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INVESTIGATION OF A MACHINE-PLANT INTERFACE FOR EXTRACTING ROOTED INVASIVE AQUATIC PLANTS

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INVESTIGATION OF A MACHINE-PLANT INTERFACE FOR EXTRACTING ROOTED INVASIVE AQUATIC PLANTS

By

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A REPORT

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Abstract

The current solutions for managing rooted aquatic invasive plants are time consuming, have negative environmental impacts, or are cost-limiting for management organizations. The most effective treatment method is hand pulling, but hand pulling is not a feasible solution for a whole lake. A new device, the invasive aquatic plant extractor, aims to replace human divers who hand pull plants with a mechanical system. The device implements a machine-plant interface that resembles the tines of a fork. These tines will be pushed linearly through the substrate, and then raised from the substrate with the plant caught in the tines. The primary purpose of this paper is to discuss the impacts of tine configuration and tine geometric traits on tine performance and identify tine geometry that consistently removes the target plants. Force, turbidity, and plant removal capability data were collected. All testing occurred in tanks containing representative substrate and common, rooted invasive plants. Wide tines with wide spacing perform the best of the four configurations tested. Tines with square or rounded edge shape perform better than pointed edges. Increasing the tine rake angle with respect to a vertical plane increases the performance of the tines. The data collected in this study suggests that tines will be part of an effective invasive aquatic plant extractor.

1 Introduction

Aquatic invasive species (AIS) are prevalent throughout North American [1] and European [2] waterbodies. AIS impede access to, decrease biodiversity in, and decrease property values on the waterbodies they inhabit. Current management methods for AIS are time consuming, cost prohibitive, and adversely impact native plants and animals. Fibrously rooted invasive plants are widespread and commonly problematic [3]. Hand-pulling fibrously rooted plants is the least environmentally harmful method of removal; however, it is time consuming and expensive. In 2019, a machine to "hand-pull" plants was proposed by the author of this report. The final vision for the machine is a system that can identify, move to, and remove a target plant with minimal human input. The preliminary machine design was completed in 2020 by Michigan Technological University Senior Capstone Design Team 11. Team 11's end effector for removing aquatic plants with fibrous roots, seen in Figure 1, required further research to meet the environmental requirements of the State of Michigan for aquatic vegetation removal. To learn more about how an end effector will interact with plants with fibrous roots and the surrounding substrate, potential configurations and geometries of a comb-like machine-plant interface were studied by the author of this report.

Figure 1. More research will be performed on the configuration and geometries of an end effector similar to the Senior Capstone Design Team 11 end effector, seen here.

The specific objectives of the research are:

- Identifying end-effector spacing, width, edge shape, and rake angle that consistently achieve complete plant removal.
- Limiting sediment kickback while working in the substrate to maintain underwater visibility to increase the effectiveness of a future, automated plant identification tool.
- Reducing forces required for plant removal to reduce mechanical design challenges.

2 Background

2.1 Eurasian Watermilfoil Impacts and Management

The most widespread and aggressive fibrously rooted non-native aquatic plant in the United States is Eurasian Watermilfoil (EWM). EWM is present in over 45 U.S. states and 3 Canadian Provinces [3]. Depending on the trophic state and sediment type, EWM can colonize an entire lake [4]. EWM can form thick, tangled surface mats that shade out native plants. Thick EWM growths clogs boat propellers, making boating and recreation difficult or impossible [5].

Cutting, herbicide, benthic barriers, and Diver-Assisted Suction Harvesting (DASH), are the primary methods of EWM population management. There are several drawbacks to these methods. Cutting is not an effective method because EWM reproduces primarily by fragmentation. Cutting serves to spread the plant [2]. Herbicide is not species-selective, and it kills native plants that are biologically similar to EWM [6]. Herbicide applications can create dead zones that negatively impact the ecosystem [6]. Additionally, herbicide applications to waterbodies used as drinking water supplies have raised human health concerns [7]. Benthic barriers can be difficult to anchor, and they require regular inspections [8]. Benthic barriers negatively impact aquatic habitats. A study of benthic barriers in Texas and Wisconsin waterbodies found that invertebrate population density beneath benthic barriers was 10-31% of populations not underneath benthic barriers [9]. Benthic barriers must be applied to an area for 8 weeks to effectively manage EWM [10]. DASH is a more efficient way of hand-pulling plants; however, DASH is still very labor and time intensive. Between 2013 and 2015, DASH divers on Squam Lakes in New Hampshire averaged 5.1 gallons of EWM removed per hour. As another point of reference, DASH divers at Pentwater Lake in Michigan worked for four days to remove 15,200 pounds of biomass at a total cost of $21,533, or about $1.42 per pound of biomass [11]. The divers at Pentwater Lake worked in an area about 12,000 square feet of a lake with a surface area of 431 acres (1.88 e+7 square feet) [11]. Management methods that are this expensive may prohibit lake organizations from effectively managing EWM.

2.2 The Invasive Aquatic Plant Extractor

During the 2019-2020 academic year, Michigan Technological University Senior Capstone Design Team 11 developed a mechanical system to remove invasive plants. The aim of this machine is to replace divers who hand-pull invasive plants. Figure 2. is a CAD model of the prototype of the invasive aquatic plant extractor. The invasive aquatic plant extractor will be affixed to the outside edge of a boat [12]. The central post is lowered from the boat into the substrate. A winch-driven collar translates vertically along the post and presses the tines into the substrate while the parallelogram linkage, which is one meter in length, is held stationary.

The linear actuator and parallelogram linkage then move the tines through the substrate towards or away from the central post. The tines catch the root crown of the target plant, lift the plant from the substrate, and a hose with light suction transports the plant to the surface, completing a successful removal. At the conclusion of the project, the

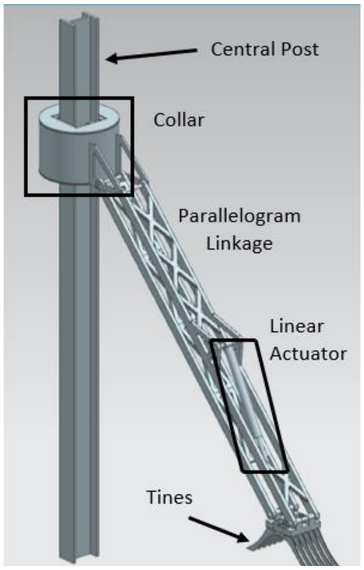

Figure 2. Invasive Aquatic Plant Extractor Concept. Reproduced From [12]

tines had been briefly tested, but the final design had yet to be verified [12].

The invasive aquatic plant extractor will have a system to guide it to target plants. Reduced water clarity may limit application of this system. The impact of the tines on water clarity had not been determined.

Team 11's work was the basis for a set of requirements that are addressed by this study, shown in Table 1. The research presented here increases knowledge pertaining to the details of these objectives.

Table 1. Engineering Objectives developed from Team 11 Research

Objective	**Requirement Details**
Broken Plant Rate	Less than 5% of plants are broken including and above the root crown during removal from sediment
Tine Depth	Tines must reach no less then 100mm into substrate
Tine block width	Total tine block width must not exceed 100mm
Maximum System Load	Pushing the tines through the substrate must require less than 400N of force
Disturbed Sediment Volume per plant removed	Substrate volume disturbed must not exceed 1500 cm^3 per plant removed

3 Materials and Methods

3.1 Test Fixture

As seen in Figure 3, a test fixture was designed to push the tines through the substrate along the x-axis and allow the tines to be repositioned along the y-axis. Tine configurations up to 100mm in width can be accommodated by the fixture. The invasive aquatic plant extractor is intended to dislodge plants by pushing the tines through the substrate. For this study, the tines were inserted 75mm into the substrate and then pushed 150mm through the substrate by a linear actuator. The tines remained in the substrate through the 150mm motion. 150mm was an appropriate actuation distance for loosening plants during preliminary trials. The speed of the tines was 0.75 inches/second. Force and turbidity data were collected while the tines were moving. After the tines stopped moving, the target plant underwent a removal quality analysis to check for fragmentation, missed plants, loose plants, and other factors that could affect removal.

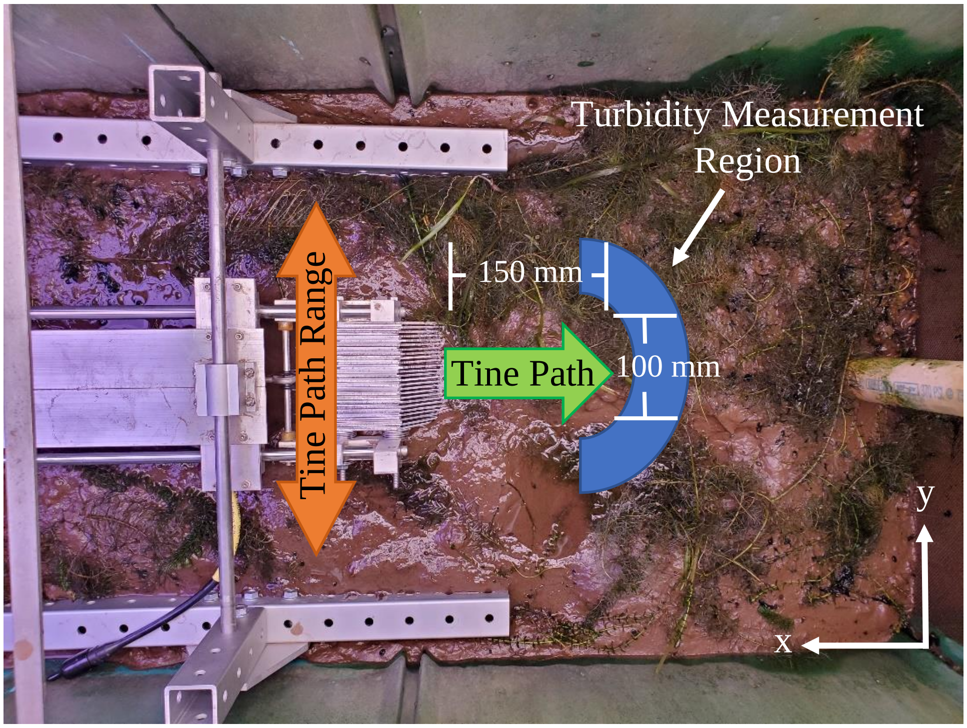

Figure 3. An overhead view of the tines and test fixture in a drained tank. The tines were pushed through the substrate 150mm along the tine path. They can be repositioned so that multiple tine paths are possible for each test stand position.

The bottom of the test fixture is shown in Figure 4. The fin was pushed 75-100mm into the substrate to keep the test fixture stationary while the tines moved. Its surface area is much larger than the tines, and the test fixture did not move during testing. Stationary linear bearings and shaft guides, fixed to the end of the linear shafts, guided the tines along a linear path. The tines, and electric linear actuator are also seen in this figure.

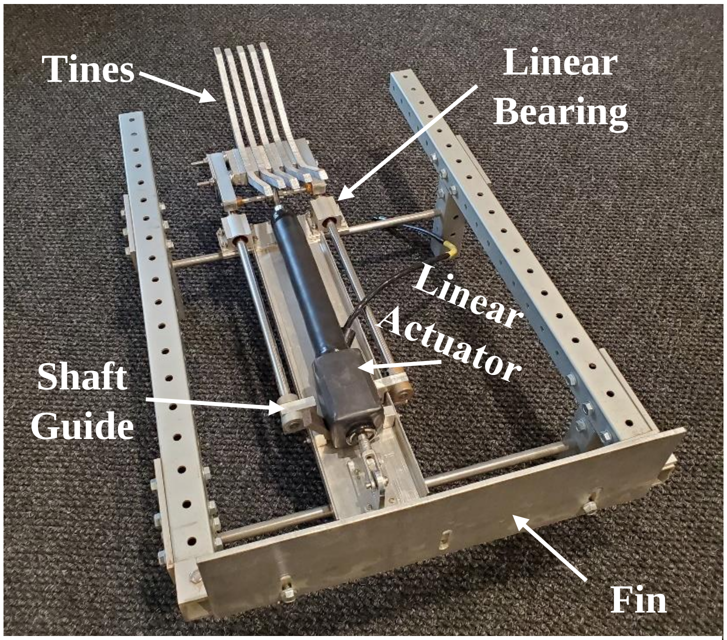

Figure 4. Flipping the test fixture upside-down reveals its important components. The linear actuator and linear guide system work together to move the tines forward through the substrate. The fin, closest in frame, was pushed into the substrate to keep the fixture stationary.

As seen in Figure 5, the frame of the test fixture rested on the substrate, and the tines and fin protruded below the test fixture frame.

Figure 5. The tines and fin protruded below the test fixture frame (l), and the test fixture frame sat on top of the substrate (r)

3.2 Test Tank Preparation

Three Living Stream LS-900 tanks were prepared with 100mm of substrate and representative plants five months prior to testing. Tank 1 contained muck substrate and *Myriophyllum Heterophyllum*. Tank 2 contained a muck/sand mixed substrate and *M. Heterophyllum*. Tank 3 contained muck and *Myriophyllum Spicatum* (EWM).

The bulk density of the muck was 36% less than the bulk density of the muck/sand mix. The plants received nine hours of full-spectrum lighting each 24-hour period. Twice per month, algae were manually removed from the plants, half of the tank water was replaced, and the plants were agitated. These treatments attempted to simulate a natural ecosystem with waterflow and wave action. The water in the tanks was from the Keweenaw Waterway. Muck was collected from Chassell Bay, part of the Keweenaw Waterway. Sand was collected from the Pike River in Chassell Township. Figure 6. includes pictures of the tank substrates. *M. Heterophyllum* was purchased through an aquarium supply company, and *M. Spicatum* fragments were gathered from the Keweenaw Waterway. As shown in Figure 7, The plants were typically spaced 120 – 150mm apart after five months of growth. The water depth during growth was between 280mm and 320mm.

Figure 6. Muck (l) and muck/sand mix (r) substrate types were used for testing. The bulk density of muck was 36% less than the bulk density of the muck/sand mix.

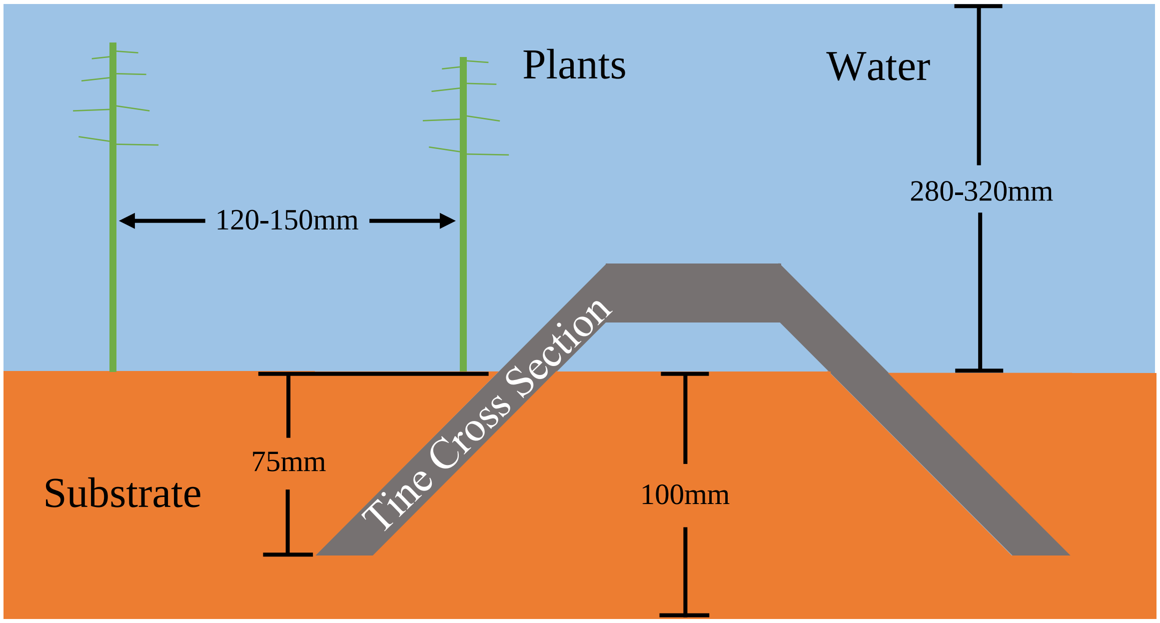

Figure 7. Tank cross section showing the depth of the tines, substrate, plant spacing, and water depth for testing. The substrate depth in the tanks was 100mm, the plants were spaced 120-150mm apart after five months of growth, and the water depth was 280-320mm.

3.3 Tine Design

The tine design considered the intended operation of the invasive aquatic plant extractor designed by Senior Design Team 11 and the observed dimensions of the target plants. The invasive aquatic plant extractor was designed to remove plants in two opposing directions, and the tines for this study were designed accordingly. Figure 8 compares the tines that were manufactured for this study to the tines manufactured for Senior Design Team 11. Both tines had 45° rake angles. As can be seen in the figure, the distance from the mounting point to the tip of the tines for this study was 95mm, 18mm less than the tines manufactured for Team 11. Team 11's tines were longer because they were designed to reach under the entire root system of the target plants, however, it is now known that just the root crown needs to be extracted to successfully remove a plant. Root crowns of the two plants discussed in this study can regrow into full plants if they are left in the substrate. Pre-test observations of *M. Heterophyllum* found the deepest root crowns to be 60 mm below the substrate. The tines for this study were designed to reach 75mm into the substrate to capture the deepest root crowns. The tines for this study had straight leading edge to standardize rake angle tests. A consistently influential curved profile would have been difficult to maintain for rake-angle testing. The distance from the center of the tine to the top of the leading edge was shortened from 50mm to 30mm because the tine mounting method was simplified for the test fixture.

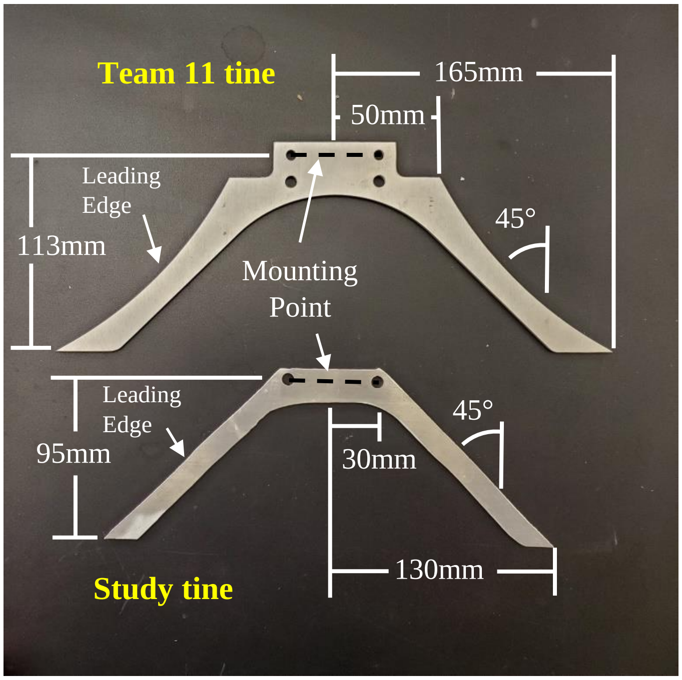

Figure 8. The height at leading edge shape of the tines used for this study (bottom) differed in from the tines manufactured for Senior Capstone Design Team 11 (top). The tines used for the study were shorter because of greater understanding of the target plant, and the leading edge shape was simplified for consistent rake angle testing.

3.4 Turbidity Measurements

The invasive aquatic plant extractor will require a plant identification tool that may only be able to identify plants in clear water. Turbidity is a measure of the amount of light that is scattered by material in the water when light is shined through a water sample [13]. Turbidity was used to track changes in clarity caused by tine movement, and it was measured by an In-Situ Aquatroll 600. Five minutes of turbidity measurements were taken for each trial, and measurements started 10-15 seconds before the tines started to move. Turbidity measurement frequency was 1 Hz, and the units were nephelometric turbidity units (NTU). Water volume was kept constant for all trials and between tanks to ensure turbidity was comparable between tests. Preliminary testing showed that the maximum turbidity increase outside of the tine path occurred around the end of the tine path, as show in Figure 4. Testing showed that the upper limit for clear, underwater imaging lies around 8 NTU, as demonstrated by Figure 9.

Figure 9. M. Spicatum in 4 NTU water (l) and 12 NTU water (r). The camera was one foot away from the plants. It is impossible to distinguish between plant species in the 12 NTU image. Clear underwater images can be taken in water up to around 8 NTU.

3.5 Force Measurements

The amount of force required for plant extraction will impact the design of the invasive aquatic plant extractor. Stronger mechanical and electrical components would be required to overcome higher forces. Cost would most likely increase with higher forces, as well. Force was calculated from the power required by the actuator. The data acquisition system was calibrated with seven weights applied to the actuator. Two, third-order voltage-force relationships were noted during testing. It is not understood why there were two relationships, however, the force measurements taken with both relationships appear to be consistent. Figures 10 and 11 show these two relationships. These two relationships do not overlap for the forces seen in this study. The first relationship applied to tests 1-4 and 7-8. The second relationship applied to tests 5 and 6. The calibration voltage ranges, relationship coefficients and R^2 values are shown in Table 2.

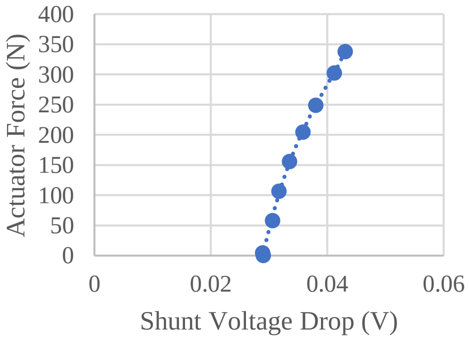

Figure 10. The first relationship between the force produced by the actuator and the voltage drop across a shunt applied to tests 1-4 and 7-8.

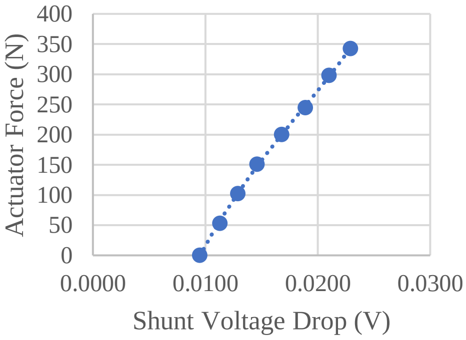

Figure 11. The second relationship between the force produced by the actuator and the voltage drop across a shunt applied to tests 5 and 6.

Table 2. Parameters of Two Force-Voltage Relationships

Best Fit Equation: $y = ax^3+bx^2+cx+d$ (y symbolizes force in newtons, x symbolizes voltage across the shunt)		
Parameter	**Relationship 1**	**Relationship 2**
Calibration Range (shunt voltage)	0.0289 - 0.0431	0.0095 - 0.0229
R^2	0.999	0.9996
a	70157015.91	48472707.99
b	-8415881.896	-2699196.376
c	353481.3257	72807.3955
d	-4881.025763	-491.2074755

3.6 Plant Removal Assessment

Plant removal capability was assessed qualitatively. The substrate region impacted by the tines was inspected before and after the tines were retracted. Trials in clear water were filmed and photographed to aid judgement of how the tines were interacting with the substrate and plants. Root position and soil position around the tines was inspected and measured, respectively. Measurements x, y, and z, as indicated in Figure 12, were taken for each trial. The number of loose plants, the number of fragment zones, and the number of plants in the tine path, but not removed ("missed"), were recorded. Plants that were not firmly anchored were removed by pulling on the stem. They were then photographed. The invasive aquatic plant extractor will separate the plants from the substrate with suction, so pulling by the stem was a relatively representative method of removal. Figures 13 through 18 show the difference between a complete plant and a fragmented zone for both species.

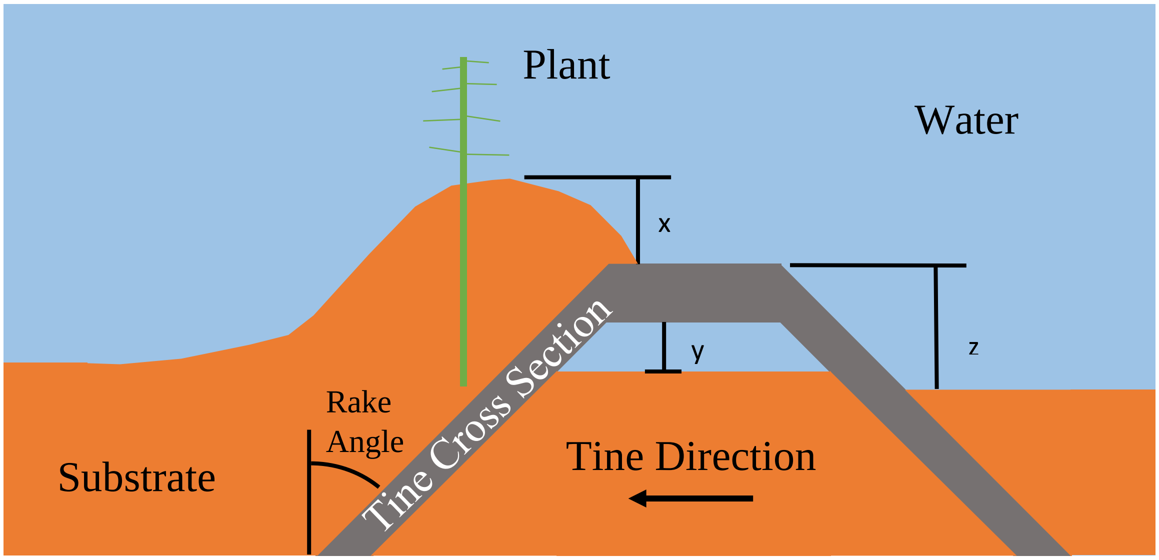

Figure 12. Typical substrate buildup around the tines after a trial. Three measurements, indicated by x, y, and z were taken for each trial. Plant looseness and root position relative to the tines were also inspected.

Figure 13. Complete M. Spicatum Plant with 30cm ruler for scale

Figure 14. Complete M. Heterophyllum Plant with 30cm ruler for scale

Figure 15. Complete M. Spicatum Root Crown

Figure 16. Complete M. Heterophyllum Root Crown

Figure 17. Fragmented M. Spicatum Stem. Each removed plant was inspected for fragmented zones.

Figure 18. Fragmented M. Heterophyllum Stem. Each removed plant was inspected for fragmented zones.

3.7 Tine Configurations and Geometries

Tine width, tine spacing, edge shape, and rake angle were the configuration and geometry parameters tested. Eight tests of five trials each tested how these parameters impacted removal force, turbidity, and plant removal capabilities.

Tests 1-4, detailed in Table 3, tested edge width and tine spacing. The number of tines for each configuration was the maximum that could fit in the 100mm space. Figures 19 and 20 show the four tine configurations, which are made up of 2.03mm- and 9.53mm-wide tines and spacers. 9.53mm is approximately 4.5 times 2.03mm, which was assumed to be a large enough width difference for there to be differences in configuration performance.

Table 3. Tine Configuration Tests

Test	**Tine Width (mm)**	**Tine Spacing (mm)**	**Number of Tines**
1	2.03	9.53	9
2	2.03	2.03	25
3	9.53	9.53	5
4	9.53	2.03	8

Figure 19. From left to right, nine 2.03mm tines with 9.53mm spacing, 25 2.03mm tines with 2.03mm spacing, five 9.53mm tines with 9.53mm spacing, and 9.53mm tines with 2.03mm spacing. Although the picture here contains just seven tines, the 9.53mm tines/2.03mm spacing configuration was tested with eight tines.

Figure 20. 9 2.03mm tines with 9.53mm isometric view.

Tests 5 and 6 tested the effect of leading edge shape on force, turbidity, and plant removal success. Rounded edges and 40° points were milled into the highest-scoring tine configuration from tests 1-4. The edge shapes are illustrated in Figure 21. Rake angle was 45° for tests 1-6. Tests 7 and 8 tested 56° and 27° rake angles, respectively. The three rake angles tested are pictured in Figure 22. Rake angle is defined in Figure 22. The edge shape for tests 7-8 was square. Details of tests 5-7 can be seen in Table 4.

Table 4. Edge Shape and Rake Angle Tests

Test	**Leading Edge Shape**	**Rake Angle**
5	Round	45°
6	Pointed	45°
7	Flat	56°
8	Flat	27°

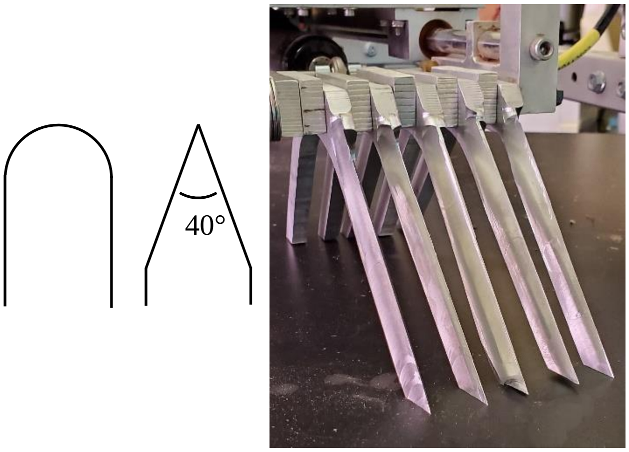

Figure 21. Round and point edge shapes were milled into the tines for tests 5 and 6, respectively. The picture on the right is tines with a point edge shape. Edge shapes were only applied to the leading edge of the forward direction, noted in Figure

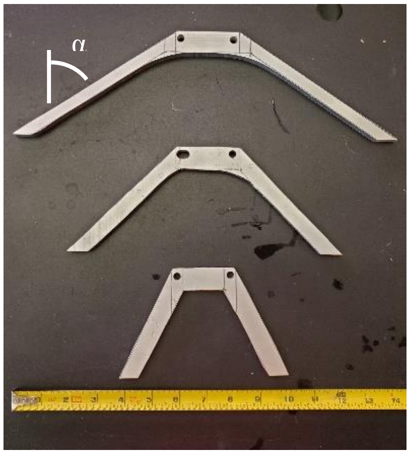

Figure 22. The three rake angles indicated by α (from top to bottom) are 56°, 45°, and 27°. Tests 1-6 used a 45° rake angle. The 56° rake angle was tested in test 7, and the 27° rake angle was tested in test 8.

4 Results

4.1 Pattern of Substrate Buildup Around Tines

Figures 12 and 23 – 25 illustrate the typical substrate buildup around the tines after a trial. The tines pushed the substrate forward, raising a portion of substrate in front of the tines, denoted by measurement x in Figure 12, and leaving a trough behind the tines, denoted by measurement z in Figure 12. The plants in the path would move with the tines if they were loosened and contacted by the tines. There was a space beneath the tines which was void of substrate in about 25% of trials, denoted by measurement y in Figure 12.

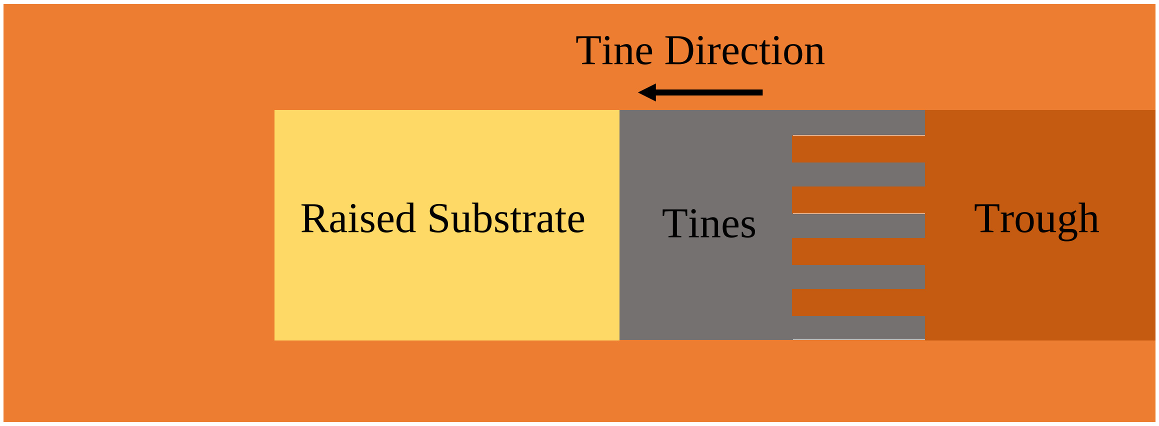

Figure 23. Top view of the region impacted by tines. The tines create an area of raised substrate and a trough as they move forward.

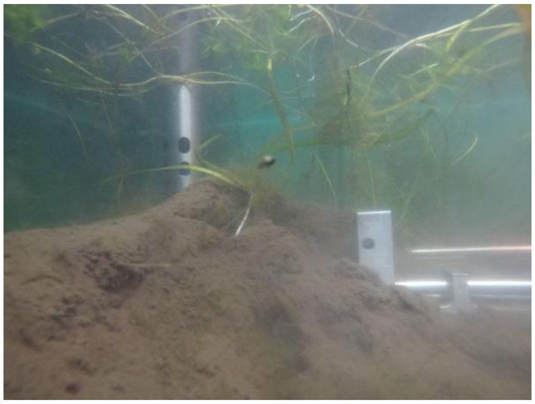

Figure 24. Substrate pile in front of tines after a trial. Trials had been performed along the width of the tank prior to the taking of this picture. The substrate mound is wider in this figure than in Figure 23.

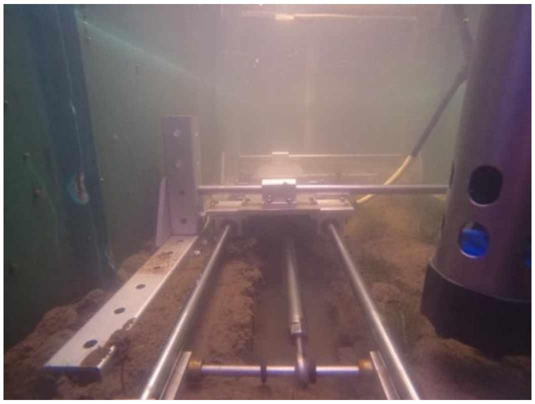

Figure 25. Substrate trough behind tines after a trial

4.2 Tine Configuration and Geometry Comparison

Tables 6 through 8 report surface area, average force, turbidity change, and potential plant removal success. Surface area, as shown in the table, is the actual surface area of the leading face of the tine block. Average force was calculated from all measurements taken while the tines were moving. Turbidity change, as reported in tables 6-8, is the difference between the turbidity prior to the tines moving, and 30-40 seconds after the tines stopped moving. Plant removal potential is a rating given based on the interaction of the tines with the plants and substrate where a “one” is a low rating. The criteria of the rating system are described in Table 5. The rating system was formed relative to the other tests in the study, and it accounts for missed plants, fragmented plants, and other issues that impede successful plant removal.

Table 5. Plant Removal Potential Rating System Criteria

Plant Removal Potential	**Criteria**
5	No issues noted
4	1. Seldom fragments or misses plants **or** 2. Some plants in tine affected area are not loose after tine motion
3	1. Regularly fragments or misses plants **or** 2. Some plants in tine affected area are not loose after tine motion
2	1. Regularly misses or fragments plants **and** 2. Substrate not loose in tine affected area
1	1. Regularly misses or fragments plants **and** 2. clear potential to fragment plants during other motions in removal process

The tine configuration tests are summarized in Table 6. The force data from these tests shows a positive trend between tine surface area and force. The configuration of 9.53mm tines and 2.03mm spaces deviates from this trend, but this set of tines was tested in a tank growing only *M. Spicatum*, which had much smaller root systems. Turbidity generally increased with increased surface area. Turbidity decreased during three tests, indicating the water was clearer after the trials than before the trials. The configuration of 9.53mm tines and 2.03mm spaces caused an increase in turbidity. The configuration of 2.03mm tines with 9.53mm spaces, test 1, missed plants. Plants remained rooted in the substrate underneath and behind the tine block. The configuration of 9.53mm tines and 2.03mm spaces, test 4, had high fragmentation potential. As pictured in Figure 26, *M. Spicatum* stems were stuck in between tines which did not allow the plants to be removed. The configuration of 2.03mm tines and 2.03mm spaces, test 2, was tested in a tank with *M. Heterophyllum*, which has thicker stems than *M. Spicatum*. It is predicted that this configuration, with the same spacing as test 4, would catch plants in between the tines. Plant removal potential for the 9.53mm tines, 9.53mm in spaces configuration was the highest among these configurations because it was the best at loosening the substrate. It did so without missing or fragmenting more plants than test 1, and no plants were caught in between the tines, as they were for test 4, and could have been for test 2.

Table 6. Tine Configuration Tests

Test	**Configuration**	**Surface Area (cm^2)**	**Average Force (N)**	**Average Turbidity Change (NTU)**	**Fragmented and Missed Plants (#)**	**Plant Removal Potential (1-5)**
1	2.03mm tines, 9.53mm spaces	13.7	75.2	-0.816	5	2
2	2.03mm tines, 2.03mm spaces	38.1	91.2	-0.317	1	2
3	9.53mm tines, 9.53mm spaces	35.7	81.4	-0.546	4	3
4	9.53mm tines, 2.03mm spaces	57.2	69.8	0.319	4	1

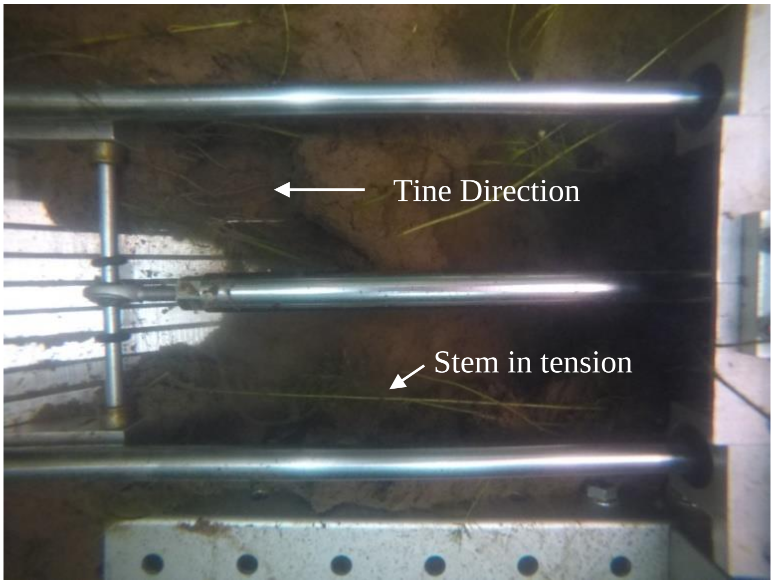

Figure 26. Plants stuck in 0.08 in-space tines after a trial. These plants started beneath the tines, however, plants in front of the tines were similarly stuck in between the tines. Plants stuck in between tines were at high risk for fragmentation.

The edge shape tests, summarized in Table 7, were performed with the 9.53mm tine, 9.53mm space configuration. Pointed tines required less force than rounded tines to move through the substrate. Turbidity decreased more during the pointed tine trials than the rounded tine trials. Rounded tines and pointed tines allowed plants to slip through, and the plants were frequently fragmented. A pointed tine trial clearly sliced a plant, leaving the root crown in the substrate. Fragmented and missed plants were found in the tine path after trials of both edge shapes.

Table 7. Edge shape tests were performed with a 9.53mm tine width, 9.53mm tine space configuration and a 45° rake angle

Test	**Edge Shape**	**Average Force (N)**	**Average Turbidity Change (NTU)**	**Fragmented and Missed Plants (#)**	**Plant Removal Potential (1-5)**
5	Rounded	79.2	-0.640	4	2
5	Point	61.8	-.992	2	2

Table 8 summarizes testing of rake angle. Test 3 is included in the table for comparison. There is no clear trend in average force. All three rake angles were tested in tanks containing *M. Spicatum* and *M. Heterophyllum*. Lower rake angles are correlated with greater turbidity decreases. The 27° and 45° rake angles were similarly successful at removing plants. The 27° rake angle did not consistently loosen its target plants, but it did not fragment plants as frequently as the 45° rake angle. The 56° rake angle was the best of this study. Every targeted plant was loose after the 56° rake angle tines contacted the plant.

Table 8. Rake Angle Tests were performed with a 9.53mm tine width, 9.53mm tine space configuration and a flat edge shape

Test	**Rake Angle (relative to vertical plane)**	**Average Force (N)**	**Average Turbidity Change (NTU)**	**Fragmented and Missed Plants (#)**	**Plant Removal Potential (1-5)**
7	56°	97.0	-.266	0	5
3	45°	81.4	-0.546	5	3
8	27°	91.6	-1.26	1	3

5 Discussion

5.1 Further Test Insights

The results of this study suggest that 9.53mm tines with 9.53mm spaces at a rake angle greater than 45° are the most effective at removing rooted invasive aquatic plants. Edge shape should be flat. Rounded and pointed edges did not effectively remove plants.

The effects of tine spacing are demonstrated in the results of trials 1-4. Narrow, 2.03mm spacing caught plants between the tines. The tensioned stems of unloosened plants could fragment as the tines are lifted out of the substrate during the extraction process. Wide, 9.53mm tines appear to perform better because they disturb more substrate around the plant. Roots in disturbed substrate are typically loose which make it easier to remove the plant.

The results of this study showed negligible differences between square and rounded edge shapes in force and turbidity measurements, and they both received a 3/5 plant removal rating. The pointed edges in this study cut and missed plants.

Higher rake angles appear to remove plants more effectively than low rake angles. The 27° rake angle did not sufficiently loosen the substrate for plant removal. No plant removal issues were noted during the 56° rake angle trials, whereas the 45° rake angle had several fragmentation incidents. There are turbidity and force penalties with the 56° rake angle. The turbidity decrease during the test was 0.280 NTU less than the 45° rake angle. This is not very significant because the turbidity decreased during testing of both rake angles. The 56° rake angle in this study required 15.6N (19.2%) more force to actuate than the 45° rake angle. The invasive aquatic plant extractor is currently planned to be anchored in the substrate and connected to, but minimally supported by, a boat. The increased horizontal force from the plant removal would need to be offset by a larger base of the invasive aquatic plant extractor. A sliding scenario of the central post is illustrated in Figure 27. In a sliding scenario, force meant to extract plants would drag the central post base through the substrate. The mounting boat would translate, as well.

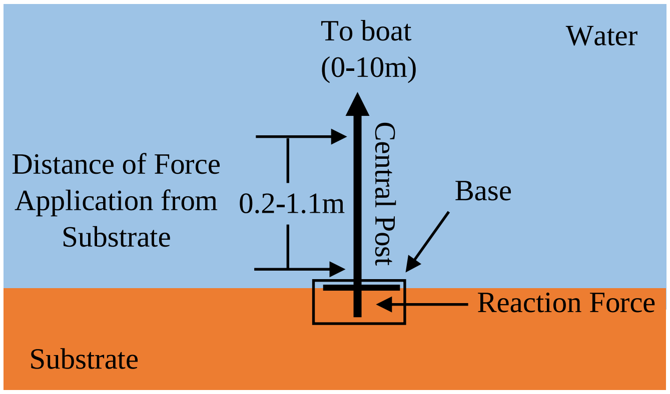

Figure 27. In a case where sliding, and not tipping, of the invasive aquatic plant extractor is assumed, the reaction force in the figure needs to be larger than the force applied by the tines. The force applied by the tines could meet the central post between 0.2m and 1.1m above the substrate. Tines that exceed the reaction force would drag the central post base through the substrate, and the boat would translate on top of the water.

Although no issues were identified in this study, the buildup of substrate in front of the tines could impact plants outside of the tine path, compromising their removal.

Substrate could bury plants or change the substrate level so that the tines cannot reach the root crown.

The tine depth, tine block width, and maximum system load engineering objectives originally presented in Table 1 can be amended based on this research. Table 9 contains recommendations for requirement revisions. The 5% maximum broken plant rate appears attainable, so no change is recommended. This study operated with a tine depth of 75mm, and no root crowns were discovered below this depth. Decreasing the tine depth requirement to 75mm is recommended. As previously mentioned, root crowns greater than 100mm in width were found during testing. Increasing the maximum tine block width to 200mm is recommended. The maximum force required to move a tine block through the substrate was 97N. Accounting for maximum dimension recommendations, a maximum system load of 200N is now recommended. Greater tine block widths will disturb more substrate, but the required depth has decreased. Increasing the disturbed sediment volume per plant removed requirement 17%, to 1750 cm^3, is recommended. A new requirement for turbidity has been added to the table. Based on testing and imaging performed as part of these tests, a maximum turbidity of 8 NTU is recommended. Plant identification will be possible when the turbidity is 8 NTU or lower.

Table 9. Engineering Objectives Revision Recommendations

Objective	**Old Requirement Details**	**Requirement Revision Recommendation**
Broken Plant Rate	Less than 5% of plants are broken including and above the root crown during removal from sediment	No change
Tine Depth	Tines must reach no less then 100mm into substrate	Decrease required tine depth to 75mm
Tine block width	Total tine block width must not exceed 100mm	Increase the allowable width to 200mm
Maximum System Load	Pushing the tines through the substrate must require less than 400N of force	Decrease maximum system load to 200N
Disturbed Sediment Volume per plant removed	Substrate volume disturbed must not exceed 1500 cm^3 per plant removed	Increase disturbed sediment volume to 1750 cm^3
Maximum Turbidity	No requirement	Turbidity must not exceed 8 NTU

5.2 Future Work

M. Spicatum removal could be more difficult than other species because the root crown and root systems of *M. Spicatum* were smaller than expected. This could have been because of the indoor tank environment; however, natural variability makes it likely that similar root systems will be found outside of the lab. Different tine configurations may need to be used for root systems of different sizes in different substrates.

Some modifications will be necessary for effective future implementation. The width of the tine block was limited to 100mm for this study, however, *M. Heterophyllum* plants were discovered with root crown systems that exceeded 100mm in width. Increasing the width of the tine block to 200mm may increase the plant removal success rate. However, increasing the width of the tine block could impact more native plants. Increasing invasive removal success rate must be weighed against increasing the number of native plants captured. The specific environmental conditions could help determine the choice of tine block width. A wider tine block may also reduce the occurrence of edge cases where the plant is only partially in the tine path.

The shape of the tines for this study was a basic inclined plane. The substrate is likely to slide off inclined plane tines as they are lifted from the lake bottom. This would allow plants to drop back to the bottom of the lake during extraction. More investigation should be done to determine if a curved tine, or perhaps a horizontal component will help capture the target plants.

The impact of the tines moving through the substrate was small. Only one test caused a positive change in turbidity, and the average turbidity change over the eight tests was -.564 NTU. Removing the tines and test fixture caused large, 10-20 NTU increases in tank turbidity during testing. Minimizing the turbidity increase caused by tine removal from the substrate will likely be an important study topic in future research.

6 Conclusion

In conclusion, tines were able to dislodge the target plants from the substrate with low force and minimal turbidity change. A challenge lies in consistent plant removal across varying plants and substrates. The best configuration in this study had 9.53mm wide tines, 9.53mm spaces between the tines, flat edge shape, and a 56° rake angle. Both plant removal force and turbidity can be reduced by reducing the surface area of the tines. Forces were lower than expected, and a new maximum force requirement of 200N was formed based on the results of this study. Turbidity is not greatly impacted by moving the tines through the substrate, but a maximum turbidity of 8 NTU is recommended for effective plant identification. Root crowns were not found to extend below 75mm; minimum required tine depth can be decreased to 75mm. Several potential areas of improvement have been identified, including increasing tine block width to 200mm to catch larger root crown systems. Development of an autonomous invasive aquatic plant extractor should continue so that waterbody management organizations have access to a control method that is less harmful to the environment and less expensive than the current treatment options.

7 Works Cited

[1] J. E. Havel, K. E. Kovalenko, S. M. Thomaz, S. Amalfitano, and L. B. Kats, “Aquatic invasive species: challenges for the future,” Hydrobiologia, vol. 750, no. 1, pp. 147–170, 2015.

[2] R. P. Keller, J. Geist, J. M. Jeschke, and I. Kühn, “Invasive species in Europe: ecology, status, and policy,” Environmental Sciences Europe, vol. 23, no. 1, pp. 9–9, 2011.

[3] “About Eurasian and Hybrid Watermilfoil,” Minnesota Aquatic Invasive Species Research Center (MAISRC), 03-Jul-2018. [Online]. Available: https://www.maisrc.umn.edu/about-eurasianwatermilfoil. [Accessed: 07-Jul-2020].

[4] C. S. Smith and J. W. Barko, “Ecology of Eurasian Watermilfoil,” Journal of Aquatic Plant Management, vol. 28, pp. 55–64, 1990.

[5] University of Wisconsin Extension, The Facts on Eurasian Water-Milfoil. 2004.

[6] “Eurasian Watermilfoil,” New York Invasive Species Information, 02-Jul-2019. [Online]. Available: http://nyis.info/invasive_species/eurasian-watermilfoil/. [Accessed: 07 Jul-2020].

[7] C. W. Boylen, L. W. Eichler, and J. W. Sutherland, “Physical control of Eurasian watermilfoil in an oligotrophic lake,” Hydrobiologia, vol. 340, no. 1-3, pp. 213–218, Dec. 1996.

[8] NYS Soil and Water Conservation Committee, Wayne County Soil and Water Conservation District.

[9] T. A. Ussery, H. L. Eakin, B. S. Payne, A. C. Miller, and J. W. Barko, “Effects of Benthic Barriers on Aquatic Habitat Conditions and Macroinvertebrate Communities,” Journal of Aquatic Plant Management, vol. 35, pp. 69–73, 1997.

[10] K. L. Laitala, T. S. Prather, D. Thill, B. Kennedy, and C. Caudill, “Efficacy of Benthic Barriers as a Control Measure for Eurasian Watermilfoil (Myriophyllum spicatum), ”Invasive Plant Science and Management, vol. 5, no. 2, pp. 170–177, 2012.

[11] R. Pugsley, DASH Cost Comparison, 09-Dec-2019.

[12] B. D. Baas, “GLRC_studentresearchgrant_MPI_v02.” 07-Aug-2020.

[13] Turbidity and Water. [Online]. Available: https://www.usgs.gov/special-topic/water-science-school/science/turbidity-and-water?qt-science_center_objects=0#qt-science_center_objects. [Accessed: 19-Apr-2021].