Article

Impacts of Water Hyacinth Treatment on Water Quality in a Tidal Estuarine Environment

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Abstract: Water hyacinth is a major invasive species that has modified ecosystem functioning in the Sacramento-San Joaquin Delta (hereafter, Delta). Studies in lakes and rivers have shown that water hyacinth can alter water quality. In tidal systems, such as the Delta, water moves back and forth through the water hyacinth patch so water quality directly outside the patch in either direction is likely to be directly influenced by the patch. In this study, we asked whether the presence or treatment of water hyacinth with herbicides resulted in changes in water quality in this tidal freshwater system. We combined existing datasets that were originally collected for permit compliance and for long-term regional monitoring into a dataset that we analyzed with a before-after control-impact (BACI) framework. This approach allowed us to describe the effects of presence as well as treatment of water hyacinth, while accounting for seasonal patterns in water quality. We focused on temperature, dissolved oxygen, and turbidity because these water quality parameters have been shown to be important drivers in the distribution of fish species of management concern. We found that although effects of treatment were not detectable when compared with water immediately upstream, dissolved oxygen and turbidity became more similar to regional water quality averages after treatment. Temperature became less similar to the regional average after treatment, but the magnitude of the change was small. Taken together, these results suggest that tidal hydrology exports the effects of water hyacinth upstream as well as downstream, creating a buffer of altered water chemistry around patches. It also suggests that although water hyacinth has an effect on dissolved oxygen and turbidity, these parameters recover to regional averages after treatment.

Keywords: water quality; invasive species; water hyacinth; estuaries; temperature; dissolved oxygen; turbidity; herbicide

1. Introduction

Invasive aquatic vegetation can change ecosystem functions such as physical structure, community composition, biogeochemical cycling, and hydrology [1, 2]. For example, submerged aquatic vegetation alters sediment dynamics, making turbid water clearer [3]. Invasive aquatic weeds reduce water velocity substantially [4], impact water quality [5, 6, 7], and provide habitat for non-native fish predators [8]. Because of these changes and because invasive aquatic vegetation impedes boat navigation and operation of water infrastructure, steps are often taken to manage these invasive species impacts and their spread. Control of invasive aquatic vegetation costs an estimated $100 million per year in the United States [9], and additional costs accrue through the loss of economically important activities such as shipping and recreation.

Water hyacinth, *Eichhornia crassipes* (Mart.) Solms, is a particularly problematic invader. It is a floating perennial aquatic plant that most often colonizes freshwater aquatic habitats with low flow. It is native to Brazil, but it has invaded 50 countries and five continents [10]. Water hyacinth is one of the fastest growing macrophytes in the world [11] and it can profoundly change the ecosystems that it invades [12]. Water hyacinth reproduces extremely quickly by producing daughter plants on stolons; 10 plants can produce a mat of 650,000 plants in one growing season [12]. This rapid growth, coupled with its ability to spread over the surface of a water body, degrades water quality by altering physical, biological, and/or chemical processes.

Studies have shown that water hyacinth can alter water quality, but most of the studies that have examined its impacts on temperature, dissolved oxygen, and turbidity have done so in lakes or small flowing rivers. A tidal environment presents a type of hydrology that is different from either of these types of systems. It is unclear how the impact of water hyacinth would differ in a system with bi-directional tidal hydrology because there are few studies on the impacts of water hyacinth in tidal systems. In systems with standing water, such as lakes and ponds, water hyacinth reduces variability in temperature [14, 15], and these effects are most pronounced with very large, dense patches of water hyacinth in standing water [12, 16] Similarly, reductions of dissolved oxygen may vary spatially, depending on hydrology. In river systems where water flows through large patches of water hyacinth, the water downstream becomes depleted of dissolved oxygen [16,17]. A study of dissolved oxygen in and around water hyacinth patches in the San Francisco Estuary (SFE) found that dissolved oxygen is reduced in areas with water hyacinth, relative to areas of open water [18]. Hydrology also plays a role in turbidity. Increased flow has been associated with reduced turbidity in laboratory tests with floating aquatic plants [19] and in a reservoir, areas with water hyacinth had higher turbidity than sites without water hyacinth [19]. In tidal systems water moves back and forth through the patch so water quality directly outside the patch in either direction is likely to be directly influenced by the patch.

In this study, we asked whether the presence of water hyacinth or the treatment of water hyacinth with herbicides resulted in changes in water quality in a tidal freshwater system. This study also explores the question of whether changes in water quality that result from treatment of water hyacinth are detectable at different spatial scales. We focused on temperature, dissolved oxygen, and turbidity because these water quality parameters have been shown to be important drivers in the distribution of various fish species of high management interest in the SFE (e.g., 21, 22). We specifically asked (1) whether water quality parameters measured in water hyacinth patches differed from nearby open water and (2) whether the area that is influenced by water hyacinth patches differed from regional water quality patterns. We combined existing datasets that were originally collected for permit compliance and for long-term regional monitoring into a dataset that we can analyze under a before-after control-impact (BACI) framework. This approach allowed us to look at the effects of presence as well as treatment, while accounting for seasonal patterns in water quality that occurred over the course of the study.

We conducted this study in the Sacramento-San Joaquin Delta, where water hyacinth is a major invasive species that has modified ecosystem functioning and vegetation community dynamics [23]. The Sacramento-San Joaquin Delta (hereafter, Delta) is a highly managed and socio-economically important system. It is the source of drinking water for over 25 million people and irrigation water for 750,000 acres of farmland that supports international agribusiness [24]. In this system, water management must balance the needs of societal demand for water with the protection of endangered species; therefore the ecological health of the system is critical to management of water infrastructure that provides water to people. Although water hyacinth was introduced in 1904, in recent years the impacts on the Delta have been increasing. The extent of floating aquatic vegetation increased from 800 acres in 2004 to over 6400 acres in 2014 [25], making control efforts crucial to maintaining the socio-economic and ecological functions of the system.

The California State Parks Division of Boating and Waterways (CDBW) was first charged with controlling water hyacinth in 1982 (California Senate Bill 1344, Garamendi and Nielsen). The goal of the control program is to control invasive plant cover that harms the State's economy, navigation, or public health [26]. The control plan leverages a suite of control tools, mainly consisting of chemical treatment with some mechanical removal [27]. The program prioritizes treatment of areas that serve as nurseries for water hyacinth as well as areas where it negatively impacts safety, water infrastructure, or boat navigation. In this study, we used water quality data collected by CDBW as part of routine monitoring for herbicide application sites.

The results of this study show that water quality around water hyacinth patches is similar to water quality within the patch in a tidal estuarine environment, probably because of daily water movement in and out of the patch. However, when using a regional baseline for analysis, it is apparent that water quality at the local scale of water hyacinth patches is changed after herbicide treatment. In addition to the direct implications for water management the Sacramento-San Joaquin Delta, these results are also generalizable to estuaries worldwide because of the cosmopolitan distribution of water hyacinth.

2. Results

At the patch scale, there was no evidence that differences in any of the three water quality parameters were driven by the treatment of water hyacinth (i.e., the location X time component was not significant; **Table 1**). The fit of the model for effects of time and location on temperature was similar to that of the intercept-only model, but the models for dissolved oxygen and turbidity were better than the intercept-only model (**Table 1**). There was no evidence that treatment with herbicides affects either dissolved oxygen or turbidity (location x time), but dissolved oxygen concentration was higher on average at both locations after treatment than before treatment. Additionally, turbidity was lower inside the patch than outside after treatment (**Figure 1**).

Table 1: Model fit information and p-values for a BACI test of water quality parameters. The BACI test was a two-way ANOVA where the fixed groups were location and time, with a random effect for sites to account for repeated measurements at the same sites. Location indicates inside or outside the vegetation patch. Time indicates before or after treatment of the patch with herbicides. Model significance shows the results of a likelihood ratio test of fixed effects portion of the model against a null (intercept-only) model with an identical random component. P-values for individual fixed effects are marginal p-values (fitted last; type 3). Models were fit using all available data (all regions).

		Temperature	Dissolved Oxygen	Turbidity
Model Significance	Likelihood Ratio	0.80	24.8	12.2
	p-value	0.85	< 0.01	0.01
Marginal P-Values for Fixed Effects	Intercept	< 0.01	< 0.01	< 0.01
	Location	0.94	0.14	< 0.01
	Time	0.50	< 0.01	0.13
	Location x Time	0.92	0.19	0.05

When using a regional mean as the baseline for comparing water quality before and after treatment, changes in water quality after treating water hyacinth are more apparent at our treatment sites than when we used a local baseline for comparison. Differences in water quality values at the treatment site were significantly different before and after treatment for temperature and dissolved oxygen, but not for turbidity (i.e., comparing anomalies at a site before and after treatment; temperature: $D = 8.69$, $p < 0.01$; dissolved oxygen: $D = 5.058$, $p = 0.02$; turbidity: $D = 2.98$, $p = 0.08$).

Using marginal estimates of means to determine the expected values of water quality parameters, regardless of site, the difference between the treatment area and the regional baseline (i.e., the anomaly value) increased after treatment for both water temperature and dissolved oxygen (**Figure 2**). Temperature measurements were similar to the regional average before treatment, but were higher than the regional average after treatment (**Figure 2 a**). Dissolved oxygen was lower than the regional average before treatment, but became similar to the regional average after treatment (**Figure 2 b**). Turbidity was higher than the regional average before treatment, but became similar to the regional average after treatment (**Figure 2 c**). It should be noted that the confidence intervals for the marginal estimates are wider than the confidence intervals for the site-specific before-after results given above because they do not account for the repeated measures on each site; hence visually comparing means based on the confidence intervals in **Figure 2** does not produce the same results and would be inappropriate.
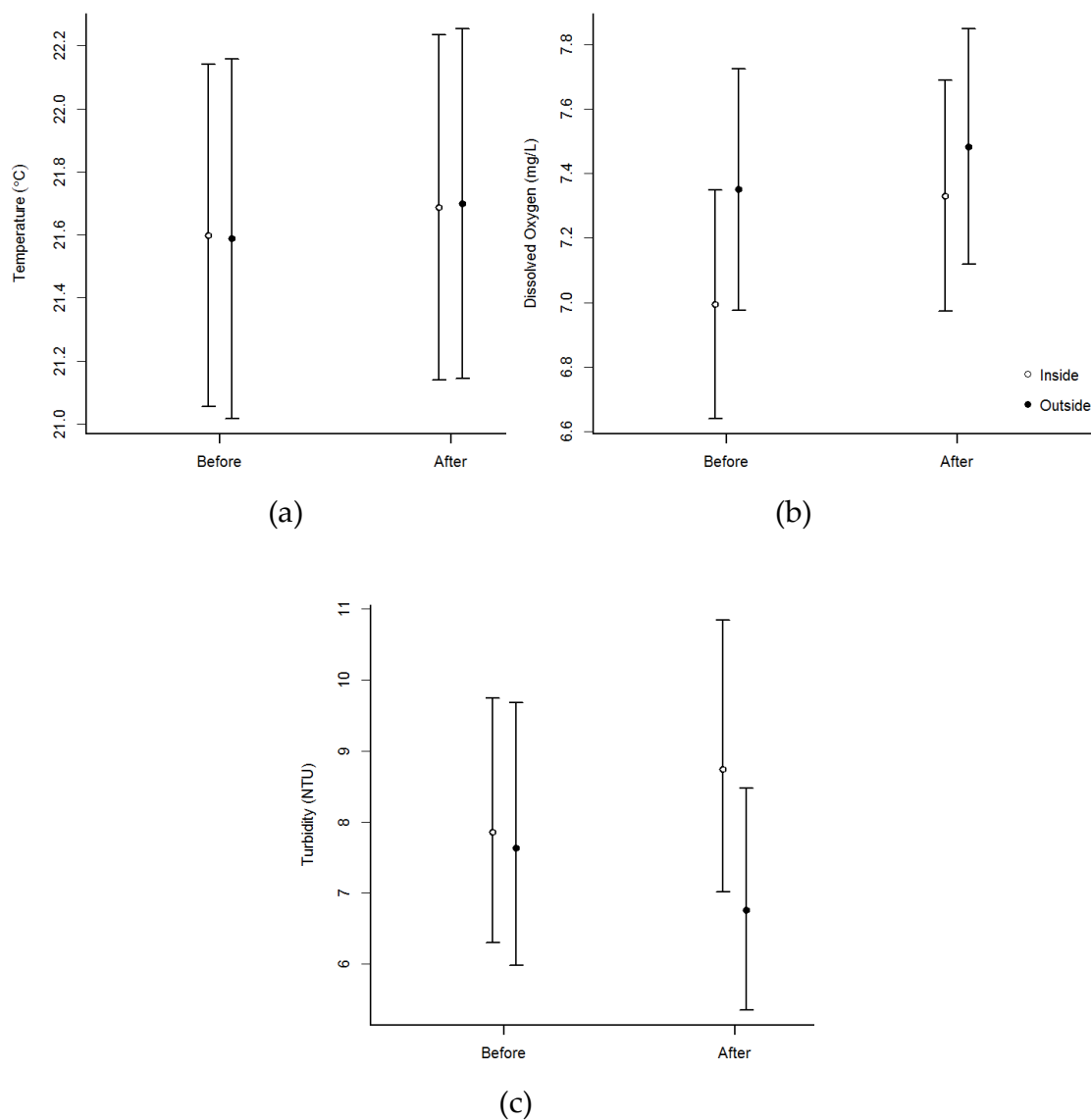
Figure 1: Marginal estimates of means (with 95% confidence intervals of (a) temperature, (b) dissolved oxygen, and (c) turbidity before and after treatment with herbicides at locations inside and outside the patch. (See Figure 1 for a diagram of sampling locations)
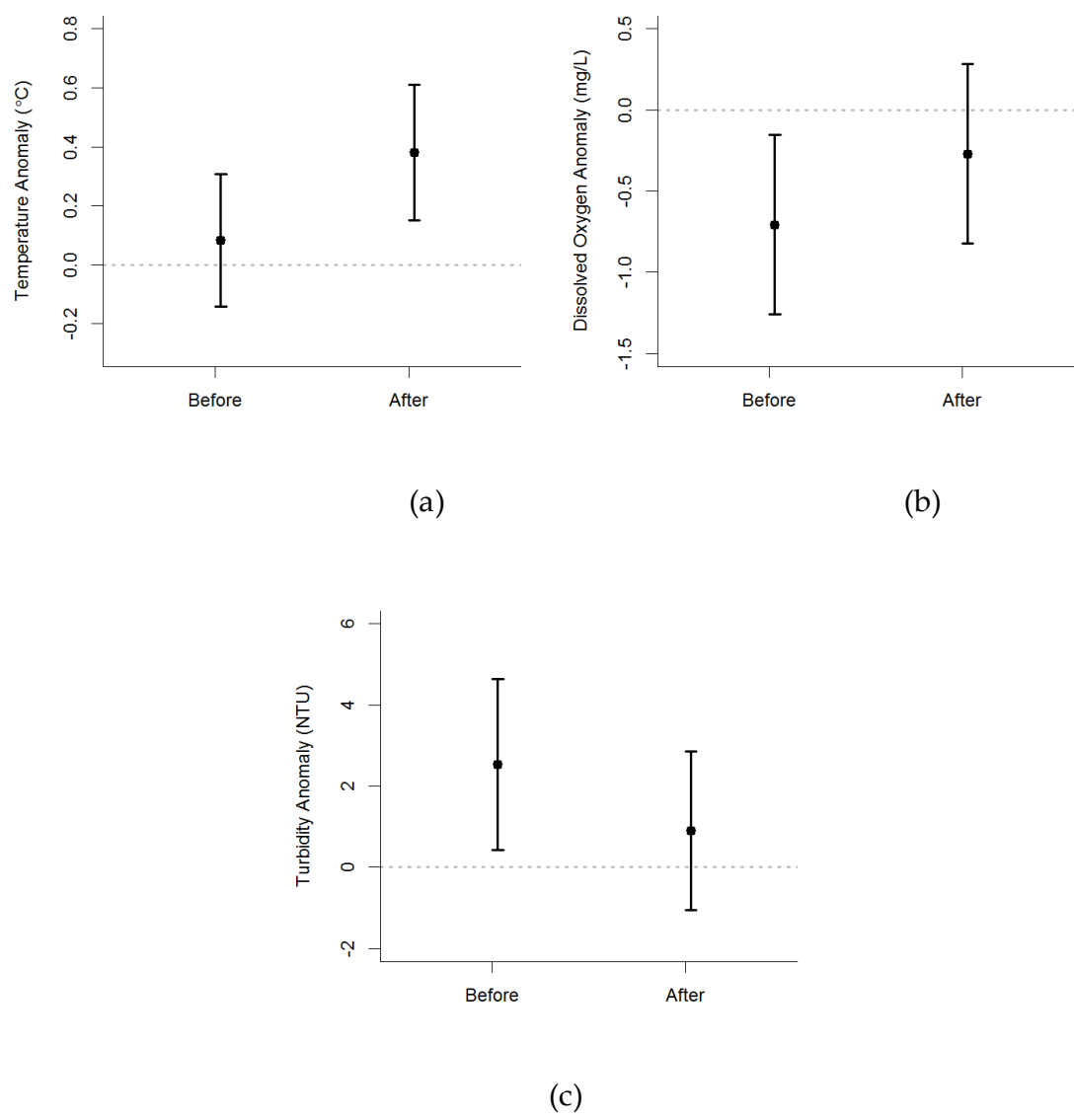
(a)

(b)

(c)

Figure 2: Marginal estimates of anomalies (means and 95% confidence intervals, calculated by LS Means; R function ref.grid in package lsmeans) for a) temperature, b) dissolved oxygen, and c) turbidity. Marginal estimates are the average response expected, regardless of site identity. The dashed line represents the regional average.

3. Discussion

The results of this study show that in a tidal system, the effects of water hyacinth are not confined to the area of the patch itself, but rather are evident in a wider area of the channel around a patch, including the area upstream of the patch. Effects of the presence and treatment of hyacinth on water quality may not be discernable at a local scale because the water chemistry inside a patch of water hyacinth and adjacent to it are similar, even when the baseline for comparison is upstream of the patch. This is likely because of the tidal hydrology in the Delta [13]. Water moves upstream and downstream, both exporting the effects of water hyacinth outside the patch and diluting the impacts of water quality within the patch with outside water. When compared with a regional baseline, rather than a local one, the effects of presence and treatment of water hyacinth are clearer. Taken together, these results suggest that tidal hydrology exports the effects of water hyacinth upstream as well as downstream, creating a buffer of altered water chemistry around patches.

On a local scale, this study found no significant difference between temperature of water inside the water hyacinth patch and outside and no effect of treatment on water temperature. Previous studies have shown that water hyacinth primarily affects water temperature by reducing variability in the vicinity of the patch [14, 15], rather than increasing or decreasing temperatures in a single direction. The presence of water hyacinth can affect water temperature through two physical mechanisms: 1) it slows water movement [12], which may increase temperature by increasing residence time, and conversely, 2) it intercepts solar radiation shading the water column, which may decrease temperatures. When compared with the regional baseline, temperatures were slightly higher than the regional baseline after treatment. This shift, although statistically significant, was small (approximately 0.3°C).

Effects of treatment on dissolved oxygen were not detectable when compared with water immediately upstream, but dissolved oxygen and turbidity became more similar to regional water quality averages after treatment. The patterns that we observed in dissolved oxygen and turbidity suggest that rapid growth and production of detritus is the mechanism through which water hyacinth impacts both dissolved oxygen and turbidity. Because water hyacinth grows so rapidly, the mats constantly produce detritus, which decomposes and increases oxygen demand in the water column [8]. When water is stationary, detritus that falls from water hyacinth remains under the patch. This contributes to lower dissolved oxygen and higher turbidity that has been documented under water hyacinth patches in lakes and ponds [14, 19]. In areas where water hyacinth mats are dense enough to form peat at the surface, the decreases in dissolved oxygen are more pronounced [12]. When water flows through large patches of water hyacinth, the water downstream has depleted dissolved oxygen [16]. In river systems where multiple mats of water hyacinth occupy a channel, dissolved oxygen content of the water gradually decreases moving downstream [17]. In the SFE, water hyacinth has been shown to reduce dissolved oxygen levels in places with tidal exchange [38].

Dissolved oxygen increased in the area around the patch as well as within the patch after treatment, relative to the regional baseline. The rate of recovery for dissolved oxygen depends on the velocity of the water in the channel, with dissolved oxygen rebounding within two weeks for flowing water and over two months for static water in lakes [16]. After accounting for regional patterns in dissolved oxygen, post-treatment values were higher than pre-treatment values. Since the dissolved oxygen numbers increased towards the regional average, there is evidence that the water hyacinth patches were negatively impacting dissolved oxygen values and that removing the water hyacinth caused dissolved oxygen to rebound to levels that are closer to the regional average.

For the locations we studied, the effect of water hyacinth on turbidity was similar to that found in ponds. In places with flowing hydrology, once established in low-flow areas, dense floating mats of water hyacinth further reduce flow [12], engineering a more pond-like environment that favors additional spread of water hyacinth. The higher turbidity values inside the patch relative to the local baseline supports the

interpretation that shedding of detritus is the driver of turbidity differences. Similar results were found in a reservoir in Zimbabwe, where sites with water hyacinth had higher suspended solids and shallower Secchi depth than sites without water hyacinth [19]. The net effect of water hyacinth on turbidity may depend on the prevailing turbidity of the system as well as the hydrology. In laboratory experiments with high turbidity waters (130-250 NTU), water hyacinth served as a net turbidity sink [19]. Although detritus production by water hyacinth patches contributes suspended solids to the water column, water hyacinth roots also contributed to settling of turbidity from external sources by slowing water flow and dropping sediment [19]. Turbidity levels observed in our study were low, but during freshwater flushing events turbidity levels in the Delta can be similar to those in Zimmels et al. [19, 39]; however, high flows would also likely dislodge and break up water hyacinth mats. This suggests that if turbidity from external sources was much greater than the turbidity generated by the detritus produced by water hyacinth plants, water hyacinth could become a net sink for suspended sediment in high turbidity areas of the Delta, but additional research would be needed in this area.

This study could have benefitted from direct data on whether water hyacinth was present after treatment. This study does not include efficacy data because efficacy data were not available with the water quality data collected for the herbicide permit. We assume that vegetation treated with herbicides showed some reduction in cover and/or biomass and that there is some tissue death and anecdotal evidence from CDBW staff supports this assumption. Increases in dissolved oxygen in the post-treatment period, at the regional scale, are consistent with effective removal of water hyacinth plants. If the herbicide has not completely eliminated a mat, the continuing presence of water hyacinth might weaken the results of this study. Also, taking measurements a longer time after herbicide application might have shown stronger effects on water quality because the herbicide would have had a longer time to eliminate the mat. Future studies could improve upon this design by increasing the frequency of data collection as well as the duration of the study, perhaps by installing water quality sondes. Future studies should also include data collection on signs of the efficacy of the herbicide treatment. In particular, it would be useful to record the presence of yellowing to indicate slowed growth and whether the mat persisted at the site when water quality data were collected.

Treatment leading to the removal of water hyacinth may return habitat and water quality values to their pre-infestation state. In our study, dissolved oxygen and turbidity became more similar to regional averages after treatment. Similarly, in severely impacted waterways of the Burdekin river floodplain of Australia, mechanical removal of dense water hyacinth mats significantly increased dissolved oxygen saturation [17]. Also in the Burdekin River, native fish became more abundant and water quality returned to un-invaded levels within 12 months following mechanical removal of aquatic weeds [17, 40]. Future studies are needed to determine the impacts of water hyacinth presence and removal on fish assemblages in the SFE.

4. Materials and Methods

4.1. Study System

The San Francisco Estuary is located in Northern California and comprises the San Francisco Bay (Bay) and the Sacramento-San Joaquin Delta. Two rivers, the Sacramento and San Joaquin, are the primary contributors of water to the SFE. Downstream of the confluence of these two rivers, fresh water flows west and becomes more saline as it moves through the Bay toward the Pacific Ocean. Upstream of the confluence is the area known as the Delta and this is the area where our study took place. Much of this area was once wetland and riparian areas, but now consists largely of channels separating islands that have been

converted to agriculture or urban areas.   Freshwater flows in the SFE are highly managed to maintain low salinity in the Delta, based on standards set by the State Water Resources Control Board, and to provide water deliveries to the State Water Project and Central Valley Project.   As a result, the area upstream of where these major rivers intersect forms a freshwater region in which tides influence water movement, but salinity is consistently fresh. The Delta spans roughly from the city of Sacramento in the North to Tracy in the South (Figure 3), and the watershed that drains into it comprises 40% of California's area [28]. The region has a Mediterranean climate, with cool, wet winters and warm, dry summers.

Figure 3: Map of locations of treated patches used for the BACI analysis.
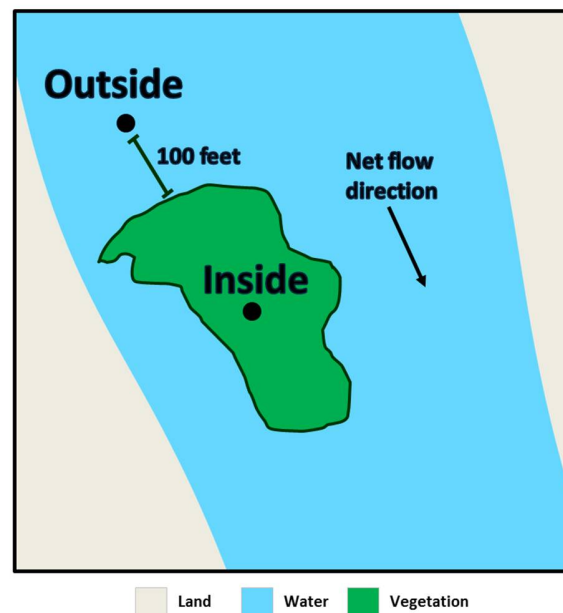
4.2. Field Collection of Water Quality

Figure 4: Diagram of sampling locations relative to a treated patch of vegetation, modified from [29].

To address our questions regarding changes in water quality as a result of water hyacinth treatment, we leveraged two existing water quality datasets: (1) discrete data collected at treatment sites by CDBW; and (2) high-frequency (every 15 min) water quality data collected by the California Department of Water Resources (CDWR) at a series of locations near selected treatment sites.

As part of the National Pollutant Discharge Elimination System (NPDES) permit for discharge of herbicide for aquatic weed control (No. CAG990005, Water Quality Order 2013-0002-DWQ), CDBW monitors water quality in and around the water hyacinth patches that are treated. Water quality is measured at two locations in and around the patch of vegetation (Figure 4). Sample sites are located inside of the treated patch of vegetation and in an adjacent non-impacted area with similar hydrological conditions as the treated patch, 100 feet upstream of the treatment area [29, 30]. CDBW also takes a sample 25 feet downstream of the patch in some cases, but we did not use the downstream measurements in this analysis because it was collected less frequently than other locations. The areas included in this study are tidally influenced so upstream and downstream directions are relative to net flow and may not indicate the direction of water flow at all times. CDBW separates the Delta into smaller regions, and treatment areas are chosen within those regions (Figure 3). The area CDBW treated for water hyacinth each year varied from 421 to 4447 acres. The acreage treated depends on several factors, including the magnitude of the infestation, regulatory restrictions, weather, and staffing levels [31].   Water hyacinth can be treated between March 1 and November 30, but the timing of applications depends on the region [29]. The herbicides used include Glyphosate, 2,4-D, and, in rare cases, Imazamox, depending on the year and location of the water hyacinth plants. The adjuvants Agridex and Competitor have also been included in the control plan. Sites that are infested with water hyacinth may be treated up to six times during a season.
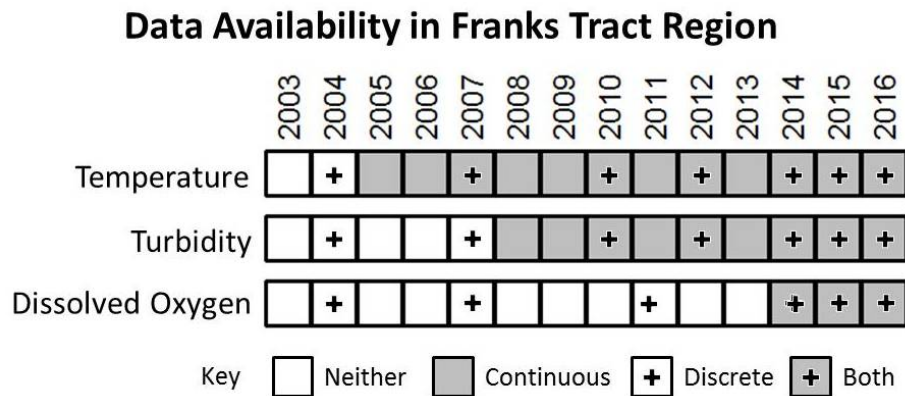
Data Availability in Franks Tract Region

Figure 5: Availability of temperature, turbidity, and dissolved oxygen datasets for the Franks Tract region by year. Analysis was done for years where both continuous and discrete data were available.

Water quality parameters including temperature, dissolved oxygen, and turbidity were measured immediately before herbicides were applied and once approximately one week after application. Water quality measurements were taken at a depth of three feet using a Hydrolab® Model MS5 mini datasonde. The purpose of water quality monitoring sampling is to ensure that changes in water quality do not exceed limits described in the Central Valley Basin Plan and those required by the NPDES permit. No data were provided on the effectiveness of herbicide treatment on removing water hyacinth; however, CDBW reports that symptoms of herbicide effectiveness, including death of water hyacinth plants were observed from all treatments [31]. Additional details about methods, rationale, and reporting requirements are available in the CDBW reports and permit documentation on the CDBW website (www.dbw.ca.gov).

Continuous water quality monitoring stations in the Franks Tract region with appropriate sensors were identified using metadata available on the California Data Exchange Center (CDEC; cdec.water.ca.gov). These stations collect water quality information in 15-minute intervals. The stations identified as being in the Franks Tract region and having appropriate sensors were FRK, BET, HOL, ORQ, and OSJ (**Figure 3**). These stations are maintained by CDWR. Data are available for direct download on CDEC, but these data have not undergone QA/QC so we requested datasets directly from the agencies that maintain the stations.

We used the data from continuous water quality recorders to calculate regional water quality averages. The purpose of this calculation was to define how water quality conditions changed in the region overall during the treatment period. This is particularly important for water quality parameters that are strongly seasonal such as temperature. Without a baseline for comparison, we might erroneously attribute changes in water quality to the treatment that were actually simply caused by seasonal water quality patterns. To calculate the regional water quality averages, the 15-minute intervals for each water quality parameter were summarized by date and hour for each station. For example, the hourly average for 08:00 was calculated as the arithmetic mean of the measurements taken at 08:00, 08:15, 08:30, and 08:45 on a particular date. After hourly means were calculated for individual stations, the hourly means were averaged across stations to produce an hourly regional average for that date. Means included measurements only for the morning and early afternoon (08:00 to 15:00) because this was the time of day when water samples were generally taken. The final dataset of regional averages contained a mean value for each water quality parameter for each hour and day combination as well as a standard deviation for that value and the number of stations that comprise the mean.

4.3. Data Analysis

We examined the effect of treatment of water hyacinth on water quality at two spatial scales. First, compared the effects of treatment on a local, or treatment area, scale. This approach looked at differences in water quality before and after treatment at locations inside and upstream of patches of water hyacinth. The local scale analysis used only data collected by CDBW for the NPDES permit. No differences were found between water quality inside and outside the patches, likely because either the treatment did not affect water quality or the spatial scale of the effect was wider than the distance between the samples. To tease out the cause, we also looked at the effects of treatment relative to region-wide measurements of water quality. To do this, we pooled observations in and around water hyacinth patches and compared them to regional water quality averages from an independent dataset. All statistical comparisons were made using R [33]. We used 0.05 as the cutoff value for significance in our tests, but we report p values so readers can make their own determinations of significance.

The design of the NPDES monitoring created pairs of impacted (sprayed) and upstream control (unvegetated, not sprayed) sampling locations. We leveraged this sampling design to assess the effect of water hyacinth treatment on water quality at the patch scale. Specifically, we used a Generalized Linear Mixed Model (GLMM), and used a Before-After Control-Impact design [34]. The BACI design was developed to detect environmental disturbance by comparing measurements inside and outside the impacted area, both before and after a disturbance event occurs. In our study, instead of a disturbance, the event was applying herbicide treatment to water hyacinth. The GLMM that we used is equivalent to a two-way ANOVA that includes the main effects, location (inside, outside; Figure 4) and time (before, after), and their interaction. In a BACI model, the test for a significant effect of herbicide treatment is the interaction between location and time. The ANOVA also included a random effect for site nested within year to pair samples on the same site within a treatment season. We fit a separate model for each water quality parameter (temperature, dissolved oxygen, and turbidity; function lmer, package lme4) [35]. A likelihood ratio test determined whether the models were significantly better than a null model consisting of only an intercept and the random component (function anova in package stats) [33]. For models that fit better than the null, we investigated whether there were significant differences in the location (function lmer in package lmerTest version; anova) [33, 36].

To address the question of regional changes in water quality as a result of treatment, we used the concept of an anomaly by comparing the CDBW discrete data and baseline data from the regional water quality averages calculated from high-frequency data. Water quality anomalies are calculated by subtracting the regional average from the measurement taken at the treatment site (anomaly = CDBW measurement – regional average) taken at the same hour. Anomaly values can be easily interpreted: an anomaly value of 0 indicates that the grab sample was equal to the regional average; an anomaly value greater than 0 indicates that the grab sample was higher than the regional average; and an anomaly value less than 0 indicates that a grab sample was lower than the regional average. This method allows the continuous measurements to form the baseline to interpret changes over time to be able to distinguish whether they are attributable to the treatment or simply changes that are occurring in the region.

As with any analysis that integrates data from multiple sources, temporal overlap can be a factor that limits the amount of data available for the analysis. Although data have been collected for the NPDES permit since 2004, continuous water quality sensors were not installed until later (Figure 5). Issues with temporal overlap did not impact comparisons for temperature and turbidity, but continuous sensors for dissolved oxygen were not in place until 2014, so comparisons for this water quality variable were only for 2014 – 2016.

To test whether the pre-treatment water quality anomalies were different than the post-treatment water quality anomalies we used a GLMM, which was similar to the GLMM used for the

51 local scale analysis. For this test, the GLMM we used was equivalent to a one-way ANOVA including
52 only a main effect for time (before, after) with a random effect for site. As in the tests for differences
53 in and around patches, the ANOVA also included a random effect for site nested within year to
54 properly pair samples on the same site within a treatment season. This method tests for differences
55 among groups while accounting for taking multiple measurements on the same site. We fit separate
56 models for each water quality parameter. As with the BACI models, models for differences in
57 anomalies were fit using function lmer in package lme4 (Bates et al. 2015). Tests of significance were
58 performed using a likelihood ratio test against a null (intercept-only) version of the model (anova;
59 test statistic = D) [33].

60   To make this information more widely applicable to any potential treatment site, it is useful to
61 know whether we should expect the value of each water quality parameter to go up or down
62 following treatment with herbicides and whether these values differ from the regional averages. To
63 determine this information, we calculated marginal means and standard deviations using the models
64 from the second question (function ref.grid, package lsmeans) [37]. These marginal means represent
65 the expected value of water quality anomalies at a site before or after treatment, regardless of the site
66 in question.

5. Conclusions

68   Although water hyacinth generally occurs in places with little to no water flow such as lakes and
69 canals, it also thrives in the tidally influenced SFE in shallow water habitats and other low-velocity
70 areas. These hydrologic conditions create a set of habitat conditions that is different than other
71 systems where water hyacinth effects on water quality have been extensively studied. The tidal
72 hydrology moves water in and out of water hyacinth patches, making conditions right for water
73 hyacinth to export water quality effects to the area immediately surrounding each patch. The spatial
74 extent of this effect cannot be determined by the data used in this study, but it should be considered
75 in future studies.

References

1.   Bertness, M.D. Habitat and community modification by an introduced herbivorous snail. *Ecology* **1984**, 65, 370-381.

2.   Vitousek, P. M. Biological invasions and ecosystem processes: towards an integration of population biology and ecosystem studies. *Oikos* **1990**, 57, 1, 7-13

3. Hestir, E.L.; Brando, V.E.; Bresciani, M.; Giardino, C.; Matta, E.; Villa, P.; Dekker, A.G. Measuring freshwater aquatic ecosystems: the need for a hyperspectral global mapping satellite mission. *Rem. Sens. Environ.* **2015**, 167: 181-195. DOI: https://doi.org/10.1016/j.rse.2015.05.023

4. Champion, P., Tanner, C. Seasonality of macrophytes and interaction with flow in a New Zealand lowland stream. *Hydrobiologia* **2000**, 441, 1–12.

5. Willoughby, N.; Watson, I.G.; Lauer, S.; Grant, I.F. An Investigation into the Effect of Water Hyacinth on the Biodiversity and Abundance of Fish and Invertebrates in Lake Victoria, Uganda. NRI Project Report 10066 Ao32g, Natural Resources Institute, Chathan, UK. 1993

6. Cordo, H.; Center, T.D. Watch out water-hyacinth! New jungle enemies are coming. *Agric. Res.* **2001**.

7. Masifwa, W.F.; Twongo, T.; Denny, P. The impact of water hyacinth, Eichhornia crassipes (Mart) Solms of the abundance and diversity of aquatic macroinvertebrates along the shores of northern Lake Victoria, Uganda. *Hydrobiologia* **2001** 452, 79–88.

8. Toft, J. D.; Simenstad, C.A.; Cordell, J.R.; Grimaldo, L.F. The effects of introduced water hyacinth on habitat structure, invertebrate assemblages, and fish diets. *Estuaries* **2003**, 26, 746-758.

9. Pimentel, D.; Lach, L.; Zuniga, R.; Morrison, D. Environmental and economic costs of nonindigenous species in the United States. *BioScience* **2000**, 50, 53–65.

10. Villamagna, A.M.; Murphy, B.R. Ecological and scoio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. *Freshw. Biol.* **2010**, 55, 282-298.

11. Wolverton, B.C.; McDonald, R.C. Water hyacinth (*Eichhornia-crassipes*) Productivity and Harvesting Studies. *Econ. Bot.* **1979**, 33, 1-10.

12. Penfound, W. T.; T. T. Earle. The Biology of water hyacinth. *Ecol. Monog.* **1948**, 18, 447-472.

13. Stacey, M.T.; Brennan, M.L.; Burau, J.R.; Monismith, S.G. The tidally averaged momentum balance in a partially and periodically stratified estuary. *J. Phys. Ocean.* **2010**, 40, 2418-2434.

14. Rai, D. N.; Munshi, J.D. The influence of thick floating vegetation (Water hyacinth: Eichhornia crassipes) on the physico-chemical environment of a fresh water wetland. *Hydrobiologia* **1979**, 62, 65-69.

15. Bicudo, D.D.C.; Fonseca, B.M.; Bini, L.M.; Crossetti, L.O.; Bicudo, C.E.; Araújo-Jesus, T. Undesirable side-effects of water hyacinth control in a shallow tropical reservoir. *Freshw. Biol.* **2007**, 52, 6, 1120-1133.

16. Lynch, J.J.; King, J.E.; Chamberlain, T.K.; Smith, A.L. Effects of aquatic weed infestations on the fish and wildlife of the Gulf States. U.S. Department of Interior Special Scientific Report 39, **1947**, 1-71.

17. Perna, C.; Burrows, D. Improved dissolved oxygen status following removal of exotic weed mats in important fish habitat lagoons of the tropical Burdekin River floodplain, Australia. *Mar. Pollut. Bull.* **2005**, 51, 1, 138-148.

18. CDBW. Submersed Aquatic Vegetation Control Program [Egeria densa and Curlyleaf Pondweed] 2016 Annual Monitoring Report. January 31, 2017. Sacramento, CA. **2017.** http://www.dbw.ca.gov/pages/28702/files/SAV%20-%202016%20Monitoring%20Report.pdf

19. Zimmels, Y.; Kirzhner, F.; Malkovskaja, A. Application of Eichhornia crassipes and Pistia stratiotes for treatment of urban sewage in Israel. *J. Environ. Manag.* **2006**, 81, 4, 420-428. DOI: https://doi.org/10.1016/j.jenvman.2005.11.014

20. Rommens, W.; Maes, J.; Dekeza, N.; Inghelbrecht, P.; Nhiwatiwa, T.; Holsters, E.; Ollevier, F.; Marshall, B.; Brendonck, L. The impact of water hyacinth (Eichhornia crassipes) in a eutrophic subtropical impoundment (Lake Chivero, Zimbabwe). I. Water quality. *Archiv für Hydrobiologie* **2003**, 158, 3, 373-388.

21. Mahardja, B.M.; Young, M.J.; Schreier, B.; Sommer, T. Understanding imperfect detection in a San Francisco Estuary long-term larval and juvenile fish monitoring programme. *Fish Manag. Ecol.* **2017**, 24, 488-503, DOI: 10.1111/fme.12257. https://onlinelibrary.wiley.com/doi/epdf/10.1111/fme.12257

22. Polansky, L.; Newman, K.B.; Nobriga, M.L.; Mitchell, L. Spatiotemporal models of an estuarine fish species to identify patterns and factors impacting their distribution and abundance. *Estuar. Coast.* **2018**, 41, 2, 572-81, DOI: 10.1007/s12237-017-0277-3. https://link.springer.com/article/10.1007/s12237-017-0277-3

23. Khanna, S.; Santos, M.J.; Hestir, E.L.; Ustin, S.L. Plant community dynamics relative to the changing distribution of a highly invasive species, Eichhornia crassipes: a remote sensing perspective. *Biological Invasions* **2012**, 14, 717-733.

24. CDWR. California Water Plan Update 2013. Investing in innovation and infrastructure, Volume 1: the strategic plan. Bulletin 160-13. Sacramento, CA. **2013.**

25. Khanna, S.; Bellvert, J.; Shapiro, K.; Ustin, S.L. Invasions in State of the Estuary 2015: Status and Trends Updates on 33 Indicators of Ecosystem Health. The San Francisco Estuary Partnership, Oakland, California, USA. **2015**.

155 26. CDBW. Floating Aquatic Vegetation Control Program Water Hyacinth, Spongeplant and Water Primrose
156   2016 Annual Monitoring Report. January 31, 2017. Sacramento, CA. **2016.**
157   http://www.dbw.ca.gov/pages/28702/files/FAV%20-%202016%20Annual%20Monitoring%20Report.pdf

158 27. CDBW. Water Hyacinth Control Program Biological Assessment. October 25, 2012. Sacramento, CA. **2012.**
159   http://www.dbw.ca.gov/pages/28702/files/WHCP-Biological_Assessment-121025.pdf

160 28. Jassby, A.D.; Cloern, J.E. Organic matter sources and rehabilitation of the Sacramento-San Joaquin Delta
161   (California, USA). *Aquatic Conservation: Marine and Freshwater Ecosystems* **2000**, 10, 5, 323-352.

162 29. CDBW. Water Hyacinth Control Program and Spongeplant Control Program Aquatic Pesticide
163   Application Plan. Sacramento, CA. **2013.**
164   http://www.dbw.ca.gov/pages/28702/files/WHCP%20SCP%20Aquatic%20Pesticide%20Application%20Pl
165   an%202013.pdf

166 30. Division of Boating and Waterways. Available online: http://www.dbw.ca.gov/ (accessed on 23 July 2018).

167 31. CDBW. Floating Aquatic Vegetation Control Program Water Hyacinth and Spongeplant Control Projects
168   2015 Annual Monitoring Report.January 11, 2016. Sacramento, CA. **2015.**
169   http://www.dbw.ca.gov/pages/28702/files/2015-Annual-Report-FAV.pdf

170 32. California Data Exchange Center (CDEC). Available online: http://cdec.water.ca.gov/ (accessed on 23 July
171   2018).

172 33. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical
173   Computing, Vienna, Austria. URL https://www.R-project.org/. version 3.3.2 "Sincere Pumpkin Patch" **2016**

174 34. Green, R.H. *Sampling Design and Statistical Methods for Environmental Biologists*. Wiley Interscience.
175   Chichester, England. 1979.

176 35. Bates, D; Maechler, M.; Bolker, B.; Walker, S. Fitting linear mixed-effects models using lme4. *J Stat. Softw.*
177   **2015**, 67, 1, 1-48. doi:10.18637/jss.v067.i01

178 36. Kuznetsova, A.; Brockhoff, P.B.; Christensen, R.H.B. lmerTest: Tests in Linear Mixed Effects Models version
179   2.0-33. R package. **2016**. https://CRAN.R-project.org/package=lmerTest

180 37. Lenth, R.V. Least-squares means: The R package lsmeans. *J. Stat. Softw.* **2016**, 69, 1, 1-33.
181   doi:10.18637/jss.v069.i01

182 38. Greenfield, B.K.; Siemering, G.S.; Andrews, J.C.; Rajan, M.; Andrews, S.P., Jr.; Spencer, D.F. Mechanical
183   shredding of water hyacinth (Eichhornia crassipes): effects on water quality in the Sacramento-San Joaquin
184   River Delta, California. *Estuar. Coast.* **2007**, 30, 4, 627-640.

185 39. Ruhl CA, Schoellhamer DH. Spatial and temporal variability of suspended-sediment concentration in a
186   shallow estuarine environment. *San Francisco Estuary and Watershed Science*. **2004**, 2, 2, Article 1.
187   http://repositories.cdlib.org/jmie/sfews/vol2/iss2/art1

188 40. Perna, C.N.; Cappo, M.; Pusey, B. J.; Burrows, D.W.; Pearson, R. G. Removal of aquatic weeds greatly
189   enhances fish community richness and diversity: an example from the Burdekin River floodplain, tropical
190   Australia. *River Res. Appl.* **2012**, 28, 1093-1104.