# Macrophyte zonation in stormwater wetlands: getting it right! A case study from subtropical Australia

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**Abstract** In Australia stormwater wetlands are becoming an increasingly popular component of water sensitive urban design. However, they must be designed to cope with the dynamic nature of urban hydrology, in particular, fluctuations in water level. The concept of macrophyte zonation relies on a thorough understanding of the water regimes of different plant species. Water depth is crucial and the hydroperiod, i.e. duration and frequency of inundation, has a significant impact on the survival of wetland vegetation. The aim of this study was to investigate plant establishment in a newly constructed stormwater wetland in Brisbane, subtropical Australia. Changes in plant distribution and density have been monitored since 2001. Rainfall and water depth data enabled us to use a hydrologic model to predict the extent of inundation of the different macrophytes zones. The field survey showed macrophyte survival was poor with the complete loss of several species in marsh and ephemeral zones. The main reason for the lack of macrophyte establishment and survival was the extended periods of inundation (supported by the hydrologic model) and deeper water levels. Stormwater wetlands must be designed to ensure that ephemeral species are not permanently inundated or the preferred water depths in marsh zones are not exceeded for extended periods.

**Keywords** Hydroperiod; inundation; macrophytes; stormwater wetland; vegetation zonation; water depth

## Introduction

### Stormwater wetlands

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.

The treatment of stormwater as it flows through a wetland is the result of a complex interaction between the physical, chemical and biological processes. Vegetation plays an important role in these treatment processes, 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 influenced by the hydraulic interaction between the vegetation and the water as it flows through the system (Jenkins and Greenway, 2005a). The hydrologic effectiveness, together with treatment efficiency, determines the overall performance of the wetland.

The hydrologic effectiveness of a wetland, which is defined as the long-term percentage of catchment runoff that enters the macrophyte zone, is influenced by the storage volume and detention time of the wetland, plus the rainfall characteristics of the site (Wong *et al.*, 1998). The treatment of this runoff as it flows through the wetland is significantly improved by the presence of the wetland vegetation. However, the density

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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. The bathymetry also defines the volume of detention storage within the wetland. Therefore, it is important in the design of constructed stormwater treatment wetlands that the adopted bathymetry provides a balance between adequate storage volume and the provision of vegetation sites, so that the maximum treatment of contaminants entering the system is achieved.

### Macrophyte zonation and hydroperiod

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" (p. 108). The duration of flooding or substrate saturation, the depth of flooding, the frequency and season of flooding and drying, can all have an effect on the plant establishment and growth. Water depth plays a critical role in the distribution of the types and species of aquatic plants. Thus, to maximise macrophyte establishment and zonation, water depths must be carefully controlled.

In natural wetlands, zonation is common, with emergent seasonally inundated species occurring at the landward interface and submerged species occurring in deeper permanent water. In the design of constructed stormwater wetlands, it is important to allow for variations in water depth, thereby accommodating both flooding and intermittent flows. Stormwater wetlands should support a zonation of wetland plants, each adapted to a specific hydroperiod (i.e. the extent of periodic or permanent inundation). "Ephemeral wetland" zones occur around the landward margins of lakes or on floodplains and can be established in locations where they would only be inundated during the wet season. This could include the upper margins of deeper open-water ponds or specially created shallow areas within the macrophyte zones which would completely dry out. Shallow wetland or marsh zones should be designed to maintain water depths of at least 5 cm during the dry season and up to 40 cm in the wet season. Deep wetland or marsh zones should maintain water depths of at least 20 cm during the dry season. Wong *et al.* (1998) recognise five wetland zones (ephemeral swamp, shallow marsh, marsh, deep marsh and open water) that can be incorporated into constructed-wetland design, and suggest these should be arranged in series across the notional flow path.

The primary aim of our study was to monitor plant establishment in a newly constructed stormwater wetland. However, it became apparent after 12 months that mortality was very high especially in the marsh and deep marsh zones. Thus we decided to undertake a topographic survey of water levels and a hydrologic assessment to investigate the impacts of water depth and inundation.

## Methods

### Site description

In Brisbane, SE Queensland, the climate is subtropical with intense rainfall events being common in the rainy season. The average annual rainfall is 1,030 mm, having an average of 10 days/y $>$ 50 mm rainfall and a 10 y average recurrence interval (ARI) 1-hour duration intensity of 71 mm/h. Seventy per cent of rain falls during the summer and autumn (December to May). During the winter months (June, July and August), total monthly rainfalls are usually less than 20 mm. These extremes of rainfall make it difficult to design stormwater wetlands that can be effective in water-quality improvement.

The Bridgewater Creek wetland, constructed in 2001, consists of six interconnected ponds (Figure 1). Pond 1 is a triangular-shaped sediment basin with an area of 1,000 m$^2$ and a depth of 2 m. Ponds 2 to 6, with a combined area of 7,000 m$^2$, were originally

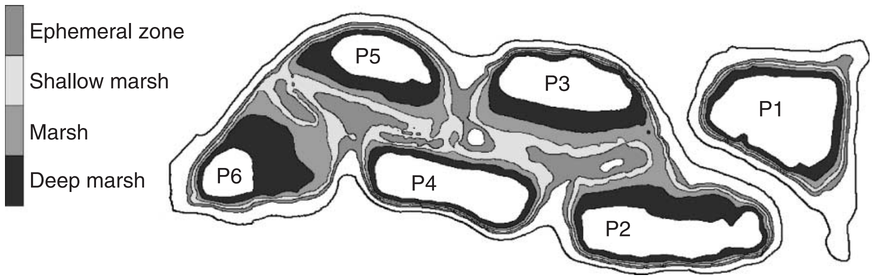


**Figure 1** Location of wetland zones, based on the wetland bathymetry (refer to Table 1 for RL of each zone)

designed as "macrophyte zones" to include open water, deep marsh, shallow marsh and ephemeral zones. Water flow from pond 1 into pond 2 is 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 adjacent to the outlet structure 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 relative level (RL) of both overflow weirs is 5.01 m AHD.

#### Vegetation survey

Macrophyte vegetation has been monitored since March 2002 (i.e. from three months after initial planting). Several permanent transects, perpendicular to the bank, were established in each pond. At six-monthly intervals species presence and abundance (stem density) were recorded in 0.25 $m^2$ quadrats at 50 cm intervals along each transect. Vegetation maps were produced using the GIS mapping software Map Info and the area of each wetland zone calculated.

#### Topographic survey

A topographic survey of the wetland system was undertaken and a digital elevation model (DEM) generated from the spot heights using a kriging algorithm (Jenkins and Greenway, 2005b). The vegetation zones based on the original plantings have been defined by the bathymetric contours. These zones have been derived from the DEM, and are shown in Figure 1. The analysis of the DEM indicates that 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).

#### Hydrologic assessment of the wetland

From August 2002 to February 2004 and from March to June 2006, water levels were monitored daily at both the inlet (P2) and outlet (P6) structures. In addition, the UrbSim hydrologic model (Jenkins and Newton, 2005; Jenkins and Greenway, 2005b), was used to model rainfall and runoff from the urban catchment draining to the Bridgewater Creek wetland. The water level record produced by the UrbSim model was used to investigate the inundation characteristics within the wetland.

The UrbSim catchment and wetland model was then run to simulate runoff from the wetland over a period of 50 years of rainfall from the Brisbane Airport rain gauge. An inundation frequency and duration analysis was then undertaken from the water levels produced from the 50-year simulation to provide a long-term statistical estimate for the wetland (Jenkins and Greenway, 2005b).

## Results and discussion

### Macrophyte establishment and survival



Table 1 provides a comparison of the temporal changes in extent of distribution of plant species in the different macrophyte zones from the initial planting in November 2001 until May 2006. The original planting scheme for the different macrophyte zones is shown in column 1 (November 2001). The wetland was designed to achieve 80% macrophyte cover in ponds 2–6. Several species did not survive the first three months: *Eleocharis sphacelata* and *Lepironia articulata* (planted in the deep marsh) and *Eleocharis equisetina* and *Philydrum lanuginosum* (planted in the marsh). Poor plant establishment occurred in all marsh zones following planting, but was worse in the deep marsh resulting in only 2% area cover. Thus by May 2002 open water was 56% of the total wetland area (ponds 2–6). Over the next four years the extent of open water increased to 80% in August 2005 as plants failed to establish and spread in the marsh zones, whereas the loss of plants in the ephemeral zone resulted in bare mud (Table 1 and Figure 2).

After 12 months (November 2003), there was further decline in macrophyte cover in the marsh zone due to the loss of clumps of *Schoenoplectus mucronatus* and shoots of *Baumea rubiginosa*, and the migration of *Bolboschoenus fluviatalis* and *Schoenoplectus validus* into the shallow marsh. Thus there was an increase in cover in the shallow marsh despite the loss of all the *Cyperus polystachys* and *Isolepis nodosa*.

By November 2003, *I. nodosa* had died in the ephemeral zone, and *B. rubiginosa* in the shallow marsh. *Philydrum* was also in decline and all plants in the shallow marsh were dead within the next few months. By May 2004, 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 *S. validus*, originally planted in the deep marsh zone, only survived where they had spread into the marsh and shallow marsh zones. *Bolboschoenus fluviatalis* spread landward up to 1 m with almost the complete loss of shoots originally planted in the marsh zone. All *S. mucronatus* clumps in the marsh zone had died.

Between May 2004 and August 2005 all *B. articulata* and *S. validus* in the deep marsh zone had disappeared, but there was little change in the distribution of the remaining species in the other zones, indicating stability. However, the natural colonisation of the submerged macrophyte, *Potamogeton javanicus,* was of particular interest. This species was first identified as isolated individuals in January 2004 and by November 2004 it had completely colonised the original marsh zones (RL 3.25–4.00) in pond 6. In 2005 it had spread into ponds 4 and 5. However, in 2006 there was a noticeable decline in *Potamogeton*.

Between August 2005 and the May 2006 survey there had been complete loss of most of the remaining species. From December 2005 until mid-April 2006 the wetland had been inundated by water depths of up to 75 cm above the ephemeral zone (i.e. RL 5.0 m), the cause being a blockage in the outlet riser orifice, which prevented draining. This extended period of inundation caused the loss of *B. articulata* and a large stand of *S. validis*. *B. fluviatilis* survived by landward migration into the terrestrial zone. The decline in *Potamogeton* also occurred during this period of increased water depths.

Mean densities of number of stems ($m^2$) over time are given in Table 2. Stem densities of most species increased in the first 12 months. Between November 2002 and November 2003 the number of clumps of *Carex* declined from $16/m^2$ to $8/m^2$ with consequent reduction in the number of stems. The number of clumps of *Juncus* declined slightly between 2003 and

**Table 1** Temporal changes in wetland zones (% area) in ponds 2–6 and species survival in Bridgewater Creek wetland. (NB RL outlet overflow weir is 5.01 m AHD)

| Wetland Zone/Species | November 2001 | May 2002 | November 2002 | November 2003 | May 2004 | November 2004 | August 2005 | May 2006 |
|---|---|---|---|---|---|---|---|---|
| Ephemeral, RL 4–4.25 | 14% | 14% | 14% | 11.5 | 10% | 8% | 8% | 1% |
| *Carex appressa* | + | + | + | + | | | | |
| *Isolepis nodosa* | + | + | + | | | | | |
| *Juncus usitatus* | + | + | + | + | + | + | + | + |
| *Juncus kraussii* | + | + | + | + | + | + | + | + |
| *Philydrum lanuginosum* | + | + | + | + | | | | |
| *Bolboschoenus fluviatilis** | | | | + | + | + | + | + |
| *Schoenoplectus validus** | | | | | | + | + | + |
| Shallow marsh, RL 3.75–4 | 23% | 10% | 14% | 7% | 7% | 7% | 7% | 0.1% |
| *Baumea rubiginosa* | + | + | + | | | | | |
| *Cyperus polystachys* | + | + | | | | | | |
| *Juncus kraussii* | + | + | + | + | + | + | + | |
| *Isolepis nodosa* | + | + | | | | | | |
| *Philydrum lanuginosum* | + | + | + | + | | | | |
| *Bolboschoenus fluviatilis** | | | + | + | + | + | + | + |
| *Schoenoplectus validus** | | | + | + | + | + | + | + |
| *Baumea articulata** | | | + | + | + | + | + | |
| Marsh, RL 3.5–3.75 | 24% | 15% | 6% | 6% | 0.2 | 0.2 | 0.2 | 0.05 |
| *Baumea rubiginosa* | + | + | + | | | | | |
| *Bolboschoenus fluviatilis** | + | + | | | | + | + | |
| *Eleocharis equisetina* | + | | | | | | | |
| *Schoenoplectus mucronatus* | + | + | + | + | | | | |
| *Lepironia articulata* | + | + | + | + | + | + | + | + |
| *Schoenoplectus validus** | | + | + | + | + | + | + | + |
| *Baumea articulata** | | | + | + | + | | + | |
| Deep marsh, RL 3–3.5 | 20% | 2% | 2% | 0.5% | 0.2% | 0.2% | 0% | 0% |
| *Baumea articulata** | + | + | + | + | + | + | | |
| *Eleocharis sphacelata* | + | | | | | | | |
| *Schoenoplectus validus** | + | + | + | + | + | + | | |
| Open water | 19% | 56% | 64% | 72% | 80% | 80% | 80% | 85% |
| *Potamogeton* in open water | | | | | | 8% | 18% | 10% |
| Bare mud | 0% | 0% | 0% | 0% | 2.6% | 4.6% | 4.8% | 13.9% |

*Species survived by spreading into shallower zones

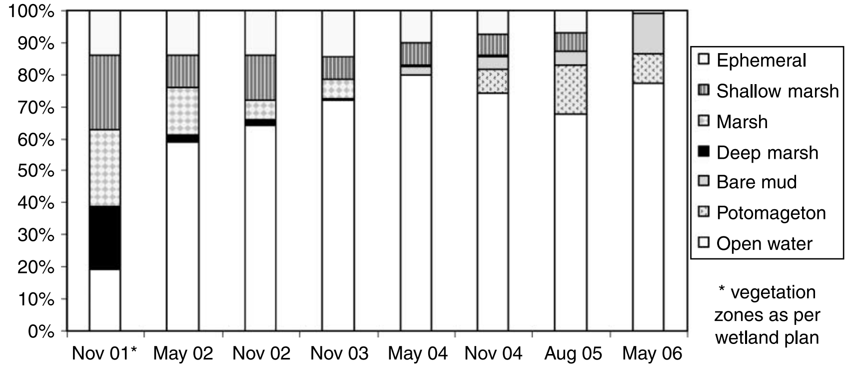


**Figure 2** Histogram plot of % distribution of vegetation zones at Bridgewater Creek wetland

**Table 2** Temporal changes in macrophyte stem densities n/m$^2$ (May 2002–May 2006)

| Species | Pond | May 2002 | November 2002 | November 2003 | November 2004 | May 2006 |
|---|---|---|---|---|---|---|
| *Carex appressa* | 5 | 140 | 296 | 20 | dead | dead |
| *Juncus usitatus* | 2 | 110 | 819 | 729 | 2,212 | 416 |
| | 4 | 250 | 1,110 | 2,219 | 2,505 | dead |
| *Juncus kraussii* | 6 | 80 | 547 | 1,087 | 1,023 | 518 |
| *Baumea rubiginosa* | 5 | 246 | 410 | April: 76 | dead | dead |
| | 6 | 123 | 171 | April: 47 | dead | dead |
| *Bolboschoenus fluviatilis* | 6 | 36 | 58 | 40 | 66 | 40 |
| *Schoenoplectus mucronatus* | 6 | 129 | 312 | 406 | dead | dead |
| *Baumea articulata* | 5 | 246 | 540 | 661 | 645 | dead |
| | 6 | 60 | 104 | 295 | 54 | dead |
| *Schoenoplectus validus* | 5 | 262 | 329 | 129 | 218 | dead |
| | 6 | 52 | 104 | 220 | 139 | 63 |

2004; however, stem numbers continued to increase until 2006 when increased water depths caused death of most of the plants. The stem densities of *B. fluviatilis* did not vary greatly but peaked in November 2004. Stem densities of *B. articulata* remained fairly constant in the shallow marsh in pond 5, but declined in pond 6.

These results for Bridgewater Creek wetland highlight the problems in establishing macrophyte zones in stormwater wetlands. A number of factors have contributed to the lack of plant establishment and survival. Water depth and hydroperiod appear to be the most important with erosion, scouring, clay substrate, lack of topsoil and water birds all contributing to the problems. *B. fluviatalis* 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 *S. mucronatus* were unable to spread into shallower areas. Although there initially had been a spread of both *S. validus* and *B. articulata* into shallower water, the removal of topsoil over time, exposing only the solid clay base, 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 *I. nodosa* and *B. rubiginosa*. *C. appressa* also died off due to extended inundation. *P. lanuginosum* gradually died, despite an increase in the first 12 months, and prolific flowering even in November 2003.

This is a species that can grow naturally for extended periods of inundation in up to 20 cm of water, suggesting other factors might have caused the decline and loss.

Seed germination is important for the spread of many macrophytes, and this is maximised in the ephemeral or shallow-marsh zones with moist soils. The timing of flooding and drying is crucial for successful germination, establishment and survival. Mass germination of Juncaceae and Cyperaceae species was observed several times in damp areas in the ephemeral zone and around the landward margins during draw down. However, these seedlings were unable to survive the extended periods of inundation.



#### Hydrologic assessment of the wetland

Figure 3 shows the frequency of inundation derived from the simulated water levels from the UrbSim model for both the establishment phase and the long-term simulation period. The frequency of inundation characteristics is similar for both the establishment phase and the long-term simulation. However, it appears that the ephemeral zone will experience slightly more frequent inundation than has occurred during the establishment phase; 30% of the time compared to 22% of the time during the establishment period. The long-term simulation indicates that the shallow marsh will be completely inundated 85% of the time, compared to 78% of the time during the establishment phase. However, a critical factor in the survival of wetland vegetation is the duration of individual inundation events. The longer an inundation event lasts, the more damage that is done to ephemeral vegetation. Therefore, the long-term simulation results from the UrbSim model were interrogated to determine the individual inundation durations for each of the wetland zones (Table 3).

Between December 2005 and April 2006 water levels remained high causing permanent inundation of the ephemeral zone and the banks of the terrestrial zone.

#### Relationship between inundation and macrophyte zones

Table 3 shows the annual average inundation for each of the wetland vegetation zones determined from the UrbSim model of the long-term simulation. 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 was inundated for 85% of the time for a mean duration period of six

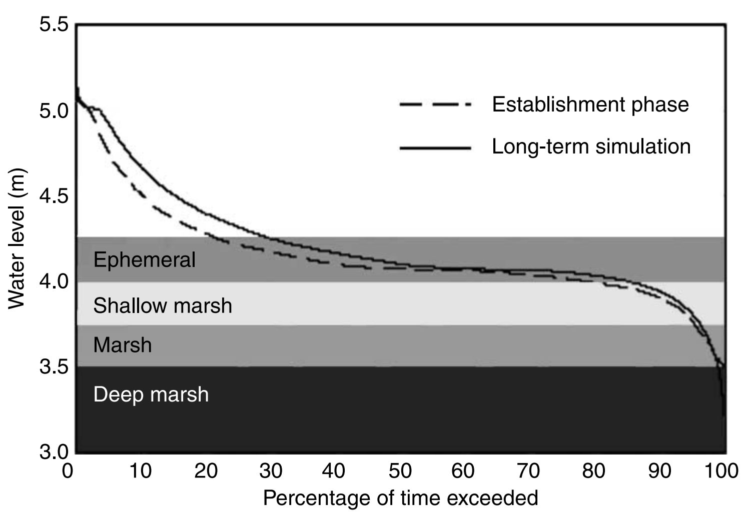


**Figure 3** Frequency of inundation within the Bridgewater Creek wetland

**Table 3** Proportion of time of inundation (%) at different depths and duration of inundation (days) in the wetland zones

| Wetland zone | Depth (cm) | % | Duration of inundation events (days) | | | |
|---|---|---|---|---|---|---|
| | | | 90%ile | Median | 10%ile | Event Mean |
| Ephemeral | | | 0.7 | 3.4 | 13.2 | 5.8 |
| | 0 | 15 | | | | |
| | 0–20 | 50 | | | | |
| | 20–40 | 15 | | | | |
| | >40 | 20 | | | | |
| Shallow marsh | | | 4.3 | 29 | 214 | 65.9 |
| | 0–20 | 7 | | | | |
| | 20–40 | 47 | | | | |
| | 40–60 | 19 | | | | |
| | >60 | 23 | | | | |
| Marsh | | | 8.0 | 189 | 734 | 338 |
| | 20–40 | 5 | | | | |
| | 40–60 | 42 | | | | |
| | >60 | 50 | | | | |
| Deep marsh | | | Permanently inundated | | | |
| | 40–60 | 1 | | | | |
| | 60–80 | 3 | | | | |
| | 80–100 | 10 | | | | |
| | >100 | 85 | | | | |

days. Wong *et al.* (1998) suggest that the ephemeral zone should only be inundated for 12% of the time. Of the original plantings, *Juncus usitatus* and *J. kraussii* were the only two species able to tolerate these extended periods of inundation. However, when the water levels in the whole wetland increased by 90 cm (February–April 2006), due to the blocked outlet riser, only *Juncus* clumps at the highest elevations were able to survive. The shallow marsh zone was inundated with water deeper than 20 cm for 93% of the time, for a mean duration of 66 days – this contrasts with Wong *et al.*'s (1998) recommendation of a water depth >20 cm for only 38% of the time. Of the original plantings a few clumps of *J. kraussii* survived until 2006. The marsh zone was inundated with water deeper than 40 cm for 95% of the time (compared to 58%, Wong *et al.* (1998)) for a mean duration of 338 days. Of the original plantings only Lepironia survived. None of the plant species survived in the deep marsh zone due to water depths >100 cm for 85% of the time.

Although the plant species selected and planted were appropriate for the zones described, their establishment and survival were 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 RL (4.25 m AHD).

## Conclusions

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 RL 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.

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