SPECIAL PUBLICATION SJ2010-SP3

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ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

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HYDRILLA MANAGEMENT OF SELECTED LAKES IN THE OCKLAWAHA RIVER BASIN

By

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Executive Summary

Hydrilla verticillata (L.f.) Royle (hydrilla) is a non-native, invasive submerged aquatic plant that was first introduced in Florida in the early 1950s. In 2007, the Florida Department of Environmental Protection (FDEP) reported hydrilla in 200 public lakes and rivers with a standing crop of more than 18,200 ha and an estimated 32,900 ha infested with tubers. Hydrilla's geographic proliferation can be attributed to its fast growth, multiple reproductive strategies, and lack of limiting herbivores, which make it difficult to manage once it has established in a waterway.

Natural resource agencies have employed various methods of biological, physical and chemical controls to manage hydrilla, each with positive and negative results. Grass carp (*Ctenopharyngodon idella*) have been moderately successful as a biocontrol, but their stocking has frequently resulted in the loss of native submerged aquatic vegetation (SAV). Four host-specific insect species have been released in Florida but have had difficulty establishing and require further study. Physical control through either mechanical harvesting or desiccation can eliminate most aboveground biomass, but it does not remove underground tubers and can leave viable fragments. Mechanical controls are also expensive and potentially remove non-target plants and animals. Contact and systemic herbicides provide control of the standing crop from a few months to a year or more. Repeated herbicide use, however, can be costly over time, conflict with the various uses and functions of water bodies, and result in increasing chemical resistance.

The difficulties associated with controlling established hydrilla populations prompted the St. Johns River Water Management District (SJRWMD), Lake County Mosquito and Aquatic Plant Management division (LCMAPM), Florida Department of Environmental Protection (FDEP) and Florida Fish and Wildlife Conservation Commission (FWC) to apply a surveillance-based, early detection/rapid response management approach in the Upper Ocklawaha River Basin (UORB) and Lake Apopka. The goal of surveillance-based management is to identify and treat hydrilla before it expands to whole-lake coverage, thus avoiding expensive, large-scale herbicide applications. To detect areas of infestation, near-shore visual surveys are conducted from a boat on a weekly to monthly basis. When hydrilla patches are observed, a contact herbicide (endothall) is applied in a targeted area. This surveillance-based management was first implemented in UORB lakes in 1990 and in Lake Apopka in 1995.

Hydrilla treatment requirements were relatively low in UORB lakes and Lake Apopka in the 1990s, but the amount of treated hydrilla increased significantly after the 2001 drought. The total area for hydrilla treatment in UORB lakes was 0.7 ha in 2001, 8.2 ha in 2002, 37.8 ha in 2003 and 176.4 ha in 2004. Lakes Eustis and Griffin required the most treatment in 2004 (50.0 and 96.7 ha, respectively). Lake Apopka had the most treatment in 2006 (74 ha). Since 2005, the areas of treated hydrilla have generally decreased in Lakes Eustis, Harris, Beauclair, Dora and Yale. Hydrilla growth in Lake Griffin was confined mostly to residential canals in 2007.

Prior to surveillance-based management, whole-lake herbicide treatments for Lakes Harris and Griffin cost over $1.7 million in 1987. Between 2002 and 2008, the average yearly cost of hydrilla surveillance management in Lakes Apopka, Harris, Griffin and Eustis combined was $543,843. If management agencies were to implement whole-lake treatments on these lakes today at a rate of once every three years, the predicted equivalent yearly cost would be $1,190,000.

Under conditions of fair weather and sufficient visibility in the water, surveillance-based management allows managers to respond to hydrilla growth with rapid and efficient treatment. In the last two decades, hydrilla coverage in UORB lakes remained below 2.2% of each lake's surface area. SAV surveys in Lake Apopka have also shown that spot chemical treatments have not had a negative effect on native eelgrass (*Vallisneria americana*), which increased dramatically in coverage from 1998 to 2007. Herbicide treatments applied in smaller amounts over time prevents hydrilla from reaching whole-lake coverage, thus reducing treatment costs, the amount of senesced biomass on lake bottoms, damage to favorable vegetation, and interference with recreation.

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List of Acronyms

FDEP	Florida Department of Environmental Protection
FWC	Florida Fish and Wildlife Conservation Commission
LCMAPM	Lake County Mosquito and Aquatic Plant Management Division
SAV	submerged aquatic vegetation
SJRWMD	St. Johns River Water Management District
UORB	Upper Ocklawaha River Basin
USACE	United States Army Corps of Engineers

Introduction

Tropical aquatic plant dealers brought hydrilla (*Hydrilla verticillata*) to the Tampa area in the early 1950s (Schmitz et al. 1993). Hydrilla was then observed in a canal near Miami and in Crystal River in 1960. By 1967, it became a major submersed aquatic weed (Blackburn et al. 1969) and by 1994, hydrilla was found in 43% of public water bodies in Florida, totaling approximately 38,450 ha (Schmitz et al. 1993, Schardt 1997).

Dense hydrilla canopies have impaired the operational function of thousands of acres of public waters, costing the state millions of treatment dollars each year. With increased populations and boating traffic between these waters, the spread of hydrilla has become a recognized problem. Numerous management strategies have been tested and implemented throughout Florida with varying results. Lake managers have debated whether hydrilla should be allowed to grow before treatment or be maintained at the lowest feasible levels. We describe here a monitoring and treatment method based on the latter approach, which we have used successfully since 1990 in Upper Ocklawaha River Basin (UORB) lakes and later in Lake Apopka to keep hydrilla under maintenance control.

Life History of Hydrilla

Description and Distribution

Hydrilla is a submersed aquatic perennial herb that grows on every continent except Antarctica. Although hydrilla likely originated in tropical Asia or Africa, it can thrive in temperate climates and a variety of environments (Cook and Luond 1982). In the United States, hydrilla presence has been confirmed in 26 states. Hydrilla has long, slender, heavily branched stems (Langeland and Burks 1998) and leaves that are whorled in groups of 3 to 8, measuring 6 to 20 mm long and 2 to 4 mm wide (Langeland 1996). Under different environmental conditions, however, hydrilla can vary in its appearance (Verkleij et al. 1985).

Hydrilla has two biotypes, monoecious and dioecious, both of which are present in the United States (Cook and Luond 1982, Pierterse 1981, Langeland 1996). Monoecious plants have reproductive units of both sexes on the same plant and are most often found in northern states such as Delaware, Washington DC, Maryland and Washington. Dioecious plants have male and female reproductive units on separate plants and are most often found in the southern states such as Tennessee, Georgia, Florida, Alabama, Mississippi, Louisiana, Texas, Arizona, and California. Both biotypes occur in North Carolina and Virginia (Langeland 1996, Netherland 1997).

Reproduction

Hydrilla reproduces sexually by seed, or asexually by vegetative fragmentation, lateral stem buds, and axillary and subterranean turions (Yeo et al. 1984, Langeland and Sutton 1980). Seeds are considered less important than other methods of reproduction because of low production and viability (Langeland and Smith 1984), but they also are researched and understood less (Langeland 1996). In Florida, hydrilla reproduces primarily by vegetative fragmentation, stolons that spread laterally in the top layers of the sediment, and the sprouting of turions.

Axillary turions, referred to in the literature as simply turions, are "green ovate structures covered with numerous overlapping leaf scales developed from axillary buds in the axils of leaves of branches (Yeo et al. 1984)." A study conducted by Thullen (1990) indicated that turion development is influenced by daily temperature range, source of hydrilla, and aeration. Turion formation increases in water temperatures greater than 15^{o}C (Miller et al. 1993), but is severely inhibited in warmer water between 25 and 30^{o}C (McFarland and Barko 1999). A day length of 11.8 to12.9 hours is optimal for production (Miller et al. 1993) and turions form more frequently on free-floating plant fragments than on those rooted in sand (Haller et al. 1976, Thullen 1990, Miller et al. 1993). Three to four weeks after formation, turions fall off the plant to the sediment surface (Harlan et al. 1985). Hydrilla in Florida typically produces turions between September and April, with the highest production between October and November and highest sprouting between March and April (Harlan et al. 1985, Miller et al. 1993).

Subterranean turions, commonly called tubers, are white to brown structures formed at the terminal nodes of erect stems with thick overlapping leaf scales (Yeo et al. 1984). These structures become detached from the plant when the stem or the support internode decomposes, usually within 1 to 2 months (Yeo et al. 1984, Langeland 2005). Monoecious biotypes produce more tubers than dioecious biotypes (Sutton et al. 1992), but dioecious biotypes produce larger tubers (Steward 2000). Tubers can been found up to 20 cm deep in the sediment (Miller et al.

1976) and have a thick cuticle that protects against desiccation or ingestion by waterfowl (Netherland 1997).

Similar to turions, tuber production is affected by temperature and day length (Steward 2000, Netherland 2005). Warm water temperatures (between 30 and 35˚C) were shown to significantly reduce tuber formation (McFarland and Barko 1999). Other studies confirmed that shorter photoperiods (usually 11 to 12 hours of daylight) resulted in increased tuber production (Van et al. 1978, Netherland 2005, McFarland and Barko 1999). Hydrilla plants in Florida produce tubers during the cooler, shorter-day months between October and May (Haller et al. 1976, Van et al. 1978, Harlan et al. 1985).

Laboratory studies indicate that the presence of light (Miller et al. 1976, Anderson 2003), temperatures between 15 and 35˚C (Haller et al. 1976), and tuber sizes between 7 and 11 mm (Haller et al. 1976, Sutton and Portier 1985) are optimal for sprouting. In Florida, tuber sprouting was reported to be non-seasonal (Sutton and Portier 1985), possibly because of the warmer, less variable climate (Netherland 2005). An environmental cue that did significantly increase sprouting rates was re-flooding after a lake drawdown in Rodman Reservoir (Haller et al. 1976). There is no strong evidence that chemical management influences tuber sprouting (Netherland 2005).

Impacts of Hydrilla

Hydrilla is highly invasive because of its diverse reproductive methods, as well as its ability to grow up to 25 mm per day and out-compete other submerged aquatic vegetation (SAV; Langeland 1996). Approximately 80% of hydrilla's total biomass grows within 0.6 m of the water surface (FDEP 2001), forming a thick canopy which can intercept sunlight and shade out native species. Dense mats of filamentous algae often form atop hydrilla canopies, further reducing light penetration. Hydrilla, however, is able to grow in 1% or less of full sunlight (Langeland 1996), establishing in deeper water and beginning active growth earlier in the day and year than many native species (Van et al. 1976). Hydrilla's other physiological advantages include its ability to metabolize either free carbon dioxide from the water column or bicarbonate under high pH and carbonate conditions (Salvucci and Bowes 1983), and to withstand a wide range of nutrient (Cook and Luond 1982) and salinity conditions (Haller et al. 1974).

Hydrilla can have several positive ecosystem impacts (Table 1). Studies conducted in Chesapeake Bay and Florida indicated that hydrilla has a high affinity for water column phosphorus (Wigand et al. 1997, Gu 2006), which could potentially reduce nutrient concentrations in eutrophic lakes. High phosphorus uptake associated with hydrilla, however, might be partly attributed to the periphyton that typically grows on it. Water clarity can increase with large expanses of hydrilla (Canfield et al. 1984) by decreasing wave action, sediment resuspension, and nutrient remobilization (Havens 2003).

Researchers have found positive and negative responses of fish populations to hydrilla. Several studies have shown that largemouth bass (*Micropterus salmoides*) populations benefit when hydrilla is present at low coverages (Tucker 1987, Estes et al. 1990, Porak et al. 1990, Langeland 1996), possibly because of the increased structure for habitat and changes in the predator/prey dynamic. The catch per hour (Tate et al. 2003) and survival rate (Moxley and Langford 1985) of age-0 bass were shown to have a positive relationship with areal hydrilla coverage in Florida.

The abundance of fish might benefit from, or at least be unaffected (Hoyer et al. 2008) by, hydrilla because its large structure provides enhanced refuge for young fish (Tate et al. 2003). Conversely, its thick canopy can decrease foraging efficiency (Theel and Dibble 2008). Colle and Shireman (1980) found that the size and weight of largemouth bass were reduced when hydrilla coverages exceeded 30%. In Lake Baldwin, FL, black crappie (*Pomoxis nigromaculatus*) growth was reduced when hydrilla coverages exceeded 50% (Maceina and Shireman 1982). The low coverages associated with positive impacts to fisheries are usually not sustainable because hydrilla can rapidly expand to detrimental levels.

The environmental and economic costs of a hydrilla infestation can be greater than the benefits. Highly productive hydrilla (7 mt ha^{-1} yr^{-1}; Bowes et al. 1979) can deposit significant amounts of organic sediment (Joyce et al. 1992), exacerbating anaerobic bottom conditions in eutrophic Florida lakes. Thick hydrilla canopies can also inhibit surface oxygen exchange, creating sub-canopy hypoxia (Colon-Gaud et al. 2004). Other studies have found that hydrilla provides a less favorable habitat for macroinvertebrates than native SAV (Colon-Gaud et al. 2004) and in fertile soils it out-competed native eelgrass (*Vallisneria americana*; Van et al. 1999). Economic losses from hydrilla infestations include damages to irrigation infrastructure (Godfrey et al. 1996), clogged power plant intakes (Balciunus et al. 2002), and decreases in recreational use (Henderson 1995; Table 1).

Table 1. Common advantages and disadvantages of hydrilla

Advantages of Hydrilla	Disadvantages of Hydrilla
+ Improves water quality and clarity at high coverage + Provides fish habitat at low to intermediate coverage + Provides food for some waterfowl species	- Can displace native SAV - Reduces flow of drainage canals used for flood control - Clogs pumps used for irrigation, restoration and flood control - Reduces commercial and recreational accessibility - Depletes dissolved oxygen, alters pH, raises surface water temperatures - Reduces sportfish size at higher coverages

Management Strategies

Biological Management

Several methods of biological control have shown effectiveness for hydrilla management in experimental settings, but have not been effective in natural settings (Blackburn and Taylor 1968, Charudattan and Lin 1974, Godfrey and Anderson 1994). In 1987, the hydrilla tuber weevil (*Bagous affinis*) and Pakistani leaf-mining fly (*Hydrellia pakistanae*) were introduced in Florida. Another fly (*Hydrellia balciunasi*) and the hydrilla stem weevil (*Bagous hydrillae*) were also introduced, but along with *B. affinis,* have had limited or no success (Grodowitz et al. 2000). In a lab experiment, however, *H. pakistanae* damaged over 50% of leaf tissue when establishment was high (> 6000 immatures/kg; Doyle et al. 2002). This amount of leaf damage was sufficient to sink mats of hydrilla, hinder photosynthetic activity, and slow regrowth, but not eradicate the plant completely (Doyle et al. 2002). Although field experiments with *H. pakistanae* in Texas resulted in hydrilla reduction, establishing the high population densities needed to cause damage has been difficult in Florida (Grodowitz et al. 2000, Doyle et al. 2002).

Triploid (sterile) grass carp (*Ctenopharyngodon idella*) have been used operationally in Florida for more than 30 years as a method for hydrilla reduction. The key to using grass carp is to stock at low numbers when hydrilla is at an early or low level of infestation. Although grass carp demonstrated some success in controlling hydrilla in the Santee Cooper Reservoirs in South Carolina (Kirk and Henderson 2006), their use in other systems often results in the loss of all SAV as well as many emergent plant species. Beginning in 1987, Lake Yale was stocked with grass carp at a density of approximately 13 fish per hectare. After several years, almost all of Lake Yale's SAV was eliminated and substantial resources were required to remove the carp (Hoyer et al. 2005).

Mechanical and Physical Management

Mechanical harvesting provides immediate relief from hydrilla by removing its aboveground biomass. Non-target SAV and biota, however, are concomitantly removed. Equipment, mobilization, and disposal costs are high and re-growth can occur quickly. Harvesting leaves small fragments that are able to sprout new plants (Langeland and Sutton 1980, Hoyer et al. 2005) and causes no short-term reduction in the sprouting rates of tubers remaining in the sediment (Netherland and Haller 2006). Although dredging upper portions of the sediment might reduce tuber numbers, the seed bank for native plants would also be impacted. In addition, it was reported that mechanically harvesting dense hydrilla removed 32% of the number of fish in the harvested area (Haller et al. 1980).

Another physical management strategy involves lowering water levels (drawdown) to desiccate the plants. Haller et al. (1976) recommended a winter drawdown to control the existing hydrilla standing crop and promote tuber sprouting, followed by a late summer drawdown to desiccate the sprouted tubers. Drawdowns may work only temporarily because tubers can remain dormant in soils and hydrilla fragments can quickly colonize shallow areas created during low water levels (Langeland 1996). Dropping water levels to the sediment surface may not adequately destroy hydrilla either. One study indicated that despite a yearlong drawdown, there was no significant desiccation stress to the tubers within sediments because the moisture content of the sediment remained above 50% (Doyle and Smart 2001). Repeated drawdowns in Florida's wet climate also are difficult to implement, especially in waters with multiple uses and functions.

Chemical Management

Two different classes of herbicides, systemic and contact, have been used extensively on hydrilla. Systemic herbicides are absorbed by the plant shoots and roots, inhibiting carotenoid synthesis and enhancing the degradation of chlorophyll (EXTOXNET 1986). Contact herbicides quickly damage the tissue they are in contact with, but do not travel through the plant. The three EPA-registered systemic herbicides for Florida are fluridone, penoxsulam, and imazamox. Fluridone (1-methyl-3-phenyl-5-[3-trifluoromethyl)phenyl]4(1H)-pyridinone) is the most commonly used systemic herbicide. Typically, fewer applications are required with fluridone than with contact herbicides (Hoyer et al. 2005), but since it is extremely soluble and quickly dissipates from the treatment site, it is most effective for large-scale or whole-lake applications. Fluridone's selectivity is dependent on the application rate, contact time, season, and growth stage of hydrilla and comingled native plants (Langeland 1996, Netherland et al. 1997). In some areas, dioecious hydrilla has developed a resistance to fluridone (Michel et al. 2004). Higher application rates of fluridone are necessary to control resistant hydrilla, but increased herbicide use could harm native species and cause a significant shift in the vegetation community and structure (Hoyer et al. 2005).

Currently, there are three contact herbicides registered by the US Environmental Protection Agency (EPA) for hydrilla use in Florida waters: copper, diquat dibromide, and endothall. Copper compounds do not degrade in the environment and are rarely approved by the FWC for use in Florida public waters. Diquat dibromide causes severe necrosis of hydrilla 14 to 21 days after application (EXTOXNET 1993, Langeland et al. 2002), but it is rapidly adsorbed to organic and clay particles and is therefore a less desirable option in the turbid waters of the Ocklawaha Chain of Lakes.

Endothall compounds are relatively selective and have been used for over 50 years. Endothall also causes necrosis of plant tissue, but does not directly inhibit photosynthesis (EXTOXNET 1995, MacDonald et al. 2002). Different combinations of these chemicals can improve selectivity, even with reduced application rates and exposure time (Pennington et al. 2001). Currently, Lake County Mosquito and Aquatic Plant Management division (LCMAPM) uses endothall, particularly the liquid formulation of Aquathol K (7-oxabicyclo [2.2.1] heptane-2,3-dicarboxylic acid), for spot treatments in UORB Lakes.

Hydrilla Management in the UORB

The Florida Fish and Wildlife Conservation Commission (FWC), Invasive Plant Management Section is responsible for coordinating and funding statewide efforts to control invasive aquatic plants and conserve native aquatic plants in Florida public waters (formerly FDEP's responsibility). Hydrilla management in the UORB, however, is a cooperative effort. The FWC funds LCMAPM for hydrilla treatment in SJRWMD-managed UORB lakes and SJRWMD for the control of hydrilla in Lake Apopka. The management goals of LCMAPM and SJRWMD include minimizing flooding risks, preserving navigational and recreational use and maintaining the natural integrity of these water bodies (Lake County 2007).

The hydrilla management philosophy of FWC, LCMAPM and SJRWMD, was adopted from a US Army Corps of Engineers (USACE) program for managing nuisance water hyacinth (*Eichornia crassipes*; Schardt 1994, Miller et al. 2000). The USACE determined that treating water hyacinth early and often avoided many of the issues that arose if it was allowed to reach problem levels. Maintaining water hyacinth at the lowest feasible levels instead of waiting for treatment required 2.6 times less herbicide, reduced sedimentation by a factor of four, and prevented the build up of anoxic conditions caused by shading and plant decomposition (Joyce 1985, Miller et al. 2000). Joyce et al. (1992) subsequently found that controlling hydrilla before it forms a canopy significantly reduces the amount of organic sediment produced, as well as the number and total weight of tubers.

Maintaining hydrilla populations at the lowest feasible levels involves frequent visual surveillance of a water body and repeated applications of contact herbicides. This method requires a significant commitment of staff time and labor. Arguments have been made for allowing hydrilla to reach whole-lake (65-80%) coverages before applying a systemic herbicide, thus reducing labor expenses. Murphy et al. (2006) suggested that hydrilla be permitted to grow to encourage a bass fishery in Lake Apopka. Controlling hydrilla to the coverages that are beneficial to fisheries could be difficult and expensive to implement (Miller et al. 2000, Coveney et al. 2006) and whole-lake treatments risk the development of fluridone resistance. Using a surveillance-based, early detection/rapid response program in the UORB and Lake Apopka offered the best management strategy for minimizing overall costs, impacts to native vegetation and water quality problems (Miller et al. 2000).

Table 2. Summary of advantages and disadvantages of herbicide management strategies

	Surveillance-based Management with Contact Herbicide	Whole-lake Management with Systemic Herbicide
Advantages	+ Uses small quantities of herbicide + Less potential for adverse effects + Minimal hydrilla expansion allows continued recreational use + More cost effective in the long-term + No development of resistance to contact herbicides +Less organic sedimentation	+ Infrequent purchases and applications of herbicide + Involves less labor with no management activities until hydrilla reaches high coverage
Disadvantages	- Surveys are labor-intensive - Failures in planning or implementation of treatment can hinder or prevent success	- Uses large quantities of herbicide - Decaying vegetation can create anaerobic conditions - May adversely affect non-target species - High coverage may disrupt a variety of uses and functions - May develop resistance to herbicide

Surveillance Methodology

Visual surveys are performed on a weekly to monthly basis by circling the perimeter of each lake in a boat and identifying newly discovered or pioneer patches of hydrilla. A sonar unit on an airboat may be used to detect deeper growing hydrilla, but successful detection with sonar usually depends on the absence of other submersed plants, water levels deeper than 1 m, and relatively consolidated bottom sediments. Hydrilla has also been identified during quarterly aerial and SAV surveys, as well as routine lake work.

In the Ocklawaha Chain of Lakes, hydrilla surveillance is conducted by contract through the SJRWMD and by LCMAPM staff. The SJRWMD Division of Land Management, Invasive Plant Management Program conducts hydrilla surveillance in Lake Apopka. When hydrilla is identified, its location and patch size are recorded and a contact herbicide is applied, usually within a two-week period. LCMAPM typically applies endothall-based herbicides at the recommended label rates.

The FWC also performs annual surveillance on Lakes Apopka and UORB Lakes Beauclair, Dora, Eustis, Griffin, Harris and Yale for native and exotic aquatic plants. Coverages for exotic plants are determined yearly, while coverages of native aquatic plants are determined approximately every five years. Lakes are surveyed more frequently if there is a concern of expansion of exotic plants.

History of Lake Treatment

The UORB is a riverine and lake system with a drainage area of 1652 km^2 (SJRWMD 1995). The major lakes in the Ocklawaha chain are Lakes Weir, Griffin, Yale, Harris, Eustis, Dora and Beauclair (Figure 1). The average water depths of Lakes Griffin, Eustis and Harris are less than 4 m (Danek et al. 1991). Lake Apopka is the fourth largest lake in Florida (12,500 ha) and is the headwater for the major lakes in the Ocklawaha chain (Figure 1). The average depth of Lake Apopka is 1.6 m. These lakes are characteristically shallow and high in nutrients from near-shore agriculture in the last century.

Ocklawaha Chain of Lakes

During the 1980s, Lakes Harris and Griffin were more than 70% infested with hydrilla. Whole-lake fluridone treatments were conducted by aircraft in 1987 at a cost of over $1.7 million dollars (in 1987 dollars) and appeared to eliminate most of the standing crop of hydrilla. Surveys revealed sprouting hydrilla several years after the treatment, but most of the plants became chlorotic and died, most likely from persistent light reduction from algal blooms.

Maintenance management was implemented by LCMAPM in 1990, but minimal or no hydrilla was observed in UORB lakes throughout the decade. In 1999, 0.1 ha and 0.24 ha were treated on Lakes Harris and Griffin, respectively. Hydrilla spread rapidly, however, after a significant drought that occurred from 2000 to 2002. Water levels decreased by up to one meter in some lakes, increasing light penetration and enabling hydrilla to expand rapidly. When water levels rose in 2002, hydrilla grew faster than competing native species, increasing its coverage.

Water levels stabilized in 2003, but the clarity, as measured by Secchi disc, increased, enabling hydrilla to spread further. Between 2002 and 2004, the total annual area of hydrilla that required treatment in the Ocklawaha chain of lakes increased from 7 ha to 177 ha (Table 3). New patches were observed in Lake Eustis. The increase in hydrilla treatment was due mostly to an increase in the number of pioneer patches (Figure 2).

Substantial decreases in water clarity were observed in Lakes Eustis and Griffin after hurricanes Charley, Frances, and Jeanne crossed central Florida in the fall of 2004. Parts of the UORB received over 50 cm of rain in August and September and experienced winds over 100 km/h. Hydrilla biomass in Lakes Eustis and Griffin decreased in 2005 (Figures 3 and 4). The hurricanes also reduced hydrilla biomass in the Lakes Poinsett, Lochloosa and Orange (N. Visscher, unpublished data) and the Kissimmee Chain of Lakes (Hoyer et al. 2005).

Between 2006 and 2007, the area of treated hydrilla decreased in Lakes Harris (Figure 5) and Eustis, but increased in Lake Griffin (Table 3). Most of the new patches in Lake Griffin were located in canals on the northwest shore of the lake, which were dredged in 2007. Hydrilla that was present in the canals was likely fragmented by the dredging, thus multiplying the number of viable plants. Although the total area of treated hydrilla in Lake Griffin was higher in 2007 than in 2003, the average size of hydrilla patches decreased from 24 m^2 in 2003 to 13 m^2 in 2007.

Significant (α=0.10) relationships were observed between the annual area of treated hydrilla and Secchi transparency for Lakes Eustis (r^2=0.58, p=0.017), Harris (r^2=0.82, p=0.001), and Griffin (r^2=0.39, p=0.073, Figure 6). These relationships suggest that hydrilla control in UORB lakes may require more resources as nutrient management improves water clarity.

Table 3. Hectares of hydrilla treated in the Ocklawaha chain of lakes from January 2000 to October 2008 (LCMAPM, “n/t”=no treatment)

Year	**Beauclair**	**Dora**	**Eustis**	**Griffin**	**Harris**	**Yale**	**Total**
2000	n/t	0.10	2.24	1.63	3.03	0.05	7.05
2001	n/t	n/t	0.05	0.48	0.20	n/t	0.73
2002	n/t	0.04	2.54	3.12	2.33	0.18	8.21
2003	n/t	n/t	5.17	19.65	12.92	0.08	37.82
2004	0.42	0.06	49.96	96.71	29.35	0.13	176.63
2005	2.06	0.55	29.45	23.31	35.78	1.93	93.08
2006	2.79	0.24	46.62	36.44	35.78	0.78	122.65

2007	0.60	0.11	1.32	52.92	6.76	0.30	62.01
2008	0.40	n/t	0.38	8.80	7.60	n/t	17.2
Total	6.27	1.10	137.35	243.0	133.8	3.4	524.95

The total cumulative area of treated hydrilla from 2000 to 2008 in the Ocklawaha chain of lakes was 525 ha (Table 3). Relative to each lake's surface area, hydrilla never exceeded 2.2% coverage. Herbicide applications were performed throughout the year on each lake, but the largest areas were usually treated between March and October.

Lake Apopka

Since 2000, SJRWMD has treated approximately 150 ha of hydrilla in Lake Apopka with liquid and granular endothall. Hydrilla coverage was minimal in Lake Apopka prior to 2001. Surveillance was suspended between 2001 and 2002 because most of the areas that normally had SAV were dry and colonized with terrestrial plants. Following the drought, coverage increased, especially in the Gourd Neck and Smiths Island areas (J. Peterson, unpublished). The majority of treatment occurred in fiscal year 2005-2006 (Table 4; Figure 7). Water clarity declined in 2006, likely due to decreased lake stage and greater internal nutrient cycling at the onset of another drought. Unlike Lakes Eustis and Harris, Secchi depth in Lake Apopka was not significantly (r^2=0.24, p=0.32) related to the annual area of treated hydrilla (Figure 6). At its highest coverage, hydrilla on Lake Apopka occupied approximately 0.6% of the lake's surface area.

Table 4. Hydrilla herbicide treatments in Lake Apopka from fiscal year (October-September) 2002-2003 to 2007-2008 (SJRWMD). Man-hours reflects the time spent searching for hydrilla, as well as treatment time

Fiscal Year	Hectares Treated	Man Hours	Endothall (kg)
2002-2003	2.3	104	129
2003-2004	21.6	366	801
2004-2005	33.0	587	1307
2005-2006	74.1	422	3343
2006-2007	22.2	499	903
2007-2008	3.3	207	108
Yearly Average	26	364	1098

Treatment Costs

Surveillance-based management costs are largely associated with the labor and herbicides required for frequent monitoring and treatments. The expenses for surveillance management in Lakes Harris, Griffin and Eustis between 2002 and 2008 are listed in Table 5. For a financial comparison of management methods on these lakes, the cost of whole-lake treatments using 10 ppb fluridone was estimated (Table 6). It was assumed that hydrilla typically would require whole-lake treatments every three years, thus the estimated cost for one whole-lake treatment was divided by three to obtain a yearly cost.

Table 5. Treatment costs (in dollars), including labor and herbicides, for Lakes Apopka (fiscal year), Harris, Griffin, and Eustis (calendar year) using surveillance-based management from 2002 to 2008 ("n/t"=no treatment)

Lake	2002	2003	2004	2005	2006	2007	2008	Average
Apopka	n/t	8,456	35,967	61,795	112,002	47,793	10,938	46,159
Harris	9,519	9,174	212,817	854,789	590,515	17,709	11,539	243,723
Griffin	4,323	27,483	388,141	98,814	152,959	69,423	14,364	107,930
Eustis	2,339	3,785	356,144	99,469	557,161	2,687	639	146,032
Total	16,181	48,898	993,069	1,114,867	1,412,637	137,612	37,480	543,843

Table 6. Predicted annualized costs (in dollars) for whole-lake treatments at three-year intervals using fluridone (10 ppb)

Lake	Volume* (ha-m)	Each treatment† ($)	Cost/yr
Apopka	19,100	1,000,000	333,333
Harris	27,700	1,500,000	500,000
Griffin	10,600	500,000	166,700
Eustis	10,900	570,000	190,000
Total	68,300	3,570,000	1,190,033

* Lake volumes from Fulton et al. (2004)
† Cost estimates based on Hoyer et al. (2005) and Coveney et al. (2006)

The average yearly cost of surveillance-based management on Lakes Apopka, Harris, Griffin and Eustis, combined, from 2002 to 2008 was $543,843, compared to an estimated annual cost of $1,190,000 for whole-lake treatments (Tables 5 and 6). On Lake Apopka, the average yearly cost for surveillance-based management between fiscal year 2002-2003 and 2007-2008 was $46,159 (Table 4), compared to an estimated annual cost of $333,333 for whole-lake treatments (Coveney et al. 2006). The predicted cost for whole-lake treatments is probably a conservative estimate because treatments might be needed more frequently than every three years, or applied more frequently initially to maintain certain herbicide concentrations. Whole-lake treatments on Lake Istokpoga were previously conducted every other year, but are now performed yearly because of the quick recovery by fluridone resistant hydrilla (Hoyer et al. 2005).

Submerged Aquatic Vegetation Trends in the UORB

Ocklawaha Chain of Lakes

Between 2003 and 2005, SJRWMD staff conducted SAV monitoring surveys on Lakes Eustis, Harris and Griffin. The main objectives of these surveys were to measure lake restoration success, provide early detection of hydrilla colonization, and detect changes in new and established plant communities. Frequent repeated samplings enabled the detection of small SAV patches. Surveys involved visually identifying SAV from a small boat in the near-shore (littoral) environment along the lakes' shorelines. Repeatedly circling the littoral zone of each lake decreased the probability of overlooking SAV due to water clarity, light quality, waves and plant community status. Lakes were sampled with multiple circuits along shoreline lengths of 24 km, 48 km and 64 km for Lakes Eustis, Harris and Griffin, respectively. Upon detection, SAV was identified and its geographic position was recorded with a GPS. Water depth, bottom type and SAV growth status were also recorded. All observed hydrilla was reported to LCAMPM.

The locations for all identified SAV species were mapped and the percent of occurrence was calculated (Figures 8-13). In 2003-2004, *Vallisneria americana* was dominant in Lakes Eustis and Harris, while hydrilla was dominant in Lake Griffin. Hydrilla thrived in Lake Griffin's shallow canals, especially near the mouth of Haines Creek. In the 2003-2005 surveys for all three lakes, over 90% of hydrilla was found in areas with a maximum water depth of 1.5 m or less.

Lake Apopka

SJRWMD has surveyed and mapped desirable SAV in Lake Apopka since 1995. Surveys occur two to three times per year and involve locating SAV from a small boat along the shoreline, either visually or with sonar. Upon detection, SAV is identified and its location and extent are recorded. Observations of hydrilla are noted and reported to SJRWMD Invasive Plant Management staff.

Between 1998 and 2007, the coverage of *V. americana* increased from 11,194 m^2 to 55,183 m^2 and hydrilla decreased from 10,329 m^2 to 44 m^2 (Figures 14-16). New patches of *V. americana* increased in number, especially on the southwest and north shores of Lake Apopka (Figure 16).

Conclusions

- Surveillance-based management was effective in controlling hydrilla in UORB lakes
- Hydrilla coverage did not exceed 2.2% of lake surface area during the multi-year treatment period
- The cost of surveillance-based management was less than half the predicted annualized cost of whole-lake treatments
- During the period of treatment, increases in native SAV were observed in Lake Apopka
- A significant relationship appeared between the area of hydrilla treatment and Secchi depth for Lakes Eustis and Harris. If water clarity shows an increasing trend, then field staff can anticipate performing hydrilla surveillance and treatment at increased frequencies and intensities.

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Figures

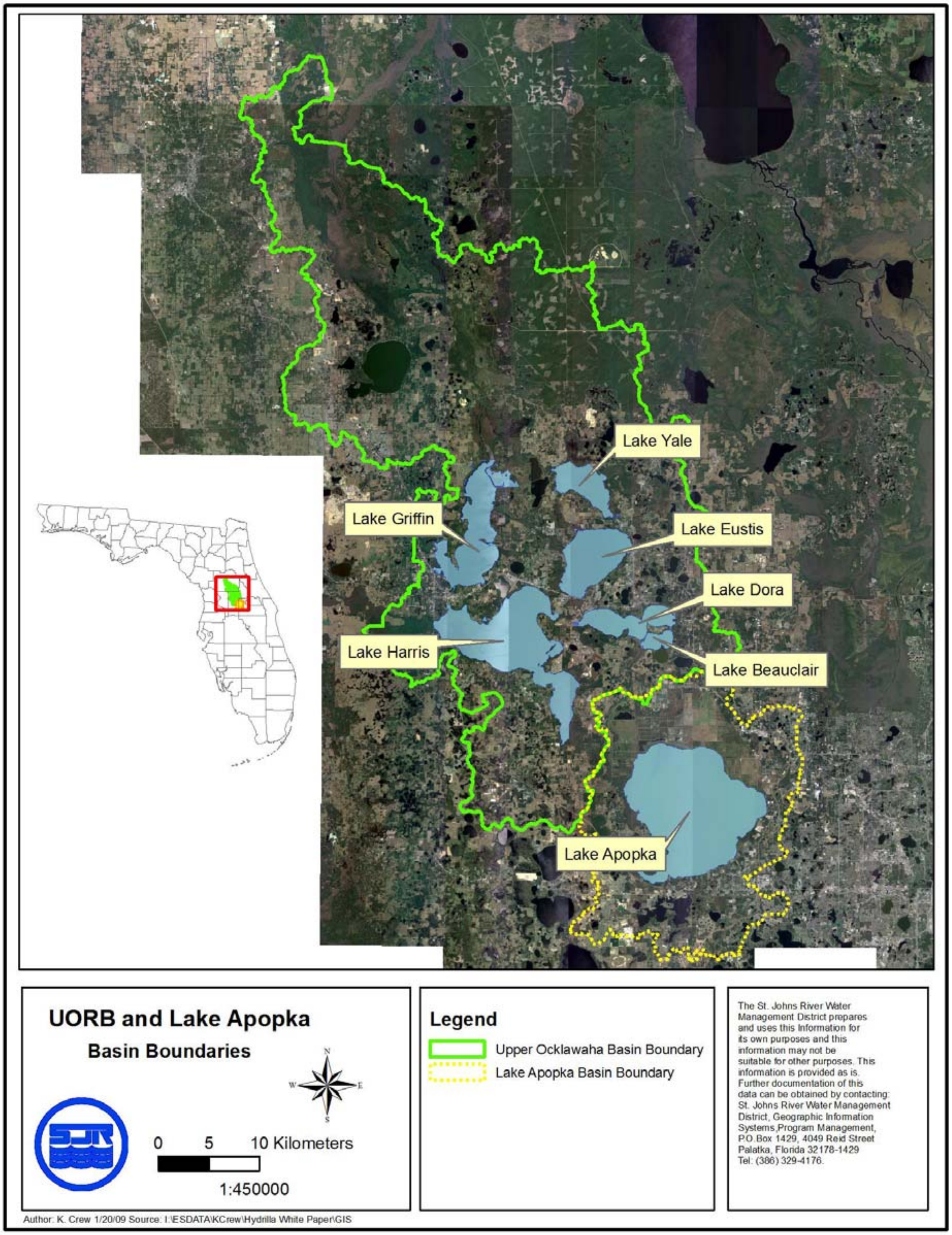

Figure 1. Boundaries for the Upper Ocklawaha River and Lake Apopka Basins

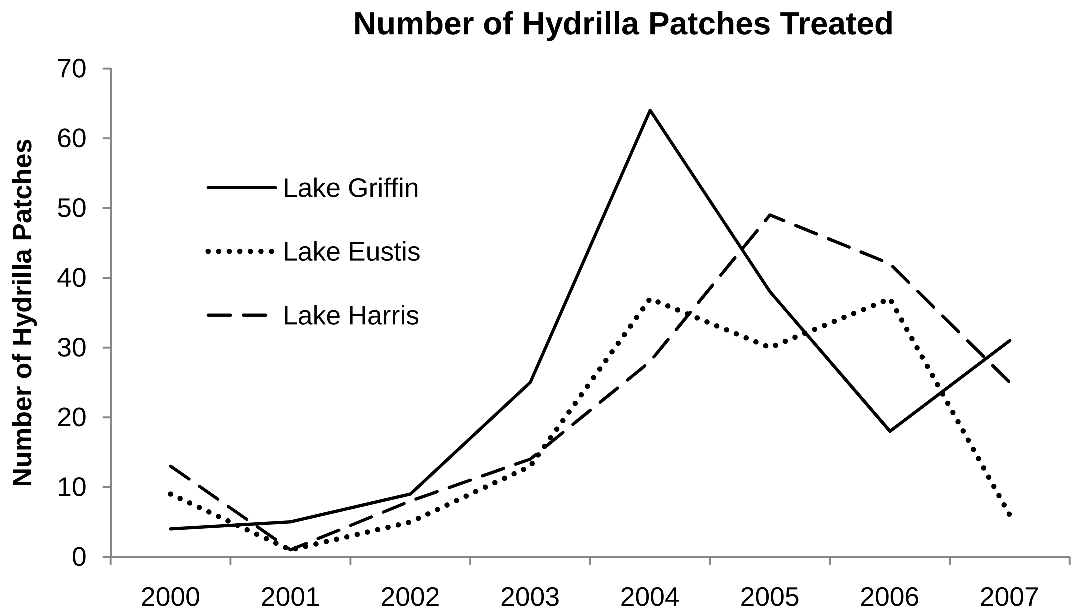

Figure 2. Number of hydrilla patches in Lakes Griffin, Harris and Eustis that required treatment with herbicide

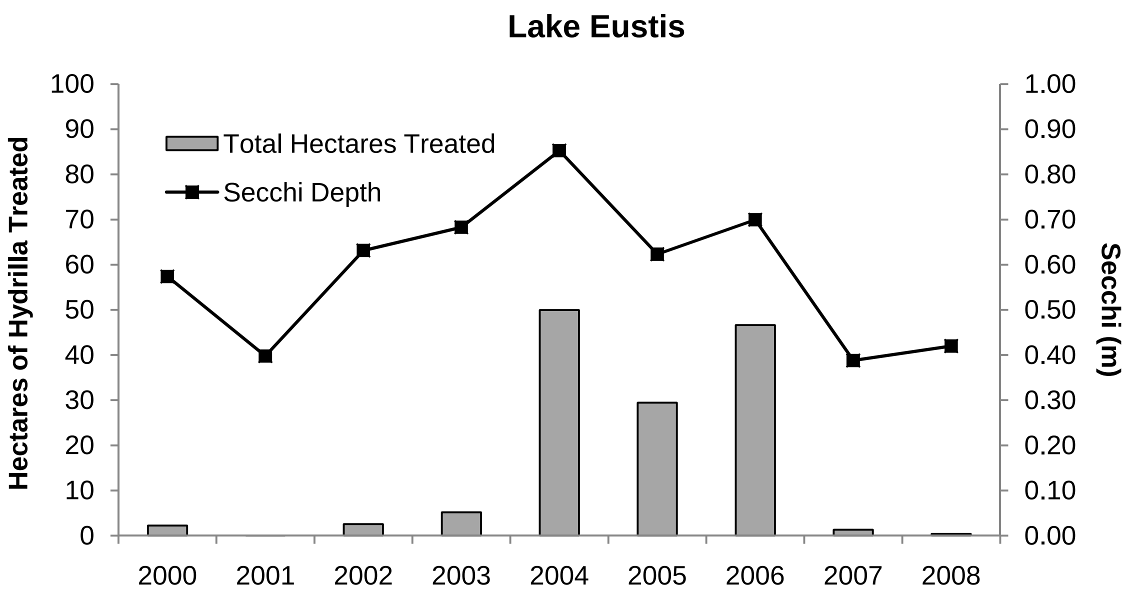

Figure 3. Total hectares of hydrilla treated and Secchi depth in Lake Eustis from January 2000 to October 2008

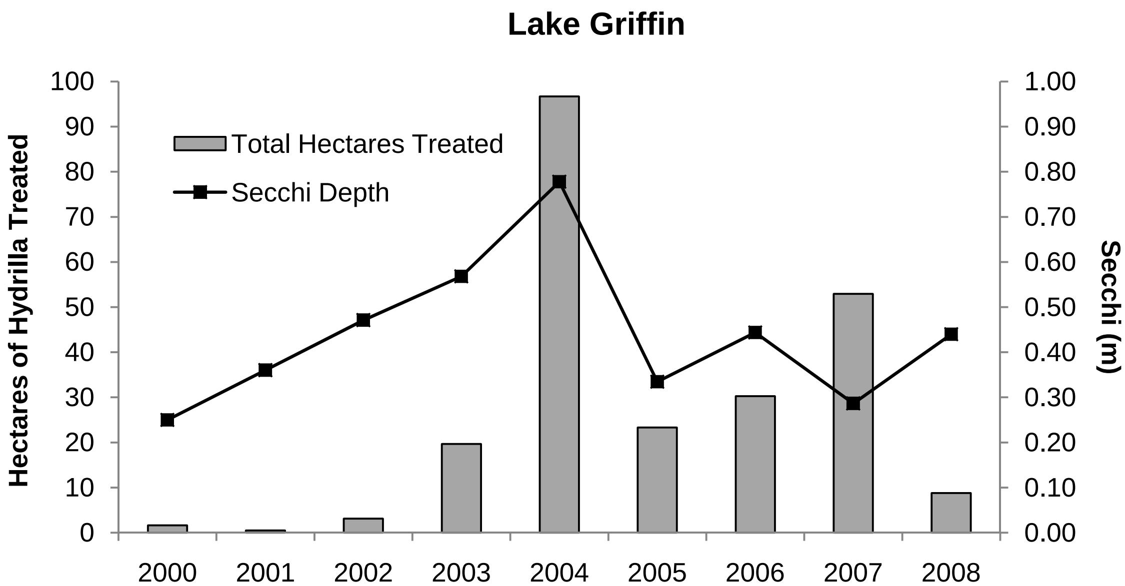

Figure 4. Total hectares of hydrilla treated and Secchi depth in Lake Griffin from January 2000 to October 2008

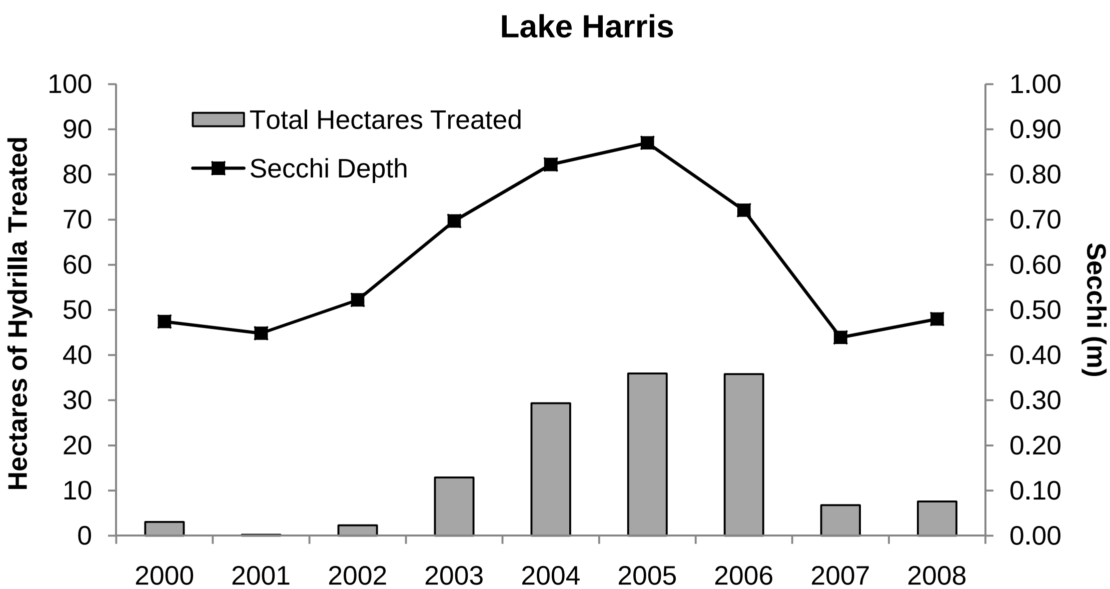

Figure 5. Total hectares of hydrilla treated and Secchi depth in Lake Harris from January 2000 to October 2008

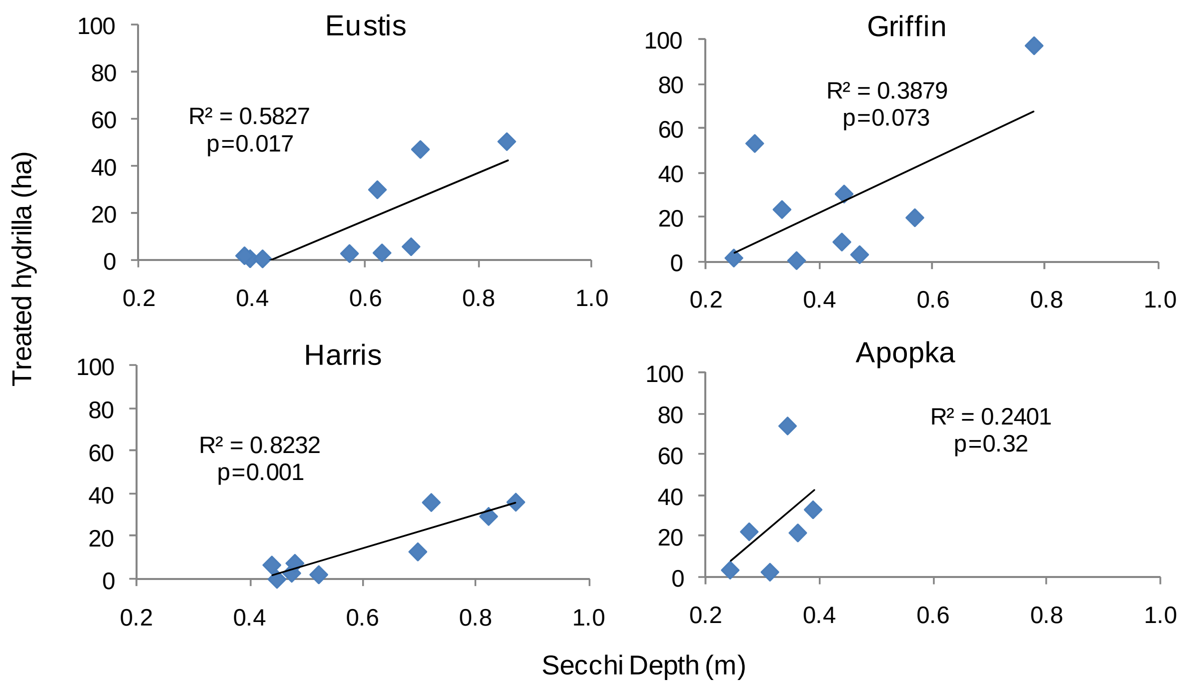

Figure 6. Secchi depth versus hectares of treated hydrilla in Lakes Eustis, Griffin, Harris and Apopka (2000 to 2008)

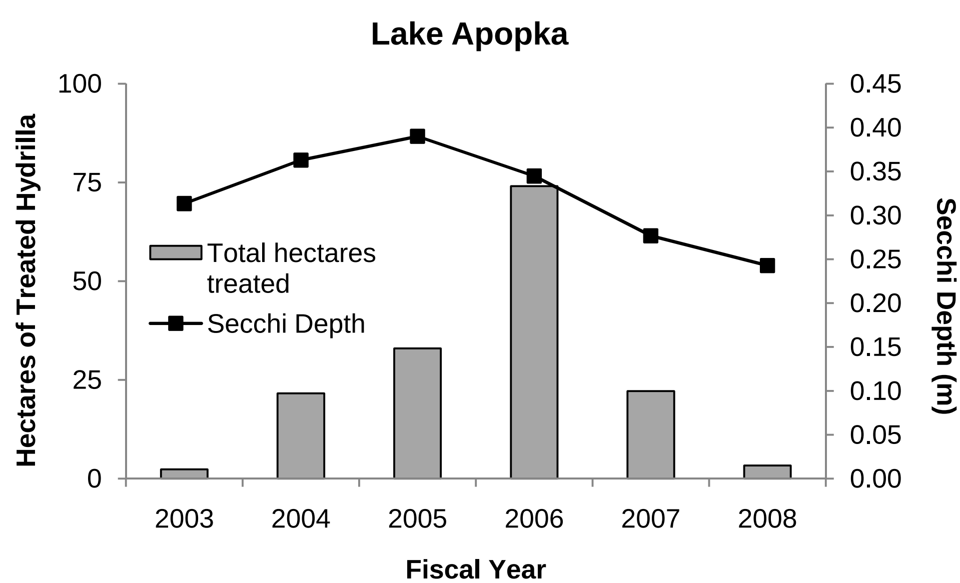

Figure 7. Total hectares of hydrilla treated and Secchi depth in Lake Apopka from (fiscal year) 2003 to 2008

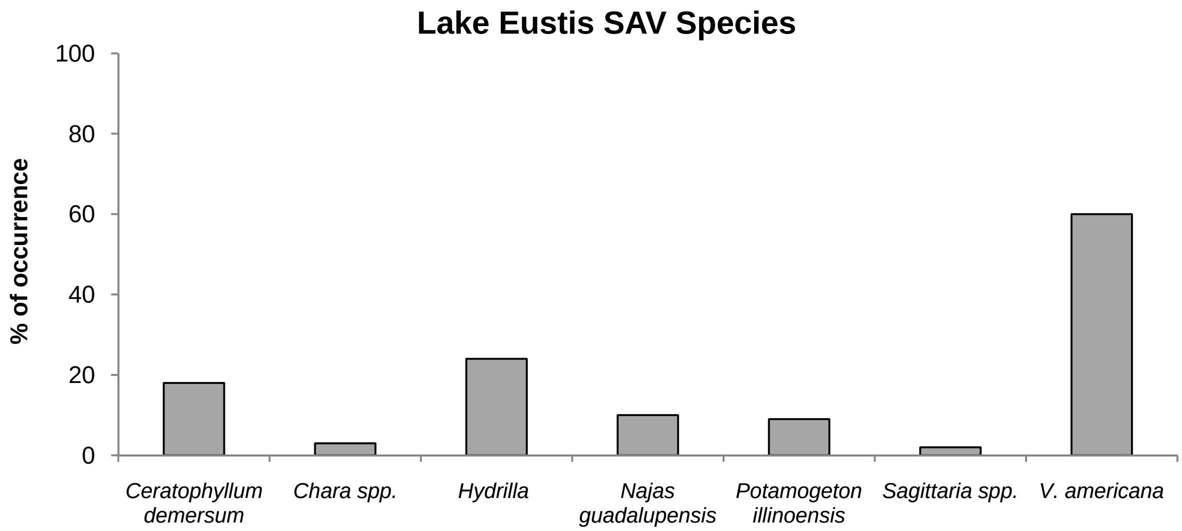

Figure 8. Percent of occurrence for SAV species in Lake Eustis (2005). Percent occurrence is the percentage of sites in which a species was present out of the total number of surveyed sites (137). Since species often occurred in mixed assemblages, the combined percentages exceed 100%.

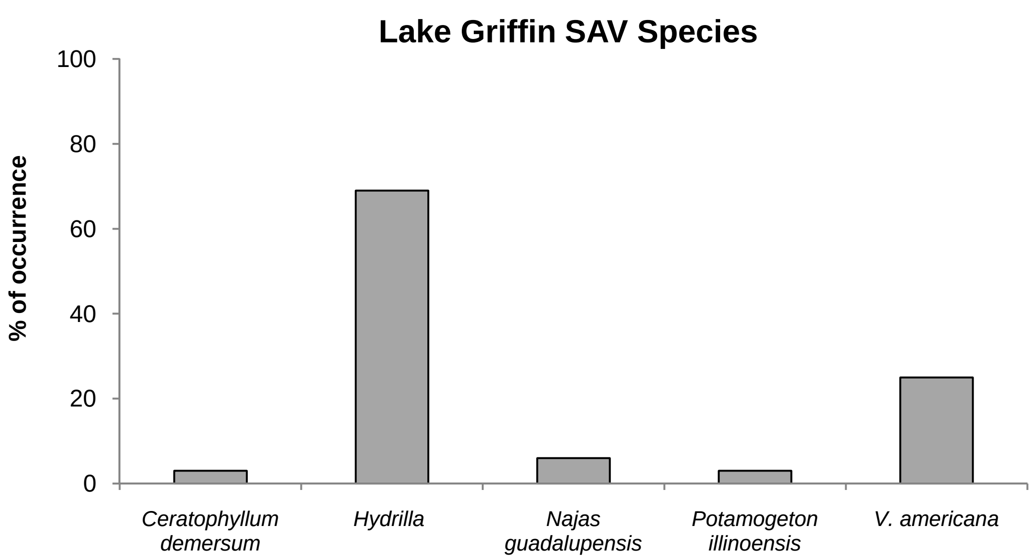

Figure 9. Percent of occurrence for SAV species in Lake Griffin (2003-2004). Percent occurrence is the percentage of sites in which a species was present out of the total number of surveyed sites (1101). Since species often occurred in mixed assemblages, the combined percentages exceed 100%.

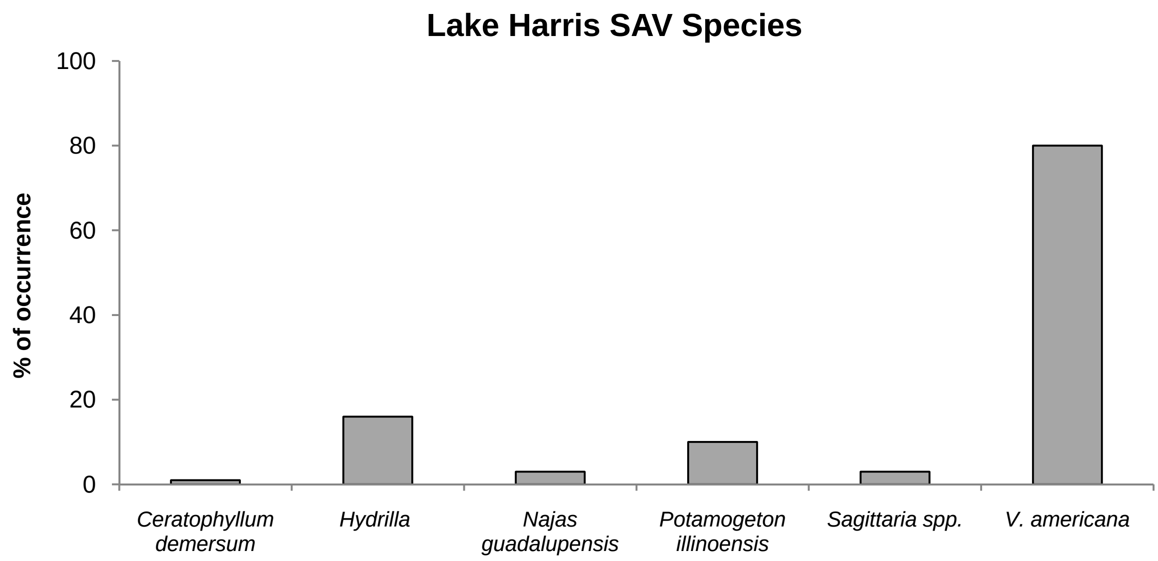

Figure 10. Percent occurrence for different SAV species in Lake Harris (2005). Percent occurrence is the percentage of sites in which a species was present out of the total number of surveyed sites (328). Since species often occurred in mixed assemblages, the combined percentages exceed 100%.

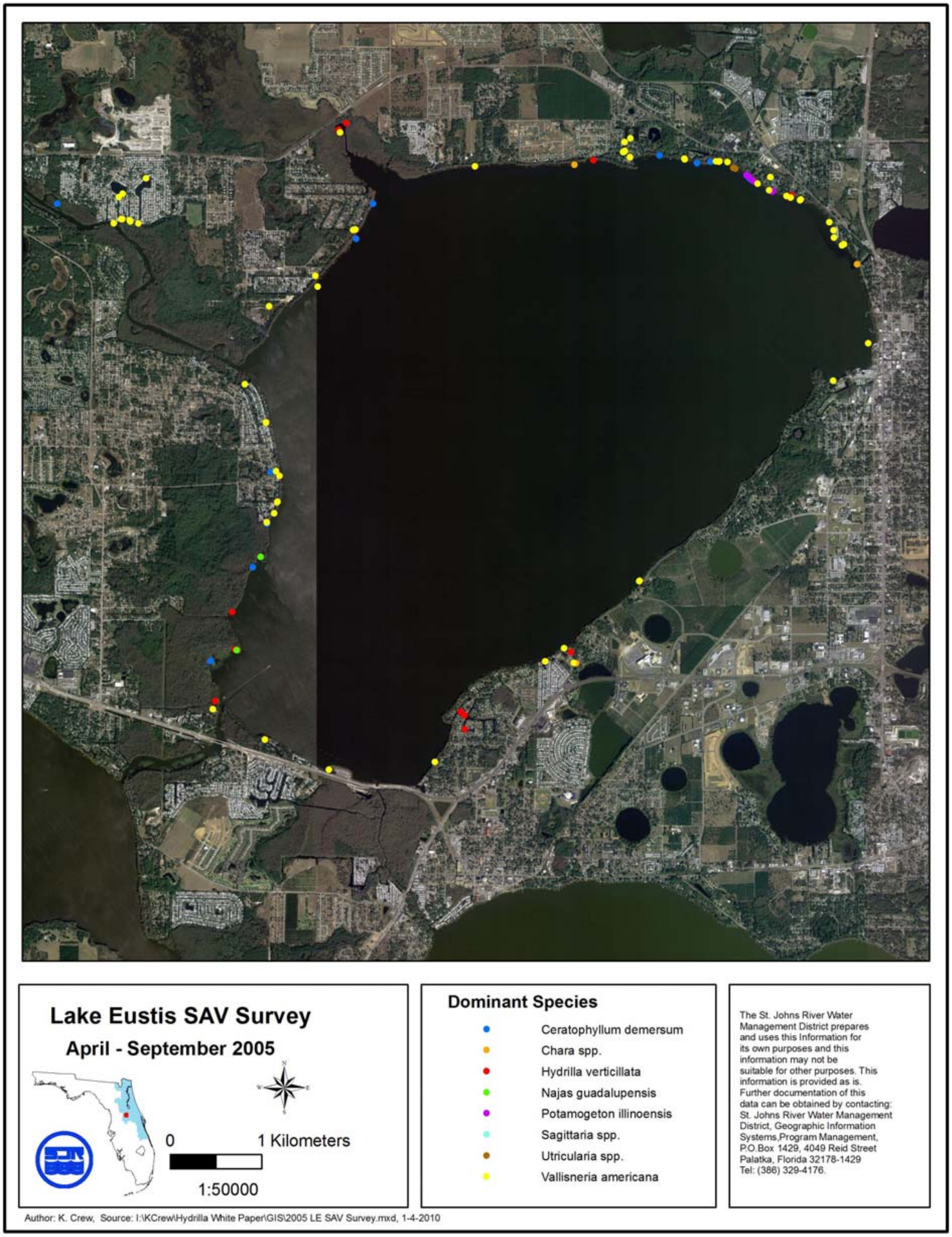

Figure 11. Dominant SAV species at survey sites for Lake Eustis (3,159 ha) between April and September 2005

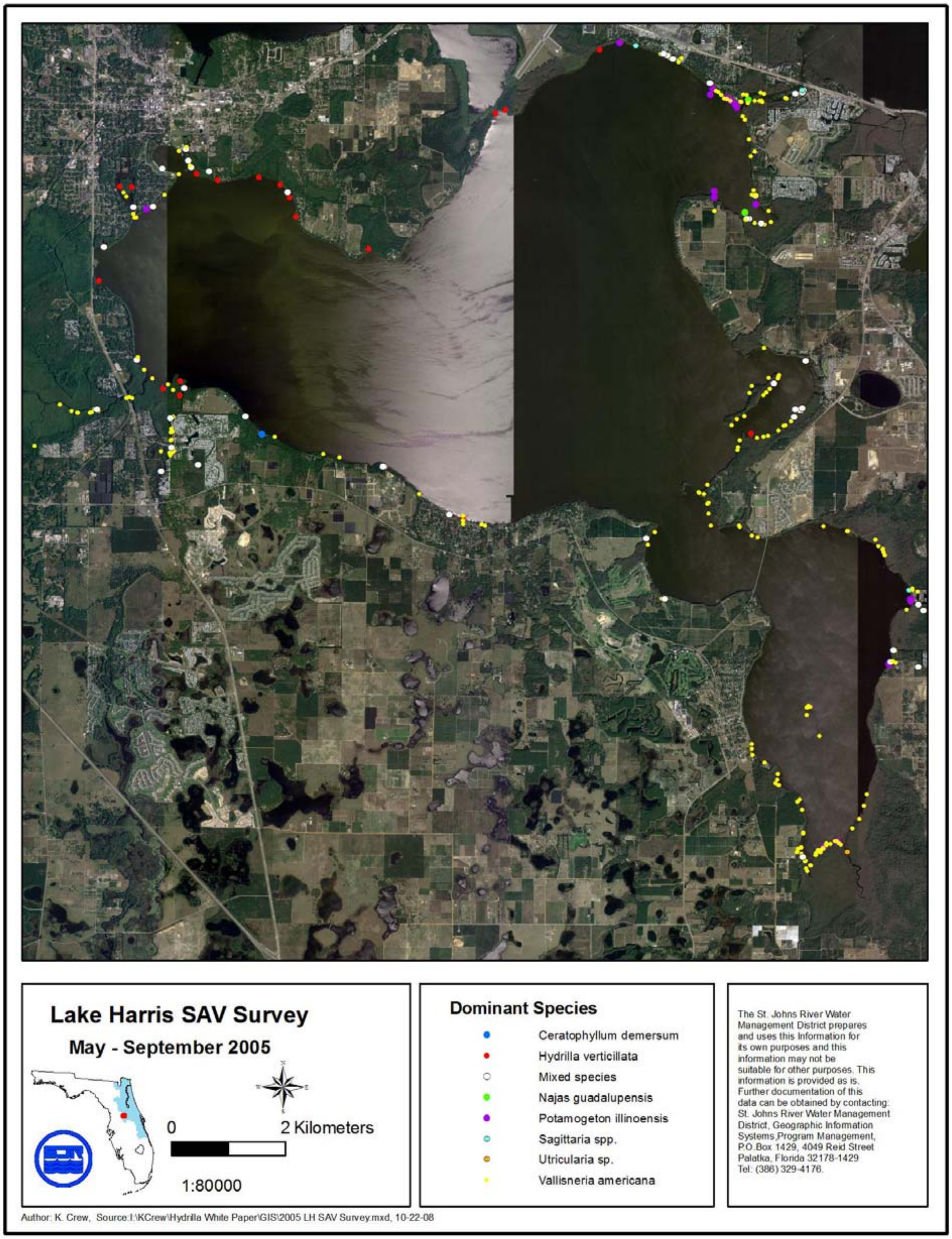

Figure 12. Dominant SAV species at survey sites for Lake Harris (6,688 ha) between May and September 2005

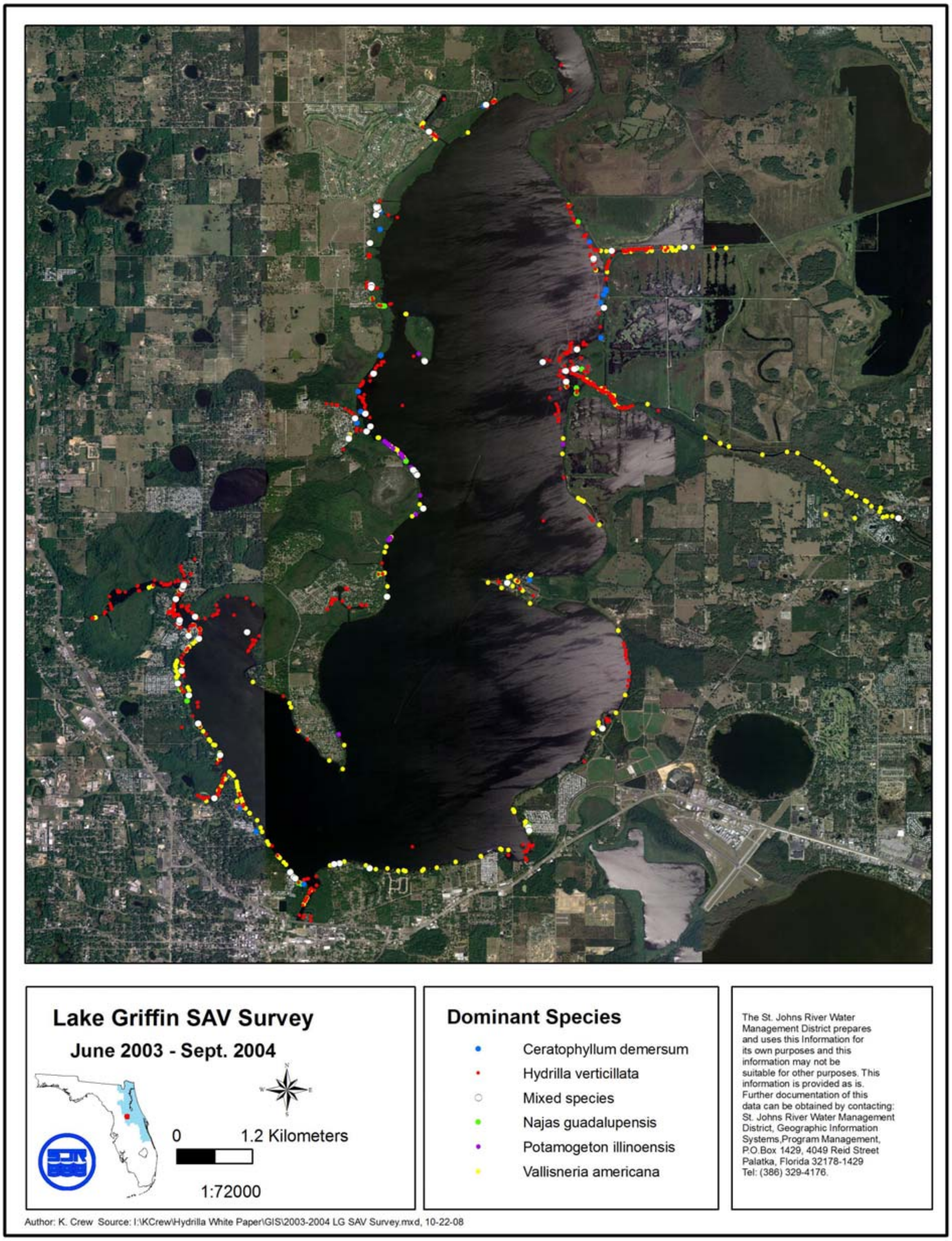

Figure 13. Dominant SAV species at survey sites for Lake Griffin (4,325 ha) between June 2003 and September 2004

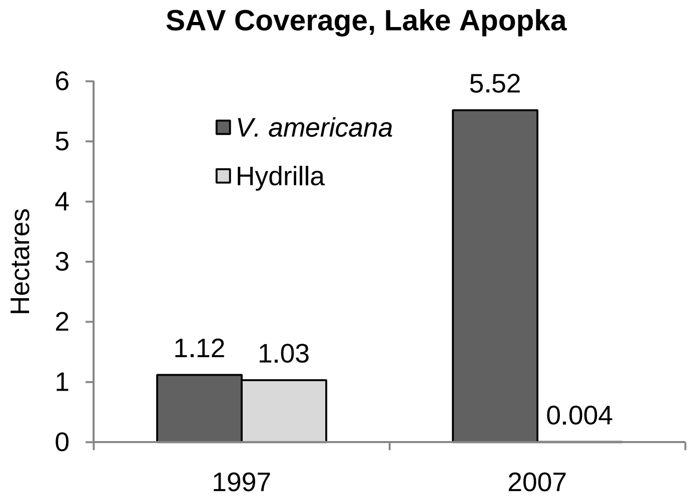

Figure 14. Number of hectares in Lake Apopka with dominant species *V. americana* or hydrilla in calendar year 1997 (2 years into surveillance management) and 2007 (12 years into surveillance management). *V. americana* or hydrilla dominated a majority of the SAV patches present

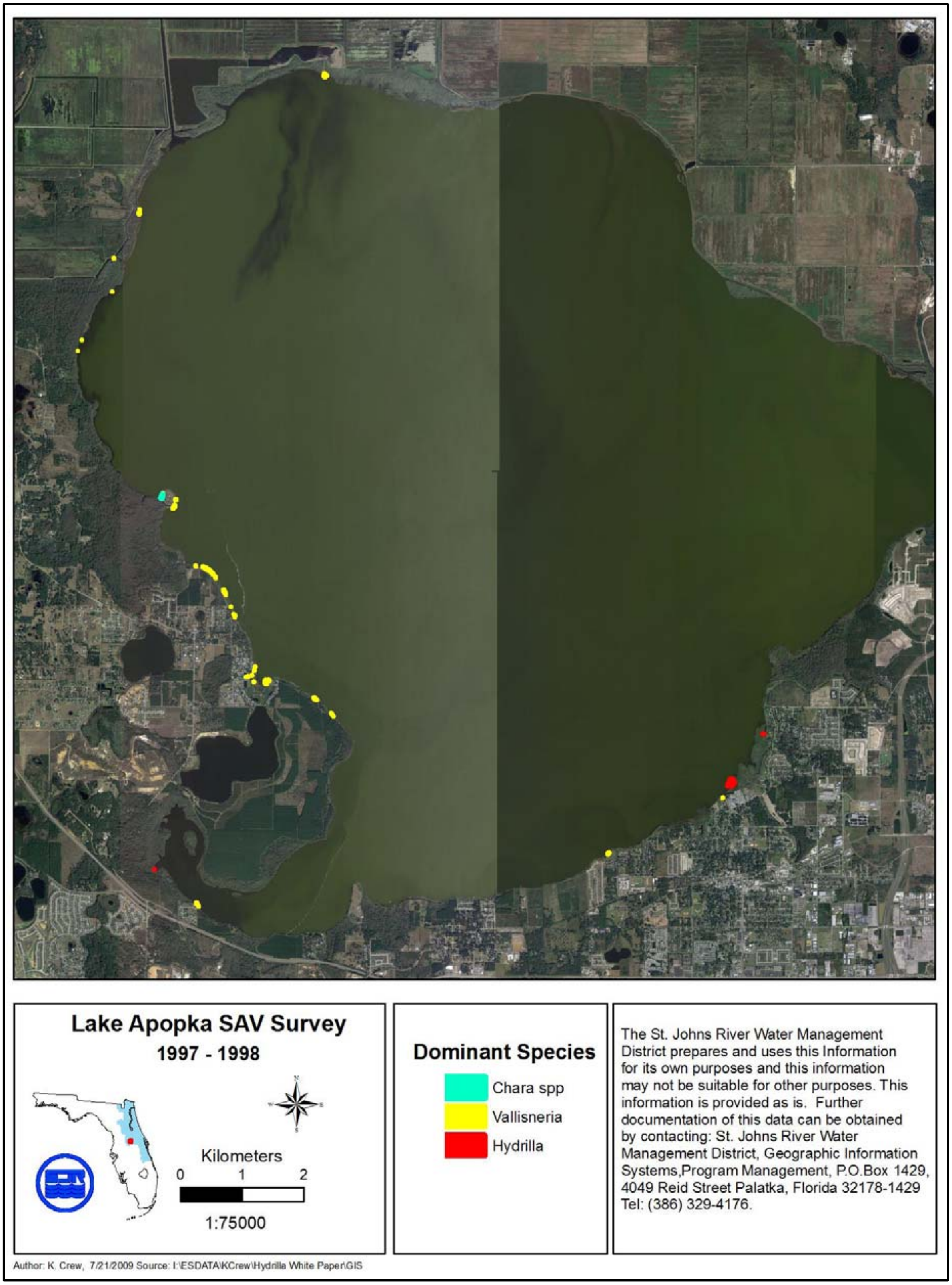

Figure 15. Dominant SAVspecies at survey sites for Lake Apopka (12,465 ha) from 1997-1998

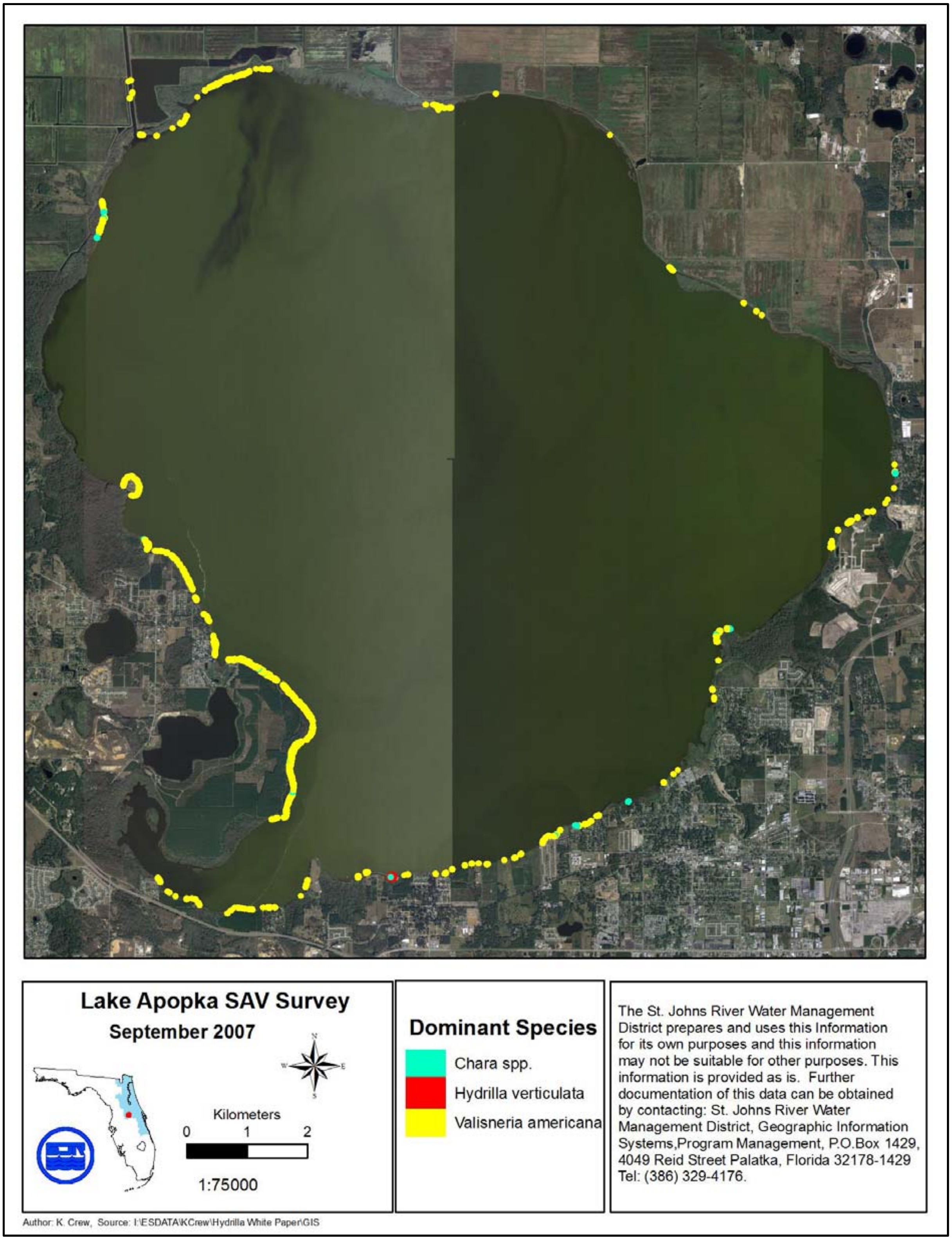

Figure 16. Dominant SAV species at survey sites for Lake Apopka in September 2007