

The Effectiveness of Mechanical Control of Water Hyacinth (*Eichhornia crassipes*)

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Abstract One of the most invasive species in the world, the water hyacinth (*Eichhornia crassipes*) overruns waterways and ecosystems, causing a number of ecological, physical, and economic problems. Water hyacinth mats decrease water quality by reducing the amount of available sunlight for aquatic organisms, leading to reduced photosynthesis rates and dissolved oxygen levels. Blockage of waterways disrupts boating, fishing, and other water activities. A lawsuit filed against the California Department of Boating and Waterways resulted in restricted use of the herbicide 2,4-D for control. An alternative mechanical method of regulating water hyacinth overgrowth offered a solution to the chemical control lawsuit. Through random sampling in sites within the control and treatment areas, the effect of the AquaTerminator, a shredding machine, on the water quality of the Dow Wetlands Preserve in Antioch, California was observed. Density counts and water quality sampling of nitrate, phosphate, dissolved oxygen, temperature, salinity, and pH were assessed nine times at each site. Water quality analysis indicated a slight decrease in overall water quality, and plant density exhibited more than 50% plant regeneration from water hyacinth fragments. Seasonal variation and tidal fluctuations influenced the study's trends. Tidal fluctuations also pull shredded material out, encouraging further spread of water hyacinth to the connecting San Joaquin River. Comparisons of water quality parameters prior to and following shredding using the BACI method demonstrated the inefficiency of the AquaTerminator as a means of water hyacinth control. This study offers a preliminary understanding of the effects of an alternative in water hyacinth control.

Introduction

Water bodies continue to endure water hyacinth (*Eichhornia crassipes*) invasions globally. The intricate and unique structure of *Eichhornia crassipes* makes it one of the most resilient aquatic plants enabling it to infiltrate major water systems throughout the world (Cohen 1995). The resilient water hyacinth like many invasive non-native species continues to invade waterways and ecosystems throughout the delicate San Francisco Bay Area. The Bay Area is filled with its own array of sensitive native species which can easily be disrupted by the more tolerant insidious non-natives originating from various foreign locales (Toft 2003). Numerous methods of controlling the invasive plant have been developed throughout the world such as biological, mechanical, physical, and chemical treatments (Wade 1990).

Different methods of water hyacinth removal research continue throughout various parts of the world. African governments spend millions of dollars testing various physical (shredding or removal by hand), chemical (herbicidal spray that could potentially affect the surrounding environment), and biological (introducing biological control agents such as weevils or moths for natural removal) means of control (CAB International 2000). None have been extremely successful because of hyacinth's extraordinary persistence in surviving.

Eichhornia crassipes grows at considerable speeds. It floats on the water's surface and grows outwards, extending its stolons to produce a new plant. Flowering is the sexual method of reproduction. The hyacinth is capable of self-fertilizing which makes it even more difficult to control. The seeds produced are viable for 20 years (Julien 2001). The water hyacinth eventually covers the surface of the water body therefore decreasing the amount of light penetration. This, in turn, will decrease algal growth which ultimately decreases the amount of dissolved oxygen available in the water for aquatic fish and other organisms to use (Toft 2003). The harsh conditions create an anoxic environment making it extremely difficult for organisms to survive.

The original strategy for control within the San Francisco Bay/Delta was chemical spraying of 2,4-D herbicide (Gargstad 1986). However the Delta Keepers, a side group of Water Keepers (an environmental non-governmental organization committed to protecting water bodies), filed a lawsuit against the California Department of Boating and Waterways to prohibit the spraying of herbicides on aquatic plants (Carlock 2003). The chemicals used could seep into the San Joaquin River thereby affecting the delicate ecosystem and ultimately the public's health

(Gargstad 1986). As a result, the San Francisco Estuary Institute (SFEI) was hired to organize an experiment for controlling *Eichhornia crassipes* by mechanical means (i.e. shredding the water hyacinth at two sample sites into one to two inch pieces) (Greenfield 2003). This alternative method to chemical spraying could potentially be an innovative substitute for the removal of water hyacinth.

This aquatic plant shredder was evaluated *in situ* at the Dow Wetlands Preserve, a naturally restored wetland habitat located in Antioch, California to determine its effectiveness as a water hyacinth removal method. Water quality analysis and plant density monitoring will assess the beneficial and detrimental effects of this mechanical treatment.

Both water quality testing and plant density counts help determine the success of mechanical removal. Water quality monitors the surrounding change in the aquatic environment. It observes whether the removal of hyacinth will have an effect on specific parameters of water quality. Plant density also effectively measures the occurrence of possible regeneration. By monitoring the plant density, the regeneration or mortality of the plant can be observed (Toft 2003). Either way the plant density will affect the water quality. If the shredding is successful decomposition will occur, or if shredding is not effective water hyacinth can regenerate from the shredded pieces. Water hyacinth is extremely resilient and has the ability to regenerate from broken up pieces with sizes as small as two inches (Penny 2003) of which can cause major damage to waterways.

This study will ascertain if controlling water hyacinth by mechanical shredding is effective. Shredding could possibly be a good control method because it emits fewer pollutants and is easier to perform than manual removal. Shredding water hyacinth, however, may cause more damage for the given water body and the environment around it. After the shredding, plant material will settle to the bottom of the marsh which could lead to increased amounts of detritus. When increased amounts of detritus settles on the marsh bottom, bacteria will use most of the surrounding dissolved oxygen to decompose this detritus and thus cause the occurrence of anoxic environments (Madsen 1997). This anoxic environment could temporarily alter the ecosystem of the aquatic organisms which could be just as detrimental as spraying.

Another concern involves the size of the shredded pieces and the tidal flow of the marsh. If the plants are not shredded into small enough pieces and the root system is still intact, regeneration may occur over a long-term resulting in further hyacinth growth (Wade, 1990). The

water hyacinth is left in the water to decompose on its own, so during the tidal flow many of the chopped-up viable pieces may escape from the marsh and travel up and down the San Joaquin River. This would be extremely harmful to the surrounding environment because it encourages the spread of water hyacinth over an extended period of time.

This research seeks to investigate the effectiveness of mechanical shredding as an alternative treatment for controlling water hyacinth. By monitoring the water quality and plant density parameters, the effectiveness of mechanical removal of water hyacinth with a shredder can be assessed. This study could be particularly helpful for the California Department of Boating and Waterways because it could determine whether mechanical shredding will be an effective alternative to herbicidal spraying of water hyacinth.

Methods

The study took place at the Dow Wetlands Preserve in Antioch, California. One of the four main bodies of water at the preserve, the tidal marsh, is the only water body connected to the San Joaquin River which flows out to the Bay just north of the tidal marsh. Water hyacinth invades the tidal marsh via tidal fluctuations and spreads along the San Joaquin River.

Mechanical shredding occurred for a total of 48 hours along the tidal marsh. A large shredding machine, the Aquaterminator®, chopped the water hyacinth into one to two inch pieces using its blades. The company that manufactured the Aquaterminator® claims that these shredded pieces are not large enough to be considered viable for regeneration (Penny 2003).

In order to assess the beneficial and detrimental effects of the mechanical shredding, sampling was performed before and after the mechanical treatment. Sampling was done once per week at both the Dow Wetlands Preserve tidal marsh and the Antioch Marina pier (Figure 1). The mechanical treatment occurred at the Dow tidal marsh therefore one control and one treatment area was setup for consistent monitoring before and after the shredding (Madsen 1997). The San Joaquin River is accessed at the Antioch Marina which has no substantial evidence of hyacinth invasion. Water from the San Joaquin River flows into the tidal marsh as the Bay tide fluctuates posing as a potential variable for change in water quality. The water quality data collected at the Antioch Marina pier acts as a reference for comparing the water quality within the tidal marsh and the connected San Joaquin River. Samples were taken from the pier at three specific sites.



Figure 1. Aerial view of sampling sites at both the Dow Wetlands Preserve and the Antioch Marina (East). Mechanical shredding occurred at the Preserve's tidal marsh. The San Joaquin River water flows into the tidal marsh with the tidal fluctuations affecting its water quality. The San Joaquin River site was utilized as a reference for possible tidal influence.

At each site, water quality was tested and data on plant density was collected. This data collection was performed at three different locations within a sample area (i.e. control or treatment) at the tidal marsh. Water quality monitors any change in the surrounding experimental environment and determines whether the removal of hyacinth will have an effect on varying parameters testing water quality. Each sample location was sampled three times in order to gather more consistent and accurate data. Six parameters (turbidity, pH, temperature, salinity, electrical conductivity, dissolved oxygen) were monitored by a HORIBA U-10 multimeter which was calibrated every week to ensure accurate data. Phosphate and nitrate were first measured by a HACH water chemistry color wheel kit but were measured by a HACH water chemistry digital DR/820 portable colorimeter later in the experiment.

Plant density was used to monitor plant regeneration or mortality after shredding. Plant density was measured within a hula hoop approximately 0.4 square meters in area. This acted as a constant area marker from which the total amount of root bodies was counted. The total

numbers of root bodies that lay within the hoop were counted and the longest hyacinth measured from bottom of stem to tip of leaf.

Due to restrictions in access to treatment sites, randomized replications of test plots was unfeasible. Instead, the data collected followed the BACI (Before After Control Impact) experimental design where data was taken from the treatment and control sites through a consistent continuum spanning pre and post treatment. BACI represents a practical method of statistical analysis for experimental designs where treatments and plots are less-easily controlled. Rather than having many replicates for treatment and control, a pair of treatment and control can equally be closely monitored for the entire span of the experiment in order to gather substantial data for statistical analysis. The data collected before the treatment is crucial for standardizing any differences between the control and treatment plots even before any impact affects them. As a result, any differences noted post treatment will not be due to the variability between the arrangements of the two sites. The BACI methods accounts for any differences between the two plots due to their placement or environmental factors. For each day's data at the treatment and control site, a difference is calculated between each parameter's values (Stewart-Oaten 1986). This difference is graphed with each water quality parameter over time for a time period from summer (three months prior to shredding) to mid-March (four months after shredding). Trends are visually noted over a period of time to document any changes in water quality and plant density.

The statistical technique used to compare between the control and treatment sites is the t-test for matched pairs. The pair will be the control and treatment data compared for the data sets varying with and without tidal fluctuations. The data is consistent with each test day because variables were the same (i.e. tide, weather) therefore a straight comparison of the data sets over time will not be statistically significant.

Multiple nonlinear regressions were also performed on each parameter to search for possible confounding factors affecting the data. Seasonal variation and tidal fluctuations were considered as key factors influencing the data collected over time.

Results

pH The pH of the treatment and control sites was consistent throughout the entire span of the experiment (average pH=7.27). There was a slight increase of 1.0 in pH by

February/March (Figure 2). There was no significant difference in pH between the pre-treatment and post-treatment data ($p=0.63$). When the data took into account tidal influence (separating tide into outgoing/incoming categories) no significant difference in pH due to shredding was established with the data (incoming $p=0.68$; outgoing $p=0.83$). The data collected at the tidal marsh remained relatively consistent with the San Joaquin River data (San Joaquin average $pH=8.01$). Multiple nonlinear regression for pH regarding seasonal and tidal variation has r^2 values of 0.63 for treatment (seasonal variation (sv) $p=0.025$) and 0.70 for control (sv $p=0.035$).

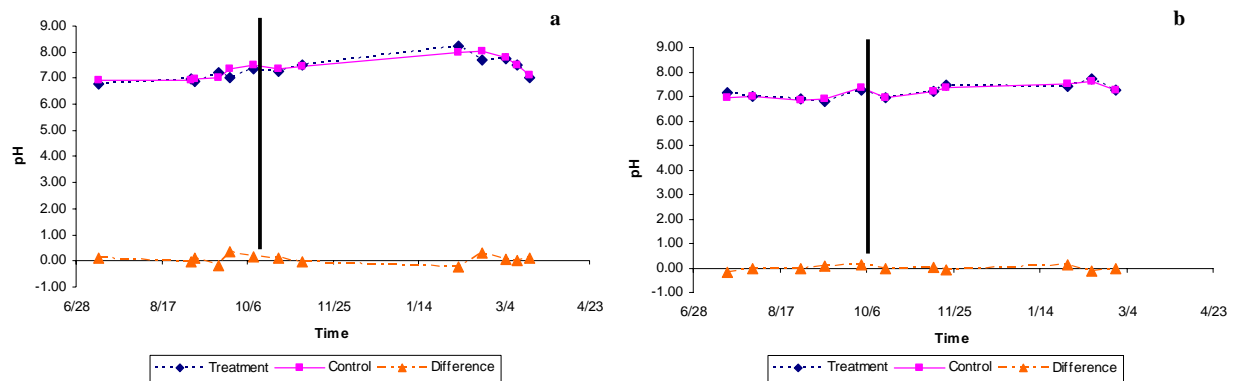


Figure 2. pH values for incoming (a) and outgoing (b) tides in control and treatment sites over time. Difference in pH between control and treatment sites is plotted. Vertical line indicates date of mechanical shredding of hyacinth.

Dissolved Oxygen Dissolved oxygen (DO) data was inconsistent throughout the data collection period. DO measurements were highly variable within each test site and slightly variable between the treatment and control sites. The DO concentration was much less in the tidal marsh (~3-5 mg/L) than in the San Joaquin River (~7-9 mg/L). The mean DO values between control and treatment somewhat varied (average control DO=4.04 mg/L; average treatment DO=3.96 mg/L) (Figure 3a). However no significant difference due to shredding was found (incoming $p=0.34$; outgoing $p=0.4$; overall $p=0.17$). The r^2 values for DO concerning seasonal and tidal fluctuations are 0.54 for control (sv $p=0.09$) and 0.36 for treatment (sv $p=0.24$).

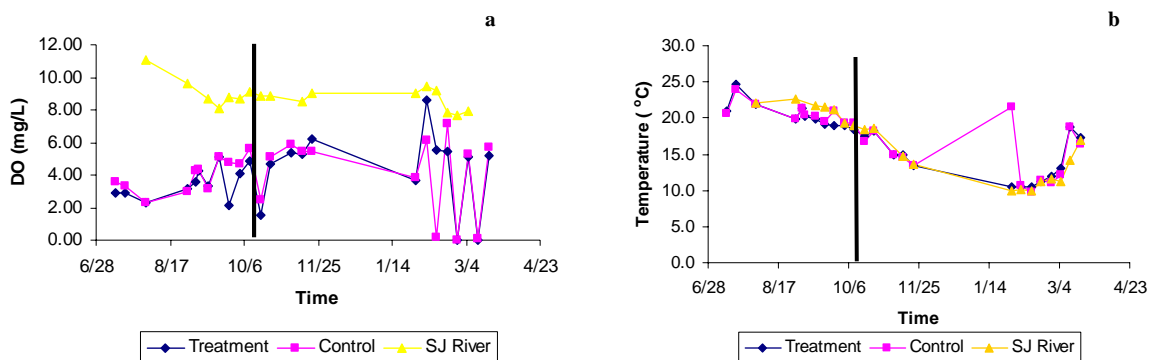


Figure 3. Comparison of dissolved oxygen (a) and temperature (b) measurements between tidal marsh control and treatment sites to the San Joaquin River DO levels. Vertical line indicates date of mechanical shredding of hyacinth for both graphs.

Temperature Temperature did not significantly vary between the treatment and control sites (average treatment temperature=16.7°C; average control temperature=17.4°C). Temperature at both wetland sites was also similar to the San Joaquin River (average SJ River temperature=16.2°C) (Figure 3b). There was a gradual decrease in temperature from November to February and by mid-March the temperature began to increase. On 1/30/2004 the tidal marsh data was collected at different times of the day therefore the tide was extremely low at the time the control site was sampled. No significance was found with the difference between the control and treatment after shredding occurred ($p=0.78$). R^2 values for temperature are 0.86 for treatment (sv $p=0.02$) and 0.64 for control (sv $p=0.02$).

Electrical Conductivity Electrical conductivity (EC) had a distinct trend in the data, steadily increasing from 0.643 mS/cm until a month after the treatment occurred to 4.23 mS/cm, then plummeting considerably to 0.207 mS/cm (Figure 4a). The difference between the control and treatment sites before and after treatment was significant ($p=0.047$) signifying a change occurred due to shredding. The shredding of hyacinth lowered the treatment value by 0.035 mS/cm. R^2 values for EC are 0.83 for treatment and 0.82 for control (all sv $p=0$).

Salinity Salinity had a similar trend like EC where the data gradually increased up to the same time period to 0.21‰ then slowly declined to 0‰ (Figure 4b). There was significance between the differences of the treatment and control sites after the shredding occurred ($p=0.037$). R^2 values for salinity are 0.87 for treatment and 0.86 for control (all sv $p=0$). Figure 5a illustrates the cyclic pattern devised from the regression analysis.

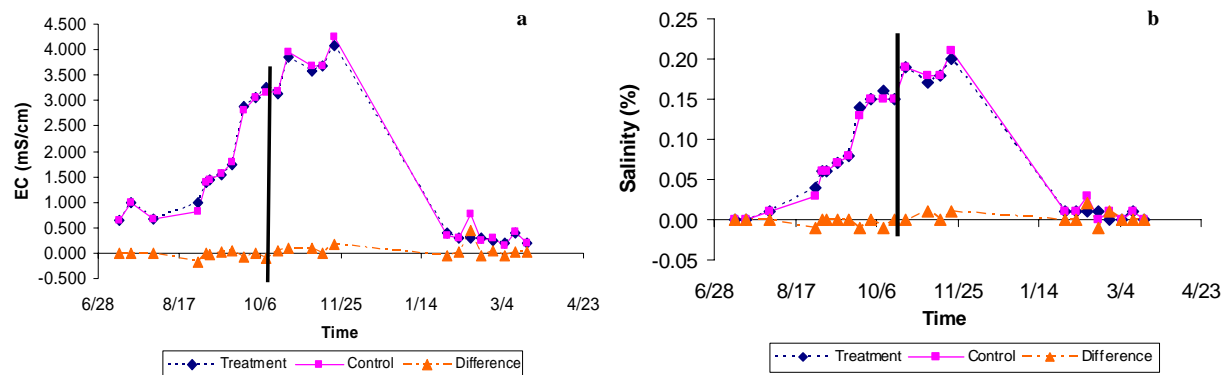


Figure 4. Electrical conductivity (a) and salinity values (b) in treatment and control sites. Differences in electrical conductivity and salinity are plotted. Vertical line represents date of mechanical hyacinth shredding.

Turbidity The data collected for turbidity had no significance ($p=0.73$).

Nitrate Nitrate was generally at low concentrations throughout the entire study (~0-1.5 mg/L). No significant difference was found between the differences in control and treatment post-treatment ($p=0.369$).

Phosphate Phosphate had low concentrations (0-4 mg/L) aside from one outlier at ~6-8 mg/L on 11/21/2003 for both control and treatment sites. A p-value of 0.608 indicated that there was no significant difference between control and treatment after the shredding occurred.

Water Hyacinth Density The data for the density of water hyacinth within each hula-hoop ring illustrated a trend with the decrease in number as time passed into the winter months of November and December (Figure 5). Density began to decrease in late September, before the shredding occurred. The average density count was 73 before treatment and after treatment averaged 39 plants per hula hoop. The water hyacinth had already begun to senesce by the time the shredding took place. The control density count totaled 49 plants per hula hoop. However most of the plant leaves were still green and photosynthetic. After the shredding took place, the pieces were not completely shredded into one to two inches. Many of the basal roots still remained intact which permitted the occurrence of water hyacinth regeneration. In an enclosed area of 20 labeled shredded pieces, only two of the shredded water hyacinth pieces did not regenerate. The difference between the control and treatment sites prior to and after treatment was not significant ($p=0.18$). The r^2 values for water hyacinth density counts are 0.55 for both treatment (sv $p=0.014$) and control (sv $p=0.02$).

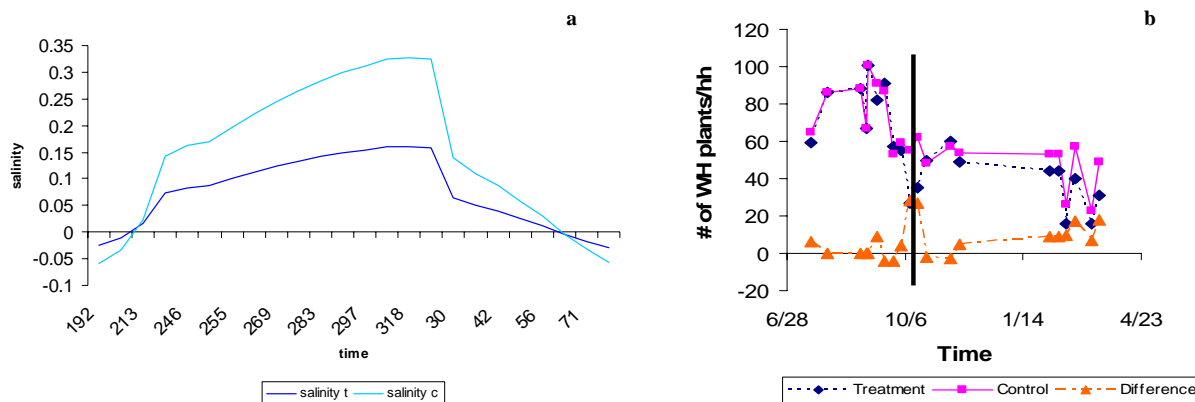


Figure 5. a.) Cyclic depiction of salinity percentages over a period of approximately 365 days. b.) *Eichhornia crassipes* density counts for treatment and control sites. Vertical line indicates time of mechanical shredding.

Discussion

For most of the measured parameters, seasonal effects on water quality and water hyacinth growth were evident. pH remained relatively constant throughout the study period while temperature, electrical conductivity, salinity, and water hyacinth density all illustrated a seasonally-affected data set. *Eichhornia crassipes* density steadily declined as the summer season transitioned into late winter. Regeneration occurred in most of the shredded plants. Dissolved oxygen was comparatively different at the connecting San Joaquin River by almost two-fold. Nitrate and Phosphate were low in most all of the samples. Turbidity had no significance in the data collected due to too many confounding factors.

pH remained consistent for the entire study period. No significant difference was found before and after the treatment between the two test plots at the tidal marsh. This indicates no change occurred in pH from the shredding event between the two test plots.

Temperature was also consistent between the three test sites however there was a declining trend in the data as time progressed from late summer to winter. This is most likely due to a change in seasonal variation: as the air temperature changes from summer to winter temperatures, water will also have a lesser decline in temperature as expressed by the results from the study. The regression analysis clearly shows the weight seasonal variation has on temperature with its p-value of 0.02. Seasonal variation has a significant impact on the data collected for this study.

Electrical conductivity (EC) and salinity had similar trend lines which reflected possible seasonal variation. Statistical significance was also found indicating that change occurred

between the treatment and control sites because of the shredding event. Even before the treatment, the water hyacinth density counts began to decline as EC and salinity levels elevated. After the treatment, the water hyacinth biomass continued to decrease further increasing the EC and salinity levels. A possible explanation for this occurrence is that water is absorbed into the plants. As the hyacinth continues to grow, more water is taken up thereby decreasing the total amount of water in the marsh. This would be a probable reason for the increase in salinity and EC up to the shredding date. Even after the shredding event, the salinity and EC continued to increase until the end of November. This increase can not be explained by the plants' uptake of water because the shredding of the pieces would have killed off most of the water hyacinth. It would be assumed that once the plants have been shredded, the salinity would begin to decrease due to water being restored from the hyacinth back into the marsh. Water could also have evaporated from the shredded hyacinth pieces thus maintaining the higher salinity content in the water body. However the change in season is the primary factor affecting the salinity and EC of the water in the marsh as shown with the p-value of 0 with the nonlinear regression analysis.

The water hyacinth density counts generally decreased with time. The density began to decline even before shredding thereby expressing possible seasonal variation with p-values well below the 95% confidence level. As air and water temperature began to decrease *Eichhornia crassipes* began to decrease in density due to their natural life cycle (Julien 2001). Water hyacinth usually senesce and die back during the winter and redevelop and germinate their seeds in late spring. The density count results varied due to the continuous flow of the tide and the inconsistency between data collectors. Tidal fluctuations would pull and push the water hyacinth around so the mats would either be spread apart or densely compacted against one another. This was the major cause of inconsistent results. Also the method of counting was not accurately standardized for the different people counting the plant densities during the experiment.

Salinity/EC and water hyacinth density have a crucial relationship. It is evident that once the shredding occurred the hyacinth was unable to grow back to its original density partially due to the higher salinity concentration of the water. This is a key concept which defines the effectiveness of the shredding process. Timing the shredding of the hyacinth to a period when the salinity concentration is high can aid in a more successful control method. Salinity is affected seasonally and has a cyclic pattern over the period of one year (Figure 5a). This cyclic pattern can be seen with most parameters affected by seasonal variation such as temperature,

water hyacinth density, and electrical conductivity. Salinity, electrical conductivity, and water hyacinth density were the main parameters that were affected by the shredding. The other parameters showed no significant difference and were mostly influenced by ulterior variables.

Dissolved oxygen values had increasing variability with time. The data collected at the tidal marsh were two times less than the results from the San Joaquin River. Even within the tidal marsh, control and treatment values had variability. When the data was filtered taking tidal influence into account, there was no significant difference between the two sites before and after the shredding occurred. It is also important to note that the data was not collected at a specific time or tidal level each week.

The data for nitrate and phosphate are inconsistent because of the change in equipment half way through the study. At the start of the project nitrate and phosphate were measured with the crude HACH colorimetric wheels which only evaluated whole number values visually. However, a few weeks after the treatment occurred, new digital HACH colorimeters were bought and utilized which gave more accurate values with spectroscopy technology. The values for both the nitrate and phosphate parameters had a small range so more exact measurements would have generated a more accurate data set.

On occasion the phosphate value would read an extremely high value. This was most likely due to contamination of the sample from otter scat found near the sampling sites. Phosphate is a main component found in animal waste and therefore can easily contaminate a water sample if found nearby.

The data collected for turbidity was inconsistent due to the lack of systematic precision. Individuals each have their own respective technique for collecting data. The substrate might have been churned up while the probe was being inserted into the water column thus altering the data for turbidity.

Many variables exist which potentially alter the data observed in the results. Such variables such as tidal fluctuation, seasonal change in the water quality, water hyacinth development, and nutrient load have an affect on the results of the experiment. Tidal fluctuations from the San Joaquin River played an integral role in the results from the experiment. Incoming and outgoing tides as well as high and low tides varied the data collected for each day. This was a difficult factor to control because tidal times change everyday which inhibits the feasibility of sampling for this thesis project. The best method of control was to

record the tide and times for each day of sampling and account for the differences during the analysis of the data. Seasonal change in water quality was also a confounding factor for the data collected. This variable would be difficult to control for unless data was collected for an entire year before and after the treatment occurred. Additionally the life cycle of the water hyacinth lasts for a year. Control of this factor would also be to record data a year prior to and after the shredding occurred. Also the preserve is located next to a wastewater treatment plant. This could allow for excess phosphate and nitrate to flow in with the tide, further nourishing the water hyacinth. The sampling area of the study was extremely large making it extremely difficult to control for each of these factors.

Nonlinear multiple regression analysis of the seasonal variation and tidal fluctuations helped determine the extent of influence these two variables had on the data. Seasonal variation was a main factor in water hyacinth density, temperature, salinity, and electrical conductivity. Tidal fluctuations were an important influence on dissolved oxygen. Nitrate and phosphate were not affected by either of these factors. Nutrient load from the nearby wastewater treatment would be the most likely confounding factor for its insignificant difference in shredding.

This mechanical shredding of water hyacinth is a cutting-edge alternative to the traditional chemical method of herbicidal control. The use of 2,4-D herbicide on controlling *Eichhornia crassipes* has generated much publicity with concerned environmentalists, public health activists, and the local government (Carlock 2003). By pursuing an innovative mechanical method of control, people will be more aware of the implications involved in chemical use and look to improving mechanical technology as a means of physically removing the invasive water hyacinth.

There are many aspects of improvement for this study. It can be enhanced and more effective by creating a longer study term before and after (at least a year) the shredding treatment occurs. This would yield data that better represents the seasonal cycle and water hyacinth growth patterns for the year. From this approach seasonal variation and water hyacinth life development will be addressed within the study allowing for more consistent data that would focus more on the actual shredding event.

Another crucial factor with a follow-up study is the actual timing of the shredding event. Optimal shredding produces the most effective results when shredding occurs during the pre-rainy season when the water hyacinth is still “restricted to smaller areas” of the water body

(Wade 1990). The timing of the shredding event is essential in determining the effectiveness of the treatment on both a short-term and long-term time scale. On a short-term time period shredding early will be more efficient because entanglements and dense mat barriers will be minimized. Pieces can then be shredded completely to one to two inches which may prevent regeneration from occurring. In the long-run shredding earlier in the water hyacinth's development will hinder it from flowering and creating a hardy seed bank which can last up to ten years in the sediment (Julien 2001).

Eichhornia crassipes is a resilient species well-adapted to almost any environment in the world. It possesses an assortment of defenses for surviving and dominating an aquatic ecosystem. Many methods of control already exist to help minimize its spread however no one technique is truly effective. Therefore it is vital to develop an effective strategy may it be devising the ultimate shredder machine and applying it at the right seasonal time with perfect salinity concentrations or combining biological, chemical, and mechanical tactics to hinder its invasion into the pristine ecosystems of the San Francisco Bay Area and throughout the world.

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