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Stormwater Wetlands: Design criteria to maximise water quality improvement and minimise mosquito breeding

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1. Introduction

Urban stormwater is now recognised as a diffuse pollution source to downstream waterways and aquatic ecosystems. The challenge for stormwater management is both non-structural and structural Best Management Practice (BMP) to minimise any potential downstream effects.

Structural BMPs include: Gross Pollutant Traps (to catch coarse sediment, organic debris and trash), Retention/Sediment Basins (to capture coarse and fine sediment), Biofiltration Systems (fine sediment and nutrient removal by filtration and biofilms), Vegetation Buffer Strips (sediment and nutrient removal by sheet flow across wide natural vegetation strips), Vegetation Filter Strips/Grass Swales (sediment and nutrient removal along concentrated flow paths), Ponds and Wetlands (effective sediment and nutrient removal by aquatic ecosystems dominated by wetland plants). It is therefore possible with new subdivisions and urban developments to minimise the amount of suspended solids and nutrients entering downstream aquatic environments by incorporating some of these BMPs. It is also possible to install Gross Pollutant Traps, Biofiltration Systems, Grass Swales and Wetlands into established urban infrastructure, however the constraints are greater.

In Australia, surface flow constructed wetlands for the treatment of urban stormwater are multi-functional, providing wildlife habitat, landscape enhancement, water storage and flood mitigation (Greenway, 2000). However, there is often public concern that wetlands will encourage mosquito breeding. While most mosquitoes are opportunistic breeders they will only deposit eggs if a suitable body of water is available. In aquatic ecosystems mosquito larvae are an integral component of aquatic food webs (US-EPA 2000, Greenway and Simpson 1996, Greenway 2000). Mokany and Shine (2003) found that female mosquitoes use both chemical and biological cues to assess the suitability of water bodies for breeding. The presence of existing larvae was a strong attractant to further egg laying, indicating that the habitat is suitable for larval development.

Thus, a critical and significant issue for successful mosquito breeding is larval survival and whether adult mosquitoes emerge from pupae. It is the authors' view that if constructed wetlands are designed to function as wetland ecosystems with a diversity of aquatic organisms, then it is likely that the predator/prey mix would control mosquito breeding.

This paper focuses on stormwater wetlands, their design and management, with particular reference to maximising water quality improvement and minimising mosquito breeding. The effectiveness of stormwater wetlands in sediment and nutrient removal is dependent upon an understanding of how these biological systems function. Correct design, operation and maintenance procedures can only be developed if the attributes of stormwater wetlands are understood.

Ecologists and engineers need to work together to maximise the efficiency of these biosystems, planners and landscape architects need to become involved to ensure that stormwater wetlands have a multifunctional role in the urban landscape. Stormwater wetlands must be designed to maximise water quality improvement and minimise mosquito breeding.

2. Wetland systems: structure and function

Wetland systems are complex ecosystems where an understanding of the interactions between water, sediment, plants, animals and micro-organisms is fundamental to the effectiveness of stormwater treatment.

2.1 Natural wetland structure

Wetlands are areas that are permanently or periodically inundated or saturated by surface or groundwater and support the growth of aquatic vegetation. Natural wetland types include mangroves, salt marshes, sedgelands, wet meadows, melaleuca swamp forests, wet heaths and shallow lagoons. Wetlands are at the interface between terrestrial and aquatic environments, and are strategically placed in the catchment where they intercept run-off water and floodwaters. Water levels fluctuate with rainfall, thus although the presence of water or waterlogged soils characterises wetlands, many wetlands completely dry out at the end of the dry season or during drought periods. Wetting and drying cycles are therefore a natural phenomenon in many wetlands.

Wetland ecosystems are composed of abiotic (non-living) components (sediment, water, air) and biotic (living) components (micro organisms, plants, animals). Plants are the most conspicuous feature of wetlands but micro-organisms are the most diverse and abundant.

(a) Macrophytes

Wetland plants known as macrophytes can be classified into 2 functional types (i) rooted plants and (ii) floating plants. Rooted plants can be further classified as emergent macrophytes ie; roots in the sediment and emergent stems and leaves, e.g. reeds (*Phragmites*), bulrush (*Typha*), sedges (*Baumea*, *Eleocharis*, *Schoenoplectus*); submerged macrophytes ie; stems and leaves submerged eg, pond weeds (*Ceratophyllum*, *Potamogeton*); floating leafed macrophytes, i.e. stems submerged and leaves floating, e.g. water lilies. Rooted emergent macrophytes are restricted to shallow water from a few centimetres to a maximum depth of 1.5m. The depth distribution of submerged plants is restricted by turbidity and light availability. Floating plants have surface leaves and roots which hang in the water, e.g. duckweed (*Lemna*), A*zolla.* Greenway (2003) has reviewed the suitability of macrophytes for treatment wetlands in tropical/subtropical climates, and identified 55 native species that can tolerate permanent inundation and high nutrient concentrations.

(b) Macro-invertebrates

Wetlands also support a diversity of aquatic animals including micro-crustaceans (copepods, ostracods, claderans) shrimps, crayfish; insects (dragonfly larvae, water beetles, water boatman); pond snails, tadpoles, frogs and fish. These organisms are a crucial component of wetland ecosystems providing invaluable food web linkages between plants, micro-organisms and other animals. Predator-prey relationships are important in the control of mosquitoes.

Wetland plant diversity is important for determining macro-invertebrate associations (De Szalay and Resh 2000) and wildlife diversity (Knight *et al.* 2001) because of the creation of habitats and food resources. Wetzel (2001) noted that the most effective wetland ecosystems “are those that possess maximum biodiversity of higher aquatic plants and periphyton associated with the living and dead plant tissue”.

(c) Micro-organisms

Micro-organisms, although inconspicuous, are the most abundant and diverse group of living organisms in wetland systems. They include bacteria, fungi, unicellular and filamentous algae and protozoans. Micro-organisms occur in the water column as 'plankton'; attached to plant surfaces as 'epiphytes' and biofilms; attached to other surfaces as 'periphyton' and biofilms; and on or in the sediment as 'microbenthos'. Anaerobic bacteria occur in low oxygen environments in the sediment.

(d) Mosquitoes

Mosquito larvae are an aquatic invertebrate, however their presence and abundance in wetland ecosystems is controlled by two factors. Firstly, the suitability of the water body for female egg laying, and secondly the suitability for successful larval development. Predation of mosquito larvae is a key factor in their presence. Predation is best avoided if the mosquito larvae can isolate themselves from predator access. Orr and Resh (1992) found that dense beds of *Myriophyllum aquaticum* were a primary habitat for *Anopheles* larvae where they survive in microhabitats. Walton (2002) noted that in the arid south western United States constructed treatment wetlands can increase mosquito production if there is poor water quality and dense coverage of submerged dead vegetation. Greenway et al (2003) found that dense stands of *Typha* with an accumulation of submerged dead stems and isolated pockets of water are suitable for mosquito breeding. Similarly dense floating mats of *Paspalum* grass and *Perscicaria* are also suitable for mosquito breeding but of limited habitat value for many macro-invertebrates due to the lack of swimming space and low dissolved oxygen. Mosquito larvae are surface breathers and can survive in anaerobic conditions, however many aquatic macroinvertebrate predators are also surface breathers, e.g. notonectid bugs, water beetles, or surface predators, e.g. pond skaters.

2.2 Natural wetland functions

Natural wetlands perform a wide range of hydrological, ecological and social functions that directly or indirectly result in benefits to human society (Greenway 1993, 1998). Hydrological functions include: water quality improvement, by filtering suspended particles and by removing, recycling or immobilising environmental contaminants and nutrients; flood mitigation, by storing and detaining precipitation and runoff thus reducing downstream flood rates and peak floods; groundwater recharge. Ecological functions include: temporary and permanent habitats for a variety of aquatic and terrestrial organisms; breeding areas for fish, frogs, waterbirds; roosting sites and feeding grounds for birds; refuges for wildlife during drought periods. Social functions include: landscape and recreational amenity; biological resources, e.g. fisheries; education and research.

Recognition of the beneficial values of wetlands associated with environmental quality and sustainability have led to the creation of constructed wetlands for a variety of purposes.

3. Wetland processes to improve water quality

The effectiveness of water quality improvement is dependent upon an array of complex and interacting processes which can broadly be classified in 3 categories — physical, biological and chemical. Most processes are facilitated by the wetland vegetation and microbial communities (Table 1).

Table 1. Role of ponds and wetlands in improving stormwater quality

Pollutant	Role of Pond or Wetland
Gross Sediment	Sedimentation in inlet pond or trapped by dense vegetation
Suspended Solids including biodegradable particulates (BOD)	Sedimentation is facilitated by the vegetation. The vegetation reduces water velocity and turbulence causing settlement. Finer particles adhere to the biofilm surface of the vegetation. The root system binds and stabilises deposited particulates. The leaf litter and vegetation reduces resuspension.
Nutrients	Direct uptake by plants and micro-organisms. Inorganic nutrients converted to organic biomass. Microbial processes facilitate the removal and transformation of nutrients, especially nitrogen removal.
Metals	Microbial bioremediation of metals. Metals immobilised by adsorption onto sediments or by precipitation plant uptake.
Hydrocarbons	Microbial hydrocarbon degradation.
Pathogens	Natural UV disinfection. Natural biocontrol by microbial predators in the wetland ecosystem. Adsorption to fine particles and sedimentation. Natural death and decay.

3.1 Physical processes

Emergent macrophyte vegetation decreases water velocity enabling the sedimentation of particles. Both submerged and emergent vegetation is particularly effective in removing finely graded particles which will adhere directly onto the plant surface. The sticky biofilm of micro-organisms facilitates adhesion, and the larger the surface area provided by the vegetation the more effective the wetland will be in the removal of fine particles. The vegetation also distributes the flow and reduces turbulence, thereby allowing settlement of particles. The root system binds and stabilises deposited particles. The deposition of plant detritus also protects particles against re-suspension. The emergent macrophytes prevent scouring during high flows.

3.2 Biological processes

Plants, photosynthetic micro-organisms and algae remove soluble inorganic nutrients (ammonium, nitrite, nitrate, phosphate) and heavy metals by direct uptake. Rooted macrophytes and benthic algae remove these nutrients from the sediment whereas submerged and floating macrophytes, algae, phytoplankton, epiphytes and biofilm flora remove the nutrients directly from the water column. These inorganic nutrients are assimilated and converted into organic matter and rendered relatively unavailable.

Submerged plants and algae also improve overall water quality by producing oxygen during photosynthesis which diffuses into the water column. Emergent macrophytes transport oxygen down their stems into the roots, where it diffuses into the sediment to produce an aerobic microenvironment around the root zone (rhizosphere).

The leaves, stems and roots of macrophytes all support biofilms, and the secretion of organic exudates promotes biofilm growth. Dead plant matter (and leaf litter) also provides a surface for growth and an organic source of carbon, nitrogen and phosphorus for detritus feeding micro-organisms and aquatic organisms.

Microbial processes of significance to the removal and transformation of nitrogen are ammonification, nitrification and denitrification. Ammonification is a decomposition process whereby dead organic matter (proteins) is converted to amino acids and then ammonia. Ammonification occurs under both aerobic and anaerobic conditions. Ammonium ions can either be assimilated by photosynthetic micro-organisms or plants, or nitrified under aerobic conditions by chemosynthetic nitrifying bacteria to nitrites and nitrates. Sediments being waterlogged are often anaerobic, therefore nitrification cannot proceed. However, in aerobic microenvironments, including the rhizosphere, nitrification occurs. These nitrates can then be taken up directly by the roots.

The dentrification process occurs under anaerobic conditions, usually in deeper sediments. Nitrates and nitrites are reduced to gaseous nitrous oxide and nitrogen which diffuse into the water and are ultimately lost to the atmosphere. Denitrification is the only significant long-term process for nitrogen removal from wetland systems. The alternation of nitrification and denitrification maximises nitrogen removal.

Micro-organisms also remove inorganic phosphate from the water column or sediment porewater and convert this to organic microbial biomass.

3.3 Chemical processes

Chemical processes facilitate adsorption and desportion of phosphorus onto and from sediment particles. Alternating drying and flooding releases phosphate (Phillips and Greenway, 1998). Diffusion of oxygen from the roots of emergent macrophytes maintains on oxidised sediment surface layer and microenvironment around the root zone. This modifies the sediment redox conditions as well as facilitating aerobic microbial processes including nitrification.

3.4 Wetting and drying cycles

Flooding and drying of wetlands, especially in the subtropics/tropics, is a natural occurrence and necessary to maintain wetland vegetation and maximise nutrient cycling. Under waterlogged (flooded) conditions organic degradation of plant material is slow and peat accumulates. This represents long-term storage of organically bound nutrients in plant biomass. Denitrification occurs under anaerobic waterlogged conditions resulting in the loss of nitrogen from the system. However, inorganic phosphorus can be released from sediments after 4-6 weeks of inundation and become bio-available again (Phillips, 1998). Repeated wetting and drying converts iron oxides and absorbed phosphorus to progressively less available forms. Microbial decomposition of organic matter is optimal under aerobic moist conditions but slow when the wetland is completely dry. Constructed wetlands can be designed for both permanently wet and seasonally dry areas.

4. Stormwater wetland design

The design of stormwater wetlands depends on the objectives and desired outcomes including any legislative requirements with respect to water quality standards for the protection of downstream waterways and aquatic ecosystems. As ecologically sustainable systems they must be designed to be structurally and functionally optimal to maximise wetland processes described in Section 3. Parameters which need to be considered in the planning and design phase of stormwater wetlands are given below in Table 2.

Table 2. Parameters to be considered in the planning and design of stormwater wetlands

Parameter	Considerations
Objectives: hydrological, ecological, social	Primary and secondary objectives; stakeholder and community influence, legislative requirements
Pollutant characteristics of the runoff: SS nutrients, coliforms	Catchment landuse; new v old subdivisions, rainfall intensity and frequency; sewer overflows
Treatment performance expectations	Water quality guidelines, reuse standards; EPA or local authority, e.g. BCC water quality objective, TSS < 15 mg/L; TN < 0.65 mg/L, TP < 0.07 mg/L
Pollutant loading	Pollutant characteristics; seasonal differences; rainfall intensity and frequency
Detention time	Catchment size, wetland size, loading, treatment performance expectations, bypass channel
Catchment size (ha)	Landuse; % impervious surface
Volume and velocity of runoff	Rainfall intensity and frequency; impervious area
Hydroperiod: extent of inundation	Depth of water table, seasonal climatic conditions, e.g. wet/dry; cold/hot
Plant species selection	Depth of water, rooted v floating, zonation, availability of local native stock
Water birds; waders and ducks	Type of vegetation; % cover v open water, water depth; public access to feeding birds
Wetland zones	Water depths; extent of shallow v deep open water or vegetation; empheral (dries out); littoral (land margin)
Mosquito breeding	Type of vegetation; % of cover v open water; water depth; predator access
Maintenance	Removal of trash and weedy species, regular clean out of sediment/detention pond

4.1 Objectives

The primary objectives of most stormwater wetlands are hydrological:

- to provide flood protection and flow control, thereby reducing downstream flood rates and peak floods.
- to improve water quality thereby minimising downstream adverse impacts on aquatic ecosystems.

Secondary or ancillary objectives include:

- habitat creation and biodiversity
- visual amenity, recreation, and community education
- water storage and reuse.

Community benefits are vital to public acceptance of stormwater wetlands.

4.2 Treatment efficiency

The treatment efficiency of a wetland system requires a balance between pollutant loading rate and hydraulic retention time. Constructed wetlands for the treatment of effluent wastewater have fairly steady hydraulic loading rates (and pollutant loadings) with the most effective retention time for removal of suspended solids and nutrients in Queensland's pilot wetlands being around 7 days (Greenway and Woolley, 1999). By contrast stormwater runoff is highly variable in hydraulic and pollutant loading due to the erratic nature of storm events in both intensity and duration.

The size (area and volume) of a wetland will depend upon catchment size, the volume of runoff, the pollutant characteristics of the runoff, the desired level of water quality treatment and the extent to which the wetland is also expected to function as a retention basin. Wong et al. (1998), used stochastic data from stormwater runoff simulations to produce a design chart summarising hydrologic effectiveness of wetlands in Melbourne based on the interaction between wetland size (storage volume as percentage of annual runoff volume) and detention time. Their results showed that an increase in storage volume (from 0.5% to 5%) led to increased hydrologic effectiveness with over 90% effectiveness at 3% storage. The computer simulation also showed that at less then 3% storage, an increase in detention time from 24 hours to 3 days, decreased hydrologic effectiveness of the wetland. The researchers conclude that a wetland designed with inadequate storage (< 3%), would lead to stormwater by-pass, especially if the wetland was already filled from previous storms.

Hydrologic effectiveness however, is only one parameter affecting treatment efficiency, the removal of suspended solids and nutrients is still ultimately dependent on the effectiveness of physical, biological and chemical processes within the wetland and the hydraulic loading of these pollutants.

Wetland design requires a balance between available area and appropriate detention time, which itself will be affected by catchment runoff and climate variability. Thus wetland design for tropical and subtropical coastal areas will differ from temperate areas in southern Australia. Land availability may be a major constraint to wetland size, however this in part can be compensated for by having a larger area of deeper open water in addition to shallower vegetated areas.

Depending on the size of the wetland and its ability to detain and treat stormwater, overflow bypass channels may be necessary to cope with additional runoff from high intensity rainfall events. If the bypass channel is engaged too frequently then treatment will be ineffective.

4.3 Wetland zones: Ponds and wetlands

A constructed stormwater wetland typically comprises deeper open water zones and shallow vegetated (macrophyte) zones. The inlet zone is usually a deep water (1.5 - 2m) pond which maximises storage and allows for the settling of coarse-to-medium-sized particles. A Gross Pollutant Trap to collect 'trash' should be installed prior to runoff entering the inlet zone. Access to the inlet zone to remove accumulated sediment should be considered. The deeper inlet zone also controls flow into the macrophyte zone. The macrophyte zone should be from 10-25cm depth with a maximum depth of 50cm, though water levels will fluctuate with rainfall events. This zone provides the highest removal efficiency of suspended solids and nutrients through a combination of physical, biological and chemical processes (discussed in Section 2.3). Outlet zones could be a combination of shallow vegetated margins and a deeper pond or a large lake with multi purpose functions.

4.4 Macrophyte zones and hydroperiod

It is important to design stormwater wetlands to allow for variations in water depth, thereby accommodating intermittent flows. Thus the macrophyte zone can also be designed to support a zonation of wetland plants each adapted to a specific hydroperiod (i.e. the extent of periodic or permanent inundation). "Ephemeral wetland" zones, which in natural wetlands occur around the margins of lakes or on floodplains, can be established in locations where they would only be inundated during the wet season. This could include the margins of the deeper open water ponds or specially created shallow areas within the macrophyte zones which would completely dry out. Ephemeral species can include a variety of trees and shrubs as well as smaller herbaceous plants. "Shallow wetland" zones should be designed to maintain water depths of at least 10cm during the dry season and up to 50cm of permanent water, while "deep wetland" zones should maintain water depths of at least 20cm during the dry season.

A diversity of vegetation zones can also enhance the overall wildlife value of the wetland as well as the landscape amenity. Ephemeral zones planted with Melaleuca trees could function as recreational parkland during dry periods. Landscape and recreational amenity is often important in urban stormwater wetlands. Lakes or lagoons downstream of the macrophyte zone can also serve as retention ponds. Islands may be added as wildlife refuges.

4.5 Macro-invertebrates

A constructed wetland with a diversity of plant species and macrophyte zones subjected to wetting and drying cycles, as well as open water zones, will maximise water treatment efficiency. It will also support a greater diversity of aquatic organisms. Deeper water zones will function as refuge habitats for these organisms during dry periods and allow rapid recolonisation of newly inundated zones. This is particularly important for the management of potential mosquito breeding since predators of mosquito larvae will already be present.

A study of four municipal treatment wetlands (Greenway et al 2003) found that the Cooroy wetland with shallow marsh and deeper ponds had the greatest species richness of macrophytes (38 species) and macro-invertebrates (90 taxa) and the lowest occurrence of mosquito larvae (< 1% of dips). The Cairns and Rosewood wetlands dominated by dense monospecific stands of *Typha* had fewer macro-invertebrate taxa (47 and 38 respectively) and a higher proportion of mosquito larvae (20% of dips at Cairns and 40% of dips at Rosewood). The Blackall wetland was mostly open water with small stands of *Typha* and sections with floating mats of water couch (*Paspalum*) and 41 macro-invertebrate taxa were found. Less than 0.5% of dips in the open water channels contained mosquito larvae whereas 16% of dips from amongst the *Paspalum* had larvae. From our study we concluded that a marsh with a diversity of macrophytes appears optimal for macro-invertebrates biodiversity and the control of mosquito larvae by predation.

A study of two stormwater wetlands in Brisbane is comparing macro-invertebrates in the stream channel, sediment basin (no vegetation), ponds (< 10% vegetation) and wetlands (> 70% vegetation cover). Preliminary data is presented in Table 3.

Table 3. Major macro-invertebrate taxa in 2 stormwater wetlands

Major Taxa	Golden Pond			Bridgewater		
	Creek	Sediment Basin	Wetland	Creek	Pond	Wetland
Gastropoda (snails)	3	3	6	4		
Annelida (worms)	2	1	2	2	1	1
Crustacean (copepods, ostracods)	2	2	2	2	3	2
Epiproctomorpha (dragonfly)	3	-	3	6	2	1
Zyoptera (damselfly)	4	-	3	4	1	1
Hemiptera (water boatman)	-	-	1	4	2	4
Diptera (flies, mosquitoes)	-	-	1	6	3	4
Coleoptera (water beetles)	3	-	-	2	2	2
Total Invertebrate Taxa	21	7	23	30	20	16

It is interesting to note that the stormwater wetlands have a lower diversity of macro-invertebrates compared to the wastewater wetlands (Greenway et al 2003).

4.6 Mosquitoes

Mosquito breeding is an issue of concern regularly raised by local communities and medical entomologists. However, extensive observations by this author working in both natural and constructed wetlands have shown that successful mosquito breeding is controlled by the presence of natural predators. Micro-crustaceans (e.g. copepods, ostracods, cladocerans), pigmy water boatman, water boatman, dragonfly and damselfly nymphs, beetle larvae are all predators of mosquito larvae and are always present in wetland ecosystems. The deliberate introduction of fish is not recommended as fish will consume the predators of the mosquito larvae in preference to the mosquito larvae themselves. The effectiveness of *Gambusia* (mosquito fish) in the control of mosquito larvae in Australian wetlands and waterways has not been scientifically proven with mosquitoes only making up a small part (< 10%) of their diet. “Several authors have observed that gambusia may actually encourage mosquito populations by preying on their invertebrate predators” (NSW-NPWS 2002). Fish will also consume frog tadpoles. The key to mosquito management is to ensure well balanced ecosystems supporting a diversity of aquatic organisms. The topography of the wetland should ensure that small pools of water are not isolated from the source of predators.

5. Maintenance issues

The construction of gross pollutant traps, retention basins, inlet and outlet structures are not novel to stormwater management, however the establishment of functional wetland systems are, and a knowledge of wetland plant species and their ecological and hydrological growth requirements is a crucial aspect. Species should be selected according to the depth of the wetland zones and the duration of inundation. At least 15 cm of top soil must be applied to allow for root development; 20-30cm may be necessary in zones of potentially higher water velocity, to support a good anchorage and prevent uprooting during storm events. At the time of planting the substrate must be moist but not necessarily flooded. In fact water levels must be controlled during the early stages of plant establishment to ensure that water depths do not exceed the height of the seedlings. In tropical/subtropical regions, planting should be carried out in early spring to enable the seedlings to develop a good root system before the summer storms.

Once the vegetation is established, maintenance issues should focus on the removal of trash, especially after storm events, and the removal of 'weed' species which may invade the wetland.

Operators or maintenance workers should be familiar with wetland plant species and understand that changes in species diversity and distribution will occur over time. Harvesting is not recommended as disturbance causes sediment resuspension and dead plant material remaining in the wetland adds to the organic nutrient load. Casual maintenance workers or gardeners also need to be briefed on the functional role of wetlands to avoid a manicured sedgeland lawn to the water's edge.

6. Conclusions

Constructed wetlands can be an important and integral component of stormwater management. Their effectiveness in improving downstream water quality will depend upon an array of physical, biological and chemical processes within the wetland system, and the design of the wetland to maximise hydrologic effectiveness and hydraulic efficiency. Land availability may be a major constraint to wetland size and hence retention volume and time. Thus in the planning phase of urban development the multifunctional role of wetlands and their community benefits should be considered. An urban stormwater wetland should be seen as a community asset. The layout of different wetland zones and lagoons is important for wildlife and landscape amenity as well as for stormwater treatment.

Mosquito breeding can be minimised by maximising macro-invertebrate predators, and this is achieved by providing suitable habitats. Our research shows that maximum biodiversity of macrophytes and macro-invertebrates, and minimal mosquito larvae survival can be achieved by having a combination of shallow marsh vegetation (20–40 cm depth) with no more than 70% plant cover and deeper (1–1.5 m) open water ponds. Aggressive plant species such as *Typha* and *Phragmites* should not be planted unless they are managed to prevent spreading and the build-up of submerged layers of dead leaves and stems. Plant species that produce thick floating mats such as *Paspalum distichum* (water couch) and *Persicaria* sp (knotweeds) should also be discouraged as they cause anaerobic conditions in the underlying water column, provide pockets of stagnant water for mosquitoes to breed and prevent predator access. Genera such as *Schoenoplectus, Lepironia, Baumea, Phylidrum, Bolboschoenus* can provide alternatives to *Typha* and *Phragmites* (Greenway, 2003).

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