MAPPING AND MONITORING INVASIVE AQUATIC PLANT OBSTRUCTIONS IN NAVIGABLE WATERWAYS USING SATELLITE MULTISPECTRAL IMAGERY

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ABSTRACT

Aquatic plant infestations impede commercial and recreational traffic through navigable waterways, block ports and passenger ferry terminals, and exert dangerous damaging pressure upon transportation infrastructure. Timely, accurate information on aquatic plant distribution and density is required both by public agencies charged with the management of navigable waterways, and by private companies engaged in aquatic plant control efforts. Traditional field-based mapping and monitoring of the extent and density of aquatic plant infestation present several challenges, including inaccessibility of areas for field sampling, rapid changes in aquatic plant location, extent, and density, and budget constraints on field sampling and monitoring. Remote sensing technology has significant potential to aid managers in detecting infestations that may be an impediment to transportation, prioritizing areas of plant infestation for control efforts, providing detailed information on plant extent and density for estimating control costs, and for assessing the effectiveness of aquatic plant control operations. This project evaluated the ability of satellite remotely sensed imagery to map water hyacinth and hydrilla in the lower Rio Grande River, Texas.

INTRODUCTION AND STATEMENT OF THE PROBLEM

Millions of acres of surface waters in the United States today are infested with non-indigenous aquatic plants, posing a serious threat to our navigable waterways used for commercial and recreational purposes. Exotic aquatic plant species cause major ecological damage to aquatic systems and impede human uses of surface waters. For more than 100 years, managers have sought to control invasive species including hydrilla (*Hydrilla verticillata*), water hyacinth (*Eichornia crassipes*), water lettuce (*Pistia strattiotes*), giant salvinia (*Salvinia molesta*), eurasian watermilfoil *(Myriophyllum spicatum)*, and others. Millions of dollars are spent annually by federal and state agencies on plant management programs. In Florida, the Florida Department of Environmental Protection estimates that $25.6 million will be needed in fiscal year 2001 alone to manage invasive plants in state waters, compared to approximately $12 million spent in 1996. Similarly expanding aquatic plant management problems exist in nearly every region of the United States and throughout the world, causing significant social and economic hardship. Economic sectors adversely impacted by uncontrolled aquatic plant infestations include water-based navigation, water quality and supply, hydropower, irrigation, fisheries, recreation, native vegetation and wildlife.

Transportation systems can be impaired by uncontrolled growth of invasive aquatic vegetation in navigational areas. Aquatic plant infestations create several significant problems for transportation:

- Dense mats of aquatic vegetation impede commercial and recreational traffic through navigable waterways, and block ports and passenger ferry terminals;
- Masses of floating aquatic vegetation in flowing waters can exert enormous, damaging pressure upon transportation infrastructure (bridge piers, locks, and docks). The immense weight of plant biomass propelled by currents has the capability to fatally undermine the strength and stability of such structures, rendering them unsafe, and costly to repair or replace.
- Canals and rivers used for commercial and recreational transportation can act as corridors for the spread of invasive aquatic plant species outside their natural range, both domestically and internationally. The assessment, monitoring, and control of invasive exotic aquatic plant species infestations is fundamentally in accordance with U.S. Department Transportation (USDOT) Policy in response to Executive Order 13112 (Invasive Species). Water hyacinth, water lettuce, and hydrilla are all aquatic plant species that have been documented as causing significant obstructions to commercial and recreational traffic in navigable waterways.

In the United States, aquatic plant invasion is a significant problem for southern and coastal states, predominantly Texas, Louisiana, Alabama, Mississippi, Georgia, and Florida, although nearly every state has some degree of infestation by one or more species. Transportation problems caused by aquatic plant cover are not limited to the US, however, and the effects of such infestations are particularly acute in tropical countries (Barrett, 1989). In South America, China, and parts of Africa, water-based transportation systems are often the only means of transporting people and freight, and consequently are particularly vulnerable to disruption by aquatic plant infestations. For example, in Kenya during the late 1990s and early 2000, extensive mats of water hyacinth growth in the Winam Gulf region of Lake Victoria were responsible for closing the port of the city of Kisumu, causing extensive commercial and economic disruption (Figure 1).

Figure 1. Water hyacinths blocking the port of Kisumu.

Traditional field-based mapping and monitoring of the extent and density of aquatic plant infestation present several challenges:

- *Areas may be inaccessible for field sampling:* Dense mats of vegetation can block boat access, and aquatic plant infestations can cover large geographic areas, necessitating extensive travel for adequate sampling.
- *Rapid changes in aquatic plant extent and density:* Invasive aquatic plants species typically have a high growth rate. Water hyacinth, for example, can double its biomass and number of plants within six to 12 days. Extensive mats of vegetation are often free-floating, and can change position rapidly owing to currents or wind action.
- *Seasonal and interannual changes:* The extent and density of aquatic plant infestations can rapidly change within a growing season and from year to year as a result of high growth rates, movement of vegetation mats, and effects of weather on plant growth rates.

Given these limitations on traditional methods of assessment, coupled with the wide geographic distribution of the aquatic plant infestation problem (affecting water-based transportation in numerous states and countries) and the need for up-to-date information on aquatic plant distribution and density required by both public agencies and private companies, TerraMetrics, Inc. is developing a strategic management planning tool for mapping and monitoring aquatic plant obstructions to transportation in navigable waterways.

Remote Sensing of Invasive Aquatic Plants

While aerial photography and remotely sensed imagery have been used to map and monitor seasonal and yearly changes in the *extent* of aquatic plant cover (Everitt et al., 1999; Malthus and George, 1997; Jensen et al., 1993; Jensen 1992; Nohara, 1991, Welch et al., 1988), few studies have attempted to address quantitative estimation of aquatic plant cover based on spectral reflectance (Jakubauskas et al., 2000; Steeves et al., 1999). By calibrating remotely sensed multispectral data with ground measurements of cover, density, biomass, or leaf area, vegetation condition measured at sample points can be then extrapolated across a large geographic region (Jakubauskas et al., 2000; Jensen, 1983).

Remotely sensed information on plant distribution and extent of coverage is valuable in determining trends, confirming field reports, assessing the efficacy of control measures, providing early warning before a developing problem reaches a critical state, and general strategic planning. Remote sensing provides a critical tool for monitoring the status of infestations as well as detecting impediments to waterborne transportation caused by aquatic plant infestations. Frequent large-scale monitoring via remote sensing furnishes managers with real-time assessment capabilities important in a broad range of transportation uses, from routing and scheduling shipping to vegetation control cost analysis.

Proposal Objectives

We address the following specific objectives in this project:

- Determine the relationship between aquatic plant cover and spectral reflectance;
- Evaluate high resolution (4 meter) multispectral imagery for mapping and estimating aquatic plant cover;
- Evaluate remotely sensed imagery for assessing aquatic plant control efforts through change detection.

METHODOLOGY

Fieldwork on Rio Grande River

In August 2001, AquaSolutions LC received a request from the Texas Department of Wildlife and Parks to conduct emergency aquatic plant control efforts on water hyacinth and hydrilla in the project study area near Brownsville, Texas. Accumulations of aquatic plants were blocking river flow for irrigation and drinking water, and were presenting a navigational block to river patrols by the US Border Patrol. This emergency presented a unique opportunity to conduct the plant cutting ahead of our original schedule. Two Aquaplant Terminators were used to conduct cutting on water hyacinth blockages on the Rio Grande within the study area. An Aquaplant Terminator performed additional cutting as directed during the August field sampling operations. AquaSolutions provided the AquaPlant Terminator and a motorboat for access to sample locations along the river.

Spectral reflectance measurements: Spectral reflectance measurements were taken using an Analytical Spectral Devices (ASD) spectroradiometer, recording 512 discrete spectral bands over the range 330 - 1055 nm (visible to near-infrared). Nadir view measurements for each quadrat were made with the sensor head at 2.0 m above the water surface (Note: The ASD system has a 0.47 radian IFOV; at 2.0 meters above the water surface, the diameter of the base of the view cone is therefore approximately 0.94 cm). Spectral reflectance measurements were taken for the same quadrats used for biophysical assessment. At each plot a white reference calibration reading was taken prior to spectral reflectance readings to normalize all reflectance values to a common standard. Ten spectroradiometer scans per quadrat were acquired and internally averaged by the system to determine spectral reflectance. Spectroradiometer readings were also taken of open water to provide baseline spectral reflectance values for 0% plant cover (e.g., 100% water).

Aquatic plant sampling: In-situ plant sampling was performed immediately following spectral reflectance measurement (if applicable) and before biomass sampling. The following information was collected:

- *Plant cover by species and condition.* Percent cover of green photosynthetically active vegetation by species within a 0.5x0.5 m square quadrat was visually estimated by two people, in 5% increments;
- *Above-water plant height:* Plant height was measured in centimeters using a meter stick from water level to top of majority of vegetation within the quadrat.

- *Number of plants per unit area:* Coincident with plant biomass sampling operations (5.0, below), the number of plants per quadrat will be counted.
- *Biomass sampling:* Biomass of invasive emergent aquatic plants (principally water hyacinth) was sampled as follows: A 0.5x0.5 m square sampling frame made of ½" PVC pipe was placed on top of the vegetation. All vegetation within the frame was removed and sorted by species. Excess water was removed by shaking the plants. Plants were then cut at the waterline and separated into two net bag/sieve buckets, one each for above-water green biomass and below-water biomass. Excess water was allowed to drain off, and the samples weighed (for each species) using metric spring scales. The scale was zeroed to account for the weight of the sampling bucket/bag. When necessary, the sampling was done in sections if the biomass amount was such that it exceeded the weight capacity of the scale. A global positioning system (GPS) unit was used to record the geographic location of each sample site.

Statistical analysis of plant cover and spectral reflectance: Correlations between plant percent cover and spectral reflectance data collected by the radiometer were calculated using a significance level of ∀ = 0.05 (Figure 2).

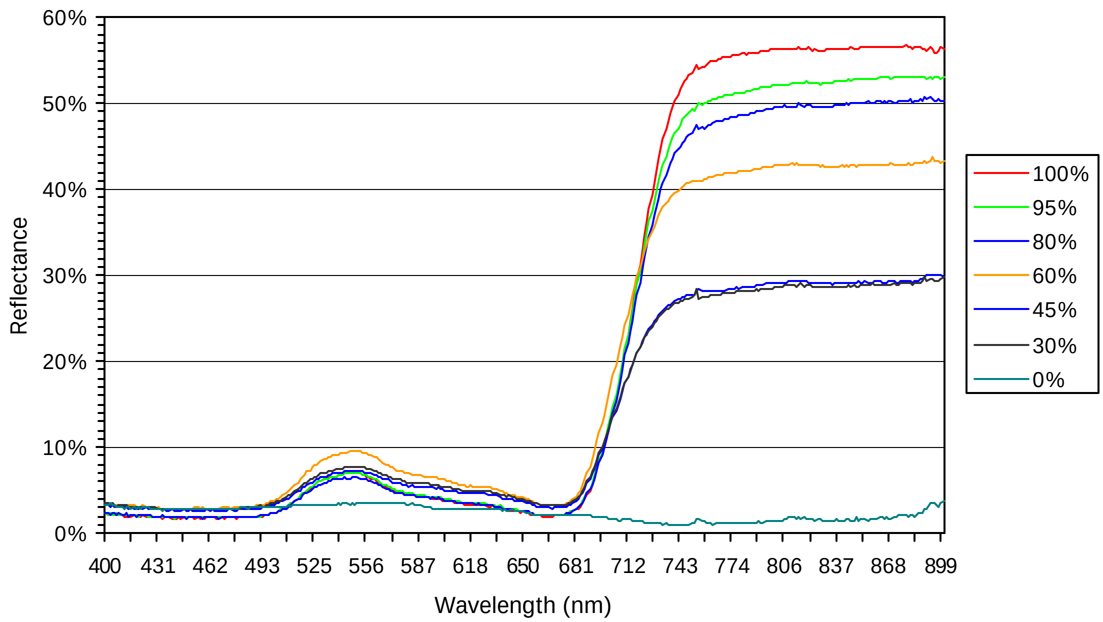

Figure 2. Spectral reflectance of water hyacinth as a function of percent cover.

Satellite imagery: IKONOS 4.0 meter multispectral data

We originally planned to acquire the image six months following plant control efforts (carried out in August 2001), which would have indicated a second acquisition of imagery sometime in February 2002. Since this was early spring in southern Texas, and the plants were relatively dormant, we elected to postpone the acquisition until later spring when plant development would be more advanced and provide a truer indication of control efforts/plant survival. Space Imaging Corporation acquired a clear, usable image on June 16, 2002. The quality of the image is excellent (see Figures 3 and 4, images of a selected portion of the study are on the Rio Grande River).

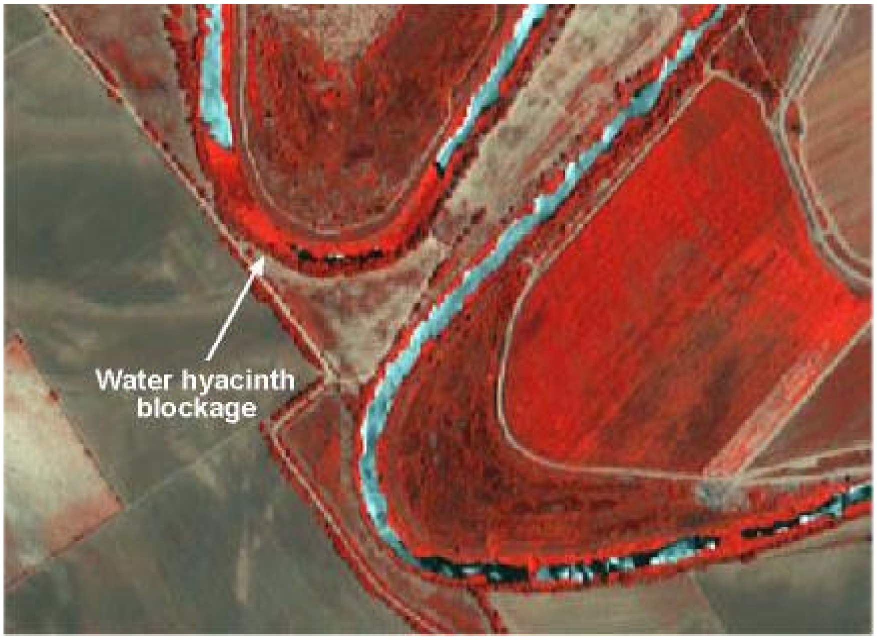

Figure 3. IKONOS image of water hyacinth blockage on Rio Grande River, July 19, 2001

Figure 4. IKONOS image of same area 10 months later, June 16, 2002.

ASTER Imagery for Change Detection

While awaiting the second IKONOS image, we acquired imagery from the EROS Data Center for the ASTER system (*Advanced Spaceborne Thermal Emission and Reflection Radiometer*) aboard NASA *Terra* satellite as part of our process of assessing different remote sensing systems for their ability and useability for invasive aquatic plant monitoring. While we are not performing quantitative computer-based classification and differencing on the ASTER data, as we are on the IKONOS data, qualitative comparison alone shows that these images can track changes in aquatic plant extent and cover. The ASTER system records visible, near-infrared, and thermal spectral bands of the spectrum. We used the 15-meter spatial resolution visible and near-infrared bands. While the ASTER has a lower spatial resolution than the 4-meter IKONOS imagery, accumulations and blockages of water hyacinths on the Rio Grande River are clearly apparent. Furthermore, the sequence of images from 2001 (pre-and post-cutting by AquaSolutions) and the spring of 2002 show the highly dynamic and changing nature of these invasive aquatic plant problems.

ASTER imagery acquired during 2001: Eight usable ASTER images were acquired for 2001 from the US Geological Survey EROS Data Center in Sioux Falls, SD. There was no charge for the data by EROS. Dates acquired spanned the full calendar year and change of seasons:

January 21, 2001
April 4, 2001
April 23, 2001
June 4, 2001
June 10, 2001
September 29, 2001
October 23, 2001
December 14, 2001

The images varied considerably in cloud cover, from completely cloudfree to approximately 50% occluded. Images with significant cloud cover over the Rio Grande River were not acquired from the EROS Data Center. Invasive aquatic plant cover is at a minimum during winter months, as the growth rate slows and plants are "knocked back" by colder temperatures. Plant cover begins to increase in the spring, forming blockages visible on the false-color composite images as bright-red patches along the course of the river. Increased springtime growth of water hyacinth is also apparent along the banks in many places. By midsummer, significant blockages by water hyacinth and hydrilla are clearly apparent on the ASTER data. By the fall of 2001, as a result of control efforts and seasonal changes, aquatic plant cover has been reduced, although persistent blockages remain on parts of the river. Four samples of ASTER imagery from 2001 are provided in Figures 5a-5d.

ASTER imagery acquired during 2002: Three ASTER images were acquired for spring 2002: March 30, April 24, and May 9. Figures 6a and 6b show a section of the Rio Grande River separating Brownsville, Texas, from Matemoros, Mexico. The top image is from March 30, 2002; the bottom image from May 9, 2002. The Fort Brown Golf Course is at the left-central side of each image. In the images, the vegetation appears bright red, and water appears black. Total image width is about 4.7 miles (7.5 km). Significant increases in water hyacinth cover in the intervening six weeks are apparent on this image pair. A similar sequence of images for the same dates for an area several miles upstream has shown a 1.5+ mile accumulation of a hyacinth blockage during this six-week period, or approximately 200 linear feet of river per day.

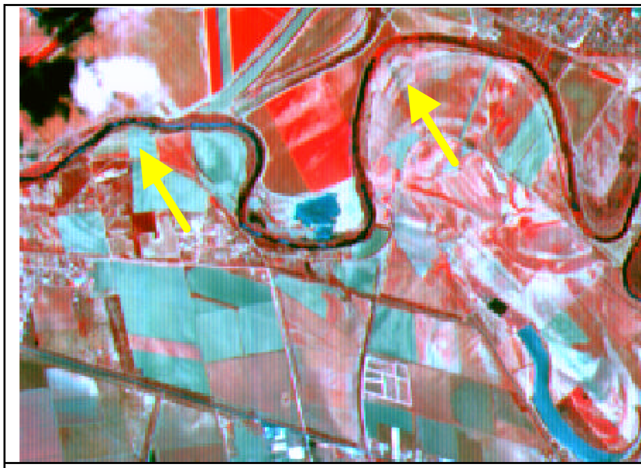

Figure 5a. January 21, 2001 ASTER imagery of Lloyd Bend area, upstream of the cities of Brownsville and Matemoros. Invasive aquatic plant cover is at a minimum on this date, appearing principally along the upper portion of the right-hand (downstream) bend).

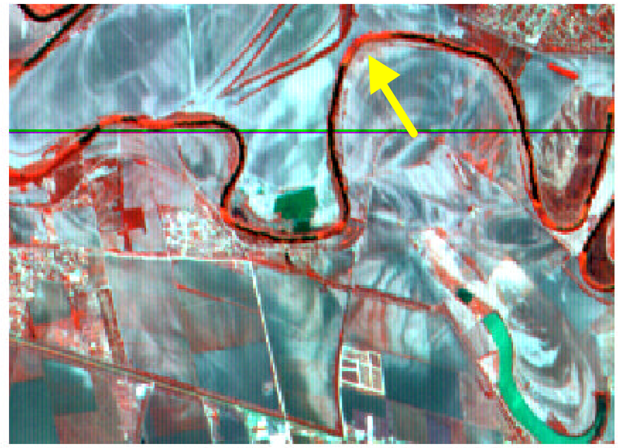

Figure 5b. April 4, 2001 ASTER imagery of Lloyd Bend area. Invasive aquatic plant cover has significant increased on the river in the intervening two months, forming blockages visible as bright-red areas along the river. Increased springtime growth of water hyacinth is also apparent along the banks in many places.

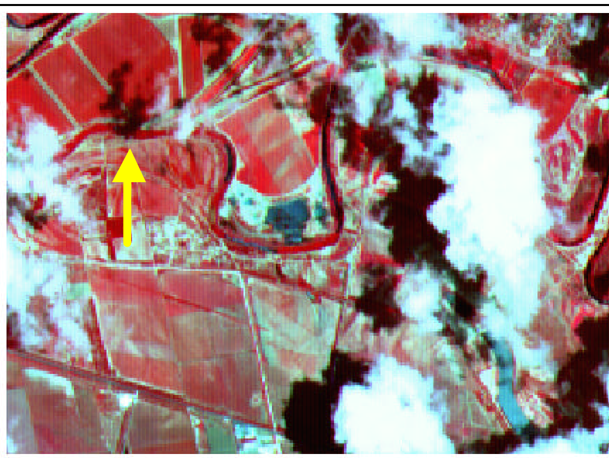

Figure 5c. June 4, 2001 ASTER imagery of Lloyd Bend area. Despite the cloud cover present over parts of the image, increases in plant cover are clearly visible. The left-hand (upstream) major river bend is now almost completely blocked by plants, significantly impeding water flow and boat movement along the river.

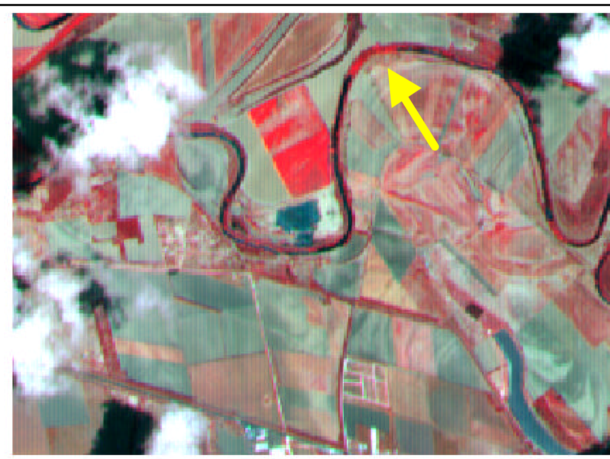

Figure 5d. December 14, 2001 ASTER imagery of Lloyd Bend area. As a result of control efforts and seasonal changes, aquatic plant cover is reduced on the image. This stretch of the river is nearly clear of water hyacinth, although a persistent blockage remains on the upper right river bend (Lloyd Bend).

Figure 6a. ASTER imagery, Brownsville-Matemoros area, March 30, 2002. Most of the 7 kilometer reach of the river on this date is free of hyacinths (bright red areas along and within river).

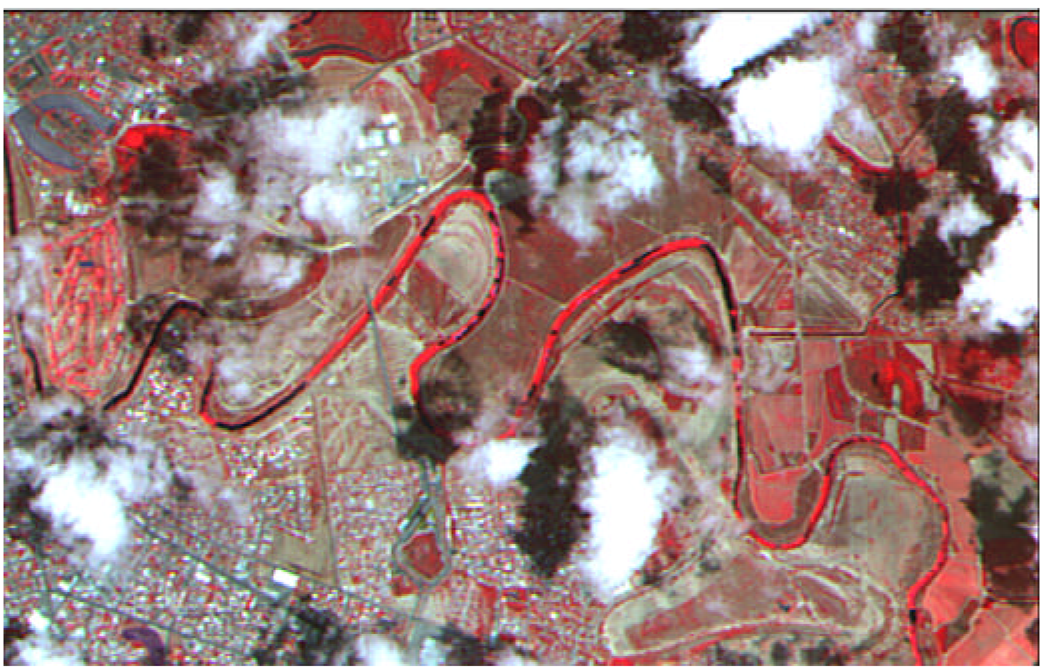

Figure 6b. ASTER imagery, Brownsville-Matemoros area, May 9, 2002. A significant proportion of the river has been overgrown by water hyacinths in the intervening six weeks (bright red areas along and within river).

BENEFITS

Adoption of remote sensing-based methodologies developed as a result of the successful completion of this project will contribute to enhanced planning and decisionmaking in waterways management and produce tangible economic benefits to both public- and private-sector entities. The possible benefits include:

- Reducing the time and resources required for mapping aquatic plant infestations in navigable waterways, resulting in more accurate maps and facilitating more frequent updates of potentially rapidly changing conditions;
- Identification of current obstructions in navigable waterways and identification of potential threats to locks, dams, docks, and bridge piers from accumulated masses of floating aquatic plants;
- Prioritization of areas for vegetation removal by mechanical and/or chemical treatment methods, provide more precise estimates of aquatic plant control costs, and permit assessment of the success or failure of aquatic plant control efforts;
- Increasing the information content of maps from simple presence/absence maps of aquatic plant occurrence, to quantitative estimates of plant cover, allowing for more precise estimates of aquatic plant control costs;
- Facilitating the operational use of remote sensing in transportation by developing reliable, replicable, easily adopted remote-sensing-based tools for use by transportation managers in mapping and monitoring aquatic plant infestations and assessing effectiveness of control efforts;
- Allowing agencies to monitor seasonal and interannual changes in aquatic plant cover, and aid in predicting areas that may be invaded by nuisance aquatic plants in the near-term future.

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