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Control Costs, Operation, and Permitting Issues for Non-chemical Plant Control: Case Studies in the San Fran cisco Bay-Delta Region, California

BEN K. GREENFIELD[1], M. BLANKINSHIP[2], AND T. J. MCNABB[3]

ABSTRACT

The state of California recommends that aquatic pesticide users obtain NPDES permits in response to recent legal decisions by the U.S. Ninth Circuit Court of Appeals. Due to the high cost of NPDES permitting, nonchemical aquatic plant control methods are receiving renewed attention in California. Five case studies were evaluated to determine cost and implementation issues for alternative plant control methods in waters of the San Francisco Bay-Delta region. The primary case study examined control costs, operation, and endangered species permitting for mechanical shredding of water hyacinth (*Eichhornia crassipes*) in the Sacramento-San Joaquin Delta. Additional case studies examined control costs for the use of backhoe excavators, manually operated weed-trimmers, or grazing by goats (*Capra hircus*) to control submersed, emergent, or riparian vegetation. In the fall of 2003 and the spring of 2004, three types of shredding boats were operated on two representative sites. Two boats were operable in all conditions, provided there was sufficient water depth (> 0.3 to 0.6 m). A third boat was difficult to maneuver, could not chop large plants, and repeatedly got mired in dense vegetation. Treatment costs varied widely as a function of plant size. In the fall, costs in three of the four sites were greater than $4,000/hectare (ha). In the spring, treatment costs ranged from $477 to $2,146/ha, comparable to chemical herbicide application. Control costs also varied widely among the other case studies, ranging from $456/ha for goat grazing on riparian vegetation to $24,200/ha using manually operated weed-trimmers to control cattails (*Typha latifola*) and bulrush (*Scirpus acutus*).

Key words: mechanical control, economic, restoration, *Eichhornia crassipes*, *Capra hircus*, excavation, permit.

INTRODUCTION

There is a continuing need for cost-effective methods to control invasive aquatic plants. The estimated annual cost of controlling invasive aquatic plants in the United States alone totals $100 million (Pimentel et al. 2000). Due to concerns about regrowth, recruitment, and control cost, mechanical methods for aquatic plant control are generally considered cost-effective only in smaller areas, when risks of spreading infestations is low (Madsen 1997). But in some western United States, recent legal developments are causing increases in regulatory costs associated with the use of chemical aquatic pesticides. Following an inadvertent acrolein release from an Oregon irrigation district, the U.S. Ninth Circuit Court of Appeals determined that pesticides registered for use in aquatic sites by the U.S. Environmental Protection Agency (USEPA), when discharged into any system that drains into U.S. natural waterways, must be considered pollutants under the Clean Water Act (U.S. Ninth Circuit Court of Appeals 2001). Responses to this legal decision, and a more recent decision that limits its applicability (U.S. Ninth Circuit Court of Appeals 2005), are likely to vary among the Ninth Circuit Court jurisdiction (California, Oregon, Washington, Arizona, Montana, Idaho, Nevada, Alaska, Hawaii, Guam and the Northern Mariana Islands). Nevertheless, as a result of this ruling, the state of California recommends that National Pollution Discharge Elimination System (NPDES) permits be obtained prior to applying pesticides registered for use in aquatic sites (State Water Resources Control Board 2005). The paperwork and

[1]Corresponding author, San Francisco Estuary Institute, 7770 Pardee Lane, Oakland, CA 94621; e-mail: ben@sfei.org.

[2]Blankinship and Associates, 2940 Spafford Street, Suite 110, Davis, CA 95616.

[3]Clean Lakes, Inc., P.O. Box 3186, Martinez, CA 94553. Received for publication October 23, 2005 and in revised form January 7, 2006.

monitoring costs for NPDES permitting can be considerable, and California agencies that have not strictly adhered to this process have faced costly legal actions. For example, in *WaterKeepers Northern California v. State Water Resources Control Board*, the State Water Board and 12 municipal agencies were sued for failing to conduct sufficient monitoring and mitigation for their 2001 NPDES permit. The legal settlement from this lawsuit required $2.6 million be spent on aquatic pesticide monitoring and alternatives evaluation.

In the Sacramento-San Joaquin Rivers Delta, in northern California (hereafter, the Delta), water hyacinth (*Eichhornia crassipes* (Mart.) Solms) has been controlled using chemical herbicide applications, mechanical harvesting, and insects introduced as host-specific biocontrol agents (Anderson 1990). In recent years, efforts to control water hyacinth in the Delta have focused on chemical herbicide application. The California Department of Boating and Waterways (CDBW) has conducted very little mechanical control, because disposal time, labor costs, and landfill costs are too expensive (CDBW 1983, 2001). Typically, mechanically controlled plants are harvested and removed from the water body due to concerns about regrowth, spreading the infestation, nutrient loading, oxygen depletion, and associated water quality degradation (Wade 1990, Crowell et al. 1994, Madsen 1997, Unmuth et al. 1998). Some Delta stakeholders advocate mechanical shredding of aquatic vegetation, allowing the vegetation to remain in the water, as a less costly alternative to vegetation harvesting.

In addition to water hyacinth, many other aquatic plant infestations interfere with beneficial uses of northern California waterways, including recreation, stormwater flow, and irrigation (Anderson 1990). To implement best management practices and fulfill NPDES permit requirements, local agencies sometimes augment or replace chemical control operations with non-chemical alternatives, including mechanical harvesters, mechanical excavators, manually operated weed cutters, and grazing by domesticated animals (Greenfield et al. 2004, San Francisco Estuary Institute et al. 2004).

We evaluate operational, permitting, and cost issues associated with mechanically controlling aquatic and riparian plants in several Delta case studies. The primary case study evaluates control of water hyacinth infestations using mechanical shredding. This case study examines three issues: 1) set up and technical feasibility; 2) permitting issues, with the focus on endangered species permitting; and 3) control costs. Control effectiveness, i.e., the ability of the method to kill the plants and inhibit future growth, is evaluated elsewhere (Spencer et al. 2006, this issue). Four additional case studies evaluate the control costs for other non-chemical techniques. These case studies evaluate grazing by goats (*Capra hircus*), mechanical removal with backhoes, and manual removal by labor crews using power equipment.

MATERIALS AND METHODS

Mechanical Shredding of Water Hyacinth

Two Delta sites were chosen for shredding evaluation; the Stone Lakes National Wildlife Refuge (Elk Grove, California; 38.321° N, 121.478° W), and Dow Wetlands (Antioch, California; 38.021° N, 121.834° W). The Dow Wetlands site is strongly tidally influenced, difficult to access, and densely infested with water hyacinth. The Stone Lakes Site has limited tidal flux and contains long narrow irrigation ditches. The Dow Wetlands site is more characteristic of the conditions that CDBW faces when controlling water hyacinth. Stone Lakes is more representative of waterways that local landowners (irrigated agriculture and vineyards) manage. The Stone Lake site is further divided into three shredding locations: West Lambert Slough, East Lambert Slough, and South Stone Lake (Table 1).

For the fall 2003 evaluation (Table 1), a contract was established with Master's Dredging Company (Lawrence, KS), a contractor that designs, builds and operates a mechanical shredder specialized for control of dense floating macrophyte infestations. This contractor was selected based on review of studies on the contractor's prior performance (e.g., Stewart and McFarland 2000, James et al. 2002) and favorable references from agency personnel having prior experience with the contractor. The contractor has two types of shredders. The "AquaPlant Terminator" is a boat that is 8.5 m (28 ft) long and 2.6 m (8.5 ft) wide. Weighing six tons, it is equipped with sets of shredding blades at the front and rear of the boat, and separate engines to operate each set of blades (Figure 1). The "Amphibious Terminator" is a modified barge, having a standard airboat fan to propel the vessel, and a set of flail chopper blades at the front of the vessel (Figure 2).

For the spring 2004 evaluation (Table 1), we evaluated the "Cookie Cutter," a shredding vessel with cutting blades that rotate in a direction perpendicular to the long axis of the boat (Figure 3). It is primarily used for cutting channels through dense emergent vegetation and shallow sediments. Although the Cooke Cutter is no longer commercially available, similar vessels that use counter-rotating blade shredding technology (e.g., the Swamp Devil built by Aquarius Systems) are commercially available. These shredders have been marketed for water hyacinth control in Lake Victoria, Africa, but scientific studies of their effectiveness are lacking.

Heights of uncut plants were estimated from randomly collected samples at East Lambert Slough (October 6, 2003; mean = 22 cm; N = 10), and at the Dow Wetlands in the fall (September 26, 2003; mean = 87 cm; N = 20) and spring (June 6, 2004; mean = 18 cm; N = 20 plants). Heights of uncut plants at West Lambert Slough ranged widely (range = 50 to 90 cm), with increased plant heights at the western end of the slough (Table 1). Plant heights were not determined at the South Stone Lake site.

Backhoe Operation to Excavate Macrophytes

We evaluated the use of an extended reach backhoe fitted with a modified bucket capable of collecting emergent and submersed macrophytes and allowing water to pass through. Once removed, plants were placed on the bank and allowed to decompose. The target species were water primrose (*Ludwigia peploides* (Kunth) Raven) and Eurasian watermilfoil (*Myriophyllum spicatum* L.). Three control plots (300 m^2 each) were established in irrigation canals, maintained by the local agricultural water reclamation district (Reclamation District 999, Yolo County, CA; hereafter RD999). One plot was in Tule Canal (38.404° N, 121.573° W), and the other two were in the upper and lower portions of the main drain that feeds into Winchester Lake (38.433° N, 121.550° W). Backhoe operations were performed on July 30, August 6, and August 27, 2003.

Manually Operated Weed-trimmer

Gas-powered brush cutters were used to cut emergent vegetation, followed by removal with cranes and trucks. The target species were cattail (*Typha latifola* L.) and bulrush (*Scirpus acutus* Muhl. ex Bigelow). Treatments were conducted by the local municipal district responsible for maintaining flood control (Public Works Department, Contra Costa County, CA; hereafter CCCPWD). Labor crews equipped with power brush cutters cut vegetation at or near the stem base while wading through water up to knee-depth. Cut vegetation was manually raked and stacked onto canvas webbing, loaded by crane onto stakebed trucks, and disposed of at the local landfill. The treatment site was Rodeo Creek, Contra Costa County, CA (38.015° N, 122.250°), an urban creek with low summer flows. These treatments were evaluated on October 6, 9, and 10, 2003.

Goat Grazing on Riparian Plants

In northern California, goats may be rented by commercial firms for use as biological control organisms to remove nuisance vegetation. Goat control of riparian weeds, including blackberry (*Rubus armeniacus* Focke), was evaluated on the banks of Elk Slough (38.393° N, 121.539° W), a perennial agricultural canal maintained by RD999 for irrigation flow. Approximately 1,000 goats were confined by electric fences into riparian parcels for two to three days per parcel. Six treatments were conducted along a one mile reach between August 5 and August 14, 2003.

Goat Grazing on Emergent Plants

A separate evaluation of goat grazing was performed for controlling emergent cattail and bulrush vegetation. The water body, Bettencourt Basin, is a stormwater ponding and runoff area (37.79 N, 121.92° W) managed by CCCPWD. During the evaluation, standing water was present in the basin at a depth of 0.3 m or less. Between October 12-16, 2003, five hundred goats were confined in this location to abate vegetation.

Control Cost Evaluations

For the mechanical shredding study, control costs were evaluated at several locations varying in access difficulty and plant size (Table 1). Control costs included set-up costs (e.g., mobilization, crane rental, and permitting) and treatment costs (i.e., shredding area per dollar spent). Treatment area was determined by georectified aerial photographs of the site within one week of shredding, or by direct GPS field measurements of the shredding area (Figure 4). Dollars spent equaled the number of hours required to shred that location multiplied by the contractor's billing rate for the operation. The contractor billing rates were $400 per hour (hr)

Table 1. Description of mechanical shredding case study plots, including site conditions, shredding area, time, and control cost. ND = not determined.

Site (stations)	Treatment	Treatment dates	Site conditions	Shredded area (ha)	Time (hr)	Rate (ha/hr)	Cost ($/ha)
East Lambert Slough	Amphibious Terminator	9/6, 9/8/2003	Dense[a]; 22 cm stem height	1.44	3	0.48	$ 836[b]
West Lambert Slough	AquaPlant Terminator	9/19-9/21, 9/26-9/27/2003	Dense; 45-90 cm stem height	4.75	49.5	0.096	$ 4,165[b]
South Stone Lake	Amphibious Terminator	9/28-9/29/2003	ND	0.75	7.5	0.10	$ 4,016[b]
Dow Wetlands (DD)	AquaPlant Terminator	9/21-9/24/2003	Very Dense; 87 cm stem height	0.37	17	0.022	$18,386[b]
Dow Wetlands (DD)	Cookie Cutter	6/3/2004	Loose; 18 cm stem height	0.51	2	0.26	$ 863
Dow Wetlands (DC)	Cookie Cutter	6/3/2004	Loose; 18 cm stem height	0.11	0.5	0.23	$ 971
Dow Wetlands (DB)	Cookie Cutter	6/3/2004	Loose; 18 cm stem height	0.46	1	0.46	$ 477
Dow Wetlands (DA)	Cookie Cutter	6/3/2004	Loose; 18 cm stem height	0.24	2.25	0.11	$ 2,039
Dow Wetlands (DE)	Cookie Cutter	6/3/2004	Loose; 18 cm stem height	0.077	0.75	0.10	$ 2,146

[a]98 plants/m^2 measured at East Lambert Slough
[b]As reported in Greenfield (2004)

Figure 1. The AquaPlant Terminator, with a view of the rear cutting blades, engine, and cut plant material. Note that there is another set of cutting blades on the front end of the vehicle, which is similar in design to the Cookie Cutter (Figure 3). Photo credit: Bob Case, Contra Costa County Department of Agriculture.

for the fall evaluations of the AquaPlant Terminator and the Amphibious Terminator, and $220 per hr for the spring evaluation of the Cookie Cutter.

For the other case studies, control costs were calculated as a combination of labor, equipment rental, and disposal fees. Labor and equipment were determined as a function of hourly staff billing rates or equipment rental rates, treatment site area, and time required to achieve treatment. Equipment rental included mobilization and rental of trucks and a crane for the weed-trimmer case study, and goats for the goat case studies. Disposal fees were required to dispose of the vegetation at a landfill in the weed-trimmer case study, but not for the other case studies.

RESULTS AND DISCUSSION

Mechanical Shredding of Water Hyacinth: Project Set-up and Operational Constraints

In general, the AquaPlant Terminator and Cookie Cutter were both able to maneuver in Delta water hyacinth stands. Launching the AquaPlant Terminator and the Amphibious Terminator required a packed gravel or concrete surface and sufficient draft in the vicinity (approximately 1.5 m depth). In the absence of these conditions, or for the Cookie Cutter, a crane was required (costs to be discussed below). The AquaPlant Terminator required about 2.0 m water depth to launch and 1.0 m depth to operate effectively. When water hyacinth plants were taller then 0.6 m, the Terminator could only operate the rear set of shredding blades. The Cookie Cutter also required about 1.0 m of water depth in the rear of the vehicle, but was capable of cutting channels in soft sediment with the cutting blades.

The Amphibious Terminator only required about 0.2 m of draft to operate. However, this experimental vessel had many operational difficulties, limiting its utility for water hyacinth control in the Delta. The Amphibious Terminator was unsuccessful at shredding water hyacinth greater than 0.5 m in stalk length (a size frequently encountered in the Delta between August and October; Spencer and Ksander 2005), and got mired in the vegetation on two occasions. The boat also could not handle the strong winds or wave conditions characteristic of open waters of the central Delta. Finally, the boat had a very wide turning radius and could not operate in re-

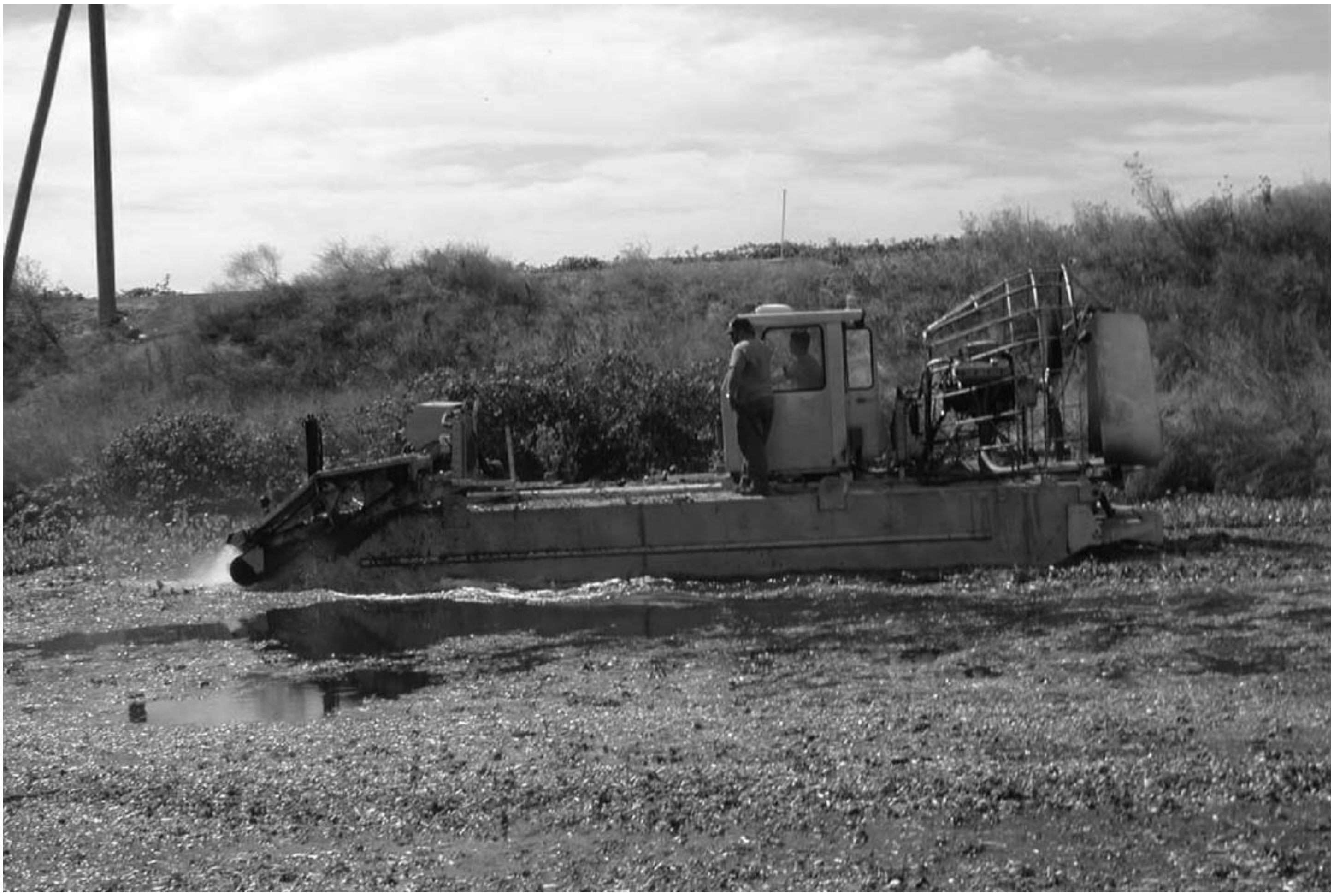

Figure 2. The Amphibious Terminator. Note the cut plant material in the foreground, uncut plant material in the background, and airboat fan on the rear of the vessel.

verse, limiting the circumstances in which operation could occur. At East Lambert Slough, an irrigation ditch about 15 m wide, the operators had to turn the boat around manually.

Mechanical Shredding of Water Hyacinth: Permitting

Permitting required for widespread application of any aquatic plant control method in the Delta includes the Federal Endangered Species Act Biological Opinion process to evaluate impacts on endangered and threatened species (CDBW 2001). The National Environmental Policy Act/California Environmental Quality Act (NEPA/CEQA) process to evaluate discharge of pollutants into the water body may also be required, depending on the inclinations of the local permitting agency representative. For the present project, the NEPA/CEQA permitting was simplified, after personnel from the Central Valley Regional Water Quality Control Board indicated that the proposed research operation would not require formal application. Finally, given that sediment resuspension may occur, California Department of Fish and Game may require a streambed alteration permit (Table 2).

Endangered species permitting presents a significant challenge in the Delta (e.g., CDBW 2001). The listed sensitive species include giant garter snake (*Thamnophis gigas*), Winter run Chinook salmon (*Oncorhyncus tshawtscha*), the Delta smelt (*Hypomesus transpacificus*), and Valley elderberry longhorn beetle (*Desmocerus californicus dimorphus*). In May 2003, consultations were initiated with the U.S. Fish and Wildlife Service (USFWS) and the National Oceanic and Atmospheric Administration National Marine Fisheries Service (NOAA Fisheries) to evaluate the impact of mechanical shredding on endangered species. Within several months of initial contact, both agencies provided official letters indicating that formal consultation was not required, and permitted the project provided that: 1) efforts be made to minimize impacts on listed species; and 2) the project occur within the dates when sensitive species are least likely to be adversely affected (between July 15 and October 31). With approval given, a fall evaluation was conducted in late September, 2003.

The spring 2004 shredding evaluation (Table 1), when plants were smaller and potentially more susceptible to shredding (Madsen et al. 1993), was also during the active movement and spawning stages of Chinook salmon, Delta smelt, and the giant garter snake. Therefore, a formal endangered species consultation was initiated with NOAA Fisheries and USFWS in November 2003. The USFWS consultation

Figure 3. The Cookie Cutter. Photo credit: Krist Jensen, Dow Wetlands.

was completed by January, 2004. However, by May, 2004, the NOAA Fisheries formal consultation was still not complete. At that time, the NOAA Fisheries agency representative determined that listed fish species had already passed through the area for spawning, and provided a letter allowing the project to proceed without a formal consultation.

Large-scale mechanical shredding operations would require extensive lead times (at least 6 to 12 months) for endangered species permitting. Chemical control operations currently underway in California require comparable lead times for endangered species permitting, in addition to NPDES permitting, and CEQA/NEPA compliance (CDBW 2001). The application fee for these permits would total at least $1,585 for chemical treatment and $654 for mechanical shredding (Table 2). However, considerable time would be required to prepare and submit these permits and consult with regulatory agencies. Estimating permit preparation time at 80 to 160 staff hours and a billing rate of $70/hr would result in $5,600 to $11,200 for a complex operation such as a shredding or chemical treatment project in the Delta. To evaluate possible impacts to wildlife for the Biological Opinion or the Streambed Alteration Permit (Table 2), a biological consultant may also be required. Assuming a 2.5 day visit, at $100/hr, the consultant fee would be $2,400.

Mechanical Shredding of Water Hyacinth: Control Cost

The total control cost of an operation includes set-up costs and treatment costs. The set-up costs of the Delta mechanical shredding operation using the Cookie Cutter included mobilization ($1,900), crane rental ($1,550), permit application and preparation (requiring 80 hr for all operations; estimated above at $5,600), and hiring a consulting biologist to evaluate the site ($450), resulting in a total set-up cost of $9,500. The set-up costs for the AquaPlant Terminator and Amphibious Terminator included mobilization of the equipment from Kansas, costing $11,500 per machine. Other set-up costs were similar for the operations; thus, the set-up cost for one of the Terminator vessels would be $19,100.

Treatment costs ranged widely, depending on the density and plant size of the stand (Table 1). In the fall of 2003, shredding efficiency was lowest at the Dow Wetland site, where dense plant stands averaging 87 cm tall impeded the shredding rate. At this site, it took two full days to shred 0.4 hectare (ha), resulting in a treatment cost greater than $18,000/ha (Table 1) (Greenfield 2004). With such large and dense plants, only the rear set of the AquaPlant Terminator chopping blades could be operated, and plants needed to be approached from an oblique angle to achieve any

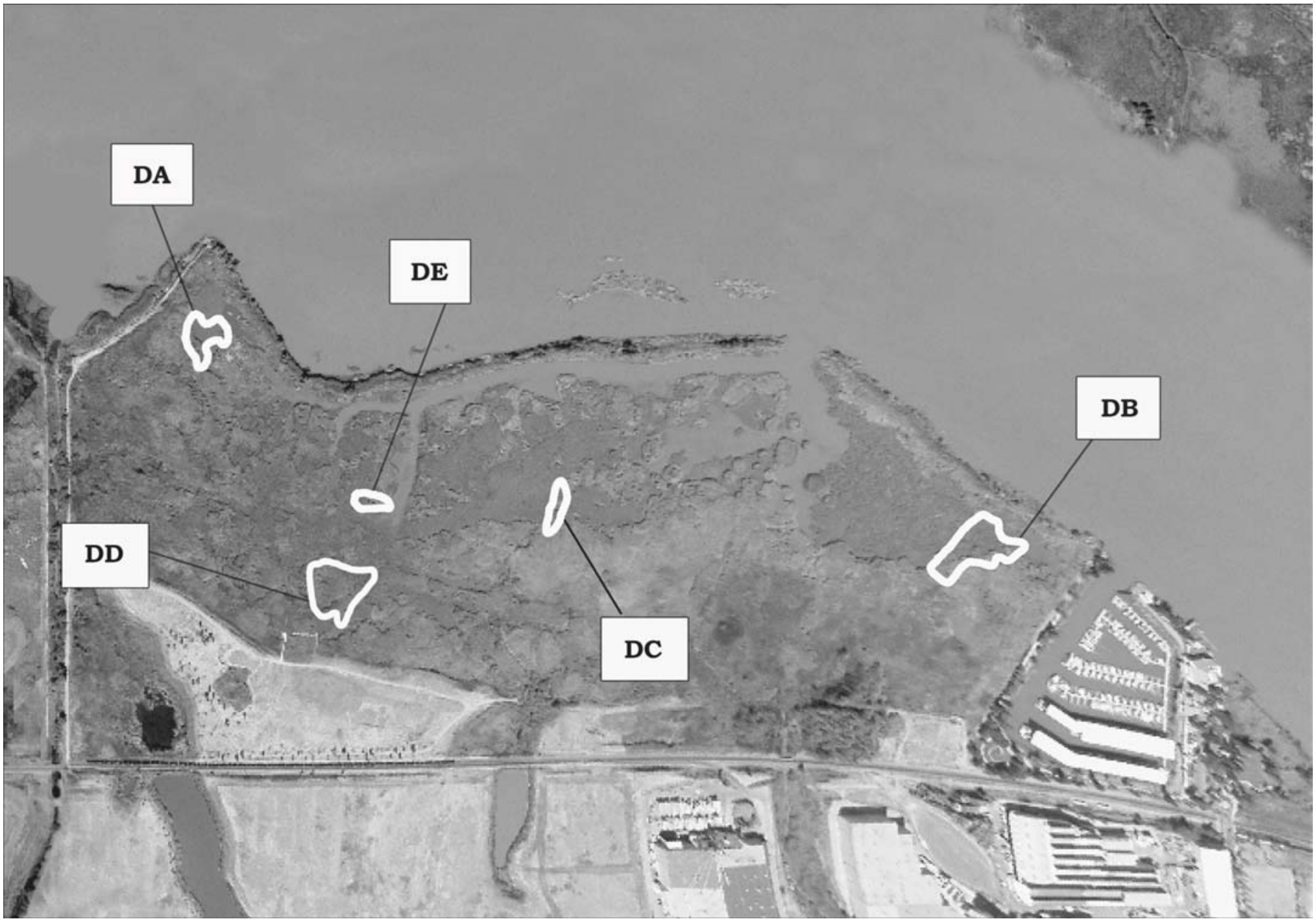

Figure 4. Aerial view of Dow Wetlands, with GIS shape files of the five areas shredded by the Cookie Cutter in 2004 (Table 1).

cutting. The plants were so densely packed that after an area was initially shredded, new uncut materials were observed to press back into that area from an adjacent unshredded location. Shredding costs were also high at West Lambert Slough and South Stone Lake, approximately \$4,000/ha (\$1,600/acre) in both cases (Table 1). Costs were relatively low in the East Lambert Slough site, with the Amphibious Terminator able to rapidly proceed through the 22 cm tall water hyacinth. Overall, the rate of shredding of the large water hyacinth was very slow, compared to a previous evaluation of the AquaPlant Terminator on water-chestnut. In that study, the boat was able to shred approximately three acres (1.2 ha) of water chestnut per hour (Stewart and McFarland 2000), resulting in a treatment cost of \$320/ha. In the spring of 2004, treatment costs using the Cookie Cutter were much lower. At the five separate Dow Wetland shredding sites in 2004, shredding cost ranged from \$500 to \$2,200 per ha (i.e., \$200 to \$900 per acre) (Table 1). The much lower control cost probably resulted from the relatively small plant size and low plant density. Combining the set-up cost listed above (\$9,500), and adding on additional anticipated cost for biological consultation (\$2,000), total control cost using the Cookie Cutter or a comparable vessel in comparable conditions would then be \$2,800 to \$4,500 per ha for a five ha site or \$730 to \$2,430 per ha for a 50 ha site.

For comparison to shredding, treatment costs of mechanical harvesting with removal from the water body can be estimated or obtained from historical studies. Assuming a harvested plant density of 0.3 to 0.7 m^3 per m^2 surface area (i.e., 30 to 70 cm plant height) and a harvester with a 22.7 m^3 (800 ft^3) payload, approximately 132 to 308 loads would be required to harvest a hectare (i.e., 3,000 to 7,000 m^3) of plant material. At a \$280 hourly contracting cost, assuming two harvested loads/hour, this would amount to between \$18,500 and \$43,170 per ha. Shore handling, hauling, and disposal would all require additional time and expense, ultimately resulting in total treatment costs exceeding \$35,000 to \$85,000 per ha. Previous studies exhibited similarly high water hyacinth harvesting costs. Harvester evaluations in northern Florida exhibited costs ranging from \$13,200 to \$39,500 per ha, when 1978 dollar values were converted to 2004 values based on annual change in the Consumer Price Index (1978 costs = \$4,550 to \$13,640 per ha) (Culpepper and Decell 1978). For a 1983 water hyacinth removal project

TABLE 2. PERMITS THAT MAY BE REQUIRED FOR AQUATIC AND RIPARIAN PLANT CONTROL IN CALIFORNIA WATERS. N = PERMIT NOT REQUIRED FOR METHOD. M = PERMIT MAY BE REQUIRED FOR METHOD, DEPENDING ON LOCATION OF WATER BODY AND LOCAL AGENCY PERSONNEL JUDGMENT. Y = PERMIT WILL BE REQUIRED FOR METHOD.

Permit	Primary Regulatory Agency	Permit fee	Required for method?					
			Shredding	Chemical	Harvesting	Excavation	Goats	Weed-trimmer
NPDES	CA State Water Resources Control Board	$1,085	N	Y	N	N	M	N
Streambed Alteration Permit (Section 1600)	California Department of Fish and Game	$154-$773	M	N	N	M	N	N
Endangered Species Act Biological Opinion	U.S. Fish and Wildlife Service/National Marine Fisheries Service	None	M[a]	M[a]	M[a]	M[a]	M[a]	M[a]
California Environmental Quality Act Section 401 Waste Discharge	CA State Water Resources Control Board	$500 or greater	M	M	N	N	M	N

[a]Endangered Species Biological Opinion required when treatment occurs on endangered species habitat.

in a Sacramento-San Joaquin Rivers Delta water delivery canal, mechanical control costs (estimated in 2004 dollars) were $47,400 per ha (1983 costs = $25,000 per ha) (CDBW 1983). Hauling and disposal costs may be reduced somewhat using machines to crush harvested water hyacinth, thereby reducing weight and volume (Mathur and Singh 2004). Nevertheless, costs at eight of the nine shredding trials in our study (Table 1) were an order of magnitude lower than previous harvesting trials.

For large infestations of water hyacinth, targeted herbicide application is often substantially more cost-effective than mechanical harvesting (Cofrancesco 1996, Haller 1996). The present study indicates that costs of mechanical shredding without harvesting may be comparable to chemical treatment costs in some management scenarios. Nevertheless, a number of potential management concerns impede widespread use of shredding as an alternative to aquatic pesticide application or mechanical harvesting (Wade 1990). Transfer of nutrients to the water column, oxygen depletion, and associated water quality degradation may result from either mechanical shredding (Wade 1990, Madsen 1997, James et al. 2002) or chemical herbicide application (Carter and Hestand 1977, Morris and Jarman 1981, Tucker et al. 1983, Struve et al. 1991). Heavy metals such as mercury bound in plant tissues (Riddle et al. 2002) may be rapidly returned to the water column as a result of these treatments. Mechanical shredding frequently leaves plants along shallow shorelines, among trees or docks, or scattered among non-target vegetation for re-infestation (Figure 3). Furthermore, sediments may be resuspended as a result of shredding or harvesting in shallow water (e.g., less than 1.5 m). Finally, the shredding operation itself may result in increased spread and recruitment of plants, ultimately worsening the infestation (Methé et al. 1993). In the present study, water hyacinth fragments viable for regrowth were produced (Spencer et al. 2006, this issue). Therefore, mechanical shredding without harvesting would only be appropriate in the following circumstances: 1. dense infestations, where boat access must be obtained quickly due to safety or economic considerations; 2. isolated waterways already infested in all available littoral habitat; or 3. if it can be demonstrated experimentally that the shredding operation does not produce more viable fragments than would be generated by the natural recruitment of the plant.

Other Case Studies: Control Costs

On a per area basis, treatment costs were relatively low when goats were used to control riparian vegetation ($456/ha), and relatively high when goats were used to control emergent vegetation ($3,089/ha; Table 3). The lower cost effectiveness of goats for emergent vegetation could have resulted from greater vegetation density, presence of standing water in the grazing area, or less desirable plant species for grazing. Although goats and other herbivores could not graze vegetation in open waters, they may prove a viable alternative to riparian and shallow-water pesticide applications. Nevertheless, grazing results in damage to non-target plant species (Coblentz 1978), and excretion and trampling could impede recreation, potability, and habitat value for wildlife

TABLE 3. CONTROL COSTS AND OTHER CHARACTERISTICS OF THE WEED-TRIMMER, BACKHOE EXCAVATION, AND GOAT CASE STUDIES.

Case study	Weed-trimmer	Backhoe excavation	Goats	Goats
Water body	Rodeo Creek	Tule Canal	Elk Slough	Bettencourt Basin
Plant type	Emergent	Emergent/submersed	Riparian	Emergent
Site area (ha)	1.13	0.030	5.26	0.32
Costs:				
Labor	$20,744	$65		
Equipment rental	$5,986		$2,400	$1,000
Disposal	$600			
Total cost	$27,330	$65	$2,400	$1,000
Control cost/ha	$24,186	$2,142	$456	$3,089

(Scrimgeour and Kendall 2003). In fact, water quality testing during use of goats indicated a temporary increase in the concentration of total and fecal coliform in and downstream of areas of grazing activity (San Francisco Estuary Institute et al. 2004). In both case studies examined, permits were not required, as endangered species or critical habitat weren't present, and the use of goats was already covered by existing maintenance permits (Chuck Jeffries, CCCPWD, pers. comm.; Bob Weber, RD999, pers. comm.). Permit preparation for goat treatment in other locations could entail endangered species permitting, and pollutant discharge permitting due to goat excretion (i.e., NPDES and NEPA/CEQA permits; Table 2).

The high per hectare cost of the weed trimmer operation ($24,186; Table 3) resulted from the very labor-intensive nature of this project. Dense cattail and bulrush vegetation had to be cut at the base, loaded onto cranes, transferred to a truck and hauled to a disposal site. During this project, crews were also exposed to potential for injury by the weed-cutters, operating overhead equipment, heat fatigue, and trip, slip, and fall hazards. At this site, mechanical and manual methods are used because the site is in a residential area, and there is stakeholder concern about exposing local residents to chemical pesticides. The high control cost encountered in this case study suggests that plant control managers should be cautious when considering manual removal of vegetation with power cutting equipment. The mechanical excavation case study ($2,142 per ha; Table 3) had costs associated with the backhoe operation labor, but disposal was on-site, no permits were required, and the backhoe equipment was already available on site for other maintenance activities (Bob Weber, RD999, pers. comm.).

Based on costs of materials and labor, permit filing and required monitoring, it is possible to obtain general costs of chemical control for comparison to the studies presented. The material cost of chemical pesticides is $56/ha for glyphosate ($30/gallon * 0.75 gallon/ac = $23/ac) or $494/ha for diquat (6,7-dihydrodipyrido [1,2-1α:2',1'-c] pyrazinediium dibromide) ($100/gallon * 0.5 gallon/ac = $200/ac). Contractor rates for a two-person spray-crew are $2,500 per day, with treatment rates ranging from 1.6 to 3.2 ha per day (4 to 8 acres per day), resulting in labor costs of $781 to $1,563 per ha. For chemical treatments in California, a $1,185 ($1,000 permit fee plus an 18.5% surcharge) annual NPDES permit fee is required for aquatic herbicide applications (Table 2), as well as the costs to develop the required Aquatic Pesticide Application Plan (APAP), permit-required monitoring, laboratory analysis, and annual reporting. In 2004, laboratory analysis at a local CA certified laboratory was $250/sample for glyphosate and $300/sample for diquat in water samples. Annual monitoring includes a minimum of two monitoring stations on three dates each (pre-application, application, and post-application), costing $1,500 to $1,800. Additionally, subcontracting to a certified pesticide application firm for supervision, preparation of an annual monitoring report, and submission of a pesticide application permit, would cost approximately $2,000 to $3,000. This would result in an estimated total cost of $1,774 to $3,254 per ha for a five ha site, or $931 to $2,177 per ha for a 50 ha site. Finally, on a Delta site such as the sites for the mechanical shredding pilot study, the endangered species permitting costs described above would also apply ($5,600 to $11,200 permit preparation and $2,400 consulting biologist), increasing the chemical control cost by between $160 (50 ha site; low-end permit preparation estimate) and $2,720 (five ha site; high end preparation estimate).

The case studies examined in this study covered different water bodies and weed types, so there would likely be some variation in the chemical treatment costs. There will also be variation in regrowth rates, and mechanical shredding may produce viable fragments. Allowing for these caveats, the costs determined for mechanical shredding in the spring removal, backhoe excavation, and goat grazing on riparian vegetation (Table 3) appear to be comparable on a per-hectare basis to estimated chemical control costs in California sites less than 50 ha. In contrast, shredding in the fall, the weed-trimmer case study (Table 3), and harvesting costs in previous studies (Culpepper and Decell 1978, CDBW 1983) appear to be much more costly than chemical control cost estimates.

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