Constructed wetlands still produce mosquitoes…

William E. Walton

Department of Entomology, University of California, Riverside, CA

Corresponding author: *william.walton@ucr.edu*

Abstract

There is renewed interest to incorporate constructed wetland technology as part of watershed water management strategies for supplemental water storage, flood control and water quality improvement. Increased variation in precipitation presumably associated with global climate change has contributed to recent multi-year droughts as well as unprecedented rainfall events. The addition of hardscape associated with human development has exacerbated flooding in urban and suburban areas. Contamination of irrigation waters and crops with pathogens associated with fecal matter has caused outbreaks of foodborne illness. Whereas constructed wetlands can lengthen conveyance times of overland water flow to enhance storage in lentic and palustrine habitats as well as facilitate infiltration of groundwater reservoirs, create multi-use habitat capable of absorbing decennial or centennial floods, and provide a cost-effective technology for improving water quality, recent publications promoting the use of constructed wetlands have failed to account for the public health consequences associated with the production of nuisance and vector mosquitoes by man-made wetlands. The importance of design and maintenance protocols for constructed wetlands to lessen the production of mosquitoes that reduce the quality of life and pose tangible threats for the transmission of mosquito-borne pathogens are reviewed.

INTRODUCTION

A desire to reduce the economic losses and loss of human life caused by flooding associated with recent storms and hurricanes has created renewed interest in constructed wetlands as a component of "un-engineering" strategies to provide ecological security for urban areas worldwide (Gies 2018). Rapid urbanization during the last several decades has converted natural areas capable of absorbing stormwater into urban hardscapes and gray infrastructure that often exacerbates the flooding caused by ever stronger storms. Recent disasters in Houston, New Orleans and Beijing are grim reminders of the consequences of the oxymoron that is "urban planning". Intensive urbanization also has contributed to water shortages as areas providing recharge to subterranean aquifers have been reduced. For example, in China, unbridled use of groundwater supplies has lowered water tables and caused subsidence, while 62% of cities flooded between 2011 and 2014 resulting in $100 billion in economic losses (Gies 2018).

Retrofitting cities for greater ecological security operates on a wide range of scale from localized projects to city-wide and watershed-level projects intended to reduce flooding and promote water storage and infiltration. Known as low-impact development in the U.S., green infrastructure in Europe and Australia, or sponge cities in China, approaches include restoration and preservation of floodplains, restoration of lotic habitats, and the creation of landscape features to provide retention and treatment of rainwater runoff such as bioswales, retention ponds, sunken parks and permeable parking lots (Gies 2018). To allow natural hydrologic and ecologic processes to fulfill a greater role in water management strategies, standing water that is conducive to mosquito production can occur as part of some technologies.

Renewed interest in constructed wetlands is not limited to applications in cities. Constructed and restored wetlands are proposed to filter and improve water quality of agricultural runoff that contains a wide range of contaminants (O'Geen et al. 2010, O'Geen and Bianchi 2015). Recent outbreaks of foodborne illness caused by contamination of lettuce and spinach grown in California with pathogens found in fecal matter has raised concerns about inadequately treated agricultural wastewater and contamination of irrigation water and crops by wildlife (Beretti and Stuart 2008, Dowd et al. 2008). Whereas construction and restoration of many wetlands in California was supported by the USDA-NRCS through the Environmental Quality Incentives Program (EQIP) and the Wetland Reserve Program (WRP) to mitigate the loss of wetlands and improve wildlife habitat, fulfilling the dual goals of agricultural water quality improvement and wildlife habitat enhancement has proven to be difficult (O'Geen and Bianchi 2015).

Besides water quality improvement and crucial wetland habitat, the projected benefits of multipurpose constructed treatment wetlands are numerous, including amenities for nearby housing developments, wildlife conservation, education and recreation (Cole 1998). The inability of man-made wetlands to fulfill multiple diverse goals is not uncommon (USEPA 2000, NRC 2001). Even if the focus of engineered wetland systems is limited to one or two key objectives (Carey 2013), the outcome of ecological

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Figure 1.—The brush cutter (left panel) used reduce emergent vegetation surrounding experimental exclosures and the wetland showing inundated cut vegetation (right panel). This practice should be discouraged because it greatly enhances mosquito production.

processes such as succession is by no means certain and repeatable even in adjacent replicate wetlands. Meeting the conservation needs of diverse fauna and flora can be problematic. For example, man-made riverine wetlands can serve the needs of riparian and wetland birds (Zembel et al. 2003) and mammals, but are habitat sinks for native fishes and amphibians because of predation and competition from non-native fauna that proliferates in lentic conditions (Why et al. 2014).

The theme of this symposium "Don't Reinvent the Wheel: Past Vector Control Research and Practices Relevant Today" is an appropriate venue for my topic. It is perplexing that despite a wealth of peer-reviewed literature on the topic of mosquito production from man-made wetlands (e.g., Russell 1999; Walton 2002, 2003, 2012; Knight et al. 2003; Metzger 2004; Lawler and Lanzaro 2005; Rey et al. 2012), many of the aforementioned recent publications promoting the use of constructed wetlands fail to mention the potential role of man-made wetlands and agricultural operations for producing mosquito populations that affect public health. Here, I revisit the evidence supporting the importance of design and maintenance protocols for constructed treatment wetlands to lessen the production of mosquitoes that reduce the quality of life and pose tangible threats for the transmission of mosquito-borne pathogens.

METHODS

The Prado Wetlands consist of 47 interconnected marshes/ponds (surface area = 186 ha) located 7 km northwest of Corona, California (33.9°N, 117.9°W) and are managed by the Orange County Water District (OCWD). The area of wetlands complex encompassed by shallow wetlands conducive to mosquito production is approximately 142 ha. The wetland complex receives approximately one-half of the flow (1.7 - 2.3 $m^{3\cdot}\ s^{-1}$) of the Santa Ana River. Data from basin-wide mosquito surveys collected using 350-mL dippers and 0.25 m^2 screen emergence traps by Keiper et al. (1999, 2003) were used to estimate the basin-wide production of female mosquitoes between July and September. Mosquito emergence rates were corrected for the proportion (~0.55) of the cohort collected by the emergence trap design during the trapping period (Walton 2009).

Unpublished data from immature mosquito surveys using 350-mL dippers in a 1-ha wetland (see Fig. 1 in Why et al. 2014) that had undergone vegetation management were used to estimate mosquito production. Mosquito production following cutting of emergent vegetation with a rotating brush cutter and leaving inundated cuttings (Figure 1) was estimated during a 6-week period. Treatment of the wetland with bacterial larvicides was required (Why et al. 2014); however, the decaying vegetation in the wetland attracted egg-laying mosquitoes for about 6 weeks.

Because this paper is primarily a review of previously published material, the relevant methods for the research cited herein can be found in the accompanying references.

RESULTS AND DISCUSSION

Multipurpose constructed treatment wetlands provide important ecological services and benefits; however, production of pestiferous and pathogen-transmitting mosquitoes is a potential drawback. Mosquito production typically increases as water quality declines and coverage by inundated vegetation increases (Walton 2012). Problems related to mosquito production can be acute in the arid southwestern U.S. where rapid human development, a susceptible populace unaccustomed to the presence of mosquitoes, endemic activity of arboviruses, and the presence of competent mosquito vectors of the causative agents of human diseases combine to create public health concerns (Walton 2002).

The design and management of a constructed wetland can influence mosquito production. Ideally, one should incorporate as many design features that reduce mosquito production as is feasible to still achieve the goal(s) of the wetland system. “Design” mosquitoes out of the wetland as much as possible. Design features that have the potential for source reduction include basin design and topographic configurations, hydrological control, vegetation management and planting design for emergent vegetation and structures that limit allochthonous subsidies (Walton 2003, 2012). Fluctuating water levels can draw immature mosquitoes out of emergent vegetation into open water where mortality is higher or strand mosquito larvae on the substrate undergoing drying (Walton et al. 2016), but flood-pulse wetlands perform comparatively poorly for improving water quality in some agricultural applications (O’Geen and Bianchi 2015). The number of wetland cells, redundancy of flow paths, configuration of the basin sides, slope of the bottom, hydroperiod, and features that hold isolated pools of water affect mosquito production (Knight et al. 2003).

What you put into the wetland matters. The abundance of mosquitoes is influenced by loading rates of organic matter and nutrients (Walton 2012). Under high loading of organic matter and nutrients ($>$ 50 mg TN liter^{-1}) such as that found in barnwash and municipal effluent that has undergone only primary treatment (i.e., removal of solids by screens), mosquito production is nearly continuous, reflecting the seasonal activity of adult mosquitoes. Immature mosquito abundance often exceeds 50 to 100 larvae per dipper sample when constructed wetlands or dairy wastewater ponds receive high levels of nitrogen in municipal or agricultural wastewater; counts may routinely exceed 500 larvae per dipper sample (O’Meara et al. 2010).

Mosquito production also may be continuous during the annual period of host-seeking activity at constructed wetlands receiving loading rates of organic matter and nutrients (e.g., secondary-treated municipal effluent: 10-30 mg TN liter^{-1}) that are comparatively lower than for dairy wastewater and sewage lagoons. Immature mosquito abundance during the summer might range between 20 and 40 larvae per dipper sample (Walton 2012).

Under low nutrient levels ($<$ 10 mg TN liter^{-1}) such as those found in tertiary-treated municipal effluent or flood irrigated rice fields, immature mosquito abundance in constructed wetlands is typically $<$ 1 larva per dipper sample (Keipter et al. 1999, 2003; Walton 2012). Predators are often capable of exerting significant mortality on immature mosquito populations in low nutrient conditions (Walton 2012). It is not uncommon to observe vernal and autumnal peaks in mosquito populations, albeit at comparatively low levels of adult production. Despite low levels of adult mosquito production per unit area, large expanses of inundated palustrine or riverine wetlands are capable of producing significant numbers of mosquitoes.

What you put around the wetland matters. The area circumscribed by a constructed wetland does not restrict the area over which adult female mosquitoes are searching for hosts. Mosquitoes are searching for blood meals both at the wetland and in the surrounding landscape. The birds living in and around constructed wetlands, and associated with surrounding regions of human habitation, may be reservoirs for arboviral pathogens transmitted by vector mosquitoes (Knight et al. 2003). Depending on the mosquito species and local environmental conditions, host seeking mosquitoes move from $<$ 1 km to tens of kilometers from wetland developmental sites.

The emergent vegetation that is planted in the wetland influences mosquito production. In general, vegetation density is directly correlated to mosquito production. Dense stands of large (height 1.5 - 3 m) emergent macrophytes planted in constructed wetlands can (1) reduce wetland performance for improving water quality during natural senescence and by channeling or short-circuiting water flow, (2) increase mosquito production by providing harborage and reducing mortality of immature mosquitoes, (3) reduce effectiveness of abatement measures by blocking control agents from contacting the target stage of the mosquito life cycle, and (4) increase the costs of wetland management (Knight et al. 2003; Walton 2003, 2012). Cutting and removal of cut plant biomass typically is expensive ($>$ \$10,000 ha^{-1}). Mosquito abatement at constructed wetlands receiving secondary-treated municipal effluent that contain dense stands of emergent vegetation is expensive (cost of mosquitocides and application in 2016 dollars: \$5,000 to \$10,000 ha^{-1} yr^{-1}) and is often ineffective. Weekly, even semi-weekly, application of larvicides and adulticides can be required (Walton 2002).

The distribution of emergent vegetation in the constructed wetland matters. Incorporating open water zones with water depths that inhibit colonization and growth of emergent vegetation will reduce mosquito production by increasing immature mosquito mortality (Thullen et al. 2002). The shallow open water present after wetland construction eventually will be colonized by emergent vegetation and mosquito production is likely to increase concomitantly (Walton et al. 2007). The distribution of emergent vegetation can influence water quality treatment (O’Geen and Bianchi 2015).

How you manage the wetland matters. Based on basin-wide surveys from May until October, the mean areal production of mosquitoes (males and females) from emergent vegetation at the Prado Wetlands ranged from 0.070 mosquitoes m^{-2} d^{-1} (Keiper et al. 1999) to 0.093 mosquitoes m^{-2} d^{-1} (Keiper et al. 2003). The total estimated production of female mosquitoes (corrected for trap efficiency) from 142 ha of palustrine wetlands ranged between 7,600,000 and 10,120,000 female (*Culex* spp. and *Anopheles hermsi*) mosquitoes between July and September. Whereas this production is low per unit area and water quality is high (tertiary-treated municipal effluent), the large area of the shallow marshes creates significant levels of adult mosquito production.

However, poor management practices can increase mosquito production $>$ 100-fold in a very small area of the wetland. Following vegetation management in a 1-ha wetland, mosquito abundance in the decaying vegetation

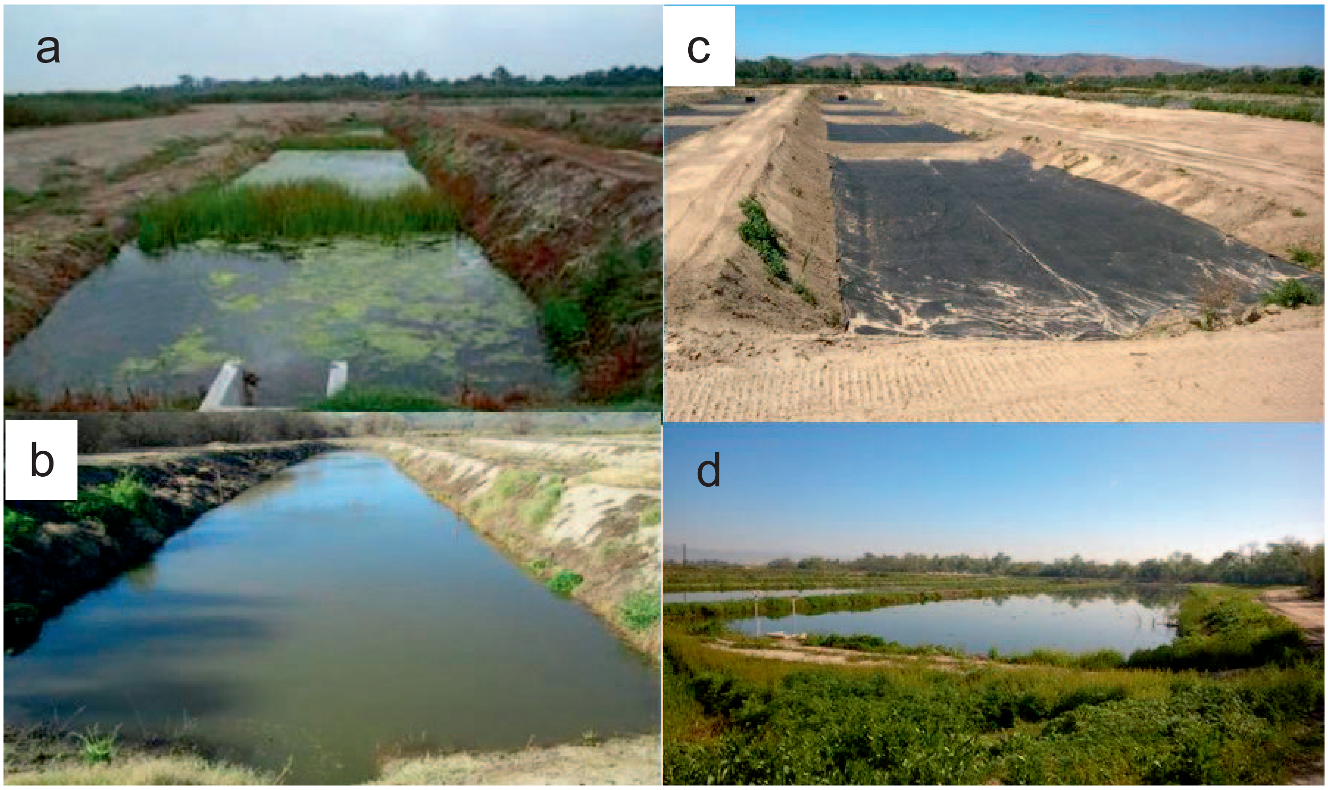

Figure 2.—A wetland with emergent vegetation (*Schoenoplectus maritimus*) restricted to narrow zones in October (a). The same wetland the following spring (March) after the emergent vegetation above the substrate died back naturally during late autumn and before regrowth (b). A wetland with raised planting beds and shade cloth to limit the distribution of emergent vegetation (c). A wetland that maintains open water by utilizing periphyton communities to improve water quality (d).

was enhanced significantly. Based on dipper samples, the emergence rate of mosquitoes was estimated at 50,128 mosquitoes m^{-2} wk^{-1}. Total mosquito production was 500,000,000 mosquitoes wk^{-1} from the 1 ha wetland. During the 6-week period following vegetation management (without mosquito abatement using bacterial larvicides), the production of female *Culex* would have been approximately 1.5 billion female mosquitoes.

Design features and operational procedures that help to limit mosquito production include the following approaches (Knight et al. 2003; Walton 2003, 2012). Create open water zones by restricting emergent vegetation to islands or raised planting beds (Figure 2). Incorporate water quality treatment processes that reduce organic matter and nutrient loading before placing water into wetlands containing emergent vegetation such as open-water settling ponds or forebays which promote settling of particulates and volatilization of nitrogen. Maintain the lowest coverage of emergent vegetation necessary to achieve the performance goals for the wetland. Recent approaches for treatment wetlands are moving away from emergent vegetation to periphyton-based systems for water quality improvement (Figure 2). Incorporate design features and management practices that enhance populations of mosquito predators, including the addition of larvivorous fishes. Compartmentalize the wetland so that source reduction for mosquitoes can be carried out in a subset of wetland cells without requiring that the entire wetland be taken offline and mosquito control agents can be applied effectively to emergent vegetation when needed. Build dikes that can accommodate mosquito control vehicles. Maintain an excellent working relationship among agencies.

CONCLUSIONS

The addition of wetlands and other landscape features to urban areas has great promise to increase ecological security by reducing the impact of flooding from ever intensified storms associated with global climate change and from the hardscape architecture that dominates cities. Green infrastructure also can address the chronic water shortages in urban areas by enhancing infiltration of water into groundwater reservoirs. In rural areas, constructed wetlands can reduce pollution and contamination from agricultural operations. Nevertheless, the failure to address the potential production of mosquitoes in standing water on the landscape while promoting green solutions to current problems does a disservice to communities by potentially decreasing quality of life from mosquito bites and increasing the prevalence of vector-borne diseases in humans, companion and domesticated animals, and wildlife.

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