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Mapping waterhyacinth drift and dispersal in the Sacramento–San Joaquin Delta using GPS trackers

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ABSTRACT

Waterhyacinth [*Eichhornia crassipes* (Mart.) Solms)] is a perennial free-floating aquatic plant species native to the Amazon region of South America. It has become invasive around the world, including in the Sacramento–San Joaquin Delta in central California. From June 2016 to February 2018, a study was conducted to determine the extent that wind, tidal movement, and mass flow drove the dispersal of waterhyacinth mats in the Delta. Global positioning system (GPS) trackers were deployed to track the movement of waterhyacinth mats, recording the location, speed, and direction of movement at 15-s intervals. The relationship between mat size and distance traveled was analyzed using linear regression and did not show correlation ($R^2 = 0.0462$, $P = 0.0738$). The movement of each waterhyacinth mat containing a GPS tracker was compared to the wind and water movement during the period the tracker was deployed. The direction of water movement, influenced by both mass flow and tides, aligned more closely with the direction of waterhyacinth mats, with a mean difference of 0.31 radians (rad) (17.75°), than the wind direction did, with a mean difference of 1.31 rad (75.34°). The pattern of plant mat movement observed using the GPS trackers presents a difficult management situation, with the waterhyacinth mats moving back and forth with tidal movement.

Key words: *Eichhornia crassipes* (Mart.) Solms, floating plants, flow, invasive species, tide, wind.

INTRODUCTION

Waterhyacinth [*Eichhornia crassipes* (Mart.) Solms)] is a floating perennial aquatic plant species native to the Amazon region in South America (Penfound and Earle 1948), but it has become invasive around the world. Waterhyacinth was first brought to the United States prior to 1890 for use as an ornamental in ponds (Penfound and Earle 1948, Owens and Madsen 1995). In the United States, it has become a management problem across the Southeast, the Gulf Coast, and in California. It was first reported in California in Yolo County in 1904 (Bock 1968). Long-distance dispersal, across continents or from state to state, is primarily facilitated by humans, whereas short- and intermediate-distance dispersal happens due to both human and environmental vectors, such as water movement (Heidbüchel and Hussner 2020). The term "water movement" shall refer to the combined force of mass flow and tidal movement. When necessary to differentiate these two forces, the terms "mass flow" and "tidal movement" will be used. Mass flow refers to water moving downstream in the river system and tidal movement refers to the water moving upstream and downstream with the tide.

In the Sacramento–San Joaquin River Delta in California (hereafter the Delta), waterhyacinth forms large, dense mats on the water surface that decrease light availability below the floating mat, and inhibit boating, wading, fishing, irrigation, and water access (Madsen 1993, Spencer and Ksander 2005). The intertwined root and leaf structure allows the plants within a mat to remain held loosely together, while occasionally separating into smaller mats. Waterhyacinth can disperse and colonize new locations by floating on the water surface (Bock 1969, Luu and Getsinger 1990, Madsen 1993). Waterhyacinth reproduces both sexually and asexually. Vegetative reproduction occurs at a very high rate, with the number of ramets (daughter plants) doubling in 7 d (Center and Spencer 1981, Luu and Getsinger 1990). Ramets grow from stolons originating from a parent plant. As ramets grow, they cause the density of a waterhyacinth population to increase, pushing the outer edge of the population away from the bank, where forces such as tidal movement, mass flow, wind, or boats cause portions of mats to break away. These free-floating plants or groups of plants are then dispersed by the water or wind until they become entrained and start new populations, which will rapidly fill available habitat.

The Sacramento River and the San Joaquin River drain the northern and southern parts of the Central Valley of California, respectively. The two rivers come together and form an inland river delta comprised of a series of braided channels and islands flowing into San Pablo Bay, and ultimately, the Pacific Ocean. The section of the river system called the Delta is a geographic area which is legally defined for the purposes of water usage, species management, and navigation. The Delta has been significantly altered since European habitation, with levees reinforcing channel sides, dredged shipping channels, and land subsidence occurring on some islands. Although a system of water-control structures helps to control upstream flows, the Delta is subject to seasonal and tidal changes in water level. The

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patchwork of ownership and responsibility for levee maintenance presents a management challenge. The California Division of Boating and Waterways (CDBW), a division of California State Parks, is the agency charged with managing invasive plants in the Delta.

Global positioning system (GPS) recording and radiotelemetry have been used to map animal dispersal, but its use has been rare with plants. Previous studies attempting to understand the dispersal of floating aquatic plant species recorded the location of the starting and recovery points, and the path the plants traveled between these points was inferred. Various floating objects were used to find where plants might drift, including cards (Howard et al. 2006), bottles (Shulman and Bryson 1961), wood blocks (Nilsson et al. 1991), and plant fragments (Riis and Sand-Jensen 2006), some using colored thread or paint to mark specific fragments (Johansson and Nilsson 1993). GPS technology now has developed to the point that it should allow researchers to map floating plants as the plants disperse throughout a body of water, recording their exact path. A 2013 study conducted on reservoirs in Mississippi used trackers enabled with GPS to map floating plants, with both success and limitations. The trackers in that study were dependent on cellular phone signals, which can be unreliable in remote areas. The present study builds on the idea of incorporating GPS into plant dispersal studies in order to capture the specific direction, distance, and speed of the plant mats. The use of GPS trackers allows the researcher to locate the tracking device, even if the device is not easily visible or ends up in an unexpected location, which is an additional benefit over previous methods such as cards or wood blocks (Fernandez 2013).

The influence of water and wind velocity on the movement of waterhyacinth have been measured and compared in a controlled laboratory environment. Downing-Kunz and Stacey (2011), using waterhyacinth mat in research flumes, found that the water drag coefficient decreased as the water velocity increased, due to the roots' flexibility, while the air drag coefficient did not change as the air velocity increased, due to the leaves' relative inflexibility. The waterhyacinth plants in that study were obtained from a pond supply store and maintained in a greenhouse prior to the experiment. These plants might have had some differences from plants growing in the wild, where they are subject to nutrient deficiency or blooms, temperature variation, wind and wave action, and inter- and intraspecific competition for light and other resources. The mats used in the Downing-Kunz and Stacey (2011) study were constructed by the researchers and held together using fiber line, designed to achieve mean leaf densities found in the field. Valuable information was obtained in the controlled conditions of a laboratory flume, but mats which have grown intertwined might behave differently than mats constructed by researchers. For the present study, rather than constructing plant mats or breaking off plant mats from established populations, we used mats that were already floating freely in the water column.

The objective of the present study was to determine to what extent wind, tidal movement, and mass flow from the San Joaquin River drove the dispersal of waterhyacinth mats in the Delta. A goal of this study was to determine if source populations of waterhyacinth could be identified, which would allow management efforts to focus on those populations.

MATERIALS AND METHODS

From June 2016 to February 2018, GPS trackers[1] were deployed to track the movement of drifting waterhyacinth mats. The waterhyacinth mats used for the study were mats that had naturally formed and were already floating away from the riverbanks and other waterhyacinth populations. Each tracker was placed into a 2,000-mL polycarbonate plastic bottle[2]. The bottle was placed in a floating mat of waterhyacinth and drifted with the mat wherever the plant mat drifted. In addition to the GPS tracker, each bottle contained a radio dog collar[3], which emitted a signal that could be picked up by a receiver located on the research boat. Using this signal, the researchers found and retrieved each bottle after 2 to 4 h of being deployed. The GPS trackers recorded location data at 15-s intervals, whereas the radio dog collars were used only to locate and recover the bottles containing the GPS trackers. GPS trackers were released 76 times, with 74 recoveries, 70 of which had recorded data that was successfully downloaded. Two of the GPS trackers were never recovered.

The length and width of each mat was measured, and the area of each mat was calculated. Wind speed and direction were recorded at the time each tracker was released using a portable weather station[4]. Tidal information was obtained from the National Oceanic and Atmospheric Administration Tides and Currents website (NOAA 2018). The water discharge (m^3s^{-1}) was obtained from U.S. Geological Service stream gauges located throughout the Delta (USGS 2018).

The location, speed, and direction of movement during the time the mat was drifting was downloaded into the GPS tracker software[5]. The data were then imported into a geospatial mapping program[6] and a GIS program for analysis[7]. Data were analyzed to determine whether the size of a plant mat (m^2) had a significant effect on the distance traveled (m). The size data exhibited high degrees of skewness (4.90) and kurtosis (27.59). The data were log-transformed and these data exhibited characteristics of data drawn from a normal population ($P = 0.094$ using Shapiro-Wilks test for normality), with reduced skewness (0.59) and kurtosis (0.51). A simple linear regression was performed to determine if mat size had an effect on the distance the mat traveled.

The water direction was determined using direction of stream flow. For each run, the GPS tracker was deployed, the compass direction in degrees (°) for the movement of each mat was obtained in the GIS program and converted to radians (rad). As each mat drifted, sometimes the direction of travel changed. When the direction of the plant mat (or water or wind movement) changed by more than 0.175 rad (10°), the segment with a different heading was analyzed as a separate run. Mass flow and tidal flow move at various directions throughout the Delta as rivers and channels curve and change direction (Figure 1). Therefore, the specific compass heading was not important for this analysis, but

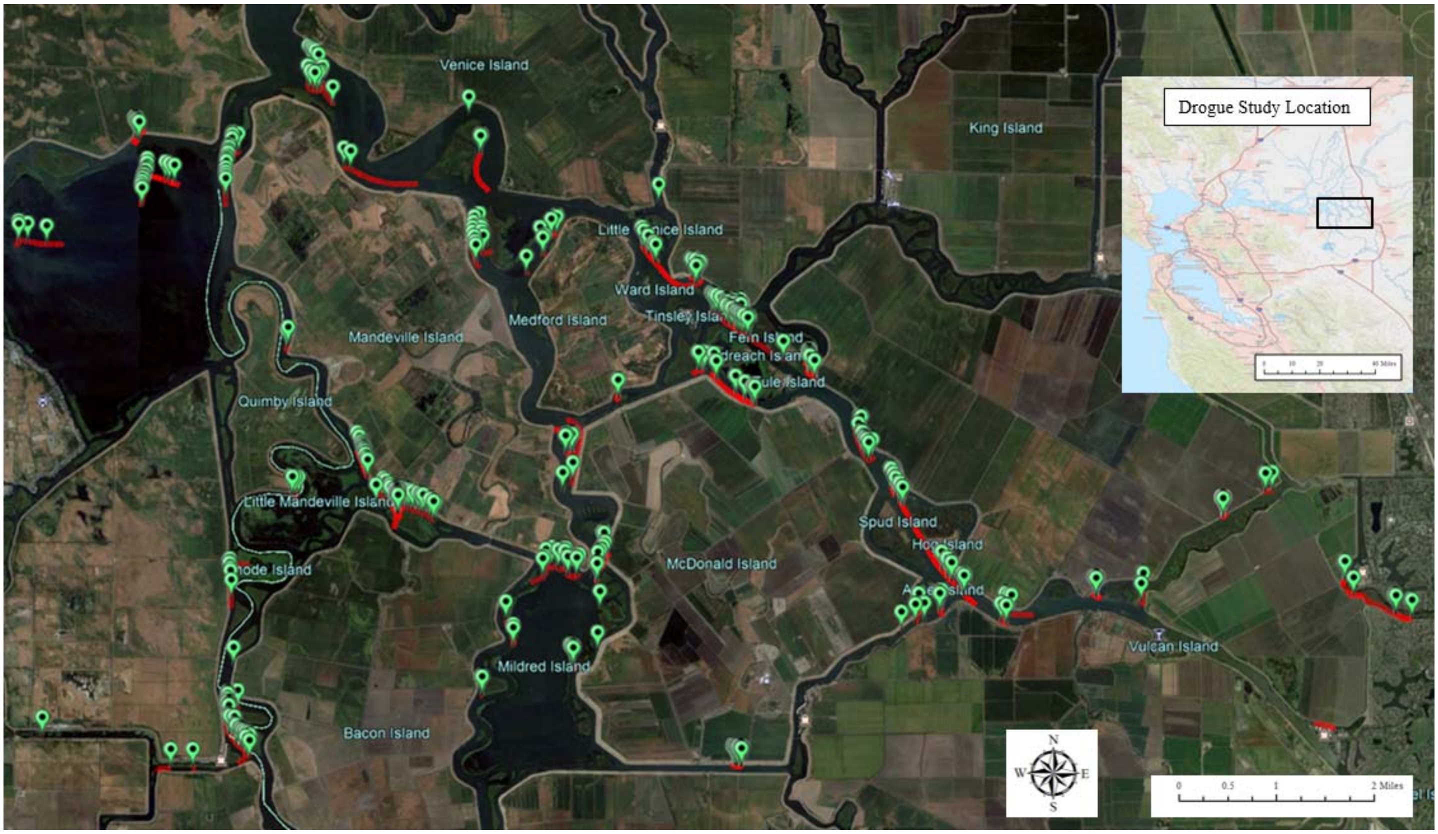

Figure 1. Plant mat paths recorded in the Sacramento–San Joaquin Delta, CA, 2016 to 2018. Lines represent paths of movement and points represent places where plant mats remained stationary for a period of time longer than 15 s ($n = 70$).

rather the difference between the direction the plant mat moved compared to the direction of the water and of the wind in the location where the plant mat was moving.

The difference in plant–water direction was plotted against the difference in plant–wind direction (Figure 2). The x and y axes in Figure 2 have the same scale, which is between 0 and π radians (0° to 180°). Each point represents one GPS tracker release, with the x value representing the difference between the plant direction and the water direction and the y value representing the difference between the plant direction and the wind direction. A value of 0 rad (0°) represents the plant mat moving in the same direction as the water (or wind, for the y axis), and a value of 3.14 rad (180°) represents the plant mat moving in the direction opposite the water (or wind). A linear regression was performed comparing the direction of plant movement to the direction of water movement, with directions rotated when the plant movement was on one side of magnetic north and the water on the other side. The same was done comparing the direction of plant movement to the direction of wind movement.

RESULTS AND DISCUSSION

A range of waterhyacinth mat sizes were used for the dispersal study, from 0.1 m^2 to 69.7 m^2, with a mean of 5.2 m^2. The mean distance traveled by the plant mats with GPS recorders was 0.55 km and the mean time the trackers were deployed was 2 h and 32 min. The distance the mats traveled did not show correlation with the size of the mats ($R^2 = 0.0462$, $P = 0.0738$).

Some of the trackers were recovered while they were still floating in the water, but most were recovered after they had become entrained on various substrates (Table 1). Twenty-two (29.7%) of the waterhyacinth mats were freely floating and continuing to disperse when they were recovered. Eleven (14.9%) were stationary and floating, caught in eddies or other water features that caused them to no longer move with the flow of water or wind. Forty-one (55.4%) of the mats had become entrained on various substrates when they were recovered.

The mean difference between the direction of the water and the direction of the plants was 0.31 rad (17.75°). The plant mats differed from the wind heading by an average of 1.31 rad (75.34°). Very rarely were the plant mats moving in a direction that was at odds with the direction of the water. For 69.6% of the tracks, the direction the plants traveled was within 0.26 rad (15°) of the water direction. In contrast, for only 11.4% of the tracks had the direction the plants within 0.26 rad (15°) of the direction of the wind. For 87.3% of the tracks, the direction the plants traveled was within 0.52 rad (30°) of the water direction, whereas only 18.9% of the plant tracks were within 0.52 rad (30°) of the wind. The plant mat direction was highly correlated with the water direction ($R^2 = 0.8957$, $P < 0.0001$, Figure 2) and less correlated with the wind direction ($R^2 = 0.4298$, $P < 0.0001$).

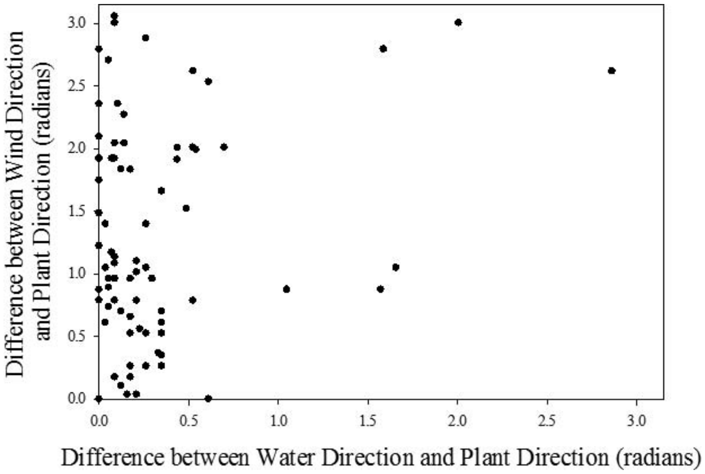

Figure 2. The difference between water direction and plant direction (radians) was plotted against the difference between wind direction and plant direction (radians). The x and y axes have a scale between 0 and π radians (0° to 180°). Each point represents one GPS tracker release, with the x value representing the difference between the plant direction and the water direction and the y value representing the difference between the plant direction and the wind direction. A value of 0 rad (0°) represents the plant mat moving in the same direction as the water (or wind, for the y axis), and a value of 3.14 rad (180°) represents the plant mat moving in the direction opposite the water (or wind). Linear regressions were performed, with directions rotated when the plant movement was on one side of magnetic north and the wind or water was on the other side. The direction of water movement explained a significant proportion of the variance in direction ($R^2 = 0.8957$, $P < 0.0001$), whereas the direction of wind movement correlates to a lesser extent ($R^2 = 0.4298$, $P < 0.0001$).

TABLE 1. LOCATION WHERE DEPLOYED GLOBAL POSITIONING SYSTEM (GPS) TRACKERS IN WATERHYACINTH MATS DEPLOYED WERE RECOVERED.

Substrate	State	*n*
Free floating	Moving	22
Floating but stationary	Stationary	11
Riprap	Stationary	19
Tules	Stationary	9
Driftwood	Stationary	1
Waterhyacinth	Stationary	10
Algae	Stationary	2
Total		74

Recording the location every 15 s allowed the researchers to map the plant mat changes in direction, which ultimately led to the stronger correlation (Figure 2) between water movement and plant mat movement. The change in direction that occurred as the tides changed was observed visually when the tracks were imported into the mapping program[6] (Figure 3). Mapping the path each GPS unit traveled, as well as the points where the mats ceased moving, showed that the plant mats did not travel long distances in the same direction at once, but moved back and forth with the tides (Figure 3), frequently getting caught on the bank. Plant mats typically became entrained for a period of time, were moved by the water a short distance, and then became caught again. One of the goals of this study was to identify source populations of waterhyacinth, and potentially focus management efforts in those areas. Unfortunately, the results show that the waterhyacinth mats are moving both upstream and downstream, as the flow of the water changes with the tides. This pattern of movement makes it difficult to identify waterhyacinth source and sink populations.

Waterhyacinth is present across the majority of the Delta and presents CDBW with a management challenge. Herbi-

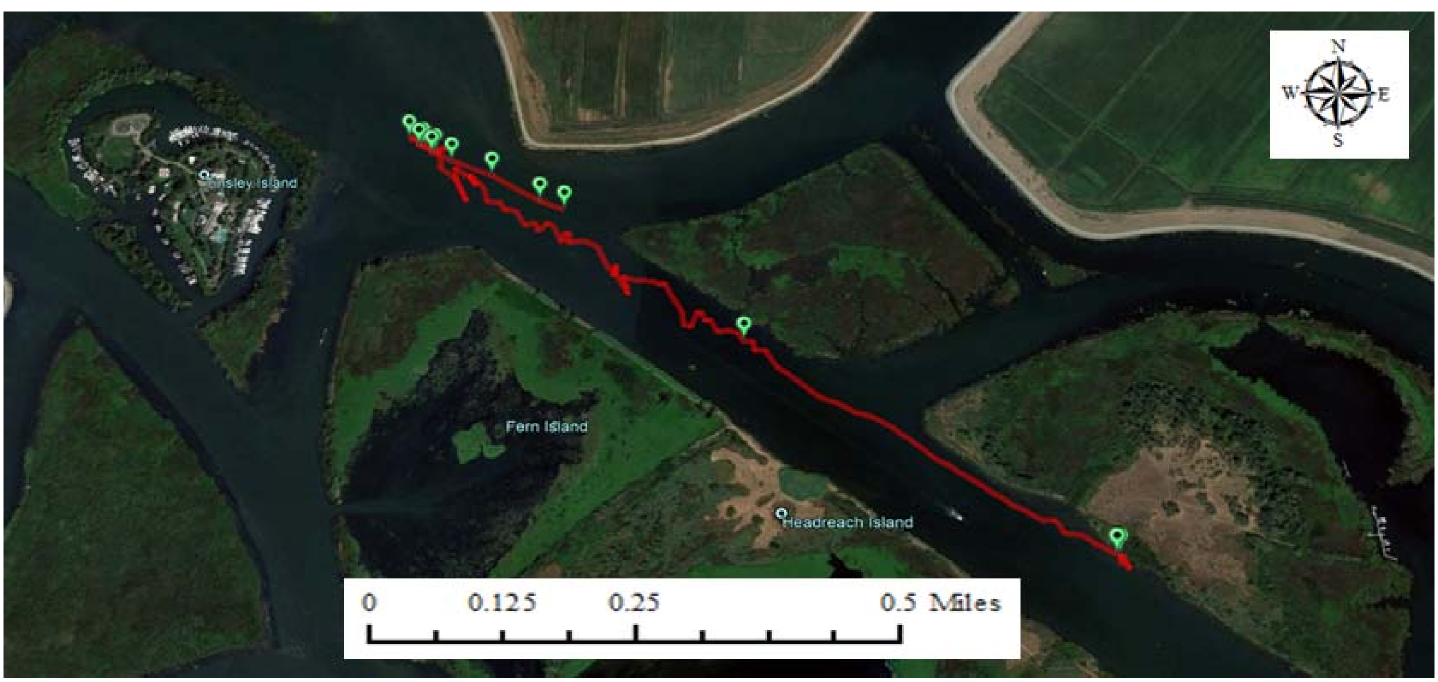

Figure 3. An example of a plant mat changing course as the tide changed in the San Joaquin main channel from November 16, 2017. Lines represent paths of movement and points represent places where plant mat remained stationary for more than 15 s.

cides that are registered for aquatic use and approved for use in the Delta provide the primary management tool. CDBW typically employs 5 to 10 treatment crews, each comprised of a boat operator and an applicator, during the treatment season. The treatment season varies by location, but generally begins March 1 to June 15 and ends November 30. In 2017, CDBW treated 1,170 ha (2,890 acres) with glyphosate and 115 ha (285 acres) with 2,4-D (CDBW 2018). Even if a waterhyacinth population is treated, floating mats can repopulate previously treated areas.

Floating mats in which waterhyacinth is the dominant species can contain viable individuals or fragments of other species, some of which are invasive. These include water-primrose (*Ludwigia* spp. L.), whorled pennywort (*Hydrocotyle verticillata* Thunb.), Brazilian waterweed (*Egeria densa* Planch.), and Eurasian watermilfoil (*Myriophyllum spicatum* L.). Floating mats can be a vector for these species, as well as other plant, algae, or insect species. When other species are transported by floating mats, their dispersal can be altered spatially and temporally. Thus, floating mats can aid the dispersal of other invasive species, in addition to waterhyacinth (Mallison et al. 2001).

Water movement plays a large role in intermediate- and short-distance dispersal for waterhyacinth. In most river systems, water movement is primarily unidirectional, and the propagule pressure is primarily downstream (Heidbüchel and Hussner 2020). In the Delta system, the propagule pressure comes from various directions throughout the daily tide cycle. As the tide meets the mass flow of the rivers, water moves into eddies and side channels, along with floating mats. Although the relationship between the direction of water movement and the direction of mat dispersal presents challenges in the hydrodynamically complex Delta, this relationship could help management in systems with simpler hydrodynamics.

The methods used in this study might prove more useful in other locations where waterhyacinth has become invasive. They could be used to predict where plant mats are likely to drift, as well as to use the drift direction to extrapolate back and find source populations. This method of GPS tracking could also be a useful method for tracking the movement and dispersal of floating mats or floating islands of other species.

The results of this study are a cause for concern for waterhyacinth management in the Delta. The mats were not emanating from a small number of source populations, nor was the direction of spread uniformly downstream, thus making management more difficult. Other than during stormflow events, mats are moving only short distances before entrainment or reversing direction. In the Delta, water movement is the primary driver in the dispersal of waterhyacinth mats. Although the area where this study was conducted is 89 km (55 miles) inland (Figure 1), tidal flows were strong enough to overcome the mass flow of the rivers. The direction of water movement, influenced by both mass flow and tides, had a greater influence on the direction of waterhyacinth mats than the wind direction. These findings should help the CDBW and other stakeholders understand how waterhyacinth spreads around the Delta and adapt management practices.

SOURCES OF MATERIALS

[1]Trackstick Mini and Super Trackstick, Telespatial Systems, Marina Del Ray, CA 90292.

[2] Nalgene, Nalge Nunc International Corp., 75 Panorama Creek Dr., Rochester, NY 14625.

[3]Sportdog TEK 1.0, Radio Systems Corp., 10427 PetSafe Way, Knoxville, TN 37932.

[4]Kestrel 5500 WeatherMeter, Neilsen-Kellerman, 21 Creek Circle, Boothwyn, PA 19061.

[5]Trackstick Manager 3.1.1 Rev. 13, Telespatial Systems, Marina Del Ray, CA 90292.

[6]Google Earth Pro 7.3.2, 2018, 1600 Ampitheatre Parkway, Mountain View, CA 94043.

[7]ESRI 2017, ArcGIS Desktop 10.6 v10.6.0.8321, 380 New York St., Redlands, CA 92373.

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