CENTRAL VALLEY JOINT VENTURE

TECHNICAL GUIDE TO BEST MANAGEMENT PRACTICES FOR MOSQUITO CONTROL IN MANAGED WETLANDS

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Photo: Jim Pickering, BLM

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TABLE OF CONTENTS

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We are extremely grateful to the many individuals and groups that provided information on the mosquito Best Management Practices for the guide. Through the practical applications of these practices and continuing experimentation, creative solutions are being found to help reduce mosquito conflicts while providing quality wetland habitat in the Central Valley. Although much of this information can be found in other published literature, the focus of this guide is on techniques from the first hand experience of wetland managers and mosquito abatement technicians who spend much of their time working in wetland habitats.

This guide would not have been possible without the encouragement and partnership of the Mosquito and Vector Control Association of California. This document exemplifies their commitment to Integrated Pest Management for mosquitoes and will be updated as additional information becomes available on habitat-based practices for mosquito control.

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LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Public attitudes about wetlands have greatly changed in the last few decades. Historically, wetlands were regarded as impediments to economic progress and "reclaimed" for agricultural production and other commercial uses. Today, wetlands are valued for their habitat for fish and wildlife, recreational opportunities, and the benefits they provide in terms of flood control, water filtration, and ground water recharge. There is greater awareness of the significance of the loss of over 95% of the Central Valley's historic wetlands, and a public desire to restore, protect, and manage these habitats (Central Valley Habitat Joint Venture 1990).

With more public interest in restoration, protection, and management of wetland habitats, conservation projects have increased from a few small, site-specific efforts to larger, cooperative programs. Partnerships have been forged between resource agencies, conservation groups, and private citizens to help further wetland restoration and protection goals. Several landscape scale restoration plans have been developed throughout California. However, as California becomes more urbanized and development encroaches into historically rural areas, conflicts can arise from public health concerns about mosquito production in wetlands, rice fields, or other rural sources.

To address these concerns as they relate to wetlands, this technical guide has been developed to provide information on habitat management strategies to reduce mosquito production in managed wetlands, and to facilitate greater cooperation among wetland habitat mangers and Mosquito and Vector Control Districts (MVCDs). The term, "Best Management Practices (BMPs)" is used to describe habitat management strategies that are generally defined as a practice or combination of practices determined to be an effective and practical means for reducing mosquito populations, production rates, or the timing of hatch. These BMPs focus on exploiting the ecological relationships among mosquitoes, their predators, and the wetland habitats they use for breeding. In many cases, these practices are also beneficial to the general management of wetlands and the wildlife they support.

The BMPs identified in this guide are also an essential component of Integrated Pest Management (IPM) for mosquitoes, which incorporates knowledge of mosquito biology and the use of effective treatments to control mosquitoes while posing the least risk to people and the environment. IPM employs a variety of mosquito control methods that include habitat management, biological control agents, and pesticide application. Ideally, BMPs can be used to lower the production of mosquitoes and reduce the need for chemical treatment without significantly disrupting the ecological character, habitat function, or wildlife use of managed wetlands.

The CVJV has prepared this guide to present a full range of BMP options specific to managed wetlands. The BMPs have been identified from the scientific literature, as well as from practical applications by wetland managers and MVCDs. The extent of their use may be limited by cost and personnel constraints, physical limitations of certain wetlands, or specific habitat and wildlife management goals. In some instances, potential disadvantages need to be weighed before implementation of BMPs. BMPs to achieve mosquito control should not greatly disrupt the ecological character or habitat function of the wetland site. Not all BMPs can be effectively implemented in every wetland environment. Some initial investigation will be required of wetland managers, in cooperation with MVCDs, to identify those BMPs most applicable to an individual site. Prior to the implementation of BMPs, consultation should be conducted with MVCDs and appropriate resource agencies to determine the suitability of BMPs, and to ensure compliance with State and Federal wetland regulations and conservation easements.

The information in this guide is applicable to managed wetlands in the Central Valley of California, including the Sacramento and San Joaquin Valleys, and the Delta-Suisun region. It is intended to be a reference for wetland stewards including: the private wetland owner or caretaker, Refuge or Wildlife Area manager, wetland biologist, or mosquito and vector control technician, and should be useful when making habitat-related decisions to reduce mosquito production. The guide is intended to be as comprehensive as possible and describe BMPs based on the best available information. As additional monitoring and research is conducted, BMPs may be refined, new BMPs may be developed, and priorities for use will be determined.

Additional copies of this technical guide can be obtained by contacting the Central Valley Joint Venture office at (916) 414-6460.

MANAGED WETLAND DESCRIPTION

There are few wetland ecosystems in North America that have been more heavily modified than those in California. Massive flood control, water storage, and water conveyance projects have altered the natural hydrology that once supported over four million acres of wetlands in the Central Valley (Central Valley Habitat Joint Venture 1990). Today, most of the remaining five percent of historic wetlands in the Central Valley require intensive management, including "artificial" flooding. It is now the task of wetland managers to emulate natural hydrology and recreate a dynamic and productive wetland system through varied flooding regimes and periodic vegetation control.

Managed wetlands are typically flooded using delivered canal water, water diverted from rivers or sloughs, or deep well pumping. Without the application of water, most managed wetlands would remain dry or experience only periodic flooding in the wettest of years. As a result, managed wetlands have levees, water control structures, and other features that allow for relatively intensive management, most notably the timing, depth, and duration of flooding. This infrastructure allows for habitat management practices to promote a variety of benefits to many species of wildlife (vegetation for food and cover, adequate water quality, breeding and resting sites). This capability can also lend itself to management practices that discourage mosquito production.

The BMPs in this document were developed for use in managed wetlands, and are not applicable to wetland habitats where natural hydrology is still intact and human intervention is minimal or nonexistent. Some examples of wetland habitats where these BMPs are not applicable include vernal pools, tidal wetlands, natural seeps, and rivers/streams and their associated water bodies (oxbow lakes, sloughs, etc.).

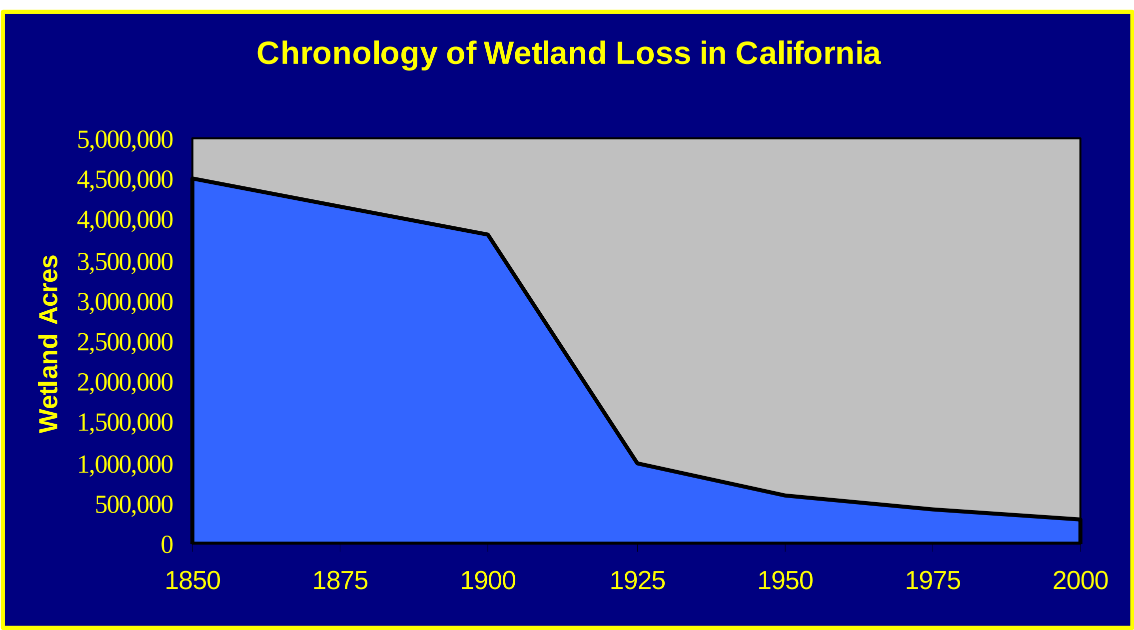

Figure 1. Chronology of wetland loss in California. Information based on data provided in the Concept Plan for Waterfowl Wintering Habitat Preservation (USFWS 1978) and CVHJV Implementation Plan (1990).

WETLAND HABITAT MANAGEMENT

In the Central Valley, managed wetlands are described by three main flooding regimes; seasonal, semi-permanent, and permanent (Smith et al. 1995). These flooding regimes are distinguished by the timing and duration that water is present on the land.

Seasonal Wetlands

Seasonal wetlands are by far the most abundant wetland habitat in the Central Valley, comprising about 85-95% of all managed wetlands (Central Valley Habitat Joint Venture 1990). They are initially flooded between August and October, remain flooded throughout the winter, and are drawn down in the spring, between March and May. Spring draw-down concentrates invertebrates in receding wetlands to provide forage for migratory waterfowl and shorebirds and exposes mudflats that germinate important seed producing plants called "moist-soil" plants. Following draw-down, most seasonal wetlands remain dry for the summer. Seasonal wetlands are the most diverse and productive type of managed wetland. They typically have the greatest diversity of vegetation and water depths, number of species (both plant and animal), and abundance of migratory birds and other wetland-dependent wildlife on an annual basis.

Depending on location, conditions, or habitat objectives, seasonal wetlands may require irrigation one to two months following draw-down to bring moist-soil plants, such as swamp timothy *(Heleochloa schenoides)*, watergrass *(Echinochloa crusgalli)*, or smartweed *(Polygonum lapathifolium)*, to maturity and enhance their production of seed for waterfowl and other wildlife (Naylor 2002). Irrigation may also be employed as a

Figure 2. **Watergrass (*Echinochloa crusgalli*) and Wetland Irrigation.** Wetlands are often irrigated to grow seed producing plants, such as watergrass, to meet the energetic requirements of migratory waterfowl and to reduce crop depredation by attracting waterfowl to wetland areas. Photos: Central Valley Joint Venture

method to control undesirable plant species, such as cocklebur (Ducks Unlimited 1995a).

Depending on the spring weather conditions, type of moist-soil vegetation that is being encouraged, or the need to discourage certain species, irrigation could occur anytime from May through July, and could vary in both number and duration. Following irrigation, when soils dry sufficiently to support heavy equipment, vegetation management (disking and mowing) is conducted to limit the extent of undesirable vegetation and promote the growth of moist-soil plants.

Additional information on seasonal wetland management can be found in *A Guide to Wetland Habitat Management in the Central Valley* (Smith et al. 1995) and *Management of Seasonally Flooded Impoundments for Wildlife* (Fredrickson and Taylor 1982).

Semi-permanent and Permanent Wetlands

Semi-permanent and permanent wetlands comprise only 5-15% of the total managed wetlands in the Central Valley (Central Valley Habitat Joint Venture 1990). Semi-permanent wetlands are typically flooded from October through mid-July and permanent wetlands are flooded year-round. These habitat types are often characterized by a combination of open water, emergent vegetation (e.g., cattails (*Typha* spp.), tules (*Scirpus acutus*), and other bulrushes), and submergent aquatic vegetation (e.g., horned (Zannichellia palustris) and sago pondweed (*Potamogeton pectinatus*)). They provide habitat important to resident wildlife, and provide breeding and molting habitats for waterfowl at a time of year when most seasonal wetlands are dry (Ducks Unlimited 1995b). Semi-permanent wetlands are drawn down after the breeding season, and measures such as disking, mowing, or burning are commonly used to manage vegetation growth. Permanent wetlands are typically drawn down every three to five years to recycle nutrients and increase productivity and, in some cases, control undesirable fish populations (e.g. carp). Similar to other managed wetland types, undesirable vegetation in permanent wetlands is typically controlled through disking, mowing, or burning.

Figure 3. **Semi-permanent Wetlands.** Semi-permanent wetlands provide critical habitat for resident wildlife at a time of year when most seasonal wetlands are dry. Photo: Jack Sparks, CDFG

MOSQUITO BIOLOGY

Mosquitoes are dipteran insects with aquatic immature stages and an aerial adult stage. They have four aquatic larval stages (instars) plus an aquatic pupal stage. The adult emerges from the pupal stage onto the surface of the water, expands its wings, hardens its exoskeleton, and flies off. Depending on seasonal and environmental conditions and the particular mosquito species involved, it generally takes from three to 12 days for a mosquito to complete its life from developed egg to early adult stage. In general, as ambient temperature increases, the number of days required from hatching to emergence as an adult decreases. Although some species of mosquitoes (e.g., *Culex tarsalis*), are capable of long flights from the aquatic habitat, the mosquito problem created by a wetland will generally be proportional to the distance from concentrations of human and domestic animal populations.

There are four primary species of mosquitoes (*Ochlerotatus melanimon*, *Culex tarsalis*, *Culex erythrothorax*, *Anopheles freeborni*) that can be produced in managed wetlands and surrounding agricultural lands that have been the subjects of control efforts by MVCDs in the Central Valley. These four species can be categorized by life history traits into two distinct groups (floodwater mosquitoes and standing water mosquitoes).

Floodwater Mosquitoes (*Ochlerotatus melanimon*)

The life cycle of the floodwater mosquito begins with flooding of ground that has undergone a dry period. The summer dry cycle in seasonal or semi-permanent wetlands fits the criteria for this species' habitat needs. Once flooded, eggs that were laid during the previous dry cycle hatch, pupate, and emerge as adults. Research conducted in Merced County found that *Ochleratatus melanimon* developed from first instar larvae to adult stage in eight to nine days in seasonal wetlands during the last half of September (Mortenson 1963). Gravid females then return to lay their eggs singly on drying soil, in leaf litter, in cracks in the soil, or at the bases of grasses and other plants in areas that have been flooded previously. Each female lays approximately 150 eggs per ovarian cycle. These eggs are very drought resistant, allowing them to survive during the summer.

Floodwater mosquitoes are often the most abundant mosquito produced by managed seasonal wetlands, especially during summer irrigations and/or fall flooding. Relative to other species, adult females are aggressive and feed primarily on mammals. During the day, females will bite if disturbed or if a host presents itself, but generally biting and swarming activities peak at dawn or dusk. Floodwater mosquitoes have been identified as a primary nuisance species and as secondary or "bridge" vectors for California encephalitis virus and western equine encephalitis, and are considered moderately effective as vectors of West Nile virus.

Standing Water Mosquitoes (*Culex tarsalis, Culex erythrothorax, Anopheles freeborni)*

Culex tarsalis

Peak numbers of *Cx. tarsalis* occur in the Central Valley during the summer. Females lay their eggs on the water surface in bunches called rafts. Each raft contains around 100-150 eggs, hatching about 24 hours after being laid. The immature stages can be found in almost any source of water except treeholes. During the summer, development from egg to adult takes about seven to nine days. Peak populations occur in late June or early July, but can continue into late summer. Adults can emerge continuously throughout the summer and fall in areas that have been flooded for an extended period of time, usually for more than 2-3 weeks (i.e. ricefields, poorly drained pastures, semi-permanent/permanent wetlands, seasonal wetlands flooded in August, sewer treatment plants, and dairy farms).

Biting and swarming activities are typically at dawn or dusk. Adults spend daylight hours resting in secluded places such as animal burrows. *Culex tarsalis* primarily bite birds, but will bite humans, livestock, and other mammals if the opportunity presents itself. In California, this species commonly feeds on song birds in spring and early summer, and switches to mammalian feeding in late summer and fall. This change in feeding habits from birds to mammals, combined with large populations and the ability to travel long distances, makes *Cx. tarsalis* a potent vector of some of California's arboviruses. *Culex tarsalis* is considered the primary vector for western equine encephalomyelitis virus (WEE) to humans and equines, and St. Louis encephalitis virus (SLE) to humans. *Culex tarsalis* has been identified as a primary vector of West Nile virus in the western United States.

Culex erythrothorax.

These mosquitoes prefer to deposit their egg rafts amid very thick aquatic vegetation in ponds and in the margins of lakes. The larvae can be difficult to sample because they are extremely sensitive to disturbances (e.g. vibrations from the collector's footsteps or dipper), tend to remain submerged longer than other mosquito species after being disturbed, and prefer to stay amid the stems of vegetation where collection can be problematic. This larval habitat can also be difficult to treat with larvicides because the water is deep, creating a much greater volume to surface area ratio than commonly encountered for *Cx. tarsalis.* In addition, the thick vegetation can protect the water surface from liquid formulations of larvicides. Fish are not always effective at controlling this species because they are visual predators and cannot find the larvae among thick growth of plants. Unlike most other *Culex* species, some individuals of *Cx. erythrothorax* bite (feed) during the day. Fortunately, this species does not migrate far (generally less than 1 mile) from the larval habitat. It is a major pest where wetlands with deep water and aquatic vegetation occur near human activity. *Culex erythrothorax* is highly susceptible to WNV infection and may act as a bridge vector of this virus in California (Goddard *et al*. 2002).

Anopheles freeborni

Anopheles freeborni also occurs in the Central Valley and is numerous during the summer, peaking in late July or August. Ricefields, and semi-permanent and permanent wetlands are the primary production areas for this species, although the immature stages are also found in ditches, seepages, and sloughs. Females lay their eggs singly on the surface of the water where they hatch approximately 24 hours later. On the average, it takes about 9-12 days for *An. freeborni* to develop from egg to adult. Like *Cx. tarsalis*, this species can produce a continuous supply of newly emerged adults under the right habitat conditions. Adults rest during the day and bite and swarm during dusk. In autumn, females enter a physiological state called diapause, during which reproduction is suspended and activity is diminished. They over-winter until January, February, or March when they come out of diapause and seek blood meals on warm days. After obtaining a blood meal, many females resume their over-wintering state until April or May when they begin laying eggs once more. The females will readily bite humans and livestock. This species can be a vector of malaria in the western United States. Malaria was a major public health problem in California through the early 1900s. A combination of case detection and mosquito control reduced transmission to very low levels by the 1920s. Three major outbreaks in the last 40 years have served as reminders that the introduction of the malaria parasite (*Plasmodium falciparum* and *P. vivax*), combined with presence of the *Anopheles* mosquito vectors, can result in transmission.

MOSQUITO ABUNDANCE IN WETLAND HABITATS

Mosquito abundance reaches its peak during the flood-up of seasonal wetlands during late summer and early fall (Figure 4). Because hundreds of acres of seasonal wetlands are flooded per week, there can be a constant influx of new mosquito cohorts, resulting in a large sustained population of mosquitoes over the flood-up period. As each wetland floods, floodwater mosquitoes (*Oc. melanimon*) can be produced initially (on average within seven to ten days), followed by *Cx. tarsalis* after approximately two weeks of inundation. There is a second smaller and much shorter-lived peak that is often observed during the spring/summer irrigation of seasonal wetlands. This involves less acreage and is not sustained since the irrigations are usually completed in seven to ten days. The irrigated wetlands then revert back to a dry period until flood-up in the fall.

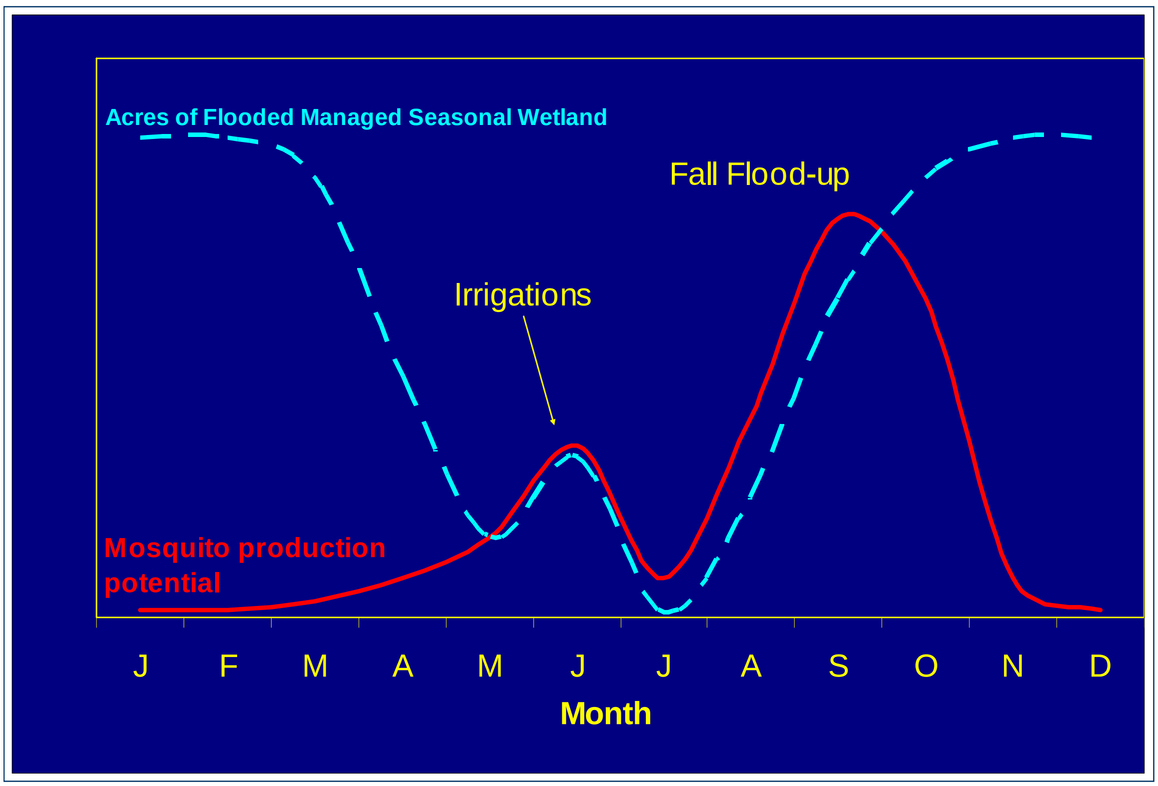

Figure 4. **Seasonal wetland flooding and potential time periods for significant mosquito production**.

Semi-permanent and permanent wetlands can produce *An. freeborni* and *Cx. tarsalis*, but because of their limited acreage, stable water levels, and abundance of mosquito predators (fish, dragonflies, and other predatory invertebrates) they are typically not considered "problem" production areas requiring additional control measures. However, they can still be managed to minimize mosquito populations by properly managing water and vegetation (Sacramento National Wildlife Refuge Complex 2000). If water levels are allowed to fluctuate, these wetlands can produce floodwater mosquitoes that may become a concern.

MONITORING MOSQUITO POPULATIONS

MVCDs determine mosquito abundance in wetlands using a variety of sampling techniques. Potential breeding sites and surrounding areas are sampled to assess mosquito populations and determine the need for control efforts. Treatment thresholds are typically determined based on monitoring both aquatic and aerial life stages of mosquitoes.

Immature Stages (aquatic)

Larvae and/or pupae are typically sampled using a “dipper”, which is a 14-ounce white cup attached to a long wooden or metal handle. The dipper is used to determine the relative density of larvae by taking standard samples of water from a potential mosquito source. The contents are examined, recording mosquito numbers and species, resulting in a “number per dip” index. Sampling immature life stages of mosquitoes serves to identify significant production sites and can help determine the potential need for treatment. This is done based on the quantity and species of larvae found (per dip), identification of the larval instar stage, number of days required for the larvae to pupate and emerge, and proximity to urban areas. Monitoring larval mosquito production throughout a wetland can help identify problem areas where certain BMPs can be employed to reduce future production.

When aquatic vegetation is abundant, some species of mosquitoes are difficult to sample in their immature stage. Larval traps have been developed, but they are not widely used. Column sampling devices have been used successfully by quickly inserting a wide pipe into the substrate and then exhaustively sampling the water within.

Adult Stage (flying)

The relative abundance of adult mosquitoes is estimated using light traps, carbon dioxide-baited traps, or landing counts, depending on the individual MVCD’s protocol. Traps are hung from trees, buildings, or special stands and usually remain in the same place throughout the season and from year to year. Light trap contents are collected weekly during the mosquito season. The total number of adult females, by species, is divided by the number of nights the trap was activated, and the index value is reported as adult females per trap night.

With landing counts, an observer stands within the sample site and faces away from the wind and counts the number of mosquitoes that land on his pant legs over a period of one minute. The count is divided by two for a “leg count” index. This procedure is usually done early in the morning or at dusk when temperatures are cool and mosquitoes are most active and is repeated three or four times per site.

BEST MANAGEMENT PRACTICES

The BMPs in this document are habitat-based strategies that can be implemented when needed for mosquito control in managed wetlands. These strategies represent a range of practices that wetland managers can incorporate into existing habitat management plans or in the design of new wetland restoration or enhancement projects. Ideally, BMPs can be used to decrease the production of mosquitoes and reduce the need for chemical treatment without significantly disrupting the ecological character, habitat function, or wildlife use in managed wetlands. It should be recognized that BMPs function as a first line of defense in deterring mosquito production and can be used in combination with other Integrated Pest Management (IPM) tools such as, biological controls, larvicides (Appendix A), and adulticides (Appendix B) when necessary.

In many cases, BMPs overlap with commonly used habitat management practices to conserve water and manage wetland vegetation for wildlife (Batzer and Resh 1992a, Batzer and Resh 1992b, Resh and Schlossberg 1996). Not all BMPs will be appropriate for a given wetland location or set of circumstances. Therefore, habitat managers are encouraged to work closely with both their local MVCD and agency biologists to select BMPs based on their potential effectiveness for regional or site specific conditions, and habitat management strategies. The implementation of BMPs will likely be limited by cost and personnel constraints, potential impacts on wetland habitat, and wildlife response to these measures.

In the following section, BMPs have been classified into five categories. These categories are not listed in order of importance and may be used in combination.

- Water Management Practices
- Vegetation Management Practices
- Wetland Infrastructure Maintenance
- Wetland Restoration and Enhancement Features
- Biological Controls

Following each category is a table summarizing the BMPs that outlines strategies, mosquito control objectives, advantages, and disadvantages (Tables 1 through 6).

Water Management Practices

Water management is one of the wetland manager's greatest tools for reducing mosquito populations (Table 1). However, it requires that water is readily available, of sufficient quantity and quality, and that the conveyance infrastructure is adequate to permit rapid flooding or drainage. In some instances, circumstances outside the control of wetland managers may limit the ability to implement water management BMPs. Such circumstances may include when agriculture drain water or delivered water is available for flooding, limited water quantity or poor water quality, and undersized water delivery or drainage infrastructure. In managed wetlands where these limitations are not an issue, the following water management practices should be considered.

Timing of Flooding: The timing of wetland flooding can greatly influence mosquito production (Fanara and Mulla 1974, Batzer and Resh 1992a). Delayed flooding may reduce mosquito production by shifting flooding schedules later in the year, when temperatures are cooler and mosquito production is less of a problem. Delayed flooding should be considered for wetlands with historic mosquito problems and those in close proximity to urban areas. However, delayed flooding means that less wetland habitat is available for wildlife during times of the year such as August and September when wetlands are particularly limited. Delayed flooding may also have limited applicability for some properties that are required to take water on a "when available" schedule and have little control over the timing of flooding. Delayed flooding may be especially difficult for State and Federal areas that are obligated to provide "early" habitat to reduce crop depredation by waterfowl.

Given the limited feasibility of delayed flooding on some properties, phased flooding of wetlands may be useful to allow habitat managers to provide some level of early flooded habitat while delaying flooding on a portion of a property. Phased flooding involves flooding habitat throughout the fall and winter in proportion to wildlife need and takes into consideration other wetland habitat that may be available in surrounding areas.

For wetlands that are flooded early (August - early September) or in close proximity to urban areas, the use of vegetation and water management BMPs should be a high priority (Tables 1 and 2).

BMPs: Delayed or phased fall flooding, Early fall flood-up planning (see Table 1 for additional explanation)

Speed of Wetland Flooding: As a general rule, the faster water can be applied during fall flooding and spring/summer irrigation, the fewer generations of mosquitoes will be hatched. Slow feather-edge flooding, although beneficial to foraging waterbirds, can produce multiple, staggered hatches of floodwater mosquitoes and, if treatment is necessary, often requires MVCDs to visit wetlands over a number of days for control activities (Garcia and Des Rochers 1983). Such an intensive treatment effort is expensive and results in additional disturbance to wildlife.

BMPs: Rapid fall flooding, Rapid irrigation (see Table 1 for additional explanation)

Figure 5. Rapid Flooding. Rapid flooding should be used to reduce the potential for multiple hatches of mosquitoes caused by slow feather-edge flooding. Photo: USFWS

Water Control: Once wetlands have been flooded, it is important for wetland managers to ensure that pond elevations do not fluctuate except during planned draw-down or periods of low mosquito production (i.e. winter months). Fluctuating water levels tend to expose wetland edges to drying and provide suitable habitat for floodwater mosquitoes to lay eggs (Garcia and Des Rochers 1983). When water levels are subsequently raised, a new cohort of mosquitoes may be hatched. Water levels should be maintained by checking water levels frequently, and adding water to offset any losses. A constant maintenance flow of water will also help maintain steady water levels, improve water quality, and reduce stagnation.

If possible, wetlands can be flooded to deeper water depths during the fall and allowed to recede during the cooler winter months to provide shallow water depths for foraging waterbirds. Deeper water depths (24 inches) at initial flooding have been shown to significantly reduce mosquito densities at Grizzly Island Wildlife Area (Batzer and Resh 1992a, b).

When flooding wetlands, water sources containing mosquito predators should be used to help colonize wetlands with predacious insects or mosquitofish that are passively transported by water from upstream locations (Collins and Resh 1989). Predator populations can be maintained in permanent waterways used to flood seasonal wetlands. In the Suisun Marsh, where water is readily available for flooding, seasonal wetlands are often initially flooded, and if mosquitoes become abundant, water levels are drawn down to concentrate mosquito larvae in ditches for biological control, larvicide treatment, or to drown larvae through turbulent water movement (Chappell pers. comm). Following this action, wetlands are immediately re-flooded.

BMPs: Maintain stable water levels, Circulate water, Use deep initial flooding, Subsurface irrigate, Utilize water sources with mosquito predators for flooding, Flood and drain wetland (see Table 1 for additional explanation)

Frequency and Duration of Irrigation: Spring and summer irrigation is a common wetland management practice used to increase seed production and biomass of moist-soil plants (Naylor 2002), and reduce competition from undesirable plants in seasonal wetlands. The need to irrigate seasonal wetlands should be assessed closely by wetland managers. During years with above average spring precipitation, irrigations may not be necessary to maximize moist-soil plant production. When possible, managers should shorten the duration of irrigation to 4 to 10 days to reduce the likelihood of hatching floodwater mosquitoes and eliminate the possibility of creating habitat for standing water mosquitoes. However, shorter irrigations may not always be feasible, especially when growing more water intensive plants such as watergrass and smartweed, or when conducting flooding to control undesirable plant species. In the case of weed control, plants should be monitored and water held only long enough to eliminate weeds. The necessary timing can be determined when weeds have turned black or have disintegrated. Finally, following wetland irrigations, water should be drawn down into waterways containing mosquito predators that can consume any mosquito larvae which may have hatched.

BMPs: Reduce number of irrigations, Use rapid irrigation, Draw down and irrigate in early spring, Irrigate prior to field completely drying, Drain irrigation water into ditches or other water sources with mosquito predators, Use subsurface irrigation (see Table 1 for additional explanation)

Table 1. Water Management Practices to reduce mosquito production in managed wetlands.

Best Management Practice	**Strategies**	**Mosquito Control Objective**	**Advantages**	**Disadvantages**
Delayed or phased fall flooding	Delay flooding of some wetland units until later in the fall. Delay flooding units with greatest historical mosquito production and/or those closest to urban areas.	To delay initiation of floodwater mosquito production in seasonal wetlands by reducing the amount of mosquito habitat available during optimal breeding conditions (warm summer/early fall weather). Reduce the time available for standing water mosquito production in seasonal wetlands.	Depending on flood date, can reduce the need or amount of additional treatment. Delayed flooding can provide "new" food resources for wildlife later in the season when wetlands are finally flooded.	Reduces the amount of habitat for early fall migrants and other wetland-dependent species, and may increase potential for waterfowl depredation on agricultural crops (especially rice). Flooding is often dictated by water availability or contractual dates for delivery. Delayed flooding may still produce mosquitoes in warm years. Private hunting clubs can't lease blinds that aren't flooded.
Early fall flood-up planning	Apply BMPs to wetlands identified for early flooding. To the extent possible, areas targeted for early fall flooding should not be near urban centers and should not have a history of heavy mosquito production.	To reduce the early season production of mosquitoes or to reduce their encroachment on urban areas.	Allows for the provision of early flooded habitat while minimizing mosquito production and conflicts with urban areas.	Some additional effort required to monitor and identify suitable areas. Requires the extensive use of BMPs to ensure mosquitoes are not produced.
Rapid fall flooding	Flood wetland unit as fast as possible. Coordinate flooding with neighbors or water district to maximize flood-up rate.	To minimize number of mosquito cohorts hatching on a given area.	Reduces the need for multiple treatments needed by synchronizing larval development and adult emergence. In turn, reduces wildlife disturbance by MVCDs.-	Requires coordination & ability to flood quickly. Reduces slow, feather-edge flooding that is heavily utilized by waterbirds.
Rapid irrigation	4-10 day irrigation (from time water enters the pond to complete draw-down).	Shorten irrigation period to reduce time available for mosquitoes (especially *Culex tarsalis* and *Anopheles freeborni*) to complete lifecycle.	Provides some level of wetland irrigation while reducing the time available for mosquitoes to complete lifecycle.	Requires ability to rapidly flood & drain wetland. If flooding is used for weed control, rapid irrigation may not be feasible.

Table 1. Water Management Practices to reduce mosquito production in managed wetlands, Continued

Best Management Practice	Strategies	Mosquito Control Objective	Advantages	Disadvantages
Maintain stable water level (summer and early fall flooding)	Ensure constant flow of water into pond to reduce water fluctuation due to evaporation, transpiration, outflow, and seepage.	To reduce conditions for additional floodwater mosquito production in summer and fall.	Provides a stable wetland environment for breeding wildlife during spring and summer. Discourages undesired excessive vegetative growth which could also become additional mosquito breeding substrate.	Requires regular monitoring and adjustments to water control structures. May be difficult if water availability is intermittent or unreliable. Reduces mudflat habitat that is attractive to shorebirds and waterfowl.
Water circulation	Provide a constant flow of water equal to discharge at drain structure.	To keep water fresh and moving to deter stagnant conditions for mosquito production; reduces water level fluctuation and potential production of floodwater mosquitoes.	Discourages warm water conditions associated with avian botulism outbreaks.	Requires landowner to purchase additional "maintenance" water. May be difficult if water availability is intermittent or unreliable.
Deep initial flooding (18-24")	Flood wetland as deep as possible at initial flood-up.	To reduce shallow water habitat for mosquito breeding. May provide more open water by over-topping vegetation, thereby facilitating mosquito predation or wind action that drowns larvae.	Potentially slows mosquito development by eliminating warm, shallow water habitat.	Requires additional water and infrastructure adequate to flood deeply. Reduces shallow water foraging habitat for shorebirds and waterfowl.
Utilize water sources with mosquito predators for flooding wetlands	Flood wetlands with water sources containing mosquito fish or other invertebrate predators. Water from permanent ponds can be used to passively introduce mosquito predators.	To inoculate newly flooded wetlands with mosquito predators.	May establish mosquito predators faster than natural colonization.	Requires source of water with already established mosquito predators. Not applicable to wetlands flooded with well water.
Drain irrigation water into ditches or other water bodies with abundant mosquito predators	Drain irrigation water into locations with mosquito predators as opposed to adjacent seasonal wetland or dry fields.	To reduce the amount of larvae through natural predation and minimize the number of adults that emerge.	Already a common wetland management practice.	Must have ditch or water body with established predator population available to accept drain water.
Flood & drain wetland	Flood wetland and hatch larvae in pond. Drain wetland to borrow or other ditch where larvae can be easily treated, drowned in moving water, or consumed by predators. Immediately reflood wetland.	Hatches mosquito larvae and moves them to a smaller area for treatment before they can emerge as adults.	Can eliminate or reduce the need for additional mosquito control efforts.	Additional cost to purchase water to re-flood wetland. Timing is critical. Requires monitoring and is labor intensive.

Table 1. Water Management Practices to reduce mosquito production in managed wetlands, Continued

Best Management Practice	Strategies	Mosquito Control Objective	Advantages	Disadvantages
Reduce number of irrigations	Evaluate necessity of irrigation, especially multiple irrigations, based on spring habitat conditions and plant growth. Eliminate irrigations when feasible.	To eliminate unneeded additional irrigations which could provide potential habitat for mosquitoes.	Reduces potential need for additional mosquito control. Saves water and manpower costs. Discourages excessive growth of undesirable vegetation (i.e. joint and bermuda grass)	May reduce seed production or plant biomass with less irrigation.
Early spring draw-down and irrigation	Draw-down wetland in late March or early April. Irrigate in late April or early May when weather is cooler and mosquitoes are less of a problem.	To reduce need for irrigation in June, July, and August, when potential for mosquito production would be higher.	Wetland irrigation can be accomplished without creating potential mosquito problems. May allow moist-soil plants to take advantage of natural rainfall during the spring.	Reduces shallow wetland habitat for migratory shorebirds and waterfowl in April and May, during a major migration period. Newly germinated wetland plants may be impacted by cold weather conditions. May stimulate germination and growth of undesirable wetland plants.
Don't let field completely dry and crack between spring draw-down and irrigation	Irrigate wetland before soil completely dries.	To eliminate necessary drying period for floodwater mosquito to lay eggs.	May reduce mosquitoes produced from irrigation	Requires close monitoring of soil moisture to correctly time irrigation.
Subsurface irrigation	Maintain high ground water levels by keeping boat channels or deep swales permanently flooded.	To reduce amount of irrigation water during mosquito breeding season.	Reduce need for surface irrigation while maintaining soil moisture to promote moist-soil plant production.	Requires deep swales or boat channels to be effective. Requires additional pipes in channels for equipment access. May not produce intended irrigation result if water table is naturally low. Requires that water be maintained longer than normal in swales. May promote unwanted vegetation growth in swales or promote irrigation of non-target plants in wetland.

Vegetation Management Practices

Wetland managers commonly use vegetation control to alter plant species composition and abundance to influence wildlife use (Smith et al. 1995). As the vegetative community in a wetland changes through time, undesirable species inevitably encroach into wetland habitats. Some species may be relatively benign, while others may be problematic, reducing habitat diversity or crowding out plants important as wildlife forage or cover. Vegetation is also an important habitat requirement for mosquitoes and can improve mosquito survivorship by providing refuge from predators (Walton and Mulla 1989) and abundant food resources for larvae. Vegetation can also increase mosquito developmental rates by raising water temperatures (Collins and Resh 1989). To manage the vegetative community to benefit wildlife, wetland managers use a number of techniques, including mowing, burning, disking, and grazing. These habitat management practices can be used alone or in combination and can also be used to reduce mosquito production (Table 2).

Any management action that alters the composition of wetland vegetation may create either benefits or detriments to wildlife. The decision to conduct such operations should be determined by the management objectives of an individual habitat manager. Site specific characteristics, habitat management objectives, cost, and recreational use (e.g., hunter access) all have to be carefully considered in vegetation management plans. Typically, any vegetation control measure will result in the short-term loss of cover for wildlife. Such compromises have to be weighed in terms of the long-term benefits they provide for wildlife resources versus the ancillary benefits they provide for mosquito control.

Mowing*:* Mowing is commonly used to create open water habitat for shorebirds and waterfowl prior to flooding seasonal wetlands. Mowing to create open water provides opportunities for the biological control of mosquitoes and enhances the effectiveness of pesticides by allowing greater saturation of mosquito habitats. Experimental mowing of approximately 50% of a wetland has been shown to reduce the density of mosquitoes and concentrate their distribution while increasing densities of invertebrates that are consumed by waterfowl (Batzer and Resh 1992a). Similarly, Garcia and Des Rochers (1984) found

Figure 6. Vegetation Mowing. Mowing can be used to create open water habitat and reduce mosquito densities. If mosquito control is necessary, mowing can concentrate mosquitoes and enhance pesticide application by allowing better penetration of vegetation. Photo: Jack Sparks, CDFG

that seasonal wetlands mowed with a 50% plant-cover ratio enhanced wind action that moved mosquito larvae to wetland edges where treatment efforts could then be concentrated.

The benefits of mowing, unlike burning or disking, tend to be short term and require that the practice be implemented on an annual basis. Mowing may also leave residual matter that, when flooded, provides habitat for mosquitoes (Brown pers. comm).

Burning*:* Controlled burning, where and when feasible, can effectively control vegetation. Burning, especially when immediately followed with disking, can offer multiple year control of mosquitoes, reduces vegetation used by mosquitoes for breeding activities, and also directly results in the kill of mosquito eggs due to high temperatures associated with fire (Resh and Schlossberg 1996, Whittle et al. 1993). Burning releases nutrients stored in plant materials and makes them available to benefit plant and invertebrate production during the following flooding cycle. However, due to liability issues, difficulty with permitting, air quality, and the coordination that must take place with multiple agencies prior to its implementation, burning has limited applicability for Central Valley wetlands, especially those on private lands.

Disking*:* Disking is commonly used by habitat managers to reduce dense stands of emergent or undesirable vegetation, and provide favorable conditions for the establishment of moist-soil plants consumed by waterfowl. Disking, unlike mowing, tends to change the vegetation composition of a wetland and provides a more permanent means of controlling vegetation. Disking has also been shown to significantly reduce densities of mosquitoes over multiple years, increase the densities of macroinvertebrates important in the diets of waterfowl, and encourage the replacement of less desirable vegetation by moist-soil plants (Resh and Schlossberg 1996). The benefit of disking can often be enhanced by first mowing or burning vegetation targeted for control.

Figure 7. **Vegetation Disking and Dense Bermuda Grass (*Cynodon dactylon*).** Dense stands of bermuda grass are known to harbor mosquitoes (Garcia and Des Rochers 1983). Bermuda grass also tends to limit habitat diversity in seasonal wetlands and is targeted for control by wetland manager using disking. Photo: Jack Sparks, CDFG and USFWS

Haying and Grazing*:* Agricultural practices such as haying and grazing may also be useful to control wetland vegetation. However, little information is available on their effectiveness as mosquito control measures. Haying, while functionally similar to mowing, may provide the same mosquito control benefits. Haying has the potential added benefit of removing cut plant material that may decay and negatively affect water quality, thereby increasing mosquito production (Brown, pers. comm). However, haying removes valuable seed resources consumed by wildlife and interrupts the cycle of nutrient release back into wetland environments. In addition, haying has limited applicability in most wetland environments because of the relative remoteness of wetlands from agricultural operations, difficulty of running haying equipment in unleveled wetland terrain, and low palatability of wetland vegetation as livestock forage.

Grazing is frequently used to reduce plant biomass in wetlands and provide short grass and open water habitats for shorebirds and waterfowl. However, grazing animals require sources of water for drinking and often irrigated grasslands for forage. Water used to meet these needs may provide additional habitats for mosquitoes. Furthermore, grazing animals can create wallows or depressions in moist wetland terrain that trap water and create additional microhabitats for mosquitoes (Brown, pers. comm.). Additional research needs to be conducted to determine the usefulness of grazing as a mosquito reduction tool.

Table 2. Vegetation management practices to reduce mosquito production in managed wetlands.

Best Management Practice	Strategies	Mosquito Control Objective	Advantages	Disadvantages
Mowing	Mow undesirable or overgrown vegetation that serves as mosquito breeding substrate prior to flooding.	To reduce standing vegetation that mosquitoes can use for egg laying and larval development. To create open water habitat that allows mosquito predators (fish, invertebrates, birds) better access to larvae and potentially more wave action to drown mosquito larvae.	Improves wildlife habitat by providing open-water.	Effects are largely temporary, so must be conducted annually. Overuse could be detrimental to some species of wildlife and non-target invertebrates. Mowed vegetation may float providing mosquito habitat and decomposition may affect water quality.
Burning	Controlled burn of undesirable or overgrown vegetation that may provide mosquito breeding substrate.	See mowing. Can also kill mosquito eggs.	See mowing.	Requires burn permit. Liability concerns. Most landowners are not adequately prepared to conduct a controlled burn. Special consideration should be taken around plastic pipes or water control structures. Overuse could be detrimental to some species of wildlife and non-target invertebrates.
Disking	Disc undesirable or overgrown vegetation that may provide mosquito breeding substrate.	See mowing.	See mowing. Can provide longer-term control of undesirable vegetation by itself or in conjunction with other management practices.	Creates walking problems for hunters. Overuse could be detrimental to some species of wildlife and non-target invertebrates.
Haying	Mow and bale undesirable or overgrown vegetation that may provide mosquito breeding substrate.	See mowing. Also removes vegetation after cutting.	Dual benefits of improving habitat and reducing mosquito breeding substrate. Removal of mowed vegetation further decreases mosquito breeding substrate and may improve water quality.	Overuse could be detrimental to some species of wildlife and non-target invertebrates. Removes seed that wintering waterfowl forage on. Expensive. Often difficult to find someone to bale and haul plant material.
Selective Grazing	Summer-Fall grazing. Short duration, high intensity grazing.	To reduce standing vegetation that provides habitat for mosquitoes.	Relatively inexpensive.	Irrigation for grass and/or livestock watering may exacerbate mosquito production. Livestock tend to forage on plants that produce seed for waterfowl. Livestock may damage levees or ditches.

Wetland Infrastructure Maintenance

Wetland infrastructure is the foundation for habitat management. A properly functioning water delivery and drainage system, well maintained levees, correctly operating water control structures, and efficient pumps are key to avoiding the unnecessary production of mosquitoes through simple neglect (Table 3). Time and money invested in these proactive maintenance activities will reduce mosquito production and help landowners avoid additional costs of controlling mosquitoes and unwanted vegetation when fall flooding or irrigating wetlands.

Levee and Water Control Structure Inspection and Repair: Levees and water control structures should be inspected on an annual basis to identify problem areas that may inadvertently leak water and produce mosquitoes. This includes identifying weak spots or rodent damage in levees that may seep water during flooding. Water control structures should be water-tight and properly sealed to prevent seepage.

Ditch and Swale Cleaning: Vegetation in water delivery ditches and swales can be problematic by creating habitat for mosquitoes or by simply impeding the flow of water that facilitates rapid flooding or drainage. Typical maintenance activities of water delivery and drainage ditches include the use of herbicides or periodic dredging to remove problem vegetation that inhibits water flow. Ditches and swales should be cut to grade to prevent the unintentional trapping of water. Likewise, silt that accumulates in front of outlet structures should be removed so it does not trap water in drainage swales.

Figure 8. Faulty Water Control Structure. Defective water control structures should be replaced with structures that can be completely sealed to prevent water seepage. Photo: USFWS

Pump Tests and Repair: If wetland managers use pumps for flooding, periodic pump testing should be conducted to make sure pumps are operating at optimum efficiency. This will ensure that pumps are providing maximum output, and will facilitate rapid flooding.

Table 3. Wetland infrastructure maintenance activities used to reduce mosquito production in managed wetlands.

Best Management Practice	Strategies	Mosquito Control Objective	Advantages	Disadvantages
Levee Inspection & Repair	Walk or drive levees, flag problem spots, repair as needed. Consider design elements to improve integrity of levee (see levee design in Table 4).	To reduce mosquito habitat/production caused by seepage into adjacent fields or dry ponds.	Allows for early identification of problem spots. Helps conserve water and reduces growth of unwanted vegetation.	Requires annual monitoring and funding for repairs.
Water Control Structure Inspection, Repair, & Cleaning	Inspect structures and repair or replace as needed. Remove silt and vegetation build-up in front of structures. Adequately close, board or mud-up controls.	To reduce mosquito habitat/production caused by seepage into adjacent ponds or drainage ditches. Remove silt blockages that may trap water and impede drainage.	Enhances water management capabilities and limits unwanted vegetation or standing water.	Requires annual monitoring and funding for cleaning or repair.
Ditch Cleaning	Periodically remove silt or vegetation from ditches to maintain efficient water delivery and drainage.	To allow for rapid flooding/drainage & reduce vegetation substrate for breeding mosquitoes.	Enhances water management capabilities and limits unwanted vegetation or standing water.	Requires funding for ditch cleaning. Excessive vegetation removal on ditch banks can result in negative impacts to nesting birds and other wildlife.
Pump Tests & Repair	Test pump efficiency and make any necessary repairs to maximize output.	Could identify output problems and if corrected, allow managers to flood more rapidly.	May promote faster irrigation and flood-up if output can be improved.	Requires pump test. May be costly to repair or replace pump/well.

Wetland Restoration and Enhancement Features

All well planned wetland restoration and enhancement projects begin with an initial survey and design phase. It is during this phase that landowners and restoration biologists have the opportunity to discuss design features with MVCDs and incorporate BMPs to reduce mosquito production. Time spent at the design stage can save thousands of dollars in annual operation and maintenance costs and prevents problems resulting from poor water management and unintended mosquito production. Wetland design typically focuses on aspects of water control that promote vegetation beneficial to wildlife, conserve water, and allow for periodic vegetation control. In turn, water control is also an important mosquito BMP (Sacramento-Yolo Mosquito and Vector Control District 1995, Contra Costa Mosquito and Vector Control District 2001).

Wetland design features to reduce mosquito production: Wetland design features that reduce mosquito production include independent flooding and drainage capabilities of wetland units, size considerations in the design of wetland units to facilitate rapid flooding, and the incorporation of design features that promote habitats for mosquito predators and allow those predators access to mosquitoes (Table 4). Water delivery ditches, water control structures, and levees should be designed and built to specifications that prevent wind and water erosion, provide equipment access for maintenance activities, and reduce damage caused by burrowing animals (Table 4). These design features will facilitate other mosquito BMPs such as water and vegetation management practices, infrastructure maintenance, and natural mosquito predation.

BMPs: Independent water management, Adequately sized water control structures, Swale construction, Wetland size consideration, Ditch design, Levee design & compaction, Deep channels or basins constructed in seasonal wetlands, Permanent water reservoir that floods into seasonal wetlands (for additional explanation see Table 4)

Figure 9. Wetland Swale. Swales can be designed into restoration or enhancement projects to facilitate rapid flooding and remove standing water during spring draw-down. Photo: Chadd Santerre, CWA

Table 4. Wetland restoration and enhancement features to reduce mosquito production in managed wetlands.

Best Management Practice	Strategies	Mosquito Control Objective	Advantages	Disadvantages
Independent water management	To the extent possible, design wetland projects to include independent inlets and outlets for each wetland unit.	To reduce the need to move water through multiple wetland units when flooding or irrigating target areas. This can reduce the number of mosquitoes produced per flood event.	Creates wetland units that are hydrologically distinct from one another allowing for diverse wetland management.	May require additional water control structures and ditches to be constructed and maintained. Increases restoration costs and complexity of management.
Adequately sized water control structures	Increase size and number of water control structures. When installing, set to proper grade to allow for complete draw-down.	To improve ability to implement rapid flooding/irrigation BMPs (Table 1).	See rapid flooding/irrigation BMPs (Table 1).	Increased size and number of water control structures will increase restoration costs and management complexity.
Swale construction (sloped from intake to drain)	Construct or enhance swales so they are sloped from inlet to outlet and allow the majority of the wetland to be drawndown.	To improve ability to implement rapid flooding/irrigation BMPs (Table 1). Creates a means to move water through wetlands without flooding entire wetland basin. Reduces mosquito habitat by allowing isolated sections of habitat to drain. Provides mosquito predators with access to all portions of wetland.	See rapid flooding and irrigation BMPs (Table 1). Provides habitat diversity and enhances capabilities to implement moist-soil management. Provides a more cost-effective and wildlife friendly alternative to laser-leveling to create drainage.	See rapid flooding and irrigation BMPs (Table 1). Reduces standing water in spring that is often used by foraging waterbirds. May result in additional expense to create swales. Shallow swales must be periodically re-cut if silt deposition or dense emergent vegetation is a problem. Could be a deep water hazard in hunting areas.
Wetland size considerations	Install cross-levees to facilitate more rapid irrigation and flood-up (Table 1). Build "underwater" levees that isolate irrigation water during the spring, but can be overtopped during fall and winter flooding.	To improve ability to implement rapid flooding/irrigation BMPs (Table 1).	Assists with faster flooding and drainage. Cross levees (checks) can provide loafing habitat for waterfowl and shorebirds.	Additional levees may result in decreased wildlife use and diversity. Expensive. Requires additional levee maintenance and water control structures.
*Ditch design (2:1 slopes & minimum 4 foot bottom)** **consider 3:1 slope or greater to discourage burrowing animal damage and potential seepage problems*	Construct or improve ditches to quality standard that prevents unwanted vegetation growth or unnecessary seepage.	Reduces likelihood of vegetation growing along ditch banks. Excessive vegetation slows water flow, traps silt, and can be used as substrate for mosquito eggs.	Improves water flow and decreases maintenance of vegetation that grows along canal banks.	May require re-designing some delivery ditches to meet specific design criteria. Could affect habitat for wildlife species such as giant garter snakes. Steeper slopes may erode more quickly and created a hazard for hunters.

Table 4. Wetland restoration and enhancement features to reduce mosquito production in managed wetlands, Continued

Best Management Practice	Strategies	Mosquito Control Objective	Advantages	Disadvantages
*Levee design & compaction (≥3:1 slopes & >80% compaction)** **consider5:1 slope or greater in areas prone to over-land flooding and levee erosion.*	Construct or improve levees to quality standard that ensures stability and prevents unwanted seepage.	To reduce mosquito habitat caused by seepage into adjacent fields or dry ponds.	Properly constructed levees prevent seepage from erosion or rodent damage, and reduce need for annual maintenance.	Additional expense to repair or build levees on existing properties.
Deep channels or basins constructed in seasonal wetlands	Excavate deep channels or basins to maintain permanent water areas (> 2.5 feet deep) within a portion of seasonal wetlands. Provides year-round habitat for mosquito predators which can inoculate seasonal wetlands when they are irrigated or flooded.	To reduce mosquito larvae through predation.	Provides on-site source of mosquitofish and other mosquito predators to seasonal wetlands. Increases overall habitat diversity.	Expensive to excavate and maintain permanent water. Potential problems with emergent vegetation. May be a deep water hazard in hunting areas.
Permanent water reservoir that floods into seasonal wetlands	Maintain separate permanent water reservoir that conveys water to seasonal wetlands. Provides year-round habitat for mosquito predators which can inoculate seasonal wetlands when they are irrigated or flooded.	To reduce mosquito larvae through predation.	Provides on-site source of mosquitofish and other mosquito predators to seasonal wetlands. Increases overall habitat diversity.	Additional expense to construct reservoir that feeds water to seasonal wetlands and expensive to maintain permanent water.

Biological Controls

Naturally occurring predators, such as fish, dragonflies, aquatic macroinvertebrates, and certain bird and bats, can contribute to the reduction of mosquitoes (Table 5). However, it often takes time before predator populations become established and have an effect on mosquito numbers, because mosquitoes frequently exploit ephemeral habitats and have relatively short lifecycles. Certain predator populations can be supplemented, for example, through the stocking of mosquitofish (*Gambusia affinis*), but in most instances a habitat manager's best strategy is to maintain natural predator populations on-site. For biological controls to be effective, wetland managers need to create an environment that is both conducive to maintaining predator populations and providing predators with access to mosquito prey.

Encourage on-site predator populations: Management practices have been developed that incorporate permanent water within seasonal wetlands to "inoculate" newly flooded habitats with an on-site predator source. This can be accomplished by maintaining permanent water in swales and deep borrow ditches, or by flooding wetlands with water from nearby permanent wetlands. Permanent water sources will need to be maintained when seasonal wetlands are dry, if wild populations of mosquitofish are to be sustained on-site. Such "dry season" predator reservoirs should be 18 inches or greater in depth to reduce predation of mosquitofish by herons and egrets (Collins and Resh 1989). Dry season reservoirs should be interconnected to seasonal wetlands through swales or ditches to allow mosquitofish to seek habitat as seasonal wetlands are drawn down and, conversely, to allow mosquitofish to disperse through seasonal wetlands as they are re-flooded in the fall.

It is critical to the success of biological control to limit the use, when possible, of broad spectrum insecticides that not only kill mosquitoes, but also eliminate their natural predators. Control programs that combine biological controls with chemical insecticides often result in suboptimal results because the predators take longer to recover from insecticide induced mortality than mosquito populations (Walton et al. 1990).

Provide predator access to mosquitoes: The extent of wetland vegetation may limit predator access to mosquitoes (Walton and Mulla 1989, Collins and Resh 1989). Wetlands with significantly dense vegetation provide an abundance of hiding places for mosquitoes and can limit aquatic predator dispersion. Vegetation management BMPs can be used to reduce dense stands of cattail, tules, or other emergent vegetation and provide predators access to mosquito prey. Isolated basins that do not interconnect to the main water body of a wetland will also limit an aquatic predator's access to mosquito prey. To encourage mosquito predation, wetland swales can be constructed to connect isolated basin with deep water areas containing aquatic mosquito predators.

Table 5. Biological Controls

Best Management Practice	Strategies	Mosquito Control Objective	Advantages	Disadvantages
Encourage or stock Mosquitofish (Gambusia affinis)	Stock managed wetlands with mosquitofish or encourage habitats for naturalized populations. Utilize water sources with mosquitofish to passively transport predators to newly flooded habitats.	To supplement mosquito predator population.	Provides a non-chemical control of mosquito larvae. Mosquito fish are often available free of charge to landowners from their local district.	May reduce non-target populations of invertebrates or other mosquito predators. Not appropriate for vernal pool habitats. May negatively impact sensitive species.
Encourage invertebrate predators	Maintain permanent or semi-permanent water where mosquito predators can develop and be maintained. Discourage use of broad spectrum pesticides.	To reduce mosquito populations through predation.	Provides biological control of mosquito larvae and adults.	None.
Encourage swallow colonies and other insectivorous birds	Do not discourage nesting swallows.	To reduce mosquito populations through predation.	Provides biological control of adult mosquitoes.	Guano. The value of insectivorous birds has not been adequately quantified.
Encourage Bats	Encourage bat colonies (e.g. build bat boxes)	To reduce mosquito populations through predation.	Provides biological control of adult mosquitoes.	Potential (or perceived potential) for transmission of rabies. The value of insectivorous bats has not been adequately quantified.

COORDINATION WITH MOSQUITO AND VECTOR CONTROL DISTRICTS

The responsibilities of MVCDs and wetland managers have some inherent conflicts. MVCDs have a responsibility to reduce vectors that may transmit disease to humans or cause a significant nuisance. Wetland managers have a responsibility to maintain and enhance wetlands; a public trust resource that provides habitat for migratory birds, threatened and endangered species, and helps to reduce depredation from waterfowl on agricultural lands. Public resource agencies are increasingly being asked to provide wetland habitat to meet the recreational demands of hunters, anglers, bird watchers, photographers, and hikers. Wetland managers recognize that mosquito production may be a by-product of wetland management and in some cases may contribute to problems requiring mosquito control. However, in order for both MVCDs and wetland habitat managers to accomplish their objectives, cooperation and coordination is essential.

MVCDs and wetland managers have a history of conflict going back over 30 years in the Central Valley (Lusk 1979). Such conflict was largely the result of MVCDs being perceived as relying solely on the use of chemical pesticides for control activities and concerns regarding the potential effects on wildlife and food-chain resources such as invertebrates. However, MVCD use of Integrated Pest Management (IPM) has helped to address this concern by employing a variety of control methods that include habitat management, biological control, and the use of more target-specific pesticide products. The increasing costs of pesticides and concerns over pesticide resistance have also spurred a more holistic approach to mosquito management.

The success of IPM depends on cooperation and sharing information on habitat and water management schedules, collaborating on the identification of problem areas, monitoring the effectiveness of BMPs, and coordinating on wetland restoration and enhancement projects (Table 6).

Coordinate habitat management and flooding schedules: By providing advanced information regarding habitat and water management schedules, wetland managers enable MVCDs to make suggestions regarding BMPs, schedule monitoring efforts, and, if necessary, control mosquitoes as efficiently as possible. In return, MVCDs can provide landowners with useful input and feedback on how to reduce mosquito production and potentially reduce their abatement costs.

Identify problem areas for mosquito production and target implementation of BMPs: Coordination is also required on the part of MVCDs to identify the highest priority wetlands for the implementation of BMPs. For example, Garcia and Des Rochers (1983) found that *Ochlerotatus melanimon* larvae were largely restricted to specific areas in a few fields on Gray Lodge Wildlife Area. As a result, limited resources could be focused on these problem areas.

Coordinate wetland habitat restoration and enhancement project design: Prior to enhancement or restoration projects, MVCDs should be consulted to determine if design features to reduce mosquitoes can be incorporated. By involving MVCDs early in the process, problems associated with design features or poor engineering that may encourage mosquito production can be avoided.

Coordinate Pest Control Activities: To facilitate the timely and effective use of pesticides in wetland areas, MVCDs should inform wetland managers about proposed pesticide applications. This can be accomplished by providing a brief, annual plan that identifies the pesticide products, approximate use rates and application methods that may be used during the year. Whenever possible, MVCDs should also provide wetland managers with information about the specific locations where pesticide products will be used. An annual summary report of pesticide use should be provided to the wetland manager after the conclusion of the application season.

Coordinate monitoring activities: Determining the success of BMPs will be largely based on the monitoring of mosquito production following their implementation. This effort will require wetland managers to work directly with MVCDs to facilitate monitoring and will also provide an opportunity for wetland managers to familiarize themselves with the methods used for monitoring and thresholds for treatment. The monitoring process will provide valuable information to refine BMPs and determine their future priority for use. Ultimately, this process will provide a unique opportunity to develop and use new techniques to reduce mosquito production in managed wetlands.

Table 6. Suggested coordination activities between wetland managers and Mosquito and Vector Control Districts (MVCD).

Best Management Practice	Strategies	Mosquito Control Objective	Advantages	Disadvantages
Habitat management and flooding schedule coordination	Consult with MVCDs on agency-sponsored habitat management plans on private lands (i.e. Presley Program). Consult with Districts on the timing of wetland flooding on public lands – urge private landowners to do the same.	Allows MVCDs the opportunity to provide input on habitat management and recommend BMPs to reduce mosquitoes.	Reduces potential conflicts between MVCDs, landowners, and agencies/NGOs when managing or flooding wetlands. Provides information exchange.	Requires a commitment of time from MVCDs, landowners, and agencies/NGOs to meet and coordinate activities.
Identify problem areas for mosquito production and target for implementation of BMPs	Identify problem locations for mosquito production with local MVCDs and work to implement mosquito BMPs. Identify potential cost-share opportunities to implement BMPs.	Work to reduce mosquito production through BMPs on properties that are most problematic.	Allows limited resources from MVCDs and agencies/NGO's to be targeted towards problem areas. Provides opportunities for monitoring the effectiveness of BMPs.	None
Wetland Habitat Restoration and enhancement project design & coordination	Consult with local MVCDs on the design of restoration and enhancement projects.	To determine where features to discourage mosquito production can be incorporated into wetland habitat restoration and enhancement projects where feasible.	Reduces potential conflicts between MVCDs, landowners, and agencies/NGOs when restoring or enhancing wetlands. Provides a priori consultation for MVCDs on wetland projects.	Requires some flexibility from MVCDs, landowners, and agencies/NGOs when designing projects. BMPs will likely increase the project cost.
Coordinate Pest Control Activities	Work with local MVCDs to understand pesticides used for mosquito treatment, and their costs and environmental impacts.	To assure the use of mosquito control agents with the greatest efficacy and environmental safety.	Reduces potential conflicts between districts, landowners, and agencies/NGOs regarding pesticides used for mosquito treatment.	May require additional coordination effort from MVCDs, landowners, and agencies/NGOs.
Coordinate Monitoring Activities	Facilitate monitoring mosquito populations of larval and adult stages before and after implementation of BMPs.	Determine the effectiveness of BMPs to refine and prioritize their future use.	Provides a means to evaluate and document effectiveness of BMPs.	Requires time and resources to accomplish.

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Appendix A. Comparison of potential mosquito larvicides used in managed wetland environments. Information provided by the Pesticides Investigation Unit of the Department of Fish and Game.

Pesticide	***Surface Oil***	***Surface Film***	***Methoprene***	***Dimilin***	***Bacillus thuringiensis israelensis (Bti)***	***Bacillus sphaericus (Bs)***
Trade Name	Golden Bear Oil	Agnique MMF	Altosid	Dimilin 25W	Vectobac Teknar Aquabac	Vectolex
Mode of Action	Suffocation	Suffocation	Growth regulator	Chitin inhibitor	Stomach poison	Stomach poison
Toxicological Impacts[1]: Fish & Frogs	Unknown	Unknown	Low	Practically non toxic	Practically non toxic	Practically non toxic
Toxicological Impacts[1]: Birds	Low; at cold temperatures may impact young waterfowl	Unknown	Very low	Practically non toxic	Practically non toxic	Practically non toxic
Potential Impacts to invertebrate forage base for wildlife[2]	Moderate to high; broad spectrum compound	Moderate to high; broad spectrum compound	Probably low; fairly narrow spectrum	Moderate to high; broad spectrum compound	Some species of midge larvae subfamily Chironominae; potentially other primitive dipteran larvae	Probably low; fairly narrow spectrum compound
Comments	Petroleum distillate; applied over surface of water; may be effective for 2-3 days	Reduces water surface tension	Juvenile hormone mimic; effective on later stage mosquitoes (instars 3-4)		Naturally occurring soil bacterium; most effective on early stage larvae (instars 1-3);effective for only 1-2 days; not effective in water with high organic content	Can be effective for weeks; used primarily for *Culex* spp. in water with high organic content; not effective on all species of mosquito

[1]Actual hazard is dependent on exposure, as well as toxicity.
[2]Very difficult to assess. Dependent on numerous factors such as the total area treated, frequency of treatment, and season of treatment.

Appendix B. Comparison of potential mosquito adulticides used in managed wetland environments. Information provided by the Pesticides Investigation Unit of the Department of Fish and Game.

	Malathion	***Naled***	***Pyrethrin***	***Permethrin***	***Resmethrin***	***Sumithrin***
Trade Name	Fyfanon	Trumpet Dibrom	Pyranone Pyrocide	Aqua Reslin Biomist Permanone	Scourge	Anvil
Mode of Action	Central nervous system (CNS) inhibitor	CNS inhibitor	Contact	Contact	Contact	Systemic
Toxicological Impacts[1]: Fish and Frogs	Variable; some fish species are highly susceptible, as are many amphibians	Moderately to highly toxic	Highly toxic	Highly toxic	Highly toxic	May be less toxic to some aquatic species than other pyrethrins
Toxicological Impacts[1]: Birds	Moderately toxic	Moderately to highly toxic	Moderately toxic	Practically non toxic	Practically non toxic	Practically non toxic
Potential Impacts to invertebrate forage base for wildlife[2]	Moderate to highly toxic; broad spectrum insecticide	Moderate to highly toxic; broad spectrum insecticide	Moderate to highly toxic; broad spectrum insecticide	Moderate to highly toxic; broad spectrum insecticide	Moderate to highly toxic; broad spectrum insecticide	Moderate to highly toxic; broad spectrum insecticide
Comments	Organophos-phate insecticide	Organophos-phate insecticide	Botanical pesticide	Synthetic pyrethrin	Synthetic pyrethrin	Synthetic pyrethrin

[1]Actual hazard is dependent on exposure, as well as toxicity.
[2]Very difficult to assess. Dependent on numerous factors such as the total area treated, frequency of treatment, and season of treatment.