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EFFECTS OF OPEN MARSH WATER MANAGEMENT ON SELECTED TIDAL MARSH RESOURCES: A REVIEW

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ABSTRACT. Open Marsh Water Management (OMWM) is a method of salt-marsh mosquito control that advocates source reduction and biological control through selective pond creation and ditching in mosquito breeding areas. This method has been used as an alternative to chemical insecticides in coastal wetlands for 30 years. This paper reviews the effects of OMWM on hydrology, topography, vegetation, mosquitoes, invertebrates, fishes, birds, mammals, and water quality. Other source reduction techniques and the economics of OMWM are also discussed.

INTRODUCTION

Open Marsh Water Management (OMWM) is a tool for salt-marsh mosquito control that involves selective ponding and ditching in salt-marsh mosquito breeding areas. The concept was developed in New Jersey in the late 1960s (Ferrigno and Jobbins 1966, 1968; Ferrigno et al. 1969). As a more ecologically sound alternative to temporary chemical control or indiscriminate mechanical drainage (i.e., parallel grid-ditching), OMWM advocates source reduction and biological control. Open Marsh Water Management evolved from the observations and recommendations of Clarke (1938), Cottom (1938) and Price (1938). Ferrigno and Jobbins (1966) used the term "quality ditching" to describe the use of tidal ditches to selectively connect mosquito breeding depressions to a tidal source. Mosquito control is realized through tidal circulation of the breeding depressions and by providing larvivorous fish access to the mosquito breeding marsh. In areas of multiple breeding depressions, quality ditching is incorporated with closed, nontidal ponds and radial ditches, with excavated spoil being used to fill in breeding depressions. Daiber (1986) described the multiple objectives of OMWM, which include controlling mosquito populations by inhibiting mosquito larvae through permanent suppression (i.e., filling in depressions with spoil) or habitat manipulation with a concomitant reduction or elimination of insecticides or other temporary measures; and encouraging nutrient exchanges, thus enhancing tidal food webs. Ferrigno and Jobbins (1966, 1968) reported how properly installed OMWM systems could be used not only to control mosquitoes, but to enhance fish and wildlife habitat and increase estuarine interactions.

Smith (1902, 1904, 1907) proposed the basic concept of OMWM when he noted in the early part of this century that not all areas of the salt marsh bred mosquitoes. He found areas of high marsh infrequently flooded by high or storm tides and dominated by salt meadow cordgrass (*Spartina patens*), short-form salt-marsh cordgrass (*Spartina alterniflora*), salt grass (*Distichlis spicata*), and black grass (*Juncus gerardi*) to be prime mosquito-breeding areas. He went on to advocate biological rather than chemical control in these breeding areas by stating in his 1904 paper that the "killies that swarm in every ditch . . . are great wiggler hunters." Furthermore, because "oil is useful as a temporary expedient only . . . permanent improvements should be the objective."

Today, OMWM is the technique of choice for providing long-term control of salt-marsh mosquitoes in many coastal areas. Lesser et al. (1978) questioned whether OMWM as practiced in New Jersey can be used in the same fashion in other marshes and achieve similar results. They noted that differences in such factors as marsh soils, salinities, and species assemblages should be taken into account when implementing OMWM. Daiber (1986) stated: "while the basic OMWM concept remains sound, it appears that modifications to accommodate local situations are in order." Ferrigno et al. (1975) described 3 basic types of alterations in New Jersey, which include tidal ditches, ponds, and pond radials. An integration of OMWM on previously grid-ditched marshes was used in Maryland (Lesser et al. 1978) to offset the negative impacts of the grid-ditch system and has since been used there extensively. Lesser (1982) and Whigham et al. (1981) described the use and effects of open tidal OMWM systems, systems with restricted tidal exchange, and closed, nontidal systems. Delaware also uses these 3 alternatives; however, open tidal ditches are used in a very limited capacity because of the undesirable effects on hydrology and vegetation that can result (Meredith et al. 1985). Similar techniques of ponding and radial ditching in the open salt marsh have been studied in New York (Lent et al. 1990) and North Carolina (Anderson 1989). Source reduction (i.e., OMWM) has also been used to connect mosquito breeding depressions in impoundments (Carlson 1986, Carlson et al. 1991, Wolfe 1992).

OTHER WATER MANAGEMENT TECHNIQUES

Several other water level management techniques for controlling mosquito populations have been employed since the early 1900s. Probably the most extensively used technique resulting in the greatest impact to tidal marsh ecology was the parallel grid-ditch system. Implemented in the 1930s as part of a Civil Works program, parallel grid-ditching was used to physically drain thousands of acres of Atlantic coast salt marshes. The grid-ditch system was an engineering technique designed to mechanically drain surface water from the marsh, with little thought or regard given to the ecological consequences. Hundreds of miles of ditches (many dug by hand) impacted thousands of acres of tidal wetlands. By 1938, it was estimated that some 90%, or 562,000 acres of original Atlantic coast tidal marsh from Maine to Virginia had been ditched (Bourn and Cottam 1950). The resulting decrease in water table levels coupled with the increase in marsh surface elevations due to deposition of excavated spoils caused significant changes in hydrologic patterns. Early studies indicated that ditching had a significant impact on vegetation, macroinvertebrates, and muskrats (Stearns et al. 1940, Bourn and Cottam 1950). However, later studies (Shisler et al. 1975, Lesser et al. 1976) suggested that plant and invertebrate species diversity may rebound and biomass may actually increase on marshes allowed to recover. To compound these detrimental impacts, the indiscriminate pattern of ditches unnecessarily drained acres of valuable nontidal waterbird habitat. Quite often this occurred in marshes that had little or no prior mosquito production. Some researchers questioned the need to alter the marsh environment so extensively in order to control mosquitoes (Clarke 1938, Price 1938). This change in philosophy helped to pave the way for taking a holistic view of wetlands functions (and mosquito control) rather than a parochial one whose goal was to destroy the pest at whatever cost to the environment. More modern mosquito control techniques using source reduction (i.e., OMWM) provide an opportunity to restore surface water hydrology to these drained habitats.

Even during the era of parallel grid-ditching, further attempts using biological control were investigated (Bradbury 1938, Clarke 1938, Cottam 1938, Price 1938). Small ponds were either excavated or blasted in mosquito breeding marshes, thereby forming a permanent reservoir for larvivorous fishes. Price (1938) advocated the use of nontidal, blind ditches to serve as fish reservoirs. Bradbury (1938) proposed plugging old grid ditches to restore drained waterbird habitat in Massachusetts marshes. He used dormant clumps of previously excavated spoil to plug the outlets of some ditches to a height of 9 in. below the marsh surface to restrict tidal exchange yet still provide adequate mosquito control. Clarke (1938) likened the action of the fishes at the surface of these ponds to champagne bubbles. Bodola (1970) claimed that even though these created "champagne pools" provided good larval control in the immediate vicinity of the pond, the fish could not penetrate the grasses surrounding the pools to reach isolated mosquito breeding depressions. Cottam (1938) took this idea one step further by creating permanent ponds with channels radiating outward to allow predaceous fish to penetrate into the marsh. This was believed to provide better mosquito control and to be less destructive to the marsh than mechanical drainage.

Impoundments are another form of water management that can be managed to control mosquitoes. The practice of diking has been used for hundreds of years for protection against the sea (Daiber 1986); however, it was not until this century that it was realized that water levels could be managed (via water-control structures) in an impoundment to enhance wildlife habitat and control mosquitoes. In his book, "Conservation of Tidal Marshes," Daiber (1986) gave a good historical perspective and review of the use of impoundments for wildlife habitat and mosquito control. In summary, water levels in impounded areas can be managed to flood aedine oviposition sites and provide fish habitat to biologically control mosquitoes that lay their eggs on the water surface. There is some restriction of water and nutrient exchanges with the open estuary, which can lead to poor water quality (Whitman and Cole 1987). Clark (1995) showed in Delaware how more frequent exchanges of water during critical times of the year (i.e., early and midsummer, late fall) can minimize these effects on water quality, ensure that the necessary biological control agent for mosquito control is present, and allow access and egress of estuarine organisms.

Today, most impoundments are managed for migratory waterfowl and other waterbirds; however, Carlson (1986) and Carlson et al. (1991) reported on how Rotational Impoundment Management (RIM) can successfully control salt-marsh mosquitoes and benefit wildlife. Likewise, Batzer and Resh (1992) found that by reducing areal plant cover to 50% and maintaining higher water levels following a drawdown, mosquito production was reduced and restricted to the wetland perimeter and other macroinvertebrate larvae, important to waterfowl diets, were higher. The use of water control structures to physically manage water levels in impounded marshes is radically different than source reduction in the open salt marsh. Therefore, impoundment should not be confused with OMWM.

Although the Atlantic coast of the USA has been the most studied in terms of habitat modification for mosquito control, water management is not exclusive to the eastern seaboard. Resh and Balling (1979) described the use of shallow "recirculation ditches" in San Francisco Bay marshes, which promote tidal circulation and dewater mosquito breeding pools. Further studies by Resh and Balling (1983) indicated that these ditches aerate the soil and reduce subsurface and soil salinities resulting in greater primary productivity of *Salicornia*. There was no significant impact on selected arthropods

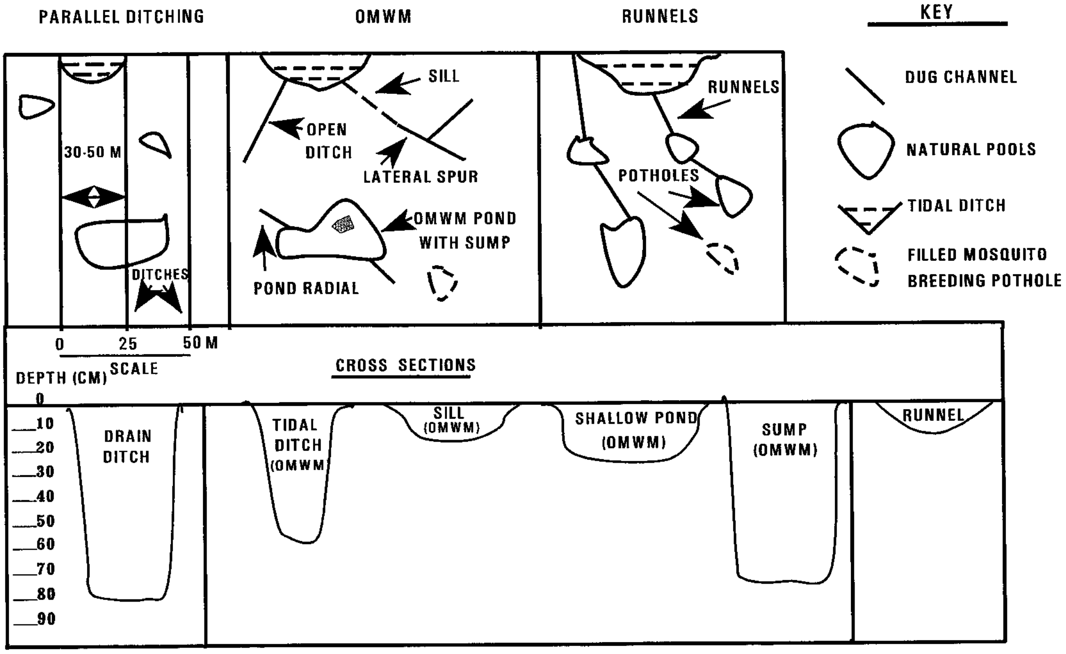

Fig. 1. Water management designs (e.g., drain ditching, Open Marsh Water Management [OMWM], and runnelling) showing general layout and channel shape (from Dale and Hulsman 1990).

(Balling and Resh 1982); however, fish diversity and density increased (Balling et al. 1980). Invertebrate biomass was not affected but diversity was reduced when compared with unditched marshes. Collins and Resh (1985) found that although these ditches were not as attractive to salt-marsh song sparrows (*Melospiza melodia samuelis*) as natural tidal guts, they did increase the amount of sparrow habitat. Similar in theory and design to recirculation ditches, Hulsman et al. (1989) described the use of wide, shallow "runnels" to allow tidal drainage of mosquito breeding potholes in Australian marshes. Their experimental runnel systems (dug by hand) effectively reduced *Aedes vigilax* (Skuse) mosquito production with no impact to other marsh resources except for a higher mean height of marine couch (*Sporobolus virginicus*) near the runnels. A later study (Dale et al. 1993) found decreased densities and heights of marine couch, probably as a direct result of increased tidal flushing and lower substrate salinity.

Dale and Hulsman (1990) gave a review of the techniques used for salt-marsh mosquito control. The designs used for habitat modification are illustrated for comparison purposes in Fig. 1.

EFFECTS OF OMWM

Hydrology and topography: In addition to the objectives of OMWM cited earlier, OMWM systems should be designed to reduce mosquito production without adversely affecting other marsh resources. Because of the impacts on surface and subsurface hydrographic patterns and the concomitant placement of spoil on the surface of the marsh as a result of OMWM excavations, the physical components most obviously and immediately affected by OMWM (or any water level management technique) are the marsh's hydrology and topography. The impacts on these components will, in turn, determine how the marsh flora and fauna will respond. Therefore, it is critical to minimize the effects on hydrology and surface elevation when implementing an OMWM program.

Although little research has been done with direct regard to hydrology or topography, a study of the geomorphology of San Francisco Bay marshes by Collins et al. (1986) claimed that mosquito ditching (which suggests OMWM-type alterations) will more than double the length of channels in some marshes. This will substantially decrease the tidal height and energy in these channels, which will lead to channel retrogression; that is, the sedimentation of headward channels that could promote mosquito pothole development. In contrast, the OMWM systems placed on Long Island marshes (Lent et al. 1990) had a 5 times increase in tidal exchange in the marsh. Also, the tidal amplitude was increased from 6 cm before alterations to 15 cm after. This increased tidal exchange resulted in a desired conversion from a freshwater plant community to one dominated by *S. alterniflora,* which was undoubtably based on an increase in salinity and not as a result of lower water table elevations.

In an early study documenting the dewatering effect of grid-ditching, Stearns et al. (1940) stated that the average water table height in a grid-ditched marsh was 5.08 m. (12.9 cm) lower than a nearby unditched marsh. The mean water table elevation also decreased over a 3-year period, causing a considerable change in vegetative cover and muskrat distribution.

This lowering of the water table by open tidal ditches was documented in later studies on Maryland's eastern shore marshes (Whigham et al. 1981, Lesser 1982) and in Delaware (W. H. Meredith et al., unpublished data). Lesser's study (1982) revealed that there was a significant difference in mean water table elevations among open, water-controlled, and closed plots. His water-controlled plot had a shallow (25-cm) tidal ditch with 3 10-cm-diam pipes placed in it to connect the OMWM system with a natural tidal tributary. This modification to New Jersey's standard provided satisfactory mosquito control while maintaining a higher water table than open tidal ditches. Similarly, Delaware constructs a shallow cut (10–15-cm) "sill" (Meredith et al. 1985) outlet, which is used on a majority of its OMWM systems (Wolfe 1992). The Lesser (1982) study also showed a dewatering effect on well transects perpendicular to the excavated ditches. The study showed a significant decrease in water table elevation in wells placed 1, 5, and 10 m away from the ditch (31.2, 36.3, and 40.7 cm above mean sea level, respectively), with wells closest to the ditch subject to the greatest degree of drainage. There was no appreciable lowering of the water table at 25 or 50 m from the ditch. Furthermore, the nontidal (closed) systems and semitidal (water-controlled) systems had a higher mean water table elevation than the tidal or open systems, which was to be expected.

Similar results were found in North Carolina (B. Pope, unpublished data), where OMWM is being proposed for operational use. Using shallow runnels in Australia, Dale and Hulsman (1990) indicated that the modification has no short-term effects on water table depth or salinity, or on soil moisture or its salinity.

Vegetation: As stated previously, changes in marsh resources are most affected by altered hydrologic patterns and spoil deposition. This effect manifests itself most obviously in the vegetative composition and distribution of the marshes. A change to higher successional plants such as *Iva frutescens* and *Baccharis halimifolia* was reported to have occurred on spoil piles placed on the marsh surface (Bourn and Cottam 1950, Shisler 1973). If implemented properly, with care given to minimize the depth of the spoil, OMWM excavations will not substantially increase the marsh surface elevation or restrict surface water movement, thereby ensuring the reestablishment of pretreatment vegetation (Ferrigno and Jobbins 1968, Ferrigno et al. 1975, Shisler 1978).

Lesser and Saveikis (1979) reported good mosquito control in 2 Chesapeake Bay high marsh areas using 3 different experimental treatments: tidal (open), semitidal (sill), and nontidal (closed). As suspected, the closed OMWM systems had the least change in plant community structure when compared to open and semitidal systems, presumably because water tables were least affected in the closed, nontidal plots. In some of the sill and open systems, a substantial (1–43% of surface area) invasion by *I. frutescens* occurred within 1 year after excavations. These incursions were correlated to decreased water tables caused by tidal or semitidal ditching and/or increased surface elevations caused by improperly spread or clumped spoils. Similar observations have been made in North Carolina, where *Iva* had obtained a foothold in clumps of excavated spoils containing a high percentage of clay (A. Anderson, unpublished data). This high clay content prevents the spoil from spreading thinly and evenly on the marsh and additional mechanical spreading may be required to flatten these clumps. Whigham et al. (1981) noticed similar *Iva* incursions in Maryland marshes adjacent to the sites of Lesser and Saveikis (1979), but also observed fluctuations in the ratios of *D. spicata* and *S. patens* depending on the type of OMWM treatment used. This fluctuation in *D. spicata* and *S. patens* ratios was also noticed in the Delaware study (W. H. Meredith, unpublished data). Preliminary observations indicate that where the water table has dropped 5 in. (12.7 cm) or more in high-marsh areas, shrub and drier-soil plants (e.g., *Pluchea purpurascens*) will invade; however, this depth of water table drop may not be the critical depth in other marshes. This is consistent with earlier observations made by Bradbury (1938) and Stearns et al. (1940).

Ferrigno (1970) found some reduction in the amount of short-form *S. alterniflora* as well as *Salicornia* and the algae *Cladophora.* This might be attributed to the increased tidal circulation and removal of the stagnant, surface sheet water associated with these types of vegetation. He found no change in the amount of salt hay grasses *D. spicata* and *S. patens* and an increase in *Ruppia* and *Limonium,* which are both valuable waterfowl foods. The only areas where undesirable vegetation (i.e., *Iva, Baccharis, Phragmites*) occurred were in those few areas where spoil was not properly disposed. Ferrigno (1970) also noticed an increase in both occurrence and density of tall *S. alterniflora* near the ditch edges. Shisler and Jobbins (1977a), while finding lower stem densities of *S. alterniflora* in OMWM-treated (397 shoots/m^2) plots vs. control (2,647 shoots/m^2) plots, also found an increased robustness of *S. alterniflora* and increased vegetation biomass in OMWM plots (1,462 g dry wt./m^2) as compared to unditched areas (852 g).

Dale et al. (1993) observed a decrease in density of *S. virginicus* and *Sarcocornia quinqueflora* (samphire), which was suspected to be caused by increased soil moisture content and decreased soil salinity due to runnelling. However, seasonal and yearly fluctuations occurred and there was no apparent trend after 5 years. Kramer et al. (1995) noted a dramatic decrease in the density of pickleweed (*Salicornia virginica*) and peppergrass (*Lepidium latifolium*) 1 year after enhanced tidal circulation and that the marsh had acquired characteristics of an immature, highly productive, tidal brackish marsh. Lent et al. (1990) stated "that while some plots change from year to year in vegetation composition, there is no clear relationship of observed vegetation changes to OMWM alterations." Noting the dynamism of salt-marsh plant communities, they concluded: "annual variation in salt marsh vegetation . . . is greater than any effects due to OMWM."

Mosquitoes: To demonstrate the effectiveness of OMWM at controlling mosquitoes, Ferrigno (1970) reported a decrease in mosquito production from more than 10,000/ft.^{2} (1.07×10^5/m^2) prior to OMWM implementation to 948/ft.^{2} (1.02×10^4/m^2) in the first posttreatment sampling to zero in subsequent sampling. On a larger scale, Ferrigno and Jobbins (1968) estimated that for every 1,000 acres of marsh treated with OMWM, 40–60 billion mosquitoes would be eliminated annually for the life of the OMWM system.

In general, OMWM should achieve greater than 95% reduction in mosquitoes (Ferrigno et al. 1975). Boyes and Capotosto (1978) reported "excellent" control in Rhode Island marshes, with elimination of insecticides in the first post-OMWM season, and Whigham et al. (1981) found 85–100% control in Maryland. Dale et al. (1993) saw larval reductions to "below nuisance levels" within the first 3 months and continuing for 6.5 years following runnel installation. In California, Kramer et al. (1995) reported a 98.7% reduction in larval *Aedes dorsalis* (Meigen) 1 year after excavating recirculation ditches. Other researchers in New Jersey (Shisler 1978), Delaware (Meredith et al. 1984), Massachusetts (Hruby et al. 1985), and North Carolina (Anderson 1989) have reported 90–100% control of mosquitoes in OMWM-treated marshes. Murdock (1990) reported a 92–99% reduction in mosquito larvae in OMWM systems in Florida but noted a shift in species composition from primarily *Aedes* species to one dominated by *Anopheles*. However, this slight shift in *Anopheles* dominance was an acceptable trade-off. Overall, these results indicate that consistent, effective, long-term control of salt-marsh mosquito populations can be achieved with OMWM.

Invertebrates: In New Jersey marshes, Ferrigno (1970), and Shisler and Jobbins (1977a) found reductions in salt-marsh snail (*Melampus bidentatus*) populations in OMWM-treated sites as compared to untreated sites. Ferrigno (1970) recorded a decrease from 529/m^2 to 403/m^2, whereas Shisler and Jobbins (1977a) noted a decrease by a factor of 10, from 850/m^2 to 85/m^2. This decrease could be hypothesized, however, as both authors indicate a progression to a low-marsh habitat in ditched New Jersey marshes and Shisler and Jobbins (1977a) point out that *M. bidentatus* inhabits the high salt marsh.

In Chesapeake Bay marshes, Lesser (1982) reported the highest number of *M. bidentatus* and isopods in closed OMWM systems (8.11/m^2 and 0.96/m^2, respectively) as compared to open (1.13/m^2 and 0.56/m^2), water-control (0.50/m^2 and 0.05/m^2), and control (3.10/m^2 and 0.11/m^2) sites. Marsh periwinkle (*Littorina irrorata*), fiddler crabs (*Uca*), or rotifers (*Brachidontes recurvus*) were found only on the control plots, whereas Ferrigno (1970) and Shisler and Jobbins (1977a) reported an increase in both fiddler crabs and isopods in OMWM-treated marshes. Ferrigno (1970) noted a change from 3.7 to 13.1 crabs/m^2, and Shisler and Jobbins (1977a) noted a change from 2.5 to 80 crabs/m^2 in treated versus untreated marshes, and an 80 times increase in isopods (from 27.5 to 215/m^2). Ferrigno (1970) also reported an increase in the ribbed mussel (*Geukensia demissa*) in treated sites. Although Lesser (1982) saw an increase in benthic infaunal species richness over a 2-year period on the OMWM-treatment plots, he stated that the impact of OMWM on benthic infauna was inconclusive. On Long Island marshes, Lent et al. (1990) found no apparent changes in major invertebrate taxa found in different habitats in OMWM-treated sites as compared to control sites, but noted a significant change in invertebrate composition in *S. patens* habitat in the first year following OMWM implementation. This change was no longer evident in the 2nd year.

Using the OMWM-derivative technique of recirculation ditching in California, Balling and Resh (1982) reported a seasonal difference in arthropod community structure based on vegetational community structure. In newly constructed ditch systems in *Salicornia* marshes, arthropod diversity in the dry season was higher near both ditches and natural channels compared to the open marsh. The converse was true in the wet season. Diversity was lower near newly constructed ditches, whereas diversity near natural guts and older ditches (e.g., 44 years) was similar to the open, unditched marsh. In more vegetationally diverse marshes, the study found no difference among ditched, natural tributary, and open marsh arthropod communities.

Fishes: Ferrigno and Jobbins (1968), Fultz (1978), and other researchers have found that tidal circulation, enhanced by ditches, replenished the larvivorous fish in the high-marsh pools. The creation of OMWM systems or restoration of drained natural ponds ensures the fish will be in abundant supply during neap periods or summer droughts. In New Jersey, OMWM-treated marshes had tidal flows and fish assemblages similar to those of unaltered marshes (Able et al. 1979, Talbot et al. 1986). Fish composition and abundance were more a function of salinity and seasonality rather than treatment. In higher salinity marshes, *Cyprinodon* *variegatus* (sheepshead minnow) and *Fundulus heteroclitus* (mummichog) were dominant, with *Fundulus luciae* (spotfin killifish) and *Lucania parva* (rainwater killifish) also common. These results were similar in Maryland (Lesser 1982) and in Long Island (Lent et al. 1990), where the mummichog was dominant in all treated and control plots. In North Carolina, Anderson (1989) reported a dramatic shift in dominance from *C. variegatus* to *Gambusia holbrooki* (mosquito fish) in OMWM-modified ponds, with *F. luciae* being abundant in all plots. Although not as dramatic as the OMWM-modified plots, this shift in dominance was noted in all treatment and control plots, indicating that the shift was related more to surface hydrology (because of drought conditions) rather than OMWM modifications.

Several commercially important species including *Leiostomus xanthurus* (spot), *Pomatomus saltatrix* (bluefish), *Cynoscion nebulosus* (spotted sea trout), and *Mugil cephalus* (striped mullet) were found in Maryland's open OMWM systems, and *L. xanthurus* was also present in the water-controlled system, indicating that these systems provide additional nursery habitat for these species.

Using recirculation ditches in San Francisco Bay marshes, Balling et al. (1980) found 10 fish species in ditched areas, versus 5 in control sites. Fish density was 3 times greater in ditched sites (11.0 fish/m^2) than in unditched areas (3.7 fish/m^2). The size and age structure of *Gambusia affinis* (which was the dominant species) indicated that there was a greater proportion of immatures at the ditched site than in the unditched marsh. It was believed that ditching increased diversity and density through enhanced tidal conditions, improved habitat accessibility for fish from other areas, and allowed water retention at low tide, providing refuge for the fish and their food. Daiber (1986) concludes that the OMWM design, by enhancing ingress to the mosquito-breeding sites, ensures that the mummichog (and other cyprinodontiform fishes) is an effective biological control agent.

Birds: The lowering of the subsurface water table and the creation of spoil piles by the parallel grid-ditch system has been shown to have dramatic effects on marsh vegetation (see section on OMWM's effects on vegetation). However, the higher successional vegetation that recolonized the elevationally higher spoil piles or along the dewatered ditch edges may be beneficial, in terms of nesting and foraging sites, to several species of birds (Burger and Shisler 1978a, 1978b; Shisler et al. 1978). Furthermore, the effect of grid-ditching apparently has no long-term, significant effect on invertebrate populations (Shisler and Jobbins 1975, Lesser et al. 1976, Clark et al. 1984), which provide a valuable forage base for many birds. Open Marsh Water Management, which avoids the creation of spoil piles and subsequent vegetational changes, and does not significantly impact invertebrate populations (see section on OMWM's effects on invertebrates), would presumably have a neutral effect on avian fauna following the recovery of OMWM excavations.

Immediately following OMWM excavations the marsh surface is covered with a thin layer of spoil. The exact amount of area covered by spoil is dependent on the extent of OMWM excavations. This exposed material is used as foraging areas for many species of birds (Lent et al. 1990), and is particularly attractive to migrating shorebirds; however, foraging declines in subsequent years as the area revegetates (Brush et. al. 1986, Cole 1991). When OMWM was used in a well-established herring gull breeding area just prior to the gulls' return in the spring, Burger et al. (1978) found fewer breeding birds using the site. Apparently, the exposed spoil is less attractive as a breeding site. The study also found that nests created in more exposed areas were more prone to predation by avian predators. Marsh passerine species were shown to decline immediately following excavations in Massachusetts, but rebounded to pre-OMWM levels after the area revegetated (Wilson et al. 1987). Similar results were found in Delaware (Meredith and Saveikis 1987), as well as in spoil areas created by recirculation ditches (Collins and Resh 1985). Studies in New Jersey (Shisler and Shulze 1976, Shisler 1979) found that clapper rails (*Rallus longirostris*) were using spoil piles not covered by shrubs and were attracted to tidal ditches because of increased numbers of fiddler crabs. Shisler (1985) also concluded that OMWM alterations apparently have no detrimental impact on northern harriers (*Circus cyaneus*). In fact, the increase in microelevation caused by the thin layer of excavated spoil was found to provide greater small mammal habitat and increased harrier nesting sites.

From a habitat management perspective, a thorough understanding of this interaction between hydrology, spoil deposition, and vegetation response could be used advantageously as part of a larger management scheme. By strategically mounding excavated spoil, islands or bands of higher marsh vegetation could be created to provide shelter or nesting habitat for waterfowl. This technique would be most effective if used to protect a pond from prevailing winds or coastal storms. However, this technique should be used very cautiously in order to avoid encroachment of phragmites or excessive shrub growth, which Widjeskog (1994) points out would concentrate mammalian predators and deter waterfowl use.

Another end result of OMWM is the increased amount of permanent ponded water that is created. Ferrigno and Jobbins (1968) noted the increased marsh management opportunities of these ponds. If performed as part of an integrated marsh management approach (Meredith et al. 1985), OMWM ponds can be attractive feeding and resting areas for migrating waterfowl and are permanent sources of forage fish that are utilized by wading birds and other piscivorous predators. Furthermore, if OMWM ponds are created at the edge of mosquito-breeding flat pans and intermittently exposed mud flats, mosquito breeding is eliminated by the presence of fish in the ponds and the integrity of the pan is maintained for shorebirds and dabbling ducks. If done in an integrated fashion, OMWM ponds can enhance or restore waterbird habitat with a neutral, or even beneficial impact to waterbirds.

Ferrigno (1970) found no difference in waterbird utilization between OMWM-treated and control ponds with the exception of the greater snow goose (*Chen caerulescens*) and Wilson snipe (*Capella gallinago*), which apparently showed a strong attraction for the wetter, poorly drained control area. Erwin et al. (1991) also found no significant differences in waterbird use between OMWM-created and natural ponds, but found a high degree of variation in bird use. The study, conducted throughout New Jersey, Delaware, and Maryland by the U.S. Fish and Wildlife Service, also concluded that seasonal effects were significant and that larger ponds (>0.25 ha) were utilized to a greater extent than smaller (0.05 ha), more typical OMWM ponds. Erwin et al. (1994) later recommended that fewer large ponds should be created to enhance waterbird use but admitted that logistical constraints of distributing excavated spoil may preclude creating ponds >0.30 ha. Furthermore, even the creation of larger ponds did not benefit waterbirds as well as nearby managed impoundments. This is a noteworthy observation but is not a viable alternative for most modern-day mosquito control agencies in an era when wetland regulations demand minimal and neutral impacts. Also, impoundments (at least in the USA) are created and managed primarily for waterbird use and are tens if not hundreds or even thousands of hectares in size, so bird use would be expected to be considerably higher than small, unmanaged excavated ponds. Some would argue that the benefits associated with such habitat enhancement still do not outweigh the cost of losing the primary productivity of the same piece of salt marsh. Also, these benefits may only be temporary due to pond senescence and the dynamic nature of salt marshes. Shisler and Ferrigno (1987) reported no negative short-term impacts of OMWM on waterfowl populations but noted the weaknesses in evaluating long-term impacts. They concluded: "The before and after management waterfowl population data for individual water management sites over a long time period must reflect (in part) macro-scale changes in populations throughout the flyway."

Mammals: Although there is little published information on OMWM's effect on marsh mammals, Shisler (1985) cites some earlier studies on the effects of parallel grid-ditching on the meadow vole (*Microtus pennsylvanicus*), stating that ditching does have an impact on vole movement and distribution even though voles are considered excellent swimmers. Furthermore, vole populations were most abundant on higher spoil piles and hummocks along the ditch edges. Winkler (1981)[1] found similar results on a Delaware salt marsh. Although OMWM avoids high spoil piles, increases in microelevation due to accumulated spoils may create slightly higher marsh habitat, which is more favored by voles. Also, because OMWM is used selectively in mosquito breeding areas and impacts much less marsh surface area than parallel grid-ditching, vole or any macrofaunal movement should not be significantly hindered. Romanowski (1991) found that vole populations were a function of revegetation following OMWM and that, in the long term, no negative effects on population densities were observed.

In terms of effects on muskrat populations, Cochran (1938) felt grid-ditching would not adversely impact muskrat populations, but Stearns et al. (1939) reported that ditching dramatically decreased the vegetation needed for food and house building, causing the muskrats to leave the area. In general, the more tidally influenced sections of salt marsh, dominated by *S. alterniflora,* are more typical of muskrat habitat. These tidal low-marsh areas seldom produce sufficient numbers of *Aedes* mosquitoes to warrant control, which was another negative aspect of indiscriminate grid-ditching. Also, muskrat burrowing will often drain low-marsh mosquito-breeding pools. Therefore, OMWM, or any mosquito control measure, may not even be needed in these locations. Looking at it another way, in areas where OMWM results in a progression to low-marsh habitat (Ferrigno 1970, Shisler and Jobbins 1977a) such activities would presumably promote muskrat use. Many anecdotal observations of muskrat activity have been made in OMWM-treated marshes in Delaware. In fact, OMWM guidelines for Delaware (Meredith et al. 1985) indicate that care should be taken in designing OMWM systems so as not to promote drainage of the system by muskrat burrowing.

Further observations have been made in Delaware of OMWM systems being used by river otters (*Lutra canadensis*), which presumably feed on the abundant fishes in the ponds. Also, tracks of raccoon (*Procyon lotor*), red fox (*Vulpes vulpes*), and white-tail deer (*Odocoileus virginianus*) have been noticed in newly excavated spoils. Whether or not these latter species actually utilize the OMWM systems in some fashion is unknown; however, there is concern that raccoons and foxes prey on nesting waterbirds that use the areas, particularly if there is heavy shrub growth around the pond system (Widjeskog 1994). This is another reason why care should be taken in pond design and spoil disposal.

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[1] Winkler, J. 1981. Movement patterns of the meadow vole, *Microtus pennsylvanicus,* on a Delaware salt marsh. Master's thesis. University of Delaware, Newark, DE.

Water quality: The effectiveness of OMWM for mosquito control depends (in part) on the system's ability to sustain a viable fish population. Maintaining favorable water quality conditions in the OMWM systems is crucial to ensure that larvivorous fish will be present as a control agent. Furthermore, favorable nursery habitat for commercially important species will be maintained, and viable populations of forage species will be present for piscivorous macrofauna. Therefore, it is imperative that OMWM has a minimal impact on water quality.

Earlier studies indicated that parallel grid-ditching decreased soil salinities and increased the pH of surface and subsurface water near the ditch edges (Daigh et al. 1938, Daigh and Stearns 1939). However, the vegetation in these areas had very wide tolerances for salinity and pH and it was found that changes in vegetation were a result of lower water table heights and not due to changes in these water quality parameters (Daigh et al. 1938, Daigh and Stearns 1939). More recently, Soukup and Portnoy (1986) found the converse. They reported that oxidized pyrites found in desiccated salt-marsh sediments produced low pH (2.6–2.85) leachates. These mobilized aluminum compounds, which caused fish kills. Ironically, the targeted pest mosquito, *Aedes cantator* (Coquillett) appeared to tolerate the acidic conditions and control was ineffective.

Shisler and Jobbins (1977b) demonstrated that open-tidal OMWM systems release significantly lower levels of total organic carbon and particulate organic carbon than unditched marshes. Changes from short-form *S. alterniflora* to tall-form *S. alterniflora* can occur in OMWM-treated marshes, presumably as a result of increased soil aeration and nitrogen fixation from the "mulching" effect of excavated spoils (Ferrigno 1970, Shisler and Jobbins 1977a). This increased robustness in tall *S. alterniflora* has also been observed in Delaware's OMWM-treated marshes.

Several studies indicated that OMWM has no significant effect on water quality (Whigham et al. 1981; Lent et al. 1990; A. Anderson, unpublished data) but dramatic fluctuations can occur among marshes with varying tidal regimes or vegetative cover types. Lesser (1982) found no significant differences in temperature, salinity, and dissolved oxygen among 3 different treatment types and control plots, with one exception. He found that closed OMWM systems exhibited dissolved oxygen levels as low as 0.0–0.5 ppm because of a high biological oxygen demand. Poor mosquito control was realized as a result of fish kills coupled with increased sheet-water mosquito breeding adjacent to the ponds and ditches with no tidal circulation capabilities. Initially, there were no significant differences found in salinity or soil moisture using the OMWM-derivative technique of runnelling (Hulsman et al. 1989). However, water and substrate salinities tended to decrease and substrate moisture content increased over time. Using recirculation ditches in California, Resh and Balling (1983) also found that tidal flushing lowered groundwater and interstitial soil salinities, resulting in a desired increase in marsh productivity and diversity.

In summary, OMWM has no detrimental long-term impacts on water quality. As has been shown, viable fish populations are maintained in OMWM systems, thus assuring the necessary biological control agent. The response of aquatic invertebrates, vegetation, and other biotic components to OMWM or any marsh alteration technique is more a function of water table height, not water quality.

ECONOMICS OF OMWM

Despite the beneficial qualities of OMWM, the question remains as to how OMWM compares to chemical treatment on an economic scale. If it is found to be too expensive to implement and maintain, OMWM may not be an economically feasible alternative to chemical spraying. If this is true, many mosquito control districts may have to use OMWM only on a small scale or abandon the idea of implementing OMWM altogether. In Rhode Island for example, Christie (1990) found ground larviciding with *Bacillus thuringiensis* var. *israelensis* (*B.t.i.*) to be 4% ($50/acre/year) of the cost of hiring a private contractor ($60,000) to install OMWM on 9 acres of salt marsh.

In the USA most states have found that, in the long run, OMWM is more economical than a chemical spray program. A study in North Carolina (DeBord et al. 1975) reported that chemical control was 1.4–3.5 times as "efficient" as ditching per dollar of expenditure. Later reports (Hansen et al. 1976, Provost 1977) strongly disagreed with this claim. Based on such things as initial cost and depreciation of equipment, fuel, repairs, and administrative costs, OMWM is initially expensive relative to chemical treatment costs. Hansen et al. (1976) calculated the cost per acre of OMWM to range from $5.05/acre to $63.45/acre depending on the type of machinery used and number of OMWM ponds that were created. Using the higher end of this range, the cost per acre would be $3.17/acre/year over an expected 20-year life of the OMWM system: the equivalent cost of one larvicide treatment would be $3.57/acre/year. Assuming 4 larvicide treatments per year were needed, it was determined that over the life of the OMWM system, chemical larviciding would be 4.5 times as expensive as OMWM (not including any adjustments for inflation). In a similar study Shisler et al. (1979) estimated that the cost of OMWM ranged from $99.12/acre to $309.76/acre, versus a range of $12.57–$20.64/acre for chemical larviciding. The higher cost of OMWM is based on using a dragline and backhoe rather than the relatively inexpensive rotary ditcher reported by Hansen et al. (1976).

Assuming a 10% inflation rate per year for 10 years, Shisler and Harker (1981) estimated the time needed to recover the cost of 4 water management projects (based on projections of annual larviciding cost) to range from 4 to 17 years. At that same rate, Candeletti and Candeletti (1990) estimated the cost of larviciding to be 8 times that of equivalent OMWM projects that have been in place for 20 years.

Using case studies in Chatham County, GA, Ofiara and Allison (1985) found that permanent control measures were initially more costly than temporary measures (i.e., larviciding) but would be more economically beneficial over time. Also, permanent control was a contributing factor to the reduction of adult mosquitoes and subsequent ground adulticide applications. Although Wolfe (1992) reported that OMWM will "pay for itself" in approximately 5 years, Provost (1977) found that the cost of ditching or impounding Florida salt marshes was recovered in 2–3 years by savings on larviciding alone. Furthermore, Shisler and Harker (1981) concluded that from a strictly economic standpoint, water management projects that take longer to recoup their costs (i.e., 15–17 years) may not be so attractive, but might still be considered from an environmental standpoint, because water management might be "environmentally preferable" to chemical control.

CONCLUDING REMARKS

In general, this review shows that OMWM is an effective method of providing long-term, cost-effective salt-marsh mosquito control with neutral to beneficial impacts to other wetland resources. Problems or observations as they relate to specific parameters or management methods have been reviewed throughout. In an earlier review of salt-marsh management techniques for mosquito control, Dale and Hulsman (1990) gave a breakdown of research and management problems, needs, and possible solutions. The problems are general in nature with respect to salt-marsh management but I will attempt to highlight some of these points as they relate to OMWM.

From this, and other reviews, there appears to be little information on marsh management for mosquito control done outside the USA even though research and a great deal of operational mosquito control is done on a global scale. A data gap exists because much of the observations and analyses of those directly involved in mosquito control goes unpublished. This may not be anyone's fault *per se,* as publishing such information may not be part of their normal job duties. As a potential solution it is suggested that a national or international database with a standard for recording observations be developed.

Another problem that still exists is the incomparability of marsh types. Due to habitat heterogeneity (even on a local scale), OMWM systems must be customized to meet the need. Also, OMWM designs are as varied as the designers. Furthermore, because of the vagaries of wetland ecosystems (and the subtle differences in wetland regulatory interpretations), no one master set of OMWM plans can or should be developed that can be applicable for all situations, either regionally nor globally. There is a need for authors to specifically state the uses of OMWM and design modifications in order to compare effects. As Dale and Hulsman (1990) point out, with a large enough database, marsh classes could be identified that behave similarly on a macro- or local scale. Such things as climate, habitat type and size, tidal characteristics, substrate, flora and fauna, and even the target mosquito species and its ecology should be included if source reduction techniques are to be made comparable.

To compound the problem of comparability, the term Open Marsh Water Management has evolved to be a catchphrase for many wetland habitat modifications: from source reduction for mosquito control to waterbird habitat enhancement to wetland restoration. The meaning seems to have strayed from its original intent in the 1960s. Suffice it to say that OMWM is a *concept* whose primary goal is to control mosquitoes with no adverse effects to other associated resources, but can be integrated into a larger management scheme to enhance selected tidal marsh resources.

Another problem that exists is one of communication and education. There is a need to facilitate 3-way communication among researchers, mosquito control managers, and political entities responsible for decision making and budgeting so that each one is aware of the other's resources, needs, and limitations. This is closely related to the need for greater education of a public that still often associates mosquito control with drainage ditching and DDT. In the USA this is being done at a national level through organizations such as the American Mosquito Control Association. There may be an even greater need at the state or district level because these are the agencies the public turns to for controlling mosquitoes.

Finally, no one appears to address perhaps the real source of the problem. That is, the continued attempt for human habitation into, or adjacent to, salt-marsh habitats. There is no question where the mosquitoes are coming from. The problem comes when humans encroach upon the same habitat. And with 70% of the world's population living within a day's journey of the coast, this problem will not be rectified in the near future. Land use zoning and regulations attempt to minimize human impacts on coastal resources. Perhaps the impact of the resources (including mosquitoes) on people should be reflected in zoning and regulations as well.

As the literature indicates, there is a trend in salt-marsh mosquito control towards source reduction and biological control while minimizing impacts to the environment. Open Marsh Water Management is an environmentally focused management tool that is designed to be compatible with nature rather than compete with it.

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