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NOTES

Integrated management of an invasive macrophyte

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INTRODUCTION

Invasive species are a serious threat to the integrity, structure, and function of ecosystems worldwide (Gordon 1998, Brooks et al. 2004, Gurevitch and Padilla 2004, Pejchar and Mooney 2009), annually causing billions of dollars in damages to agriculture, recreation, and human health (Pimental et al. 2005). More specifically, exotic aquatic weeds are a significant problem, altering habitat and nutrient cycling, outcompeting native species, and negatively impacting recreational use of waterways. Active control measures of aquatic plant species have become necessary. In the United States a total of $100 million is invested annually in control of non-native aquatic plants (Office of Technology Assessment 1993). As the number of invasive species requiring management continues to grow resource managers must identify strategies for managing and/or eradicating these species (Mehta et al. 2007). While most experts agree that the best way to manage for invasive species is by preventing their initial introduction, there is no strong legal authority for prevention, and most managers are not allocated resources in proportion to the risks invasives pose (Lodge et al. 2006, Mehta et al. 2007).

In many cases, invasive species have already become well established long before managers must make a decision whether or not to implement control or eradication programs. Methods for managing and controlling invasive aquatic plant species include chemical control through the application of aquatic herbicides, introduction of biological control agents, and use of physical and mechanical removal techniques (Madsen 2000). Unfortunately, non-native aquatic plant species are often within close proximity to native species and are often cited as significant factors related to Endangered Species Act (ESA) listings (The Nature Conservancy 1996, Wilcove et al. 1998). As a result, control or eradication measures must be measured against their probability of success and at what cost they may pose to listed species.

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Decisions about what techniques to employ are commonly made on a site-to-site basis and often involve a combination of techniques to be effective (Madsen 1997). One example of a highly invaded aquatic ecosystem is the San Marcos River in Hays Co., Texas. The San Marcos River has been invaded for more than 100 years by introduced species; released aquaria specimens and stocking for the purpose of supplementing sport fisheries of the river are the primary sources (Bowles and Bowles 2001). Bowles and Bowles (2001) documented the naturalization of 16 non-native plant species including Beckett's water trumpet (*Cryptocoryne beckettii* Thw. Ex R. Trim). Scattered patches of Beckett's water trumpet were reported in the San Marcos River as early as 1993, and monitoring studies carried out between 1998 and 2000 documented patch expansion at an average rate of 80% per year within a 1.7-km stretch of the upper San Marcos River (Doyle 2001).

Cryptocoryne species are popular decorative plants for tropical aquaria (Rataj and Horeman 1977) and Beckett's water trumpet is one of the most popular of the species (Bastmeijer 2001) because it is hardy and vigorous (Rataj and Horeman 1977, Miller 1998). Beckett's water trumpet, a native of Sri Lanka (Jacobson 1985, de Graff and Arends 1986), is thought to have been introduced into North American aquatic systems as a result of aquaria releases (Jacono 2002). In the United States, Beckett's water trumpet has been introduced in the Rainbow Springs Aquatic Preserve in Marion County, Florida (Wunderlin 1998) and the San Marcos River (Rosen 2000).

In 2001, the USFWS and state and local San Marcos River stakeholders, including Texas Parks and Wildlife Department and the City of San Marcos, met to discuss the invasion of Beckett's water trumpet in the San Marcos River. It was determined that the Beckett's water trumpet population was encroaching into designated critical habitat of Texas wild-rice (*Zizania texana* Hitch.), an endangered macrophyte endemic to the San Marcos River. Beckett's water trumpet and Texas wild-rice have similar microhabitat preferences, including nearly identical depth zones and high current velocities (Doyle 2001). The flood of 1998 decimated downstream stands of Texas wild-rice, leaving unvegetated areas susceptible to invasion by an aggressive macrophyte. It was decided that initially the most upstream colonies of Beckett's water trumpet (Figure 1) should be

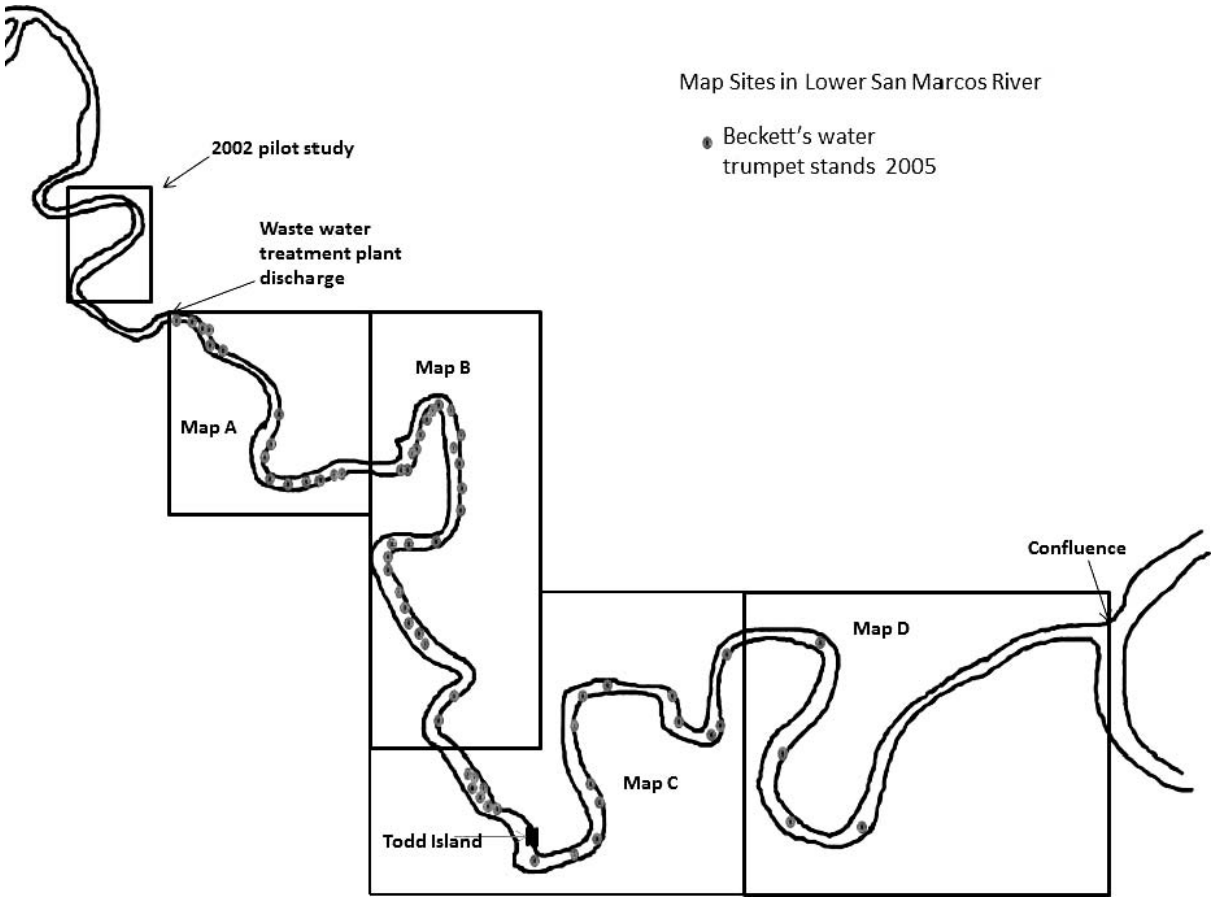

Figure 1. Beckett's water trumpet distribution pre-dredging 2005, San Marcos River, Hays County, Texas. Map A, 2,895.6m – 2,286m upstream of confluence; Map B, 2,286m – 1,676.4m upstream of confluence; Map C,1,676.4m – 1,066.8m upstream of confluence; Map D, 1,066.8m – 0m upstream of confluence.

removed to create a buffer between it and populations of Texas wild-rice (United States Fish and Wildlife Service 2002). The final goal of the project was to completely eradicate Beckett's water trumpet from the San Marcos River where it was established.

Various methods of control were discussed at this and subsequent meetings. Since the San Marcos River ecosystem supports eight federally listed threatened and endangered aquatic species including fish, invertebrates and an aquatic plant (Texas wild-rice) (United States Fish and Wildlife Service 1995), widespread herbicide use was not a feasible control method. Biological control was not a consideration as it requires extensive research before release to ensure that biological control agents are host specific and will not negatively harm the environment. Given the ESA-listed species that occupy the system and the imminent invasion into Texas wild-rice critical habitat, mechanical control was given the most consideration. Mechanical control methods for aquatic plant management include various cutters, mowers, harvesters, dredges, drags, rollers, suction devices, and similar equipment (Aquatic Restoration Foundation 2005). A large-scale mechanical removal program that included dredging to remove rhizomes followed by manual hand removal was suggested as the preferred method to remove Beckett's water trumpet. Dredging, in this case, was the use of a diver-operated suction removal system. Diver-operated suction removal systems have been suggested for use in control and management of aquatic invasive species (Madsen 2000), although the technique is not widely used by weed managers. As a management tool, dredging offers several advantages: it allows the selective removal of targeted plants, is applicable for small or large areas, is effective in areas where plants are too large to be hand harvested, and increases water depth in dredged areas (Madsen 2000). Among the disadvantages are that it can be inefficient, costly, nonselective and it provides only short term control of problematic species, but inadequate long-term control (Richardson 2008). Concerns within the San Marcos River included the removal of benthic habitat and invertebrates, disruption of the fish community, increased turbidity, and loss of vegetative cover (United States Fish and Wildlife Service 2006).

Given the uncertainly of success, a USFWS pilot study was initiated in 2002, that used a hand-operated suction dredge to remove Beckett's water trumpet from the San Marcos River (Alexander et al. 2008). A total of 537 m^2 aerial cover of Beckett's water trumpet was removed from the study area. From 2004 to 2008, the study area was monitored 11 times to remove new growth. The pilot study showed promising results and suggested that the technique may be

Table 1. Total number of Beckett's water trumpet plants removed from each river segment (maps a, b, c, and d shown in figure 1) of the dredged area during post-dredging monitoring periods. Dredging occurred in June/July 2006.

	River Segment			
Monitoring Date	A	B	C	D
Spring/summer 2006	104	151	331	466
Winter 2006/2007	526	169	127	33
Spring 2007	152	161	85	0
Summer 2007	43	63	29	7
Fall 2007	25	11	16	10
Spring 2008	35	10	4	10
Summer 2008	10	11	3	4
Fall 2008	6	2	1	2
Spring 2009	9	1	3	0
Summer 2009	2	1	1	0
Fall 2009	1	0	2	2
Spring 2010	2	2	1	1
Summer 2010	0	0	3	0
Fall 2010	1	0	1	1
Spring/summer 2011	1	0	0	1
Spring 2012	0	0	0	0
Fall 2012	0	1	0	1
Spring 2013	0	0	0	0

a successful control method (Alexander et al. 2008). Based on these results, USFWS selected diver-operated dredging coupled with manual removal of missed plant or growth of residual rhizomes to eradicate the species. A commercial dredging company was hired by USFWS in June 2006 and large scale removal of Beckett's water trumpet began.

MATERIALS AND METHODS

In 2005, a geomorphic monitoring program was designed for the upper San Marcos River to examine channel adjustment in response to channel dredging to remove Beckett's water trumpet. A variety of geomorphic and sedimentologic methods were employed within three phases of monitoring from November 2005 to February 2011 including 1) predredge channel characterization, 2) channel characterization immediately following channel dredging in spring 2006, and 3) post-dredge channel characterization and geomorphic response (Hudson 2013).

Before commercial dredging began in 2006, each colony of Beckett's water trumpet was swept for the endangered fountain darter (*Etheostoma fonticola*), using a seine or a dip net depending on the site conditions and colony size. These darters were then moved to a safe location nearby. Commercial dredging efforts targeted stands of Beckett's water trumpet along a 1,500-m stretch of the river beginning at the San Marcos Wastewater Treatment Plant (29°86′90.57″N; 97°92′64.53″W) and extending downstream to Todd Island (29°51′26.75″N; 97°55′14.30″W) (Figure 1). This particular area is designated as critical habitat for Texas wild-rice. Access to the river and the study site was provided by the City of San Marcos and private landowners whose property borders the study site.

The study site was dredged by Dredge America Inc. during June and July of 2006 using the Godwin Dri-prime 6″ CD150M 71 hp hydraulic dredge with a pumping capacity of 6,434 Lpm (1,700 gpm). Plant material and sediments removed during dredging were pumped into four geotextile tubes measuring 61 by 13.7 m with a maximum filled height of 2.1 m and positioned on the river bank. The tubes were located at the wastewater treatment plant area on City of San Marcos property. The tubes rested on plastic sheeting that extended at least 3.05 m (10 ft) outside of the footprint of the tubes and extended as far as necessary to prevent soil erosion. In July 2006, following dredging, the dredged areas and 2.4 km down to the confluence of the Blanco River were searched by USFWS SCUBA divers for Beckett's water trumpet plants. All Beckett's water trumpet plants found were counted and hand removed.

A monitoring program was then implemented by USFWS in which SCUBA divers searched the dredged area and a continuous 2.4 km downstream reach to the confluence of the Blanco River from the fall of 2006 through the fall of 2013. The surveyed area was divided into four map sites for record keeping (Figure 1). Divers manually removed all individual Beckett's water trumpet plants found by hand on a seasonal basis. Manual removal entailed digging out the entire plant, including roots and rhizomes, sometimes to sediment depths of 1 m, and depositing material in 200 μm mesh bags. Full bags were then emptied into floating containers at the surface. In areas of high flow (> 350 cfs) when large patches of plants were found (> 3 m^2), two divers worked together removing the same plant and seine nets with 200 μm mesh were positioned just downstream of the plants to catch any loose drifting plant material. Since the goal was to eradicate the species, the entire river bottom along the survey area was searched. To ensure search efforts were similar among seasons and years, twenty-three 152-m monitoring segments were established beginning at the wastewater treatment plant and ending at the confluence of the Blanco River. Post-dredging, the number of plants and the amount of above ground biomass (square meters) was recorded by site. All plants discovered during each monitoring effort were removed and the number of plants removed was recorded.

RESULTS AND DISCUSSION

In July 2006, immediately following dredging, 1,052 plants were found in the area and removed by hand. In the first year following dredging, a total of 1,200 additional individuals were found and removed (Table 1). Regrowth of plants in the dredged area then dramatically decreased, with 149 plants found in the second year post-dredging, 27 plants found in the third year, 14 in the fourth year, five in the fifth year and two in the sixth year (Table 1). In the spring and fall 2013 monitoring, no plants were found (Table 1).

Overall through the years we observed a particular pattern to plant regrowth. The majority (99.3%) of plants were found in shallow (< 2m depth), swift current (> 250 cfs) areas with little to no overhead forest canopy. Plants found in these areas required successive removal events to completely eradicate them from the area. Often smaller plants were found just downstream from larger (2 m^2) parent plants. This was the predominant situation for plants found in the two furthest upstream sites (Figure 1, maps A and B). Plants found in the two furthest downstream sites occurred

in deeper (from 3 to 4m), more turbid areas (Figure 1, maps C and D). Plants found in these downstream reaches were commonly in smaller patches ($< 1m^2$) and had much larger broader leaves than those found in the shallow upstream sites. Often these plants had deep (0.5 m), extensive thick root systems. These plants commonly had orange colored roots as opposed to the white roots of younger plants. In spring of 2008, most plants (84.6%) removed from the most upstream site (Figure 1, map A) were found in an area where a large snag had shifted due to high flows in the prior season. Eleven of the 13 plants had deep orange roots and large broad leaves and appeared to have been there for years. In the summer and fall of 2008 due to dropping river levels, we found plants growing on dry areas of the river bank. These plants were morphologically different than fully submerged plants. They were very small in size with purple leaves. From 2011, all plants discovered were found as a result of shifting snags. Over the entire monitoring period no plants were found at a water depth greater than 4 m, even though river depths reached 7.62 m.

Eradicating invasive plants requires the elimination of every potentially reproducing individual plant and seed from a targeted area (Myers et al. 1998). Such endeavors require large amounts of funding, time and effort (Panetta and Timmins 2004). Eradication efforts must be tailored to specific situations and take into account the complexity and interaction among species within each habitat. The type of species being removed, the degree to which it has replaced the native taxa, and the presence of other non-native species can affect the eventual success of invasive species removal (Zavaleta et al. 2001). Cumulatively these concerns can be overcome as demonstrated by our study; however, successful eradication will most likely occur only if persistent and rigorous monitoring and removal efforts occur following initial removal. As a result we recommend that monitoring and removal efforts be considered one of the most critical and essential parts of any exotic eradication effort or plan.

Dredging has been used for aquatic plant management with varying degrees of success (Tobiessen et al. 1992, Sabbatini and Murphy 1996). Likewise the dredging operation in our study, while successful did not remove over 1,000 individual scattered plants, which then had to be removed by hand. Over the course of our monitoring and removal efforts nearly 1,400 new plants were found growing in the dredged area and 3.2 km downstream to the confluence of the Blanco. Beckett's water trumpet has been shown to be capable of vegetative reproduction via rhizome segments (Oxley 2013). Dredging is a disturbance-based management technique that can cause fragmentation of plants. There were no known occurrences of Beckett's water trumpet upstream from the dredged site that could have been a source for plants found post-dredging. Therefore, the new plants found post-dredging were likely produced by small rhizome segments left behind when the area was dredged. The dredging effort would have had better initial success and less latent new plant growth had we established 200 µm mesh nets downstream of the mechanical dredge to capture and contain fragmented plant material floating downstream.

Another aspect of large scale invasive macrophyte removal must involve the restoration of native plants to cleared areas. Control plans that focus on a single alien species without addressing the underlying disturbance phenomena that permitted the successful invasion deal only with the effect of environmental degradation and not the causes (Edwards 1998). In the San Marcos River, Beckett's water trumpet invaded portions of the river that were virtually devoid of aquatic vegetation (Doyle 2001). Eradication efforts should be followed by an aggressive restoration effort to fill the "empty niche" with more desirable native vegetation (Doyle 2001). Throughout the SCUBA monitoring surveys from 2006 to 2010, hydrilla was never observed in the upper most dredged river site (i.e., Figure 1, map A), an area previously heavily infested by Beckett's water trumpet. Once water trumpet was completely eradicated from that area in 2010, hydrilla began to become established in that site and currently dominates the plant assemblage.

As Madsen (1997) pointed out, it is often a combination of techniques that prove to be effective. This was the case with our Beckett's water trumpet removal project. Dredging would not have been effective without the immediate hand removal of remaining plants coupled with consistent monitoring and hand removal over many years. While labor intensive, continued hand removal was and is required to prevent re-establishment of the species. To date, the total cost to USFWS and its partners for the Beckett's water trumpet dredging and monitoring program in the San Marcos River is $842,926. The USFWS plans to continue to monitor the stretch of river from the City of San Marcos wastewater treatment plant to the confluence of the Blanco (approximately 3.21 km) one to two times per year and remove any Beckett's water trumpet plants found. We consider that complete eradication has occurred once a period of two years has passed with no observation of Beckett's water trumpet in the monitored stretch of the river. Given that the San Marcos River has a history of exotic species introductions and successful establishment we suggest that annual monitoring occur. Necessary steps should be taken to remove an exotic species as soon as it is found and before habitat and native species are negatively affected. Monitoring and removal of new exotics as soon as discovered needs to be an essential component of any critical habitat management plan particularly if the site is prone to non-native invasion.

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