Culex Mosquitoes, West Nile Virus, and the Application of Innovative Management in the Design and Management of Stormwater Retention Ponds in Canada

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Stormwater best management practices have helped to address environmental concerns regarding peak water flows and accumulation of sediment and contamination by pollutants, but often overlook potential public health repercussions such as creating habitat for virus-carrying mosquitoes. Retention ponds frequently hold standing water for more than two weeks during the mosquito breeding season, creating development habitat for the aquatic stages of West Nile virus vectors. To avoid this problem, knowledge of vector ecology should be incorporated in the design of best management practices and integrated stormwater management plans. An integrated approach that incorporates hydrological management of water depth, flow, and surface agitation combined with manipulation of native biota and habitats based on the unique ecology and behaviour of the vector species can deter egg-laying mosquitoes by mimicking natural processes. Such an approach could help prevent disease transmission and alleviate the need for widespread application of pesticides.

Key words: West Nile virus, stormwater, integrated mosquito management, *Culex pipiens, Culex tarsalis, Culex restuans*

Introduction

For centuries, numerous diseases have spread as a result of poor drainage and sanitation systems, some causing deadly pandemics across the globe (Karlen 1995). In particular, the rapid spread of arthropod-borne viral diseases (arboviruses), such as yellow fever, dengue, and now West Nile virus (WNv), may have been fuelled by the creation of artificial aquatic habitats, facilitating the invasion of new vector species.

WNv is an infectious disease caused by an arbovirus of the flavivirus family, which is spread by mosquitoes. WNv can be transmitted to humans by mosquito species that also bite birds. Less than 20 such species exist out of the over 80 known species of mosquitoes in Canada (Thielman and Hunter 2007). Of these 20, only a few are highly competent vectors of WNv (Belton 1983, 2006).

WNv was first reported in Uganda in 1937, but has now extended to Europe and the Americas. In North America, the virus was first detected in New York City in 1999 (Kramer et al. 2008). Despite a rapid and widespread intensive emergency response by New York City, and surrounding mosquito control areas, the virus was not contained (Reisen and Brault 2007). Within four years, WNv had moved from the east to the west coast, and it has now spread across all of the contiguous 48 states of the U.S.A. and across Canada from Quebec to Alberta (PHAC 2008). There have also been cases in Mexico and the disease is now extending into Central and South America (Komar and Clark 2006). This spread may have been facilitated by general features of stormwater management in North America, through which the creation of manmade artificial aquatic habitats has encouraged the invasion of new vector species.

In many urban areas of North America, stormwater management has focussed on relieving flooding by channelling stormwater from extensive impervious surfaces through a complex system of water storage and debris collection (Ward and Trimble 2003), feeding ultimately into natural ecosystems. The input of nutrients and chemical contaminants from stormwater runoff may affect the stability of such freshwater systems. For example, shallow water bodies have been shown to react by switching from a diverse macrophyte-dominated community to a degenerate one dominated by planktonic algae (Scheffer et al. 1993; Sayer et al. 2006), a change favoured by WNv vectors, such as *Culex pipiens*. Algae and suspended solids that predominate in artificial waters increase water turbidity, supplying mosquito larvae with the food upon which they thrive, as well as providing camouflage from their visually-driven predators (Jacob et al. 2008).

Recently, stormwater best management practices (BMPs) have been designed to address environmental concerns regarding peak water flows, sediment accumulation, and contamination from pollutants (Ward and Trimble 2003), but these BMPs often ignore potential public health issues, such as habitat creation for vector mosquitoes (Wallace 2007). Now, integrated stormwater management plans (ISMPs) are being designed to reduce stormwater volume at the source (Stephens et

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al. 2002), and to incorporate more natural ecosystem-based methods such as infiltration fields, swales, and constructed wetlands to manage discharges. Some of these techniques have inherent flaws, such as excessive sediment accumulation, which may affect long-term efficiency (Booth et al. 2002; Brydon et al. 2006) and encourage the development of mosquito populations. Therefore, there could be health benefits in improving their effectiveness and sustainability (Wallace 2007).

Understanding specifics of the ecology of WNv vectors enables managers to manipulate artificial water bodies to discourage vector survival. In this review, we explore how management of artificial water bodies using integrated biological and ecological principles can reduce development habitat for WNv vector mosquitoes, lessen the risk of human infection, and help alleviate the need for the wide-scale use of pesticides.

Development of WNv Vector Mosquitoes in Stormwater Systems

In Canada, three of the major vectors of WNv, *Culex pipiens*, *Culex restuans*, and *Culex tarsalis*, have larvae that develop mostly in shallow, stagnant, warm, nutrient-rich waters (Rydzanicz and Lonc 2003). These species often lay eggs in surface detention and retention ponds (Tennessen 1993; Gingrich et al. 2006).

Two of these WNv vectors, *Culex pipiens* and *Culex restuans*, have similar ecological requirements (Reiskind and Wilson 2008) and both also lay eggs in subterranean structures such as the sumps of catch basins (Kronenwetter-Koepel et al. 2005). *Culex restuans* has an eastern Canadian distribution, with a western limit reaching central Alberta (Wood et al. 1979). *Culex pipiens* is found in the southeastern and southwestern regions of Canada, which, in British Columbia, includes the Lower Mainland, the Okanagan, and Vancouver Island (Wood et al. 1979). It may be no coincidence that in western Canada, the introduction of *Culex pipiens* at the turn of the last century appears to have coincided with the construction of stormwater drainage systems with catch basins (Vinogradova 2000). The geographic range of *Culex tarsalis* extends from southwest Ontario to the west coast (Wood et al. 1979).

Samples collected by Culex Environmental Ltd. as part of their Integrated Mosquito Management Program (IMMP) in the Greater Vancouver area of British Columbia, highlight the preference of *Culex pipiens*, and to a lesser extent *Culex tarsalis*, for artificial water bodies as oviposition sites. Larvae and pupae were sampled from a range of different broad habitat types using the standard larval sampling procedure described in the *Municipal Mosquito Control Guidelines* (Ellis 2004). Numbers of larvae (early and late instars) and pupae were recorded in the Greater Vancouver Area during the summers of 2006 and 2008.

Figure 1 and Table 1 demonstrate that *Culex pipiens* larvae are significantly ($p = 0.001$) more abundant in
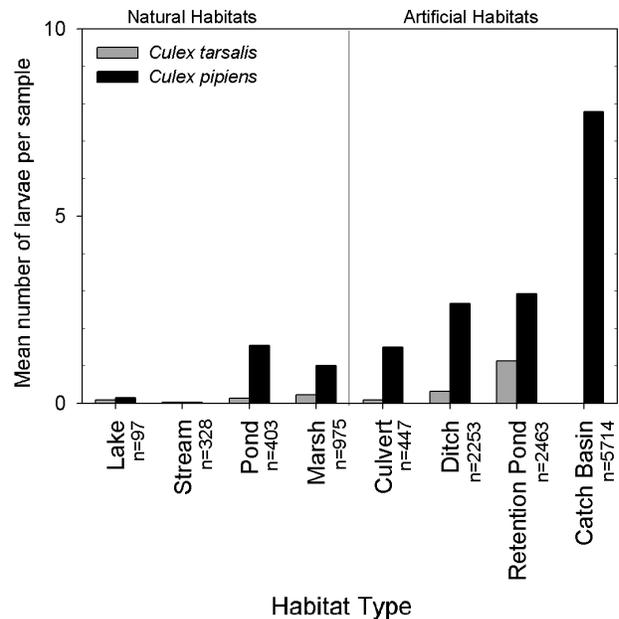
Fig. 1. Mean number of *Culex pipiens* and *Culex tarsalis* larvae collected in dip samples in different habitat types (n = number of samples) (unpublished IMMP data from Culex Environmental Ltd.).

artificial water bodies such as retention ponds and catch basins than they are in natural water bodies such as lakes, ponds, and marshes. *Culex tarsalis* is also significantly ($p < 0.001$) more abundant in artificial water bodies, although it is not found at all in catch basins.

The sumps of catch basins are largely predator-free and are not easy to manipulate through natural measures. New designs should seriously consider reducing the numbers of catch basins with sumps and incorporating more infiltration measures. *Culex pipiens* and *Culex tarsalis* populations in retention ponds might be reduced if conditions could be created that closely mimic the ecological function of natural systems. Designing retention ponds in this way also provides an opportunity for enhancing local and regional biodiversity.

Integrating Ecological Principles to Improve Stormwater Management Practices

Integrating ecological principles into stormwater retention pond design requires sensitive site-specific planning, careful monitoring, and responsive maintenance regimes. The following review of physical and biotic factors that influence mosquito production in retention ponds offers additional opportunities to tailor BMPs to reduce breeding of WNv vector mosquitoes in stormwater systems.

Water Depth Management

The depth of water in a pond greatly influences its

TABLE 1. Results of a *t*-test (assuming unequal varianc e) comparing mean number of larvae found in artificial and natural habitat for *Culex tarsalis* and *Culex pipiens*

	Culex tarsalis		Culex pipiens	
	Artificial	Natural	Artificial	Natural
Mean	1.8	0.6	7.3	2.6
Variance	207.5	6.4	1,381.1	604.5
Observations	1,979	391	1,979	391
Hypothisized mean difference	0		0	
Degrees of freedon	2,352		790	
t Stat	3.375		3.183	
P(T < = *t*) one -tail	0.000		0.001	
t Critical one -tail	1.646		1.647	
P(T <= *t*) two -tail	0.001		0.002	
t Critical two -tail	1.961		1.963	

suitability as a mosquito oviposition site. Water temperature usually decreases with depth, and cooler water generally slows mosquito development (Mori et al. 1988) and reduces fecundity (Gillespie and Belton 1980). While *Culex pipiens* females generally oviposit in warmer waters associated with ephemeral or stagnant shallow ponds, many of their predators require the cooler water of deeper, more permanent water bodies (Garcia 1973, 1983; Offill and Walton 1999). Increasing water depth also promotes a diverse aquatic community by fostering the growth of aquatic plants that contribute to the water quality and clarity of the pond, and provide refuge for ambush predators such as dragonfly nymphs and fish (Carpenter and Lodge 1986). Altering the depth of a pond to maintain water at relatively cool temperatures (below 20°C) therefore increases the survival of predators as well as reducing the suitability of the water body for *Culex pipiens* development.

Water Flow and Surface Agitation

Water flow is a crucial factor in determining mosquito oviposition sites. Gravid females of most mosquitoes, especially highly competent WNv vector species, seldom lay eggs in running or agitated water (Lothrop and Mulla 1996; Mogi and Montomura 1996). Furthermore, surface agitation also reduces the numbers of mosquito larvae because the air-breathing larvae cannot survive for long periods if the water surface is constantly in motion since it disrupts the surface tension at the air/water interface and interferes with the functioning of the mosquito's respiratory siphon (Schober 1966).

Water agitators, aerators, and fountains can all increase surface water movement. When placed appropriately, agitators and fountains can disturb the water surface, redistribute organic material, reduce sedimentation levels, and destratify oxygen-poor and nutrient-rich water layers. By stabilizing oxygen levels, they increase water clarity, reduce opportunities for algal growth, and decrease unpleasant odours and fish kills (Boyd and Egna 1997; Diana et al. 1997).

Water Quality Management

Water quality strongly influences the selection of oviposition sites by gravid female mosquitoes. *Culex pipiens* and *Culex restuans* larvae thrive in sediment- and nutrient-rich water (Rydzanicz and Lonc 2003), such as that received by retention ponds from stormwater runoff. In addition to creating mosquito habitat, sedimentation can decrease the capacity and retention time of ponds, and block pond inlets and outlets. Primary treatment filtration devices used with highly productive aquatic plants can help to alleviate these problems. Ideally, incoming water should be filtered to remove suspended sediment and organic matter before it enters the main retention pond. Upstream filtration ponds, such as sediment forebays, should be easily accessible for removing built-up sediment and organic matter, while leaving the main ponds undisturbed.

Aquatic and Terrestrial Biota

(a) Vegetation. Pond vegetation can be categorized into a number of distinct zones. Marginal vegetation growing above the water line around the perimeter of the pond includes trees and shrubs. The shade created with their overhanging branches can deter gravid females of vector mosquito species, such as *Culex tarsalis*, which prefer to lay eggs in open sunlit areas (Brust 1990). In Southeast Asia and South America, mosquito problems in areas cleared for development have been successfully managed by landscaping water bodies to produce shade (Garcia 1983). Marginal vegetation also provides extensive foraging habitat for predators of adult mosquito, such as insectivorous birds and amphibians.

Further inwards, emergent plants, such as reed and sedges that grow partially in the water along the littoral fringe, help diminish erosion and increase bank stability while taking up nutrients from runoff and helping to limit algal growth in the water. Emergent plants provide perches for predators such as dragonflies, as well as a wide array of microhabitats for predatory birds, amphibians,

and invertebrates.

Floating-leaved and submerged vascular plants (aquatic macrophytes), such as water lilies and pondweeds, reduce suspended solids and improve water quality by assimilating nutrients and contaminants (Comings et al. 1998), and may also reduce algal growth both by providing refuge for algal grazing zooplankton (Carpenter and Lodge 1986) and by releasing algal inhibitors or allelopaths (Elankovich and Wooten 1989). Floating-leaved and submerged macrophytes provide refuge for many ambush predators of the aquatic stages of mosquitoes, such as dragonfly nymphs and water beetle larvae, and for competing species, such as other dipterans and crustaceans (Richardson and Jackson 2002).

The variation in plant morphology between different species in these different zones determines the availability of specific microhabitats, providing opportunities for predators, as well as safety for prey and freedom from competition (Rydzanicz and Lonc 2003). Perhaps for this reason, different zones and particular plants appear to be more or less attractive to different mosquito species.

Results from thousands of standard dip samples in the Greater Vancouver area (unpublished IMMP data from Culex Environmental Ltd.) show that larvae of *Culex pipiens* congregate among emergent macrophytes and in amongst beds of filamentous algae, but avoid plants with floating or submerged leaves (Fig. 2). *Culex tarsalis* larvae are generally found in markedly lower numbers than *Culex pipiens*, and are found predominantly in filamentous algae. *Culex territans*, an amphibian biter which is not a WNv vector, has almost directly opposing habitat preferences to *Culex pipiens* in the aquatic stages. Such habitat preferences between different mosquito species are directly relevant to the design and management of retention ponds.

The particular plants that are chosen for landscaping newly created retention ponds in order to reduce mosquito infestation depend primarily on which species of mosquito are being targeted. Landscaping will depend on a range of physical and environmental factors, including the geography and climate of the region, the size and location of the pond, as well as detailed hydrology of the system. Native plant species are more likely to attract local native invertebrates that either prey on or compete with mosquito larvae.

(b) Mosquito predators and competitors.

Mosquitoes are highly opportunistic and often develop in new aquatic habitats, such as the predator-free oxygen-depleted waters of sewage lagoons, before other organisms become established. Their immature aquatic stages can, however, be influenced by both competition and predation. Potential competitors, such as insects, molluscs, amphibians, and copepods, compete with larval mosquitoes for food and may reduce their populations (Mokany and Shine 2002, 2003).

Common predators of mosquito larvae include small fish, larval salamanders, frogs, and toads, as well as many types of invertebrates, including grazing invertebrates
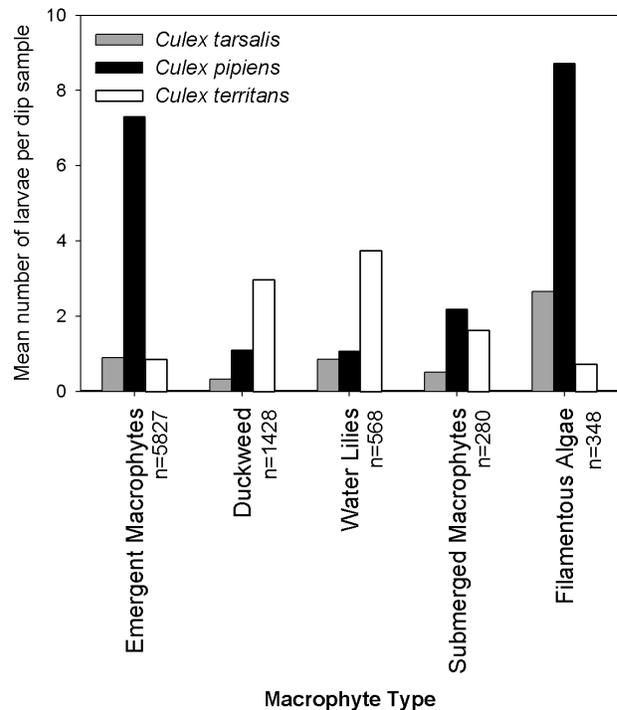
Fig. 2. Mean number of mosquitoes recorded from standard dip samples in water bodies with different aquatic vegetation (*n* = number of samples) (unpublished IMMP data from Culex Environmental Ltd.).

(e.g., snails, mayfly, and chironomid larvae), neustonic (surface) insects (e.g., water striders, water boatmen, whirligig beetles), and benthic invertebrates (e.g., flatworms, leeches, water lice, shrimps; Chesson 1984; Biebighauser 2007). The most common adult mosquito predators cited as potential biological control agents are fish, bats, birds, and dragonflies (Dixon and Brust 1971; Garcia 1983; Hussell and Quinney 1987; Bence 1988; Martinez-Ibarra et al. 2002).

Fish. The collection, possession, and transport of native fish require compliance with provincial and federal restrictions, but fish introductions as part of an approved ecologically sensitive program could reduce the use of pesticides while adding to the biodiversity of newly created ponds. Many stormwater retention ponds are small and shallow and only certain native fish species survive introduction. One suitable species for ponds might be the threespine stickleback, *Gasterosteus aculeatus*. This fish grows to about 8-cm long, lives in shallow waters, and can tolerate a range of temperatures between -1 and 30°C, with a preference for temperatures less than 18°C (Guderley 1994). Stickleback feeding habits have been studied in numerous environments and the species feeds readily on mosquito larvae (Snyder 1984; Offill and Walton 1999).

Amphibians. Most amphibian species are generalist feeders. Frogs and toads start their lives as mostly vegetarian tadpoles, becoming predatory as adults,

whereas salamanders are predators throughout their lives (Corkran and Thomas 2006). DuRant and Hopkins (2008) showed that adult red-spotted newts (*Notophthalmus viridescens viridescens*) and larval mole salamanders (*Ambystoma talpoideum*) were both capable of consuming hundreds of mosquitoes per day.

Bats. Bats are nocturnal hunters and their foraging activity overlaps with the flight of mosquitoes. In the British Isles, many studies have shown that dipterans and culicids, in particular, constitute a large component of the diet of bats (Vaughan 1997). One of Canada's most abundant bats, the little brown bat, *Myotis lucifugus*, feeds mostly on insects in the order Diptera (Whitaker et al. 1981). This bat is particularly efficient at feeding on mosquitoes (Rydell et al. 2002). Augmentation of bat habitat in areas surrounding retention ponds may increase the numbers of bats that may prey upon mosquitoes. Bat roosting boxes are most likely to succeed when properly constructed and positioned, and when bats are already known to use the area for summer feeding. The boxes should be installed before the bats return in spring, and located to receive several hours of direct sunshine daily. There should also be water within 500 meters, and diverse habitat with natural vegetation (Tuttle and Hensley 1993).

Birds. Many birds are insectivorous and may feed on mosquitoes either whilst foraging in vegetation or in flight throughout the day. Tree swallows, *Tachycineta bicolor*, have been observed to feed nestlings with mosquito larvae skimmed from water surfaces (Dods 2002), and flies are a significant part of their diet, particularly around sewage treatment lagoons (Hussell and Quinney 1987). Nest boxes can attract insectivorous birds and help to reduce the populations of both larval and adult mosquitoes. Swallow nest boxes can be constructed inexpensively and installed near retention ponds.

Invertebrates. There are numerous invertebrates in any natural water body (Richardson and Jackson 2002), and many of them may prey on developmental stages of mosquitoes, including eggs, larvae, and pupae. Flatworms, nematodes, copepods, and *Hydra* species can all be effective predators of mosquitoes in small water bodies (Garcia 1983). The larvae and adults of both dragonflies and damselflies (Odonata) prey efficiently on mosquito larvae (Miura and Takahashi 1988; Sebastian et al. 1990). Ponds can be enhanced for larval dragonflies by ensuring adequate water depths year round and preventing anoxic conditions. Perching sites around the margin of the ponds can help maintain a healthy adult dragonfly population.

Natural colonization of invertebrate mosquito predators could be accelerated by inoculating new ponds with suitable biota from established ponds nearby, but federal and provincial regulations need to be strictly adhered to.

Monitoring and Maintenance of Retention Ponds

Creating habitat for natural colonization of predators and competitors of vector mosquitoes is a long-term goal of management of retention ponds for health purposes. Monitoring vertebrate and invertebrate populations in and around retention ponds helps inform management decisions. Vegetation management is also essential for the proper functioning of stormwater retention ponds. Management options will depend on the nature of the water body, as well as the plant and animal species native to the particular locality, but some general principles apply. Although it is preferable to incorporate ecological design from the outset rather than to attempt to modify existing structures, a new monitoring and management regime for an existing pond may offer considerable health benefits.

Excessive plant production is often related to nutrient inputs and the use of fertilizers in the immediate vicinity of the pond. Regular water quality monitoring and sediment analysis help assess conditions and act as an early-warning signal for preventive measures. Shedding leaves of marginal trees and shrubs may lead to accumulations of organic matter in the water that will need to be removed in the fall. Emergent vegetation can also create puddles of nutrient-rich, warm, predator-free water, particularly with large fluctuations in water level, and if this cannot be controlled, then the plants may require cutting back. Periodic harvesting may also be required if excessive growth covers over the water surface and if colonization by opportunistic exotic plants occurs. Grass clippings, leaves, and other vegetative debris close to the pond should be collected and removed.

Conclusions

In Canada, the design and maintenance of stormwater systems may have increased the distribution of potential vector mosquitoes and led inadvertently to the spread of diseases such as WNv. Competent WNv vectors such as *Culex pipiens*, *Culex restuans*, and *Culex tarsalis* have expanded their range while colonizing artificially created stormwater structures such as catch basins and retention ponds.

We believe that a thorough understanding of the ecology of mosquito development and production, coupled with appropriate design and management, can assist in significantly reducing serious health concerns, such as WNv. Established wetland ecosystems have well-developed natural feedback mechanisms, such as predator-prey interactions, which have evolved over thousands of years. These tend to keep opportunistic species, such as mosquitoes, in check, but such systems are not straightforward to duplicate artificially.

Wetland retention pond design, on the other hand, is still in its infancy and has had both successes and failures. Much more research is required to find solutions to better mimic natural processes. This review

has given some insight into those possibilities. Through the successful collaboration of planners, engineers, entomologists, botanists, and ecologists, we can further integrate ecological practices into safe, economical and sustainable engineering approaches.

The rapid advance of WNv in recent years warns of potential future health concerns related to stormwater management. There are many other potential mosquito vectors of disease around the world that can invade new geographical regions. For example, *Aedes albopictus* (the Asian tiger mosquito), a known vector of dengue, was first discovered in Memphis, Tennessee in 1983. It has now spread across 36 U.S. states and much of Central America (Enserink 2008). Outbreaks of other zoonotic mosquito-borne diseases are also on the rise (Jones et al. 2008). For example, there have been recent outbreaks of the arbovirus Chikungunya in Italy and Australia, also carried by *Aedes albopictus* (Reiter et al. 2006). Incidence of mosquito-borne diseases may increase due to climate change, the decline of predatory species, degradation of natural habitats, and changes in the distribution and abundance of mosquito vectors. With innovative stormwater management techniques, the vector populations can be reduced, lowering the incidence of mosquito-borne disease.

Acknowledgments

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