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Review

Strategies for effective mosquito control in constructed treatment wetlands

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Abstract

Constructed wetlands hold considerable promise for providing water quality and wildlife habitat benefits. At the same time, constructed wetlands have been described as "mosquito-friendly habitats" and may raise potential conflicts with neighboring human populations. Conflicts arise because some design features, such as shallow water and emergent vegetation that are essential for optimizing water quality polishing, can result in undesirable increases in mosquito production. The attraction of large numbers of birds to constructed wetlands could also increase the risk of transmission of mosquito-borne viral infections to humans in the vicinity of the wetland. The potential for conflict is typically highest in arid regions where natural mosquito populations have limited abundance and are found near newly urbanizing areas.

The creation of wildlife habitat is a significant goal of many treatment wetlands. Humans are also welcome in many treatment wetlands for recreational and educational activities. Risks of disease transmission to humans and livestock as well as the inconvenience of mosquitoes as pests must be offset by the economic savings of inexpensive water quality enhancement and the resulting reduction in pollution that also poses a risk to society's health and well-being. Ecological risks associated with the use of mosquito control chemicals must be offset by the increased habitat benefits provided by these constructed wetlands. The right balance between these competing goals can be recognized by the design that provides the greatest net environmental and societal benefit. This paper describes these tradeoffs between mosquito control and the constructed wetland technology and provides a synthesis of information that can be used to optimize the benefits of these wetland systems. Basic research is recommended to better define the cost-effectiveness of the various design and management options.

Keywords: Constructed wetlands; Mosquito abatement; Water quality; Wastewater treatment

1. Introduction

Most shallow aquatic ecosystems, including natural and constructed wetlands, provide suitable habitat for a variety of mosquito species. Although risks

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from mosquito-borne diseases are greatly diminished, they have not been eliminated. Also, many mosquito species are human pests with painful bites that limit outdoor activities. A conflict exists between our appreciation of wetlands and some of their inevitable inhabitants.

The technology of designing and building constructed wetlands is expanding rapidly throughout the United States and the world (Kadlec and Knight, 1996; IWA, 2000). The discovery that wetlands can purify surface waters at low cost and with significant ancillary benefits for habitat creation has been widely heralded, and the growing inventory of these constructed water quality treatment wetlands is helping to offset the historic loss of wetland habitat in areas such as San Francisco Bay, California, and the Everglades of Florida. An undesirable side effect is that all wetlands produce mosquitoes. In some areas with large expanses of existing natural wetlands, additional mosquitoes will not significantly add to the nuisance issue, but in areas that are accustomed to few mosquitoes, constructed wetlands may create social conflict. This conflict presents a challenge to wetland designers and mosquito control experts. This paper describes the scientific and engineering research that is being applied to resolve this problem. The goal of this research is to optimize constructed wetland design and operation for water quality and habitat benefits while simultaneously minimizing mosquito production potential.

2. Mosquitoes and treatment wetlands

Mosquito populations have been studied in a relatively small number of treatment wetlands. Municipal treatment wetlands typically have stable water levels and offer habitat for pool-breeding mosquitoes but offer limited opportunities for floodwater species (O'Meara et al., 1988; Tennessen, 1993; Walton et al., 1998). Immature mosquito population densities are highly variable among sites in different geographical areas, over the course of system maturity, and over time and space within individual systems. A general conclusion from those areas that contain both treatment wetlands and unimpacted natural wetlands is that adequately designed and appropriately managed treatment wetlands do not pose any greater mosquito threat than the existing natural wetlands (Davis, 1984; Carlson and Knight, 1987).

Many land uses provide habitat for mosquito development. Irrigated agriculture, ruderal lands with shallow isolated pools, dump sites, and ephemeral wetland areas all may serve as significant mosquito breeding habitat. The locations where the greatest potential conflict exists between the advantages of treatment wetlands for cost effective water quality improvement and their potential as mosquito habitats is where natural wetlands have been drained or where they never existed initially. This potential conflict is especially acute in the arid West (Dill, 1989; Martin and Eldridge, 1989). Background levels for mosquito abundance are so low in some of these areas that even well-maintained, traditional treatment wetland designs may not be able to maintain such sparse host seeking mosquito populations. Design criteria that maximize treatment efficiency while minimizing mosquito populations are sorely needed in these regions.

Collins and Resh (1989) provide a set of guidelines for ecological control of mosquitoes inhabiting non-tidal wetlands in the San Francisco Bay area of California that are relevant wherever the conflict between mosquitoes and wetland creation exists. Design criteria for wastewater lagoons (Smith and Enns, 1967; Carlson, 1983; Martin and Eldridge, 1989) and stormwater treatment wetlands (Schueler, 1992; O'Meara and Purcell, 1990; Santana et al., 1994) also are pertinent. A growing body of technical information is also available on the ecology and management of mosquitoes in wetlands treating municipal wastewaters (Mortenson, 1983; MVCAC, 1997; FCCMC, 1998; Walton and Workman, 1998; Walton et al., 1990a, 1990b, 1996, 1997, 1998, 1999; CH2M HILL, 1999; Thullen et al., 2002; Walton, 2002; Keiper et al., 2003).

2.1. Mosquitoes associated with treatment wetlands

Mosquito species found in treatment wetlands can be classified into two groups based on their egg laying and hatching behavior. Females of some species lay their eggs directly on the water surface or on the leaves of aquatic plants (stagnant water species). The eggs hatch usually within a few days and do not need an external hatching stimulus (Bohart and Washino, 1978). These behavioral traits are characteristic of mosquitoes of the following genera (or subgenera): *Anopheles*, *Coquillettidia*, *Culiseta*, *Culex*, *Mansonia* and *Uranotaenia*. By contrast, the eggs of floodwater mosquitoes in the genera *Aedes*, *Ochlerotatus* and *Psorophora* normally are deposited on moist soil or debris on the shore around aquatic systems and do not hatch until submerged by rising water levels (Bohart and Washino, 1978). Treatment wetlands seldom generate severe floodwater mosquito problems, but those containing emergent or floating plants, steady water levels, and nutrient-rich wastewater, may provide suitable habitats for the immature stages of several stagnant water species (Walton, 2002; Keiper et al., 2003).

2.1.1. Mosquitoes in permanent or semipermanent aquatic habitats

Culex tarsalis, *Cx. erythrothorax*, *Cx. stigmatosoma*, and to a lesser extent *Cx. quinquefasciatus* are the *Culex* most frequently found in wastewater systems in the southwestern United States; whereas in the southeastern part of the country, *Cx. quinquefasciatus*, *Cx. nigripalpus*, *Cx. salinarius* and *Cx. restuans* are the predominant species of this subgenus.

Coquillettidia perturbans inhabits natural ponds and marshes and constructed wetlands, especially where aquatic plants (e.g., *Typha* spp.) have roots that penetrate a muck layer. The larvae and pupae of *Cq. perturbans* do not come to the surface to breathe like most other mosquito species; instead, they obtain oxygen from the root hairs of aquatic plants by using a specialized breathing tube for attaching to and piercing into roots. This species is a major pest and pathogen-vectoring mosquito in the eastern part of the United States and a common mosquito in parts of California, Oregon and Washington.

The immature stages of *Mansonia* also extract oxygen from the roots of aquatic plants. However, *Mansonia* larvae and pupae normally attach to floating aquatic plants, such as water hyacinth (*Eichhornia crassipes*) and water lettuce (*Pistia stratiotes*) rather than plants rooted in the substrate. *Mansonia* egg masses are deposited on both the upper and under surfaces of *Pistia stratiotes* leaves (Lounibos and DeWald, 1989). Currently, *Mansonia* mosquitoes have a very limited distribution in the continental United States (*Mansonia titillans* in Florida and Texas and *Mansonia dyari* in Florida and south Georgia).

In the eastern United States *Uranotaenia lowii* and *Uranotaenia sapphirina* are common mosquitoes in freshwater marshes. In Florida, immature *Ur. lowii* are, at times, extremely abundant in man-made lagoons receiving untreated wastewater from dairy barns (O'Meara and Evans, 1983).

Culiseta inornata is distributed throughout the continental United States, occurring in variety of aquatic habitats including those that are grossly polluted. However, at the lower latitudes *Cs. inornata* populations tend to be active only during the cooler months of the year. *Culiseta particeps*, which is restricted in its distribution to southern Arizona and California, tends to be rare or uncommon mosquito. *Culiseta incidens* also tends to be uncommon.

Females of the mosquito genera listed above deposit their eggs in rafts or clusters; whereas *Anopheles* mosquitoes lay their eggs individually on the water surface. Each egg is equipped with special structures (floats), which enable the egg to remain on the water surface. Depending upon the species and the environmental conditions, essentially all the eggs may hatch shortly after egg deposition, hatching may be staggered over a period of several weeks, or (a less frequent occurrence) some eggs may become stranded on moist substrate above the water and not hatch until after a flooding episode.

2.1.2. Floodwater mosquitoes

Aedes vexans and members of the *Psorophora columbiae*/*confinnis* group are the most widely distributed floodwater mosquitoes in the continental United States. These mosquitoes, along with *Ochlerotatus nigromaculis*, *Oc. trivittatus*, *Oc. dorsalis*, *Ps. signipennis* and *Ps. discolor* would most likely be found in or around areas with constructed treatment wetlands in the southwestern US. Sites receiving runoff are likely to generate a floodwater mosquito problem. For example, if the runoff from a constructed wetland is sent to a disposal or recharge area in a floodplain, then suitable microhabitats for these mosquitoes may be created, especially if the soils become impermeable. In the eastern US, some wastewater disposal sites have been invaded by the saltmarsh mosquitoes *Oc. taeniorhynchus* and *Oc. sollicitans* (Santana et al., 1994). In some cases, the salt content of soils receiving water from treatment wetlands could increase to levels that would attract such mosquitoes.

2.2. Factors affecting adult mosquito abundance

2.2.1. Weather/climate

Throughout much of the temperate zone, low air temperatures greatly reduce mosquito activity in the wintertime. During the late summer or fall, floodwater mosquitoes lay diapausing eggs which do not hatch until the following spring. *Culex* and *Anopheles* mosquitoes normally diapause in the adult stage. The duration of the diapausing condition is directly related to severity and persistence of cold weather conditions. In the southernmost part of the temperate zone, *Culex* mosquitoes might have a very brief or no hibernation (Nelson, 1971). High temperatures may be a factor inducing inactivity among adults *of Cx. salinarius*, *Cx. restuans* and *Cx. quinquefasciatus* during the summertime in southern Florida and southeast Texas (O'Meara and Evans, 1983; O'Meara et al., 1989). Variation in relative humidity may also influence the seasonal activity of adult mosquitoes.

Predictable annual changes in environmental factors such as photoperiod and temperature are used by mosquitoes and other organisms as cues to initiate or cease activity and, not surprisingly, seasonal activity patterns change with latitude and differ among mosquito species. A north-south clinal shift from a unimodal late summer pattern in northern valleys to a bimodal pattern with a larger spring peak and a smaller autumnal peak in the southern agricultural valleys of California is typical for *Cx. tarsalis* (Nelson, 1971; Bohart and Washino, 1978; Reisen and Reeves, 1990) and, probably, for many species. In arid southern regions of its range, *Cx. tarsalis* host seeking populations often aestivate during the hot summer months and exhibit greatest activity from autumn through spring.

2.2.2. Diurnal patterns

Culex tarsalis, *Cx. quinquefasciatus* and *Cx. nigripalpus* are active only at night and rest in the daytime. Floodwater mosquitoes also rest during the daytime, but they are opportunistic blood feeders and will take flight and seek a blood meal if a suitable host invades their daytime resting areas. Similar behavior is exhibited by *Cx. erythrothorax*. Flight activity for male mosquitoes is confined primarily to the crepuscular periods. Females are most active during dawn and dusk; but activity continues throughout the night, particularly for *Anopheles* and *Culex* mosquitoes.

2.2.3. Host abundance

Culex nigripalpus and *Cx. tarsalis* obtain blood meals from a wide range of hosts; including birds, mammals, reptiles and amphibians (Dow et al., 1957; Edman, 1974). *Culex quinquefasciatus* and *Cx. erythrothorax* are opportunistic, general feeders; *Culex stigmatosoma* feeds primarily on birds; *Cx. salinarius* is a general feeder, but in certain areas it feeds primarily on mammals (Edman, 1974; Bohart and Washino, 1978; Walton et al., 1999). *Aedes vexans*, *Oc. dorsalis*, *Oc. nigrimaculis*, *Ps. columbiae*, *Cs. inornata*, *Cq. perturbans*, *M. titillans*, *An. franciscanus* and *An. freeborni* obtain blood meals mostly from mammals; while *Ur. lowii* feed on cold-blooded animals (Edman, 1971). Host-feeding patterns are influenced by the (1) the mosquito's host preference, (2) the availability of specific hosts and (3) environmental conditions that impact the process of finding a suitable host (Day and Edman, 1988).

3. Mosquitoes and health risks

Mosquitoes deteriorate the external environment by creating a biting nuisance that precludes or inhibits outdoor activities and the internal environment by the transmission of pathogens that may produce disease. Both aspects may have a significant economic impact by driving away visitors resulting in the loss of tourist income and in costs related to mosquito control and case management. The risk of human infection with a mosquito-borne pathogen in the US is generally low; however, even the perceived threat of infection may cause public alarm and a demand for public health action. In addition, the clinical management of viral encephalitis cases requires considerable medical care and may impart a severe economic impact (Villari et al., 1995).

3.1. Nuisance problems

Although many mosquito species are not important in pathogen transmission, their aggressive biting behavior may create important nuisance or pest problems. Their impact as pests depends on their host-seeking behavior and the response of humans and domestic animals to their bite.

Females of most mosquito species require a blood meal from a vertebrate host to stimulate the development of each clutch of eggs and this behavior potentially places the surrounding human population at risk of mosquito contact. Species associated with wetlands exhibit ambushing and/or hunting behavior to acquire blood. Species that ambush during the day create the greatest demand for control due to public awareness.

3.2. Potential health problems

For disease transmission, a female mosquito must acquire a critical number of pathogens from an infectious host during blood feeding, survive long enough for the pathogen to replicate/develop and infect the salivary glands, and then transmit the pathogen to a susceptible host when salivary secretions are released into the bite wound during a subsequent blood meal. Surveillance and control strategies depend upon whether the pathogens are anthroponoses or zoonoses. Anthroponoses such as malaria have a human reservoir and are maintained by a simple human to mosquito to human cycle. Zoonoses such as the mosquito-borne viral encephalitidies have a primary transmission cycle among mosquitoes and wild birds, with transmission to humans and domestic animals incidental or tangential to the basic cycle.

Although at least 10 arboviruses are known to be transmitted by mosquitoes in the US, only eastern equine encephalomyelitis (EEE), western equine encephalomyelitis (WEE), St. Louis encephalitis (SLE), and West Nile (WN) viruses have caused widespread illness in humans and are likely to be transmitted by mosquitoes associated with wetlands (Reeves, 1990; CDC, 2003). The distribution, transmission cycles and epidemiology of these four important arboviruses are discussed below.

EEE occurs in tropical and temperate zones of the New World. EEE is distributed in the eastern half of North America and, in the United States, is endemic east of the Mississippi River and along the Gulf Coast and Atlantic seaboard, but has been found as far west as Nebraska (Foote, 1959). EEE is a zoonosis maintained in a basic enzootic cycle involving birds and several mosquito species, particularly *Culiseta melanura* (CDC, 2003). EEE can be an important source of mortality for horses, game birds such as pheasant, domestic fowl, emus and whooping cranes (Foster and Walker, 2002). This virus causes one of the more pathogenic mosquito-borne diseases in the US with a human case fatality rate of 35% (CDC, 2003). The primary transmission cycles take place in regions adjacent to the coast and freshwater swamps.

WEE is distributed widely throughout the New World (Reisen and Monath, 1989), but in North America west of the Mississippi typically is associated with riparian corridors and irrigated agriculture habitats supporting large populations of the primary vector, *Cx. tarsalis* (Mitchell, 1977). WEE is a zoonosis maintained in a basic enzootic cycle involving *Cx. tarsalis* mosquitoes and birds in the orders Passeriformes [especially house finches, house sparrows], Columbiformes [mourning doves, common ground doves] and Galliformes [e.g. Gambel's and California quail]. Domestic chickens frequently become infected in rural settings, but adult chickens do not develop sufficient viremia to infect mosquitoes making them an excellent sentinel (Reisen et al., 1994). Humans and horses become infected incidentally by the bite of either *Cx. tarsalis* or *Aedes* mosquito species, but do not develop sufficient viremias to infect mosquitoes and therefore are dead end hosts for the virus.

SLE is distributed widely throughout the New World, but most outbreaks typically have occurred at warm latitudes in North America (Hess et al., 1963). Strains vary markedly in virulence. Geographic variation in strain virulence has been related to coevolution with susceptibility to infection by the three regional vectors, *Cx. tarsalis* [western US], *Culex pipiens* complex [southern, central and eastern US], and *Culex nigripalpus* [Florida] (Mitchell et al., 1983; Meyer et al., 1983).

SLE [like WEE] is amplified in nature within a primary enzootic cycle involving *Cx. tarsalis* and birds in the orders Passeriformes and Columbiformes. After amplification in the primary cycle, secondary vectors including *Cx. quinquefasciatus* and *Cx. stigmatosoma* may become involved, especially in suburban/urban situations. Humans are infected tangentially and are a dead-end host for the virus. SLE causes clinical central nervous system illness in humans; domestic animals and poultry appear to be unaffected by infection (Tsai and Mitchell, 1989). Unlike WEE, SLE continues to be a significant health problem in the

United States with substantial epidemics occurring in the Ohio River drainage during 1975–1976 and in Florida during 1992. In California, outbreaks of 25–35 cases have occurred in the Los Angeles basin during 1984 (Murray et al., 1985) and in the southern San Joaquin Valley during 1989 (Reisen et al., 1992).

Prior to its introduction into North America in 1999, West Nile virus was found in the Old World and Oceania (Africa, Europe, the Middle East, west and central Asia and landforms of the southern Pacific Ocean: CDC, 2003). Since its introduction to North America, WN has spread rapidly across the US and into Mexico, Central America and the islands in the Caribbean Ocean. WN is maintained in nature within a primary enzootic cycle involving mosquito vectors and bird reservoir hosts. WN has been found in nearly 140 North American bird species (CDC, 2003), about 15% of these species occur frequently in or near wetlands, but only a subset of the 140 species is severly affected by WN infection. Like the three aforementioned arbovirus encephalitides, humans, horses and other mammals are incidentally infected, primarily by blood-feeding mosquitoes. Other less common forms of WN transmission have been suggested (CDC, 2003). While most WN infections in humans are mild and do not manifest symptoms of illness, approximately 20% of infections develop West Nile fever. Severe infections occur in about 1 in 150 cases. Neurological disease, encephalitis, paralysis, rash and sometimes death occur from severe infections (CDC, 2003).

In addition to arboviruses that are detected annually by surveillance programs in the US, mosquitoes associated with wetlands have been linked to the transmission of pathogens causing other diseases of humans, wildlife and domestic animals. For example, human malaria occurred routinely in the United States until early in this century.

4. Mosquito control strategies

Biological control agents for mosquitoes can be placed into eight general categories: four microbial agents (viruses, protozoans, fungi and bacteria) and four multicellular agents (nematodes, cyclopoid copepods, predaceous aquatic insects, and larvivorous fish). Extensive reviews of biological control agents for mosquitoes and other pestiferous flies have been published (Chapman, 1974, 1985; Mulla, 1985; Lacey and Undeen, 1986; de Barjac and Southerland, 1990; Lacey and Mulla, 1990). Although particular species within each of the parasite or predator groups can be responsible for mortality of mosquitoes under specific conditions, only a subset of these agents is suitable for large-scale biological control in constructed treatment wetlands. There are no effective biological control agents for adult mosquitoes. Even though some aerial vertebrate predators consume mosquitoes, bats and birds such as purple martins do not routinely eat mosquitoes, do not feed during the peak activity period of many mosquito species, feed on non-biting adult mosquitoes (i.e. swarming males) and, at natural densities, cannot consume sufficient numbers of mosquitoes to reduce population size significantly (Kale, 1968; Whitaker and Long, 1998). The most effective biological agents against immature mosquitoes are mosquito-specific bacteria and larvivorous fish (Chapman, 1985).

4.1. Mosquito-specific bacteria

Two *Bacillus* species are currently registered for use against mosquitoes in much of the United States. *Bacillus thuringiensis* variety *israelensis* (*Bti*) was federally registered for mosquito control in 1981. *Bacillus sphaericus* (*Bs*) was approved for larval control more recently (1991). *Bacillus sphaericus* is a more effective control agent for mosquitoes in wastewater with high organic content and/or suspended sediment than is *Bti*. However, *Bs* has a narrower host range than *Bti*; most *Aedes* species are not susceptible to *Bs*. *Bacillus* toxins exhibit specific pathenogenicities and are safe to humans and to other non-target organisms at current application rates and by common modes of contact (see reviews in Lacey and Undeen, 1986; Mulla, 1990; Walton and Mulla, 1992). The toxin is short-lived and degraded rapidly by UV light in aquatic environments.

Bacillus is a very attractive and effective candidate for controlling mosquitoes associated with treatment wetlands; however, any program using *B. sphaericus* should be carried out in such a manner as to reduce the likelihood of resistance induction in the mosquitoes. The effectiveness of the mosquitocidal toxins against mosquito larvae will vary with environmental conditions such as the concentration of suspended solids, water temperature, water depth, ionic content of the water, larval density, solar radiation, flow regime, and vegetative cover (Walton and Mulla, 1992). Pelletized and granular formulations of the bacteria are recommended for vegetated habitats; however, it is very difficult to penetrate thick vegetation and to uniformly apply mosquitocidal dosages. Because the spores containing the toxin precursors readily settle out of the water column and treatment wetlands are flushed continuously, repeated applications are necessary (Walton et al., 1998).

4.2. Larvivorous fish

The mosquitofish (*Gambusia affinis*) is the most widely distributed larvivorous fish used for mosquito control (Meisch, 1985), having been used worldwide for more than 80 years. The use of mosquitofish recently has become controversial because it has been suggested that *Gambusia* affects the biodiversity and abundance of local fish local fauna (Gamradt and Kats, 1996; Rupp, 1996), particularly certain rare fishes in western drainages (Page and Burr, 1991). The mosquitofish is an effective biological control agent in only a subset of the habitats to which the fish has been introduced (Rupp, 1996; Gratz et al., 1996). The mosquitofish is tolerant of a wide range of environmental conditions (Meisch, 1985): temperature tolerances range from 0.5 to 42 °C; mosquitofish populations have been observed to maintain themselves at pH 5–9.5 with a greater range possible; as long as access is provided to the water surface, mosquitofish persist at dissolved oxygen concentrations circa 0 ppm; *Gambusia* will frequent brackish water and is known to occur in power plant cooling ponds with salinities as high as 15 ppt; and successful reproduction has been observed in chemical oxygen demand (COD) concentrations between 40 and 150 ppm, and survival is possible in CODs as high as 200 ppm (Coykendall, 1980; Meisch, 1985).

The mosquitofish is a live-bearer and reproduces from early spring through the late autumn in the western US (Coykendall, 1980). Females are ovoviviparous; eggs hatch within the body of the female and clutch size can be as high as several hundred young. Interbrood intervals average approximately 3 weeks during the summer and approximately 60 days at the beginning and end of the annual reproductive period. Reproduction is typically rapid after introduction into a newly inundated habitat or at the beginning of the summer; however, following a rapid increase in population size, population growth can often become food limited.

Dietary preferences, a capacity for rapid numerical response after stocking, and wide environmental tolerances make the mosquitofish a preferred biological control agent in a wide range of habitats which includes wetlands and wastewater (oxidation) ponds. *Gambusia* has a broad diet and is opportunistic, concentrating its feeding at the water surface where mosquito immature stages are likely to congregate. Environmental tolerances are wide. Hardiness is particularly important in some treatment wetlands where dissolved oxygen concentrations near the sediment, and within the water column during periods of each day, can be extremely low. The effectiveness of any larvivorous fish declines in dense vegetation (Coykendall, 1980) and under low ambient oxygen concentrations found in many constructed treatment wetlands (Walton et al., 1997).

4.3. Source reduction

Emergent vegetation in constructed treatment wetlands is an integral component of the water treatment process; however, dense emergent vegetation promotes mosquito production and impedes mosquito abatement efforts (Schaefer and Miura, 1986; Orr and Resh, 1990; Walton et al., 1990b; Westerline, 1995; Russell, 1999; Walton et al., 1998; Thullen et al., 2002). Wetland vegetation provides treatment benefits such as organic carbon needed for microbial transformation processes, reduced flow rates that enhance settling of suspended particulates, absorption of certain pollutants into plant tissues, physical structure for the attachment of microbes, moderation of environmental factors such as water temperature and oxygen concentrations in the sediment, and habitat for wildlife (Kadlec and Knight, 1996). Dense stands of plants physically obstruct access to mosquitoes by predators and hinder mosquito control efforts. Some authors have ranked different wetland plant species based on their contribution to mosquito production (TVA, 1947, Collins and Resh, 1989). All *Typha* species, several *Schenoplectus* {=*Scirpus*} species, and *Phragmites communis* are at the bottom of the desirable plant list (Table 1).

Table 1
Estimated mosquito production propensity of various wetland plant species (from Collins and Resh, 1989)

Plant group	Plant species	Common name	Mosquito production score
Rooted emergent plants	*Alisma geyeri*	Water-plantain	7
	Alisma trivale	Water-plantain	7
	Alopercurus howellii	Foxtail	9
	Carex obnupta	Sedge	11
	Carex rostrata	Sedge	14
	Carex stipata	Sedge	13
	Cyperus aristatus	Flat sedge	9
	Cyperus difformis	Flat sedge	11
	Cyperus esculentus	Flat sedge	13
	Cyperus niger	Flat sedge	12
	Deschampsia danthonides	Grass	11
	Echinochloa crusgalli	Barnyard grass	11
	Echinodorus berteroi	Burhead	10
	Eleocharis palustris	Spikerush	10
	Equisetum arvense	Horsetail	14
	Frankenia grandifolia	Alkali heath	14
	Glyceria leptostachya	Mannagrass	12
	Juncus acutus	Softrush	13
	Juncus effusus	Softrush	10
	Jussiaea repens	Primrose	16
	Leersia oryzoides	Rice cutgrass	11
	Leptochloa fasicularis	Salt-meadow grass	10
	Ludwigia spp.	Primrose willow	9
	Lythrum californicum	Loosestrife	13
	Oryza sativa	Rice	9
	Phalaris arundinacea	Reed canary grass	14
	Phragmites communis	Common reed	17
	Plantago major	Common plantain	9
	Polygonum amphibium	Water smartweed	14
	Polygonum hydropiperoides	Smartweed	12
	Polygonum pennsylvanicum	Pinkweed	12
	Polygonum punctatum	Smartweed	12
	Polypogon elongatus	Rabbitfoot grass	11
	Potentilla palustris	Cinquefoil	11
	Pterididum aquilinum	Fern	13
	Sagittaria latifolia	Duck-potato	7
	Sagittaria longiloba	Arrowhead	7
	Sagittaria montevidensis	Giant arrowhead	8
	Scirpus acutus	Bulrush	15
	Scirpus americanus	Three-square bulrush	10
	Scirpus californicus	Giant bulrush	15
	Scirpus olneyi	Alkali bulrush	12
	Sparganium eurycarpum	Burreed	13
	Typha angustifolia	Narrowleaf cattail	16
	Typha glauca	Cattail	16
	Typha latifolia	Common cattail	17
	Zizania aquatica	Wildrice	13
Floating aquatic plants	*Azolla filiculoides*	Water fern	10
	Bacopa nobsiana	Water hyssop	13
	Brasenia schreberi	Water shield	12
	Eichhornia crassipes	Water hyacinth	18
	Hydrocotyle ranunculoides	Pennywort	15

Table 1 (*Continued*)

Plant group	Plant species	Common name	Mosquito production score
	Hydrocotyle umbellata	Pennywort	15
	Lemna gibba	Duckweed	9
	Lemna minima	Duckweed	9
	Nasturtium officinale	Water cress	15
	Nuphar polysepalum	Spatterdock	11
	Pistia stratiotes	Water lettuce	18
	Potamogeton crispus	Curled pondweed	8
	Potamogeton diversifolius	Pondweed	8
	Ranunculus aquatilis	Buttercup	16
	Ranunculus flammula	Buttercup	15
	Spirodela polyhyiza	Duckmeat	9
	Wolffiella lingulata	Bog mat	9
Submerged aquatic plants	*Callitriche longipedunculata*	Water starwort	11
	Ceratophyllum demersum	Coontail	15
	Eleocharis acicularis	Spikerush	8
	Elodea canadensis	Waterweed	8
	Elodea densa	Waterweed	11
	Isoetes howellii	Quillwort	7
	Isoetes orcuttii	Quillwort	7
	Lilaeopsis occidentalis	Lilaeosis	7
	Myriophyllum spicatum	Water milfoil	14
	Najas flexilis	Naiad	11
	Najas graminea	Naiad	11
	Poamogeton filiformis	Pondweed	13
	Potamageton pectinatus	Sago pondweed	13
	Ruppia spiralis	Ditchgrass	11
	Utricularia gibba	Bladderwort	12
	Utricularia vulgaris	Bladderwort	13
	Zannichellia palustris	Horned pondweed	10

Low scores indicate that the plant species are compatible with effective ecological mosquito control. According to Collins and Resh, scores less than 9 indicate minimal mosquito breeding problems, scores between 9 and 13 indicate a need to maintain a low coverage for this plant species, and scores of 14 and above indicate a need to minimize the occurrence of the plant species in the wetland to avoid mosquito issues.

An effective environmental control for vegetation and mosquitoes is proper water level control (Cardarelli, 1976; Collins and Resh, 1989) and the incorporation of design features that reduce mosquito production. Contrary to normal design of wetland littoral zones, optimal design for mosquito control includes steep, nearly vertical basin sides and conveyance structures that eliminate standing water. Channelization to increase the water flow, to steepen banks and provide access to predators of mosquitoes will reduce the likelihood that isolated pools and marshy areas, which are favorable for mosquito development, will occur (Service, 1993). Management practices that create depressions and collect standing water should be avoided. Partial drawdown is an effective abatement strategy in habitats where mosquito habitats are restricted to the wetland periphery (Collins and Resh, 1989). However, partial drawdown is often a counter-productive mosquito control strategy in thickly vegetated wetlands (Collins and Resh, 1989).

Augmentation of water levels is generally more successful than is drawdown, because mosquito habitat in submerged vegetation and emergent vegetation is reduced by inundation. Augmentation of water level is an effective control strategy for mud flats in the high zone of salt marshes (Carlson, 1983; FCCMC, 1998). Mosquito habitat just below the water surface in rooted submergent and floating plants of non-tidal wetlands is eliminated by flooding (Collins and Resh, 1989). Emergent vegetation is drowned and further proliferation is discouraged by raising water levels. Increasing water depth 5–8 cm (2–3 in.) (Collins and Resh, 1989) is probably sufficient in wetlands where submerged vegetation is prevalent. Water depth must be maintained for extended periods at depths greater than 80–150 cm to discourage the growth of bulrush (*Schoenoplectus*) and cattail (*Typha*) (Kadlec and Knight, 1996). If emergent vegetation at the wetland periphery is the primary source of mosquitoes, augmentation could exacerbate mosquito problems by increasing the amount of wetted vegetation (Collins and Resh, 1989). Augmentation is impractical for many wetlands because (1) designs cannot accommodate the vertical change in water levels necessary for effective management of emergent vegetation, (2) the loss of the majority of emergent macrophytes is contraindicated for water quality improvement and (3) water supply is not predictable or sufficient to carry out manipulations of water depth. Steep-sided basins also may pose a safety concern for wetlands accessible to the public.

Other forms of vegetation management by physical control include herbiciding, harvesting and controlled burning (Collins and Resh, 1989; Kadlec and Knight, 1996). Herbiciding on a large scale is impractical in situations where water quality is the primary concern. Some herbicides are toxic to aquatic fauna and desirable plant species and their usage can adversely affect water quality in freshwater ecosystems (McComas, 1993). Harvesting requires either heavy equipment such as backhoes and bulldozers (Thullen et al., 2002) or expensive amphibious/aquatic mechanical weed-harvesting equipment (McComas, 1993). If backhoes or bulldozers are to be used, then the ability to dry habitats without compaction and/or furrowing of the substrate is needed. Cut vegetation should not be left in the basin to decay (Keiper et al., 2003). Disposal of the harvested material requires access to the basin floor and along the perimeter of the wetland.

Effects of various vegetation management methods on mosquito production was the focus of research at a constructed pilot wetland project in Sacramento, California (Wright et al., 1995; Nolte and Associates, 1997). Various cells received different treatments including thatching (complete removal of standing vegetation), combing (partial vegetation removal), edging (removal of bank vegetation), and channelization (creating of deep channels). Reduction in vegetation density had a positive effect on mosquitofish density and mosquito control. It was noted that plant regrowth quickly replaced the removed vegetation and negated the effects of thatching, combing, and edging. The need for annual vegetation maintenance equates to a relatively high cost for these vegetation management methods.

Burning of dried emergent vegetation allows large areas to be cleared quickly and cheaply (Walton, 2002). Burning and discing have been shown to reduce mosquito production and enhance waterfowl habitat in saltgrass (*Distichlis spicata*) and pickleweed (*Salicornia virginica*)-dominated seasonal wetlands in central California (Schlossberg and Resh, 1997). Burning destroys the organic carbon source for denitrifying bacteria and mobilizes stored nutrients and pollutants (Kadlec and Knight, 1996). The impact of ash and other residuals could affect water quality. Air quality concerns and forest/brush fire potential are important considerations for burning programs.

There is a need to design mosquitoes out of wetlands (as much as possible) rather than relying on control measures after dense vegetation develops. Vegetation management strategies need to be evaluated not only for vector control, but also for their impact on water quality goals and hydrological considerations.

4.4. Chemical control

Conventional chemical pesticides, such as the organophosphate compound temephos, still remain economical for larviciding in large-scale abatement efforts (FCCMC, 1998). Even though such chemicals are not particularly toxic to mammals, their toxicity to wetlands wildlife, such as fish and birds, is a concern.

Mosquitocidal oils, such as Golden Bear 1 1 1 1 or Bonide Mosquito Larvicide, kill mosquito larvae and pupae by interfering with air intake at the water surface. Mosquitocidal oils typically are reserved for emergency use when pupae are present and the emergence of adults is imminent. Oils frequently are combined with surfactants and other agents that enhance spreading across the water surface. The oils volatize within about 48 h when exposed to sunlight and are federally and state approved for vector control.

In regions where rainfall is common and large expanses of water are present, adulticiding is the only means of controlling mosquitoes. However, in the arid regions where surface waters can be delineated, surveyed and treated, adulticiding is used primarily as a last resort to control mosquitoes. For situations where larviciding is ineffective or under emergency situations when a disease outbreak is imminent, adulticiding is the only effective means of quickly eliminating infected mosquito populations. Recent studies indicated that adulticides (i.e. pyrethrin, malathion and permethrin) applied at mosquitocidal dosages were not acutely toxic to common freshwater insects and aquatic vertebrates (Lawler et al., 1997).

The cost of mosquito abatement for small wetlands is several hundred dollars for each application of mosquitocidal materials. The costs rise rapidly once aircraft or helicopters are needed; the cost of *each* mosquito abatement treatment (labor, materials, and larvicides) by helicopter for a moderately sized wetland (10 ha) is approximately US$ 4000 (Walton, 2002).

Integrated pest management approaches combine source reduction, biological control agents and application of mosquito-specific larvicides. Native biological control agents are preferable to exotic species. Mosquito control is moving away from application of conventional chemical pesticides to more environmentally friendly methods such as mosquito-specific bacteria in the genus *Bacillus* and insect growth regulators (IGRs). Although long-term effects on aquatic food webs of the latter mosquito control agents have been suggested (Hershey et al., 1998), subsequent studies (Schmude et al., 1998; Balcer et al., 1999) failed to confirm that either mosquito control agent causes the food web effects observed in the study of Hershey et al. Nevertheless, judicious use of any control agent is advisable.

5. Constructed treatment wetland design to avoid mosquito problems

This section describes how constructed treatment wetland design may conflict with published guidelines to reduce mosquito production or mosquito-related nuisance conditions. The apparent ramifications of each wetland design decision in light of the mosquito issue are described, and the available alternative design methods are discussed. When known, the efficacy of these design alternatives are quantified, both for their effect on reducing mosquito nuisance conditions and for their effect on meeting water quality treatment goals.

5.1. Treatment wetland siting

Site selection for new treatment wetlands must consider the costs and benefits of alternative locations. Conveyance of wastewaters and stormwaters is expensive and impractical over long distances. Large centralized collection and treatment facilities may have the resources to pump water to a remote wetland treatment location, but local stormwater treatment facilities and small municipal treatment wetland systems usually require sites near the wastewater source. All sites have some potential for mosquito production prior to their conversion to a treatment wetland site. If all other factors are equal, sites with a pre-existing land use that is favorable for mosquito production should be ranked higher for selection than sites without existing mosquito problems. This criterion will result in the lowest net effect of the treatment wetland project on increasing mosquito populations.

Adult mosquitoes effectively disperse up to several kilometers from developmental sites (Service, 1993). Distances within the flight range of a significant percentage of the mosquitoes produced at wetlands are a siting consideration when nuisance biting by mosquitoes is the primary concern. Dispersal distance curves are generally decreasing exponential functions (Southwood, 1978). A typical range of distances reached by 90% of the emerging mosquitoes from a freshwater treatment wetland might be from 1–5 km (Service, 1993; Tennessen, 1993; Walton et al., 1999); yet, species-specific differences in dispersal behavior may result in nuisance biting, and the need for mosquito abatement near human residences at much greater distances.

While efforts need to minimize mosquito development from the treatment wetland through design and control measures, some mosquitoes are almost always present and will disperse in search of hosts. The fewer people who are living or working within the mosquito flight radius of a treatment wetland, the lower the risk of nuisance conditions or disease transmission. A conflict can be created over time as suburban sprawl encroaches on rural areas where treatment wetlands frequently are sited. On the other hand, some people like to live near wetlands or to engage in wetland-related recreational activities. These people might choose to live near an aesthetically designed and maintained treatment wetland and brave the potential mosquito nuisance in favor of the view and the wildlife.

If mosquito dispersal distances were well known, then a criterion of a percent reduction (for example 90%) could be used to establish an appropriate buffer zone around a treatment wetland. This buffer zone, if any, will be dependent upon regional mosquito population size, production of adult mosquitoes in the wetland, the neighbor's tolerance to mosquitoes and desire to be near wetlands, and the actual risk of disease transmission. The buffer zone also will depend upon the mosquito species of concern and local conditions (e.g. topography, meteorological conditions, etc.).

5.2. Pretreatment to minimize mosquito production

Wastewaters and stormwaters frequently are pretreated before discharge into a treatment wetland (Kadlec and Knight, 1996). The appropriate level of pretreatment is an important consideration in the design of any treatment wetland because the treatment wetland may need to be larger or smaller depending on its influent water quality.

There are numerous references documenting an apparent relationship between mosquito production and poor water quality (Carlson and Knight, 1987; Collins and Resh, 1989; Kramer and Garcia, 1989; Tennessen, 1993). High levels of dissolved organic matter are thought to provide nutrients for the bacteria and algae used as food by mosquito larvae. Compounding this apparent enhancement of mosquito production is the potential effect of high organic matter concentrations leading to high decomposition rates, low dissolved oxygen, and unsuitable conditions for aquatic mosquito predators such as dragonflies or fish (Mian et al., 1986; Walton et al., 1996, 1997). Insecticides may be less effective in highly polluted waters (Russell, 1999), particularly the environmentally friendly bacterial larvicides that require ingestion by mosquito larvae.

The levels of dissolved organic matter that can occur in partially treated wastewaters may lead to explosive increases in mosquito abundance (Smith and Enns, 1967; Rutz et al., 1980; O'Meara and Evans, 1983). Secondary treated wastewaters do not appear to support these rapid and excessive outbreaks; however, minimum mosquito production criteria in some regions are often exceeded in treatment wetlands receiving even advanced secondary and tertiary treated wastewaters (Schaefer and Miura, 1986; O'Meara et al., 1988; Martin and Eldridge, 1989). These ecological conditions may be the result of autochthonous production of organic matter rather than allochthonous inputs (Sartoris et al., 2000). Although pretreatment before discharge into a treatment wetland may reduce mosquito production, it is not a guarantee against mosquito presence.

No quantitative correlation or model for predicting the effects of water quality in wetlands and ponds and their resulting mosquito production is available (O'Meara and Evans, 1983; Martin and Eldridge, 1989), although eutrophication may predictably alter the species composition of the mosquito fauna. Such a prediction is essential before allocating limited resources towards wastewater pretreatment prior to discharge into a treatment wetland. Based on available information, it can be assumed that discharge of raw or primary treated municipal wastewaters into a vegetated lagoon or shallow vegetated wetland periodically can result in mosquito larval abundance from several hundred to over 1000 larvae per dipper sample (animal wastewater lagoons: Rutz et al., 1980; O'Meara and Evans, 1983). Treatment to secondary standards may limit average densities to less than 200 mosquito larvae per sample (Walton and Workman, 1998). Average densities of 0.2–0.5 mosquito larva (*Culex* plus other species) per dipper sample have been used as threshold values for intervention against mosquitoes in seasonally-flooded and treatment wetlands (Tennessen, 1993). However, wetland size must be considered in combination with larval density for estimating the impact on the host-seeking adult mosquito population. Although enhancing oxidation of nitrogenous compounds in wastewater might lessen potential mosquito production by providing more favorable conditions for mosquito predators, additional benefits for mosquito abatement, if any, from removing nitrogen or phosphorus through tertiary treatment have not been quantified.

5.3. Wetland basin design to minimize mosquito production

5.3.1. Wetland type

Treatment wetlands typically are designed for either surface flow (SF) or subsurface flow (SSF). Well-designed and operated SSF wetlands largely eliminate the potential for mosquito production. However, SSF wetlands typically cost from 1.4 to 7.1 times more than SF wetlands for treatment of a given amount of BOD, TSS, nitrogen, or phosphorus (Kadlec and Knight, 1996). SSF treatment wetlands may be a clear favorite when mosquito breeding must be near zero and total installation and operation & maintenance (O&M) cost is a lesser concern. This has only been the case for relatively small treatment systems and on-site SSF wetlands at single family residences and housing clusters.

In spite of their relatively high cost, SSF wetlands are not mosquito-proof. SSF wetlands can create nuisance mosquito populations if flow is greater than hydraulic capacity or solids plug the subsurface filtration matrix. Accumulation of water above the wetland surface can be particularly attractive to mosquitoes because wastewater usually receives less pretreatment and has higher organic loads in SSF systems than water in SF systems. SSF wetlands typically do not have predatory fish or insect larvae available to prevent mosquito outbreaks when surface flow occurs.

SF wetlands are generally the lowest cost treatment wetland alternative (Kadlec and Knight, 1996). They simulate most of the conditions typical of natural wetlands, including conditions suitable for production of immature mosquitoes and aquatic predators that eat mosquito larvae. While most SF treatment wetlands are predominantly vegetated with emergent plants, they frequently include areas of open water with floating and submerged aquatic plants. A complete range of water depths and plant diversity options is included in existing SF treatment wetlands. All of these options have different potentials for mosquito production; however, quantitative criteria are seldom available for selection of one design option compared to another.

SF treatment wetlands receiving pretreated wastewaters typically have mosquito production rates similar to natural wetlands (Davis, 1984; Carlson and Knight, 1987; Tennessen, 1993). Russell (1999) noted that permanently flooded habitats, with a diverse invertebrate and vertebrate fauna, generally produce fewer mosquitoes than newly or intermittently flooded habitats without predators. This is especially true for colonizing mosquito species such as *Cx. tarsalis* that typically track newly created oviposition sites or perturbations that renew primary productivity rates. SF treatment wetlands designed for wildlife habitat creation typically meet these criteria.

5.3.2. *Wetland sizing*

Selection of the wetland area necessary to meet effluent limits without excessive conservatism is the key to cost effective wetland design. Treatment wetland capital cost is a direct function of wetland area. Excessively large wetlands result in unproductive expenditures, but they also buffer inflow variations and pollutant loads. Wetland sizing typically is based on determining the area needed to effectively treat the single most restrictive effluent limitation. Differing types of wetlands have different performance efficiencies and may call for different design models or parameters. Densely vegetated wetland cells with limited open or deep-water areas typically provide higher pollutant removal rates than deep-water cells or ponds (Kadlec and Knight, 1996). Cells without short circuiting channels from the inlet to the outlet also provide higher treatment efficiencies. Incorporation of large open water areas and channels perpendicular to water flow to reduce mosquito production, as described below, result in the need to construct larger treatment wetlands and, in some cases, may result in the inability of a treatment wetland to meet effluent regulations.

5.3.3. *Wetland configuration*

Typical treatment wetland design requires two or more parallel wetland cells to provide the ability to continue treatment when one cell is removed from operation (Kadlec and Knight, 1996). Wetland cells also may be arranged in series to adapt a project to a sloped site or to ensure flow redistribution at various points through the treatment wetland. Design for mosquito control flexibility also requires multiple cells. Some authors have suggested that dry down may be an effective tool for control of the immature stages of some mosquitoes (Chanda and Shisler, 1980; Tennessen, 1993; Mitsch and Gosselink, 2000). Maximizing wetland system operation flexibility by incorporating alternate flow paths does not present a conflict between treatment wetland design and mosquito control.

5.3.4. *Selection of design water depths*

Water depth is an important aspect of treatment wetland design due to its effect on plant growth, diffusion distance, and hydraulic residence time. Very shallow water depths (less than 15 cm) may not result in complete flooding of wetland cells that have not been graded to close elevation tolerances. However, shallow water depths increase linear flow velocities and shorten diffusion gradients important for exchange of gaseous and dissolved pollutants and limiting substances such as atmospheric oxygen. Higher linear flow velocities are known to reduce the potential for mosquito production due to their effect on mosquito survival (Russell, 1999); however, a quantitative estimate for the inverse relationship between flow velocity and mosquito production does not exist.

Limited empirical evidence indicates that wetland treatment performance does not typically increase at average water depths greater than about 30 cm (Kadlec and Knight, 1996). Water depths over 30 cm also may result in decreased health and growth of emergent plants in treatment wetlands. The result is increased plant mortality and eventual replacement by floating aquatic plant species. Both of these conditions may actually result in increased mosquito production. Deeper water is often included in limited areas of treatment wetlands. These “deep zones” are most effective at enhancing treatment when they are arranged perpendicular to the direction of flow. In this configuration deep zones help to redistribute waters that are sheet flowing across shallow emergent marsh areas. They also provide a sump for long-term retention of settled solids and a safe harbor for fish and other fauna that may prey on mosquito larvae and pupae.

The literature on mosquito control in treatment wetlands suggests that water depths should be up to and greater than 1 m (Russell, 1999). However, any water depths over about 60 cm ultimately will result in pond or shallow lagoon conditions. There is preliminary evidence that a shallow wetland that is colonized heavily with submerged aquatic plants is just as effective or more effective for water quality treatment than an emergent marsh at low nutrient concentrations (Chimney and Moustafa, 1999). However, controlling shallow pond environments to promote submerged aquatic plant growth over floating plant growth is not an exact science at this time. Also, mosquito control professionals are not looking to replace an emergent marsh with a weed-filled shallow pond. They are looking for open water with minimal vegetation resulting in maximum access by fish and wind fetch for disruption of mosquito oviposition. Such a system is the antithesis of a treatment wetland and when propagated over more than half of a treatment wetland area is likely to result in significant performance impairment and creation of algal solids (Kadlec and Knight, 1996).

5.3.5. Wetland grading and bottom slopes

Wetland cell grading and bottom slopes are both potentially important in the effective control of mosquitoes. Typical grading is within the range of ±15 cm. Constructed treatment wetland cells can be graded using laser-leveling to a consistent elevation with a variation as low as ±3 cm. Wetland operation at shallow water depths in poorly graded cells will likely result in isolated areas that are not accessible to mosquitofish and other aquatic predators. Varying inflow rates may result in periodic wet/dry cycles on the highest ground that could result in production of floodwater mosquito species. Effective grading of treatment wetlands provides the double benefits of increased areal treatment performance and reduced mosquito production potential.

Inclusion of a slight slope in wetland cells facilitates drainage. Bottom slopes in SF treatment wetlands typically range from zero to about 0.5%. Excessive bottom slopes result in difficult water depth management in the wetland; a high bottom slope (greater than about 0.1%) makes maintenance of a consistent water depth along the length of the wetland cell impossible. In the interest of operational flexibility, a slight bottom slope (typically 0.01–0.05%) is recommended for wetlands.

5.3.6. Wetland embankments

Constructed treatment wetland embankments typically are built with the steepest side slopes that are compatible with mowing and levee maintenance and with safety concerns. These slopes typically are in the range from 2.5:1 to 4:1 (horizontal:vertical). Steeper side slopes cost less to construct due to the smaller earth volume that must be moved and compacted. However, excessively steep slopes result in increased erosion and slumping potential prior to establishment of groundcover. When habitat is an important consideration in treatment wetlands side slopes may be lengthened to 5:1 to 10:1. These broad, gentle sloping embankments (littoral “shelves”) are conducive to establishing a gradient of dominant plant growth zones and are easier for many wetland animals to climb and colonize.

Steep embankments adjacent to deep water are a preferred mosquito control design configuration for ponds (O'Carroll, 1978; Mortenson, 1983). Steep slopes and deep water (>60 cm) reduce the amount of emergent vegetation coverage and allow better access by aquatic predators. In the case of embankment slope there is typically no conflict between treatment wetland cost and performance considerations and mosquito production potential–both can benefit from relatively steep side slopes. As discussed above, water depth is the principal conflict between these goals. This potential conflict is greatest where wetland habitat creation is an important project goal.

5.3.7. *Wetland liners*

Constructed treatment wetlands may or may not be lined—depending on wastewater or stormwater quality, site-specific groundwater considerations, soil types, and mosquito management. The presence or absence of a liner in a treatment wetland may be important in mosquito control due to its effect on the operator's ability to rapidly dry down the wetland. Unlined wetland cells can be drained faster than lined cells because of the lack of any impermeable liner and a high hydraulic conductivity. Addition of a liner slows drainage time making it dependent upon gravity flow out of the wetland cells and evapotranspiration. No liner is necessary in some poorly drained soils. Rapid drainage of wetlands is not necessary for routine mosquito control and may impact survival of fish populations in event-driven wetlands. For these reasons the liner decision is site specific.

5.4. *Hydrological control to minimize mosquito production*

Water control is an important feature of treatment wetland design. Control of water flows and depths allows the operator flexibility in setting hydraulic residence time and the resulting level of treatment. Effective water distribution and collection structures are required to direct water to all areas of the treatment wetland. Inlet valves or splitter weirs allow flow regulation to each cell individually. Adjustable outlet weirs or stop log structures allow positive control of water levels in the cells. All of these design criteria are important for optimizing treatment performance and for mosquito management. There are no apparent treatment versus mosquito control conflicts that result from incorporating good hydrological control in treatment wetlands.

5.5. *Vegetation selection to minimize mosquito production*

There is ample evidence that the presence of dense stands of emergent plants is critical for optimal performance of treatment wetlands (Kadlec and Knight, 1996; Vymazal et al., 1998). The species composition of the wetland plant community appears to be less important for treatment performance than the density and net biomass production of the plants (Kadlec and Knight, 1996). The three most widely used plant genera in treatment wetlands are: *Typha* (cattails), *Schoenoplectus* (bulrush), and *Phragmites* (reed) (CH2M HILL, 1998).

Most of the major plant species that commonly occur in treatment wetlands have been implicated as mosquito production and control problems. The presence of dense emergent and aquatic plant populations in treatment wetlands is the biggest single source of conflict between the goals of pollutant reduction and mosquito control. Design options to reduce this conflict may include:

- Selecting plant species that optimize both treatment performance and mosquito production control.
- Incorporating deep water zones that are free of emergent and aquatic plants to provide fish habitat and access to vegetated areas.
- Limiting the width of emergent plant zones to facilitate access by predaceous mosquitofish and for application of chemical control agents.

Collins and Resh (1989) rank plants in terms of their compatitbility with promoting low mosquito productivity in constructed wetlands. Each parameter is rated between 1 and 5 with a low value indicating compatibility with mosquito control and a high value indicating increased mosquito production. The Collins and Resh ranking system is based on four semi-quantitative ecological parameters:

1. *Intersection line value*. This value is high for plants with many stems and leaves that pass through the

water surface (menisci) and lower for plants with a simple structure and few stems.

2. *Crayfish food value*. This value is low for plants that are preferred food for crayfish and high for plants that are not palatable or accessible to crayfish.
3. *Waterfowl food value*. This value is low for plants that are preferred food for waterfowl and high for plants that are not grazed by waterfowl.
4. *Fish obstruction value*. This parameter has a high value for plants that block fish access and low for plants with a simple structure and wider spacing that does not block fish access.

The values for the four indices are summed and the total is used as the plant assessment score. Table 1 summarizes point rankings for a number of the plant species that are common in treatment wetlands.

Selection and ranking of the parameters in the Collins and Resh method is somewhat subjective. Quantitative data show a positive correlation between mosquito larval density and the intersection line, whereas correlations between the other indices and mosquito density are less quantitative. Although the four indices reflect common sense about the apparent effects of plant growth on mosquito production, they miss other possible correlates that are much easier to quantify (e.g. plant biomass, net annual production, percent standing dead cover, tissue nutrient content, etc.). Quantitative mosquito sampling data have not been correlated with the plant species assessed by the Collins and Resh ranking method. However, if use of these plants will not significantly diminish treatment efficiency, then plant species that are most likely to result in low mosquito production should be utilized. The general rankings in Table 1 can be used as a starting point for this decision, but quantitative research on this issue is essential for effective design.

5.5.1. Incorporation of plant-free zones

Wetland designers have the ability to control the distribution of rooted emergent wetland plants by excavating deep-water zones within a treatment wetland. Typically these zones are at least 1 m deeper than the surrounding cell bottom elevation (Kadlec and Knight, 1996). These deep zones are typically linear and arranged perpendicular to the direction of flow and are often limited to less than 25% of the entire wetland surface area (Knight et al., 1994). In some treatment wetlands that specifically have a wildlife habitat creation goal these deep zones may have sinuous margins and may occupy up to 50% of the entire wetland area (Knight, 1992). Low islands are often constructed within these larger deep zones to increase the wetland/upland edge and to create protected refuges for nesting and roosting of birds.

Incorporation of deep-water zones in treatment wetlands is compatible with mosquito control objectives. However, deep water zones that run adjacent to the shores of the treatment wetland cells or from the inlet to the outlet are not compatible with efficient hydraulics and optimum treatment performance (Kadlec and Knight, 1996).

5.5.2. Maintenance of narrow emergent plant zones

Access by aquatic predators to mosquito larvae and pupae may be prevented by dense emergent plant growth (Collins and Resh, 1989). It was observed that this difficulty increases with distance into the emergent plant zone. One possible approach to alleviate this potential problem is to limit the width of emergent plant areas to allow fish to penetrate to at least the center of any emergent plant zone. Collins and Resh (1989) reported that these plant zones might need to be limited to as little as 1 m in width to provide effective fish access for mosquito predation. The density of the plant growth is the only important factor—if a fish cannot penetrate to the middle of a cattail clump it does not matter if the cattail zone is limited in width. Jiannino and Walton (2004) found that immature mosquito abundance in and adult mosquito production from comparatively dense bulrush stands were significantly greater than for cattail stands when water level was maintained at a depth of 0.5 m. Moreover, in shallow zones where emergent vegetation can rapidly recolonize, enhanced mosquito production following wetland drying and vegetation management offset the short-term reduction in mosquito abundance provided by increasing the area of open water zones. No recommendation for limiting the width of plant zones currently can be supported by data.

The Tres Rios Cobble Site Demonstration Wetlands in Phoenix, Arizona, were redesigned in 1998 to limit the width of emergent plant zones and to facilitate movement of aquatic predators within the wetlands for more effective control of mosquito larvae (Wass, 1998). Quantitative mosquito sampling results following that re-engineering indicated reduced breeding and adult mosquito populations associated with that constructed wetland project; however, long-term trends indicate that host-seeking adult mosquito populations at that site are affected more by regional breeding success than by breeding in the constructed wetland cells (Knight and Wass, in preparation). Additional research must be conducted to provide a quantitative basis for incorporating deep zones in constructed treatment wetlands to reduce mosquito production.

5.5.3. Plant harvesting and removal

Plant harvest by use of mechanical equipment is very disruptive to flocculent wetland soils and can result in the export of significant quantities of dissolved and particulate pollutants from a treatment wetland. Mechanical harvesting is expensive and disposal of the harvested biomass, which is mostly water, is problematic. For these reasons plant harvesting is not a practical tool for management in most full-scale treatment wetlands.

Controlled burning on a reasonable schedule (every 2–5 years) with bypass for a period of one or more months around the burned cells is a reasonable method to maintain a relatively lower quantity of plant biomass in a wetland and to favor growth of new plants. Published results following a controlled burn of small (0.1 ha), replicated wetlands in southern California indicated that there was a net increase in the ratio of phosphorus/nitrogen upon inundation because of greater volatilization of nitrogen by the fire and that, during the three months of operation after inundation following a burn of *Schoenoplectus californicus*, less-vegetated wetlands were more efficient at converting a highly reduced nitrogenous secondary-treated effluent to nitrate than were more thickly vegetated wetlands (Thullen et al., 2002).

5.6. Design for chemical control of mosquito populations

Maintenance of low mosquito production rates is likely to be contingent on periodic use of chemical control agents as described elsewhere in this report. Treatment wetland design can facilitate access for this chemical control. Specific recommendations to provide good access include:

- Incorporate wide embankments to allow drivable shoreline access to all wetland cells. These embankments will typically have a top width no less than 4 m and should have side slopes no steeper than 3:1 to allow mowing and sampling access.
- Provide access structures with appropriate slopes to allow access into deep water zones. Boats can be launched into these areas to provide spraying access. Airboats can be used for access to larger wetland cells.
- Keep embankments and all wetland areas free of powerlines and other tall obstructions that might limit aerial spraying.
- Provide piping and valving needed to apply chemical and biological control agents directly into the flowing water. Water management structures provide a convenient point of application throughout the constructed wetland.

6. Research needs

Several areas of research still need to be pursued to resolve the potential conflict between use of treatment wetlands and their reputation as “mosquito-friendly habitats.” This proposed research agenda includes additional basic mosquito ecology studies as well as side-by-side comparisons of the efficacy of treatment wetland design criteria. This additional research is needed to determine the extent and relevance of the mosquito problems at constructed treatment wetlands and to develop more effective procedures for minimizing these problems in full-scale projects. Priority areas for research into better management of mosquito issues in constructed wetlands include:

- Additional research needs to be conducted on the effect of wetland design and O&M on water quality and mosquito production. Investigation of factors such as surface area coverage by particular types of vegetation (emergent, floating, and submerged species), pollutant loading rates, flow/velocity rates, etc. is warranted. The purpose of this proposed research is to determine whether minor modifications in flow rates, water quality conditions and plant cover in the constructed wetlands significantly reduce the abundance of immature mosquitoes or change species composition.

- The effect of wetland immature mosquito production on populations of host-seeking adults needs to be clarified. If larval mosquitoes are just "fish food", then they are an ecological benefit to the wetland. If these larval populations are correlated with the number of emerging adults, then they are a potential nuisance. Additional population studies need to be conducted to quantify the relationship between larval mosquito populations and emerging adults.
- Mosquito production from constructed treatment wetlands needs to be quantitatively compared with production from other man-made and natural sources in the area. Relationships should be determined between land use patterns and mosquito production from areas adjacent to the treatment wetland site.
- Additional information should be obtained concerning larvicidal treatment methods and other mosquito abatement practices to achieve the best results for mosquito abatement. The research question is how to better integrate conventional control with habitat manipulations and natural mortality factors.
- Approriate thresholds for mosquito control need to be developed that avoid nuisance conditions in differing areas.
- Additional research needs to better document the dispersal patterns of mosquitoes produced by treatment wetlands. Research questions include: how do disperal patterns change seasonally (particularly if meterological conditions, such as prevailing wind direction, change seasonally); how do the dispersal distance relationships of mosquitoes relate to the spatial pattern of host seeking mosquito abundance in the region surrounding the site; is mosquito production from the wetland complex a major contributor to the host seeking mosquito abundance in adjacent wetland and floodplain environments, or might mosquito production be higher at surrounding sites; and can a buffer zone around a treatment wetland realistically be estimated?
- Quantitative research needs to be conducted to determine the actual risk of viral infections resulting from mosquitoes produced by treatment wetlands. Specific research questions related to health issues include: how does the intensity of enzootic encephalitis virus activity as measured by seroconversion rates in sentinel chickens and infection rates in *Cx. tarsalis* mosquitoes compare to the surrounding wetland habitats; what will be the effect of riparian or wetland habitat enhancement on virus activity levels; what is the seasonal pattern of disease transmission from constructed wetlands; what are the effects of wetland habitat creation on wildlife composition and abundance; and what are the zoonotic implications of wildlife enhancement and the potential risk to the human populations?
- Additional research also needs to be conducted on the potential impacts of mosquito control activities on the wildlife inhabiting constructed and natural treatment wetlands. The ecological risk of all biological and chemical control agents need to be tested in constructed wetland environments.
- Together, these research efforts may provide a successful strategy for resolving the mosquito/treatment wetland conflict.

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