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REDUCTION OF *AEDES DORSALIS* BY ENHANCING TIDAL ACTION IN A NORTHERN CALIFORNIA MARSH

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ABSTRACT. Full tidal action was restored to a 28-ha marshland in the brackish region of the San Francisco Bay Estuary to evaluate the impact of increased tidal circulation on *Aedes dorsalis* abundance. One year after project completion, mosquito abundance had decreased by 98.7%, from an average of 3.6 to 0.3 4th-instar larvae per dip. Larvicide applications have consequently been reduced from approximately 6 to zero per year. The effects on the marsh plant community and marsh elevation were assessed during the first 2.3 years since project completion. Total coverage by sedges, rushes, reeds, cattails, and brass buttons increased almost 80% at the expense of pickleweed (−65%) and peppergrass (−34%). Sedimentation on the marsh plain has averaged 1.2 cm/year, which is about 10 times greater than the average rate of sea level rise for the region. In general, the marsh ecosystem has begun to acquire characteristics that typify immature, highly productive, fully tidal brackish marshes of the region.

INTRODUCTION

Salt marsh mosquitoes, such as *Aedes dorsalis* (Meigen), have been a chronic problem in the San Francisco Bay area. In fact, the first mosquito abatement district in California was formed in 1915 in response to these pestiferous mosquitoes. Several arboviruses have been isolated from *Ae. dorsalis,* including western equine encephalomyelitis (Reisen and Monath 1989, Fulhorst et al. 1994), St. Louis encephalitis, and California encephalitis (Meyer et al. 1988). About 45,000 ha of salt and brackish water marshlands are in the San Francisco Bay area. Approximately ⅓ of the marshlands are fully tidal; the rest are diked, with limited or no tidal influence (Josselyn 1983). These marshlands, many of which are located close to dense human populations, provide extensive potential habitat for *Ae. dorsalis.*

Contra Costa County, CA, has over 4,000 ha of marshlands extending along the Sacramento–San Joaquin River Delta and San Francisco Bay. About 85% of the historical tidal marshes have been altered or affected by human activity (Meiorin 1991). For instance, marshes have been diked for agriculture or industry, water control structures have been installed, and from 1927 to 1978, mosquito abatement agencies constructed miles of ditches to "dewater" diked marshes or to circulate larvivorous fish.

During the 1987–92 California drought, mosquito problems in the marshes intensified (V. L. Kramer, unpublished data), and the ditches previously put in for mosquito control did not alleviate the problem. There are several possible reasons for this increase in *Ae. dorsalis* abundance. For instance, because the drought reduced flows in the rivers feeding the San Francisco estuary, tidal inundations of the marsh plains were less frequent and shorter (Malamud-Roam 1994) and may have led to declines in populations of larvivorous fish or other predators. Also, the changes in inundation frequency and duration may have promoted conditioning of *Aedes* eggs or stimulated oviposition by some unknown changes in water chemistry. Finally, poor initial design or deferred maintenance of the ditch networks may have contributed to the increase in *Ae. dorsalis* abundance.

This last hypothesis is supported by the observation that semitidal marshes with the most extensive ditch networks have often generated the most *Ae. dorsalis.* The number, size, and arrangement of mosquito control ditches in Contra Costa County generally were not planned in relation to careful surveys of marsh geomorphology and tidal hydrology. Therefore, in many marshes, water is not effectively circulated throughout the channels and onto the marsh plains. Subsidence, siltation, and repetitive maintenance requirements, and thus, in some cases, increased mosquito production have resulted.

Although historical mosquito control ditches are no longer alleviating mosquito problems in Contra Costa County marshlands, carefully planned designs to alter marsh hydrology could provide long-term solutions to marsh mosquito problems, thereby minimizing the need for repeated larvicide applications. One such approach would be to restore marshlands from limited to full tidal action. The purpose of this study was to design a drainage system to enhance tidal

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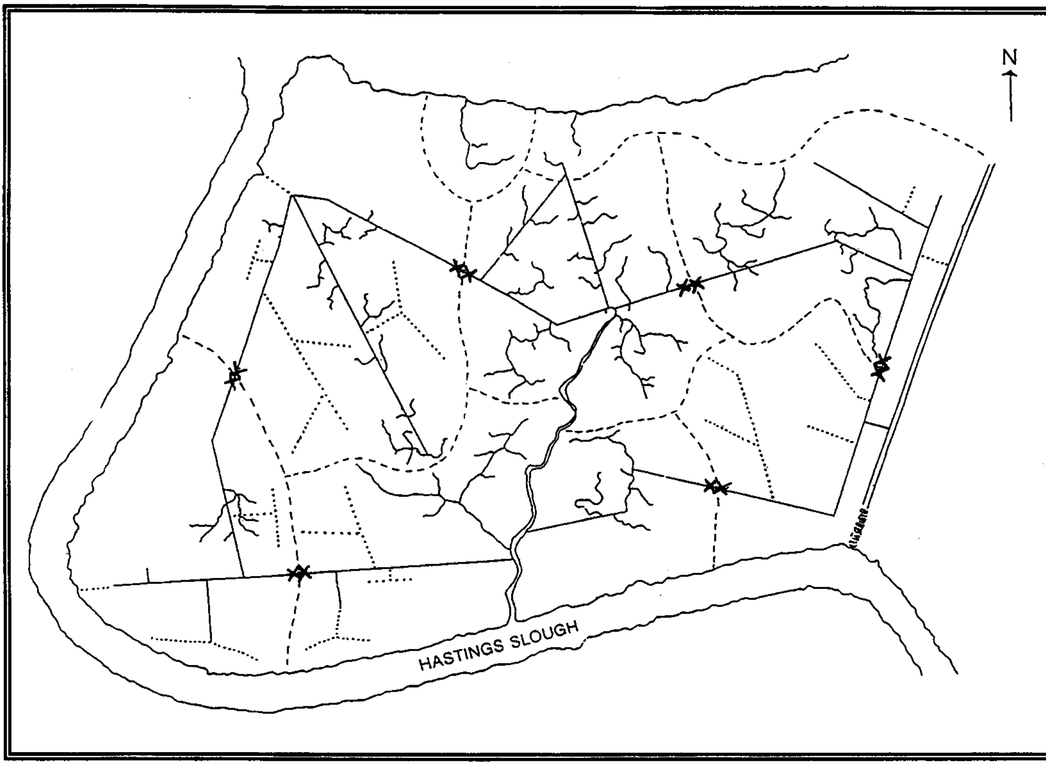

Fig. 1. Drainage system design for tidal enhancement project indicating new ditches (········), existing ditches (———), drainage divides (— —), and eliminated ditches (xxxxx); Contra Costa County, CA, 1991.

action and then to evaluate the impact of increased tidal circulation on *Ae. dorsalis* abundance. The effects of tidal restoration on the marsh plant community and marsh elevation were also assessed.

MATERIALS AND METHODS

Study site: A 28-ha marsh on U.S. Navy property in north central Contra Costa County was selected for the study, because it had recurrent mosquito problems, and because it was isolated hydrologically from surrounding marshlands. It was bordered to the north by the Sacramento–San Joaquin River Delta, to the west and south by Hastings Slough, and to the east by a large, man-made channel (Fig. 1). The drainage network within the project site therefore could be manipulated without significantly influencing the hydrology of surrounding marshlands. The site had an extensive network of ditches, typically 45–120 cm wide and 75–150 cm deep, created for mosquito abatement in the 1930s. Prior to the enhancement project, the only major tidal source for the entire marsh was through the mouth of the natural channel almost bisecting the marsh, where flow was restricted by a 100-cm-diam culvert. The site had subsided to about 33 cm (range: 16.4–41.4 cm) below the Mean Higher High Water (MHHW) datum, which approximates the average elevation of natural tidal marshland in the region.

Mosquito abundance: The distribution and abundance of *Ae. dorsalis* larvae were determined prior to tidal enhancement by inspecting the marsh and establishing monitoring stations in the poorly drained areas where mosquitoes were produced. Five dips (400 ml each) were taken at each station after each of the 7 tidal cycles between May and October 1991 that were high enough (>1.8 m above Mean Lower Low Water) to inundate the stations. Only 4th-instar larvae were sampled so that larvae would be exposed to approximately the same attrition period during each tide cycle. Average mosquito density was determined for each inundated monitoring station, and these densities were then averaged to determine the mean number of larvae per dip for each tide cycle. The same procedure was used in 1992 and 1993 following enhancement of tidal action. To control for factors other than tidal action, 50 random dips were taken in adjacent marshlands from areas of similar vegetation and elevation after each high tide cycle.

Marsh plant community: To determine the impact of the tidal enhancement project on the marsh plant community, vegetation maps were generated from color infrared photographs of the site (photographed at 1:4,800, enlarged to 1: 2,400) taken before (June 1990) and after (March 1994) project completion. Standard photo-interpretation methods (Lillesand and Kiefer 1987) were used to map dominant vegetation, based on "ground-truthing," in June 1991 and March 1994. The plant maps were digitized to determine patch size and thus the percentage of coverage of each plant species (or genus, for tules and cattails). The total percentage of cover for each taxa was calculated by adding together its extent within all patches. For example, the 1991 extent of cattail, which was observed both as a clear dominant and mixed equally with saltgrass, was calculated from the total area of cattail patches plus ½ of the total area of patches codominated by cattail and saltgrass. The change in coverage for each plant category during the 2.3 years since tidal enhancement was then calculated.

Marsh elevation: To determine the impact of the project on the elevation of the marsh surface, 3 sets of 3 benchmarks (2.5-cm-diam PVC pipes) were driven to resistance in low-lying areas. Initial ground level was recorded as a notch on each benchmark in November 1991. A second notch was made at ground level on each pipe in March 1994. For each benchmark, net accretion was measured as the distance between the 2 notches. An average rate of sediment accumulation was calculated for the 2.3 years since tidal enhancement.

Drainage system design: A topographic map of the marsh surface was needed to assure the design of an efficient tidal drainage system. To generate this map, several types of survey equipment were used, including simple laser levels and total station instruments. Elevations were mapped to the nearest 2 cm at 2,500 locations along 40 transects, which were spaced 5–30 m apart, depending upon local patterns of relief. Transects were closest together where topography was steepest or relatively complex. Quality control was ensured by multiple circuits to achieve maximum closure of 2 cm. Elevations were referenced to local MHHW by the "alternate method" of tidal datum reckoning (Swanson 1974) based upon local National Oceanic and Atmospheric Administration (NOAA) benchmarks.

The topographic map was used to determine the approximate location of drainage divides or high areas on the marsh, and these divides were used to delineate 7 drainage subsystems (Fig. 1). To provide a tidal source for each drainage subsystem, the plan included breaching the perimeter levee of the site in 3 places. The plan also included backfilling 3-m sections of existing ditches where they crossed drainage divides. The number and location of new ditches extending into mosquito sources were determined in relation to marsh topography.

Each existing or proposed ditch or channel was assigned a code number, and its dimensions were calculated using empirical formulae derived from regional studies of natural tidal marsh geomorphology (Haltiner and Williams 1987). These formulae calculate channel width and depth from the area of the drainage basin and from marsh elevation relative to tidal datums. It was considered critical that the depth and width of the ditches be adequate to effectively convey water to and from all regions of the marsh during each tidal cycle.

Plan implementation: The project was initiated in November 1991. The locations of new ditches were carefully flagged in the field. Specified ditch dimensions were referenced by ditch code and flag color. Ditching was accomplished using an excavator with a 60-cm-wide bucket. The new ditches ranged from about 0.3 to 1.3 m deep and 0.6 to 4.0 m wide; the widest ditches were those that breached the levees. Spoils were placed in low mounds, alternating from one side of a ditch to the other, and were widely spaced so that water would not become trapped behind them.

The project took 6 wk to complete and involved excavating 1,200 m of new ditch, enlarging 760 m of existing ditch, backfilling 18 m of existing ditch at drainage divides, excavating 3 levee breaks, and removing the culvert that restricted flow into the natural channel bisecting the marsh. The costs of approximately $7,000 for equipment rental and materials and $24,000 for in-house labor were covered, in part, through a contract with the U.S. Navy.

RESULTS

Mosquito distribution and abundance: The distribution of *Ae. dorsalis* larvae prior to tidal enhancement is represented by the location of the 64 mosquito monitoring stations (Fig. 2). Some stations were contiguous, whereas others were isolated low spots. Mosquito abundance was concentrated in certain regions of the marsh, especially in areas between ditches where the organic marshland soils had oxidized and subsided. Water apparently collected in these low-lying areas behind the ditch spoil lines.

Average 4th-instar *Ae. dorsalis* densities for

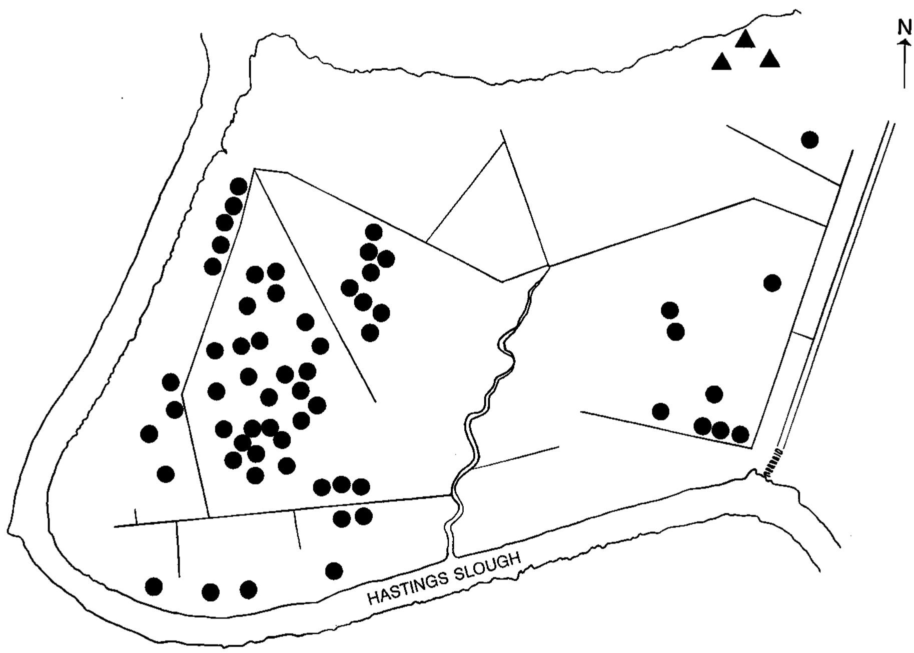

Fig. 2. Distribution of *Aedes dorsalis* monitoring stations (both symbols); all positive in 1991. Triangles indicate locations of monitoring stations positive for larvae in 1992.

each high tide cycle ranged from 0.5 to 7.8 larvae/dip (Fig. 3). The seasonal (May–October 1991) average was 3.6 larvae/dip (range = 0.0–52.8 larvae/dip). The proportion of monitoring stations that were inundated and that had larvae also varied with the tide cycles, with the highest tides resulting in mosquito production at the most stations (Fig. 3). Marsh mosquito production was therefore a product of larval densities and the number of breeding sites.

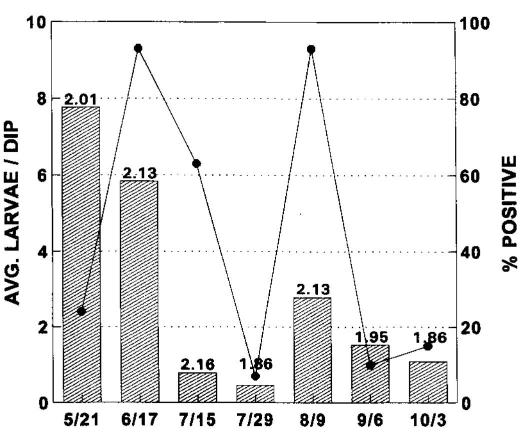

Fig. 3. Densities of 4th-instar *Aedes dorsalis* (bars), maximum tidal heights (m) as predicted for the Golden Gate (above bars), and percentage of stations inundated and with larvae (line), 1991.

In 1992, after tidal enhancement, larvae were found only during 2 of the 5 high tide cycles, and only at 3 of the 59 monitoring stations shown in Fig. 2. There was an average of 1.9 larvae/dip at the 3 positive stations, and the seasonal average was only 0.05 larvae/dip (range = 0.0–2.1 larvae/dip). An average of approximately 70% of the monitoring stations was inundated during the 5 high tide cycles. Numbers of *Ae. dorsalis* in the surrounding marshlands averaged 2.1 and 3.8 larvae/dip in 1991 and 1992, respectively, and therefore did not reflect the change in density at the project site. The tidal enhancement project therefore resulted in a larval reduction of approximately 98.7%. In 1993, no larvae were found in the project site, but larval numbers in the surrounding marshes were much lower (0.3 larvae/dip) than during the preceding 2 years. The reasons for this regional decline in *Ae. dorsalis* production were not clear, but it may have resulted from the unusually heavy, late rains and associated changes in the hydrology of all area marshes.

Marsh plant community: Prior to tidal enhancement, most of the plant community consisted of nearly pure stands of pickleweed (*Salicornia virginica* Linn.), saltgrass (*Distichlis spicata* Rafinesque), cattail (*Typha latifolia* Linn.

Table 1. Composition of marsh plant communities before (1991) and after (1994) completion of tidal enhancement project.

Plant	1991 coverage ha	1991 coverage %[1]	1994 coverage ha	1994 coverage %[1]	Change ha	Change %[2]
Peppergrass	9.20	34.3	6.11	22.8	−3.1	−33.6
Pickleweed	7.45	27.8	2.59	9.7	−4.9	−65.2
Sedges & rushes	3.26	12.2	4.97	18.6	1.7	52.3
Cattail	1.84	6.9	4.97	18.6	3.1	170.0
Saltgrass	1.21	4.5	2.90	10.8	1.7	140.3
Other[3]	3.85	14.3	5.25	19.5	1.4	36.5
Total	26.80	100	26.80	100		

[1] % = Percent coverage of marsh site.
[2] % = Relative change as percent of initial coverage.
[3] Includes levee community (coyote brush, gum plant), shoreline community (mostly sedges), and brass buttons, fat hen, and common reed.

and some *Typha augustafolia* Linn.), alkali bulrush (*Scirpus robustus* Pursh), coyote brush (*Baccharis pilularis* Candolle), and peppergrass (*Lepidium latifolium* Linn.), although some patches were codominated by pickleweed and saltgrass, by cattail and saltgrass, or by a multispecies shoreline complex. A parasitic plant, salt-marsh dodder (*Cuscuta salina* Englemann), was present in some pickleweed patches.

During the third growing season since tidal action was enhanced, the same species were still major dominants, but the overall mosaic had changed. Three species that were not previously mapped, brass buttons (*Cotula coronopifolia* Linn.), common reed (*Phragmites communis* Trinius), and Olney's bulrush (*Scirpus olneyi* Gray), were present on the site in significant numbers. The common reed, which in this region is mainly associated with freshwater, was found adjacent to new channels. Olney's bulrush, which is associated with brackish conditions, was found along the borders of existing patches of alkali bulrush. Salt-marsh dodder was no longer abundant.

The coverage and associations of previously noted species showed some significant changes (Table 1). Pickleweed coverage decreased, as did coverage by peppergrass, being replaced in part by cattails, sedges and rushes, and saltgrass. The plant mosaic increased in complexity. There was a shift from large patches clearly dominated by single species to a much more complex array of codominance.

Marsh elevation: During the 2.3 years since tidal enhancement, the marsh surface built up 2.1, 2.2, and 4.0 cm (average 2.8 cm, or 1.2 cm/year) in the 3 low-lying areas where changes in elevation were monitored. The area of most rapid accretion was closest to a tidal source and therefore received the greatest supply of suspended sediment. The shift in plant species dominance from sparse pickleweed to abundant brass buttons occurred largely in these areas of rapid accretion.

DISCUSSION

Mosquito abundance: Restoration of full tidal action to the marsh achieved the desired level of mosquito control. Larvae were found only at the base of a perimeter levee in one region of the marsh where the hydrology had not been altered. The enhanced tidal circulation may have reduced mosquito abundance by impeding the conditioning process of the eggs, by promoting predator circulation, or by decreasing the amount of standing water available for mosquito development. The latter is evidenced by the lack of other mosquito species, such as *Culex tarsalis* Coq., which typically colonize brackish water marshlands if standing water is present.

The immediate impact of enhanced tidal action on mosquito production is apparent, but as the marsh evolves, parameters affecting mosquito production change and need to be monitored. At present, the project appears to be cost effective; the frequency of larvicide applications has been reduced from approximately 6 to zero per year.

Plant community and wildlife: Enhanced tidal action has prompted rapid changes within the plant community. In general, plants such as tules, reeds, cattails, and brass buttons, which can tolerate increased frequency of inundation and rapid sedimentation, have moved into low areas previously dominated by pickleweed and peppergrass. Whereas the decline in pickleweed probably means some loss of habitat for the endangered salt marsh harvest mouse (*Reithrodontomys raviventris* Dixon), the net productivity of the marsh is probably higher (Josselyn 1983), and food for waterfowl has increased (Miller et al. 1975). Field notes from seasonal reconnaissance taken throughout the site before and after tidal restoration indicate that numbers and kinds of migratory waterfowl and shorebirds have increased. The decrease in peppergrass might be regarded as a benefit of the project, because peppergrass is an invasive weed that displaces native vegetation and associated wildlife along channel margins. Most of the changes to the marsh plant community have apparently improved wildlife habitat. The marsh ecosystem has begun to acquire characteristics that typify immature, highly productive, fully tidal brackish marshlands of the region.

Drainage system design: The new drainage system design apparently conveys adequate tidal flows to and from most regions of the marsh site. Collins et al. (1986) reported that if extensive ditches are added to a tidal marsh drainage network without increasing the cross-section of its tidal source, too much water can be diverted to the ditches, leaving insufficient water to maintain the upper reaches of natural channels. Portions of these upper channels can fill in, creating isolated potholes of water that can potentially breed mosquitoes. This phenomenon has not been observed at the project site.

New tributary channels have formed, mostly near the headwaters of existing or new ditches; these new channels are typically up to 30 cm wide and 15 cm deep. In addition, some larger channels have formed across some of the drainage divides on the eastern side of the marsh. These are apparently due to an off-site culvert, which restricts tidal height in channels feeding the eastern side of the project site. During peak flooding on the marsh, water probably flows from the unrestricted central channel toward the constrained eastern channel, eventually cutting across some divides. These unplanned channels reinforce the importance of understanding local hydrologic controls when planning the channel design.

Sedimentation has occurred in some channels, but this has primarily occurred near the reaches intentionally filled during the project. Channels that were designed to carry large volumes of water have remained clear of sediment. Problems of soil salinization, acidification, and cracking that were pervasive at the site have been eliminated.

Marsh elevation: The project site had subsided by approximately 33 cm since the time it was diked (in the early 1900s). Based on the present rate of sediment accumulation (1.2 cm/year), an approximate time frame for equilibrium can be constructed. For 15–20 years, sedimentation will most likely be dominated by mineral matter, and at the end of that time, the mean elevation of the marsh should reach Mean High Water. This elevation is generally associated with immature, highly productive marshes dominated by sedges, rushes, and cattails. After this time, the surface will continue to rise, but the accumulating matter will be increasingly organic peat. Based on undisturbed marshes in the area, once an elevation equal to Mean Higher High Water is reached, sediment accumulation will be balanced by loss to oxidation, and will rise only as fast as sea level. The rate of peat accumulation is difficult to estimate, because it depends highly on colonization phenomena, succession, and seasonal variations in primary production (Krone 1982, Kusler and Kentula 1990), but an additional 20 years seem reasonable. As the marsh plain rises and the frequency of flooding decreases, the salinity and moisture gradients of the soil will change, and the marsh plant community may evolve to resemble that of a mature, fully tidal marsh.

Ditching has repeatedly been shown to be an effective means of reducing numbers of salt marsh mosquitoes, but questions of environmental impact and cost-effectiveness have restricted its application (Dale and Hulsman 1991). Studies of open marsh water management in New Jersey and other Atlantic coast states (Ferrigno et al. 1975, Shisler and Harker 1981, Hruby et al. 1985), rotary ditching in Florida (Heydt 1994), and runnelling in Australia (Dale et al. 1993) have all demonstrated that increasing circulation in tidal salt marshes can provide effective, low-cost mosquito control with minimal disruption to wildlife and that in many cases wildlife habitat can be significantly enhanced by high-quality ditching. Although the short-term biotic effects of small artificial channels in fully tidal marshes in California have been examined and were found to be both minor (Balling and Resh 1983, Resh and Balling 1983) and potentially significant (Barnby et al. 1985), this is the first California study to evaluate simultaneously the effects of tidal enhancement on mosquito abundance and the marsh plant community. This study corroborates studies done in other regions of the world. Increased tidal circulation reduced densities of *Ae. dorsalis* while improving habitat for many types of wildlife.

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