COASTAL INFRASTRUCTURE RESILIENCE RESEARCH AND DEVELOPMENT

SHORELINE MITIGATION FEASIBILITY STUDY

DULUTH, MINNESOTA

Prepared for:
City of Duluth and St. Louis County

Prepared by:
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1690022045

RAMBOLL

ENVIRONMENT & HEALTH

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1. INTRODUCTION

Duluth, Minnesota is located on the western most shoreline of Lake Superior in St. Louis County in northeastern Minnesota. Portions of the Lake Superior shoreline and associated infrastructure have been damaged as a result of major storm events and ongoing natural erosional processes. The objectives of the Coastal Infrastructure and Resilience Research and Development project are to demonstrate economically feasible methods for reducing shoreline erosion and failure and to provide mitigation recommendations that could be used in similar situations and locations along the lakeshore. This Feasibility Study identifies and evaluates potential mitigation measures for vulnerable shoreline areas and provides the City of Duluth (the City) and St. Louis County (the County) with practical solutions to address shoreline erosion, bank failures, and corresponding infrastructure risks along the North Shore of Lake Superior.

2. BACKGROUND

2.1 Site Location and History

Duluth is known for its port (Port of Duluth-Superior) and consistent shipping traffic into and out of Duluth Harbor. Lake Superior, the largest of the North American Great Lakes, experiences fluctuating water levels over time and large storms throughout the year, which can lead to erosion along susceptible stretches of shoreline. Over the past decade, record high and low water levels, along with several storm events, have lead to erosion along the North Shore.

The site is separated into two sections, the North Shore and Park Point Recreation Area. The North Shore section consists of shoreline from the northern boundary of Brighton Beach to the mouth of the Knife River, as outlined in Figure 1. The Park Point Recreation Area consists of the recreational fields and harbor facing shoreline. This Feasibility Study focuses on shoreline stabilization alternatives for the North Shore; options for mitigating erosion in the Park Point are provided in a separate Feasibility Study.

2.2 Site Characterization

2.2.1 Topography

Duluth is positioned on the western-most shore of Lake Superior, which is situated approximately 600 feet above mean sea level (AMSL). Much like Duluth, a majority of the North Shore has a steep hillside leading to the lake as a result of geology and geomorphological processes.

2.2.2 Hydrodynamics

Lake Superior currents generally display movement in a counterclockwise pattern around the lake. Although this current direction is the main pattern observed, wind and waves often are the dominant influence on the lake's hydrodynamics. While the prevailing winds of Lake Superior are from the west/southwest, the wind direction on the lake fluctuates frequently and is controlled by short-term weather patterns and cyclonic weather patterns. As a result of the length of Lake Superior east to west, winds originating from the northeast generate the most wave energy due to the longest possible fetch and associated seiche. Because of the size of Lake Superior, it is not uncommon for large storm systems to form over the lake, causing wind direction to shift drastically. In addition to the energy of waves caused by wind and currents, the western edge of Lake Superior, where Duluth is located, is shallow compared to the rest of the lake, forcing waves entering this section of Lake Superior to break with strong forces on the shoreline, contributing to erosion.

Lake Superior's lake levels naturally fluctuate over time. From 2013 to 2019, average lake levels increased to their highest point since the late 1980s. This combined with the aforementioned storms has resulted in wave action at higher shoreline elevations, resulting in greater erosion potential along the North Shore.

2.2.3 Geology

The North Shore consists of igneous and sedimentary bedrock with overlain unconsolidated sediments. The igneous bedrock formed as a result of continental rifting, resulting in both volcanic and intrusive rocks that ourcrop today. Once the rifting ceased and rocks started to cool, the newly formed bedrock began to subside, causing sediment to fill the rift valley. Those sediments eventually turned to sandstone and can be seen outcropping along sections of the North Shore. As glaciers advanced and retreated over time, the more erodible sandstones were carved out, while the igneous rocks lining the edge of the rift were more resilient and formed the edge of the Lake Superior Basin. Approximately 11,000 years ago, the continental glaciers retreated for the final time and meltwater filled the lake basin, where lake levels fluctuated until the modern day Lake Superior was formed. In its current setting, the shoreline of Lake Superior contains a variety of characteristics based on its geologic history. The interface between unconsolidated sediments and bedrock is observed at different elevations along the North Shore. When the interface is located at lower elevations, the bluff is more susceptible to wave action, whereas interfaces located at higher elevations are better protected from erosion caused by lake-related events. Through time, freeze-thaw cycles, along with other weathering and erosional processes, has caused much of the bedrock shoreline along the North Shore to become highly fractured. Weak points in the rocks are more susceptible to additional erosion from storms and other high wave energy events on Lake Superior.

2.2.4 Shoreline Vegetation

There are a number of species of mature trees along the North Shore, including red pine (*Pinus resinosa*), jack pine (*Pinus banksiana*), eastern white pine (*Pinus strobus*), black spruce (*Picea mariana*), white spruce (*Picea glauca*), quaking aspen (*Populus tremuloides*), paper birch (*Betula papyrifera*), red maple (*Acer rubrum*), sugar maple (*Acer saccharinum*), American elm (*Ulmus americanus*), green ash (*Fraxinus pennsylvanica*), bur oak (*Quercus macrocarpa*), American basswood (*Tilia americana*), and other species. These mature trees are located in the least disturbed areas, or pocket zones such as next to or on private property; there are also smaller trees of these species along the coastline. There are also clusters of shrub species along the shoreline primarily consisting of willows (e.g., *Salix bebbiana,* and *Salix petiolaris*), smooth shadbush (*Amelanchier laevis*), redosier dogwood (*Cornus sericea*), pin cherry (*Prunus pensylvanica*), and smooth rose (Rosa blanda). The shoreline also features forbs such as dogbane (*Apocynum androsaemifolium*), harebell (*Campanula rotundifolia*), large-leaved aster (*Eurybia macrophylla*), anise root (*Osmorhiza longistylis*), giant goldenrod (*Solidago gigantea*), long-leaved starwort (*Stellaria longifolia*), Lindley's aster *(Symphyotrichum ciliolatum*), blue verbane (*Verbena hastata*), Labrador violet *(Viola labradorica*), smooth white violet (*Viola macloskeyi var. pallens*), and other species.

3. HIGH-PRIORITY SHORELINE AREAS

To identify high-priority shoreline areas at risk of failure or associated asset loss, Ramboll conducted a shoreline risk assessment, as outlined in the document "Shoreline Risk Assessment and Prioritization" (Ramboll, 2022). Using a combination of satellite imagery, drone footage, and visual observations along the North Shore, Ramboll evaluated the shoreline risk based on three categories:

1. presence and value of asset;
2. shoreline stability; and
3. distance from shoreline to asset.

The three categories were scored on a scale of 1 to 3, with 1 signifying less value or lower risk and 3 signifying greater value or higher risk. The criteria for scoring each category are outlined below. The values were then summed across the three categories to generate a rating of 3 (lowest priority) to 9 (highest priority). Scores of 8 and 9 were identified as being high priority locations.

Score	Presence and Value of Asset	Shoreline Stability	Distance from Asset to Shoreline
1	No assets present	Hardened feature No visible erosion	> 50 feet
2	Turn outs, fish hatchery	Bluff < 10 feet Heavily vegetated Some shoreline protection	< 50 feet
3	Roads, culverts, residential properties, utilities, historical sites, WTP	Bluff > 10 feet Little to no vegetation Visible evidence of erosion	~0 feet, currently impacted

A total of 20 locations (approximately 2.0 miles total) had a shoreline prioritization score of 8 or 9. The location of these high-priority areas are provided in Figure 2. Photographs of all 20 high priority locations along with changes between 2021 and 2022 are provided in Appendix A.

Following the identification of the high priority locations, these locations were categorized into four groups with similar characteristics:

A. steep/tall failure, sediment based;

B. steep/tall failure, bedrock exposed;

C. shallow/short failure, sediment based; and

D. shallow/short failure, bedrock exposed.

The categorization of high priority shoreline areas into these groups is based on observations from the drone footage and include an evaluation of failure type/geomporphology, geology, and size of failure. Shoreline stabilization alternatives were then identified and evaluated for each these four groups of high priority areas.

4. SHORELINE MITIGATION ALTERNATIVES

Shoreline erosion and slope instability along Lake Superior is a multifaceted problem. Slopes failure results when forces acting on soil masses become stronger than the cohesive forces holding the soil particles together. Erosion can take place along soil grain boundaries and along large surfaces called failure planes. In addition to soil type and soil cohesion, other conditions that influence slope stability are the amount, type and condition of vegetative cover; the presence and route taken by surface water moving from the land to the lake, and lake currents and waves. In the case of the North Shore, these processes are resulting in slope failures and land loss. While the rate of change varies, areas with less erosion protection, both natural and engineered, have shown higher rates of erosion.

Several mitigation alternatives were assessed for each of the identified high-priority areas. The alternatives were then narrowed for each similar group of failure described in Section 3. The remedy evaluation considered potential Engineering with Nature (EWN®) enhancements to promote natural and nature-based features where feasible. In addition, traditional, hardened approaches, such as steel piling, armor stone revetment, and retaining walls were reviewed. Descriptions of the various alternatives reviewed are included in Appendix B.

There are three basic slope stabilization strategies, when relying on natural and nature-based solutions: 1) vegetation enhancement, 2) reshaping the slope, and 3) toe protection. Planting vegetation is a simple, cost-effective green strategy. Reshaping the slope can improve stability if there is sufficient space between an asset and the edge of the slope. Adding toe protection such as rip rap prevents further erosion at the shoreline.

Additional conditions that contribute to slope failure is the movement of surface water into the ground through fractures in clay layers or water seeping through sand layers and lenses behind the slope face. Therefore, it is necessary to understand and address any instability as a result of upland surface water runoff or groundwater migration prior to implementing the selected shoreline mitigation alternative. In areas where it is practical, reducing the amount of surface/groundwater reaching the bluff will contribute to shoreline stabilization. Where diversion is not possible, it will be necessary to create an alternative route for the water to travel, such as through a drain outlet or French drain system.

- *Drain outlet* - If it is feasible to collect existing surface water along the top of bluff, a drainpipe can be installed from this collection area that is directed to the bottom of the bluff. Rock should be placed around the outlet to prevent erosion at the bottom of the drain.
- *French drain system* - Surface water and some ground water can be drained before it reaches the bluff by installing a French drain which is a narrow trench set back from, but parallel to, the top of the bluff and filled with free-draining sand or gravel. A perforated, corrugated pipe at the bottom collects water and drains it away from the bluff. The entire perforated length of pipe must be wrapped with fabric or a filter sock. Installing deeper drains will intercept more ground water and provide better protection for the bluff.

The following shoreline stabilization alternatives were identified for each of the four shoreline categories listed in Section 3. Although the alternatives are similar for each of the four shoreline categories, the effectiveness, implementability, and cost for each alternative can differ across the four shoreline categories during the evaluation of the alternatives, as discussed in Section 5.

- ***Alternative 1 – Managed Retreat or Reconfiguration*:** This strategy involves moving the asset away from the failure zone or reconfiguring the top of slope to allow for natural erosion to continue without financial or safety concerns for the asset.
- ***Alternative 2 – Nature-Based Slope Stabilization*:** Slope stabilization strategies include planting of deep-rooted vegetation, reshaping the slope, toe protection, or a combination of these strategies. Reshaping the slope may include:
    - reducing the angle of the slope where sufficient space is available;

  - terracing the slope with improved vegetation;
  - filling and regrading the failed slope area to the smallest slope angle possible and strengthening the slope with geogrid reinforced soil, stone reinforcement at the toe of the slope, or a combination of two or more of these; and/or
  - creating a living shoreline, which provides erosion control techniques that mimic natural, native habitat, and provides increased opportunities for species diversity and productivity; living shorelines can serve to improve water quality and the ecological integrity of the area.
- ***Alternative 3 – Hardened Protection*****:** Hardened protection options include the following:
  - Retaining walls, which are vertical structures or walls designed to prevent erosion; materials may include steel, wood and concrete.
  - Sloped revetments, which are constructed of hard materials such as rock or concrete and placed on the banks to absorb energy from incoming wave action; revetments are usually built to preserve the existing uses of the shoreline and protect the slope from erosion.
  - Articulated Concrete Blocks (ACBs) are made of a matrix of individual concrete blocks placed together to form an erosion-resistant overlay with specific hydraulic performance characteristics. The system includes a filter underlay that allows infiltration and exfiltration to occur while providing particle retention of the soil subgrade. The filter layer may be comprised of a geotextile or properly graded aggregate or both. The blocks within the matrix must be dense and durable while providing a matrix that is flexible and porous.
- ***Alternative 4 – No Action*****:** The no action alternative would allow continue subsidence, as erosion and scour result in further shoreline retreat and degradation. However, there may be areas in which the most feasible alternative is to monitor the area over time to determine if or when an active solution is necessary.

Table 1 summarizes the pros and cons of each of these alternatives. Preliminary concepts were developed and discussed with the City, including benefits and limitations of different technologies and where and how they may be applied to the priority areas.

5. EVALUATION OF MITIGATION ALTERNATIVES

An evaluation of the shoreline stabilization alternatives for each category outlined in Section 3 was conducted to identify an effective, implementable, and cost-effective approach for stabilizing the high-priority areas along the North Shore. The alternative approaches consider nature-based approaches that are robust and resilient enough to stabilize the shore and adapt to future changing conditions. The focus of the evaluation was an integrated approach that combines green and grey-solutions and associated best practices to protect critical infrastructure, restore habitat, and provide long-term resiliency. This integrated approach recognizes the need for some hardened infrastructure, while also recognizing the limitations of such infrastructure to provide habitat and aesthetic value.

For each of the identified alternative, an assessment was performed to include the following.

- *Long-term effectiveness and resilience* - This criterion evaluates the alternative for long-term effectiveness and permanence with respect to the ability to maintain shoreline stabilization. Factors considered under this criterion include the potential for additional erosion or slope failure after implementation.

- *Implementabilty* - The implementability criterion evaluates the feasibility of implementing an option in terms of practical considerations including design considerations, availability of services, materials and equipment, monitoring requirements, access, limitations, regulatory, political and community acceptance, and permitting requirements.
- *Operation and maintenance (O&M) requirements* – This criterion evaluates the need and extent of maintenance required for the mitigation alternative to remain effective over time. The costs associated with O&M are captured within the costs criterion.
- *Costs* - The cost criterion evaluates the cost of the alternative by considering the scope of work to be completed under the alternative including grant funding costs, capital costs, and installation and monitoring costs.

Table 2 summarizes the evaluation of each of the four alternatives against the evaluation criteria for each group of shoreline characteristics/failure type. Each mitigation alternative was assigned a score between 1 and 5 for each evaluation criterion, with 1 representing an option that is less effective and implementable and/or with more O&M and higher cost, and a score of 5 representing an option that is more effective and implementable and/or with less O&M and lower cost. The values were then summed together across each alternative, such that a lower score represents a less preferred alternative and higher score represents a more preferred alternative (Table 2).

The stabilization alternative with the highest score is typically slope stabilization and/or hardened toe protection for each shoreline failure type. In addition, managed retreat may be a preferred option for shallow/short failure areas depending on the presence and location of the assets at these locations. The results of the evaluation in Table 2 were used to identify recommended mitigation alternatives for the North Shore high-priority areas, as further discussed in Section 6. As shown on the table many of the scores are similar. Each location needs to be evaluated independently to determine the best recommended option.

6. RECOMMENDED MITIGATION ALTERNATIVES

Based on the findings from the evaluation of the mitigation alternatives against the four criteria outlined in Section 5 and Table 2, recommended alternatives were identified for each of the 20 high-priority sites. The proposed mitigation approaches for each high-priority area are summarized in Table 3 with a preliminary cost for comparison. Photos of these locations with the comparisons of the alternatives and preliminary costs are also included in Appendix C.

The costs identified in Table 3 were derived from a combination of RS Means, prior construction projects by Ramboll, and prior bid prices from City of Duluth shoreline repairs. Other cost assumptions included the following:

- Several of the locations will include a combination of identified alternatives.
- Costs include design, permitting, construction and oversight.
- Costs are preliminary for budgetary purposes only (-10% + 30%).
- Costs for upland water control will be option specific and evaluated for each project.
- Costs for additional vegetation other than seeding will be on a site-specific basis.

Following additional discussions with the City and the County, a preferred mitigation option for each priority area will be selected. Once mitigation measures have been identified, Ramboll will work with the City and the County to identify grant opportunities and to prepare grants to financially support the implementation of the selected shoreline mitigation measures.

7. REFERENCES

Ramboll US Consulting. 2022. Shoreline Risk Assessment and Prioritization, Duluth, Minnesota. March.

TABLES

TABLE 1

Shoreline Stabilization Alternative Pros and Cons

Alternative		Pros	Cons
1. Managed Retreat or Reconfiguration		Keeps area open to the public, allows time to review other slope repair options	Bank erosion is likely to continue. Loss of infrastructure and public assets
2. Slope Stabilization	Physical Stabilization	Increases stabilization of bluff, limited maintenance requirements	Treatment consideration subject to accessibility to reshape slope, minimal habitat enhancement Vegetation restoration required after slope changes
	Biostabilization	Effectiveness increases with time as vegetation becomes permanently established, use of live woody vegetation provides erosion control, habitat uplift, and improves aesthetics/visual resource	Treatment consideration subject to availability of plant materials, requires maintenance, labor intensive
3. Hardened Toe Protection	Riprap revetment	Increases protection should lake levels rise again, easily installed, material readily available	No habitat enhancement, increased scour at toe and ends of installed riprap
	Concrete retaining wall or Tieback sheet pile wall	Increases resistance to wave energy, life-span of practice is usually significant and can be prolonged with proper maintenance	Treatment often not viewed as aesthetically pleasing, no habitat enhancement
4. No Action		No initial investment	No active repair or mitigation Erosion and shoreline migration continues

Table 2: Evaluation of Stabilization Alternatives by Shoreline Category

Failure Category	Option	Long Term Effectiveness and Resilience	Cost	Operations and Maintenance Requirements	Implementability		Comments
		1-Least Effective 5-Most Effective	1-Highest Cost 5-Least Cost	1- Most O&M Required 5-Least O&M Required	1-Least Implementable 5-Most Implementable	Total	
A. Steep/tall failure, sediment based	Managed Retreat	5	1	5	1	12	Majority of Type A locations would require moving roadway and utilities with limited publicly owned space.
	Slope Stabilization	4	3	3	4	14	Along with slope stabilization many locations will also require additional hardened toe protection. The effectiveness will increase with time, as vegetation becomes permanently established. The use of live woody vegetation provides erosion control, habitat, and aesthetics.
	Hardened Toe Protection	5	2	4	5	16	No habitat enhancement, increased scour at edges of installed rip rap.
	No Action	1	3	1	5	10	Will ultimately result in continued slope failure and potential infrastructure loss - Costs associated with continual maintenance
B. Steep/tall failure, bedrock exposed	Managed Retreat	5	1	5	1	12	Majority of Type B locations would require moving roadway and utilities with limited publicly owned space.
	Slope Stabilization	4	4	3	4	15	The effectiveness will increase with time, as vegetation becomes permanently established. The use of live woody vegetation provides erosion control, habitat, and aesthetics.
	Hardened Toe Protection	5	3	4	2	14	No habitat enhancement, increased scour at edges of installed rip rap.
	No Action	1	4	1	5	11	Will ultimately result in continued slope failure and potential infrastructure loss
C. Shallow/short failure, sediment based	Managed Retreat	5	1	5	1-4	12-15	Implementability 1-4 depending on location/asset.
	Slope Stabilization	3	3	3	4	13	The effectiveness will increase with time, as vegetation becomes permanently established. The use of live woody vegetation provides erosion control, habitat, and aesthetics.
	Hardened Toe Protection	5	2	4	5	16	No habitat enhancement, increased scour at edges of installed rip rap.
	No Action	1	3	1	5	10	Will ultimately result in continued slope failure and potential infrastructure loss. Higher mainteanance costs than exposed bedrock areas
D. Shallow/short failure, bedrock exposed	Managed Retreat	5	1	5	1-4	12-15	Implementability 1-4 depending on location/asset.
	Slope Stabilization	3	3	3	4	13	The effectiveness will increase with time, as vegetation becomes permanently established. The use of live woody vegetation provides erosion control, habitat, and aesthetics.
	Hardened Toe Protection	5	2	4	5	16	No habitat enhancement, increased scour at edges of installed rip rap.
	No Action	1	4	1	5	11	Will ultimately result in continued slope failure and potential infrastructure loss

Table 3: Summary of Mitigation Alternative Evaluation

ID	Failure Category	Alternatives	Potential Nature-Based Enhancements*	Approximate Total Cost**
0.5	B	Geogrid reinforced slope with toe protection and upland water management	Additional deeper rooted vegetation on bluff face	$720,000
		Toe protection with geotextile and stone to 20’ Geogrid/ Vegetation above with upland water management		$850,000
1.2	B	Geogrid reinforced slope and upland water management	Additional deeper rooted vegetation on bluff face	$510,000
		Reshape and install articulated concrete – upland water management		$880,000
1.3	B	Retaining wall to match outfall wall structure	Additional vegetation at crest	$540,000
		Sheet Pile with tieback system		$700,000
2.9	C	Managed retreat of pullout area - stone along bank	Enhanced vegetation around pullout	$630,000
		Retaining wall with repair or replacement of turnout		$1,430,000
3.6	A	Managed retreat of pullout area - Articulated concrete on bluff - upland water flow management worked in to pullout area	Possible permeable pavers for pullout area	$930,000
		Regrade add geogrid reinforced slope with additional toe protection and surface water capture from pullout		$1,055,000
3.9	A	Geogrid reinforced slope and upland water management	Additional vegetation on bluff face	$1,140,000
		Reshape and install articulated concrete – upland water management		$1,530,000
4.4	B	Geogrid reinforced slope and upland water management		$570,000
		Continued monitoring		$50,000
4.9	A	Reshape with reinforced stone – reuse where possible limited toe protection with management of surface water	Enhanced vegetation top of slope	$970,000
		Reshape with reinforced vegetation and toe protection with management of surface water		$1,100,000
5.0	A	Managed retreat of turnout - Reshape and add reinforced stone bank	Possible permeable pavers for pullout area	Note 1
		Reshape and add reinforced stone bank - will require repair or replacement of turnout if needed		$480,000
5.3	A	Geogrid reinforced slope with toe protection and upland water management	Additional deeper rooted vegetation on bluff face	$1,300,000
		Reshape with stone up 10 feet and vegetation above, toe protection and water management		$1,300,000

Table 3: Summary of Mitigation Alternative Evaluation

ID	Failure Category	Alternatives	Potential Nature-Based Enhancements*	Approximate Total Cost**
7.1	C	Reshape and add reinforced stone		$480,000
		Sheet Piling with tiebacks - will likely require repairs to turnout after installation		$770,000
8.5	A	Reshape and add articulated concrete along bank with upland water management		$4,000,000
		Reshape with reinforced vegetation, toe protection and water management	May be able to reuse some existing riprap to decrease cost	$4,700,000
9.6	A	Geogrid reinforced slope and upland water management	Additional deeper rooted vegetation on bluff face	$480,000
		Reshape - reinforce with stone to 15 feet vegetation above - redirect surface water		$650,000
10.3	A	Geogrid reinforced slope with toe protection and upland water management	Additional deeper rooted vegetation on bluff face	$4,100,000
		Reshape with stone to 20 feet vegetation above, toe protection and water management		$4,450,000
10.9	D	Reshape – Geogrid with vegetation redirect surface water flow	Additional deeper rooted vegetation on bluff and crest	$400,000
		Monitor Erosion	Additional deeper rooted vegetation on bluff and crest	$50,000
11.9	A	Geogrid reinforced slope and upland water management		$1,200,000
		Reshape – Geotextile with stone to 15 feet – vegetation above		$1,700,000
12.0	C	Move turnout closer to roadway - repair outfall		Note 1
		Monitor Erosion		$50,000
14.1	A	Geogrid reinforced slope and upland water management-repair existing retaining wall as needed	Additional deeper rooted vegetation on bluff and crest	$480,000
		New Retaining Wall		$800,000
14.3	C	Reshape and add reinforced stone bank	Additional deeper rooted vegetation on bluff and crest	$3,000,000
		Reshape – Geogrid reinforced vegetation with additional toe protection		$3,400,000
15.2	C	Tie in additional rip rap to existing protection		$283,000
		Monitor Erosion		$50,000

Note 1 - Dependent on Utility corridors and access and cost of excess property,

* Not included in proposed costs but could be added to the alternative selected

**Costs are preliminary for budgetary purposes only (-10% + 30%)

FIGURES

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North Shore Study Area
Park Point Study Area
City of Duluth Boundary

0 0.5 1 Miles

SITE LOCATION MAP

COASTAL INFRASTRUCTURE RESILIENCE RESEARCH AND DEVELOPMENT

FIGURE 01

RAMBOLL US CORPORATION
A RAMBOLL COMPANY

North Shore Primary Locations

0 0.5 1 Miles

HIGH PRIORITY SHORELINE LOCATIONS

COASTAL INFRASTRUCTURE RESILIENCE RESEARCH AND DEVELOPMENT

FIGURE 02

RAMBOLL US CORPORATION
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APPENDIX A

HIGH PRIORITY AREAS CHANGES FROM 2021 TO 2022

Appendix A

High Priority Areas

Legend

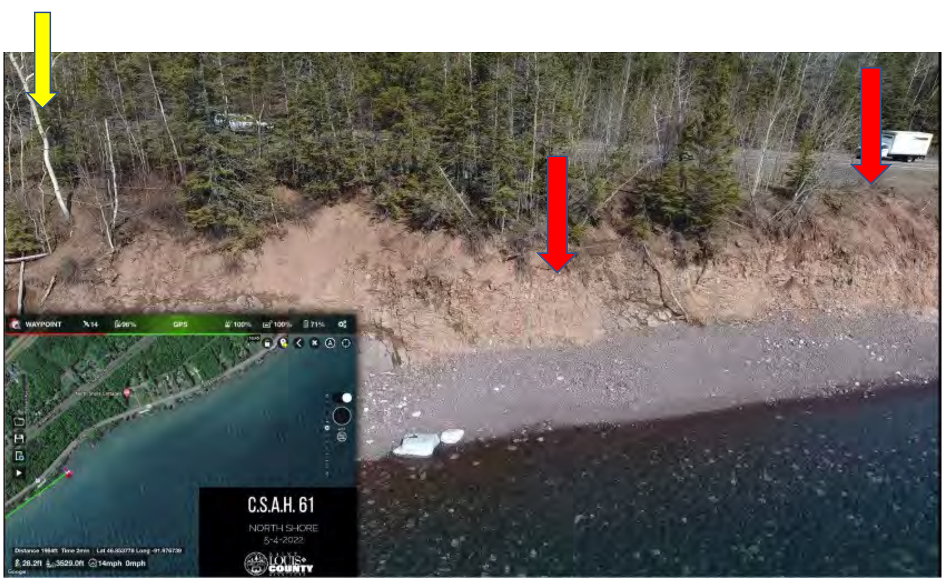
- Point of reference between years
- Area of change
  - Arrows placed only for locations with noticeable changes

Location 0.5 - 2021

Location 0.5 – 2022

Location 1.2 - 2021

Location 1.2 - 2022



Location 1.3 - 2021

Location 1.3 - 2022

Location 2.9 - 2021

Location 2.9 - 2022

Location 3.6 - 2021

Location 3.6 - 2022

Location 3.9 - 2021

Location 3.9 - 2022

Location 4.4 - 2021

Location 4.4 - 2022

Location 4.9 - 2021

Location 4.9 - 2022

Location 5.0 - 2021

Location 5.0 - 2022

Location 5.3 - 2021

Location 5.3 - 2022

Location 7.1 - 2021

Location 7.1 - 2022

Location 8.5 - 2021

Location 8.5 - 2022

Location 9.6 - 2021

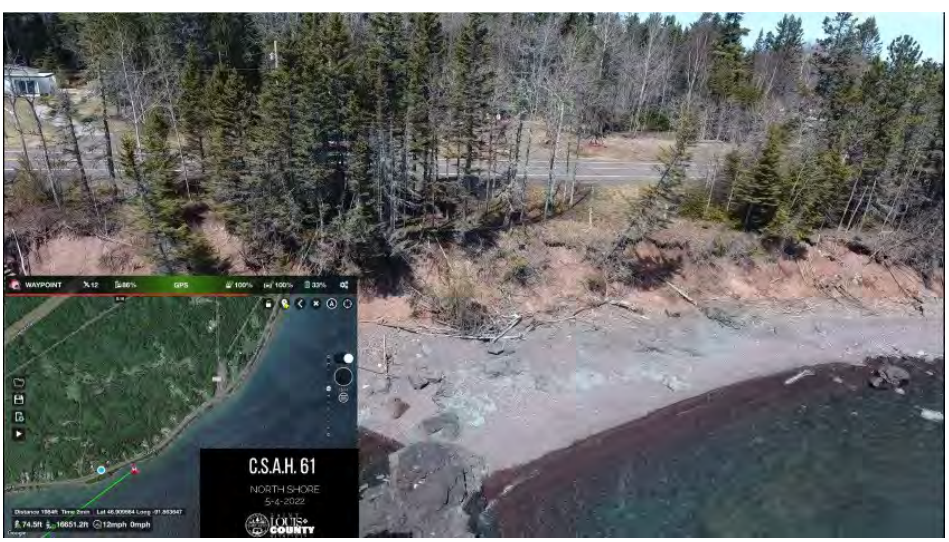
Location 9.6 - 2022

Location 10.3 - 2021

Location 10.3 - 2022

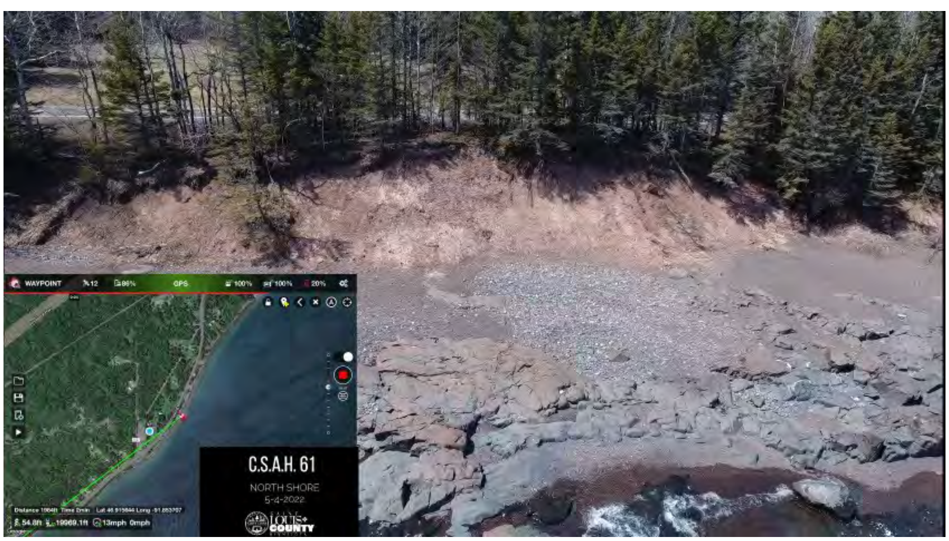
Location 10.9 - 2021

Location 10.9 - 2022



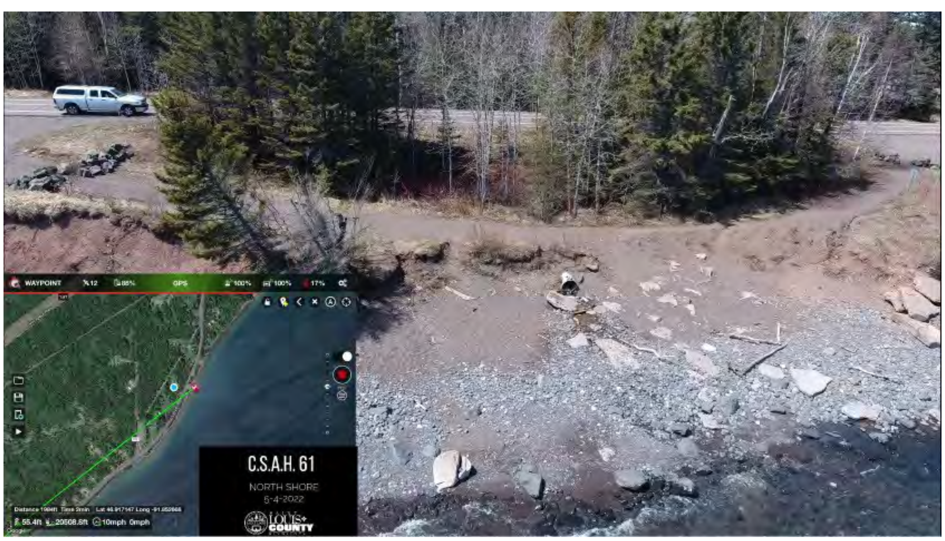
Location 11.9 - 2021

Location 11.9 - 2022



Location 12.0 - 2021

Location 12.0 - 2022

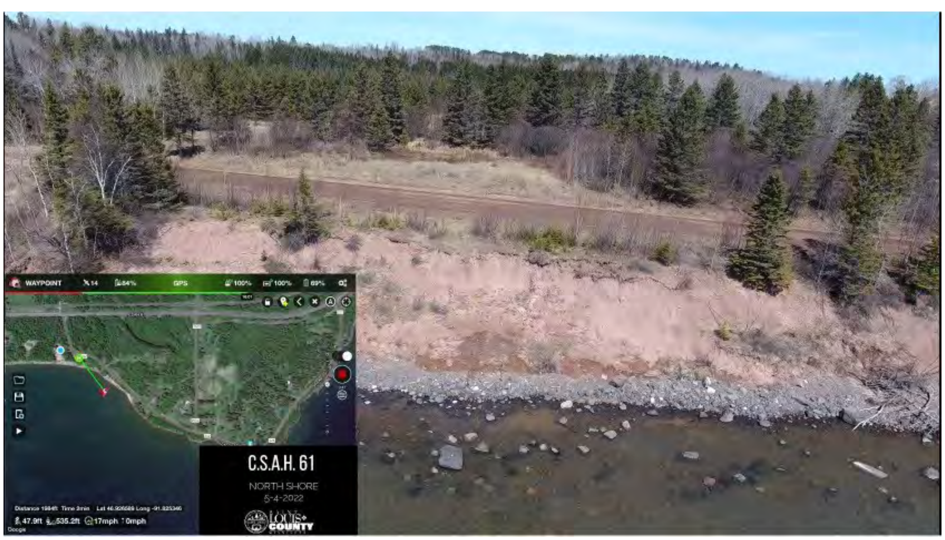


Location 14.1 - 2021

Location 14.1 - 2022

Location 14.3 - 2021

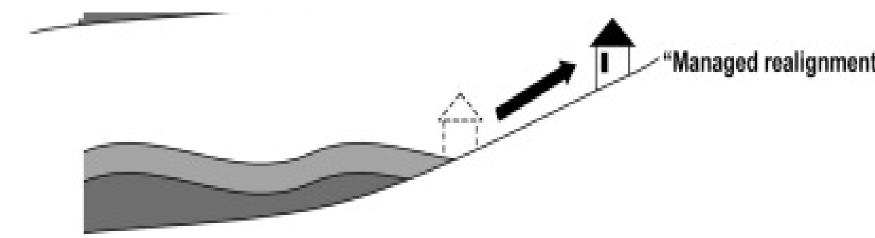
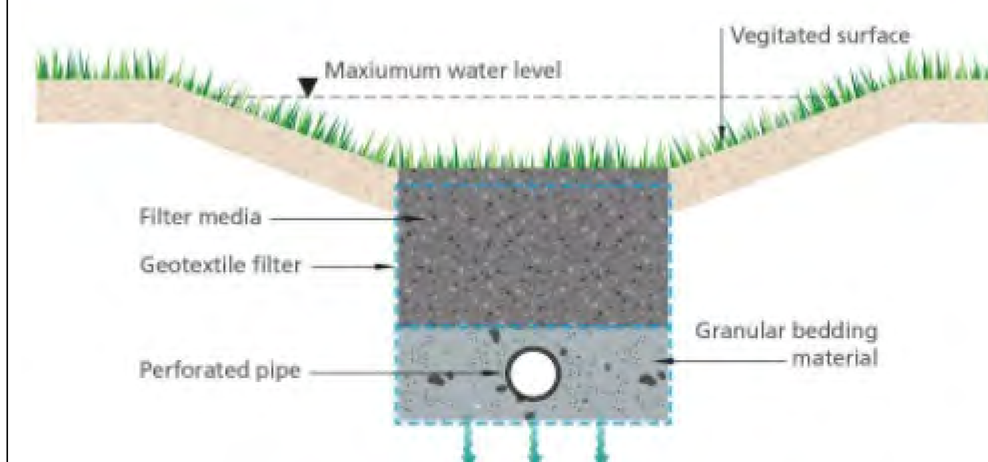
Location 14.3 - 2022

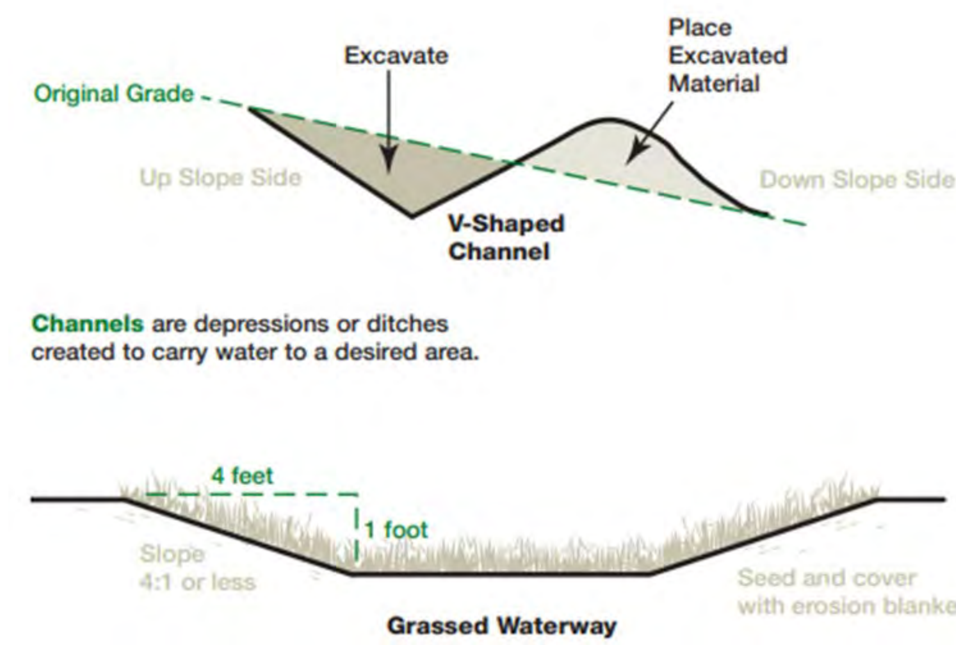


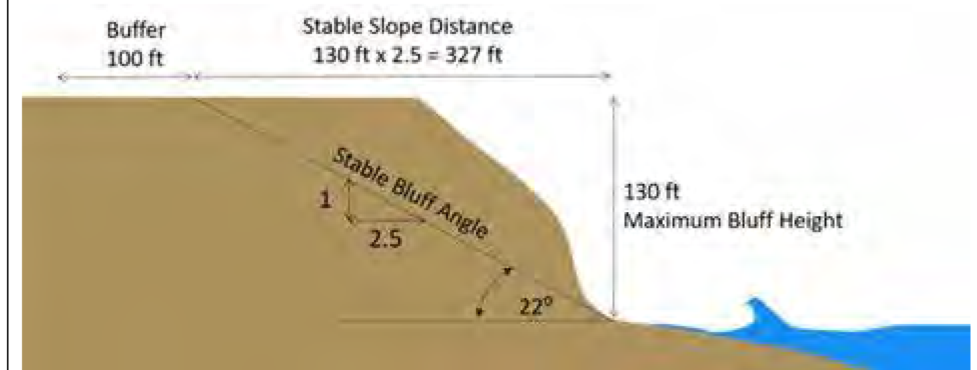
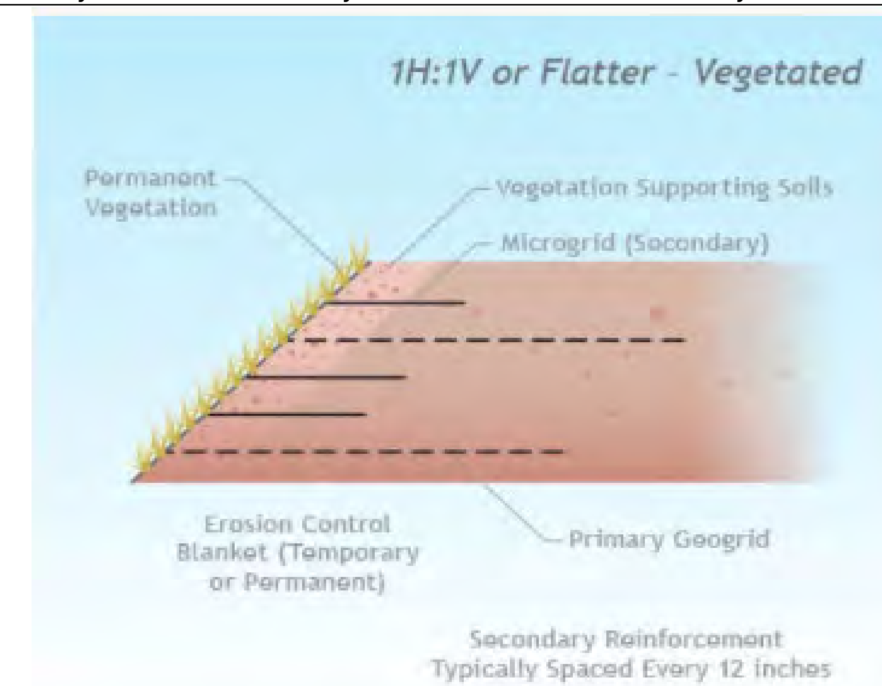
Location 15.2 - 2021

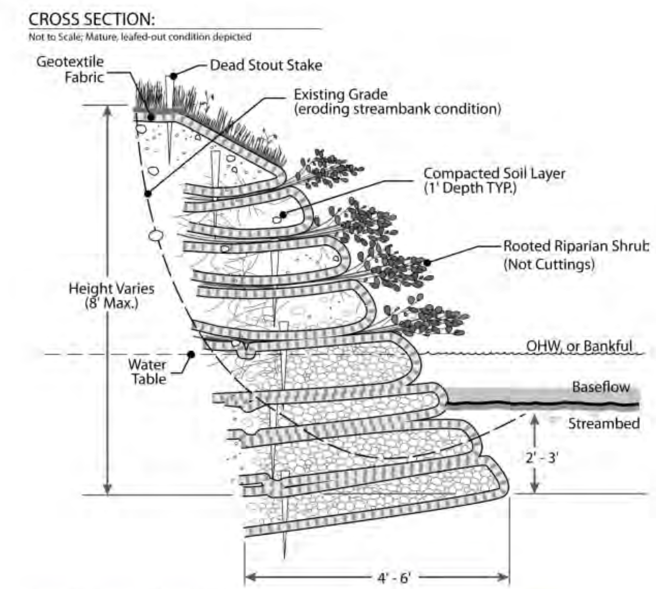
Location 15.2 - 2022

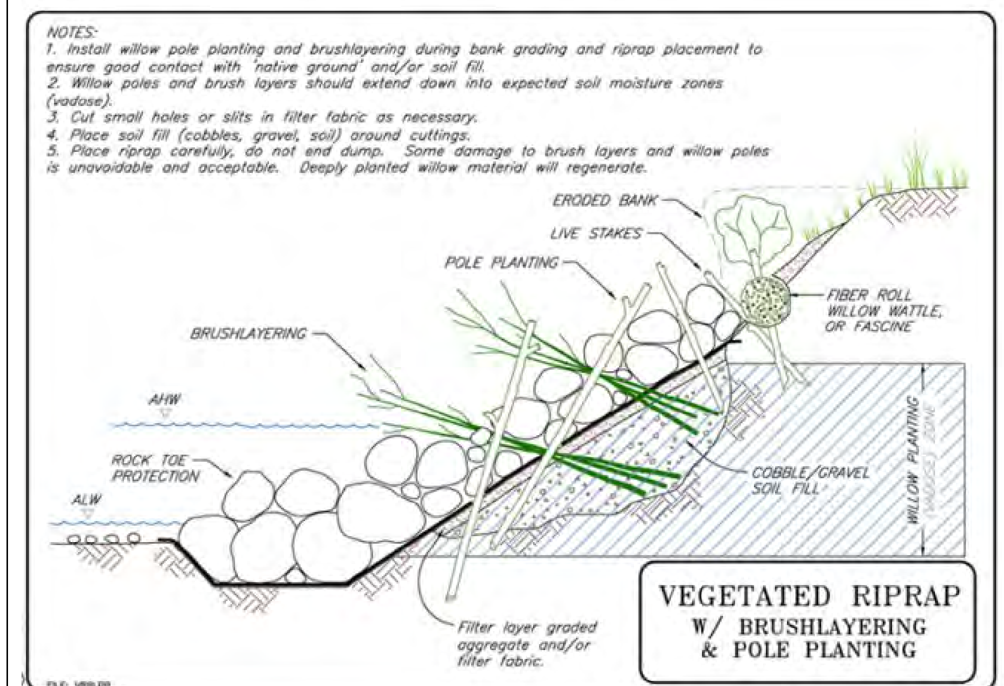
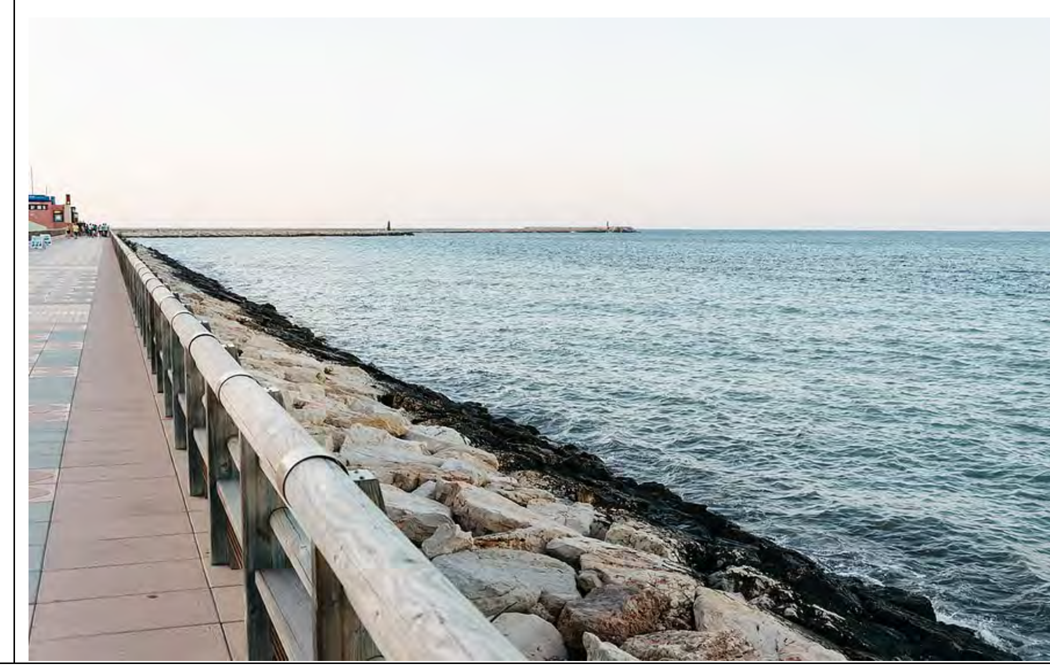
APPENDIX B
STABILIZATION ALTERNATIVES

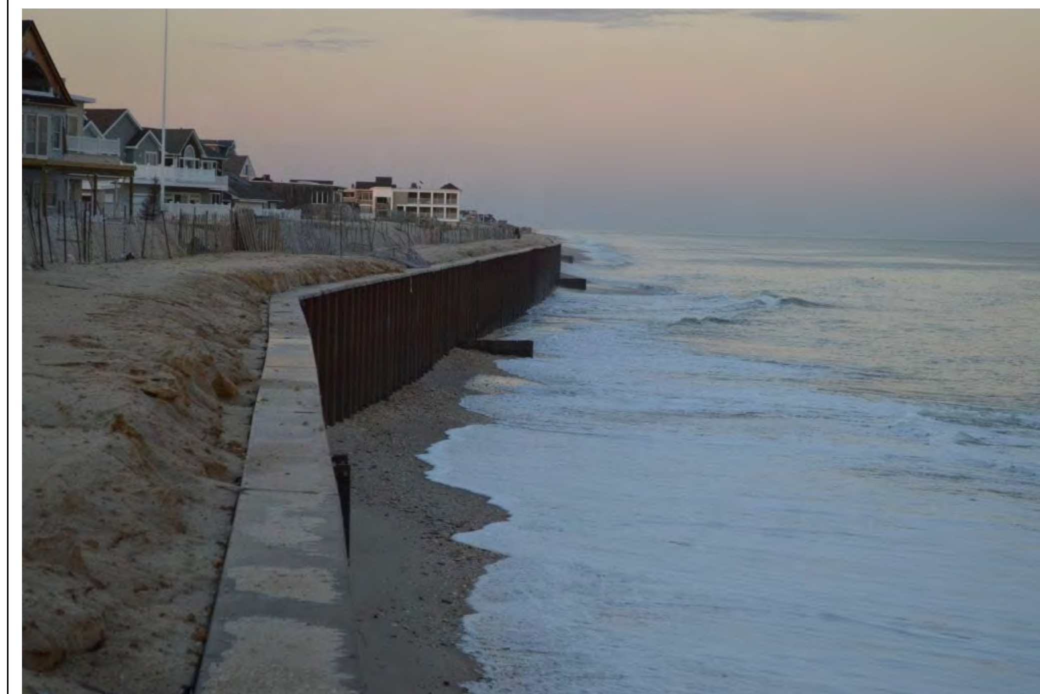
Duluth North Shoreline				
Shoreline Management Alternative Matrix				
Alternative	**Applicability**	**Constraints**	**Shoreline Classification**	**Example**
NON-STRUCTURAL				
Managed retreat/ realignment - Move infrastructure (roads, buildings, parking lots, etc.) away from shoreline	Use non-structural measures whenever possible.	Size of property, type and size of structure, cost. Roadway relocation would require substantial resources and political/public approval. Retreat of parking areas may include truncated options to move but not eliminate.	All shoreline types	 Roca E, Villares M. 2012. Public perceptions of managed realignment strategies: The case study of the Ebro Delta in the Mediterranean basin. Ocean & Coastal Management. 60:38–47.
SURFACE WATER MANAGEMENT				
Surface water management- diversion swale with pipe/ French drain	Assist with collecting and diverting surface water runoff from bluff and/or slope face that often leads to bluff erosion.	Size of property, drainage needs to connect to culverts and surface drainage infrastructure. Benefits from comprehensive infrastructure planning for local drainage systems. Expensive.	Inland of all shoreline types. Could assist with surface water runoff that leads to bluff erosion.	

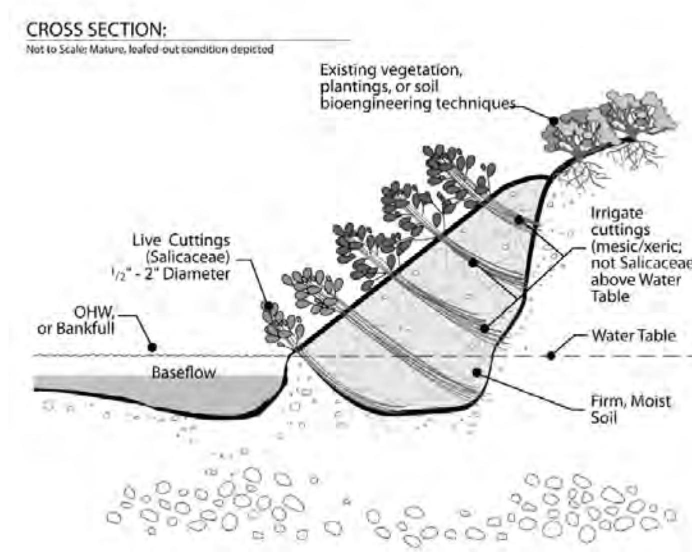
Duluth North Shoreline				
Shoreline Management Alternative Matrix				
Alternative	**Applicability**	**Constraints**	**Shoreline Classification**	**Example**
Surface water management- reduce runoff rate toward bluff, diverting surface runoff away from bluffs and shorelines by creating a grasses waterway between road and top of bluff.	Assist with collecting and diverting water runoff from the pavement/ roads away from bluffs.	Size and width of property. End location of the grassed waterway/ drainage. Proximity of road to top of bluff. Benefits from comprehensive infrastructure planning for local drainage systems.	Inland of all shoreline types. Could assist with surface water runoff that leads to bluff erosion.	
Subsurface drainage management on bluffs to protect from erosion	Areas with elevated groundwater or subsurface drainage that can lead to slope face seepage. Improving subsurface drainage will help minimize seepage erosion, lower permanent water table thereby increasing bluff's capacity to absorb groundwater during heavy precipitation. The groundwater flows into the conduit rather than through the ground. The drains direct the collected water to a discharge point away from the bluff.	Size of property, depth to groundwater or impenetrable layer, requires a drainage outlet, depending on scope could be expensive. Would require protection at the toe of the bluff to prevent erosion from wave action. Benefits from comprehensive infrastructure planning for local drainage systems. Expensive.	All shoreline types, but mostly applicable to bluffs. To identify seepage zones, look at bluff face and note the level at which water seeps. Also, they could test holes to the top of the bluff to determine depth to impenetrable barrier layer over which the water is moving.	

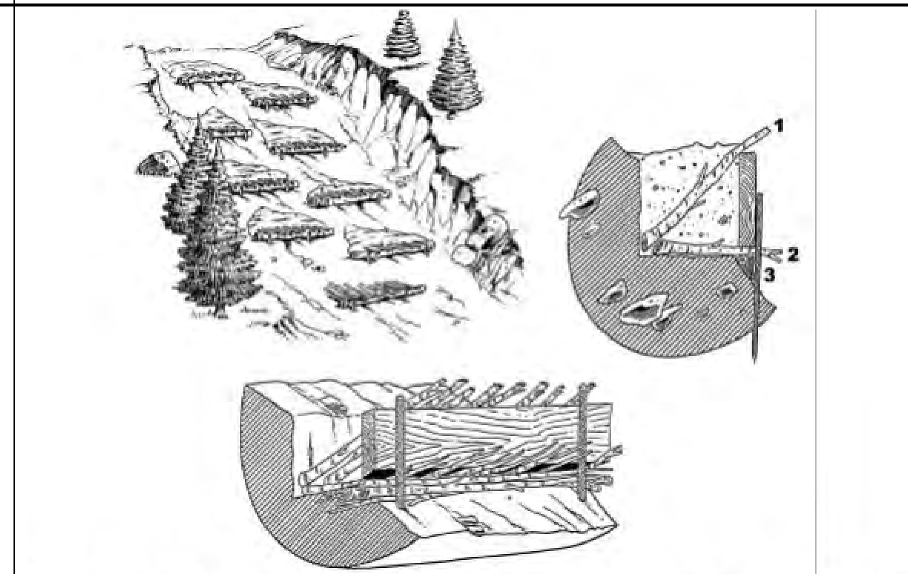
Duluth North Shoreline				
Shoreline Management Alternative Matrix				
Alternative	**Applicability**	**Constraints**	**Shoreline Classification**	**Example**
NATURE AND NATURE-BASED MEASURES				
Bluff stabilization- slope reshaping	Used to improve access to the shore and reduce bluff erosion. Used in areas that require vegetation establishment.	Requires sufficient room at the top of the slope to allow for regrading, does not solve subsurface or surface water flow problems. It would need to be paired with toe protection and slope revegetation. Reduces amount of usable land at the top of the slope.	Bluffs and banks where the slopes are steeper than the angle at which the soil particles will remain naturally. Often areas devoid of vegetation.	 Case Study: Milwaukee County Coastal Resources Inventory
Geogrid reinforced steepened slope (GRSS)	Can be used in areas where banks cannot be regraded to a shallower slope, can be used in areas that are severely eroded. Geogrid layers act as a soil reinforcement. The geogrid has resistance to tensile and shear stresses that occur within the soil fill, thus reinforcing slip planes in the soil mass.	Need space to reconstruct slope and install geogrid horizontally back into bank and compact soil in lifts over primary and secondary geogrid. Will need to be combined with toe protection.	Steep banks and areas that cannot be regraded to a shallow slope.	

Duluth North Shoreline				
Shoreline Management Alternative Matrix				
Alternative	**Applicability**	**Constraints**	**Shoreline Classification**	**Example**
Biostabilization-vegetated soil lifts with live stakes	Can be used in areas where bank cannot be regraded to a shallower slope, can be used in areas that are severely eroded, promotes rapid vegetation growth.	Can be used on banks with low to moderate shear stress. Requires adequate soil and rock to fill void in eroded bank and fill the soil lifts. Will need to include toe protection.	Steep banks and areas that cannot be regraded to a shallow slope.	 Figure 30. Vegetated Geogrid (Adapted with permission from Eubanks and Meadows 2002).
HARD STRUCTURAL MEASURES				
Articulated concrete block (ACB)	Large waves, long fetch length, open coast sites	Shoreline width, slope. Requires smooth, uniform surfaces to avoid erosion and differential settling.	All shorelines	

Duluth North Shoreline				
Shoreline Management Alternative Matrix				
Alternative	**Applicability**	**Constraints**	**Shoreline Classification**	**Example**
Joint planted revetment	Aids in natural regeneration colonization. Minimal site disturbance. Protects banks from shallow slides and stabilizes banks. Dissipates flow energy and traps sediment. Branches add tensile strength to bank. Combination of boulder cobble toe with joint plantings provides added tensile strength and toe protection. Boulder cobble toe stabilizes the toe of the bank providing protection while vegetation stabilizes mid and upper. Joint plantings deflect overbank high flows when planted close together	Size of property, width of property, proximity of development to shoreline. Plantings and soil matrix with stone only an option above wave runup zone	Areas highly vulnerable to storm surge and wave forces. Areas adjacent to critical infrastructure. High wave energy settings	
Bulkheads/seawalls	Seawalls and bulkheads are parallel to the shoreline and are vertical or slopes walls intended to hold soil in place and allow for a stable shoreline. Harbors, marinas, other working waterfronts, areas without room for a rock revetment.	Large waves, erosion of seaward, seabed, disrupt sediment transport, high up-front cost, loss of intertidal zone, prevents upland from being a source of sediment to the system, can be damaged from overtopping oceanfront storm waves.	Bluffs, areas highly vulnerable to storm surge and wave forces. Areas adjacent to critical infrastructure. High wave energy settings.	

Duluth North Shoreline				
Shoreline Management Alternative Matrix				
Alternative	**Applicability**	**Constraints**	**Shoreline Classification**	**Example**
Retaining walls	Retaining walls are also parallel to the shoreline and are vertical walls intended to hold soil in place and allow for a stable shoreline. Harbors, marinas, other working waterfronts, areas without room for a rock revetment	Disrupt sediment transport, high up-front cost, prevents upland from being a source of sediment to the system, can be damaged from overtopping oceanfront storm waves. Expanding ice sheets can damage vertical walls.	Bluffs, areas highly vulnerable to storm surge and wave forces. Areas adjacent to critical infrastructure. High wave energy settings.	
Riprap rock revetment	Revetments are hardened areas that lay over a slope of a shoreline to project from erosion and waves. Large waves, long fetch length, open coast sites. Benefits include mitigates wave energy, little maintenance, and indefinite life span	Loss of intertidal and coastal habitat, requires more land area, potential erosion of adjacent unreinforced sites, prevents upland from being a sediment source to the system.	All shorelines, including bluffs, are experiencing toe erosion. Sites with pre-existing hardened shoreline structures.	

Duluth North Shoreline				
Shoreline Management Alternative Matrix				
Alternative	**Applicability**	**Constraints**	**Shoreline Classification**	**Example**
OTHER REVIEWED OPTIONS				
Biodiversity Enhancement: Native open space revegetation and Pollinator habitat	Increases biodiversity, habitat provision, beauty, and soil stability. Flowering plants attract pollinators (insects, birds etc.), which are responsible for fertilizing over 70% of flowering plants. They also increase biodiversity across trophic levels and contribute to many ecosystem services (clean air, water, and soil). Other non-flowering species can provide habitat for pollinators and other wildlife as well.	Property size, soil condition, labor costs. Flowering plants can take longer to establish and are more expensive to plant than grasses. Needs to be located above any wave runup.	All shorelines and upland habitats with adequate soil.	 University of Minnesota
Biostabilization- brush layering	Unvegetated bluffs, steep slopes, areas undercut by wave action, slump areas that require erosion protection. Benefits include reinforcing bank through the placement sequential layers of cuttings and soil, providing sub subsurface bank stability, riparian vegetation and streamside habitat restoration and revegetation.	Size of property, width of property, proximity of development to shoreline. would need shoreline protection with plantings above wave run up zone	Bluffs and banks	 https://extensionpublications.unl.edu/assets/html/g1307/build/g1307.htm

Duluth North Shoreline				
Shoreline Management Alternative Matrix				
Alternative	**Applicability**	**Constraints**	**Shoreline Classification**	**Example**
Biostabilization - terracing-modified brush layer	A modified brush layer is using a small log or board to support a brush layer along steep gravely slopes. The board creates a terrace that can serve to catch materials (rocks/soil) rolling down the slope. It also creates terraces where vegetation can more easily establish. Effective on sites too dry for wattle fences.	Needs to be paired with toe protection if shoreline lake erosion is also contributing to bluff erosion. Does not include infiltration systems/swales.	Bluffs and slopes	 **igure 3.2.2-1.** Modified brush layers should be staggered across the slope (left). Boards or logs can be used for support. Three different positions for placement of cuttings are shown in the diagram on the right. On mesic sites, modified brush layers should be built with the cuttings above the board or log ("1"). On dry sites, the cuttings should go below the board or log (2), while on very moist sites a small wattle fence can be installed below the board or log (3) to provide drainage. Modified brush layers are perfect for ravelling gravel slopes (from Polster, 2001).

Definitions:

Natural and Nature-Based Measures: Measures that use the landscape to provide engineering functions relevant to flood risk management while production additional economic, environmental, and/or social benefits. Examples include beaches, dunes, salt marshes, etc.

Living Shorelines: Living shorelines use plants and other natural elements such as sand and rocks to protect and stabilize a shoreline. Living shorelines can be used alone or in combination with other harder features to stabilize a shoreline.

Bioengineering or Biostabilization: Practice of using natural vegetative materials to provide long-term bank stability and strength by using root systems to bind soil particles and impart cohesion to the soil and resistance to erosional loss.

Non-Structural Measures: includes modification in public policy, management practices, regulatory policy, and pricing policy. Examples include flood preparedness planning, emergency response plans, flood proofing, or acquisitions and relocations.

Hard or Grey Structural Measures: Structural measures that use non-natural materials such as concrete, piping, etc. to reduce coastal risks by decreasing shoreline erosion, wave damage, and flooding. Examples include sea walls, groins, and riprap.

Subsurface Drainage Management: The process of managing water discharges from subsurface systems (natural groundwater seepage or manmade drainage systems) with water-control structures.

APPENDIX C
PROPOSED MITIGATION ALTERNATIVES

Assumptions

- Many of the locations will be a combination of identified options
- Length of priority locations include additional areas identified in 2022 drone flight
- Costs include design, permitting, construction and oversight
- Costs are for budgetary purposes only (-10% + 30%)
- Costs were derived from a combination of RS Means, prior construction projects by Ramboll, prior bid prices from City of Duluth shoreline repairs

Location 0.5

Bank Height (Feet)	Length (Feet)
60	130

Recommended Option	Estimated Cost
Toe protection with geotextile and stone to 20' Geogrid/Vegetation above with upland water management	$850,000

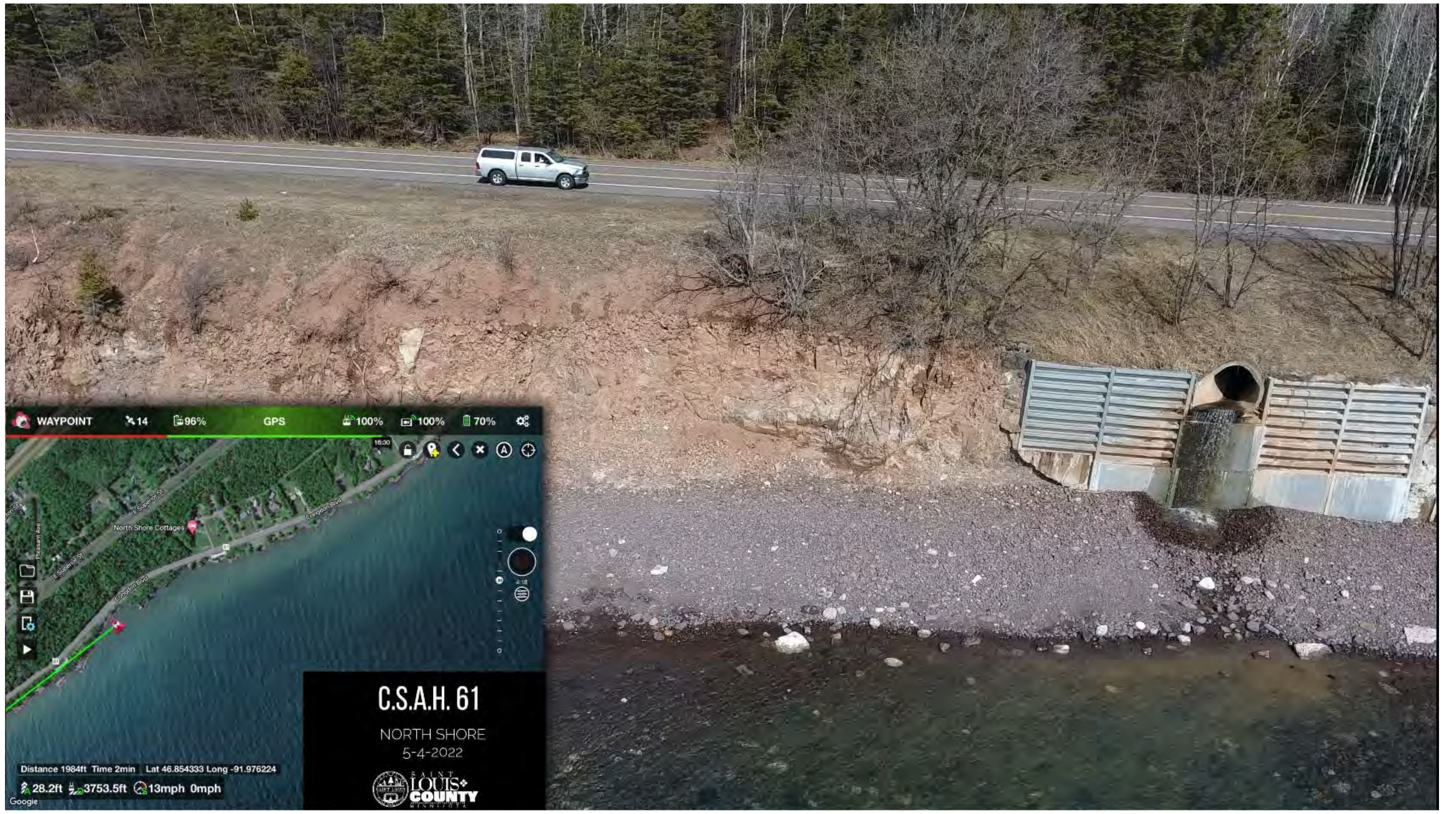
Location 1.2

Bank Height (Feet)	Length (Feet)
40	210

Recommended Option	Estimated Cost
Reshape and install articulated concrete – add geogrid with vegetation above and upland water management.	$880,000

Location 1.3

Bank Height (Feet)	Length (Feet)
25	170



Recommended Option	Estimated Cost
Retaining wall tied into existing structure – geogrid with vegetation above and water management	$740,000

Location 2.9

Bank Height (Feet)	Length (Feet)
10	400

Recommended Option	Estimated Cost
Retreat turnout, revegetate the slope, add watermanagment.	$1,430,000

Location 3.6

Bank Height (Feet)	Length (Feet)
35	370

Recommended Option	Estimated Cost
Retreat to road, regrade, add geogrid with vegetation above and toe protection below and water management.	$1,055,000

Location 3.9

Bank Height (Feet)	Length (Feet)
20	1285

Recommended Option	Estimated Cost
Regrade add reinforced stone 10 ft up slope – reinforced vegetation above with water management.	$1,530,000

Location 4.4

Bank Height (Feet)	Length (Feet)
35	310

Recommended Option	Estimated Cost
Reshape, add geogrid with vegetation and surface water collection and distribution	$570,000

Location 4.9

Bank Height (Feet)	Length (Feet)
15	450

Recommended Option	Estimated Cost
Reshape, geogrid reinforced vegetation above and toe protection with management of surface water	$1,100,000

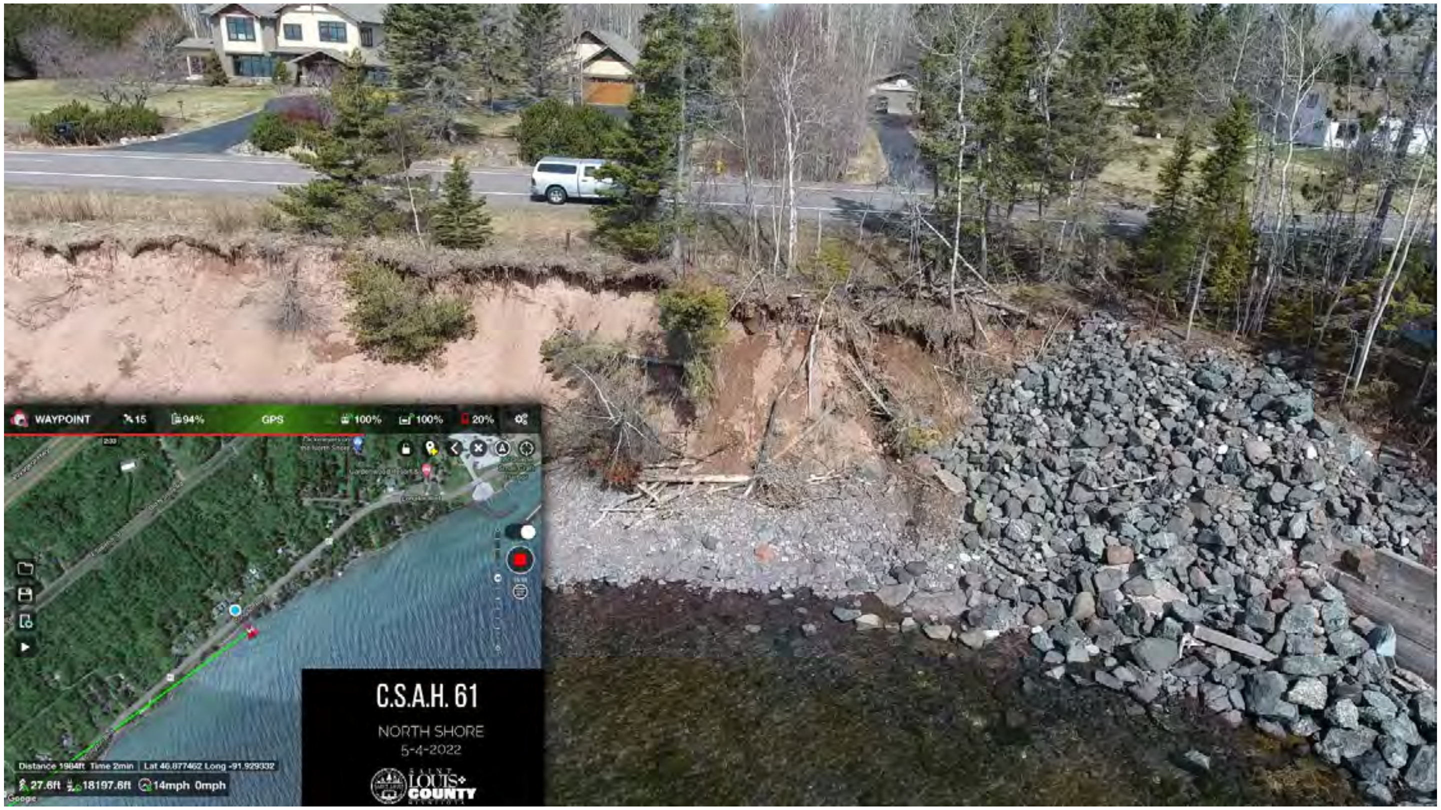
Location 5.0

Bank Height (Feet)	Length (Feet)
10	325

Recommended Option	Estimated Cost
Retreat turnout to roadway, reshape with geogrid vegetation and toe protection	$1,160,000

Location 5.3

Bank Height (Feet)	Length (Feet)
20	490



Recommended Option	Estimated Cost
Reshape , toe protection up 10 feet, vegetation above, and water management	$1,300,000

Location 7.1

Bank Height (Feet)	Length (Feet)
6	400

Recommended Option	Estimated Cost
Retreat to roadway, reshape with vegetation above and reinforced toe stone.	$1,630,000

Location 8.5

Bank Height (Feet)	Length (Feet)
50	1730

Recommended Option	Estimated Cost
Reshape with reinforced stone to 20 feet vegetation above with toe protection and water management.	$5,100,000

Location 9.6

Bank Height (Feet)	Length (Feet)
40	270

Recommended Option	Estimated Cost
Reshape – Stone to 15 feet – vegetation above – redirect surface water	$690,000

Location 10.3

Bank Height (Feet)	Length (Feet)
50	1485

Recommended Option	Estimated Cost
Reshape with stone to 20 feet, geogrid with vegetation above, toe protection and water management.	$4,450,000

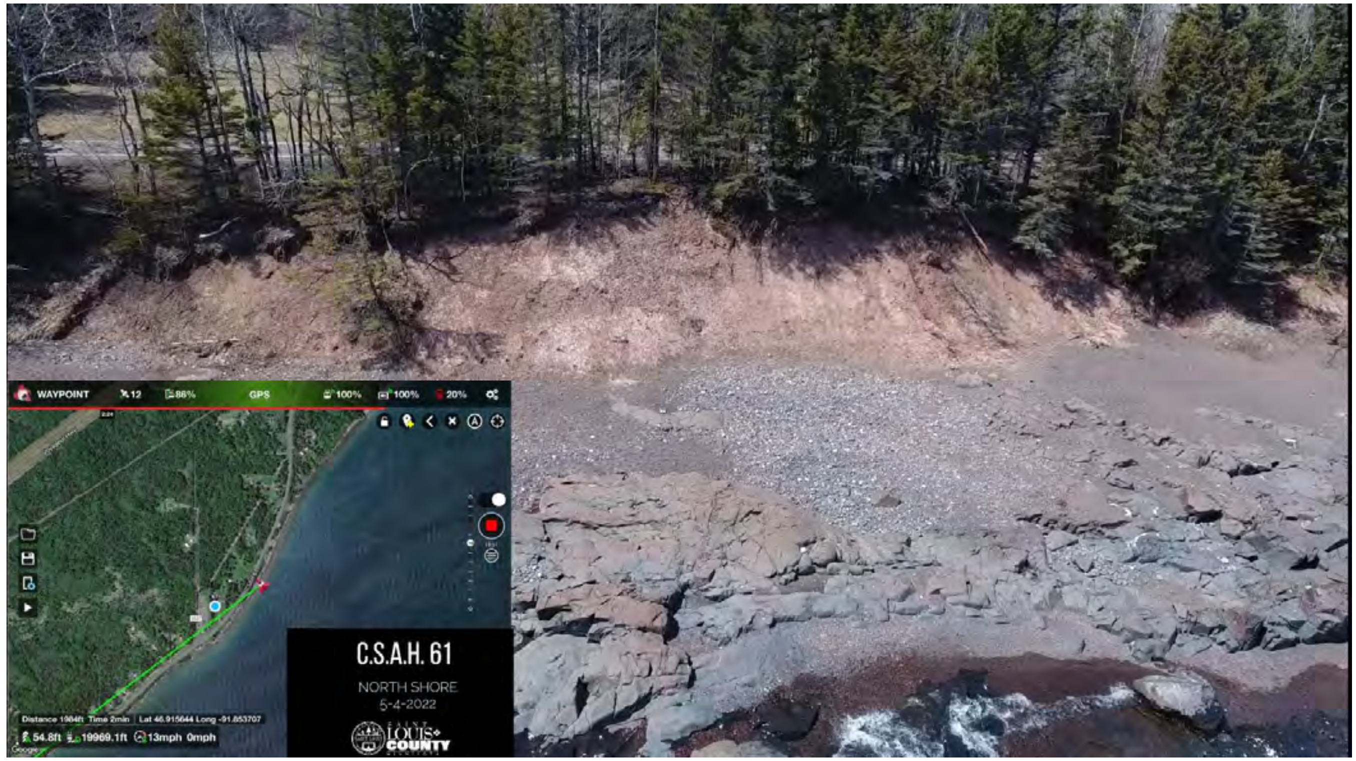
Location 10.9

Bank Height (Feet)	Length (Feet)
20	400

Recommended Option	Estimated Cost
Reshape – Geogrid with vegetation and redirect surface water flow	$400,000

Location 11.9

Bank Height (Feet)	Length (Feet)
25	1475



Recommended Option	Estimated Cost
Reshape - toe stone to 15 feet – –Geotextile with vegetation above	$1,700,000

Location 12.0

Bank Height (Feet)	Length (Feet)
5	590

Recommended Option	Estimated Cost
Abandon loop, retreat / rebuild turnout, repair outfall, reshape slope, reinforced stone with vegetation above.	$1,850,000

Location 14.1

Bank Height (Feet)	Length (Feet)
45	330

Recommended Option	Estimated Cost
Design and Repair existing wall structure, reshape, add reinforced vegetation	$800,000

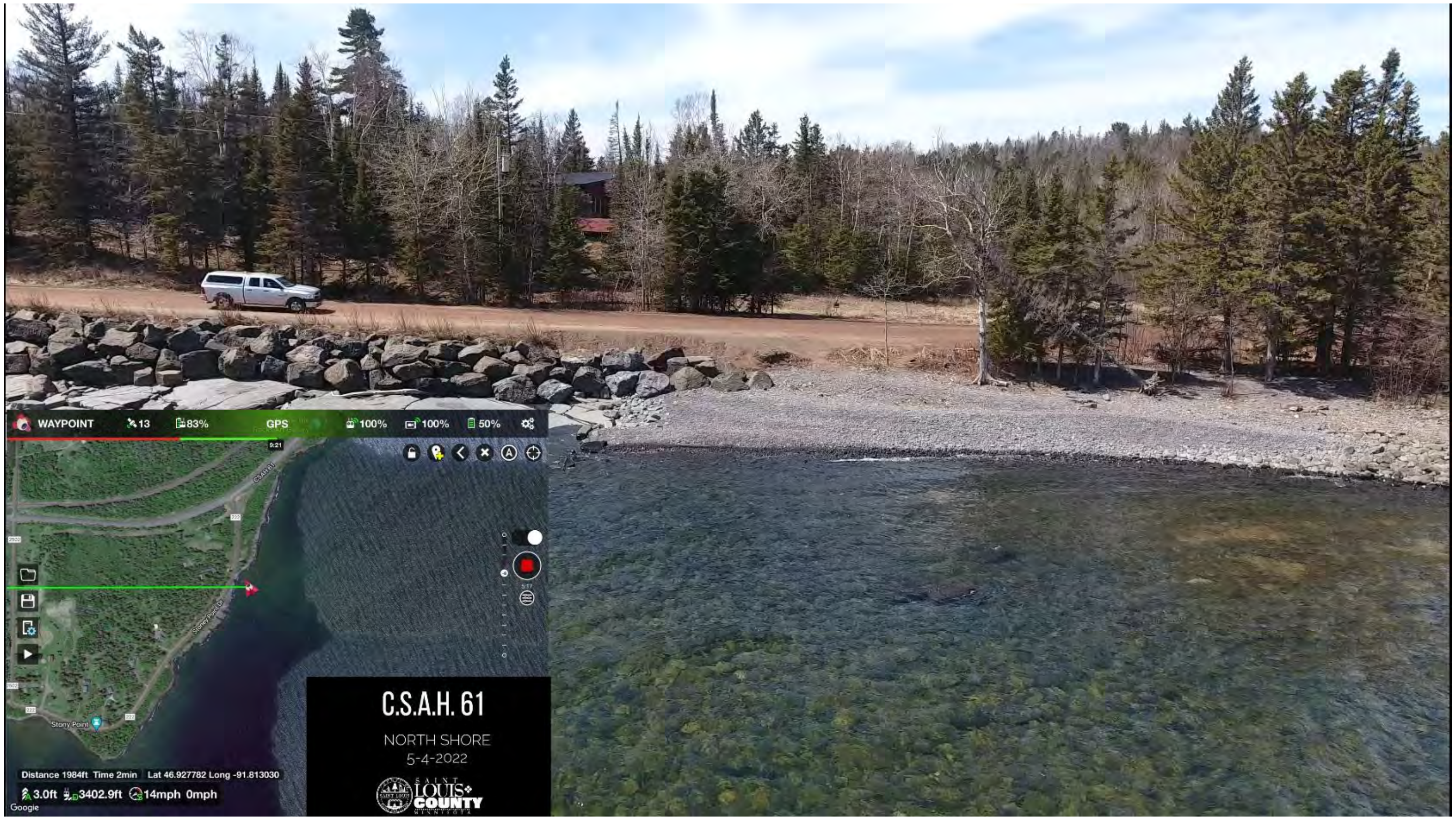
Location 14.3

Bank Height (Feet)	Length (Feet)
25	2900

Recommended Option	Estimated Cost
Reshape – Geogrid with vegetation and toe protection to 15 feet with Vegetation above.	$3,400,000

Location 15.2

Bank Height (Feet)	Length (Feet)
5	145



Recommended Option	Estimated Cost
Riprap to tie in to existing with vegitation above.	$283,000