Harmful Algal Bloom at Ross Island

Analysis of Hydraulic and Chemical Modifications

Design Team 2

June 14, 2019

Table of contents:

1. Statement of objective
2. Current Hydraulic conditions
3. Alternatives
    - 3.1 Hydraulic
        - 3.1.1 Mechanism for HAB control
        - 3.1.2 Conceptual design
    - 3.2 Alum
        - 3.2.1 Mechanism for HAB control
        - 3.2.2 Conceptual design
4. Methods
    - 4.1 Hydraulic model
    - 4.2 Alternatives analysis calculations
    - 4.3 Failure modes and effects analysis
5. Results
    - 5.1 Hydraulic Alternative Results
        - 5.1.1 Impacts on Stratification
        - 5.1.2 Project maps
            - 5.1.2.1 GIS analysis
            - 5.1.2.2 Model results
    - 5.2 Alternatives analysis
    - 5.3 Failure modes analysis
6. Additional information needed for final design
7. Design recommendation
8. References
9. Appendix

1. Statement of objective

The primary objective of this study was to identify and model possible solutions that may reduce harmful algal bloom (HAB) duration and frequency at Ross Island lagoon. These solutions must protect and not disturb sensitive existing confined aquatic disposal (CAD) cells and create or maintain the existing amount of habitat for native species. Three alternatives were evaluated including no action, a hydraulic solution, and a microbial solution.These alternatives were evaluated using hydraulic modeling in HEC-RAS, GIS, alternative analysis including cost, and failure modes and effects analysis.

2. Current hydraulic conditions

Under current hydraulic conditions there are not sufficient velocities in Ross Island Lagoon to prevent severe temperature stratification. Figure 1 in Appendix 9.1 shows a graph of the temperature profile of Ross Island Lagoon on 6/5/18 at 1:38 pm (Carpenter 2018). The first 10 meters of the lagoon, or the epilimnion, is approximately 17 degrees C which is significantly warmer than the deeper layers of the lagoon. This stratified temperature profile is due to the low velocities in the lagoon and absence of mixing during most of the year. The harmful algal blooms require this temperature stratification during summer months to survive and thrive.

We examined the hydraulic conditions in the lagoon using flows from March 2019. At high (flood) tides water flows into the lagoon entrance, as shown in Figures 2-4 in Appendix 9.1. Water velocities slow significantly as they enter the lagoon and they eventually slow to zero before flowing out the lagoon again. Flows peak at approximately 0.12 ft/s during high tides (Figure 5). During periods of low (ebb) tides, water begins to flow out of the lagoon in the northern section of the entrance and any flow entering the area enters at low velocities at does not penetrate into the middle of the lagoon. The minimum velocity at low tide is approximately 0.06 ft/s. The lagoon entrance is deepest at times of high tide with a maximum depth of about 61 feet at its center (Figure 6). The center of the channel is shallowest at times of low tide with a minimum depth of about 58 ft (Figure 6). This three foot change in depth is not very apparent when observing the middle of the channel, but it becomes more pronounced at the edges of the channel where the water recedes during low tides. The patterns of depth and velocity in the lagoon varies with tidal influences, which increases the complexity of designing solutions for harmful algal blooms.

3. Alternatives

3.1 Hydraulic

<u>3.1.1 Mechanism for HAB control</u>

Hydraulic modifications to Ross Island were designed to increase flow velocities throughout the lagoon and disrupt temperature stratification. A surface channel will be excavated in the northwest portion of the lagoon to provide flow conveyance from the main stem of the river into the lagoon. The entrance of the lagoon will also be expanded to provide increased flow from Holgate Channel into the lagoon and provide cross-current mixing with the surface channel flow. Increasing the velocities in the lagoon facilitates deeper mixing in the top layers of the lagoon and breaks up temperature stratification. This impedes the harmful algal colonies by disrupting their buoyancy mechanisms and altering nutrient supplies.

The surface channel will be located at the point of highest velocities in the main stem of the river to provide maximum flow conveyance. The channel will be lined with concrete and armored with large boulders at the entrance and exit to prevent scour. The channel entrance was expanded and excavated to the same depth as Holgate Channel. A total of 175,000 square feet of material was removed for the expansion.

3.1.2 Conceptual design

The design specifications for the proposed surface channel and entrance expansion are shown below in Figure 1 and Table 1. Note that the surface channel was modeled as a box culvert in HEC-RAS to simplify terrain modifications.

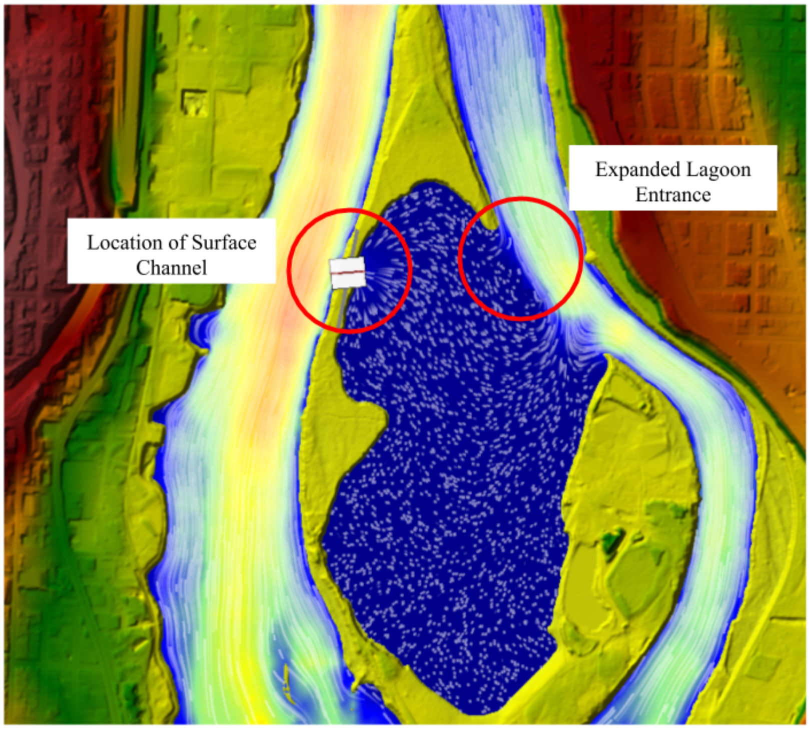

Figure 1*: Location of Hydraulic Modifications*

Table 1*: Hydraulic Design Specifications*

Surface Channel Design	
Width	250’
Depth	40’
Length	400’
US Invert Elevation	-10’
DS Invert Elevation	-15’
Entrance Expansion Design	
Depth Removed	-14’ (from Ross Island Datum)
Area Removed	175,000 ft^2

3.2 Alum

3.2.1 Mechanism for HAB control

Alum is a coagulant that can be used to control HAB by flocculating cells or toxins and allowing them to settle and bind to sediment (Herman, 2017). This flocculation occurs when the coagulant attaches to cells and sediment through a short time period (~ 1 min) of rapid mixing with velocity gradient of 600 to 5000 s^{-1}. This is followed by a longer duration (~ 45 min) of gentle mixing with a velocity gradient of 20 to 50 s^{-1}; which causes these coagulated cells to collide with one another and form larger clumps known as flocc. These collisions are driven by particle to particle interactions including Brownian motion (microflocculation), fluid shear (macroflocculation), and differential sedimentation. As the flocc forms, its density increases until it is greater than that of water, which allows for this sedimentation. After it is settled, the coagulated flocc is able to bind to sediments, preventing cells from floating back to the surface.

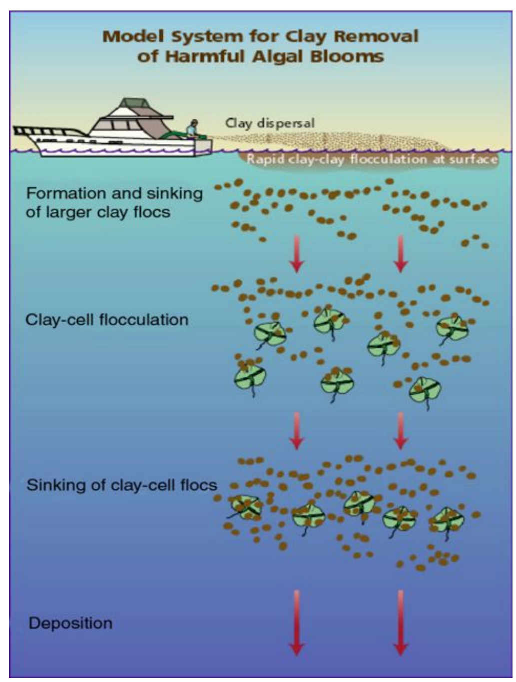

Figure 2: *Conceptual design model of how alum will be distributed and how it will affect the HAB*

4. Methods

4.1 Hydraulic model

Our team developed a 2D unsteady model of the Ross Island Lagoon using HEC-RAS modeling software. We created the existing conditions model of the lagoon using observed discharge and stage height values from March 26-28, 2019. We created the model geometry by importing a terrain file provided by Professor Tullos. We then created a 2D flow area with a computational node size of 100 ft. All 2D hydraulic models require information about boundary conditions that define flow conditions in and out of the modeled flow data. We used three days of hourly discharge data from a USGS gauge for the upstream boundary conditions. We used the same three days of five minute gauge height data for the downstream boundary condition and adjusted the readings for the models datum. Our team improved the model stability and accuracy by adjusting the ramp-up time, theta implicit weighting factor, and the Courant number. We adjusted the ramp-up time to four hours in order to establish more appropriate initial conditions and "warm-up" the model. The Theta implicit weighting factor improves model stability through implicit solutions of the St. Venant equations, but higher theta values result in decreased accuracy. We set theta to 0.8 as this was the largest value that did not cause numerical instability. The Courant number should remain between 0.45 and 1 to optimize run times and accuracy based on the grid size. We adjusted the default minimum Courant number to 0.45.

After we created the existing conditions model, we created a modified model that reflected our proposed hydraulic solution. Our team chose to model the northwest surface channel conveyance as a concrete box culvert. We chose to position the channel at the location of maximum velocities in the western channel. After experimenting with several culvert geometries, we ultimately chose a culvert that is 250 ft wide, 40 ft tall, and 400 ft long. The upstream and downstream invert elevations were -10 and -15 ft, respectively. We modeled the expanded lagoon entrance by editing the outcrop's terrain to match the elevation of Holgate Channel. The elevation of the new terrain is -14 ft from the Ross Island Datum. To edit the terrain we created a polygon feature class that masked the outcrop at the channel opening. This polygon was then converted to a raster with the same spatial resolution as the Sellwood Morrison TIFF file. The two rasters were combined using the *Mosaic to New Raster* function, with the pixel values of the masking raster replacing the values of the Sellwood Morrison raster.

After adding our hydraulic modifications to the model we ran the model for three flow scenarios: low August flows (8/23/18-8/27/18), high April floods (4/9/19-4/15/19), and the March calibration flows (3/23/19 - 3/27/19). We used the modeled velocities at the mouth of the culvert to calculated mixing for each scenario.

4.2 Alternatives analysis calculations

In evaluating alternatives, there were six main criteria used: capital costs, operation and maintenance costs (O&M), habitat loss and creation, effectiveness, likelihood of failure, and species benefitted. To calculate capital and O&M costs, first a list of cost line items were made for each solution, then each line item price was found using the *2019 Building and Construction Costs using RSMeans Data* by Gordian (77th annual edition). Then each line item was multiplied by the number needed; this is where some assumptions were made, such as how many people were needed in a crew, and how many hours of installation the alternative will take. To find the area of habitat loss and created, the ArcGIS model was used to measure the area being excavated and the area of habitat being added. Effectiveness of the hydraulic solution was determined using the HEC-RAS model to evaluate how velocities are changing, however exact flow patterns and mixing are uncertain. Effectiveness of the non-hydraulic solution was approximated through literature reviews, however effectiveness for the lagoon specifically would need to be determined through bench scale pilot tests. The likelihood of failure was estimated using the PFMA scales for severity, likelihood, and detection. To evaluate species benefitted, first the species present at the site was determined, from there the impact of the alternative on each species was evaluated The species that were positively impacted from the results of the alternative are the species benefitted.

4.3 Failure modes and effects analysis

There are three alternatives that were evaluated for this project including doing nothing, excavating a surface channel in the NW section of the island and widening the lagoon entrance, and mixing alum into the lagoon. All three of these alternatives were assessed using the Potential Failure Modes Analysis (PFMA) template provided. The only key design feature for the do nothing alternative is doing nothing. This would likely lead to temperature stratification and an algal bloom. The impact of this would be habitat destruction, possible negative effects on human health, decrease in biodiversity, and a decrease in aesthetic. This is likely to be caused by a lack of circulation and could be controlled by regular observation of the area and could be prevented by a hydraulic or chemical modification of the lagoon. The severity, likelihood, detection, and RPN were determined to be 4, 7, 5, and 140 respectively using the scales provided which can be referenced in Table 10, 11 and 12 in the Appendix.

The key design features identified for the hydraulic solution were armouring, gate, and excavation and these can be seen, mapped out, in Figure 3 below. The processes investigated in the PFMA for this alternative were armouring failure, gate failure, surface channel having insufficient geometry, and the widening of the lagoon entrance being insufficient. These processes had RPN values of 12, 6, 8, and 24 respectively resulting from the PFMA. All of the failure modes, failure effects, causes, controls, and recommended actions for these processes can be seen in Table 9 in the appendix below. All of the RPN values summed to 50 for this alternative.

The third alternative was the microbial solution and the key design features that were identified included mixing propellers, coagulant, flocculates, and application. All of these design features can be seen mapped out in Figure 4 below. The processes identified for PFMA for this alternative included improper flocculation and impacts on the local ecosystem. The evaluation of these processes resulted in RPN values of 18 and 32 respectively. The failure modes, failure effects, causes, controls, and recommended actions that contributed to these scores can be seen in the completed PFMA table below. All of the RPN values for this alternative summed to 50.

The highest RPN was for the do nothing alternative with a value of 140 and the lowest was for the hydraulic and microbial alternatives with the value of 50. The confidence level in these RPN values is moderate due to the error that may be associated with the interpretation of each scale. Even though there could be error associated with this analysis, it is still important to incorporate into the decision of choosing the best possible alternative. This analysis may have some uncertainty, but is one of the only ways to incorporate foreseeable failure into the design decision.

5. Results

5.1 Hydraulic Alternative Results

5.1.1 Impacts on Stratification

The Richardson number (RI) was used to estimate the depth of mixing for three different flow scenarios in the lagoon. The Richardson number was used to estimate mixing because the 2D HEC-RAS model cannot calculate velocities across depth and spread modeled velocities out of the surface channel across the entire depth of the lagoon. Refer to Table 7 in Appendix 9.3 for RI numbers and mixing depths for all flow plans. The maximum velocity that could be achieved from the combination of the northwest surface channel and expanding the entrance of the lagoon was 0.37 ft/s during April flood flows. This velocity substantially decreased the Richardson number from 1069 to 0.78, assuming a mixing depth of 10 m. However, the reduced Richardson number is still above the critical RI number of 0.25 needed for complete mixing. Additionally, this velocity would theoretically only achieve 1.02 ft of mixing which is small relative to the total 33 ft depth of the epilimnion. This hydraulic design configuration achieved RI numbers of 8.84 and 42.8 for the March and August flows, respectively. The lagoon was predicted to mix 1.1 inches for the March velocity of 0.11 ft/s and 0.22 inches for the August velocity of 0.05 ft/s. It is important to note that these velocities represent the best case scenario for mixing as they were taken just outside the mouth of the surface channel during maximum flows for each time period. The levels of mixing predicted at this location are not representative of the entire lagoon and it is likely that little to no mixing will occur at the southern end of the lagoon which was not impacted by either hydraulic modification. It is also important to consider that the harmful algal blooms occur in Ross Island Lagoon during the summer months when river velocities are the lowest. The August flow scenario is the best representation of conditions when blooms would occur. Unfortunately, very little mixing is predicted to occur during this time, so the hydraulic solution will not achieve the levels of stratification disruption desired.

Refer to Figures 11-13 in Appendix 9.1 for velocity contour maps from the March, April, and August flows for our hydraulic design.

5.1.2 Impacts on Shallow Water Habitat

Constructing the culvert leads to the destruction of 32,000 square feet of shallow water habitat, and the expansion of the lagoon entrance leads to the creation of 175,000 square feet of new habitat. Figure 14 in the Appendix shows the changes in habitat. Shallow water habitat is defined as regions with water depth of 20 feet or less (Prescott *et al* 2016). Widening the lagoon entrance excavates the terrain down to 14 feet below the Ross Island Datum, and therefore creates new shallow water habitat. Changes in habitat were calculated by reclassifying the edited terrain to only include the area of habitat between 0 and -20 feet deep.

5.2 Alternatives analysis

Table 2: *Alternative One - Do nothing.*

Criteria	Result	Explanation
Capital Costs	$0	Nothing is being done so there is no initial costs for equipment, materials, nor labor.
Operation and Maintenance Costs	$0	Nothing is being done so there is no operation costs nor maintenance costs.
Habitat Loss/Creation	None	No habitat is being removed nor added. However, habitat may be impacted due to the presence of the HAB.
Effectiveness	None/low	Does not do anything to control or prevent HAB.
Likelihood of Failure	High	Based on PFMA report completed for this alternative, high chance that HAB will worsen by not doing anything to address it.
Species Benefitted	Cyanobacteria	They will not be controlled or inhibited, allowing for continued growth.

Table 3: *Alternative Two - Hydraulic solution including expanding the lagoon entrance and adding a surface channel to the northeast side of the island.*

Criteria	Result	Explanation

Capital Costs	$3,430,549.28	Calculated using *2019 Building and Construction Costs using RSMeans Data* by Gordian (77^{th} annual edition). Assumptions: 20 person installation crew, and 160 hours for installation. See Table 4.
Operation and Maintenance Costs (per year)	$116,418.50	Calculated using *2019 Building and Construction Costs using RSMeans Data* by Gordian (77^{th} annual edition). Assumptions: 2 person operation and maintenance crew, 50 hours per year, and everything is repaired within 4 years (complete replacement costs divided by 4). See Table 5.
Habitat Loss/Creation	143,000 ft^2 gain	Based on the ArcGIS mapping of this alternative, 32,000 square feet of habitat will be lost and 175,000 square feet of habitat will be gained.
Effectiveness	Moderate	Based on the HEC-RAS model of this alternative, additional flow added should help reduce stratification. However exact flow patterns and mixing are uncertain.
Likelihood of Failure	Low	Based on PFMA report completed for this alternative, low chance that amouring failure, exit scour, gate failure, or insufficient flow will occur.
Species Benefitted	Salmon species, birds and waterfowl, aquatic organisms	All of these species will benefit from increased flow in the lagoon and from the reduction in HAB. This will allow salmonids and aquatic organisms to have more dissolved oxygen and reduce exposure to cyanotoxins. This in turn benefits birds and waterfowl as they have easier access to the water surface, more prey available, and that prey is less contaminated.

Table 4: *Alternative Three - Non-hydraulic solution using alum coagulant.*

Criteria	**Result**	**Explanation**
Capital Costs	$72,581.00	Calculated using *2019 Building and Construction Costs using RSMeans Data* by Gordian (77^{th} annual edition). Assumptions: 5 tons of alum, 20 boats to distribute and mix, 5 people per boat, 12 hours of labor. See Table 6.
Operation and Maintenance Costs (per year)	$72,581.00	Calculated using *2019 Building and Construction Costs using RSMeans Data* by Gordian (77^{th} annual edition). Assumptions: same as capital costs, one application per year. See Table 6.
Habitat Loss/Creation	None	No habitat is being removed nor added. However, aquatic habitats may be impacted by the addition of alum through chemical reactions.
Effectiveness	Moderate	Based on *Review and Evaluation of Reservoir Management Strategies for Harmful Algal Blooms* (Herman, 2017), this method had a result of 80% reduction on HAB in Lake Wister, OK. However there are enough uncertainties, such as dosing required to treat the entire lagoon, that effectiveness is not guaranteed. Pilot studies would need to be done in order to accurately predict effectiveness.

Likelihood of Failure	Moderate	Based on PFMA report completed for this alternative, moderate chance that improper flocculation or local ecosystem impacts occur.
Species Benefitted	Birds and waterfowl	The reduction in HAB allows for easier access to the water surface and the aquatic organisms in the water for feeding.

5.3 Failure modes analysis

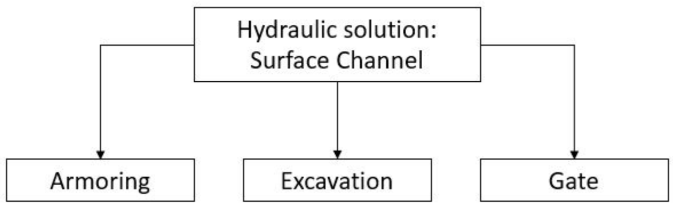

Figure 3*: Key design features of the hydraulic solution*

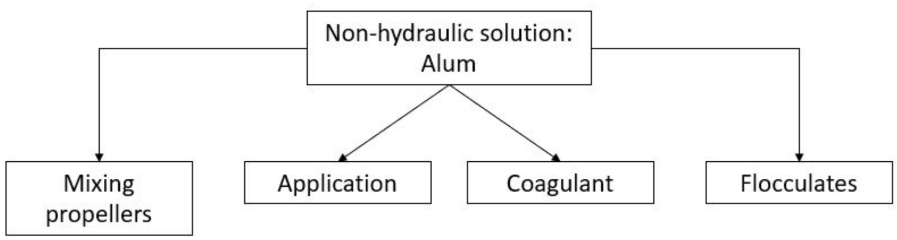

Figure 4: *Key design features of the microbial solution*

6. Design recommendation

Neither the hydraulic or chemical solutions are projected to fully control the HABs. There have been few studies on the use of alum on this scale as an effective method for controlling algal blooms. There is a moderate to high likelihood of failure for this alternative due to the high levels of uncertainty surrounding the proper dosing and mixing requirements for the lagoon. We expect that it could take several years of pilot programs to determine the amount of alum needed and correct mixing procedure to fully control the HABs and effectively control them in the long term. This could be an expensive option as each application of alum is predicted to cost $72,581.00. Alum may also have unintended impacts on the aquatic ecosystem of the lagoon that would need to be studied before the alum was deployed.

The hydraulic solution only resulted in 0.22 inches of mixing during low August flows when the algal blooms are present. This mixing only occured in the northern half of the lagoon at all of the monthly flows analyzed. This suggests that the combination of the norwest surface channel and the entrance expansion is not sufficient to achieve the desired level of mixing in even a small portion of the lagoon during the summer, let alone the entire lagoon area. This alternative is also very expensive with a capital cost of $3,430,549.28 and $116,418.50 in yearly operation and maintenance costs. Additionally, there is also a large amount of uncertainty surrounding this design due to modeling constraints.

We recommend further investigation into alternate hydraulic solutions in the lagoon including additional surface channels or combinations of conveyance methods.

7. Additional information needed for final design

The main source of uncertainty surrounding our proposed hydraulic solution comes from the model we chose to use. The 2D HEC-RAS model cannot accurately represent how flows will spread out over depths or how they will cause mixing. The velocities pulled from this model are likely underestimates of the actual velocities that would occur in the lagoon as HEC-RAS spread the momentum from the surface flows out over the entire 35 meter depth of the lagoon. A 3D hydraulic model of the lagoon could be created to better estimate the amount of mixing across the entire depth profile of the lagoon for the final design.

If the stakeholders decide to pursue the use of alum for the lagoon, we would recommend completing a pilot study to determine the amount of alum needed to control the algae and the most effective methods of mixing it into the lagoon. The estimates we provided for the amount of alum and number of boats needed for application are very rough and will likely be different than the final design requirements. Scientific studies should also be done to study the effects of alum on sensitive species native to the shallow water habitat of the lagoon such as salmonids and wildfowl.

8. References

Carpenter, Kurt. "Temperature profile of Ross Island lagoon on June 05, 2018 at 13:38 pm. United State Geological Survey. 2018

Gordian. *2019 Building and Construction Costs with RSMeans Data*. 77th ed., Construction Publishers and Consultants, 2018.

Herman, Brook, et al. *Review and Evaluation of Reservoir Management Strategies for Harmful Algal Blooms*. Environmental Laboratory (U.S.), 28 July 2017. *Crossref*, doi:10.21079/11681/22773.

Prescott, Chris., Bushman, Mary., Helzer, Dave., Smith, Libby. *Characterization of Current and Historical Habitat and Biological Conditions in the Lower Willamette River through Portland*. City of Portland Environmental Services. 2016. https://www.portlandoregon.gov/BPS/article/581166.

Spann, G and Larson, L. "Unsteady, 2D HEC-RAS Model Tutorial." 2019.

9. Appendix

9.1 Figures

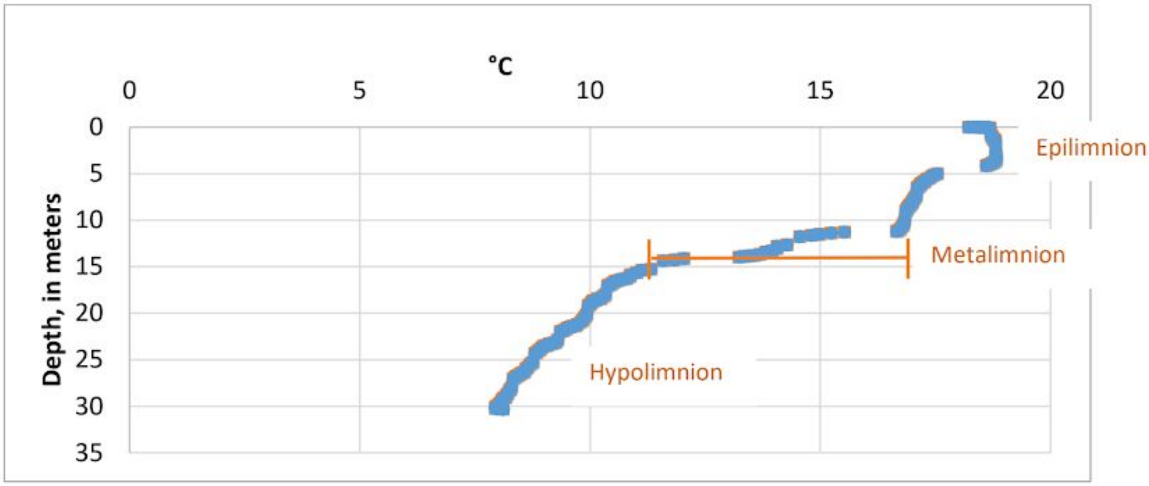

Figure 5: *Temperature profile of Ross Island Lagoon on June 5, 2018 at 13:38 (Source: Kurt Carpenter, USGS)*

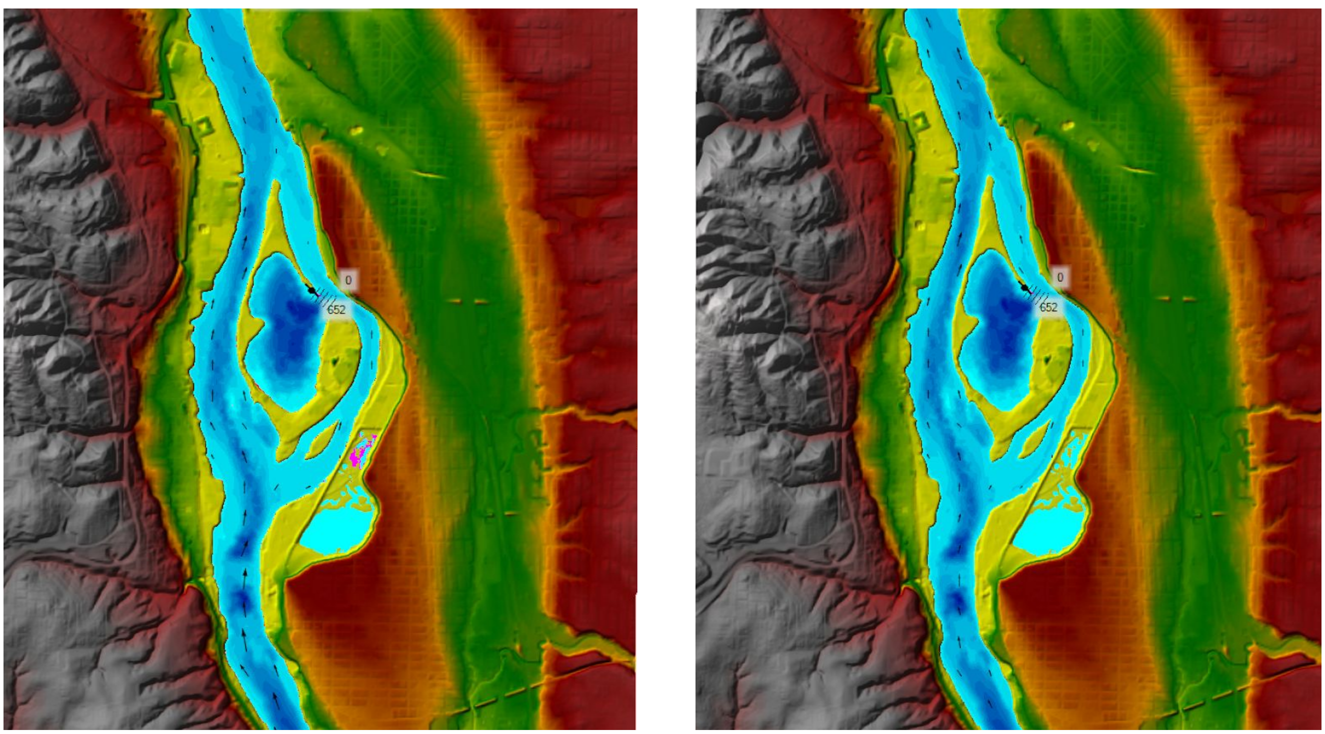

Figure 6: *Velocity Vectors and Depth of Ross Island Lagoon and Channel at Low Tide (left) and Maximum High Tide (right)*

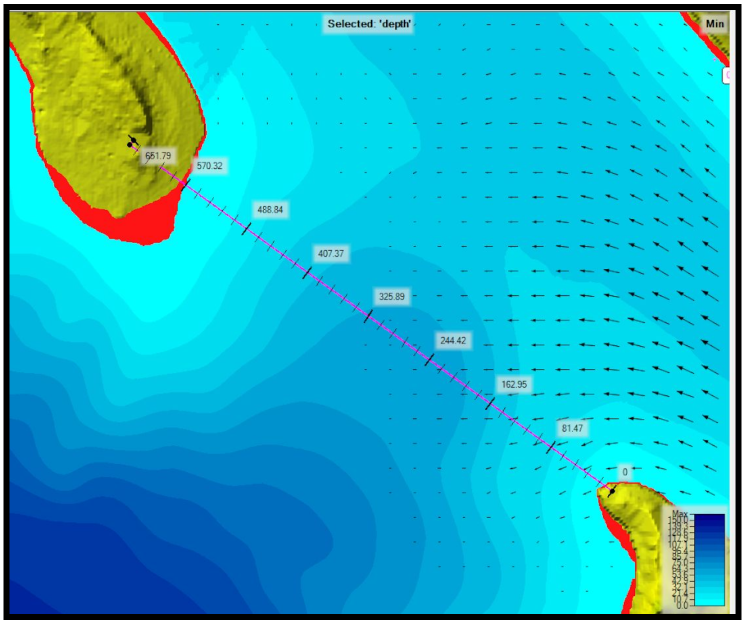

Figure 7: *Zoomed in View of Velocity Vectors and Depth of the Ross Island Lagoon Entrance at Low Tide*

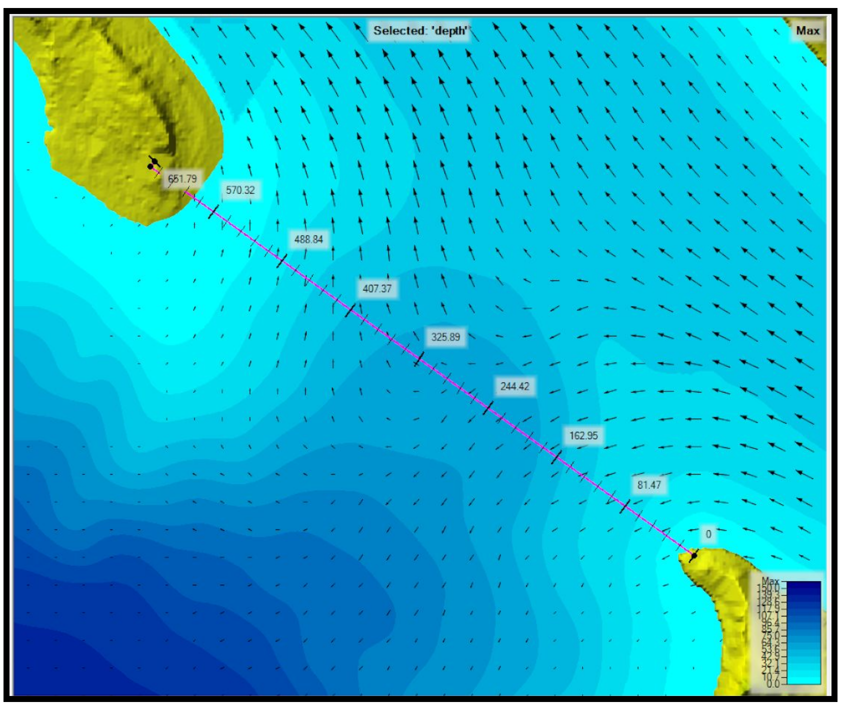

Figure 8: *Zoomed in View of Velocity Vectors and Depth of the Ross Island Lagoon Entrance at High Tide*

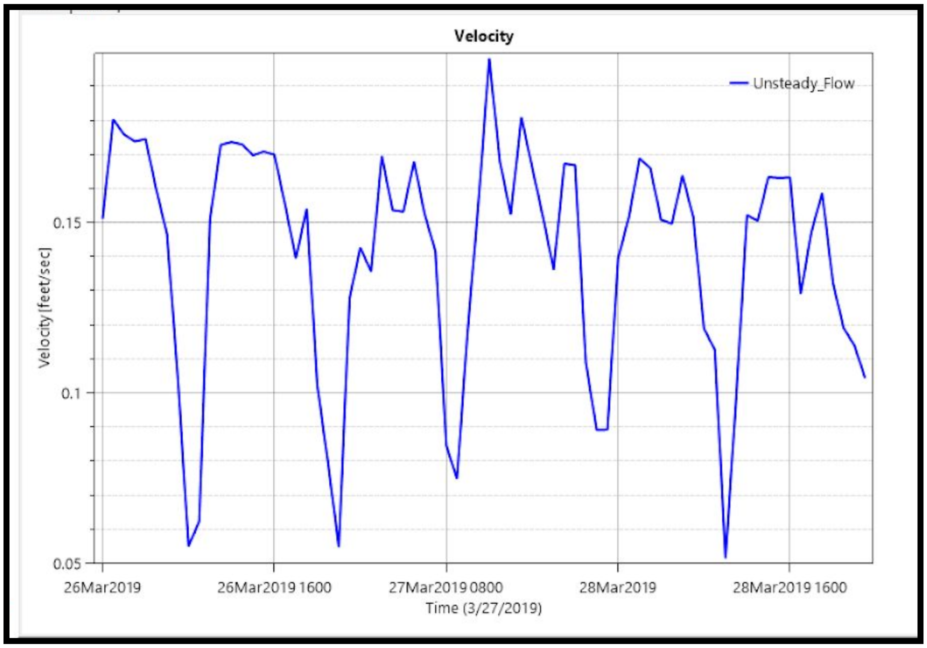

Figure 9: *Velocity at center of Lagoon Entrance from March 26-29, 2019*

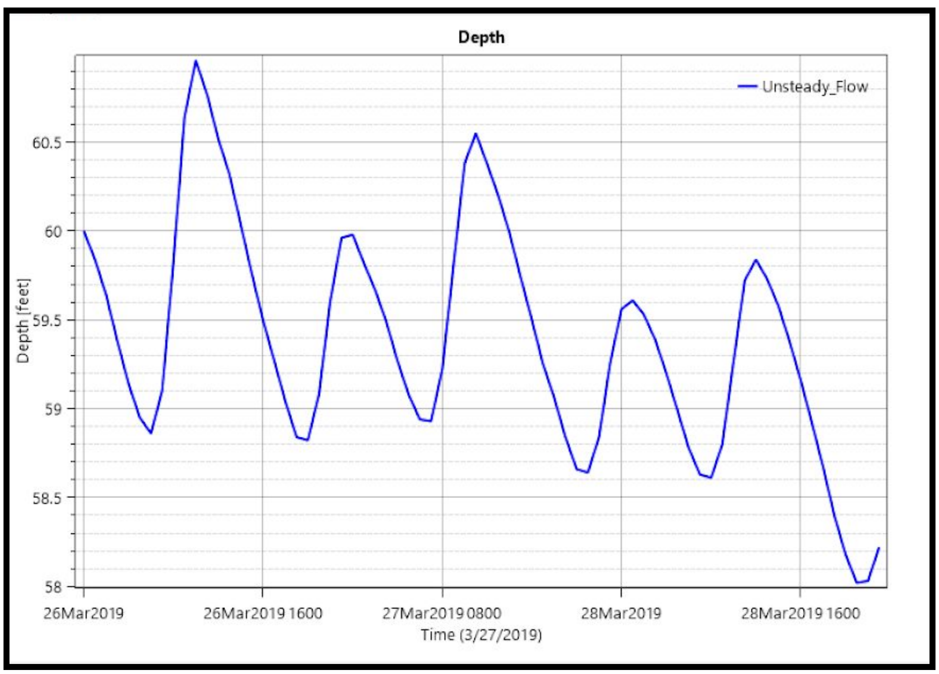

Figure 10: *Depth at Center of Lagoon Entrance from March 26-29, 2019*

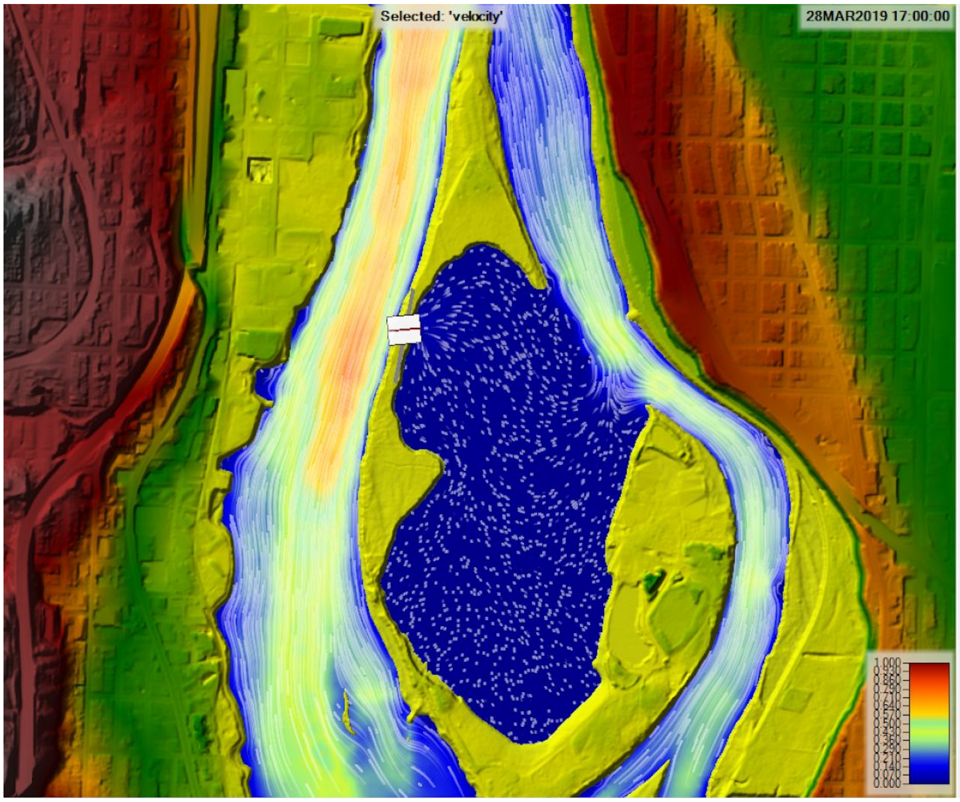

Figure 11: *Velocity Profile for March Flows under New Hydraulic Conditions*

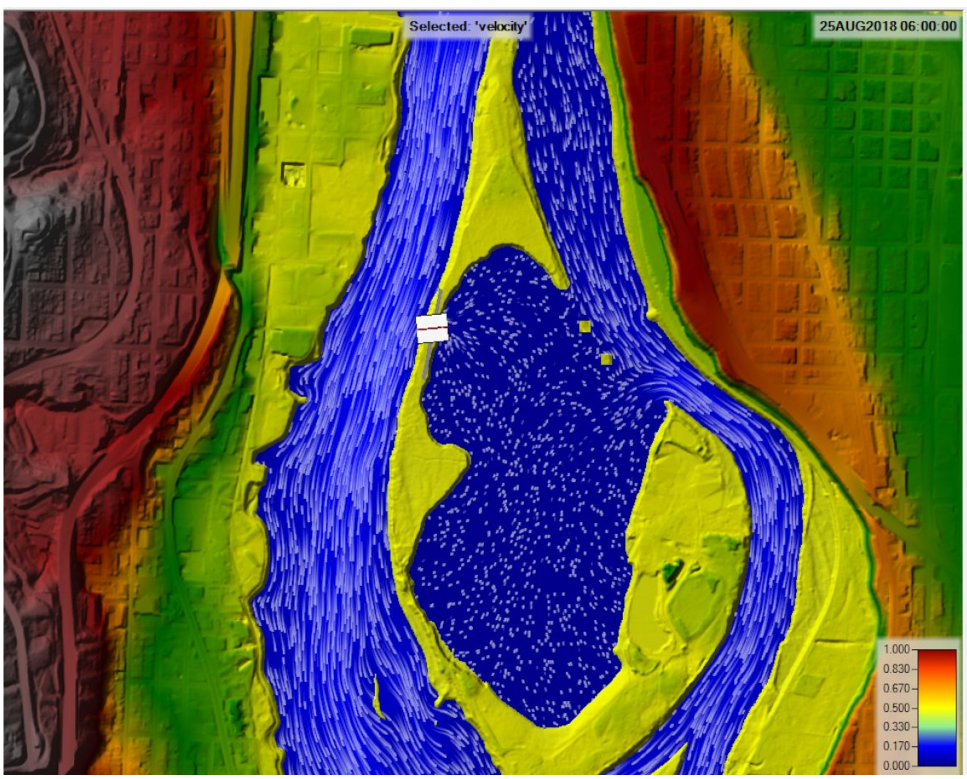

Figure 12: *Velocity Profile for August Flows under New Hydraulic Conditions*

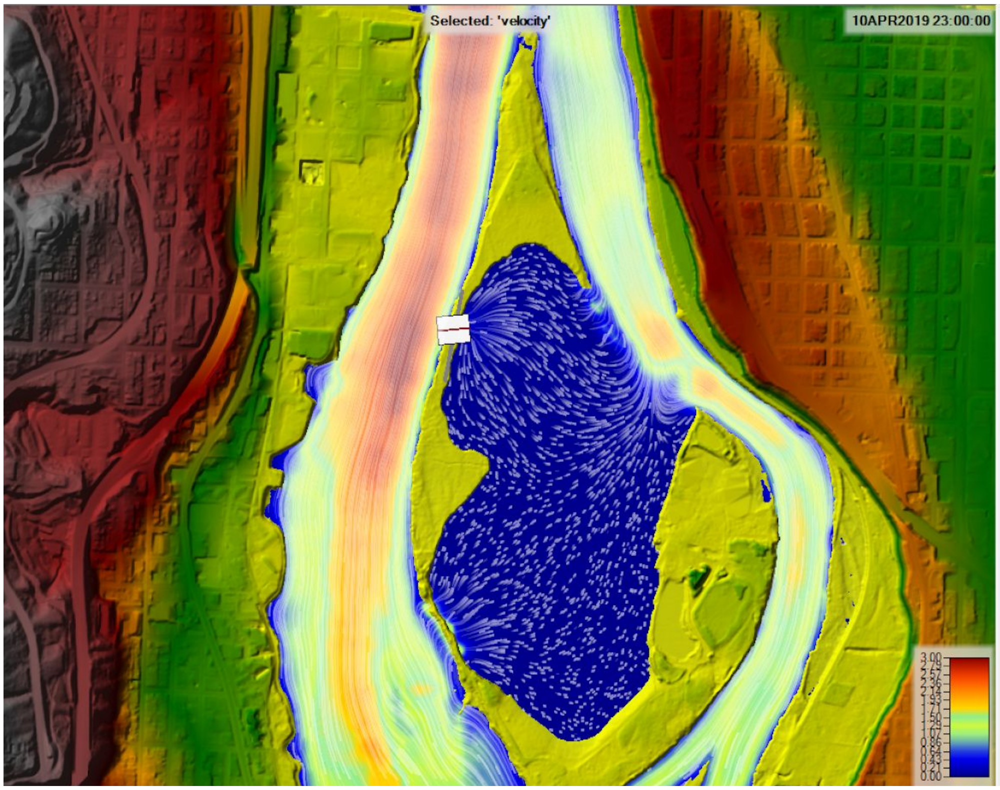

Figure 13: *Velocity Profile for April Flows under New Hydraulic Conditions*

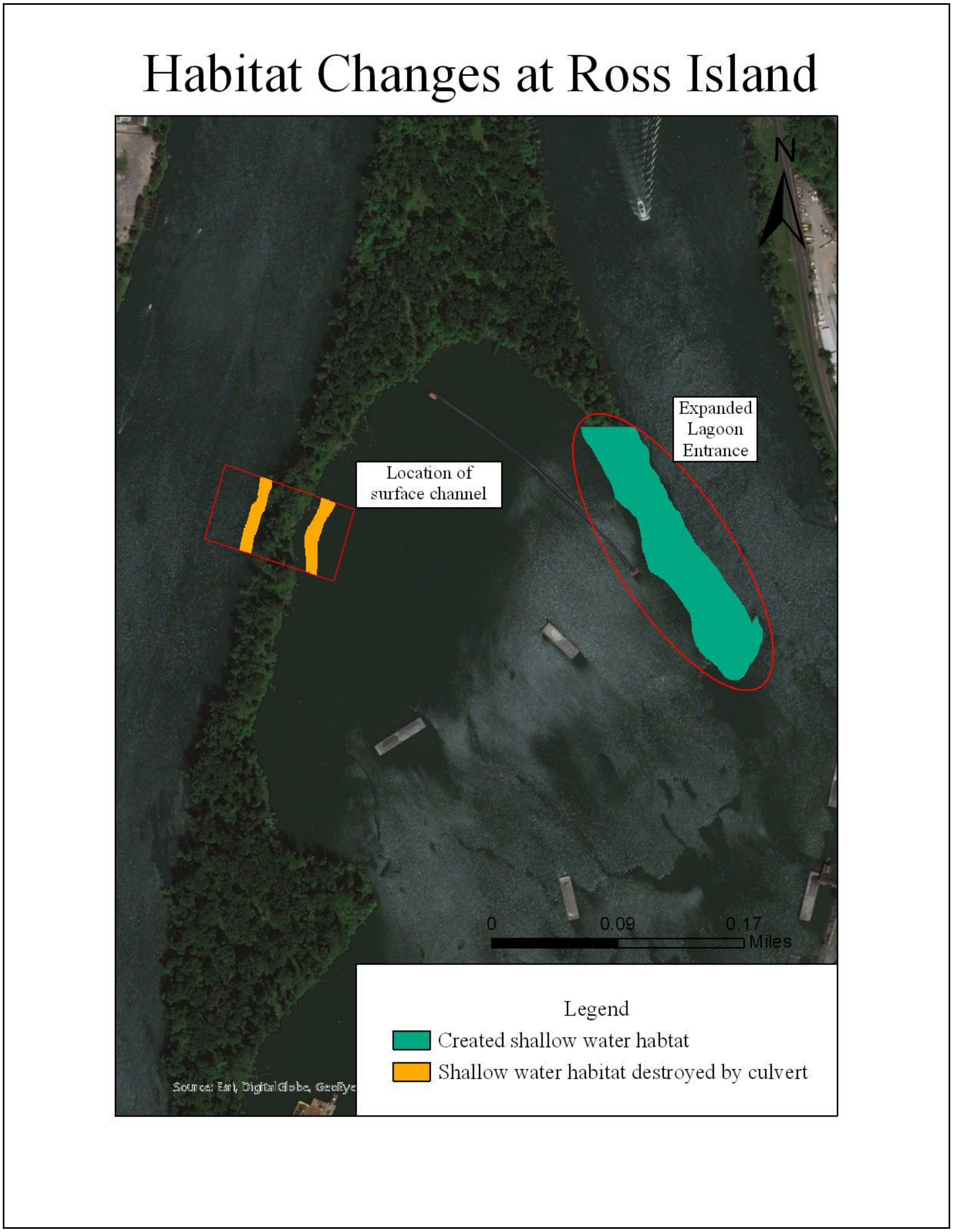

Figure 14: *Changes in Shallow Water Habitat*

9.2 Cost Tables

Table 5: *Alternative 2 - Capital Costs*

Line Item	**Cost**	**Per Unit**	**# Needed**	**Total Cost**
Excavation w/dozer	$8.48	Bank yd^3	352,991	$2,993,363.68
Armoring	$8.48	Bank yd^3	2,045	$17,341.60
Concrete Material (Surface Channel)	$114	yd^3	2,045	$233,130.00
Installation Labor	$57.67	Person	20	$184,544.00
		Hour	160	
Mechanical Gate (Metal)	$6.84	Linear ft	250	$1,710.00
Mobilization	$115	Each crane	2	$230.00
Demobilization	$115	Each crane	2	$230.00

Total: $3,430,549.28

Table 6: *Alternative 2 - Operation and Maintenance Costs*

Line Item	**Cost**	**Per Unit**	**# Needed**	**Total Cost**
Armoring Repair	$8.48	Bank yd^3	500	$4,240.00
Surface Channel Concrete Maintenance	$3.84	ft^2	27,600	$105,984.00
Labor	$57.67	Person	2	$5,767.00
		Hour	50	
Mechanical Gate Maintenance	$6.84	Linear ft	62.5	$427.50

Total per year: $116,418.50

Table 7: *Alternative 3 - Capital & Operation and Maintenance Costs*

Line Item	**Cost**	**Per Unit**	**# Needed**	**Total Cost**
Alum Addition	$200	Ton	5	$1,000.00
Boat Rentals	$118.85	Each	20	$2,337.00
Installation Labor	$57.67	Person	20	$69,204.00
		Hour	160	

Total per application: $72,581

9.3 Hydraulic Results

Table 8: *Richardson Numbers and Expected Mixing Depths for all Flow Events*

	Existing Conditions	March Flows	April Flood	August Low Flows
Max Velocity	0.01 ft/s	0.11 ft/s	0.37 ft/s	0.05 ft/s
RI # (assuming 10 m of mixing)	1069	8.84	0.78	42.8
Depth of complete mixing	negligible	0.09 ft (1.1”)	1.02 ft	0.019 ft (0.22”)
Mixing in entire lagoon?	No, no mixing except right at lagoon entrance	No, still zero velocity at south end of lagoon	No, still zero velocity at south end of lagoon	No, still zero velocity at south end of lagoon

9.4 PFMA Results

Table 9: *PFMA for the alternatives doing nothing (1), surface channel (2), and alum (3)*

Alternative	Process Step	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 5)	Potential Causes	LIKELIHOOD (1 - 7)	Current Controls	DETECTION (1 - 5)	RPN (S * L * D)	Action Recommended
	What is the process or feature under investigation?	In what ways could the process or feature go wrong?	What is the impact if this failure is not prevented?		What causes the process or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?
1	*temprature stratification*	*algal bloom*	*habitat destruction, detrimental to human health (if cyanotoxins are released), decreased biodiversity, decrease aesthetic value*	*4*	*lack of circulation*	*7*	*regular observation or sampling of the area*	*5*	*140*	*hydraulic or chemical modification of lagoon*
2	*armouring failure*	*armouring wasn't high enough and erosion occurs and displacement of armouring*	*the channel widens, will take up wetland area, sediment deposit downstream, might not meet optimum mixing*	*3*	*undersizing rock, miscalculating flows, flows above design flow*	*2*	*design reviews and regular monitoring*	*2*	*12*	*multiple calculations using a factor of safety*
2	*gate failure*	*buckling of gate arms, failure of connections, left open, overtopping*	*habitat damage, lagoon capturing maistem Willamette*	*2*	*inadequate design, improper opperation, aging material, high flood event*	*3*	*monitoring and design review*	*1*	*6*	*Regular maintenance schedule*
2	*surface channel geometry not sufficient for flow conveyance*	*water does not flow through culvert*	*Insufficient mixing for lagoon to stop algal blooms*	*4*	*insufficient design and hydraulic modeling*	*2*	*design reviews and monitoring*	*1*	*8*	*Model design over large range of flows*
2	*Widening of lagoon enterance insufficient*	*not enough flow through widened lagoon enterance*	*Insufficient mixing for lagoon to stop algal blooms*	*4*	*insufficient design and hydraulic modeling*	*2*	*design reviews and monitoring*	*3*	*24*	*Model design over large range of flows*
3	*improper floculation*	*improper dosing, not enough mixing*	*algal blom will persist*	*3*	*propelors don't mix enough, chemical balance is off*	*3*	*pilot studies (right pH and amount of coagulant), make sure propelors get up to a high enough speed, regular observation*	*2*	*18*	*pilot tests to estimate correct dosing*
3	*impact local ecosystem*	*cause algal blooms or chemical imbalances in ecosystem causing deaths of other organisms that were not intended*	*death of different aquatic organisms*	*3*	*overdosing or underdosing the coagulant*	*3*	*studies or calculations of toxicity*	*4*	*32*	*studies, research, calculations*

9.5 PFMA Scales

Table 10: *Severity scale provided for PFMA*

Severity Scale		
Effect	**Criteria: Severity of Effect**	**Ranking**
Catastrophic	Could result in death, permanent or total disability, loss exceeding $1M, or irreversible severe environmental damage that violates law or regulation	5
Critical	Could result in permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, loss exceeding $200K but less than $1M, or reversible environmental damage causing a violation of law or regulation	4
Marginal	Could result in injury or occupational illness resulting in one or more lost work days, loss exceeding $10K but less than $200K, or mitigable environmental damage without violation of law or regulation where restoration activities an be accomplished.	3
Negligible	Could result in injury or illness not resulting in lost work day, loss exceeding $2K but less than $10K, or minimal environmental damage not violating law or regulation.	2
None	No effect	1

Table 11: *Likelihood scale provided for PFMA*

Likelihood Scale		
Likelihood of Failure	**Criteria: Likelihood failure will occur**	**Ranking**
Failure Progression Observed	Performance confirms progression toward failure is occurring. Annualized likelihood of failure is greater than 1/10.	7
Failure Progression Likely	Performance suggests failure is initiating and likely to progress in the near future. Annualized likelihood of failure is between 1/100 and 1/10.	6
Very High	There is direct evidence or substantial indirect evidence to suggest a failure has initiated or is likely to occur in the near future. Annualized likelihood of failure is between 1/1,000 and 1/100.	5
High	A fundamental condition or flaw is known to exist; indirect evidence suggests failure is plausible; and key evidence is weighted more heavily toward “more likely to fail” than “less likely to fail.” Annualized likelihood of failure is between 1/10,000 and 1/1,000.	4
Moderate	A fundamental condition or flaw is known to exist; indirect evidence suggests failure is plausible; and key evidence is weighted more heavily toward “less likely to fail” than “more likely to fail.” Annualized likelihood of failure is between 1/100,000 and 1/10,000.	3

Low	The possibility of failure cannot be ruled out, but there is no compelling evidence to suggest it will occur or that a condition or flaw exists that could lead to initiation. Annualized likelihood of failure is between 1/1,000,000 and 1/100,000.	2
Remote	Several events must occur concurrently or in series to cause failure, and most, if not all, have negligible likelihood such that the failure likelihood is negligible. Annualized likelihood of failure is more remote than 1/1,000,000.	1

Table 12: *Detection scale provided for PFMA*

Detection Scale		
Detection	**Criteria: Likelihood the existence of a defect will be detected by process controls before next or subsequent process**	**Ranking**
Almost Impossible	No known controls available to detect failure mode	5
Low	Low likelihood current controls will detect failure mode	4
Moderate	Moderate likelihood current controls will detect failure mode	3
High	High likelihood current controls will detect failure mode	2
Almost Certain	Current controls almost certain to detect the failure mode. Reliable detection controls are known with similar processes.	1