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GUIDELINES FOR "OPEN MARSH WATER MANAGEMENT" IN DELAWARE'S SALT MARSHES - OBJECTIVES, SYSTEM DESIGNS, AND INSTALLATION PROCEDURES

William H. Meredith, David E. Saveikis, and Chester J. Stachecki

Mosquito Control Section, Division of Fish and Wildlife, Delaware Department of Natural Resources and Environmental Control, PO Box 1401, Dover, Delaware 19903

Abstract. Open Marsh Water Management (OMWM) is a method for controlling salt-marsh mosquitoes using physical alterations of marsh habitat. Ponds and ditches are selectively excavated in order to create unsuitable environs for mosquito eggs and larvae while creating suitable habitat for larvivorous fishes. Based on environmental effects observed at two experimental sites, plus operational experiences in Delaware and adjacent states, guidelines are presented for designing and installing OMWM systems in Delaware. These guidelines should be applicable to other salt marshes from New England to Florida that have similar environmental characteristics.

The guidelines are intended to produce OMWM systems that will control mosquitoes while minimizing long-term ecological disruptions of the marsh community. They emphasize the following topics, including the environmental or economic reasons for why particular approaches were chosen: 1) use and location of open tidal ditches; 2) interspersion of open tidal ditches with closed, non-tidal ponds and pond radial ditches; 3) use of semi-tidal sill ditches and ponds; 4) incorporation of OMWM systems into previously parallel-grid-ditched marshes; 5) permissible lowering of the water table elevation in relation to local marsh surface, as caused by spoil deposition on the marsh surface and/or drainage from open tidal ditching, but not to such an extent that the original vegetation is replaced by other species during vegetative recovery; 6) protocols for designing, demarcating and installing OMWM systems; 7) density, depth and surface areas of ponds; 8) geometric vs. naturalistic excavations; 9) habitat enhancement for waterfowl use; 10) water quality, fish kills and dependable mosquito control; 11) OMWM alterations under special situations, such as upland border marshes with excessive freshwater runoff or marshes with intensive muskrat burrowing activity; 12) blending of OMWM with other marsh management goals.

INTRODUCTION

Open Marsh Water Management (OMWM) is a method for controlling salt marsh mosquitoes using physical alterations of marsh habitat. OMWM alterations involve selective excavation of ponds and ditches which create unsuitable environs for mosquito egg deposition and larval maturation, while simultaneously providing stable habitats for larvivorous fishes (Ferrigno and Jobbins 1968; Ferrigno *et al*. 1975). As such, OMWM promotes and maximizes biological control through physical manipulations. The Delaware

Mosquito Control Section is proposing to use OMWM, where appropriate, as a primary means of salt-marsh mosquito control on much of Delaware's tidal wetlands. It has become obvious that a set of operational guidelines is necessary for OMWM system design and installation. Since water management practices, when incorrectly conceived or installed, have potential for adverse environmental impacts (Daiber 1982), it is essential that a protocol for design and installation be formulated in order to avoid detrimental effects.

Guidelines for OMWM have been written for New Jersey (Bruder 1980) and Maryland (Lesser 1982). These guidelines adequately define the local OMWM process for regulatory or permitting agencies, but do not fully address the reasons for many recommended procedures, nor do they account for OMWM use under unusual conditions (e.g. in atypical border marshes, in areas of snow goose feeding). Guidelines for OMWM in Massachusetts are being prepared by Hruby and Montgomery (ms. in prep.) which provide greater insights into the "why" of recommended procedures. The Delaware OMWM guidelines attempt to elaborate upon the reasons for recommended procedures. Our guidelines should be applicable to other mid-Atlantic regional marshes, and also to marshes of similar environmental characteristics (e.g. tide range, vegetation, soil type) in New England and along the southeast Atlantic coast. The Delaware OMWM protocol is partially based on the experiences and recommendations of OMWM programs in New Jersey and Maryland; it is strongly influenced by studies done by the Delaware Mosquito Control Section, sponsored by the Delaware Coastal Management Program (DCMP), of the environmental effects of prototype OMWM systems on marshes of the Bombay Hook and Prime Hook National Wildlife Refuges (Meredith et al. 1983); and it also relies on observations of operational OMWM systems in Delaware which were begun in 1980.

OBJECTIVES FOR OMWM IN DELAWARE

The objectives of OMWM in Delaware are as follows:

1) Control of Pestiferous Salt-Marsh Mosquitoes

The primary objective is to provide a water management technique that will control the dominant species of Delaware salt-marsh mosquitoes: *Aedes sollicitans*, *Aedes cantator*, *Aedes taeniorhynchus*, *Culex salinarius*, and *Anopheles bradleyi* (Lake 1973).

2) Reduction in Use of Chemical Insecticides

If the primary objective is achieved, then the current reliance on chemical insecticides will be reduced. Successful control via OMWM will be considered achieved if the frequency of insecticide spraying on a given marsh is at least 80% less after OMWM than before OMWM.

3) Minimize Adverse Secondary Impacts on the Marsh Community

The application of OMWM should not adversely impact other existing marsh resources or functions. A primary gross environmental alteration to be avoided when using OMWM is promotion of higher elevation plants through increasing the marsh surface elevation due to spoil deposition and/or excessive lowering of the water table elevation due to drainage. Since the ecological consequences of altering marsh vegetation patterns are not fully

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understood, it is both responsive and prudent to install OMWM systems that will not grossly alter existing vegetation. With minimal alterations to extant vegetation, other components of the marsh community (e.g. surface invertebrates, edaphic alge, detritus production and export) will not be radically changed.

4) Habitat Enhancement for Waterbirds

As a result of the creation of mosquito-control OMWM ponds, habitat may be created that is also beneficial to waterfowl, shore birds, and wading birds (Meredith et al. 1984). OMWM pond creation may help to mitigate the loss of high marsh ponds that historically were abundant on Delaware's salt marshes, but were drained by the old mosquito control method of parallel-grid ditching.

5) Cost-Effective Mosquito Control

The use of OMWM is potentially more cost effective than the use of insecticides. According to economic analyses conducted in New Jersey (Hansen et al. 1976; Shisler et al. 1979; Shisler and Schulze 1985), properly installed OMWM systems will be less expensive than continual treatment with chemical insecticides.

PROTOCOLS FOR OMWM IMPLEMENTATION

1) Marsh Breeding Habitats Where OMWM Could Be Used

The environmental requirements necessary for breeding of salt-marsh mosquitoes are usually delineated by vegetation zones. In Delaware, the most severe breeding habitats are on the highest marshes (i.e. marshland that is only flooded by spring or storm tides, and which often goes dry between rainfalls or surface inundations). Plant species characteristically associated with the high marsh are the salt hay grasses, *Spartina patens* and *Distichlis spicata*, and the short-form of the cordgrass, *Spartina alterniflora*. Short-form *S. alterniflora* in the high marsh may be found in extensive stands, or may be confined to shallow depressions surrounded by salt hay that hold water long enough for a mosquito brood to progress to adult emergence; in either case, zones of short-form *S. alterniflora* can produce severe broods, but usually not at the frequency of salt hay habitat. The salt hay contains two types of breeding sites: 1) discrete, relatively deep potholes; 2) "tussocky" areas that hold surface water at the base of grass clumps. Both of these salt hay sites are major problem habitats. Mosquito breeding can also occur near the upland fringe in salt hay zones which are in association with marsh elder (*Iva frutescens*), groundselbush (*Baccharis halimifolia*), marsh hibiscus (*Hibiscus* spp.), marsh mallow (*Kosteletzkya virginica*), or panic grasses (*Panicum* spp.). Depending upon locality within the State, the short-form *S. alterniflora* found in shallow, mosquito-breeding depressions surrounded by salt hay may be replaced by three-squares (*Scirpus* spp.) or black needlerush (*Juncus roemerianus*), both which can form mosquito-producing habitat under such conditions. A final type of salt-marsh mosquito breeding habitat in Delaware can be found in potholes or depressions in zones of common reed, *Phragmites australis*.

Any of the above described breeding habitats are candidates for OMWM treatment. These marsh breeding habitats are found in extensive, open salt marshes extending landward from tidal rivers and coastal embayments; in

small pocket or finger marshes along the upland fringe; in the more brackish marshes near headwaters of tidal creeks; and in swales behind coastal dunes.

OMWM will not be used in marshes or marsh zones subject to an average of at least one high tide per day, since such areas usually do not produce mosquitoes. Non-breeding marshes or marsh zones in Delaware are typically vegetated by tall- or intermediate-form S. alterniflora. Also, extensive stands of cattails (Typha) spp. or three-squares (Scirpus spp.) are not candidates for OMWM. Permanent ponds on the marsh surface (which are relatively large and deep) do not serve as breeding habitat and will not be drained.

2) Factors Considered in OMWM Site Selection and System Design

OMWM alterations must directly affect potential mosquito breeding sites within known breeding marshes. The determination of which marshes breed, and are thus candidates for OMWM, will be based on historical aerial spray records and/or historical larval inspection records for specific marshes. Potential breeding sites within a candidate OMWM marsh will be identified by staff biologists and/or mosquito control supervisors via on-site evaluations of: 1) vegetative cover, 2) tidal flooding and runoff patterns, 3) physical characteristics of surface depressions, 4) potential for access and survival of larvivorous fishes, and 5) when practical, direct observation and quantification of mosquito larvae. To aid in design of the OMWM systems, other environmental factors may be considered on a site-specific basis. Such factors could include local topographic relief, soil characteristics (particularly peat vs. mineral content), depth of mean water table below local marsh surface, and proximity to critical or unique wildlife habitats. Which factors will be examined for a specific tract, and how they will be integrated to assist in the OMWM system design, will vary from site-to-site. Staff biologists will use this information to aid in formulating regional OMWM design concepts specific to geographic areas.

3) Field Demarcation of OMWM Systems and Alterations

Prior to any excavations, all breeding sites and their specific methods of OMWM treatment will be demarcated with surface stakes. If there is to be an on-site, regulatory review of the proposed alterations, the post-staking stage is the most logical point to have such a review. It is important that a uniform, consistent system for indicating alterations be designed and used by all parties. Since the field lay-out of OMWM systems will be done under supervision of staff biologists and/or mosquito control supervisors, but the actual machine excavations supervised by foremen or machine operators, it is mandatory that excavation personnel be able to interpret and understand the staked designs.

The staking system should clearly indicate pond borders; island locations; location of deeper reservoirs in ponds; the beginning and termination of primary ditches, pond radial ditches, and lateral spurs; where a semi-tidal ditch's shallow sill outlet begins and terminates; and whether or not a ditch approaching a tidal source will be connected at full depth to daily tidal flow. Stake tips can be color coded to indicate various features, and various combinations of stakes used to further discriminate features.

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The staked OMWM design should be drawn on a map which also indicates major natural features. Such maps will be used by the equipment operators and could also be valuable to regulatory agencies. The maps could be of particular value in indicating to which side(s) of an excavation spoil should be directed or placed. This is especially important if spoil is to fill breeding depressions that are not staked for ditching. The amount of excavation planned will be the minimum required to satisfy the OMWM objectives.

4) Excavation Equipment Used in OMWM

Whenever feasible, excavations in OMWM are to be made with a rotary excavator (either amphibious or land-limited). The rotary cutting head broadcasts spoil as a crude slurry, thinly covering the marsh surface for distances up to 15 m from an excavation. Other heavy machinery (e.g. dragline, backhoe, front-end loader) can be used in OMWM as long as the OMWM objectives are met, particularly in regard to satisfactory deposition of spoil. Spoil from non-rotary excavations may be used to fill breeding depressions or old ditches, or can be deposited in small mounds and then spread to a depth less than 10 cm over the marsh surface. Care must be taken during spreading and compaction not to pack the overburden of spoil too densely to permit vegetation recovery. Also, the creation of ruts by the machinery during the spreading process should be avoided. The most likely use for non-rotary equipment in OMWM is to excavate ponds in soils with high mineral content.

5) Removal of Shrubs Impeding Spoil Broadcasting

In some instances, it may be necessary to cut down wetland fringe vegetation, especially shrubs (e.g. *Iva*, *Baccharis*), in order to permit unimpeded broadcasting of rotary spoil. Care should be taken to leave at least a 1.5 m wide band of shrubs along the marsh's upland edge. This will help preserve the natural wetland-upland transition.

6) Location and Ranking of Candidate OMWM Marshes

Of Delaware's 34,500 ha of tidal wetlands, about 6000 ha have been identified as severe salt-marsh mosquito-breeding habitat and are thus candidates for OMWM treatment. Marshes to be treated with OMWM are ranked for work priority according to degrees of breeding severity in relation to human population centers, in terms of both nuisance problems and disease potential. This ranking of work areas may then be modified by factors of landowner cooperation, efficient deployment and transport of heavy equipment, and impact on reduction of aerial spraying.

DESCRIPTION OF OMWM ALTERATIONS

1) Terminology and Types of Alterations

Three types of alteration systems are used in Delaware OMWM: 1) Full-depth tidal ditches (45-90 cm deep), with relatively deep tidal outlets (e.g. 75 cm below marsh surface), plus associated lateral spur ditches, creating a system that has daily tidal exchange; 2) Semi-tidal systems consisting of full-depth ditches (e.g. 75 cm) with a shallow tidal outlet or sill (e.g. 10-20 cm deep - see Fig. 1), plus associated lateral spur ditches landward of the shallow outlet, creating a system that has more tidal exchange than if no ditching was done, but not as much as full-depth tidal

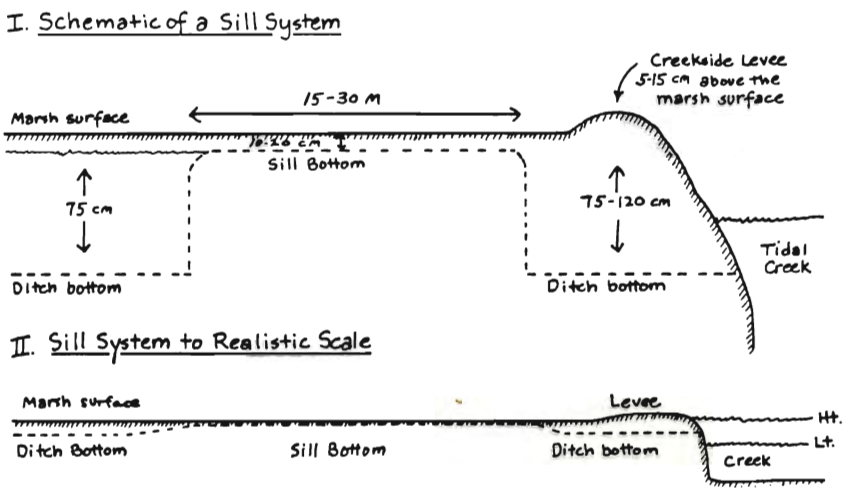

Figure 1. Side-view diagram of a sill (semi-tidal) OMWM system, with emphasis on the sill's shallow outlet.

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ditches; 3) Shallow ponds of 50-1000 square meter surface area (averaging 30 cm deep), with deeper reservoirs (75-90 cm deep), plus associated pond radial ditches of full-depth (e.g. 75 cm), with both ponds and radial ditches lacking any tidal outlets, creating a system that has tidal exchange during only spring or storm tides.

The full-depth tidal ditches with deep outlets are often referred to as "open" systems; when these systems are made semi-tidal via shallow outlets, then these modified systems are known as "sill" systems; the essentially non-tidal systems of ponds and pond radials are often called "closed" systems. The word "Open" in Open Marsh Water Management refers to the fact that OMWM systems do not contain elevated structures above marsh surface to prohibit tidal exchange (e.g. no impoundments, dykes, or sluice gates). OMWM systems may have various combinations of tidal, semi-tidal, and non-tidal systems (i.e. open, sill, and closed systems - see Fig. 2).

When digging open ditches, deeper ditches are preferable since they will not fill-in as rapidly with tidally-borne sediment and will have a longer functional life. Open ditches can be connected to tidal sources at more than one point in order to promote circulation.

The shallow outlets for sill systems should be at least 30 m long in peaty soils and at least 15 m long in mineralogical soils. These lengths will help promote sill longevity in areas where the sill might erode to deeper depths, since the maximum rates of erosion occur at the sill ends. Past the tidal end of the sill, the outlet should slope gradually toward the tidal source in order to minimize undercutting by ebbing water. The shallow sill should not go through any creekside levee since it is along the creekside where sedimentation rates are highest, and where sill longevity would be least. An extra wide (e.g. 150 cm), extra deep (e.g. 120 cm) ditch is constructed at the seaward end of the shallow sill, cutting through the creekside levee. This larger ditch will serve as a "catch basin" for tidally-transported sediments and debris on flooding tides, prolonging the functional longevity of the more landward sill. A correctly designed and installed sill system will remove very shallow, standing surface water from tussocky mosquito-breeding areas while still maintaining a high subsurface water table at low tides. It will also enhance tidal exchange (since the creekside levee has been broached), promoting good water quality to the benefit of larvivorous fishes. Because of the shallow nature of the sill's outlet, breeding depressions greater than 5 cm deep or more than a few meters away from a sill ditch will not be drained; these deeper or more remote breeding depressions should be directly treated with sill ditch lateral spurs.

Closed ponds are excavated in areas of concentrated breeding depressions. Ponds should have a uniform depth of about 30 cm over most of their surface area. Slate (1978) found this depth to be the average depth of potholes containing widgeongrass (*Ruppia maritima*), a valuable waterfowl food. To insure fish survival during droughts, reservoir ditches from 75-90 cm deep should be dug along one or two sides of the pond. Natural or OMWM ponds with several full-depth pond radial ditches (e.g. 75 cm deep) extending outward from the main pond body may not need ditch reservoirs within the pond. Islands should be left in ponds when feasible to provide

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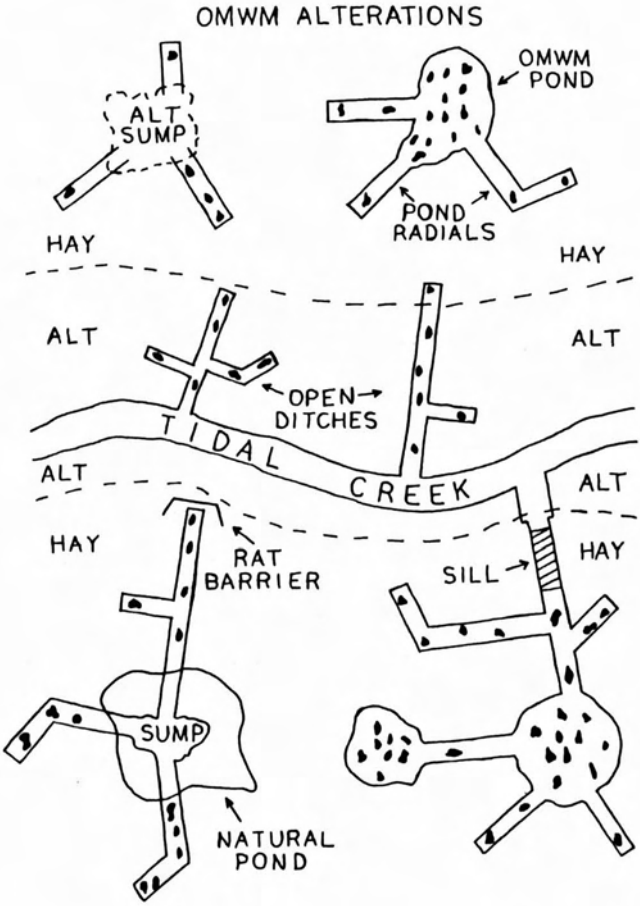

Figure 2. Various marsh excavations and alterations used in the OMWM technique. The darkened spots represent former mosquito-breeding depressions.

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protected areas for bird nesting plus additional edge habitat, while reducing spoil volume around pond perimeters.

2) Interfacing the Old, Parallel-Grid Ditch System with OMWM Alterations

The open tidal ditches of the old parallel-grid ditch network slowly fill with tidally-borne sediment. In the past, these ditches have been cleaned of deposits, restoring the ditch network to its original design and function. This routine cleaning of parallel-grid ditches is a questionable procedure, since many ditches were placed in marshes or sections of marsh that did not require mosquito control, and in some areas these open ditches caused drainage of waterfowl ponds (Clarke et al. 1984) plus excessive depression of the subsurface water table. Routine, wholesale cleaning of the parallel-grid ditch system is not part of Delaware OMWM. Parallel-grid ditches that are filling will not be reexcavated if the cleaned ditches fail to met all of the objectives and specifications for OMWM alterations.

Parallel-grid ditches may be cleaned and restored to open tidal flow in zones of short-form cordgrass where mosquito breeding is evident. Lateral spurs may be dug from these cleaned ditches, treating breeding depressions that might exist between parallel-grid ditches in zones of short-form cordgrass. However, restoring the parallel-grid ditches in salt hay zones to open tidal flow will usually not be done.

Since the installation of sill and closed systems in salt hay areas of the high marsh requires limited or no direct tidal exchange, and since many areas of the high marsh have been treated with parallel-grid ditches, it may be necessary to block, or at least not clean, these high marsh grid ditches. A desirable location for ditch blockage would be at the transition from predominantly short-form cordgrass zones to predominantly salt hay zones. The parallel-grid ditches seaward from this transition edge, in short-form cordgrass zones, could be cleaned and spur ditched if breeding occurs in the lower marsh. Landward from ditch blockages, parallel-grid ditches could be cleaned in order to deepen them for inclusion in sill or closed systems in the high marsh.

If a parallel-grid ditch in the high marsh area has not silted enough to have a short segment of the ditch serve as blockage for a sill or closed system, then spoil "plugs" may be used to achieve blockage. These plugs should fill the parallel-grid ditch to marsh surface level and be at least 8 m long in marshes with mineralogical soil to at least 15 m long in marshes with peaty soils. The plugs should be installed on the salt hay side of a cordgrass-salt hay interface, taking advantage of the more consolidated soils in salt hay zones.

In summation, the basic strategy for managing parallel-grid ditches in Delaware OMWM is to "break-up" the grid network: 1) clean only those ditches that directly contribute to mosquito control; 2) allow other non-breeding ditches to fill naturally; 3) prohibit excessive tidal flow and drainage in the high salt marsh via plugs, thereby restoring standing surface water to the upper marsh with sill and closed systems (see Fig. 3 for an example of OMWM superimposed over a parallel-grid ditch system).

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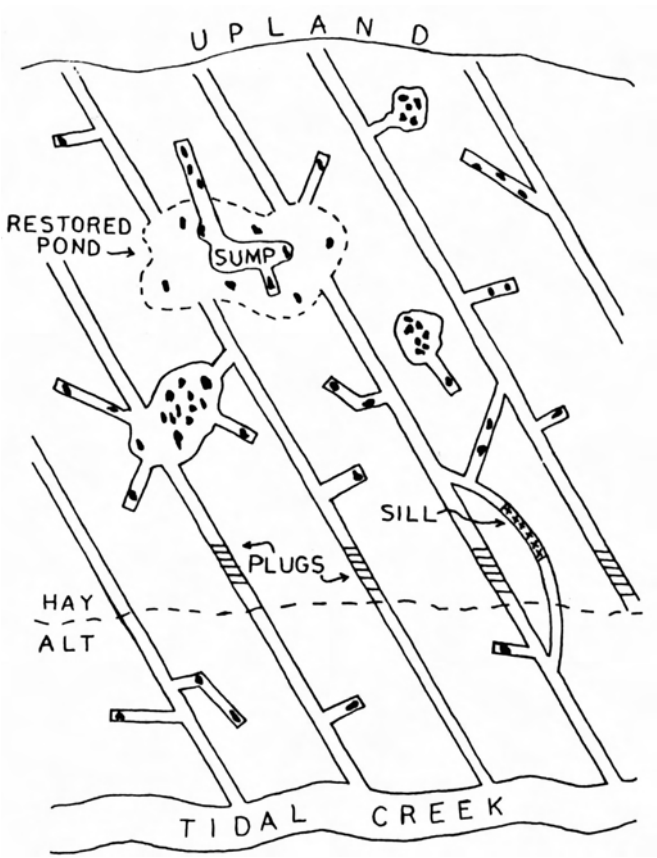

Figure 3. An OMWM system superimposed over a previously parallel-grid ditched marsh. The darkened spots represent former mosquito-breeding depressions.

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TAILORING OMWM ALTERATIONS TO MEET OMWM OBJECTIVES

1) Maintenance of a High Subsurface Water Table

A basic management goal is to insure that no OMWM alteration causes the mean subsurface water table to drop more than 15 cm below local marsh surface elevation. The OMWM studies sponsored by the Delaware Coastal Management Program (DCMP) have found that the mean water table in study site zones of *Iva*, *Baccharis*, and robust *Phragmites* is 15 cm or more below local marsh surface, creating a soil condition that is drier and more aerated than soils in salt hay or short-form cordgrass zones (Meredith *et al*. 1983). In order to discourage conditions that may cause establishment and growth of marsh shrubs and common reed, excessive subsurface drainage and/or excessive spoil deposition, which either separately or in combination may establish a greater than 15 cm average distance between marsh surface and mean water table, should be avoided. While the correlation between vegetation cover type and depth to mean water table may be somewhat variable from site-to-site (especially for *Phragmites*, which may grow in areas of considerable tidal flooding), the avoidance of creating a mean distance between the marsh surface and water table greater than 15 cm provides an initial management criterion for maintaining existing vegetation patterns.

Spoil from ditches and ponds should be spread over the marsh surface at initial depths no greater than 10 cm (after a period for spoil settling, any permanent increase in surface elevation should be less than 5 cm).

Generally, open tidal systems should not be put in areas of salt hay. However, breeding depressions in salt hay within 3 m of an existing tidal feature (natural or man-made) may be treated with open spur ditches. This will permit operational treatment of isolated potholes near tidal features without having to extend closed or sill ditches close to these tidal sources, thereby minimizing the risk of non-tidal systems becoming directly connected to tidal sources (e.g. via muskrat burrowing).

Sill systems in salt hay zones may have their shallow outlets from 10-20 cm deep, depending on local tidal amplitude and soil composition. The DCMP-sponsored studies suggest that deeper sill depths (e.g. 20 cm) can be installed in areas of high tidal amplitude and peaty soil, whereas shallower depth sills (e.g. 10 cm) should be used in areas of low tidal amplitude and mineralogical soils.

An exception to avoiding creation of a water table elevation which averages a distance of 15 cm or more below local marsh surface could be made for low elevation areas that are subject to enough tidal surface flooding to retard colonization and/or growth of high elevation plants (e.g. in short *S. alterniflora* zones near tidal sources). In such areas, a 15 cm or greater water table displacement would be allowed, but only if created by open ditch drainage, not by spoil deposition on the marsh surface. Excessive deposition of spoil could raise surface elevations above heights where high marsh plants would no longer be suppressed by tidal flooding.

2) Efficient Dispersion and Use of Spoil

A second basic management goal is efficient use of spoil to fill

breeding depressions. Effort should be made in all OMWM systems designs to take advantage of spoil for beneficial filling of breeding depressions. Breeding areas filled with spoil will not require further modification. Precautions to take are not to fill depressions to heights above marsh surface and not to compact the fill too densely to prevent future plant growth.

3) Creating Natural-Looking OMWM Systems

A third basic management goal is creation of systems which look natural. Until the marsh surface is substantially revegetated following spoil deposition, a period of time usually taking one or two growing seasons, portions of the marsh will have an unavoidable muddy and/or barren look. After the vegetation has recovered, the positioning and configuration of the excavations will have the greatest impact on marsh aesthetics. The principal, long-term considerations for designing natural looking systems are to construct, whenever practical, irregular pond edges, islands in ponds, and curvilinear ditches. Geometric ponds (e.g. square or rectangular ponds) and long, straight ditches should be avoided.

INTERFACING OMWM WITH OTHER MARSH MANAGEMENT GOALS

The Delaware Division of Fish and Wildlife has embarked on a comprehensive marsh management program known as Integrated Marsh Management (IMM). . The purpose of IMM is to make sure that individual marsh management projects are not working at contradictory purposes and that projects with the potential to augment each other do so. Marsh management goals identified by the Division encompass environmentally-compatible mosquito control; waterfowl habitat enhancement, including selective creation or restoration of marsh ponds and optimum management of existing impoundments; *Phragmites* control; habitat conservation for fish spawning and nursery areas; habitat management for muskrat production and deer utilization; and integration of goals of the non-game and endangered species program (e.g. osprey production, protection of colonial waterbird nesting colonies and heronries, peregrine falcon hacking towers, etc.).

When the Mosquito Control Section performs OMWM, it has the potential to impact several of these other projects. Excessive spoil deposition or lowering of the subsurface water table could promote *Phragmites* growth, which must be avoided. OMWM activities detrimental to nesting sites of colonial waterbirds or raptors must be minimized. The creation of standing water on the marsh surface with OMWM (via sill and closed systems) can enhance habitat for waterfowl, wading birds, shorebirds, and muskrats. However, it must be understood that OMWM is first and foremost a mosquito control technique.

OMWM SYSTEM LONGEVITY

1) "Routine" Maintenance

Based on projections from New Jersey OMWM programs (Hansen *et al.* 1976), it is anticipated that "cleaning" (re-excavation) of most OMWM features will not have to be done more frequently than once every 15 to 20 years. **Open tidal ditches may require more frequent cleaning than sill or** closed systems, since sediment loads are deposited in the open ditches

twice per day. The shallow outlets of sill systems may also require more frequent maintenance (e.g. once every five years), but this cleaning could be rapidly and inexpensively accomplished because of the small areas and spoil volumes associated with sill outlets.

2) Corrective Actions and Preventive Measures

It may sometimes be necessary to return to a recently treated area in order to make corrections in either OMWM system design or installation. The two most likely problems to correct would be: 1) satisfactory mosquito reduction has not been achieved because of flaws in the site-specific OMWM design - additional, more intensive excavation is needed; 2) OMWM systems have been altered (e.g. surface ponds have drained) due to design flaws or animal damage - restoration of these systems must be done.

The most likely damage by animals is from snow goose grazing or muskrat burrowing. Snow goose creveys ("eat-outs") which produce mosquitoes should eventually be retreated with OMWM excavations. Muskrat burrowing damage can be lessened by terminating all sill or closed excavations no closer than 15 m from a tidal source in peaty soil and no closer than 8 m in mineral soil. To further prevent muskrat burrowing damage, or to repair drainage damage already done, barriers impervious to muskrat penetration (e.g. heavy-gauge fencing wire or plywood sheets) can be installed below the marsh surface between the end of a sill or closed system feature and an open tidal source (see Fig. 2). The barriers should extend one meter or deeper below marsh surface and extend laterally at least two meters to either side of a line between the end of the OMWM feature and the tidal source.

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