplectus mucronatus* were unable to spread into shallower areas. Although there initially had been a spread of both *Schoenoplectus validus* and *Baumea articulata* into shallower water, the removal of topsoil over time, prevented further landward colonisation.

Plants in the ephemeral and shallow-marsh zone were exposed not only to extended periods of inundation and deeper water, but to exposure during dry periods. These elevated zones between the ponds were used as roosting sites for water birds - mostly ibis and water hens. Patches of *Carex appressa* were favoured, resulting in complete denudation over time. *Cyperus polystachys* was one of the first shallow-marsh species to disappear as a result of increased water depth, followed by *Isolepis nodosa* and *Baumea rubiginosa*. *Carex appressa* also died off due to extended inundation. These results highlight that water depth and hydroperiod appear to be the most important problems in establishing macrophyte zones in stormwater wetlands.

3.2 Hydrologic Assessment of the Wetland

Figure 2 shows the frequency of inundation derived from the simulated water levels from the UrbSim model for both the establishment period and the long-term simulation period. The frequency of inundation characteristics are similar for both the establishment period and the long-term simulation. The simulation results show that the water level within the wetland exceeds the overflow weir 3.0% of the time. However, 76% of the total volume of water flowing out of the wetland flows over the overflow weir, producing a hydrologic effectiveness of 24%.

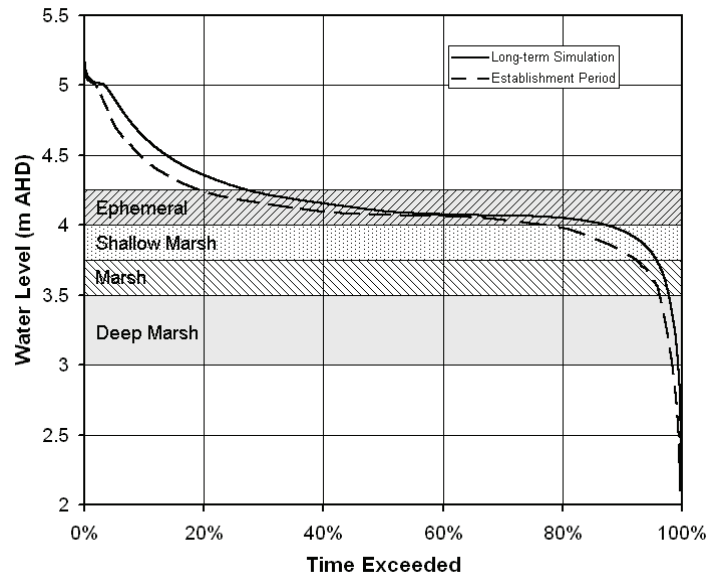


Figure 2 Frequency of inundation within the Bridgewater Creek Wetland

The lack of establishment and survival of the macrophyte species planted in the ephemeral and marsh zones can be explained by the inundation periods and the water depths experienced. The ephemeral zone will be inundated for 87% of the time for a mean duration period of 5 days. Only *Juncus* at the highest elevation was able to tolerate these extended periods of inundation. The shallow marsh zone will be inundated with water deeper than 20cm for 91% of the time, for a mean duration of 155 days – this contrasts with Wong *et al.* (1998) recommendation of a water depth > 20cm for only 38% of the time. The marsh zone will be inundated with water deeper than 40cm for 93% of the time (compared to 58% Wong *et al.* (1998)) for a mean duration of 198 days.

Although the plant species selected and planted were appropriate for the zones described, their establishment and survival was adversely affected because water depths and hydroperiods were greater than the tolerance range for these species. Bonilla–Warford and Zedler (2002) highlighted the problem of limited knowledge of plant tolerances to fluctuating water levels as one of the main reasons for the lack of variety of native macrophyte species in stormwater wetlands in the United States. In Bridgewater Creek Wetland, *B. fluviatilis* and *S. validus* were able to survive by spreading landward, *Juncus spp.* only survived at the highest level (RL 4.25m AHD).

Wong *et al.* (1998) define the ephemeral zone of the wetland as being that part which is inundated between 12% and 17% of the time. The simulation results indicate that the water level in the Bridgewater Creek wetland will exceed RL 4.46 m AHD for 15% of the time. This indicates that the original ephemeral zone plantings should have been placed between RL 4.46 m AHD and RL 5.01 m AHD. However, this zone only represents 13.7% of the wetland surface area, which is approximately equal to the area of the wetland that remained vegetated throughout the vegetation monitoring phase. Figure 3 shows each of the vegetation zones based on the frequency and depth of inundation criteria by Wong *et al.* (1998). The imposed hydrologic regime

has produced a wetland with a large amount of open water (74% of the wetland area), and very little space within the existing bathymetry for suitable vegetation zones. Therefore, stormwater flowing through the wetland system will not be able to take full advantage of those treatment processes that are facilitated by wetland vegetation.

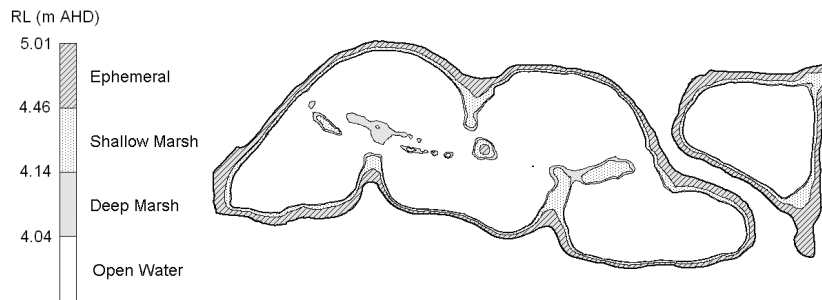


Figure 3. Wetland vegetation zones based on the hydrologic regime by Wong *et al.* (1998)

3.3 Modifying the Wetland to Improve Vegetation Survival

Two modifications have been proposed to the wetland system to investigate the impact on the inundation characteristics produced. Each case was modelled using the UrbSim model and the results were analysed to determine the duration and frequency of inundation produced. The two cases investigated included:

Case 1: Lowering the outlet orifice plate structure by 500 mm;

Case 2: Modifying the wetland bathymetry to produce a system with the open water and ephemeral vegetation zones covering approximately 15% and 30% of the macrophyte ponds respectively. This requires approximately 4,570 m³ of fill being deposited within the macrophyte ponds.

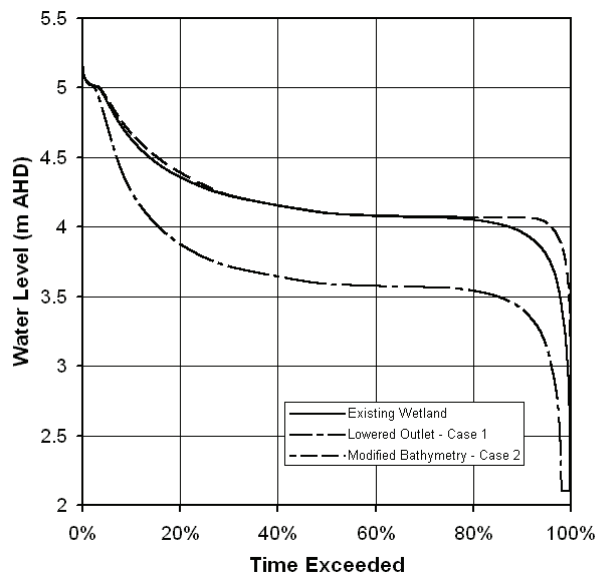


Figure 4. Frequency of inundation for the existing and modified wetlands.

Figure 4 shows the cumulative frequency of inundation for each of the modified bathymetries and the existing wetland. Lowering the outlet orifice plate structure has the biggest influence, while modifying the wetland bathymetry has only had a minor effect on the frequency of inundation response for the wetland.

The hydrologic effectiveness has increased to 28% for Case 1 and 25% for Case 2, compared to 24% for the existing wetland. For Case 1, the hydrologic effectiveness has increased because the extended detention volume has increased, as predicted by Wong *et al.* (1998). For Case 2 there has also been a slight increase in the hydrologic effectiveness, even though the extended detention volume has been reduced as there has been a reduction in evapotranspiration resulting from the reduced wetland water surface area. This indicates that changes to the storage volume do not strongly influence the hydrologic effectiveness of this wetland system.

A wetland with a higher hydrologic effectiveness will result in more runoff being treated both during and immediately after storm events. However, the survival of emergent vegetation is vital for the reduction of pollutant concentrations within the wetland during inter-event periods, Kasper and Jenkins (2005). Figures 5 and 6 show the vegetation zones derived from the simulation results for each of the modified cases, based on the frequency and depth of inundation criteria by Wong *et al.* (1998).

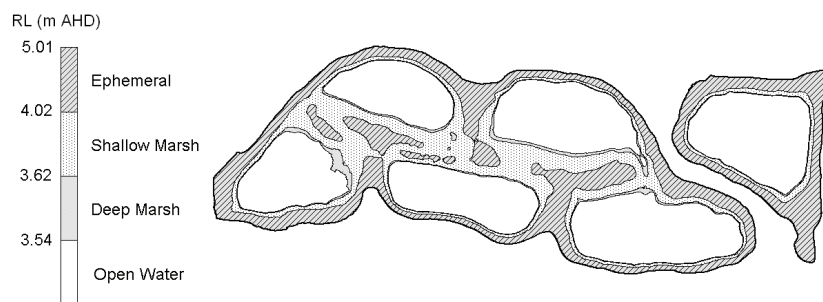


Figure 5. Wetland vegetation zones for the lowered outlet Case 1.

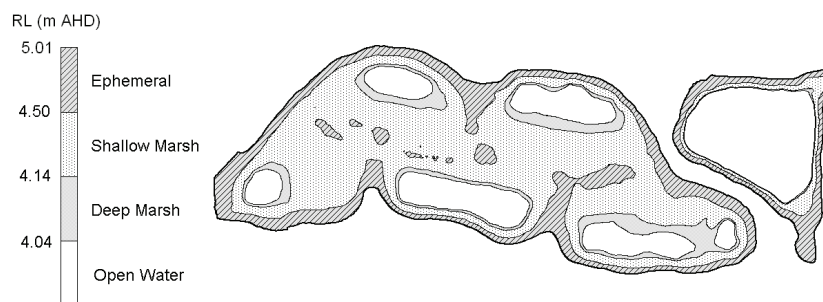


Figure 6. Wetland vegetation zones for the modified bathymetry Case 2.

The results for Case 1 show that the Ephemeral, Shallow Marsh, Deep Marsh and Open Water zones cover 28%, 19%, 3% and 50% of the wetland area respectively. The results for Case 2 show that the Ephemeral, Shallow Marsh, Deep Marsh and Open Water zones cover 22%, 44%, 8% and 26% of the wetland area respectively. It is important to note here that both the ephemeral and shallow marsh zones will be

significantly increased over the existing wetland conditions and the open water area will be significantly reduced for both wetland modifications. Although Case 1 generally produces larger vegetation zone areas than produced in the existing wetland, the open water area is twice that produced in the modified bathymetry, Case 2. The ephemeral, shallow marsh and deep marsh zones in Case 1 will be 1.0 m, 1.4 m and 1.5 m deep respectively when flow occurs over the bypass weir. This may not be desirable for vegetation survival in these zones. Therefore, this suggests that Case 2 may be a more attractive option. Although this will be a more expensive option, due to the extensive fill required within the macrophyte zone.

4 CONCLUSION

Monitoring of macrophyte establishment has identified many hurdles facing plant survival. The greatest challenge for stormwater wetlands is successful vegetation zonation, and the hydroperiod is the key factor. The failure of macrophyte establishment at the Bridgewater Creek Wetland was due to deeper water in the marsh zones and prolonged inundation in the ephemeral zones. Thus, careful consideration must be given not only to water depth, but also to the duration of inundation. Riser and weir levels must ensure that water levels recede to the appropriate level post storm/ flood event to prevent extended periods of inundation. More research needs to be undertaken into understanding the tolerance of different species to periods of inundation. Our study has shown that modifying the bathymetry of the wetland can result in improvements to the inundation characteristics which will result in larger vegetation zones. Although lowering the outlet orifice structure will also increase the areas of vegetation zones, the extended depth of inundation during storm events may adversely affect vegetation survival.

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