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An assessment of mosquito breeding and control in 4 surface flow wetlands in tropical–subtropical Australia

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Abstract

In Queensland, Australia, the tropical–subtropical climate is ideal to promote macrophyte growth in surface flow wetlands, however there have been concerns that constructed wetlands are potential breeding sites for disease-bearing mosquitoes. The aim of this study was to assess whether mosquitoes were breeding in these constructed wetlands, and if so, where they breed, and what parameters might influence breeding: e.g. water quality; vegetation, or macroinvertebrate communities. A study of 4 surface flow constructed wetlands located in different climatic regions was undertaken. Mosquito larvae were sampled using 240 ml dippers and macroinvertebrates using dip nets. The wetland with the greatest biodiversity of macrophytes and macroinvertebrates had the least number of mosquito larvae (< 1 % of all dips). Samples with most mosquito larvae occurred amongst dense mats of *Paspalum* grass or dead *Typha*. Despite the presence of larvae in some parts of these wetlands very few late instars or pupae were found, i.e. completion of the mosquito life cycle to adult mosquitoes was unsuccessful.

This study has shown that the presence of mosquito larvae can be minimised by increasing macroinvertebrate biodiversity, by planting a variety of macrophyte types and species, excluding aggressive plant species, and maintaining at least 30% open water. Macroinvertebrates are probably a crucial factor in the control of mosquito larvae ensuring that predation of the early instars prevents or limits the development of pupae and the emergence of adults.

Keywords:
Constructed wetlands, macrophytes, macroinvertebrates, mosquitoes, predation.

Introduction

An awareness of healthy waterways and water re-use have created the need to develop and implement wastewater management strategies which are economically and ecologically sustainable. Constructed wetlands are an excellent option for water quality improvement particularly where land is available. Constructed wetlands for wastewater treatment are designed as ecological systems. Water quality enhancement is achieved through a combination of physical, chemical and biological processes facilitated by the plants and micro-organisms. Freewater Surface Flow (FWS) constructed wetlands are similar to many natural wetlands with plants being the most conspicuous feature. As ecological systems they support a variety of living organisms: plants, algae, macroinvertebrates, vertebrates, and a plethora of micro-organisms. However, the plants and animals living in FWS wetlands must be adapted to permanent flooding and often eutrophic water quality.

In Australia surface flow constructed wetlands for the treatment of municipal wastewater and urban stormwater are multi-functional, providing wildlife habitat, landscape enhancement, water storage and flood mitigation (Greenway and Simpson 1996; Greenway 2000). Despite these benefits to wildlife and humans, concerns have been raised by government authorities and the community that surface flow wetlands may be potential breeding sites for disease-bearing mosquitoes (NHMRC 1998, QDNR 2000). These limitations are also recognised by the USEPA 2000: "While a constructed wetland's attractiveness to wildlife may be regarded as a benefit to the human community, the potential for breeding mosquitoes can be an obstacle to permitting, funding, siting of a constructed wetland" p.17. This view is also shared by entomologists (Walton *et al.* 1998, Walton 2002, Russell 1999). Medical entomologists have claimed that constructed wetlands are directly responsible for an increased risk of disease due to an increase in mosquito breeding habitat, however not all species of mosquito are disease vectors or nuisances. Most mosquitoes are opportunistic breeders and if a suitable body of water is available they will deposit eggs. However, mosquito larvae are an integral component of aquatic food webs (US-EPA 2000, Greenway and Simpson 1996, Greenway 2000). Thus, the critical and significant issue is whether the larvae survive 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. If health risks can be avoided, this will increase public acceptance of the value of constructed wetlands for the treatment of wastewater. This is of particular significance to the wastewater industry since in order to promote the concept of constructed wetlands they must also demonstrate that risks of mosquito borne disease is minimal.

Observations by the first author indicated that mosquito breeding was not a problem in the 9 pilot scale wetlands in Queensland (Greenway and Woolly, 1999); however this needed to be quantified. A study commenced in November 1999 to investigate whether mosquito breeding was occurring in four surface flow constructed wetlands. The aim of the study was to determine if these constructed wetlands provided a suitable habitat for successful larval development of mosquitoes, and to try and identify which factors they either prevent or encourage larval development.

Methods

Site description — wetland design and water quality

Four surface flow constructed wetlands at different geographical locations with different climatic conditions were selected for this study. Cairns, coastal northern Queensland (tropical–wet); Blackall, inland central Queensland (arid); Cooroy (Noosa Shire), south east coastal Queensland (subtropical–wet); and Rosewood (Ipswich City Council) inland south east Queensland (subtropical–dry).

The Cairns Wetland was constructed in 1994 and was originally band planted with a diversity of species *Typha* spread rapidly and now covers 60% of Channel 1; 100% of Channel 2 and 70% of Channel 3; the remainder is predominantly *Eleocharis*; water depth is 40–50 cm. It receives secondary effluent after passing through an oxidation ditch. Water quality is low in ammonia but high in phosphorus (Greenway and Woolly, 1999; 2001).

The Blackall Wetland was constructed in 1993 and planted with 6 local species. The original depth of the channels was 50 cm, however in 1999 the channels were deepened to 1.5 m with steep vertical banks (along one or both sides), except at the inlet and outlet sections. *Typha* and floating rafts of *Paspalum distichum* now dominate these shallow areas, however 60–95% of the channels are open water. Channel 1 is 95% open water with a narrow band of *Typha* at the inlet and outlet section and along the perimeter on one side. Channel 2 is 75% open water with *Typha* at inlet and outlet sections and floating rafts of *Paspalum distichum* and *Persicaria attenutum*. Channel 3 is 60% open water; 30% is a dense raft of *Paspalum* and *Persicaria*, and 10% *Typha*. Channel 4 is 95% open water with small patches of *Typha* and isolated clumps of *Paspalum*. It receives secondary treated effluent (Greenway and Simpson, 1996; Greenway and Woolley, 1999).

The Cooroy Wetland near Noosa is the largest wetland. The first wetland was built in 1995 and consists of 3 large cells linked by pipes. The second wetland of similar dimensions was built in

1999. Each cell is separated by septa into sections producing a sinusoidal flow path. Cell 1 is shallow (20–40 cm) throughout. Cell 2 and Cell 3 each have a deep pond (1–2 m) in the first section (30 m length), the remainder is shallow. The wetland supports a diversity of plants. The secondary effluent is treated by a trickling filter followed by alum dosing (to remove phosphate by precipitation), it then flows into an open water lagoon prior to release into the wetlands.

The Rosewood Wetland near Ipswich was built in 1995 and consists of 4 rectangular cells. Cell 1 is a deep open water lagoon (150 cm); Cells 2 and 3 are surface flow wetlands dominated by a wide band of *Typha* around the periphery, with a deeper open water pond in the centre; Cell 4 is a subsurface flow wetland planted with *Phragmites australis*. The wetland receives primary settled effluent which flows into Cell 1 where further settling takes place, before discharge into the vegetated cells.

Water depth, temperature and dissolved oxygen were recorded at each sampling station. Annual temperatures ranged from 15^{o}C to 27^{o} at Cooroy and from 22^{o} to 30^{o} at Cairns. Dissolved oxygen was highly variable — varying seasonally, diurnally, with depth and vegetation. Open water areas had the highest DO (up to 16 mg/L). Cairns recorded 13 mg/L amongst submerged pond weed (*Ceratophyllum*) and algae. DO decreases with depth to negligible values amongst or beneath dense or dead vegetation.

Field sampling

At each site a minimum of 3 sampling stations were established in each channel or cell. Where possible these were located where there was vegetation. At Blackall, Rosewood and Cooroy open water sections and storage lagoons were also sampled. Vegetation in the wetlands was recorded according to species, type and percentage cover.

Mosquito larval distribution was assessed by taking 10 surface dips, using a 240 ml dipper, at each station. Mosquito larvae numbers were counted and for each dip categorised into: no larvae (0), 1–10 larvae, 11–40 larvae and greater than 40 larvae. In addition, the developmental stage of the larval instars — 1st, 2nd, 3rd, 4th and pupae were noted. Where possible the larvae were identified to species. Dip nets were used to sample the aquatic biota by swoops conducted within a 2 m radius of each station. Water depth, temperature and dissolved oxygen were recorded.

Results

Macrophytes

Table 1. Macrophyte species richness in the 4 surface flow constructed wetlands

Macrophytes	Cooroy	Cairns	Blackall	Rosewood
Emergents	23	10	4	3
Attached with floating Leaves	7	8	1	1
Free floating	4	6	3	3
Submerged	4	1	–	–
Total species	38	26	8	7
% Cover	70%	95%	10%	95%

A summary of the categories of macrophyte types and the overall percentage cover vegetation is given in Table 1. For details of plant species refer to Greenway *et al.* 2002.

Cooroy had the greatest species richness with a total of 38 species. Of the emergent macrophytes the most abundant species were the sedges *Baumea articulata, Baumea rubiginosa, Lepironia articulata, Schoenoplectus validus* and the flowering *Phylidrum lanuginosum*. The diversity of species can be attributed to direct planting, natural colonisation and active management to remove invasive weed species. The shallow depth 20 cm for most cells is optimal for the growth of these emergent species. The deep cells (1.5–2 m) were suitable for water lilies and submerged species.

Cairns had 26 species, however *Typha* was the dominant species forming dense monospecific stands of live and dead shoots in all 3 channels. Only 2 channels had sections which had not been completely colonised by the spread of *Typha*. In Channel 3 these sections were dominated by *Eleocharis sphaceolata;* in Channel 1 there were sections of *Eleocharis, Schoenoplectus* and *Paspalum. Ceratophyllum* occurred beneath the *Schoenoplectus.*

Rosewood was also dominated by *Typha*, which formed dense stands of live and dead shoots, isolated clumps of *Baumea articulata* extended into the deeper centre of Cell 2 and clumps of *Cyperus* sp occurred at the margins. The channels at the Blackall wetland were mostly free of vegetation except for the shallower inlet and outlet sections which contained *Typha*. Dense mats of water couch *Paspalum distichum* and knotweed *Persicaria attenuatum* had formed in sections of Channels 2 and 3.

Macroinvertebrates

A summary of the total number of macroinvertebrates taxa in the major classes is given in Table 2 — For a complete list of these taxa identified to family, genus and species refer to Greenway *et al.* 2002. Cooroy had the greatest species richness, in particular the larval stages of dragon flies (Epiproctomorpha), damsel flies (Zygoptera) and caddis flies (Trichoptera), and pond snails. Cooroy and Rosewood both had large numbers of water beetles. Macroinvertebrate sampling at Cairns was limited to three collections, hence species richness at Cairns is much lower than expected.

Table 2. Major macroinvertebrate taxa present in the four wetlands

Taxa	Cooroy	Cairns	Blackall	Rosewood
Gastropoda (snails)	8	2	1	
Annelida (worms/leeches)	3	1	5	2
Crustacea (copepods, ostrarods)	5	4	3	3
Ephemeroptera (May flies)	3	3	1	
Epiproctomorpha (dragonfly)	17	8	3	
Zygoptera (damsel fly)	8	4	2	1
Hemiptera (water bugs)	8	6	9	4
Diptera (flies/mosquitoes)	9	11	5	8
Coleoptera (water beetles)	19	4	8	18
Trichoptera (Caddisfly)	7		1	
Total taxa	87	43	38	36

Mosquitoes

Ten species of mosquito larvae were identified: *Anopheles annulipes*, *Culex annulirostris*, *C. australicus*, *C. gelidus*, *C. halifaxii*, *C. squamosus*, *Culicinae* sp, *Uranotaenia* sp. *Verrallina carmenti*, *V. lineatus*. All species were found at Cairns. Only *C. annulirostris* is a known vector of Ross River virus. Larvae of this species and *C. annulipes* were found in all four wetlands.

A summary of the relative abundance of mosquito larvae based on the percentage number of dips containing either no larvae, less than 10 larvae, 11–40 larvae or more than 40 larvae are given in Table 3. At Cooroy less than 1% of dips in Cells 2 and 3 contained any larvae. 2% of dips in Cell 1 contained larvae and these were only found at the sampling station with dense *Phragmites* and overgrown mats of *Paspalum* grass. At Blackall all sampling stations in Channel 1 were open water and only 0.5% of dips contained larvae. In Channels 2 and 3 the mid station was open water but the other two stations contained either *Typha* or isolated *Paspalum* clumps; the dips with > 40 larvae were sampled from within the *Paspalum* clumps. Channel 3 had the greatest cover of vegetation (40%) — with dense stands of *Typha* and floating mats of *Paspalum* and *Persicaria*, 16% of dips contained larvae. All dips with larvae were sampled at the station with the floating mats of vegetation.

At Cairns 10–20% of the dips contained larvae. Only 1 dip contained 11–40 larvae and 1 dip contained > 40 larvae and these both occurred on the same sampling day. All samples were taken at stations with dense stands of live and dead *Typha*.

Table 3. Relative abundance (% of dips) of mosquito larvae

Location		# dips	No larvae	< 10 larvae	11–40 larvae	> 40 larvae
Cooroy:	Cell 1	210	98%	2%	–	–
	Cell 2	210	99.5%	0.5%	–	–
	Cell 3	210	99%	1%	–	–
Cairns:	Channel 1	40	80%	17.5%	–	2.5%
	Channel 2	40	87.5%	12.5%	–	–
	Channel 3	40	80%	17.5%	2.5%	–
Blackall:	Channel 1	220	99.5%	0.5%	–	–
	Channel 2	210	95%	2%	–	3%
	Channel 3	190	84%	14%	2%	–
	Channel 4	200	96.5%	3.5%	–	–
Rosewood	Cell1 pond	200	95%	5%	–	–
	Cell 2 Typha	170	68%	25%	6.5%	0.5%
	Cell 3 Typha	140	54%	40%	6%	–

At Rosewood the open water settlement pond (Cell 1) recorded the least larvae (5% of dips), whereas the vegetated cells had the highest number of larvae: 32% of dips in Cell 2 and 46% of dips in Cell 3. Most of these larvae were concentrated in the dense stands of *Typha* with dead submerged stems and leaves, around the shallow edge of the cells. At each of the 4 wetlands 70–90% of the larvae found were early instars (1^{st} and 2^{nd} stages) and less than 1% were pupae.

Discussion

Macrophytes facilitate water treatment in constructed wetlands but they are also essential for ecosystem functioning. Sustainable populations of organisms are dependent upon habitats that provide the attributes for a species complete life history. Wetland plant diversity is important for determining macroinvertebrate 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”. In constructed wetlands macroinvertebrate biodiversity is also enhanced by good water quality — secondary or tertiary treated effluent, and aerobic conditions.

Our study of four surface flow constructed wetlands found that the Cooroy wetland with shallow marsh and deeper ponds had the greatest species richness of macrophytes (38 species) and macroinvertebrates (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 macroinvertebrate 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 macroinvertebrate 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. A marsh with a diversity of macrophytes appears optimal for macroinvertebrates biodiversity and the control of mosquito larvae by predation.

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 macroinvertebrates 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. 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. An abundance of notonectids in the settlement pond (Cell 1) at Rosewood probably accounted for low numbers of mosquito larvae.

Despite the presence of more mosquito larvae at Rosewood and Cairns the low numbers of $3^{rd}/4^{th}$ instars and pupae suggests predation. Walton and Workman (1998) attributed the lack of late instars in a Californian constructed wetland to invertebrate predators, mostly notonectid bugs.

There is limited published material on the ecological characteristics of constructed treatment wetlands, in particular with respect to aquatic invertebrates. Knight *et al.* (2001) summarised some of the key finding of the North American Treatment Wetland Database (NADB v 2.0) with respect to quantitative data on habitat, wildlife, human uses and ecological risks. Martin *et al.* (2001) conducted an ecological survey of a cypress-gum swamp forest in Florida that had been receiving secondary treated effluent since 1984. In addition to biological monitoring for vegetation, benthic macroinvertebrates and fish, they also monitored mosquito larvae and pupae in the summer months from stations that were 70% vegetation cover. Although direct quantitative comparisons cannot be made with the present study due to different methods of recording larval abundance they noted that “the number of immature mosquitoes collected at each station was typically low”. Using twenty 450 mL dippers at each station they recorded an average number of larvae between 143–527/m^3, i.e. 0.64–2.4 larvae per dip. They also noted that macroinvertebrate density measured using Hester-Dendy samplers was also low. They attribute low dissolved oxygen as the most significant factor affecting macroinvertebrate populations. The wetland supported a diverse and abundant fish population which Martin *et al.* suggest “appears to provide a significant control on mosquito populations” p.323.

The exotic mosquito fish *Gambusia holbrooki* was found at Cooroy and Blackall where it was deliberately introduced to control mosquitoes. However, the effectiveness of *Gambusia* 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). As with most introduced species *Gambusia* is competing with native species for food and habitat. The Cairns wetland supported a large tadpole (and frog population) probably due to the absence of *Gambusia*.

Walton and Workman (1998) conducted a comparative study of mosquito larvae and macroinvertebrates in two structurally different constructed wetland cells. Design 1 consisted of a shallow (0.5 m) densely vegetated marsh (*Schoenoplectus californicus*); design 2 had shallow inlet and outlet marshes separated by a section of deeper (1.2 m) open water. Larvae were sampled in the vegetated sections of both designs. Larvae abundance was higher in design 1 and contained proportionately more later ($3^{rd}/4^{th}$ stage) larval instars. Average larval numbers ranged from 10 per dip (400 ml) in early summer to less than 1 per dip in late summer in design 2, and from 40–60 per dip in early summer, to 2–5 per dip in later summer, in design 1. Predatory macroinvertebrates (notonectids, dragonfly nymphs, beetle larvae) were more abundant in early summer in design 2. Differences in larval abundance were attributed to larger populations of predators in design 2 facilitated by habitat preference for open water — particularly for notonectids.

Our study has also shown that maximum biodiversity of macrophytes and macroinvertebrates, 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. Harvesting may be a management option. 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. Greenway (2003) has reviewed the suitability of macrophytes in surface flow wetlands in tropical–subtropical climates, with genera such as *Schoenoplectus, Lepironia, Baumea, Phylidrum, Bolboschoenus* providing alternatives to *Typha* and *Phragmites*.

The management of wastewater must be consistent with protection of risks to human and animal health from mosquito-borne disease. Constructed wetlands should be designed to optimise wastewater treatment and ecological benefits to wildlife while minimising the potential for nuisance conditions such as mosquito breeding. Invertebrate predation is an important method for mosquito control. The value of constructed wetlands as low-cost alternatives to traditional wastewater treatment facilities has even greater significance in populated developing countries such as Africa and India where there is limited wastewater treatment. Constructed wetlands in these countries offer an economical solution to wastewater treatment providing they can be assured that other health risks such as mosquito-borne diseases are eliminated.

Conclusion

This study of four surface flow constructed wetlands in Queensland, Australia, has shown that the Cooroy wetland has the greatest species richness of macrophytes and macroinvertebrates and the lowest occurrence of mosquito larvae, suggesting that vegetation diversity (type, species and cover) is a significant factor in the control of mosquito breeding in constructed wetlands. Both the Cairns and Rosewood wetlands were dominated by dense monospecific stands of *Typha* and had a large build-up of dead organic matter — stems and leaves — beneath the surface. These woven mats of leaves formed small isolated pockets of water suitable for mosquito larvae development. These isolated pockets make it harder for predator access as well as having low dissolved oxygen concentration associated with microbial decomposition of dead organic matter. At Blackall mosquito larvae were of greatest occurrence amongst the dense mats of *Paspalum* grass — again the interwoven stems and roots restricting predator access, but very few larvae occurred in the open water sections.

Our study showed that although mosquitoes lay eggs in the wetlands and these hatch into larvae, very few larvae are likely to emerge as adults due to predation of the early instars. There needs to be wider recognition that mosquito larvae are an integral component of wetland ecosystems, and providing ecosystem functioning is maintained, then predator–prey relationships will ensure the control of mosquito breeding. Wetland design and maintenance is necessary to ensure wetland ecosystems support a diversity of macroinvertebrate predators. In Australia the introduction of the mosquito fish *Gambusia* is not recommended. Public acceptance that constructed wetlands are multi-functional systems providing benefits for human use, wildlife and downstream aquatic ecosystem health, will ensure that these treatment systems become an integral component of our urban landscape.

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