Michigan Department of Transportation

Infrastructure Protection and Rehabilitation Response to High Lake Levels

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Infrastructure Protection and Rehabilitation Response to High Lake Levels

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16. Abstract

This multifaceted planning study addresses risks to MDOT assets associated with high water levels in the Great Lakes, as experienced in 2019 and 2020. The project classifies exposure, vulnerability, and risk for flooding and erosion hazards statewide, focusing on areas hydrologically connected to the Great Lakes. For five priority sites, a conditions assessment was completed, and mitigation alternatives or appropriate next steps were suggested. Schematic design and costs were developed for the preferred mitigation alternative where able. Research methods leveraged a mixture of published literature, guidance from federal and state agencies, local knowledge from regional leaders, and subject matter experts. MDOT decision makers can leverage this analysis to help decide between relying on temporary mitigation measures and capital investment for at-risk sites. Additionally, the study provides the foundation for prioritizing investment needs statewide. Planning and policy recommendations to increase resilience long-term are suggested.

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As Arcadis does not have a complete control over the accuracy of the data used in the conceptual engineering and design completed in this report, it is recommended that the results shown not be used without first obtaining additional information and confirming all results. This includes, but is not limited to, the roadway survey data, the recommended bridge structures, the soils and geotechnical data, the erosion control calculations, the wave calculations, future high water and wave forecasts, and all other engineering design. The statements provided herein shall not be relied upon for any specific application without independent verification and assessment of suitability by the project’s engineer of record, architect, or another party acting in similar capacity, as stipulated by the authority having jurisdiction or other applicable contractual regulations.

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Executive Summary

In 2019 and 2020, Michigan experienced record high water levels in the Great Lakes, to extents not seen since the mid-1980s. It is well established that Great Lakes water levels are cyclical and fluctuate between years of relatively high lake levels, followed by years of lower water levels. These fluctuations are in addition to the typical annual variations, with water levels peaking during summer months and then declining in winter. As the 2019 and 2020 high lake levels followed an extended period of low water (from the late 1990s to mid-2010s), the Michigan Department of Transportation (MDOT) had not directly planned for such impacts. Further, the institutional knowledge of how high lake levels had been addressed in the 1980's is limited. In response to impacts to transportation assets seen across the regions, MDOT convened a High Water Team of regional representatives. This team shared knowledge and approaches to dealing with the extended period of high lake levels. Additionally, impacts, emergency actions, and implemented mitigation projects were documented. [1]

MDOT's need for a deeper understanding of the long-term trends in lake level fluctuations, as well as permanent solutions for at-risk sites, drove this research and planning project. MDOT retained the Arcadis Team (a collaboration between Arcadis and Michigan Technological University, hereafter shortened to Arcadis) in early 2021 for a multi-faceted planning study on MDOT's coastal assets. This study addresses transportation assets directly adjacent to the Great Lakes, as well as inland waterbodies hydraulically connected to the Great Lakes.

This project centered around three analyses:

1) A condition assessment of five sites around the state that had seen high water levels in 2019 and 2020,
2) A benefit cost analysis (BCA) for those same five sites, and
3) A statewide assessment and decision-making matrix.

Arcadis leveraged the work of the High Water Team as a starting point for these analyses. Throughout the study, there was ongoing regional participation, through email, data requests, interviews, site visits, and Project Review Sessions.

Past and Future Lake Levels

The Great Lakes water levels naturally show significant variability, both seasonally and across years or decades. Annual swings are relatively predictable, with higher water levels in summer and lower water levels in winter. The total water level fluctuation between times of high lake levels and low lake levels across the period of record (going back to the early 1900s) is around

[1] Generally, these mitigation projects were paid for out of yearly regional maintenance budgets.

4 - 6.5 feet, depending on the lake. An example of these long-term trends for lakes Michigan-Huron is shown in Figure 0-1.

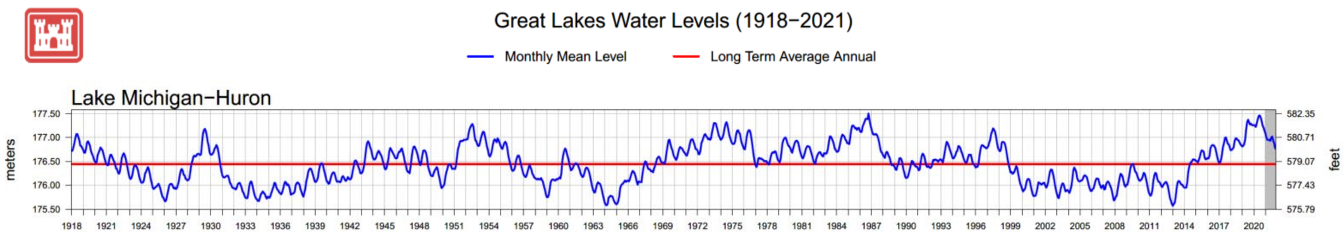

Figure 0-1. Historic lake level variability for Lake Michigan – Huron. Source: USACE Detroit District, 2021. [2]

Multidecadal (across decades) and interannual (across years) trends exist, however there remains significant “randomness” to these variations. Two dominant long-term lake level cycles have been identified, one around 80 years, and one around 30 years. However, statistical trends only explain around 7 inches of lake level variation (Hanrahan et al., 2010).

Lake levels are driven by drainage basin runoff, overlake precipitation, and lake evaporation. These components make up net basin supply. Prior to the 1980s, the long-term lake level variability very closely matched historic precipitation records. After around 1980, evaporation began having a significant impact on long-term water level variations due to climate change and rapid global warming (Hanrahan et al., 2010). It is uncertain whether historically identified multidecadal and interannual patterns in lake levels will hold into the future, or which factor (precipitation or evaporation) will drive lake levels in the future.

While climate models agree that temperatures will increase, this leads to both increased precipitation and increased evaporation. Long-term lake levels averages may moderately decrease or moderate increases depending on which factor dominates. If long-term average lake levels do trend upwards, current models suggest a maximum of approximately 6 inches to 1 foot increase in average lake levels by 2050. This may double to 1 foot to 2 feet by 2090 (Notaro et al., 2015).

MDOT will need to plan for both highs and low water levels, regardless of long-term trends. While not quantified in the literature to date, it is noted that given emerging weather patterns and observed extreme events to date, water levels are likely to be increasingly variable in the future, fluctuating between extreme highs and lows (Gronewold and Rood, 2019).

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[2] USACE updates this graphic regularly with future water level projections. The most recent version can be found online, at: https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Water-Level-Data/

Five Site Analysis Key Findings

A key starting point for this research project was the High Water Team's catalog of impacts seen by the regions during 2019 and 2020. From an initial list of around 50 sites, Arcadis was tasked with classifying impacts and prioritizing five sites for additional analysis. Arcadis interviewed MDOT staff to understand the sites, historic impacts, and regional priorities. Two inundation sites and three erosion sites were chosen for additional analysis, a summary of which is detailed below.

M- 22 Elberta/Frankfort

Underlying Issue. The M-22 Elberta/Frankfort site was chosen to represent sites where roadway assets are adjacent to inland waterbodies hydrologically connected to Lake Michigan. During 2020 when Lake Michigan was at record highs, this two-lane causeway was inundated for extended periods of time. Inundation typically consisted of standing water in part of the lanes in the spring through fall. The region installed a temporary signalized closure that allowed two-way traffic to share the single available lane. Shorter, wind-driven events caused both lanes to be closed occasionally throughout the inundation period. To accommodate this, MDOT installed a permanent signed detour. Wind driven events would fluctuate and could last 15 minutes to an hour, or as long as a week. Damage to date includes scour to the bridge and pavement degradation.

Preferred Mitigation Alternative. Due to cost considerations, raising the road and bridge at the same location was preferred over lengthening the bridge. The critical design elevation was chosen as 583.1 North American Vertical Datum of 1988 (NAVD88), on top of which of 2 feet of freeboard to the proposed bottom of beam elevation of the new structure was added. To achieve 585.1 NAVD88 to bottom of beam, raising the road a minimum of 18 inches to a maximum of about 3 feet was proposed. See *Appendix E: M-22 Elberta/Frankfort Expanded Documentation* for the schematic design and design parameters.

Cost. The total estimated construction cost is **$1.625 million,** including a 30 percent contingency to cover any incidentals not noted in the estimate. See *Appendix E: M-22 Elberta/Frankfort Expanded Documentation* for the schematic cost estimate.

The costs for the no action, temporary mitigation (sandbags), and permanent mitigation options for two potential future high water level scenarios are shown in Table 0-1. The cost of even one installation of temporary sandbags exceeds the cost of investing in a capital project at the beginning of the 10-year planning horizon. [3]

[3] The model assumes that the preferred mitigation alternative would be implemented in year 9 of the 10-year planning horizon based on the remaining asset useful life provided by MDOT.

Table 0-1. Summary of M-22 Elberta/Frankfort cost and benefit scenarios, discounted.

Scenario	Cost	2-Years of 1 Month High Water	5-Years of 4 Months High Water
No Action	Construction Costs	$950,000	$950,000
	Maintenance Costs	$1,300,000	$1,300,000
	Loss of Function Costs	$2,100,000	$20,000,000
	Total	**$4,300,000**	**$22,000,000**
Temporary Mitigation	Construction Costs	$1,200,000	$1,400,000
	Maintenance Costs	$1,500,000	$1,900,000
	Loss of Function Costs	$71,000	$130,000
	Total	**$2,800,000**	**$3,400,000**
Permanent Mitigation	Construction Costs	$1,500,000	$1,500,000
	Maintenance Costs	$1,200,000	$1,200,000
	Loss of Function Costs	-	-
	Total	**$2,700,000**	**$2,700,000**

Notes:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Results represent a 7 percent discount rate over a 10-year planning horizon.

M-29 St. John's Marsh

Underlying Issue. M-29 St. John's Marsh roadway runs through the natural, marshy delta between the St. Clair River and Lake St. Clair. The site is somewhat protected, and so is not categorized as a Coastal High Hazard Area (Zone V or VE on the Federal Emergency Management Agency [FEMA] flood maps) for wave impacts. However, the whole area is within FEMA's AE zone, with the base flood elevation (BFE) alternating between 579 and 580 feet NAVD88. This represents a 1 percent or greater change of the area flooding to 579-580 feet NAVD88 each year. The roadway surface of M-29 west of the adjacent community of Pearl Beach is particularly close to encroaching water sources, even under normal water levels. With high lake levels and calm wind conditions, water has approached or exceeded pavement edge markings. The available detour is quite lengthy at 24 miles, adding an additional 30 minutes.

Preferred Mitigation Alternative. The preferred alternative based on cost considerations was raising the roadway. Arcadis suggests additional coordination with the Michigan Department of Natural Resources (MDNR) to obtain their concurrence if MDOT chooses to move forward. Adding a bridge opening or additional culverts may mitigate environmental concerns. A hydrologic and hydraulic (H&H) study will be required to determine the necessary size of any additional openings. See *Appendix F: M-29 St. John's Marsh Expanded Documentation* for the schematic design and design parameters.

Cost. The total estimated construction cost is **$4.956 million,** including a 30 percent contingency. See *Appendix F: M-29 St. John's Marsh Expanded Documentation* for the schematic cost estimate.

The total costs for the no action, temporary mitigation (sandbags), and permanent mitigation options for two potential future high water level scenarios are shown in Table 0-2. Due to the extended length of the site – over a mile – the installation, operation, and maintenance of a temporary measure is expected to be quite expensive. Again, the cost of even one installation of temporary sandbags exceeds the cost of investing in a capital project at the beginning of the 10-year planning horizon.[4]

[4] The model assumes that the preferred mitigation alternative would be implemented in year 9 of the 10-year planning horizon based on the remaining asset useful life provided by MDOT.

Table 0-2. Summary of M-29 St. John's Marsh cost and benefit scenarios, discounted.

Scenario	Cost	2-Years of 1 Month High Water	5-Years of 4 Months High Water
No Action	Construction Costs	$2,900,000	$2,900,000
	Maintenance Costs	$2,900,000	$2,900,000
	Loss of Function Costs	$9,000,000	$83,000,000
	Total	**$15,000,000**	**$89,000,000**
Temporary Mitigation	Construction Costs	$4,300,000	$5,400,000
	Maintenance Costs	$4,200,000	$5,300,000
	Loss of Function Costs	$300,000	$540,000
	Total	**$8,800,000**	**$11,000,000**
Permanent Mitigation	Construction Costs	$4,600,000	$4,600,000
	Maintenance Costs	$2,800,000	$2,800,000
	Loss of Function Costs	-	-
	Total	**$7,400,000**	**$7,400,000**

Notes:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Results represent a 7 percent discount rate over a 10-year planning horizon.

M-116 Ludington

Underlying Issue. Beach and dune erosion has reduced the width of the beach between the Lake Michigan and the road and has exposed groins along the shoreline. MDOT is concerned that the combination of beach and dune erosion plus high lake levels may lead to shoreline erosion becoming a threat to M-116.

Preferred Mitigation Alternative. Several alternatives were considered including raising the roadway, adding additional erosion protection measures along the shoreline, and building up the dunes to provide more protection to the roadway. Given the recreational nature of this site, any additional erosion protection would diminish the natural value of the area. Arcadis determined the most economical and least impacting long-term solution is to relocate the roadway for the two key stretches at highest risk. It was determined to use a critical design elevation of 590.0 feet NAVD88 with an additional 1.5 feet of freeboard (591.5 feet NAVD88). This pushed the proposed edge of pavement for the relocated section of the roadway inland between 75 feet and 100 feet from the 590.0-foot water surface elevation contour. See *Appendix G: M-116 Ludington State Park Expanded Documentation* for the schematic design and design parameters.

Cost. The total estimated construction for relocating the roadway cost is **$9.26 million,** including a 30 percent contingency. See *Appendix G: M-116 Ludington State Park Expanded Documentation* for the schematic cost estimate.

Table 0-3 presents considerations for MDOT decision makers when determining whether to move forward with a capital project. Based on geotechnical expert judgement, it is likely that the slope will fail, and it is highly likely that the roadway will fail. However, there are minimal safety concerns at this site.

Table 0-3. Summary of key qualitative and quantitative benefits, cost, and risk for M-116 Ludington State Park.

Consideration	No Action	Mitigation
Estimate of duration of loss of function if slope were to fail	30 – 60 days	0 days
Estimate of potential costs from loss of function after a slope failure	$22 – 44 million	$0
Life safety risk of asset failure	None	None
Likelihood of **slope** failure based on physical site conditions and mitigation measures	Likely	Likely
Likelihood of **asset** failure based on slope distance to MDOT asset	Highly Likely	Unlikely

I-94BL St. Joseph

Underlying Issue. The I-94BL St Joseph (Lakeshore Drive) site is an ongoing erosion challenge for the region. The site has been extensively studied and various levels and forms of mitigation have been put in place. The findings from this and previous analyses of the site indicate that the fundamental driver of erosion is a disruption of longshore (or littoral) sediment transport due to the presence of jetties north of the site at the mouth of the St. Joseph River.

Mitigation Options. Mitigation options for this site include doing nothing, decommission and deconstructing the jetties to restore natural sediment process, regularly nourishing the beach, and/or constructing shoreline protection structures to mitigate additional erosion. It is anticipated that the most effective solution for mitigating erosion at I-94BL St Joseph will be a combination of beach nourishment and shoreline protection, some of which has been previously planned by MDOT. Arcadis notes that doing nothing may be an acceptable alternative because although shorelines comprising cohesive materials are prone to small, localized slope failures that are generally induced by undermining, shorelines comprising cohesive materials are less prone to major, catastrophic failures (like the failure at Petoskey) than non-cohesive shorelines.

Costs. Costs from the existing estimate put the planned riprap revetment at approximately $13.4 million (approximately $4,600 per linear foot), and a 2015 estimate from the Southwest Michigan Planning Commission estimates that 54,000 cubic yards of material were dredged from the outer harbor in 2014 at a cost of $8.25 per cubic yard, or total cost of $445,500.

Table 0-4 presents considerations for MDOT decision makers when determining whether or not to move forward with a capital project. Based on geotechnical expert judgement, while it is likely that the slope will fail, it is unlikely that the roadway will fail. However, there still is a level of risk, with medium-high life safety concerns associated.

Table 0-4.Summary of key qualitative and quantitative benefits, cost, and risk for I-94BL St. Joseph.

Consideration	No Action	Mitigation
Estimate of duration of loss of function if slope were to fail	60 – 90 days	0 days
Estimate of potential costs from loss of function after a slope failure	$3.6 – 5.5 million	$0
Life safety risk of asset failure	Medium-High: Life safety risks to a small number of people	Low: No life safety risks
Likelihood of **slope** failure based on physical site conditions and mitigation measures	Likely	Not Likely
Likelihood of **asset** failure based on slope distance to MDOT asset	Not Likely	Not Likely

US-31 Petosky

Underlying Issue. The US-31 Petosky site was identified due to the 2020 slope failure which occurred within the area of interest that destroyed a section of the Little Traverse Wheelway, a paved multi-use trail below US-31. Although the failure did not damage the highway, the need to understand the problem is evident. The driving factors and signs of an impending incident leading up to the slope failure include recent small failures and historically large failures in the area, erosion of sediment at the toe of the bluff, elevated groundwater conditions, and, potentially, inadequate groundwater drainage from the uphill side of the Little Traverse Wheelway to the downhill side.

Mitigation Options. Options for mitigation actions at the site include doing nothing and monitoring the slope, shoreline protection coupled with re-grading the slope and improving drainage, installation of slope reinforcement, or relocating MDOT assets. Before determining a mitigation option or rebuilding the Little Traverse Wheelway multi-use trail, it is recommended to first conduct a thorough ground and surface water investigation to better understand current conditions and those that led to the 2020 slope failure. It is also recommended that MDOT address the risk of headcutting of the existing scarp, potentially by having a plan to divert excessive runoff when intense precipitation is expected. **Additionally, a target factor of safety against slope failure of 1.5 should be considered for the any future remediation design.**

Costs. Costs for options presented by a previous study of the site are estimated to be between $5-10 million, although the designs previously put forward do not meet the target factor of safety recommended here. Furthermore, it is expected that additional drainage improvements required would push the cost to the high end of that range if not beyond it. Nevertheless, the first need for this site is gaining a comprehensive understanding of ground and surface water conditions at the site to provide a more thorough basis for selecting appropriate remediation alternative.

Table 0-5 presents considerations for MDOT decision makers when determining whether or not to move forward with a capital project. Based on geotechnical expert judgement, while it is highly likely that the slope will fail, it is not likely that the roadway will fail. However, there still is a level of risk, with medium life safety concerns associated.

Table 0-5. Summary of key qualitative and quantitative benefits, cost, and risk for US-31 Petosky.

Consideration	No Action	Mitigation
Estimate of duration of loss of function if slope were to fail	60 – 90 days	0 days
Estimate of potential costs from loss of function after a slope failure	$16 – 24 million	$0
Life safety risk of asset failure	Medium: Life safety risks to a small number of people	Low: No life safety risks
Likelihood of **slope** failure based on physical site conditions and mitigation measures	Highly Likely	Not Likely
Likelihood of **asset** failure based on slope distance to MDOT asset	Not Likely	Not Likely

Statewide Assessment Key Findings

The statewide assessment resulted in an assessment of 53 sites statewide, broken into 16 inundation sites, 27 erosion sites, and 10 sites with characteristics of both and erosion and inundation risk. Criticality /consequence for an asset measures its importance within the larger context of the road network and the areas that are served by them. It was scored for all sites within the assessment, based on traffic flow, access to critical facilities, access to community facilities, and detour time. Scores ranged from 2 to 90. The highest scores were often seen by those sites which had no realistic detour route available, requiring detour times that exceeded 45 minutes with some as high as 87 additional minutes. Other sites that ranked at the top of the list for criticality were those that provide key access to both critical and community facilities and had detour times that exceeded 15 minutes.

Each site was also classified by their flood risk based on their relation to FEMA flood zone and the freeboard between the site elevation and the historic lake maximum elevation. Those sites scoring highest among the inundation sites were those that were within the limits of a FEMA Special Flood Hazard Area (SFHA), and at or near an elevation that corresponded to the maximum historic lake level for the site.

A combined score was also produced for the inundation sites by adding the criticality/consequence score to the flood risk score. Values for this score ranged from 5 to 96 and included those sites that were classified as facing both inundation and erosion risk.

Ranking was largely driven by the criticality/consequence score and differentiated through the flood risk.

The highest-ranking site was in the Upper Peninsula along Lake Superior with a score of 96. US-41 between Baraga and L'Anse scored highly for traffic count, access to critical facilities, and scored moderately for access to community facilities due to their availability in each of the respective villages. The route had no realistic detour option with detour time estimated to be 47 minutes and even then, it would involve travelling on sections of unpaved road, and likely not feasible for commercial travel. This scenario was seen often in the Upper Peninsula as the sparsely populated Upper Peninsula has a low redundancy of facilities and road networks.

The ranking from the statewide assessment can serve as a filtering mechanism for prioritizing high lake level mitigation projects. In addition to a quantitative ranking, qualitative considerations including recreational/tourism value, environmental concerns, jurisdictional issues, life safety concerns, and regional priorities. It is recommended that criticality/consequence and flood risk should be confirmed with on the ground stakeholders and regional leaders. For erosion sites, the criticality/consequence score should be used to determine priorities for completing the full erosion matrix (a ranking tool for erosion sites provided herein). As erosion assessments are done, they can be added to the criticality/consequence score to determine a ranking for erosion sites.

Limitation for the statewide assessment exist primarily in the quality and coverage of data. As the Michigan Statewide Authoritative Imagery & LiDAR (MiSAIL) program concludes its collection of higher resolution elevation data, it should be leveraged to gain greater accuracy in the assessment.[5] Conducting site specific surveys should be another consideration to gain greater insight into site characteristics, as should the inclusion of additional input, both qualitative and quantitative. Overall, the assessment maps out the highest priority sites based on use and site characteristics. Qualitative inputs and cost of mitigation will inevitably play a factor in actual prioritization; however this assessment serves as a framework for making those decisions.

Recommendations and Implementation

The following 11 priority next steps have been identified by Arcadis for MDOT to continue to plan for and address coastal hazards and future cycles of high Great Lakes water levels.[6]

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[5] At the time of this assessment, only a few counties had data outstanding: Alpena in the Lower Peninsula; and Menominee, Schoolcraft, Luce, Keweenaw, Houghton, and Ontonagon in the Upper Peninsula.

[6] Arcadis notes some of the recommendations listed below may already be in initial stages by MDOT or conducted on an informal basis.

Recommendations begin with next steps for the five priority sites, followed by general planning and policy recommendations:

1) **M-22 Elberta/Frankfort.** Arcadis recommends implementing raising the causeway and bridge. In order to refine and finalize the schematic design, Arcadis suggests a H&H study for the site, given its location at the mouth of the Betsie River.
2) **M-29 St. John's Marsh.** Arcadis recommends an H&H study to refine a preferred alternative and determine the necessary quantity and size of openings along this route, prior to proceeding with just raising the roadway.
3) **M-116 Ludington.** Arcadis recommends implementing relocation of the roadway. Priority may be given to higher consequence sites.
4) **I-94BL St. Joseph**. It is anticipated that the most effective solution for mitigating erosion at the I-94BL St Joseph site will be a combination of beach nourishment and shoreline protection. A design for beach nourishment was beyond the scope of this project and will need the engagement of a coastal engineer. Arcadis notes that doing nothing may be an acceptable alternative because although shorelines comprising cohesive materials are prone to small, localized slope failures that are generally induced by undermining, shorelines comprising cohesive materials are less prone to major, catastrophic failures (like the failure at Petoskey) than non-cohesive shorelines.
5) **US-31 Petoskey.** Before determining a mitigation option or rebuilding the Little Traverse Wheelway, it is first recommended that a thorough ground and surface water investigation take place to better understand conditions that currently exist and those that lead to the 2020 slope failure. Arcadis recommends MDOT consider addressing the risk of headcutting of the existing scarp, potentially by having a plan to divert excessive runoff when intense precipitation is expected. Additionally, a target factor of safety against slope failure of 1.5 should be considered for the any future remediation design.
6) With the great length of shorelines in Michigan, it is recommended that MDOT develop coastal design standards specific to its assets and similar to the criteria outlined in the American Association of State Highway and Transportation Officials' (AASHTO's) Drainage Manual (Current Edition). The criteria should specify items that are specific to Michigan's coastal features and climate. Considerations should include setbacks, maximum design water levels, erosion protection guidelines, etc. Procedures around hydraulics in coastal areas should be outlined. These standards would be applicable to sites with risks of coastal flooding, wave impacts, or erosion and would be in addition to riverine flooding standards. At a minimum, frequency and elevation data should be prescribed (such as design elevation of the road needs to have at least 3

feet of freeboard above the 1 percent annual exceedance probability [AEP] for coastal flooding).

7) Instead of having regions rely on their yearly maintenance budget, MDOT should consider setting up a capital improvement program explicitly for shoreline flooding and erosion control. MDOT can leverage the statewide matrix as a modifiable tool to finalize the project ranking as a basis for the capital improvement plan.
8) MDOT should consider formalizing at least twice-yearly meetings to discuss planned projects, available funding, and updated water level forecasting with U.S. Army Corps of Engineers (USACE), as they are the greatest resource for MDOT on these issues.
9) Arcadis recommends implementing an inspection program to monitor high risk areas on a biennial term to monitor the erosion along the shorelines.
10) MDOT should consider developing a funding strategy where they match projects with appropriate funding sources (such as, the Federal Highway Administration [FHWA], FEMA, USACE, etc.). This could be done in conjunction with the capital improvement plan, or as a separate effort.
11) MDOT should consider continuing to streamline elevation data into existing asset databases and prioritize gathering survey data for priority at-risk sites where it does not exist.

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1 Introduction

1.1 Background

In 2019 and 2020, Michigan experienced record high water levels in the Great Lakes, to extents not seen since the mid-1980s. It is well established that Great Lakes water levels are cyclical and fluctuate between years of relatively high lake levels, followed by years of lower water levels. These fluctuations are in addition to the typical annual variations, with water levels peaking during summer months and then declining in winter. As the 2019 and 2020 high lake levels followed an extended period of low water (from the late 1990s to mid-2010s), the Michigan Department of Transportation (MDOT) had not directly planned for such impacts. Further, the institutional knowledge of how high lake levels had been addressed in the 1980's is limited. In response to impacts to transportation assets seen across the regions, MDOT convened a High Water Team of regional representatives. This team shared knowledge and approaches to dealing with the extended period of high lake levels. Additionally, impacts, emergency actions, and implemented mitigation projects were documented.[7]

MDOT's need for a deeper understanding of the long-term trends in lake level fluctuations, as well as permanent solutions for at-risk sites, drove this research and planning project. MDOT retained the Arcadis Team (a collaboration between Arcadis and Michigan Technological University, hereafter shortened to Arcadis) in early 2021 for a multi-faceted planning study on MDOT's coastal assets. This study addresses transportation assets directly adjacent to the Great Lakes, as well as inland waterbodies hydraulically connected to the Great Lakes.

1.1.1 Objectives and Scope

This project centered around three analyses:

1) A condition assessment of five sites around the state that had seen high water levels in 2019 and 2020,
2) A benefit cost analysis (BCA) for those same five sites, and
3) A statewide assessment and decision-making matrix.

The analysis of the five priority sites will help MDOT decide if capital investment is worthwhile for these sites in the near term, and if so, provide guidance on the next steps. For the more straightforward sites, schematic designs are presented herein. For the more complex sites, a synthesis of work done to date, along with recommendations on next steps is included. The statewide assessment a decision-making matrix will allow MDOT to prioritize potential projects

[7] Generally, these mitigation projects were paid for out of yearly regional maintenance budgets.

within and across regions and demonstrate the overall need of mitigating coastal hazards to MDOT leaders. The statewide decision making matrix is meant to be an internal modifiable tool, that can continue to be refined by the regions.

As pre-requisites to these three analyses, Arcadis also undertook a literature review and carried out regional engagement. Key takeaways from regional engagement are documented, and the findings informed the subsequent analysis. The literature review was carried out across multiple topics – future water level trends, potential adaptation solutions, best available data sources, design level for other coastal assets, and appropriate BCA approaches.

Following this introduction, the report is structured as follows:

- **Literature Review Key Findings.** This section provides an overview of key topics that informed the direction of the subsequent analyses, including water level trends, coastal hazards, adaptation solutions, and best practices. A comprehensive look at future long-term lake level trends, including effects of climate change, is discussed in *Appendix A: Expanded Literature Review of Long-Term Lake Level Trends, Including Climate Change Effects. Appendix B: Proposed Coastal Design Criteria* presents existing drainage criteria in comparison to potential coastal design standards for MDOT to consider.
- **Methods.** This section first covers the classification of hazards, how sites were chosen for the more in-depth analysis, and regional engagement. It then details the methods of the five site analysis for both inundation and erosion sites.
- **Five Site Analyses.** The five priority sites are presented by dominant hazard. The differences in approaches between inundation and erosion sites are explained.
    - **Inundation Sites** include M-22 Elberta/Frankfort and M-29 St. John's Marsh. Historic design and costs for temporary sandbag mitigation are presented in *Appendix C: Whitehall/Montague 2019/2020 Temporary Mitigation Measures Reference Design and Cost* as they provide typical costs used in the BCA analysis for the inundation sites. A duration analysis depicts days these sites have historically likely seen subgrade saturation and overtopping. A detailed methodology is included in *Appendix D: Inundation Duration Analysis Methodology*. The preferred long-term mitigation solution presented for both sites is raising the roadway. Schematic designs and costs, as well as additional backup documentation, are provided in *Appendix E: M-22 Elberta/Frankfort Expanded Documentation* and *Appendix F: M-29 St. John's Marsh Expanded Documentation*.
    - **Erosion Sites** include M-116 Ludington, I-94BL St. Joseph, and US-31 Petosky. The preferred long-term mitigation solution presented for M-116 Ludington is relocating the roadway. Full designs and costs for this solution are included as

Appendix G: M-116 Ludington State Park Expanded Documentation. Due to the complex nature of the St. Joseph and Petosky sites, the Arcadis Team recommends additional assessments and preliminary actions beyond the scope of this report prior to making a determination of the best-fit solution.

- **Statewide Matrix and Erosion Matrix.** This section presents the key inputs and thresholds used to rank sites. Key takeaways are presented. The full excel tool is provided in *Appendix H: Statewide Matrix*.

Relevant data sources are presented by section, as appropriate, as well as in *Section 7: References* at the end of this document.

2 Literature Review Key Findings

This section provides literature review key findings that shaped the direction of the project. Throughout the development of the project, the literature review was treated as a dynamic, living document. Interim findings helped guide methodology decisions and were shared with MDOT during Project Review Sessions.

The following subsections cover:

- Findings on past water level trends as well as potential long-term future water level scenarios for the Great Lakes;
- An overview of coastal hazards that put transportation infrastructure at risk;
- An overview of FHWA's synthesis on coastal adaptation strategies for transportation infrastructure, and
- Best practices including best available data, online viewers and dashboards, and coastal design standards.

Appendix A: Expanded Literature Review of Long-Term Lake Level Trends, Including Climate Change Effects provides a deeper look at lake level trends in the Great Lakes, including the impacts of climate as seen in the region to-date and the processes and tools used to develop long term water level trends. It also expands on historic lake level variability and future lake level trends outlined below. *Appendix B: Proposed Coastal Design Criteria* presents example coastal design standards and provides a comparison to MDOT's existing drainage standards.

2.1 Great Lake Water Level Trends

As noted in the introduction, in 2019 and 2020 the Great Lakes experienced record high lake levels not seen since 1985 and 1986. This was after persistently low lake levels due to mild climate conditions between 1999-2012 (Notaro et al., 2015). In the 1980s most research around water levels in the Great Lakes was focused on determining whether water levels were in permanent decline; once lake levels rebounded, the focus shifted toward the potential expected highs. This shift in focus was partially informed by predominate climate change projections of the time.

This section summarizes the state of the literature to-date on multi-decadal lake level projections. It should be noted that researchers and practitioners generally accept that there is an untapped opportunity to conduct additional research in this realm. Further research would advance our understanding of the impacts of climate change on geomorphological conditions in the Great Lakes and their impacts on the social and built environment. In comparison to work done on sea level rise, proportionally fewer resources have been dedicated to understanding future conditions in the Great Lakes. Resources thus far have been heavily focused on regulatory (five year) timeframes associated with hydropower production.

An extended literature review regarding Great Lake water levels can be found in *Appendix A: Expanded Literature Review of Long-Term Lake Level Trends, Including Climate Change Effects*.

2.1.1 Historic Lake Level Variability

The Great Lakes water levels naturally show significant variability, both seasonally and across years or decades. Annual swings are relatively predictable, with higher water levels in summer and lower water levels in winter. However, these annual fluctuations in water levels are significantly smaller than the fluctuations seen across years or decades (by approximately one third) (Hanrahan et al., 2010). The total water level fluctuation between times of high lake levels and low lake levels across the period of record (going back to the early 1900s) is approximately 4– 6.5 feet, depending on the lake. These long-term trends are shown in Figure 2-1.

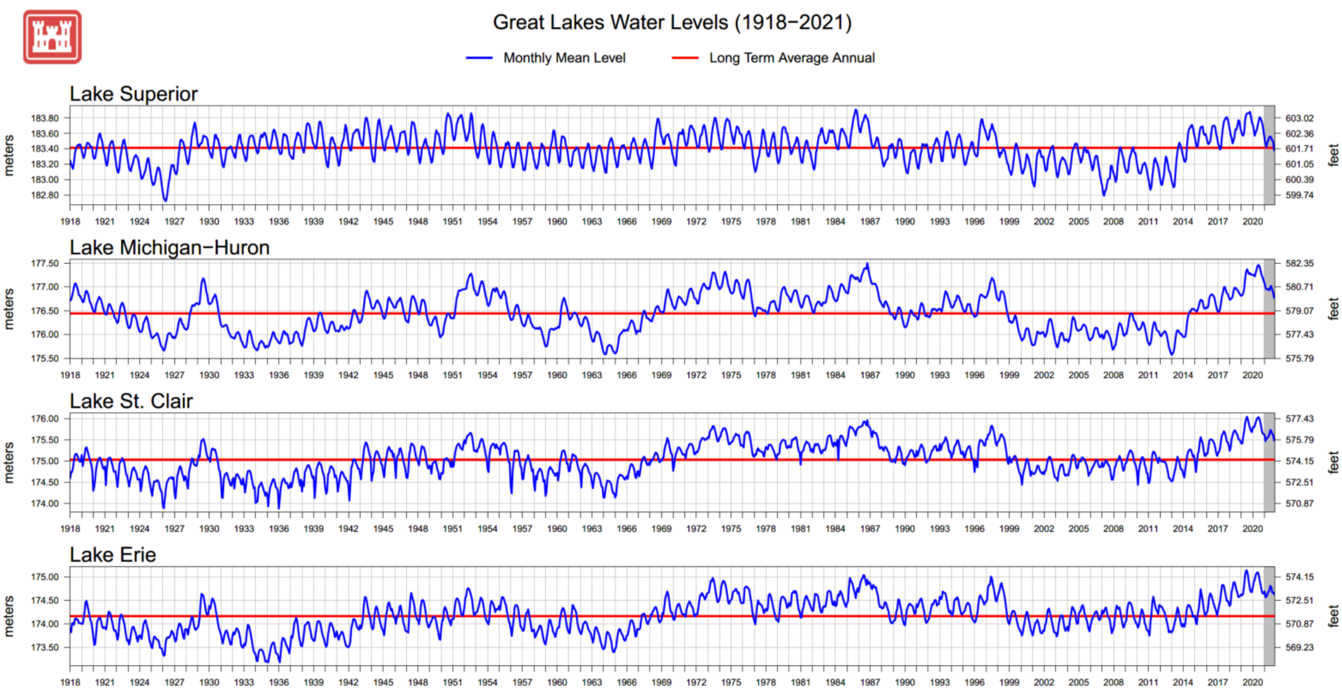

Figure 2-1. Historic lake level variability for Lakes Superior, Michigan – Huron, St. Clair, and Erie. Source: USACE Detroit District, 2021a.[8]

While longer term, multidecadal (between decades) and interannual (between years) trends have been identified qualitatively in the literature since 1976, the historic record was only recently considered long enough to statistically verify these historic patterns. Two dominant longer-term water level cycles have been identified, one at around 80 years, and one at around 30 years. Both patterns are driven by regional climate patterns (Hanrahan et al., 2010). However, only approximately 7 inches of lake level variation can be attributed to long-term trends. As the total water level fluctuation across the period of record is around 4 – 6.5 feet depending on the lake, there remains a significant "randomness" to the variations seen across years and decades.[9]

Lake levels are driven by the inputs into net basin supply, including drainage basin runoff, overlake precipitation, and lake evaporation. Prior to the 1980s, the long-term lake level

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[8] USACE updates this graphic regularly, with their future water level projections. The most recent version can be found online, at: https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Water-Level-Data/

[9] In terms of "predicting" future water levels, the level of variation explained by these decadal cycles is important. The relatively low percent of total fluctuation explained means that for planning purposes, even if where you are within those larger cycles is identified, the predicted range spans feet. As such, identifying where the lakes currently are on these larger cycles was not a priority for this project.

variability very closely matched historic precipitation records (Figure 2-2) (Hanrahan et al., 2010). While this historic correlation did not help with future, long-term predictions of lake level swings, it at least meant that the driving input for lake levels was understood.

However, after around 1980, evaporation began having a significant impact on long-term water level variations due to climate change and rapid global warming (Gronewold and Rood, 2019). Although previously evaporation did not vary much from year to year, the Great Lakes region began seeing large variations in evaporation across years (Hanrahan et al., 2010). In terms of predicting future lake levels, this shift in the driving factors means that it is uncertain whether historically identified multidecadal and interannual patterns in lake levels will continue to be applicable into the future, or if precipitation or evaporation will be the driving input for lake levels in the future.

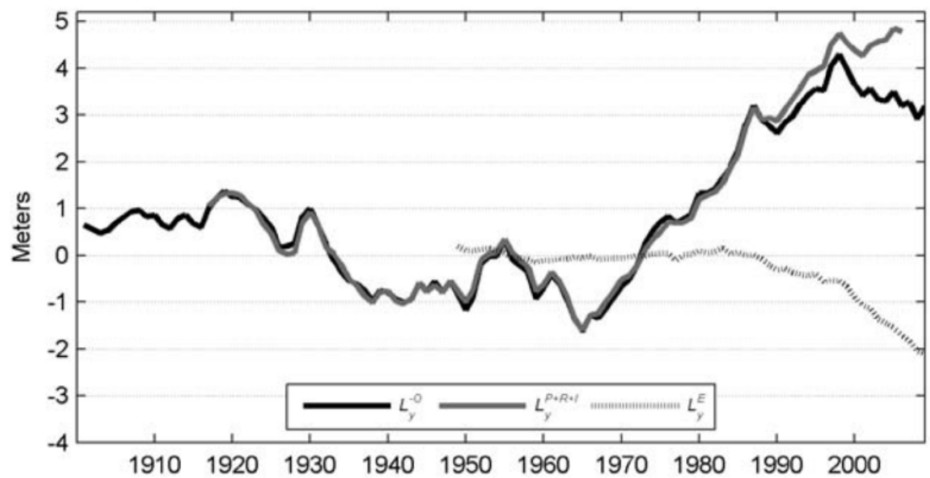


Figure 2-2. Outflow removed lake level curve (black) closely followed the precipitation driven components of net basin supply curve (gray; includes overlake precipitation, runoff, and inflows) prior to the mid-1980s, after which the lake level trends decreased, following the evaporation curve (dotted). Source: Hanrahan et al., 2010.

2.1.2 Future Lake Level Variability

To model future lake levels, it requires first predicting net basin supply, and then translating that water supply into lake levels by stimulating channel flow between the lakes and accounting for diversions (Gronewold et al., 2017; Notaro et al., 2015). Net basin supply is calculated as:

$$Net\ Basin\ Supply = Drainage\ Basin\ Runoff + Overlake\ Precipitation - Lake\ Evaporation \quad \textit{Equation 1}$$

There is an established body of literature going back to the mid-1980s that has attempted to predict future long-term lake levels. Two key flaws in earlier predictions have surfaced recently. First, early reliance on global climate models only modeled the regional climate at a very coarse level, and generally did not include the impacts the Great Lakes themselves have on the regional climate (MacKay and Seglenieks, 2012; Notaro et al., 2015). Second, Lofgren et al. (2011) identified a significant weakness in how overland evapotranspiration was handled in a suite of models developed by the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) [10] to simulate net basin supply components.

Both of these factors led to significant overestimation of evaporation and evapotranspiration, and resulted in "dire" predictions of long-term lake level declines. Some estimates predicted an average decrease of over 5 feet in the coming decades (Notaro et al., 2015). More current projections, discussed more below, result in a much more tempered view.

Given the unreliability of the earlier predictions, Arcadis utilized available projections developed after 2011 and focused on interpreting findings from *On the simulation of Laurentian Great Lakes water levels under projections of global climate change* (MacKay and Seglenieks, 2013) and *Dynamically Downscaling-Based Projections of Great Lakes Water Levels* (Notaro et al., 2015).

In summary, it is well established that climate change is already affecting Michigan through increased temperature, less ice cover, and later-season winter overturning and stratification of lake waters. While climate models agree that temperatures will increase, researchers also agree that this will lead to ***both*** increased precipitation and increased evaporation (and evapotranspiration). Different climate warming scenarios (maximum temperature increase occurring in winter versus spring) will determine which of these factors will play the dominate role in long-term water levels and whether the lake levels will, on average, show moderate decreases or moderate increases. If increased precipitation proves to be the dominant driver and lake levels trend upwards, current models suggest an upper end of approximately 6 inches to 1 foot increase of average water levels by 2050. This may double to 1 foot to 2 feet on average by 2090.

Given the overall fluctuation of lake levels established above, MDOT will need to plan for both unprecedented high and low water levels in the Great Lakes, regardless of long-term trends. While not quantified in the literature to date, it is noted that given emerging weather patterns and observed extreme events to date, water levels are likely to show increased variability in the future (Gronewold and Rood, 2019). This is schematically depicted in Figure 2-3, which

[10] The GLERL suite includes the large basin runoff model (LBRM), large lake thermodynamic model (LLTM), and the coordinated Great Lakes regulation and routing model (CGLLRM).

demonstrates that even if long term lake levels trends downward, MDOT will likely see years of high water, that may even result in peaks above those in the historical record.

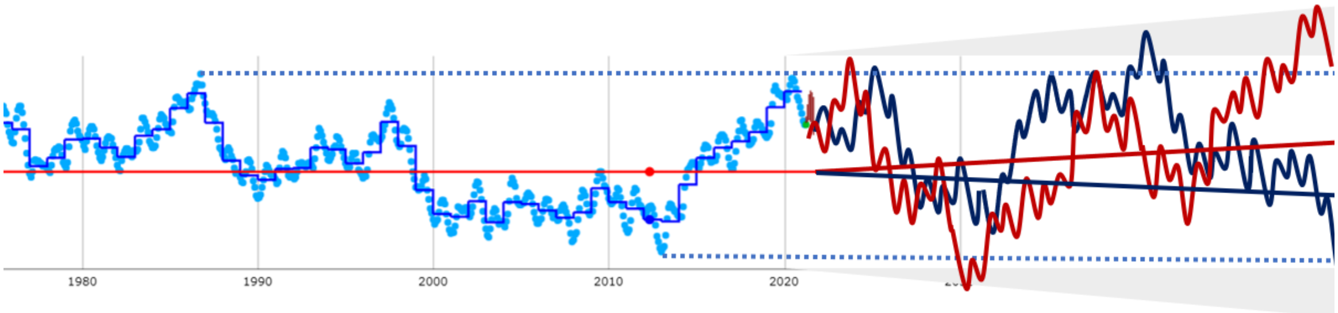


Figure 2-3. Schematic depiction of potential variability around an increasing long-term lake level average and a decreasing long-term lake level average. Base graphic source: Great Lakes Water Level Dashboard, NOAA/GLERL.

2.1.3 USACE Great Lakes Water Level Future Scenarios Experimental Forecast and Six-Month Forecast

Also of note is the USACE Great Lakes Water Level Future Scenarios forecast. In addition to the available mid- to end-of-century long term trends available in the literature, NOAA/GLERL and the USACE have developed an unofficial (or experimental) forecast, which is updated monthly (USACE Detroit District, 2021a; Gronewold et al., 2017; USACE Detroit District, 2018). These forecasts were specifically developed to help hydropower authorities with decision support relating to flows along the Niagara and St. Lawrence rivers. While they don't provide estimates across the lifespan on MDOT assets, they are a useful ongoing resource for MDOT for monitoring and management. Figure 2-4 shows an example of the forecast for Lake Michigan, which shows approximately 2.7 feet of uncertainty in water level range of possible outcomes over the next year.

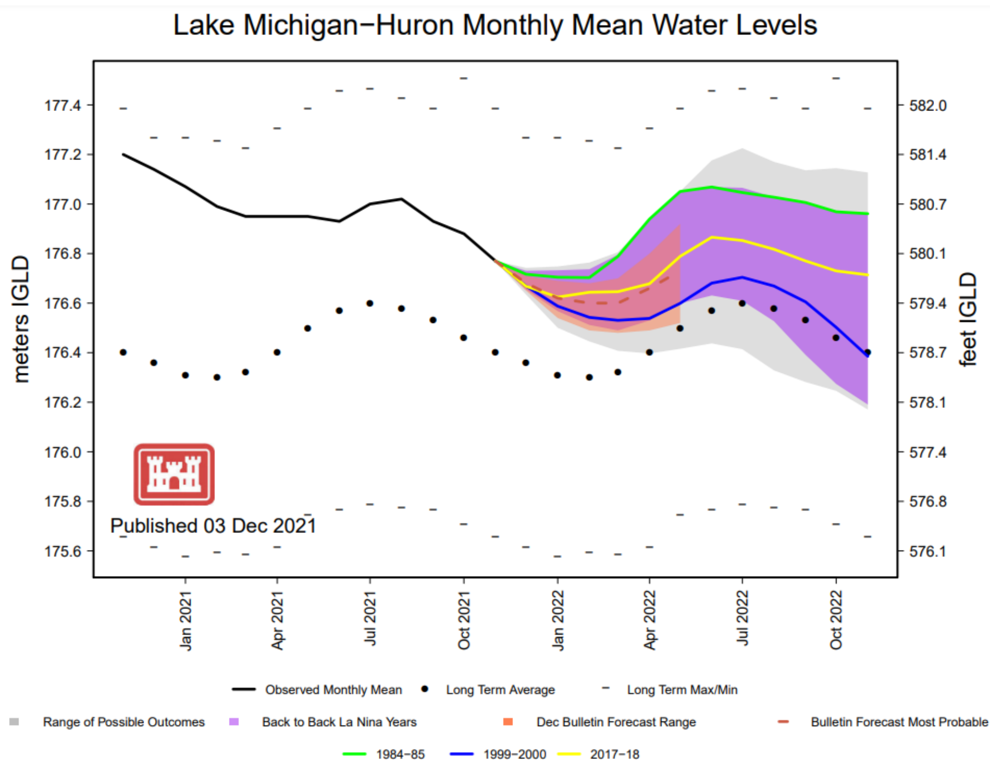


Figure 2-4. USACE October 2021 experimental forecast for Lakes Michigan-Huron. Source: USACE Detroit District, 2021b.

Additionally, USACE publishes monthly updates to their regulatory water level predictions, in coordination with Canada. These predictions are limited to a six month outlook, but do take into consideration climate predictions. As shown in Figure 2-5, both the average prediction and 95 percent confidence interval are provided.

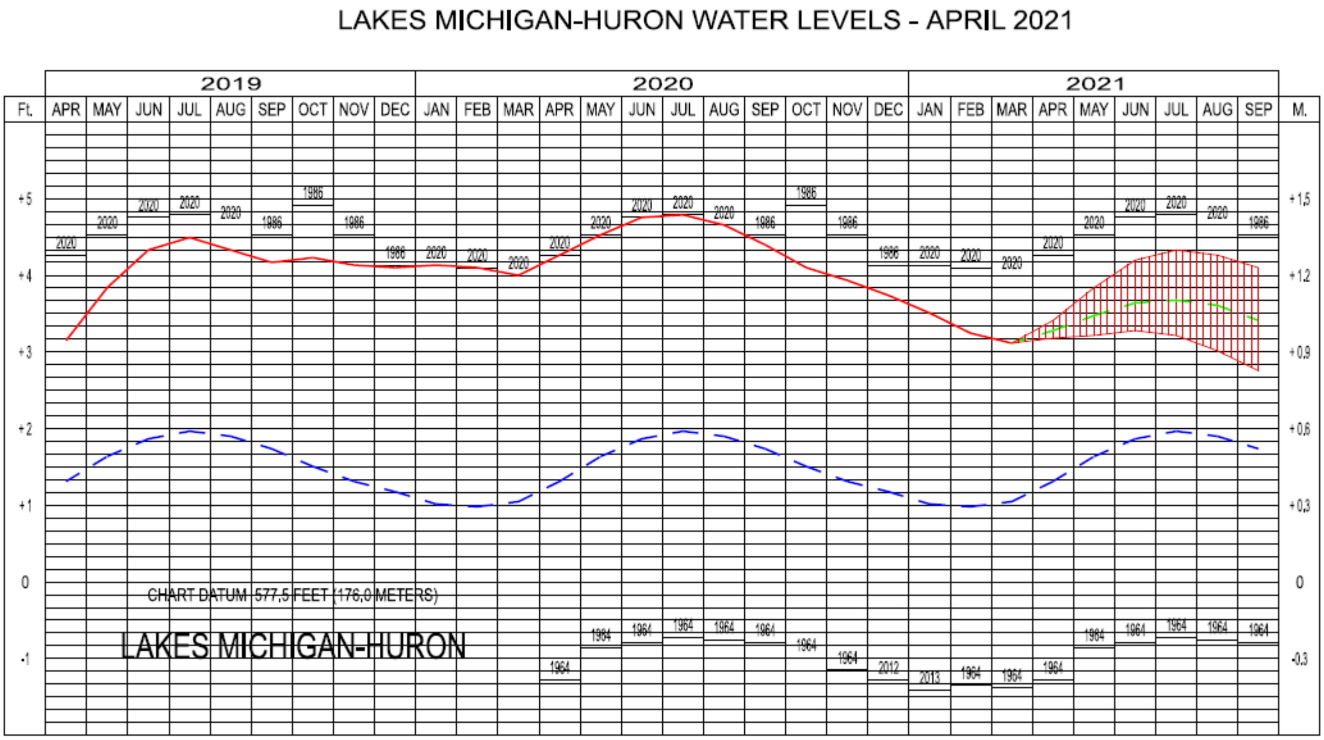


Figure 2-5. USACE April 2021 regulatory forecast for Lakes Michigan-Huron. Source: USACE Detroit District, 2021a.

2.2 Transportation Asset Coastal Hazards Related to High Water

2.2.1 Prolonged Inundation

When lake levels exceed and overtop banks, water spreads into the surrounding area resulting in inundation. A flood is an event where water inundates normally dry land, whereas a floodplain is the area of land that is known to be susceptible to inundation by flood waters.

Changes in precipitation patterns and fluctuating lake levels may increase flooding and inundation. Freeboard, or the vertical distance between Stillwater lake levels and the bank, is one factor in flooding and inundation. In the Great Lakes, precipitation and evaporation rates are the primary drivers of water level fluctuations and available freeboard (HEC 25 Vol. 2, Third Edition). Both evaporation and precipitation rates, and thus freeboard, are impacted by climate change. As discussed in *Section 2.1.2 Future Lake Level Variability*, the predicted impact of climate change on lake levels in the Great Lakes region is uncertain. Lake levels may trend towards either a decrease or increase, depending on whether precipitation or evaporation becomes the primary driver.

While inundation from precipitation or storm surges is usually temporary, inundation of even small segments of the intermodal system can render much larger portions impassable, disrupting connectivity and access to the wider transportation network. Further, after a surge dissipates, highways must be cleared of debris before they can function properly.

Prolonged flooding, or inundation in excess of one week, occurs when the water is not adequately discharged and can damage pavement substructure. Data from the Louisiana Department of Transportation and Development suggests that prolonged inundation can lead to long-term weakening of roadways. A study of pavements submerged longer than three days during Hurricane Katrina (some were submerged several weeks) found that asphalt concrete pavements and subgrades suffered a strength loss equivalent to two inches of pavement. Although Portland concrete cement pavements suffered little damage, composite pavements showed weakening in the subgrade (equivalent to one inch of asphalt concrete) (HEC 25 Vol. 2, 2014).

The frequency or extent of droughts or inundation, regardless of whether the inundation is the result of seasonal fluctuation in the lake levels or long-term climate-related lake level changes, could also impact soil structure, and thus impact the integrity of roadways or other transportation assets.

Lake level rise coupled with storm surges can inundate roads that would not have been inundated in the past, necessitating more emergency evacuations, and require costly, and sometimes recurring, repairs to damaged infrastructure. It can also result in the lifting of substructure slab units or bridge spans (HEC-17, 2016).

In order to assess the vulnerability of transportation systems to inundation, an integrated assessment of all drivers and assets must be considered.

2.2.2 Coastal Wave Action and Storm Surge

Water levels in the Great Lakes fluctuate in response to precipitation in their drainage basins, temperature, and ice cover, as described above. These cyclical, long-term fluctuations in lake levels are a significant driver of wave action in the Great Lakes (Mickelson, Edil, and Guy, 2004). In addition to seasonal fluctuations, the size of the Lake allows for considerable wind-generated surge and waves during routine windstorms or extreme meteorological events, causing overtopping, inundation and damaging wave forces to reach further inland and at higher elevations. Coastal wave action and storm surge is also a driver of sand transport along shorelines, resulting in shoreline accretion in some places and recession in others (HEC 25 Vol. 2, 2014).

Waves are key geologic processes in the Great Lakes, impacting and shaping the natural and built environment, including and especially the transportation assets owned by MDOT. In addition to waves, both storm surge and "seiching" of the lakes can also be significant factors. Seiching is a several-hours-long oscillation of water levels following a weather front. Meteotsunamis (meteorologically-induced long-wave motions), although less frequent, also impact transportation assets (see *Section 2.2.3* below).

Lake ice, present during the winter months, diminishes the occurrence of coastal wave action and storm surge. However, as climate change affects the extent and duration of ice coverage in the Great Lakes, we anticipate that more of the year will be ice-free and subject to wave action.

Many coastal roads are on constructed embankments or natural bluffs. Wave action erodes these bluffs, and in extreme cases this leads to undermining of the roadway. These embankments are often damaged to the extent that the roadway pavement is undermined and damaged. The sensitivity of roadways to wave damage depends on factors such as surge level, duration, and wave height, as well as the material and condition of the embankment. HEC 25 Vol 2 (2014) states that the single most important parameter is likely wave height at the embankment.

Coastal wave action can also result in wave overtopping, a relevant issue for coastal tunnels, bridges, and highways. Overtopping occurs when waves breach the walls or high edges of the transportation infrastructure and water moves into the tunnel, onto the bridge, or across to the opposite side of the road. Overtopping is a function of freeboard and wave height. During a storm surge, the presence of waves can raise the likelihood of overtopping and increase the scour potential on both the seaward and the landward side of the road as the surge waters either flow back toward the lake or move parallel to the roadway. As the water moves into and around the infrastructure, the scouring action results in damage to the infrastructure itself or the embankment.

If the storm surge is so high that the still water level is at or slightly above the low part of the deck of the bridge, the bridge has an elevated likelihood of damage. However, most bridge decks can withstand wave and surge action if they are simply being licked by the crest of a wave.

It is important to note that while wave action and storm surge are known stressors to our transportation infrastructure, there is no existing guidance on the effect of climate-related lake level changes on storm surge and waves (HEC 25 Vol 2, 2014). Further research is needed to quantify and describe the potentially nonlinear relationship the between climate change and storm surge or waves in the Great Lakes.

2.2.3 Seiches and Meteotsunamis

Meteotsunamis and seiches are two phenomena that can occur in the Great Lakes. Both are driven by strong weather fronts and affect enclosed water basins such as the Great Lakes. Meteotsunamis last a few minutes to a few hours and occur from a drastic change in atmospheric pressure along a coastline as it is being directly affected by a weather front. Seiches occur when the water of the basin is pushed by strong winds to one end of the lake and, when the winds die down, oscillate the water to the other side of the basin in return. Seiches are predominantly caused by winds that stretch across long Lake distances and can last for hours to days (NOAA, 2021a; NOAA 2021b). These types of water fluctuations in the Great Lakes are often mistaken for tidal force, as they are experienced as “standing waves.”

Lake Erie experiences the most frequent seiches, has been documented to have had wave heights as high as 22 feet in 1844 (NOAA, 2021b). According to regional staff, Lake Erie had six documented events in 2019. In 2020, a storm caused a seiche in which Toledo had a lowering in water levels by almost 7 feet and Buffalo (225 miles across Lake Erie) experienced 7 feet in surface water level increases (Weather Channel, 2021).

2.2.4 Erosion and Bluff Recession

The most significant contribution to erosion along the Great Lakes’ shorelines is wave action. The Great Lakes shorelines experience storm surges, as well as long term lake level fluctuations. These fluctuations are, in turn, the most significant contributions to wave action and drive the coastal erosion processes (Mickelson, Edil, and Guy, 2004). Waves, and particularly those from storms can erode coastal bluffs and dunes, leading to damages to roads that rely on these features for stability and protection. Wave action is also a driver in the process of littoral drift or longshore sand transport. These processes result in large amounts of sand being moved down the coast leading to shoreline accretion in some places and recession in others. (HEC 25 Vol 2, 2014).

Erosion rates are particularly difficult to predict, due to the variability of factors that cause erosion. Factors that influence erosion rates and bluff recession include wave action just mentioned, as well as wave climate, water level trend, shoreline orientation and fetch, shoreline structures, beach morphology, bluff morphology, bluff and near shore lithology, rainfall, groundwater levels, seepage, the freeze-thaw cycle, and influences from coastal ice (Swenson et. al 2006).

Additionally, the prediction of erosion, and in particular bluff recession, is further complicated by its non-linear nature. Erosion may occur slowly for a long period of time, followed by a moment of large failure sometimes but not always correlated with other factors such as high-water levels and/or a storm event. Following a failure, the shoreline will often have returned to state of stability equal to or greater than it had experienced prior to the event. Again, these many idiosyncratic factors make accurate and reliable erosion predictions difficult and even more so if the application is to be over a broad area with a range of conditions (Swenson et. al 2006).

Although widespread erosion rate prediction remains a challenge, there have been efforts to quantify such rates in select locations. Aerial photographs have been used to measure bluff recession along the Wisconsin coast of Lake Superior finding a recession rate of between 0.07 and 0.57 meters per year for the years 1966 to 1998 (Swenson et al. 2006). Additionally, the Michigan Department of Environment, Great Lakes, and Energy (EGLE) has conducted recession rate research in order to inform zoning and structural property loss. Similarly, their research used historical aerial imagery to identify the High Erosion Risk Area (HERA), classified as areas where the recession rates has been occurring at a long-term average rate of one foot or more per year, over a minimum period of 15 years (EGLE, 2021).

2.3 Adaptation Strategies

In response to changing climate conditions, employment of adaptation strategies will increase resilience of transportation infrastructure. In their publication *Synthesis of Approaches for Addressing Resilience in Project Development* (FHWA-HEP-17-082, 2017), FHWA concluded that adaptation solutions generally fall into five categories:

1) Maintain and Manage
2) Increase Redundancy
3) Protect
4) Accommodate
5) Relocate

These types of adaptation solutions are unique to solving the challenges of community susceptibility to coastal hazards. Table 2-1 below displays the adaptive solutions to hazards from the preparation in routes to the protection from structures in place.

Table 2-1. FHWA Adaptation Categories. Source, FHWA-HEP-17-082.

Adaptation Category	Asset-Specific Strategy	Pros	Cons
Maintain and Manage	Maintain existing protection systems (e.g., riprap)	No substantial changes to existing protections Maintains current design standards	May be insufficient under future climate conditions
	Reroute traffic in extreme events	Can be implemented immediately with pre-planning Low cost	Operational issues and loss of function have costs May not be appropriate for critical routes
Increase Redundancy	Build an alternative access route at a higher elevation and thus a higher resilience level	Maintains access to critical facilities during extreme events	Cost of building an alternative access road
Protect	Revetment/seawall along coastal roadway to prevent wave damage	Would protect asset under climate scenarios Well understood design and construction methods	Can have negative impacts on beach and beach access
	Living shoreline to prevent wave damage	Would protect asset under climate scenarios Preserves more natural coastal habitat Can be more cost-effective than revetment	Typically limited to short-fetch situations along sheltered shorelines May be additional permitting challenges in some states
	Buried shoulder protection along roadway to prevent overwashing damage	Will protect asset under climate scenarios Economically justified with today's sea levels and more so with future sea level rise	Additional initial capital costs Some post-storm sand replacement may be needed

Adaptation Category	Asset-Specific Strategy	Pros	Cons
	Periodic beach nourishment or sand dune construction to prevent wave damage	Reduces frequency of overwashing and provides small reservoir of sand, which buries the road early in the storm reducing damage in some situations Costs can be justified by reduced future damages over the life of the project	Adequate local sand sources may be problematic
Accommodate	Modified revetment to prevent wave damage	Would protect asset under climate scenarios	May not be the preferred local option
	Increasing coastal bridge deck elevation to prevent damage from waves on surge	Has proven successful as a coastal extreme event resilience approach for new construction Would protect bridge asset from climate hazards	Lower approach spans still vulnerable Cost typically high
	Building coast-parallel roads at lower elevations farther back on barrier islands	Can result in burial under sand early in storm, which reduces pavement damage	Can be high property costs and valuable wetland habitats May be increasing exposure as sea levels rise
	Strengthen connections on coastal bridge to prevent damage from waves on surge	May provide slight increase in extreme event and climate resilience	Will likely lead to failure by another damage mechanism, "negative-bending" slightly later in storm
	Modify bridge cross-section to prevent damage from waves on surge	Possible reductions in wave induced loads are theoretically possible	No guidance available for design as this is a research need/knowledge gap
	Install flood gates over tunnel entrances	Can protect against any storm level	Operational issues closing the gates before storm arrival

Adaptation Category	Asset-Specific Strategy	Pros	Cons
	Raise tunnel approach walls and/or include breakwater/berm to reduce wave runup and overtopping	Reduces the risk of flooding of tunnel	May be a limited improvement in risk reduction
Relocate	Abandon local coast parallel road to prevent wave damage	Allows natural processes to resume Costs can be justified by reduced future damages over the life of the project Coast-perpendicular roads can be used to access certain coastal points of interest	May not be possible due to legal reasons
	Relocate asset to avoid wave damage	May be locally preferred option	Cost may be high

Protection-oriented adaptation strategies - those strategies designed to reduce damage by providing protective physical barriers for climate stressors and extreme events - range from beach nourishment, dune construction, and living shorelines to hard structures such as buried shoulder protection or revetments. So-called “hard” shoreline treatments, particularly a sloping compilation of rocks or concrete units parallel to the shoreline called revetments, are currently the most common method of providing physical protection for coastal communities (Keillor and White, 2003). Sea walls are another example of parallel hard structures, while jetties and groins are installed perpendicular to the coast. Hard structures are used in long duration projects and are effective against high energy waves but may cause additional erosion problems and are susceptible to harsh winters.

Beach nourishment, or the deposition of new sand or beach materials where erosion has occurred, is one way to restore a beach. The sand could be sourced from inland areas or dredged from nearshore environments. However, beach nourishment project generally have a limited life span, and as such require repeated installations.

Living shorelines which use one or a combination of small vegetation, rocks, and sand are an innovative solution to coastal erosion. They are considered a “soft” or “green” solution because they allow water to pass into them as a reservoir or absorb the energy of the waves. The roots and rocks help stabilize the sand against the currents and waves, conserving the shoreline. Additionally, these shorelines offer habitat to a range of other species that have had habitat range shrink because of coastline development. Other examples of living shorelines are restoring wetlands and bluffs along the coastline and riverine floodplains. Living shorelines require maintenance if vegetation is used and may not alone stop still-water flooding in the areas they protect.

2.4 Best Practices

Best practices are considered to be a set of procedures, guidelines or ideas that represent the most effective or prudent course of action, as generally accepted by industry practitioners and researchers. Best practices in the categories of data, data viewers, and coastal design standards are highlighted below.

2.4.1 Best Available Data

Table 2-2, Table 2-3, and Table 2-4 provide key publicly available data sources that the team used. They are organized by data type, and focus on on erosion and shoreline classifications, historic water levels and flood data, and lidar and aerial imagery.

Table 2-2. Erosion and Shoreline Classifications publicly available data sources.

Source	Description, Use, Limitations	Link
30-year Bluff Risk Retreat Area	Displayed in a "Michigan's Great Lake Shorelines Through Time" web viewer, the 30-year bluff retreat risk area marks the estimated shoreline in 2048 using aerial imagery from 1938, 1980, 2009, and 2019. It is only available for the Lower Peninsula and is read only.	https://portal1-geo.sabu.mtu.edu/mtuarcgis/apps/webappviewer/index.html?id=d758800bb18e460ab39aa66631051156
Humphrey's Shoreline Erosion	This source digitized and classified the shorelines in the Lower Peninsula (as well as two counties in the Upper Peninsula) to measure the health and risk of coastal dunes along the Great Lakes. It is read-only and meta-data/methods documentation is limited.	https://portal1-geo.sabu.mtu.edu/mtuarcgis/apps/webappviewer/index.html?id=d758800bb18e460ab39aa66631051156
Great Lakes Aquatic Habitat Framework Classification	Data was compiled from NOAA's Environmental Sensitivity Index. The classifications can be used to assume where erosion is most likely to occur. Includes the best available data for most of the Upper Peninsula.	https://www.glahf.org/data/

Source	Description, Use, Limitations	Link
EGLE High Erosion Risk Area	High erosion risk areas are based on studies from historic aerial imagery. Areas that see a long-term average rate of erosion of 1 foot or more per year, over a minimum of 15 years, are deemed high risk for regulatory purposes. Rate (feet per year) provided at the parcel level.	Coverage: https://miwaters.deq.state.mi.us/nsite/map/layers Detailed studies with erosion rates: https://www.michigan.gov/egle/0,9429,7-135-3313_3677_3700_3995-344443--,00.html#:~:text=High%20risk%20erosion%20areas%20are,minimum%20period%20of%2015%20years.

Notes:

EGLE = Michigan Department of Environment, Great Lakes, and Energy

NOAA = National Oceanic and Atmospheric Administration

Table 2-3. Historic Water Levels and Flood Data publicly available data sources.

Source	Description, Use, Limitations	Link
NOAA Water Level Gauge Data	NOAA provides water level gauge data from 29 stations across the state from the 1970s to present day at a 6-minute timescale. This data source is exceptional for present water levels near the shorelines across the state and is updated real time. Historical data prior to 1970 is available at broader timescales.	Water Levels: https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels Map Viewer: https://tidesandcurrents.noaa.gov/map/

Source	Description, Use, Limitations	Link
Great Lakes Coastal Flood Study and FEMA Flood Maps	The Great Lakes Coastal Flood Study was developed to build a comprehensive model to predict inland flooding. This updated the FEMA flood maps the show coastal SFHA. VE zones indicate waves 3 feet or higher, while coastal AE zones indicate waves of less than 3 feet. Coastal flood hazard modeling included wave height, wave runup, storm surge, overtopping, and erosion modeling, in partnership with USACE. Mapping that came out of this study is now housed on FEMA's Flood Map Service Center. As of the date of this project, some flood maps were still preliminary.	Methodologies: https://www.greatlakescoast.org/ Maps (preliminary and adopted): https://msc.fema.gov/portal/home

Notes:

FEMA = Federal Emergency Management Agency

NOAA = National Oceanic and Atmospheric Administration

SFHA = Special Flood Hazard Area

USACE = U.S. Army Corps of Engineers

Table 2-4. Lidar and Aerial Imagery publicly available data sources.

Source	Description, Use, Limitations	Link
USGS Topographic LiDAR Surveys	USGS and MiSAIL have the same Q2 LiDAR (produced by MiSAIL, housed by USGS)	https://www.usgs.gov/special-topics/earth-mri/science/topographic-lidar-surveys
US Interagency Elevation Inventory	High-accuracy topographic and bathymetric source elevation data. Coverage restricted to areas where a federal project may have collected such data.	https://coast.noaa.gov/inventory/

Notes:

LiDAR = Light Detection and Ranging

MiSAIL = Michigan Statewide Authoritative Imagery & LiDAR

USGS = U.S. Geological Survey

2.4.2 Viewers and Dashboards

Table 2-5 highlights online viewers and dashboards that helped inform the desktop analysis for the at-risk sites, as well as provide background context for this project.

Table 2-5. Relevant Online Data Viewers and Dashboards

Viewer Name	Description, Uses, Limitations	Link
Great Lakes Water Level Dashboard	Interactive dashboard for historic water level data, useful to see water level trends across the decades. Displayed by lake.	https://www.glerl.noaa.gov/data/dashboard/GLD_HTML5.html
Lake Level Viewer	Interactive map that allows user to raise water level to visualize inland flooding.	https://coast.noaa.gov/llv/
USGS National Map Viewer	Extensive dataset including LiDAR, wetlands, watershed boundaries, land cover and more. Ability to reference in additional data layers (including FEMA flood layers). Includes a profile elevation tool.	https://apps.nationalmap.gov/viewer/
Great Lakes Aquatic Habitat Framework	A comprehensive geospatial database that brings together studies that identify critical habitats, invasive species, fish locations, and much more.	https://www.glahf.org/data/
Great Lakes Surface Water Currents	A viewer that depicts the present time flow pattern of the Great Lakes based on simulations from the Great Lakes Coastal Forecasting System. Limitation are that results may not reflect site conditions.	https://www.glerl.noaa.gov/res/glcfs/currents/
Michigan's Great Lake Shorelines Throughout Time	A web application that allows for visual inspection of past erosion and insight into potential future trends. It features historic aerial imagery, historic coastlines, the 30-year Bluff Retreat Risk Area, and multiple shoreline classification systems.	https://portal1-geo.sabu.mtu.edu/mtuarcgis/apps/webappviewer/index.html?id=d758800bb18e460ab39aa66631051156

Notes:

FEMA = Federal Emergency Management Agency

LiDAR = Light Detection and Ranging

USGS = U.S. Geological Survey

2.4.3 Coastal Design Standards

Currently, Michigan does not have required coastal design standard, only guidelines around riverine and stormwater flooding. As such, the engineering team identified the following three documents as industry best practice:

- USACE Coastal Engineering Manual (USACE, Current Edition).
- *Ohio Coastal Design Manual: Guidance for professionals designing structures along Lake Erie* (OH DNR, 2011).
- AASHTO's Drainage Manual (2014 Edition)

The USACE Coastal Engineering Manual is a coastal engineering document that contains the most robust technical assessment for coastal projects. The manual is split into two sections, one is science-based and the other engineering-based. Science-based research explains wave actions, erosions, and shoreline dynamics. The engineering section dives into guidance on project materials, management, and the effectiveness of hazard solutions.

More specifically, the Ohio Coastal Design Manual was developed to highlight protocols that help future coastal projects be successful along Lake Erie. This manual offers guidance and describes the necessary data and efforts that are needed for site information, site surveying principles, design fundamentals, and erosion control structures. Additionally, it offers samples and suggestions for conducting a proper coastal project.

While MDOT has riverine design specifications, it does not have specifications for coastal projects. The engineering team reviewed the above standards as well as Michigan's existing drainage guidelines, and has proposed draft suggestions for coastal design standards, available in *Appendix B: Proposed Coastal Design Criteria*.

While Arcadis has provided draft standards, this topic deserves a level of analysis that is outside the scope of this study. With the great length of shorelines in Michigan, it is recommended that either MDOT develop coastal design standards specific to Michigan's coastal features and climate. The AASHTO Drainage Manual can provide guidelines for establishing these policies and procedures. Considerations should include, at a minimum, setbacks, maximum design water levels, and erosion protection guidelines. Procedures around hydraulics in coastal areas (directly on the Great Lakes, as well as inland water bodies hydrologically connected to the Great Lakes) should be outlined. Frequency and elevation data should also be prescribed (such as design elevation of the road needs to have at least 3 feet of freeboard above the 1 percent AEP).

3 Methodology

This section outlines the methodology the team utilized to perform the necessary research activities contained within this study. The section will describe:

- How Arcadis classified impacts and prioritized study sites;
- The methodology used to conduct regional interviews;
- Procedures for the engineering analysis and duration analysis; and
- The BCA, including the valuation of travel time and inundation and erosion methodology.

3.1 Hazard Classification, Site Selection, and Regional Interviews

As noted in the Introduction, a key starting point for this research project was the High-Water Team’s cataloguing of impacts seen by the regions during the 2019 and 2020 high water levels. For each site of interest, the regions noted the area of impact (by beginning mile point and end mile point from MDOT’s Linear Reference System), the nature of the issue, mitigation projects already implemented, estimated costs for short term and long-term solutions, among other items.

From this initial list of around 50 sites, Arcadis was tasked with classifying impacts and prioritizing sites for the more in-depth engineering and BCA analyses. In order to fully understand the sites, Arcadis met with MDOT staff for an initial round of interviews. In these meetings, the regions identified any additional sites of concern, and provided feedback on their priority sites for consideration for the five site analyses.

Key overarching findings from these regional interviews included:

- Generally, the regions did an excellent job at keeping the roadways open across the state, as there were very few road closures or partial closures.
- Three main issues were seen repeatedly across the state – roadway overtopping and drainage issues, bridges with water near the beams and scour concerns, and bank and bluff erosion.
- Many times, recreational and adjacent assets experienced impacts before the roadways. For example, bike paths, overlooks, and parking areas may have been damaged, however the adjacent roadway was not. MDOT may or may not be responsible for these assets, depending on the location.
- Jurisdictional issues came up across the various regions. Impacts were felt outside of the purview of MDOT, but still pose a threat to MDOT assets.

- Across the state, implemented and planned solutions fell into two categories: 1) armoring, and 2) temporary dikes in conjunction with pumping.
- Regions noted that erosion will always be an issue, which needs monitoring on a continued and ongoing basis.

After a first round of regional interviews, Arcadis classified the various assets into five categories, and documented the most prevalent impacts by category, as shown in Table 3-1.

Table 3-1. Asset classifications and impacts confirmed during regional interviews

Asset Categories	Associated Impact
Roadways	Roadway overtopping, freeze-thaw, saturated base
Bridges	Water near beams; Scour
Drainage systems	Increased maintenance due to sand build-up
Culverts	(No lake level impacts documented to date)
Other (overlooks, parking lots, trails)	Bank and bluff erosion

After reviewing these findings, Arcadis presented a short list of sites to MDOT as part of Project Review Session 2, and which time the regions and Arcadis workshopped which sites should be prioritized for the five site analysis. Considerations were given to sites that represented a range of hazards, were representative of similar issues seen elsewhere in the state and addressed both inland water bodies (hydraulically connected to the Great Lakes) as well as coastal assets. Less emphasis was placed by the regions on making sure sites were evenly distributed between lakes. Per the project scope, site selection was limited to the Lower Peninsula. The final five sites selected were:

1) Bay Region: M-29 St. John's Marsh, roadway inundation.
2) North Region: M-22 Elberta/Frankfort, roadway inundation.
3) Grand Region: M-116 Ludington State Park, bank erosion.
4) Southwest Region: I94-BL St. Joseph, bluff erosion.
5) North Region: US-31 Petosky, bluff erosion.

The location of these sites statewide is represented in Figure 3-1.

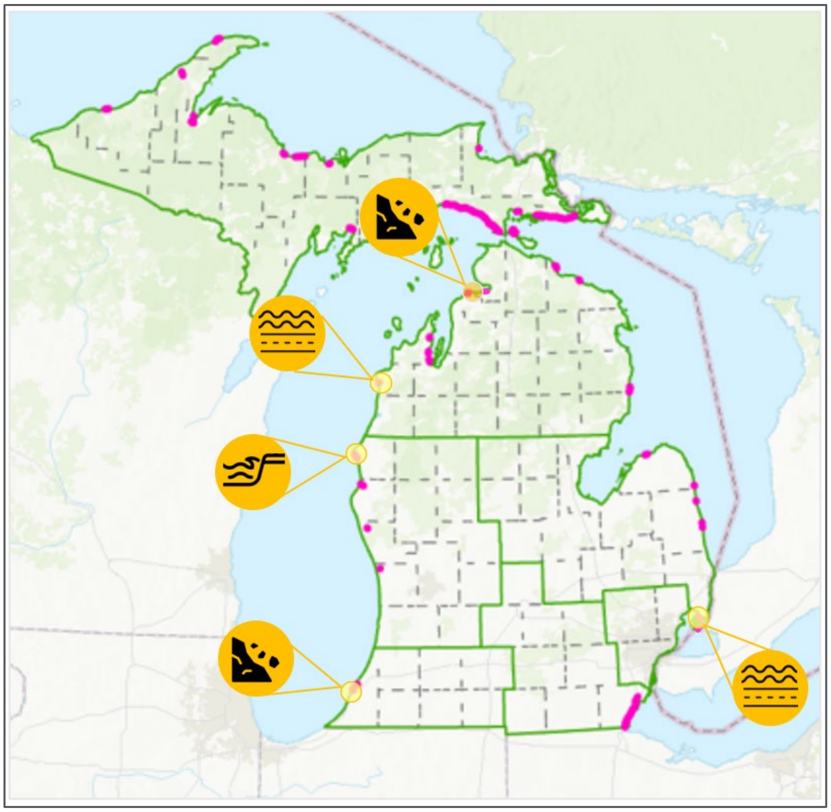


Figure 3-1. The five sites chosen for in-depth analysis, in relation to MDOT regional boundaries (green), and other sites that experienced effects of high water (pink).

3.2 Site Analysis Methods

After site selection was complete, the team continued to dive deeper into understanding each of the chosen sites. The core team included transportation, structural, and geotechnical engineers. The team based their analysis off the following key data inputs:

- **Regional Interviews.** A second round of regional interviews was conducted, focused specifically on the chosen sites. Regional High Water Team representatives invited local staff, as appropriate, to provide additional context around historic impacts, existing mitigation efforts, and additional context (such as jurisdictional issues, recreational impacts, etc.). Additionally, MDOT's geotechnical engineer participated in interviews for sites with erosion considerations.
- **Existing Drawings and Studies**. Existing drawings were provided by the MDOT regions, where available. Additionally, any recent relevant studies were also made available.
- **Site Visits and Aerial Imagery.** Site visits were conducted in May 2021 and drone imagery was captured. Physical damage at each of the sites was captured. At the time

of the site visits, water levels had begun to recede. Historic high-water marks were captured where they were visible (for example, on buildings, in brush, etc.). However, as the water levels had receded, the team relied heavily on the input from regional representatives for descriptions of the areas that saw past inundation.

After reviewing the above documentation, the team reviewed mitigation options for each site. Options ranged from maintain and monitor, to the “Cadillac” of permanent solutions. The team then reviewed the potential mitigation options based on site restrictions and cost. Throughout the regional interviews and project review sessions, the need to balance costs between coastal assets with ongoing operation and maintenance needs was stressed. As such, Arcadis prioritized preferred alternatives that were less costly, and therefore, more likely to be implementable. For the cases where additional data is needed prior to recommending a preferred solution, the necessary data needs are outlined.

Arcadis then developed an engineering assessment for each site. The structural engineer led the assessment of M-22 Elberta/Frankort, M-29 St. John’s Marsh, and M-116 Ludington State Park. For each of these sites, a preferred alternative was identified, and schematic drawings and costing information were developed. The geotechnical engineer led the assessment of I-94BL St. Joseph and US-31 Petosky. These sites are quite complex, and so a strong emphasis was placed on identifying the underlying causes of potential failure. This analysis led to the recognition that additional study, outside the scope of this assessment, may be required for these two sites. As costing information was previously developed, additional considerations for costs are noted.

3.3 Duration Analysis Methods

To better understand the long-term pattern of historic flooding at the two inundation sites chosen for analysis, Arcadis performed a water level duration analysis (duration analysis) in order to determine 1) the number of times water levels exceeded a certain threshold, and 2) compute the duration this threshold was exceeded. A summary of these methods is provided below, with the full methodology included as *Appendix D: Inundation Duration Analysis Methodology*.

The intent of performing this analysis was to supplement the qualitative data received by the regions and understand the history of these sites at a longer time scale (past the institutional knowledge of current staff). While these results informed the mitigation alternatives chosen by the engineering team, they were integral to interpreting the BCA results. As discussed below, the BCA was performed based on a scenario approach. While future water level data is not certain enough to assign a probability of risk, the future scenarios can be contextualized by looking at the water levels the assets have seen over their lifespan.

The duration analysis leverages a unique 51-year hourly water level time series from the Algonac and Ludington NOAA monitoring stations. The Ludington station (9087023) was chosen as the best approximation for water levels experienced a M-22 Elberta/Frankfort, while the Algonac station (9014070) was used as a proxy for M-29 St. John's Marsh.

Two key asset elevations were chosen for the thresholds of the analysis, the top of pavement at the should and the bottom of subgrade (assumed).

As existing roadway drawings for the full site lengths were not available, these elevations were determined by identifying the lowest point along the area of interest via a desktop analysis, by reading the elevation off of auto-contoured lines produced from the 1/9 arc second Digital Elevation Model (DEM). NAVD88 datums were converted to International Great Lakes Datum (IGLD) datums using NOAA's conversion tool.[11] After identifying the top of pavement at the shoulder, the bottom of subgrade was assumed based on a 36 inch build up at M-22 Elberta/Frankfort (based on available boring data) and a 34 inch build up for M-29 St. John's Marsh (based on typical MDOT roadway build-ups).

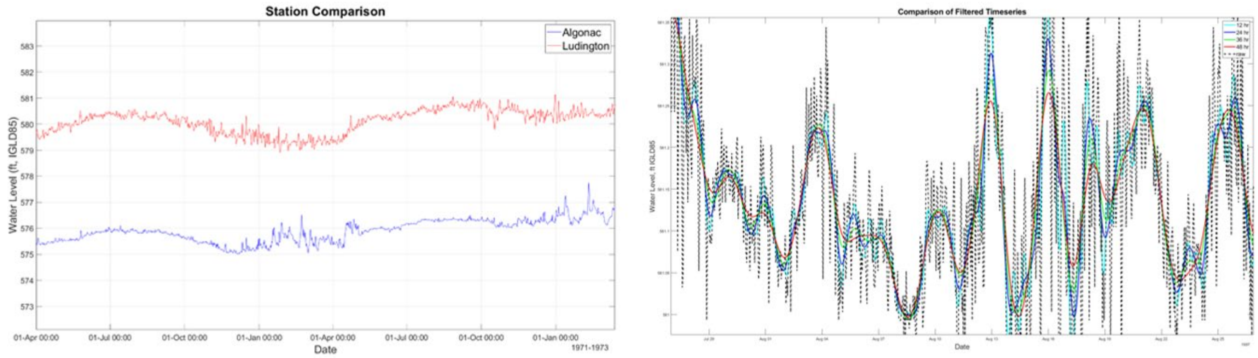
The water level time series data processing workflow consisted of the following steps:

- Database generation in Matlab, inspecting the data for gaps and repetitive entries.
- Performing data pre-processing including removing missing entries (NaN) and performing linear interpolation to fill gaps.
- Performing filtering and sensitivity analysis on the data series, choosing a 24-hour band pass filter.
- Identifying the incidence of exceedance occurs using the peak over threshold method.
- Computing the duration of exceedance to support risk analysis.

See *Appendix D: Inundation Duration Analysis Methodology* for a detailed description of the above steps.

As noted in the literature review, the Great Lake water level times series data is quite unique. Figure 3-2 Inset A presents a comparison between the two gauges over approximately a year of observations, demonstrating the annual cyclical nature of the water levels, along with expected noise. Figure 3-2 Inset B demonstrates the smoothing of the noise, to distill the standing water level.

[11] Available at: https://geodesy.noaa.gov/cgi-bin/IGLD85/IGLD85.prl



a b

Figure 3-2. a) Algonac and Ludington timeseries comparison; b) comparison of filtered timeseries.

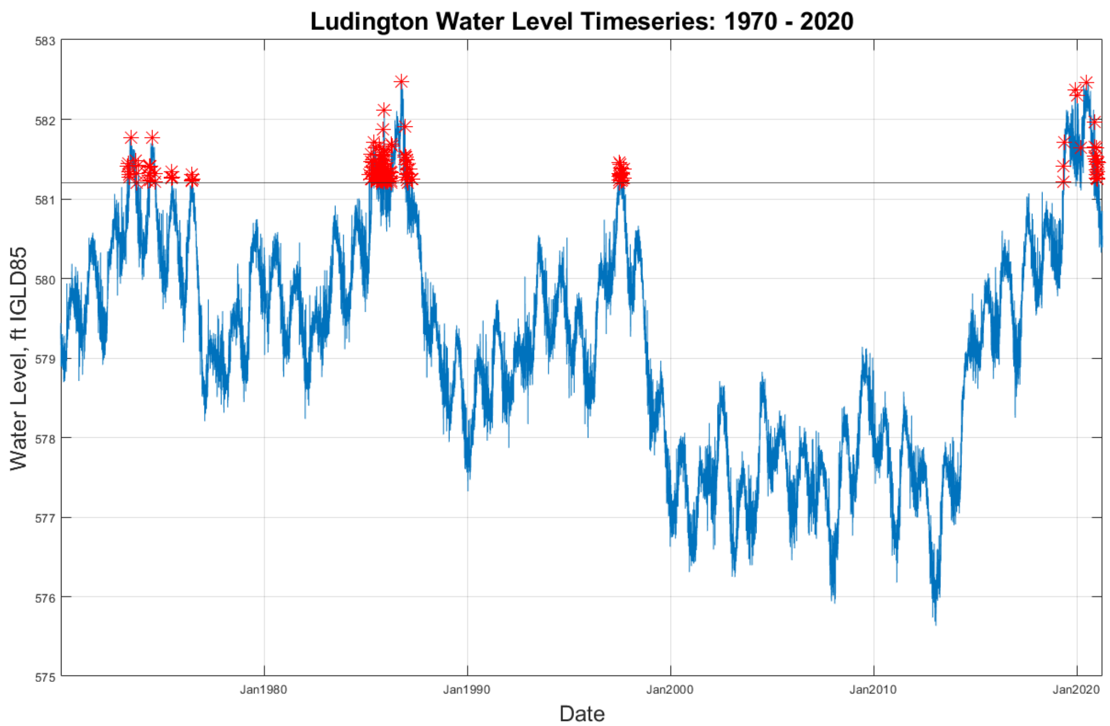


Figure 3-3. Ludington timeseries and Edge of Pavement incidence of exceedance.

After data processing, the Peak-Over-Threshold method was used to identify exceedance occurrences throughout the water level timeseries, an example of which is shown in Figure 3-3. This is a method to model extreme values in a dataset and establishes a threshold to identify values that exceed this threshold. The Peak-Over-Threshold method identifies the peak at the center of the exceedance. An event is defined by an up crossing past the defined threshold and closed by a down crossing below the threshold. The duration is then computed at each peak. The time and date of both the initial up cross past the threshold and the final down cross below the threshold were identified and the difference between these two time and dates was computed.

The results from this analysis are presented by site, in *Section 4.1.1.3* and *Section 4.1.2.3* later in this report. The following limitations should be noted when interpreting the results of this analysis:

- The analysis uses the closest NOAA gauges as proxy sites. Arcadis feels that these are appropriate given the similar protected nature of the gauges and the sites.
- The analysis does not capture smaller, site-specific wind driven events.
- The bottom of pavement threshold assessment assumes the groundwater levels are at the same level as the adjacent water.
- The edge of pavement elevations were estimated based on a relatively coarse elevation dataset, and should be interpreted with a factor of error.

The duration analysis is a useful tool for looking at an extended period of record, beyond the more qualitative data captured in the regional interviews.

3.4 BCA Methods

A BCA was performed to complement the engineering analysis at each of the five sites. The intent of the BCA is to help MDOT decide if it is beneficial to invest in a permanent mitigation solution.

A BCA is based on quantifying all potential costs and benefits of a project, and monetizing those costs and benefits, where able. Costs of a project are presented relative to the no-action alternative and include upfront and ongoing costs. Benefits are generally defined as the avoided future costs of damages give the baseline of no-action. Additionally, both costs and benefits are adjusted to a chosen point of time (or discounted). Benefits may also include the added value to a community or to the environment conveyed by a project. Costs and benefits include both direct and indirect measures incurred by both the asset owners (here, MDOT) and asset users (US DOT FHWA, 2017).

As there are a variety of approaches to quantifying the economic benefits of a project, as well as a range of metrics that may be appropriate. As such, Arcadis reviewed transportation specific BCA guidance at the beginning of the task. The following documents informed the assessment:

- *Economic Analysis Primer* (USDOT, 2003)
- *Synthesis of Approaches for Addressing Resilience in Project Development* (USDOT FHWA, 2017, Chapter 6)
- OMB Circular A-94, Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs (OMB, 1992, rev. 2015)

- *Benefit Cost Analysis Guidance for Discretionary Grant Programs* (US DOT, 2021)

The literature review established there is a high level of uncertainty around future Great Lake water levels, as well as high variation between potential water levels. Per FHWA guidance, a scenario approach is most appropriate when probability data is unavailable or not easily calculated (US DOT FHWA, 2017). After testing a more traditional area under the curve approach, it was jointly agreed by MDOT and Arcadis to pursue a scenario approach to the analysis. For the inundation sites, this translated to identifying two plausible scenarios for future high water levels across a designated planning period, as discussed in below.

For erosion sites, a different approach was required. Erosion losses can be annualized based on assumed average erosion rates. EGLE HERA's provide area-wide rates for some locations across the state. However, this approach does not address the life-safety considerations that are part of MDOT's mission. As established in the literature review, average erosion rates for a slope don't represent the actual erosion pattern for high-risk sites. A site may experience little or no erosion, then a triggering event happens (storm, year of high water levels, etc.), after which 100 feet could be lost overnight. Douglas et al. (2017) summarizes the challenges of quantifying these losses as follows, "One question that often arises is how extreme events under climate change will impact catastrophic road failures such as washouts. However, there are very few existing models for predicting the failure of roads because of the action of moving water and there is no database that contains adequate information for understanding and studying the factors that contribute to these failures." As such, Arcadis performed a mixed qualitative and quantitative assessment for the erosion sites, explained in *Section 3.4.3* below.

3.4.1 Value of Travel Time Savings

In both the inundation and erosion methodologies, the major category of losses avoided that was quantified was value of travel time savings. This is a methodology for calculating the costs associated with loss of roadway or bridge function that is based on the value of lost time.

USDOT standard values distinguish between business and commercial travel time (reimbursed at 100 percent of the wage rate) and personal and recreational time (reimbursed at 50 percent of the wage rate) (US DOT FHWA, 2017). The full wage rate is not typically used to measure personal travel or recreation travel because it is assumed that individuals benefit from the travel (e.g., a scenic drive), or they are willing to accept the travel time in order to gain something (e.g., a higher paying job) (FEMA, 2021).

The calculation is shown in Equation 2:

$$Value\ of\ travel\ time\ savings = (AADT \times avg\ vehicle\ occupancy \times added\ detour\ time\ \times adjusted\ wage\ rate) + (CAADT \times added\ detour\ time\ \times wage\ rate)$$

Equation 2

AADT = annual average daily traffic

CAADT = commercial annual average daily traffic

Here, average vehicle occupancy (across weekends, weekdays) for vehicular trips is used. It is assumed that occupancy of commercial vehicles is one. Per USDOT guidance, the following standard values were used:

- **Adjusted wage rate**. A value of $17.90 was used, adjusted from 2019 to 2021 values per the Consumer Price Index (CPI). This represents a pre-weighted average of personal and business trips for in-vehicle travel (US DOT, 2021).
- **Commercial wage rate**. A value of $30.80 was used, adjusted from 2019 to 2021 values per the CPI. This represents the commercial rate for truck drivers (US DOT, 2021).

Data sources and assumptions for the remaining values were as follows:

- **AADT/CAADT.** Annual average daily traffic (AADT) and commercial annual average daily traffic (CAADT) were retrieved from the MDOT open data portal as a shapefile that was joined to road segments of interest for the project. 2019 Traffic Volumes were used to account for anomalous traffic patterns driven by the COVID-19 pandemic during 2020.

  Arcadis used seasonal adjustments for AADT where appropriate, as summer peaks of high water correspond to time of higher tourist travel in many coastal areas. The season multiplier of 1.5 was provided by the regions.
- **Additional Detour Time:** Detours routes were collected through regional interviews where they were either planned or put in place. A desktop analysis then determined additional mileage and time that detours required.

MDOT is charged with keeping the roadways open, and the level of service to customers across the state is taken very seriously. The value of lost time is one method of monetizing this core value.

3.4.2 Inundation BCA Methodology

Two scenarios were selected to represent potential future high water impacts. The scenarios chosen do not directly correlate to a single water level, but instead assume a given impact—closure of the road. When comparing these scenarios to the effects seen in the 2019 and 2020 seasons, it translates to long-term water level averages slightly higher than historically seen. Lower water levels (where part of the roadway stays open) limit the ability to calculate value of travel time savings.

As the US DOT recommends analysis based on the useful service life of the asset, Arcadis chose a planning horizon of 10-years, as the current asset remaining life are estimated at 0 and 8 years (USDOT, 2021).[12]

The two potential future water level scenarios are as follows:

- Two consecutive years of high water, with loss of function for 30 days (that is, during peak summer month each year). These were assumed to occur in years 3 and 4 of the analysis.
- Five years of high water, with loss of function for 120 days (that is, the full summer season). Arcadis assumed two peaks, the first lasting from year 2 to year 4 (3 years), and the second lasting from year 7 to year 8 (2 years).

For each of these high-water scenarios, three mitigation alternatives are presented, with the following assumptions:

- **No Action.** This alternative assumes maintenance of current conditions ongoing until the end of the asset useful life, at which time reconstruction (with the preferred alternative) is required. For the case where the asset is already at 0 years remaining useful life, Arcadis assumed reconstruction could be put off till the year 9 of the analysis.
- **Temporary Mitigation.** This mitigation option is modeled off the temporary mitigation measure implemented in Whitehall/Montague – a combination of sandbags on both sides of the road with pumping. It is assumed that traffic is reduced to one lane. Again, reconstruction with the preferred mitigation alternative is assumed at the end of the roadway's useful life.
- **Permanent Mitigation.** This option assumes planning and engineering occur in year one, with implementation raising the roadway in year two. Roadway maintenance costs still accrue after the capital project is complete.

Detailed costing for the temporary mitigation option were provided by the Grand Region. These are included in *Appendix C: Whitehall/Montague 2019/2020 Temporary Mitigation Measures Reference Design and Cost* for reference. Using the total cost provided by the region of $137,000 for 900 total feet of sandbags, the per foot cost of sandbag installation was

[12] Arcadis notes that while the "0-year" data layer was requested, the data made available was the "FIX_LIF_YEAR" layer, which is the layer associated with the last large job done at the site. For the purposes of this analysis, Arcadis assumed that this was the time at which another major capital improvement would be needed at the site.

calculated as $88.33 per foot, 1 year of operations and maintenance was calculated as $64.44, and removal costs were calculated as $53.33 per foot.[13]

Arcadis assumed that while temporary, the sandbags would stay in place as long as water levels stayed relatively high, to reduce the need to re-deploy. As such, it was assumed that for the first scenario, sandbags were installed in year 3, stayed in place (even when water levels temporarily declined as part of the annual cycle), and then were removed in year 4. Two years of sandbag operations and maintenance, on top of regular roadway maintenance, was assumed during this timeframe. Assumptions were similar for the second scenario, but instead of one deployment, two deployments were calculated.

Loss of function was calculated using the value of time travel savings methodology outlined above. For the no action alternative, these costs accrued for the period of high water (30 days and 120 days) for the no action alternative. For the temporary mitigation alternative, it was assumed that one day would be lost during installation and removal, as traffic may need to be rerouted.

After assigning the appropriate construction, maintenance, and loss of function assumptions to the appropriate years across the planning time horizon, these costs were then discounted. To arrive at the present value of future costs and benefits it is necessary to discount those values back to present day terms, accounting for the time value of resources. OMB Circular A-94 (8)(b) recommends a real discount rate of 7 percent to approximate the “marginal pretax rate of return” of an average private sector investment. Discounting was calculated using the following equation:

$$Present\ Value = \frac{Future\ Value}{(1+i)^t} \qquad \textit{Equation 3}$$

i = discount rate

t = years in the future for payment (where base year of analysis e is t=0

Data inputs as well as intermediate calculations that then went into the model are presented in Table 3-2 for both M-22 Elberta/Frankfort and M-29 St. John’s Marsh. Final models are presented in *Section 4*.

[13] Total costs excluded the semi-permanent traffic control included in the Whitehall/Montague estimate, as those costs were site specific. Removal costs were assumed to be the same as labor and equipment costs for installation.

Table 3-2. Inputs and intermediate calculations for inundation BCAs.

Input or Intermediate Calculation	M-22 Elberta Frankfort	M-29 St. John's Marsh
Length of Roadway	1150 feet (excluding bridge)	5,800 feet
AADT	3,862 plus a 1.5 seasonal multiplier, for a total of 5,793	10,463
CAADT	62	271
Detour Time (additional)	13 minutes	30 minutes
Detour Distance (additional)	13.4 miles	24 miles
Remaining Asset Life	8 years	0 years
Daily Loss of Function	$41,727	$176,614
Roadway Construction Cost (Preferred Alternative)	$1,625,299	$4,956,288
Roadway Maintenance Costs (1-year)	$183,782	$420,939
Sandbag Installation Cost	$203,167	$1,024,667
Sandbag Maintenance Cost (1-year)	$148,222	$747,556
Sandbag Removal Cost	$122,667	$618,667

Notes:

AADT = annual average daily traffic

CAADT = commercial annual average daily traffic

3.4.3 Erosion BCA Methodology

The methodology for erosion sites used a combination of quantitative and qualitative metrics combined with expert opinion on erosion risk for the three sites examined. Quantitative metrics used were similar to those leveraged for inundation sites and discussed in the data sources section above. These include AADT, detour times and lengths, construction/mitigation costs, and standard values to calculate the cost incurred from loss of function of the asset.

An erosion risk matrix was also created, drawing from a mix of literature and guidance on erosion risk and expert engineering opinion. This two-part matrix aggregates multiple factors into two scoring tables that roughly estimate the likelihood of failure of an asset and the consequences if failure were to occur. The first table was used to analyze a list of mostly physical characteristic to determine a high, moderate, or low likelihood of failure of the slope or bluff in question. These characteristics include groundwater presence, bluff makeup, bluff slope, vegetation, existing protection, and the ability to intervene among other factors. This table was used by a geotechnical engineer to examine the site and develop an opinion of risk. See *Section 5* for the erosion matrix.

The second table aggregates characteristics of the asset of interest to determine a high, moderate, or low consequence of a slope failure occurring. These characteristics include life safety risk, distance from slope to asset, AADT, ease of a detour, and the costs and impacts of implementing a permanent fix of the problem. The resulting score is intended to indicate the overall impact that an assumed slope failure would result in, including the risk of death or injury, traffic impact, and the cost to return the asset to it's functioning state. The two tables together provide a semi-quantitative analysis of erosion risk and consequence for each of the three erosions sites examine and can be used as a tool to examine other sites of interest for MDOT.

4 Five Site Analysis

This section provides the analyses for the five key sites chosen by MDOT, organized by hazard type. The two inundation sites, M-22 Elberta/Frankfort and M-29 St. John's Marsh are discussed first, followed by the three erosion sites, M-116 Ludington State Park, I-94BL St. Joseph, and US-31 Petosky. Key findings and recommendations are discussed.

4.1 Inundation Sites

After regional review of past issues statewide, two inland sites were chosen for further study, M-22 Elberta/Frankfort and M-29 Algonac:

- M-22 Elberta/Frankfort is in MDOT's North Region, under the Traverse City Transportation Service Center (TSC). The causeway and bridge run across Betsie Lake, with water levels driven by Lake Michigan.
- M-29 Algonac is in MDOT's Bay Region, under the Huron TSC. The causeway runs through St. John's Marsh, which is connected to Lake St. Clair.

For both of these sites, raising the roadway was identified as the preferred engineering mitigation alternative, and schematic drawings and costs are provided. However, elsewhere around the state sandbags (such as "Super-Sack" sand barrier) have been employed as a successful temporary mitigation measure for high water events lasting a season or two.[14] The cost benefit analysis is leveraged to compare potential losses between the no-action alternative, temporary mitigation, and permanent mitigation alternative, to help MDOT decide if capital investment should be prioritized for these sites.

While these analyses are site-specific, key costs component and lessons learned can be applied to other sites around the state.

4.1.1 M-22 Elberta/Frankfort

The M-22 Elberta/Frankfort site was chosen to represent similar sites along Lake Michigan where roadway assets are adjacent to inland waterbodies that are still hydrologically connected to a Great Lake. Other similar sites include US-31 BR in Whitehall and Montague (Grand Region).

This section 1) describes the site, the flooding hazard, and impacts from 2019 and 2020; 2) discusses permanent mitigation alternatives and provides an overview of schematic design and costs for the preferred alternative; 3) showcases the duration analysis findings; and 4)

[14] The Muskegon TSC employed "Super-Sack" sand barriers along US-31 BR in Whitehall and Montague during the 2019 and 2020 high water seasons.

presents a benefit cost comparison between no action, temperary mitigation, and the preferred (permanent) mitigation alternative across a 10-year planning horizon.

The detailed documentation on the schematic design for the preferred alternative (raising the roadway) is found in *Appendix E: M-22 Elberta/Frankfort Expanded Documentation* and includes the design criteria; schematic plan, profile, and section drawings; and rough order of magnitude quantity and cost estimates.

4.1.1.1 Site Description and Problem Statement

The M-22 (Lake Street/Frankfort Avenue) causeway and bridge over Betsie Lake is a key point of connection between downtown Elberta (to the south) and Frankfort (to the north). The Bestie River flows into Betsie Lake, which then empties into Lake Michigan. As Betsie Lake is somewhat protected, it is not categorized as a Coastal High Hazard Area (Zone V or VE on FEMA flood maps) for wave impacts, and as such is expected to see wave heights less than 3 feet. Anecdotally, the area frequently sees wind driven run-up during high water levels that can exacerbate flooding during periods of long-term inundation. Upstream, Bestie River has a large intact natural floodplain, which moderates downstream flooding seen due to rainfall runoff (Figure 4-1, insets a, d). However, the assets are still in a 1 percent AEP flood zone, with the causeway acting as the boundary between FEMA’s AE and A floodway designations (Figure 4-1, inset b).

Figure 4-1. Overview of M-22 Elberta/Frankfort site and surrounding context. a) Region aerial photograph depicting relation of Betsie River, Betsie Lake, and Lake Michigan (not to scale). b) FEMA flood map showing AE and A flood zones in relation to project extents, c) the larger Betsie Valley Trailway bridge opening to the south of the site, d) aerial overview of site and surrounding context, looking toward Lake Michigan.

The site considered for analysis extends for approximately 1215 feet from the intersection of M-22 and River Road (Country Road 608) to the intersection of M-22 and Frankfort Ave. The Betsie Valley Trailway (Trailway) walking and biking path extends on either side of the bridge, adjacent to the bridge on the northern side, and separated from the bridge by water on the southern side. MDOT is not responsible for the maintenance of the Trailway, as it is a local asset. On the southern side (the spur), the Trailway bridge opening is larger (both taller and wider) than the M-22 bridge, and therefore the M-22 bridge is the limiting factor for downstream riverine flow (Figure 4-1, inset c).

During 2020 when Lake Michigan was at record highs, this two-lane causeway was inundated for extended periods of time (Figure 4-2, inset b). Even when water receded from the causeway, the sub-base remained saturated, delaying a planned repaving for two years. Inundation typically consisted of standing water in part of the lanes for long periods of time, causing traffic to be restricted to one way traffic. The region installed temporary signals to accommodate this (Figure 4-2, inset c). The area that experienced the most frequent flooding was from approximately the Trailway crossing on the west to the wider “pull-off” to the east (north side of the road).

Shorter, wind-driven events cause both lanes to be closed occasionally throughout the inundation period. In the spring through fall of 2020, overtopping occurred frequently and forced MDOT to install a permanent signed detour. Wind driven events would fluctuate, and could last 15-minutes, an hour, or as long as a week. As the bridge is higher than the causeway, the roadway over the bridge never flooded, though water levels were elevated above the bottom of beams for an extended period (Figure 4-2, inset a).

Figure 4-2. Photographs during the 2019 and 2020 high water. a) elevated winter water levels near the bottom of bridge beams. b) water extending across the causeway, c) signalled one-way traffic due to partial lane flooding.

Damage to date includes scour to the bridge and pavement degradation. The pavement experienced bad ruts from traffic and a prolonged saturated sub-base. While the region was able to skim coat the ruts and topcoat the area that usually floods, there are still areas that show bad cracking and ruts (to the point where the crown is crushed down) (Figure 4-3, inset c). Additionally, water overtopping the road has washed out around guard posts and long-term saturation is rotting the posts. This is most visible on the southern side of the causeway (Figure 4-3, inset b). Now that washout has begun, rainwater is exacerbating the erosion. When looking at the bridge, there are high-water marks on the bottom of the beam (Figure 4-3, inset a). The bridge is categorized as “scour critical,” and while the most recent underwater inspection report found no undermining of the footings, one major storm event could easily change this.[15]

Figure 4-3. Damage as captured in May 2021. a) high water mark on bottom of bridge beams. b) debris from high water and rotting of guardrail posts, c) ruts and cracking on pavement.

Key considerations for the assessment are summarized in Table 4-1.

Table 4-1. Summary of M-22 Elberta/Frankfort site considerations.

Metric	Description
Area of Interest:	M-22 causeway and bridge crossing Betsie Lake between Elberta and Frankfort, Michigan. Between the intersection of M-22 and the 608 to the intersection of M-22 and Frankfort Ave Michigan.
Asset Classification	Causeway (2-lane) and bridge
Begin Extent	190’ NE of Frankfort Avenue DMS: 44°37’09.09” N, 86°13’32.76” Decimal Degrees: 44.619167, -86.225556
End Extent	River Road DMS: 44°22’14.25” N, 86°13’15.0” W Decimal Degrees: 44.620556, -86.220833
Approximate Length	Total: 1215 feet Roadway: 1150 feet Bridge: 65 feet

[15] The most recent underwater bridge inspection report provided to Arcadis was dated July 9, 2020.

Metric	Description
Body of Water	Betsie Lake (hydrologically connected to Lake Michigan)
Distance from roadway to shoreline	Approximately 7 feet – 35 feet; causeway traverses Betsie Lake
Damages to Date	Two lane road down to one lane/one-way traffic, maintained with temporary signal Intermittent full road closures Frequent overtopping to quarter crown of road, and sub-base saturation
Past Mitigation Efforts	Two-lane traffic reduced to one-way (one lane), temporary signaling in place Permanently signed detour of approximately 13.2 miles in place Intermittent road closures coordinated with the County
Costs Expended to Date	In 2020 there was $30,000 in costs from detour signage, signals, barricades, etc.
FEMA FIRM Data	Flood Zone: AE, A BFE: 583 feet NAVD88
Exposure and Critical Elevations	Shoulder: 581.5 feet NAVD88 Bottom of subgrade: 578.5 feet NAVD88 (assumed)
Consequence	AADT: 3,862 CAADT: 62 1.5 Seasonal Multiplier Detour: 13.4 Miles, 13 added minutes

Notes:

AADT = annual average daily traffic

BFE = base flood elevation

CAADT = commercial annual average daily traffic

FEMA = Federal Emergency Management Agency

FIRM = Flood Insurance Rate Map

NAVD88 = North American Vertical Datum of 1988

4.1.1.2 Site Analysis and Preferred Mitigation Alternative

MDOT is concerned that rising lake levels may increase the frequency of overtopping. Therefore, the intent of studying the M-22 causeway and bridge is to evaluate alternatives to mitigate causeway inundation and structural stability of the bridge, considering effects of rising lake levels.

After reviewing the site layout, severity of past flooding, and existing available bridge drawings and soil borings, Arcadis identified the following four potential mitigation alternatives:

- Monitor/Maintain.
- Raise the road and bridge at the same location (preferred).
- Raise the road and lengthen bridge at same location.
- Relocate the road.

Due to cost considerations, raising the road and bridge at the same location was preferred over lengthening the bridge. However, Arcadis recommends MDOT consult with MDNR on the ecological benefits that lengthening the bridge may bring. As this is a critical connection between two existing cities that directly links to downtown Elberta, and given the large intact floodplain of the Betsie River, no preferred location for relocating the roadway was identified. As such, raising the road and bridge at the same location was pursued as the preferred alternative for a schematic design.

From review of the FEMA Flood Insurance Rate Map (FIRM) and Flood Insurance Study (FIS) data, as well as historic lake levels for this area, it was determined to use a critical design elevation of 583.1 NAVD88 which equates to be slightly above the FEMA BFE of 583 feet NAVD88. Also, to comply with the MDOT criteria, a minimum of 2 feet of freeboard was provided from this surface to the proposed bottom of beam elevation for the new structure. To limit the overall impact to the intersecting roadways and drives along the corridor, the projects termini and length were limited to be between the Betsie Valley Trailway entrance and River Road. The design proposes to raise the road a minimum of 18 inches to a maximum of about 3 feet to provide additional freeboard. From reviewing prior years' traffic data along with the current traffic, not much growth is expected for this area and consequently, the proposed roadway typical section is the same as the existing section (Figure 4-4). A calculation for the pavement buildup assuming the current traffic indicated that 7 inches of asphalt over 6 inches of aggregate will be sufficient. See *Appendix E: M-22 Elberta/Frankfort Expanded Documentation* for the schematic drawings and for a summary of the design criteria used for the roadway design.

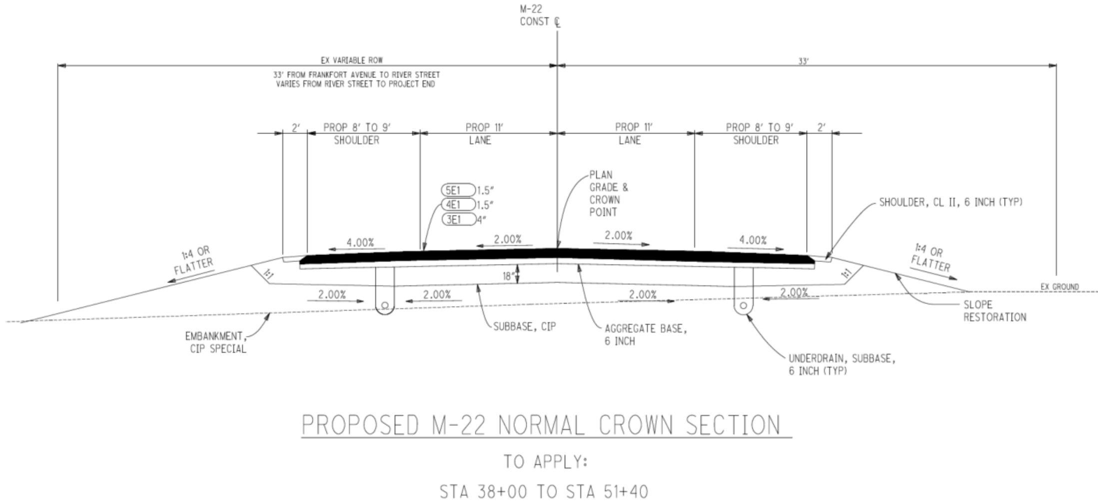


Figure 4-4. Schematic causeway crown section for M-22 Elberta/Frankfort

The existing bridge was constructed in 1995 and is currently in fair condition according to the most recent inspection report. Therefore, it was assumed that the substructure will still have another 50 to 75 years of life expectancy and will be re-used for the proposed improvements. A similar superstructure is proposed to replace the existing bridge superstructure and consists of a 6-inch concrete deck on 17 inches x 36 inches prestressed concrete box beams (Figure 4-5).

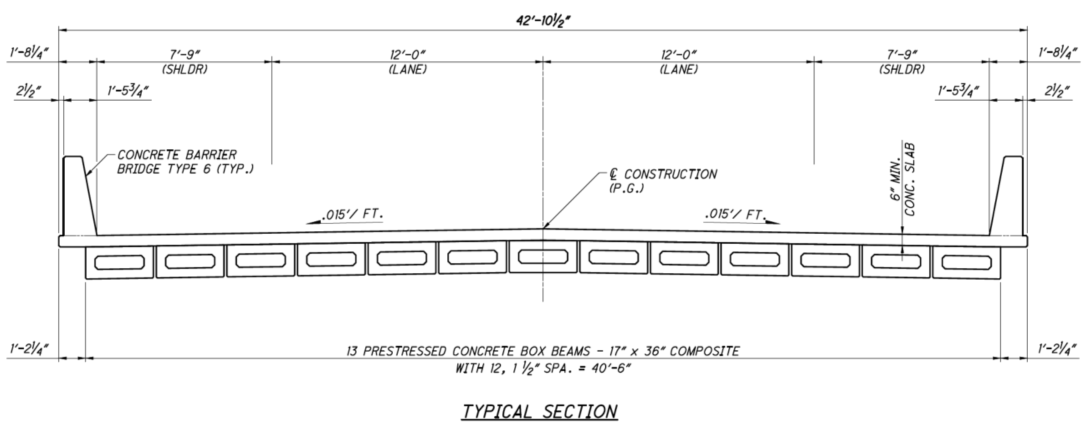


Figure 4-5. Schematic bridge section for M-22 Elberta/Frankfort

The other impacts to the corridor from potentially raising the roadway include needing to the lower and/ or relocate three utility lines which include a sanitary force main, gas main, and telephone lines. It was noted that the telephone ducts are attached to the bridge deck between the existing spread box beams. Environmental impacts should be minimal because the bridge substructure will be salvaged and used for the proposed alternative, and no right-of-way impacts were noted.

Finally, the total estimated construction cost is **$1.625 million.** It is based on MDOT's most recent bid tabs for work done in the region and includes a 30 percent contingency to cover any incidentals not noted in the estimate. See *Appendix E: M-22 Elberta/Frankfort Expanded Documentation* for the schematic cost estimate.

4.1.1.2.1 Limitations and Future Considerations

Arcadis has identified the following recommendations for potential future refinements to the design and cost:

- As an H&H analysis is outside the scope of this study, if MDOT decides to proceed with this project, MDOT should consider further examining the hydraulics at the site. As there is also an opening for where the Betsie Valley Trailway crosses Betsie River, any study should include both adjacent openings, though the M-22 structure will drive the hydraulics.
- Prior to moving forward with a design, MDOT should coordinate with MDNR and other relevant stakeholders on the ecological benefits of a larger bridge opening.
- An additional contingency should be added to the final cost if it is determined lightweight fill is most appropriate.
- Currently, the square foot cost for bridge reconstruction does not assume a larger opening. This would increase the estimated cost due to the need for new abutments.

4.1.1.3 M-22 Elberta/Frankfort Duration Analysis

While M-22 Elberta/Frankort recently saw impacts during the 2019 and 2020 period of high water, there have been similar impacts throughout the life of the asset. As MDOT has just recently started tracking the effect of high water, Arcadis performed a duration analysis on the two critical elevations for the causeway, the top of pavement and bottom of subgrade. These elevations are listed in Table 4-2.

Table 4-2. M-22 Elberta/Frankfort Critical Elevations

Threshold	IGDL Critical Elevation (feet)	NAVD88 Critical Elevation (feet)
Top of Pavement (At Shoulder)	581.2	581.5
Bottom of Subgrade	578.2	578.5
Design Elevation	584.9 (582.9 + 2 feet freeboard)	585.0 (583.0 + 2 feet freeboard)

Notes:

IGLD = International Great Lakes Datum

NAVD88 = North American Vertical Datum of 1988

As discussed in Section 3, the duration analysis uses the proxy NOAA gauge station at Ludington to estimate the number of times Lake Bestie/Lake Michigan water levels have exceeded the asset critical elevations, and if so, for how long. These results are shown in Table 4-3, with additional data visualization included in *Appendix D: Inundation Duration Analysis Methodology*.

Table 4-3. M-22 Elberta/Frankfort Duration Analysis Summary

Year	Top of Pavement (Days)	Bottom of Subgrade (Days)	Design Elevation (Days)
1970	-	364.7	-
1971	-	365.0	-
1972	-	366.0	-
1973	114.8	365.0	-
1974	101.8	365.0	-
1975	7.7	365.0	-
1976	2.7	366.0	-
1977	-	365.0	-
1978	-	365.0	-
1979	-	365.0	-
1980	-	366.0	-
1981	-	365.0	-
1982	-	365.0	-
1983	-	365.0	-
1984	-	366.0	-
1985	166.4	365.0	-

Year	Top of Pavement (Days)	Bottom of Subgrade (Days)	Design Elevation (Days)
1986	277.3	365.0	-
1987	15.2	365.0	-
1988	-	306.9	-
1989	-	309.1	-
1990	-	254.8	-
1991	-	348.8	-
1992	-	363.9	-
1993	-	365.0	-
1994	-	365.0	-
1995	-	362.3	-
1996	-	366.00	-
1997	33.9	365.0	-
1998	-	358.7	-
1999	-	196.5	-
2002	-	107.6	-
2004	-	119.1	-
2005	-	9.75	-
2008	-	19.8	-
2009	-	229.5	-
2010	-	43.8	-
2011	-	45.5	-
2014	-	239.2	-
2015	-	365.0	-
2016	-	366.0	-
2017	-	365.0	-

Year	Top of Pavement (Days)	Bottom of Subgrade (Days)	Design Elevation (Days)
2018	-	365.0	-
2019	238.3	365.0	-
2020	346.2	366.0	-
2021*	2.3	90.9	-

* Only partial data was available for 2021.

Since 1970, it is likely that high water has exceeded the edge of pavement around 158 times. Incidences of exceedance occurred in distinct clusters in the time periods between 1973 – 1976, 1985 – 1987, 1997 and 2019 – 2021. For many of those years, the length of exceedance was over 100 days, with some instances closer to a year.

When looking at the assumed bottom of subgrade, over the past 50 years, water levels have been high enough in Lake Michigan to constantly saturate the bottom of the subbase. Except for the period of extreme low water levels in late 1990s to mid-2010s, water levels have been at or above the bottom of the causeway subbase, not surprisingly given the location of the causeway. This finding bolsters the case that the existing asset is likely to deteriorate at a faster rate than normal, suggesting that earlier capital improvement may be warranted.

This data provides necessary context for MDOT to determine if near-term capital investment is warranted at this site.

4.1.1.4 BCA Results

As noted in *Section 3*, Arcadis compared three mitigation options across two potential future high water level scenarios. Additionally, these results are presented without discounting as well as with a 7 percent (standard federal) discount rate.[16]

As the causeway has an expected 8-years left of asset lifespan, it is assumed MDOT will replace the asset at this time with the preferred mitigation alternative (including the bridge raising). As such, the results below compare the potential added benefits (or avoided losses) of implementing this project ahead of schedule. In all three scenarios – the no-action

[16] The discussion focuses on the discounted values, as discounting is standard practice. The non-discounted version is presented for clarity of seeing when costs are applied, and to provide an upper bound if a lower discount rate was to be chosen.

alternative, temporary mitigation, and permanent mitigation – costs for raising the roadway and bridge are included, just at different years.

Table 4-4 presents the costs assuming 2 consecutive years of high water resulting in road closures for 1 month (that is, the peak summer month) with a 7 percent discount rate. Table 4-5 is the same scenario with no discounting. For this scenario, one deployment of temporary sandbags (lasting 2 years) is assumed.

Table 4-6 presents a more extreme case, assuming 5 years of high water lasting long enough to close the roadway for 120 days each year (that is, 1 full summer season) with a 7 percent discount rate. Table 4-7 is the same scenario with no discounting. In this second scenario, 2 deployments of temporary sandbags (one lasting 2 years, one lasting 3 years) are assumed.

Table 4-4. M-22 Elberta/Frankfort BCA – 2-Years of 1 Month High Water, Discounted

Scenario	Cost	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Totals
No Action	Construction Costs	-	-	-	-	-	-	-	-	$950,000	-	$950,000
	Maintenance Costs	$180,000	$170,000	$160,000	$150,000	$140,000	$130,000	$120,000	$110,000	-	$100,000	$1,300,000
	Loss of Function Costs	-	-	$1,100,000	$1,000,000	-	-	-	-	-	-	$2,100,000
	Total	**$180,000**	**$170,000**	**$1,300,000**	**$1,200,000**	**$140,000**	**$130,000**	**$120,000**	**$110,000**	**$950,000**	**$100,000**	**$4,300,000**
Temporary Mitigation	Construction Costs	-	-	$140,000	$100,000	-	-	-	-	$950,000	-	$1,200,000
	Maintenance Costs	$180,000	$170,000	$290,000	$270,000	$140,000	$130,000	$120,000	$110,000	-	$100,000	$1,500,000
	Loss of Function Costs	-	-	$36,000	$34,000	-	-	-	-	-	-	$71,000
	Total	**$180,000**	**$170,000**	**$470,000**	**$410,000**	**$140,000**	**$130,000**	**$120,000**	**$110,000**	**$950,000**	**$100,000**	**$2,800,000**
Permanent Mitigation	Construction Costs	-	$1,500,000	-	-	-	-	-	-	-	-	$1,500,000
	Maintenance Costs	$180,000	-	$160,000	$150,000	$140,000	$130,000	$120,000	$110,000	$110,000	$100,000	$1,200,000
	Loss of Function Costs	-	-	-	-	-	-	-	-	-	-	-
	Total	**$180,000**	**$1,500,000**	**$160,000**	**$150,000**	**$140,000**	**$130,000**	**$120,000**	**$110,000**	**$110,000**	**$100,000**	**$2,700,000**

Notes:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Discount rate = 7 percent

Table 4-5. M-22 Elberta/Frankfort BCA – 2-Years of 1 Month High Water, not Discounted

Scenario	Cost	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Totals
No Action	Construction Costs	-	-	-	-	-	-	-	-	$1,600,000	-	$1,600,000
	Maintenance Costs	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	-	$180,000	$1,700,000
	Loss of Function Costs	-	-	$1,300,000	$1,300,000	-	-	-	-	-	-	$2,500,000
	Total	**$180,000**	**$180,000**	**$1,400,000**	**$1,400,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$1,600,000**	**$180,000**	**$5,800,000**
Temporary Mitigation	Construction Costs	-	-	$170,000	$120,000	-	-	-	-	$1,600,000	-	$1,900,000
	Maintenance Costs	$180,000	$180,000	$330,000	$330,000	$180,000	$180,000	$180,000	$180,000	-	$180,000	$2,000,000
	Loss of Function Costs	-	-	$42,000	$42,000	-	-	-	-	-	-	$83,000
	Total	**$180,000**	**$180,000**	**$540,000**	**$500,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$1,600,000**	**$180,000**	**$3,900,000**
Permanent Mitigation	Construction Costs	-	$1,600,000	-	-	-	-	-	-	-	-	$1,600,000
	Maintenance Costs	$180,000	-	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$1,700,000
	Loss of Function Costs	-	-	-	-	-	-	-	-	-	-	-
	Total	**$180,000**	**$1,600,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$3,300,000**

Note:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Table 4-6. M-22 Elberta/Frankfort BCA – 5-Years of 4 Months High Water, Discounted

Scenario	Cost	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Totals
No Action	Construction Costs	-	-	-	-	-	-	-	-	$950,000	-	$950,000
	Maintenance Costs	$180,000	$170,000	$160,000	$150,000	$140,000	$130,000	$120,000	$110,000	-	$100,000	$1,300,000
	Loss of Function Costs	-	$4,700,000	$4,400,000	$4,100,000	-	-	$3,300,000	$3,100,000	-	-	$20,000,000
	Total	**$180,000**	**$4,900,000**	**$4,500,000**	**$4,200,000**	**$140,000**	**$130,000**	**$3,500,000**	**$3,200,000**	**$950,000**	**$100,000**	**$22,000,000**
Temporary Mitigation	Construction Costs	-	$190,000	-	$100,000	-	-	$140,000	$76,000	$950,000	-	$1,400,000
	Maintenance Costs	$180,000	$310,000	$290,000	$270,000	$140,000	$130,000	$220,000	$210,000	-	$100,000	$1,900,000
	Loss of Function Costs	-	$39,000	-	$34,000	-	-	$28,000	$26,000	-	-	$130,000
	Total	**$180,000**	**$540,000**	**$290,000**	**$410,000**	**$140,000**	**$130,000**	**$380,000**	**$310,000**	**$950,000**	**$100,000**	**$3,400,000**
Permanent Mitigation	Construction Costs	-	$1,500,000	-	-	-	-	-	-	-	-	$1,500,000
	Maintenance Costs	$180,000	-	$160,000	$150,000	$140,000	$130,000	$120,000	$110,000	$110,000	$100,000	$1,200,000
	Loss of Function Costs	-	-	-	-	-	-	-	-	-	-	-
	Total	**$180,000**	**$1,500,000**	**$160,000**	**$150,000**	**$140,000**	**$130,000**	**$120,000**	**$110,000**	**$110,000**	**$100,000**	**$2,700,000**

Notes:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Discount rate = 7 percent

Table 4-7. M-22 Elberta/Frankfort BCA – 5-Years of 4 Months High Water, not Discounted

Scenario	Cost	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Totals
No Action	Construction Costs	-	-	-	-	-	-	-	-	$1,600,000	-	$1,600,000
	Maintenance Costs	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	-	$180,000	$1,700,000
	Loss of Function Costs	-	$5,000,000	$5,000,000	$5,000,000	-	-	$5,000,000	$5,000,000	-	-	$25,000,000
	Total	**$180,000**	**$5,200,000**	**$5,200,000**	**$5,200,000**	**$180,000**	**$180,000**	**$5,200,000**	**$5,200,000**	**$1,600,000**	**$180,000**	**$28,000,000**
Temporary Mitigation	Construction Costs	-	$200,000	-	$120,000	-	-	$200,000	$120,000	$1,600,000	-	$2,300,000
	Maintenance Costs	$180,000	$330,000	$330,000	$330,000	$180,000	$180,000	$330,000	$330,000	-	$180,000	$2,400,000
	Loss of Function Costs	-	$42,000	-	$42,000	-	-	$42,000	$42,000	-	-	$170,000
	Total	**$180,000**	**$580,000**	**$330,000**	**$500,000**	**$180,000**	**$180,000**	**$580,000**	**$500,000**	**$1,600,000**	**$180,000**	**$4,800,000**
Permanent Mitigation	Construction Costs	-	$1,600,000	-	-	-	-	-	-	-	-	$1,600,000
	Maintenance Costs	$180,000	-	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$180,000	$1,700,000
	Loss of Function Costs	-	-	-	-	-	-	-	-	-	-	-
	Total	**$180,000**	**$1,600,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$180,000**	**$3,300,000**

Note:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

The total costs from the above four models are summarized in Table 4-8. If at least 2 years of 1 month high water occurred within the next 10 years, the cost of deploying sandbags ($2.8 million, discounted) is $100,000 more than investing in the permanent mitigation option ($2.7 million, discounted). Both these options are less costly than the no-action alternative due to the associated costs with loss of roadway function, which accrues $1.5 - $1.6 million in additional costs.

While deploying sandbags once in the next 10 years is on par with the permanent mitigation option, if water levels peak twice, the temporary option is again more costly than investing in the permanent solution early on, by approximately $700,000 (discounted). With no action, losses are approximately 6-8 times the cost of mitigation.

Taken together, these two scenarios suggest that if capital funding is available, it is reasonable to invest in the permanent mitigation solution earlier than originally planned due to coastal flooding risks. While there is a chance that water levels may again recede for an extended period of time, with the cost of even one temporary mitigation installation, costs incurred are similar to investing in permanent mitigation.

Table 4-8. Summary of M-22 Elberta/Frankfort cost and benefit scenarios

Scenario	Cost	2-Years of 1 Month High Water		5-Years of 4 Months High Water	
		Discounted	Not Discounted	Discounted	Not Discounted
No Action	Construction Costs	$950,000	$1,600,000	$950,000	$1,600,000
	Maintenance Costs	$1,300,000	$1,700,000	$1,300,000	$1,700,000
	Loss of Function Costs	$2,100,000	$2,500,000	$20,000,000	$25,000,000
	Total	**$4,300,000**	**$5,800,000**	**$22,000,000**	**$28,000,000**
Temporary Mitigation	Construction Costs	$1,200,000	$1,900,000	$1,400,000	$2,300,000
	Maintenance Costs	$1,500,000	$2,000,000	$1,900,000	$2,400,000
	Loss of Function Costs	$71,000	$ 83,000	$130,000	$170,000
	Total	**$2,800,000**	**$3,900,000**	**$3,400,000**	**$4,800,000**
Permanent Mitigation	Construction Costs	$1,500,000	$1,600,000	$1,500,000	$1,600,000
	Maintenance Costs	$1,200,000	$1,700,000	$1,200,000	$1,700,000
	Loss of Function Costs	-	-	-	-
	Total	**$2,700,000**	**$3,300,000**	**$2,700,000**	**$3,300,000**

Notes:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Discount rate = 7 percent

4.1.2 M-29 St. John's Marsh

The M-29 St. John's Marsh site was chosen as it is an ongoing issue in the Bay Region. The North and Bay Regions have already addressed many of the other sites on the eastern side of Michigan that saw significant impacts from high water in 2019 and 2020 with mid-term to long-term mitigation measures.

This section 1) describes the site, the flooding hazard, and impacts seen in 2019 and 2020; 2) discusses permanent mitigation alternatives and provides an overview of the schematic design for the preferred alternative; 3) showcases the duration analysis findings; and 4) presents a benefit cost comparison between no action, temporary mitigation, and the preferred (permanent) mitigation alternative across a 10-year planning horizon.

The detailed documentation for the preferred alternative (raising the roadway) is found in *Appendix F: M-29 St. John's Marsh Expanded Documentation* and includes the design criteria; schematic plan, profile, section, and deck plan drawings; and rough order of magnitude quantity and cost estimates.

4.1.2.1 Site Description and Problem Statement

M-29 St. John's Marsh roadway connects Algonac and Pearl Beach area to the southwest with Perch Point and Fairhaven to the northeast. The roadway runs through the marsh that is part of the natural delta as the St. Clair River flows into Lake St. Clair (Figure 4-6, inset a, b). Similar to M-22, the site is somewhat protected, and so not categorized as a Coastal High Hazard Area (Zone V or VE on FEMA flood maps) for wave impacts. However, whole area is within FEMA's AE zone, with the BFE alternating between 579 and 580 feet NAVD88 (representing a 1 percent or greater change of flooding to the BFE each year) (Figure 4-6, inset c).

Figure 4-6. Overview of M-29 St. John's Marsh site and surrounding context. a) Region aerial photograph depicting relation of St. Clair River, Lake St. Clair, and St. John's Marsh (not to scale). b) FEMA flood map showing 580 NAVD88 and 579 NAVD88 AE flood zones in relation to project extents, c) aerial overview of site and surrounding context, looking north toward Perch Point.

The site considered for analysis extends for about 5,800 feet from approximately 385 feet north of Flamingo Road to approximately 100 feet south of Anchor Bay Drive. While Arcadis captured a larger extent during the site visit, upon review of the most realistic and cost beneficial project, project extents were limited to the portion of M-29 that runs through the marsh. As the site runs through the St. John's Marsh wildlife area, MDOT must also consider coordination with MDNR.

The roadway surface of M-29 (Dyke Road) west of Pearl Beach is particularly close to encroaching water sources, even under normal water levels. Under high lake level conditions, and calm wind conditions, water has approached or exceeded pavement edge markings (Figure 4-7, inset a). Under unfavorable wind conditions the road has experienced near complete overtopping affecting visibility and safety. Conditions during these times have made the road nearly impassable, and the designated detour route takes travelers 22 miles out of their intended way (*Appendix F: M-29 St. John's Marsh Expanded Documentation*). There are not many existing routes for water to equalize on either side of the roadway. Arcadis noted two existing culverts along the 5,800 feet under consideration, one box culvert in the south, and one pipe culvert to the north (Figure 4-7, inset b). As such, water makes its way over the road.

Damage documented includes significant longitudinal cracking, especially between the east white line and the edge of pavement. Additionally, the region noted ongoing issues with muskrats, where muskrats burrow under the roadway and remove ballast, causing the pavement to sink. Muskrat damage can be identified by small round tar and chip "patches" along the east side of the shoulder along with small ballast washed out into the water at other locations (Figure 4-7, inset c, d).

Key considerations for the assessment are summarized in Table 4-9.

Figure 4-7. Historic flooding and current condition of roadway. a) debris showing extent of high water that has since receded (as well as an unapproved “turtle crossing” sign), b) a pipe culvert, one of the two culverts along the 5,800 feet considered, c) evidence of muskrat damage on the shoulder, d) typical cracking and rutting of this section of roadway.

Table 4-9. Summary of M-29 St. John’s Marsh site considerations.

Metric	Description
Area of Interest	M-29 (Dyke Road) west of Algonac and east-southeast of Fair Haven, Michigan. The section of roadway traveling through St. John’s Marsh between the residential feeder streets of Anchor Bay Drive and Flamingo Road.

Metric	Description
Asset Classification	Roadway (2-lane)
Begin Extent	3385’ North Flamingo Road: DMS: 42º38’17” N, 82º37’00” W Decimal Degrees: 42.638056, -82.616667
End Extent	100’ South of Anchor Bay Drive: DMS: 44º 39’ 14” N, 82º37’08” W Decimal Degrees: 44.653889, -82.61889
Approximate Length	Total: 5,800 feet Roadway: 5800 feet Bridge: 0 feet
Body of Water	St. John’s Marsh (hydrologically connected to Lake St. Clair)
Distance from roadway to shoreline	0 feet (roadway through St. Johns Marsh)
Damages to Data	Water consistently at level of pavement edge marking Wind driven overtopping Additional problem with muskrats digging under road and shoulder
Past Mitigation Efforts	Water over road signs put in place Detour was set up, but only one night of closures occurred Temporary flood barriers purchased, but not used
Costs Expended to Date	Costs associated with purchase of flood barriers and detour/signage
FEMA FIRM Data	Flood Zone: AE BFE: 579 - 580
Exposure and Critical Elevations	Shoulder: 577.5 feet NAVD88 (577.3 feet IGLD) Bottom of Subgrade: 574.7 feet NAVD88 (574.5 feet IGLD)
Consequence	AADT: 10,463 CAADT: 271 Not seasonal traffic Detour: 24 miles, additional 30 minutes.

Notes:

AADT = annual average daily traffic

CAADT = commercial annual average daily traffic

BFE = base flood elevation

FEMA = Federal Emergency Management Agency

FIRM = Flood Insurance Rate Map

NAVD88 = North American Vertical Datum of 1988

4.1.2.2 Site Analysis and Preferred Mitigation Alternative

This site has been a concern for MDOT in the past, and has been considered for causeway placement. However, to-date cost has been a limiting factor. The purpose of studying M-29 is to evaluate engineered alternatives to mitigate roadway inundation.

After reviewing the site layout and floodplain extents, pattern of past flooding, and existing available drawings, Arcadis identified the following four potential mitigation alternatives:

- Monitor/Maintain
- Raise the road in the same location
- Construct a raised, long bridge structure
- A combination of raising the road and a raised long bridge structure.

Arcadis determined that while the ideal solution, construction of an extended raised bridge structure would be prohibitively expensive. Combining a raised roadway with a bridge or additional culverts/animal crossings may mediate some environmental concerns. Still, Arcadis noted that this alternative would be hard to prioritize due to costs. As such, simply raising the road was chosen as the preferred alternative. Arcadis suggests additional coordination with MDNR to obtain their concurrence if this project is chosen to move forward. Currently, the two existing culverts are included in the scope and cost presented below.

From review of the historic lake levels, USACE historic data, and FEMA flood maps, it was determined to use a critical design elevation of 580 feet NAVD88, or the higher of the two BFEs experienced across the site.

To comply with the MDOT criteria, a minimum of 1.5 feet of freeboard was provided from this surface to the proposed edge of pavement for the raised roadway. To meet these requirements, raising the road a minimum of 18 inches to a maximum of about 3 feet is proposed. The project limits were intentionally set to be outside of the residential areas of Algonac so impacts to intersections, drives, and utilities can be limited. However, from the review of record drawings and other information, Arcadis noted that three major utility lines are located within the M-29 corridor – an existing 16-inch sanitary force main, 12-inch water main, and 6-inch gas main. While the existing water main is set about 5-feet ± from the existing west right-of-way line and should not be an issue, the sanitary and gas main are within the grading embankment areas of the roadway and may need to be raised as well. From reviewing recent traffic data, not much growth is expected for this area. Therefore, the proposed roadway typical section is the same as the existing section which appears to comply with all MDOT criteria (Figure 4-8). A calculation for the pavement buildup assuming the current traffic indicated that 9 inches of asphalt over 6 inches of aggregate will be sufficient. See *Appendix F: M-29 St. John's Marsh Expanded Documentation* for the schematic drawings and for a summary of the design criteria used for the roadway design.

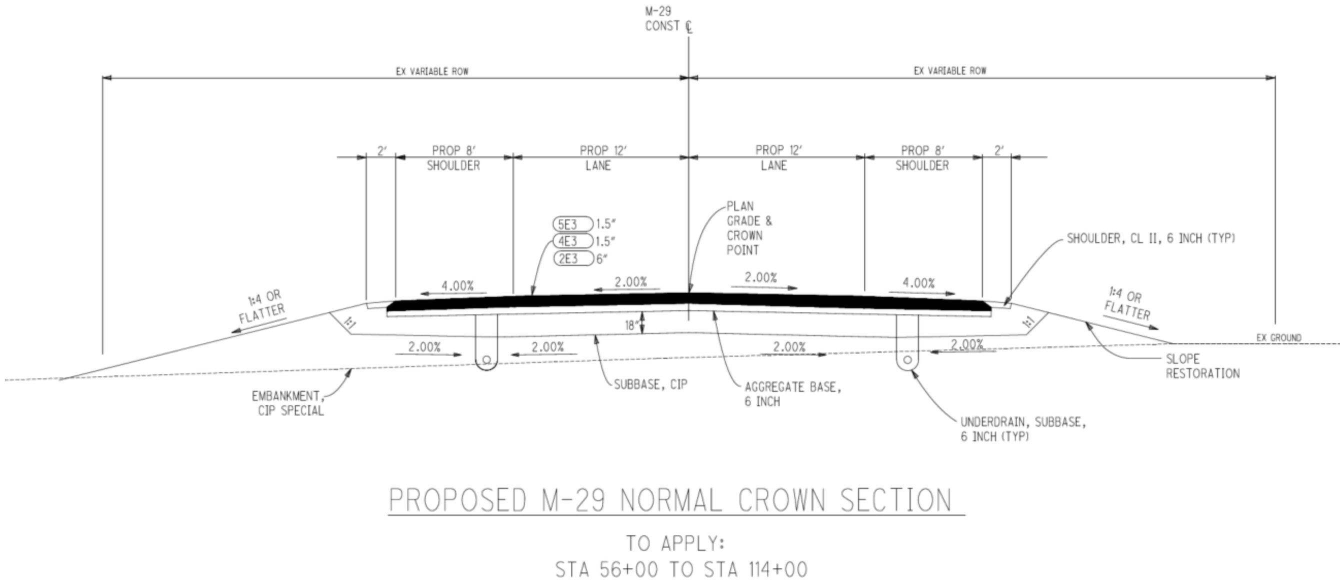


Figure 4-8. Schematic crown section for M-29 St. John's Marsh.

There are no large (that is, > 10 foot span) drainage structures within the project's limits, and there are only two culvert crossings, both pipes being 29 inches x 45 inches Reinforced Concrete Elliptical Pipes. Some consideration was given to adding a larger structure within the corridor so the water levels on either side of the roadway could be equalized. This can certainly be studied further to determine its benefits, but for the purpose of this study, no additional water crossings or culverts were included.

The other impacts to the corridor from the roadway raise include environmental impacts to the marsh including filling in wetlands disturbances and endangered species impacts. With a wider than normal arterial existing right-of-way width of 106 feet, it is anticipated that there will be no right-of-way impacts.

The total estimated construction cost is **$4.956 million.** It is based on MDOT's most recent bid tabs for work done in the region and includes a 30 percent contingency to cover any incidentals not noted in the estimate. These include such items as removal and backfill of subgrade materials, additional drainage improvements, and barrier protection where required.

See *Appendix F: M-29 St. John's Marsh Expanded Documentation* for the schematic cost estimate.

4.1.2.2.1 Limitations and Future Considerations

Arcadis has identified the following recommendations for potential future refinements to the design and cost:

- MDOT should coordinate with MDNR, for both finalizing a proposed alternative, as well as coordination regarding any environmental impacts (such as disturbing wetlands or endangered species impacts).
- MDOT can continue to study the benefits of adding an additional larger structure within the corridor.
- MDOT should consider increasing the potential freeboard. While kept at MDOT's current standards to keep the costs as low as possible, there is a growing trend to provide additional freeboard in the face of climate uncertainty. Also, to comply with the MDOT Geotechnical Manual, because the soils adjacent to the road are organic and are considered poor for a roadway subgrade, consideration should be given to raise the road to a minimum of 5 feet of fill depth to eliminate any possibility of negative pore water pressures/capillary rise in the subgrade.

4.1.2.3 M-29 St. John's Marsh Duration Analysis

Again, similar to M-22 Elberta/Frankfort, Arcadis performed a duration analysis on two critical elevations for the roadway, the top of pavement and bottom of subgrade. These elevations are listed in Table 4-10.

Table 4-10. Critical Elevations at St. John's Marsh

Threshold	IGDL Critical Elevation (feet)	NAVD88 Critical Elevation (feet)
Top of Pavement (At Shoulder)	577.3	577.5
Bottom of Subgrade	574.5	574.7
Design Elevation	581.3 (579.8 + 1.5 feet freeboard)	581.5 (580.0 + 1.5 feet freeboard)

Notes:

IGLD = International Great Lakes Datum

NAVD88 = North American Vertical Datum of 1988

As discussed in *Section 3*, the duration analysis uses the proxy NOAA gauge station at Algonac to estimate the number of times Lake St. Clair water levels have exceeded the asset critical elevations, and if so, for how long. These results are shown in Table 4-11, with additional data visualization included in *Appendix D: Inundation Duration Analysis Methodology*.

Table 4-11. M-29 St. John's Marsh Duration Analysis Summary

Year	Top of Pavement (Days)	Bottom of Subgrade (Days)	Design Elevation (Days)
1970	-	337.4	-
1971	-	359.1	-
1972	-	366.0	-
1973	4.8	365.0	-
1974	1.4	365.0	-
1975	-	365.0	-
1976	-	366.0	-
1977	-	365.0	-
1978	-	365.0	-
1979	-	365.0	-
1980	-	366.0	-
1981	-	367.9	-
1982	-	365.0	-
1983	-	365.0	-
1984	-	357.7	-
1985	9.2	365.0	-
1986	200.0	365.0	-
1987	16.6	365.0	-
1988	-	362.3	-
1989	-	290.2	-
1990	-	331.5	-

Year	Top of Pavement (Days)	Bottom of Subgrade (Days)	Design Elevation (Days)
1991	-	357.9	-
1992	-	366.0	-
1993	-	365.0	-
1994	-	365.0	-
1995	-	365.0	-
1996	-	335.0	-
1997	1.3	365.0	-
1998	-	345.2	-
1999	-	211.2	-
2000	-	57.0	-
2002	-	122.2	-
2004	-	136.1	-
2005	-	176.1	-
2006	-	61.5	-
2007	-	20.8	-
2008	-	107.8	-
2009	-	258.7	-
2010	-	133.8	-
2011	-	212.0	-
2012	-	33.8	-
2013	-	63.4	-
2014	-	247.5	-
2015	-	319.7	-
2016	-	366.0	-
2017	-	365.0	-

Year	Top of Pavement (Days)	Bottom of Subgrade (Days)	Design Elevation (Days)
2018	-	365.0	-
2019	148.2	365.0	-
2020	199.3	366.0	-
2021*	1.3	90.9	-

* Only partial data was available for 2021.

Since 1970, it is likely that high water has exceeded the edge of pavement around 66 times (significantly fewer than M-22's 158). Again, the incidences of occurrence are clustered during periods of elevated water conditions in the following time periods; 1973 – 1974, 1985 – 1987, and 2019 – 2021. A single incident of exceedance is observed in 1997. Compared to M-22 Elberta/Frankfort, the times of exceedance are much shorter, though 1986 saw a duration of 200 days, in additional to extended periods during the 2019 and 2020 cycle.

The bottom of subgrade results are quite similar to M-22 Elberta/Frankfort. Here too, the subbase sees almost continuous saturation except during times of extreme lows. Again, the asset as built is likely to deteriorate at a faster rate than normal, suggesting that earlier capital improvement may be warranted.

4.1.2.4 BCA Results

Again, for M-29 St. John's Marsh, Arcadis compared three mitigation options across two potential future high water level scenarios. The results are presented without discounting as well as with a 7 percent (standard federal) discount rate.[17]

While currently the roadway has an expected 0-year asset lifespan, it was assumed that replacement could be deferred until year 9 of the planning horizon.[18] When replacement occurs, it was assumed that MDOT will replace the asset with the preferred mitigation alternative, as opposed to replacing as-is. As such, the results below compare the potential added benefits (or avoided losses) of implementing this project ahead of schedule. In all three

[17] The discussion focuses on the discounted values, as discounting is standard practice. The non-discounted version is presented for clarity of seeing when costs are applied, and to provide an upper bound if a lower discount rate was to be chosen.

scenarios– the no-action alternative, temporary mitigation, and permanent mitigation – costs for raising the roadway and bridge are included, just at different years.

Table 4-12 presents the costs assuming 2 consecutive years of high water resulting in road closures for 1 month (that is, the peak summer month) with a 7 percent discount rate. Table 4-13 is the same scenario with no discounting. For this scenario, one deployment of temporary sandbags (lasting 2 years) is assumed.

Table 4-14 presents a more extreme case, assuming 5 years of high water lasting long enough to close the roadway for 120 days each year (that is, one full summer season) with a 7 percent discount rate. Table 4-15 is the same scenario with no discounting. In this second scenario, two deployments of temporary sandbags (one lasting 2 years, one lasting 3 years) are assumed.

Table 4-12. M-29 St. John's Marsh – 2-Years of 1 Month High Water, Discounted

Scenario	Cost	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Totals
No Action	Construction Costs	-	-	-	-	-	-	-	-	$2,900,000	-	$2,900,000
	Maintenance Costs	$420,000	$390,000	$370,000	$340,000	$320,000	$300,000	$280,000	$260,000	-	$230,000	$2,900,000
	Loss of Function Costs	-	-	$4,600,000	$4,300,000	-	-	-	-	-	-	$9,000,000
	Total	**$420,000**	**$390,000**	**$5,000,000**	**$4,700,000**	**$320,000**	**$300,000**	**$280,000**	**$260,000**	**$2,900,000**	**$230,000**	**$15,000,000**
Temporary Mitigation	Construction Costs	-	-	$890,000	$510,000	-	-	-	-	$2,900,000	-	$4,300,000
	Maintenance Costs	$420,000	$390,000	$1,000,000	$950,000	$320,000	$300,000	$280,000	$260,000	-	$230,000	$4,200,000
	Loss of Function Costs	-	-	$150,000	$140,000	-	-	-	-	-	-	$300,000
	Total	**$420,000**	**$390,000**	**$2,100,000**	**$1,600,000**	**$320,000**	**$300,000**	**$280,000**	**$260,000**	**$2,900,000**	**$230,000**	**$8,800,000**
Permanent Mitigation	Construction Costs	-	$4,600,000	-	-	-	-	-	-	-	-	$4,600,000
	Maintenance Costs	$420,000	-	$370,000	$340,000	$320,000	$300,000	$280,000	$260,000	$240,000	$230,000	$2,800,000
	Loss of Function Costs	-	-	-	-	-	-	-	-	-	-	-
	Total	**$420,000**	**$4,600,000**	**$370,000**	**$340,000**	**$320,000**	**$300,000**	**$280,000**	**$260,000**	**$240,000**	**$230,000**	**$7,400,000**

Notes:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Discount rate = 7 percent

Table 4-13. M-29 St. John's Marsh – 2-Years of 1 Month High Water, Not Discounted

Scenario	Cost	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Totals
No Action	Construction Costs	-	-	-	-	-	-	-	-	$5,000,000	-	$5,000,000
	Maintenance Costs	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	-	$420,000	$3,800,000
	Loss of Function Costs	-	-	$5,300,000	$5,300,000	-	-	-	-	-	-	$11,000,000
	Total	**$420,000**	**$420,000**	**$5,700,000**	**$5,700,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$5,000,000**	**$420,000**	**$19,000,000**
Temporary Mitigation	Construction Costs	-	-	$1,000,000	$620,000	-	-	-	-	$5,000,000	-	$6,600,000
	Maintenance Costs	$420,000	$420,000	$1,200,000	$1,200,000	$420,000	$420,000	$420,000	$420,000	-	$420,000	$5,300,000
	Loss of Function Costs	-	-	$180,000	$180,000	-	-	-	-	-	-	$350,000
	Total	**$420,000**	**$420,000**	**$2,400,000**	**$2,000,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$5,000,000**	**$420,000**	**$12,000,000**
Permanent Mitigation	Construction Costs	-	$5,000,000	-	-	-	-	-	-	-	-	$5,000,000
	Maintenance Costs	$420,000	-	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	$3,800,000
	Loss of Function Costs	-	-	-	-	-	-	-	-	-	-	-
	Total	**$420,000**	**$5,000,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$8,700,000**

Note:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Table 4-14. M-29 St. John's Marsh – 5-Years of 4 Month High Water, Discounted

Scenario	Cost	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Totals
No Action	Construction Costs	-	-	-	-	-	-	-	-	$2,900,000	-	$2,900,000
	Maintenance Costs	$420,000	$390,000	$370,000	$340,000	$320,000	$300,000	$280,000	$260,000	-	$230,000	$2,900,000
	Loss of Function Costs	-	$20,000,000	$19,000,000	$17,000,000	-	-	$14,000,000	$13,000,000	-	-	$83,000,000
	Total	**$420,000**	**$20,000,000**	**$19,000,000**	**$18,000,000**	**$320,000**	**$300,000**	**$14,000,000**	**$13,000,000**	**$2,900,000**	**$230,000**	**$89,000,000**
Temporary Mitigation	Construction Costs	-	$960,000	-	$510,000	-	-	$680,000	$390,000	$2,900,000	-	$5,400,000
	Maintenance Costs	$420,000	$1,100,000	$1,000,000	$950,000	$320,000	$300,000	$280,000	$730,000	-	$230,000	$5,300,000
	Loss of Function Costs	-	$170,000	-	$140,000	-	-	$120,000	$110,000	-	-	$540,000
	Total	**$420,000**	**$2,200,000**	**$1,000,000**	**$1,600,000**	**$320,000**	**$300,000**	**$1,100,000**	**$1,200,000**	**$2,900,000**	**$230,000**	**$11,000,000**
Permanent Mitigation	Construction Costs	-	$4,600,000	-	-	-	-	-	-	-	-	$4,600,000
	Maintenance Costs	$420,000	-	$370,000	$340,000	$320,000	$300,000	$280,000	$260,000	$240,000	$230,000	$2,800,000
	Loss of Function Costs	-	-	-	-	-	-	-	-	-	-	-
	Total	**$420,000**	**$4,600,000**	**$370,000**	**$340,000**	**$320,000**	**$300,000**	**$280,000**	**$260,000**	**$240,000**	**$230,000**	**$7,400,000**

Notes:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Discount rate = 7 percent

Table 4-15. M-29 St. John's Marsh – 5-Years of 4 Month High Water, Not Discounted

Scenario	Cost	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Totals
No Action	Construction Costs	-	-	-	-	-	-	-	-	$5,000,000	-	$5,000,000
	Maintenance Costs	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	-	$420,000	$3,800,000
	Loss of Function Costs	-	$21,000,000	$21,000,000	$21,000,000	-	-	$21,000,000	$21,000,000	-	-	$110,000,000
	Total	**$420,000**	**$22,000,000**	**$22,000,000**	**$22,000,000**	**$420,000**	**$420,000**	**$22,000,000**	**$22,000,000**	**$5,000,000**	**$420,000**	**$110,000,000**
Temporary Mitigation	Construction Costs	-	$1,000,000	-	$620,000	-	-	$1,000,000	$620,000	$5,000,000	-	$8,200,000
	Maintenance Costs	$420,000	$1,200,000	$1,200,000	$1,200,000	$420,000	$420,000	$420,000	$1,200,000	-	$420,000	$6,800,000
	Loss of Function Costs	-	$180,000	-	$180,000	-	-	$180,000	$180,000	-	-	$710,000
	Total	**$420,000**	**$2,400,000**	**$1,200,000**	**$2,000,000**	**$420,000**	**$420,000**	**$1,600,000**	**$2,000,000**	**$5,000,000**	**$420,000**	**$16,000,000**
Permanent Mitigation	Construction Costs	-	$5,000,000	-	-	-	-	-	-	-	-	$5,000,000
	Maintenance Costs	$420,000	-	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	$420,000	$3,800,000
	Loss of Function Costs	-	-	-	-	-	-	-	-	-	-	-
	Total	**$420,000**	**$5,000,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$420,000**	**$8,700,000**

Note:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

The total costs from the above four models are summarized in Table 4-16 below. Due to the extended length of the site – over a mile – the installation, operation, and maintenance of a temporary measure is expected to be quite expensive, for a total cost of $8.8 million (discounted) across the planning horizon. As such, even with only one installation, this exceeds the expected cost of $7.4 million (discounted) of the permanent measure across the planning horizon. MDOT could consider ways to decrease the cost of the temporary sandbags, such as limiting the length for which they are installed or finding efficiencies in operations and maintenance costs. However, with water levels even slightly higher than those seen in 2019 and 2020, it is expected that water would be over much of the roadway during high wind events. Without any mitigation, costs from lost roadway function are almost 2 times either mitigation option, due to the relatively high volume of traffic (10,463 AADT / 271 CAADT) and extended detour time (30 additonal minutes).

If sandbags need to be deployed more than once, the case grows stronger for the permanent mitigation option. Over the planning horizon, relying on temporary mitigation measures would cost $3.6 million more dollars than installing a permanent solution early in the planning cycle (discounted). Due to extended loss of function over multiple years, with no action, losses could reach up to $89 million (discounted).

Taken together, these two scenarios suggest that if capital funding is available, it is reasonable to invest in the permanent mitigation solution as early as able. However, efficiencies may be able to be realized in a temporary solution decreasing the actual costs, given the total costs over the planning lifecycle. Additionally, there is potential savings if water levels do not exceed what they reached in 2019 and 2020 over the next ten years.

Table 4-16. Summary of M-29 St. John's Marsh cost and benefit scenarios

Scenario	Cost	2-Years of 1 Month High Water		5-Years of 4 Months High Water	
		Discounted	Not Discounted	Discounted	Not Discounted
No Action	Construction Costs	$2,900,000	$5,000,000	$2,900,000	$5,000,000
	Maintenance Costs	$2,900,000	$3,800,000	$2,900,000	$3,800,000
	Loss of Function Costs	$9,000,000	$11,000,000	$83,000,000	$110,000,000
	Total	**$15,000,000**	**$19,000,000**	**$89,000,000**	**$110,000,000**
Temporary Mitigation	Construction Costs	$4,300,000	$6,600,000	$5,400,000	$8,200,000
	Maintenance Costs	$4,200,000	$5,300,000	$5,300,000	$6,800,000
	Loss of Function Costs	$300,000	$350,000	$540,000	$710,000
	Total	**$8,800,000**	**$12,000,000**	**$11,000,000**	**$16,000,000**
Permanent Mitigation	Construction Costs	$4,600,000	$5,000,000	$4,600,000	$5,000,000
	Maintenance Costs	$2,800,000	$3,800,000	$2,800,000	$3,800,000
	Loss of Function Costs	-	-	-	-
	Total	**$ 7,400,000**	**$ 8,700,000**	**$ 7,400,000**	**$8,700,000**

Notes:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Discount rate = 7 percent

4.2 Erosion Sites

After regional review of past issues statewide, three erosion sites were chosen for further study:

- M-116 Ludington State Park is in MDOT's Grand Region under the Muskegon TSC. The roadway runs through low sand dunes and is adjacent to Lake Michigan.
- I-94BL St. Joseph is in MDOT's Southwest Region under the Kalamazoo TSC. The roadway is on an elevated bluff, adjacent to Lake Michigan.
- US-31 Petosky is in MDOT's North Region, under the Traverse City TSC. The roadway is on an elevated bluff, adjacent to Little Traverse Bay in Lake Michigan.

4.2.1 M-116 Ludington State Park

The M-116 Ludington State Park site was chosen due to the site's critical nature of being the only access point into and out of Ludington State Park. Additionally, the site can serve as reference for other areas in the state where roadway relocation may be warranted.

This section 1) describes site and erosion hazard; 2) discusses permanent mitigation alternatives and provides an overview of schematic engineering design for the preferred alternative; and 3) presents a mixed qualitative and quantitative BCA.

The detailed documentation for the preferred alternative (relocating the roadway) is found in *Appendix G: M-116 Ludington State Park Expanded Documentation* and includes the design criteria; schematic plan, profile, and section drawings; and rough order of magnitude quantity and cost estimates.

4.2.1.1 Site Description and Problem Statement

M-116 between Ludington State Park and Piney Ridge Road runs effectively north-south near the shore of Lake Michigan. This portion of M-116 is approximately 3 miles long, 60 to 400 feet east of the shoreline, and approximately 10 feet higher than the typical lake elevation. The route is the only access to Ludington State Park and the associated recreational facilities in the area, with the beach and campgrounds just past the Big Sable River to the north. Two key areas along this larger stretch of particular concern, 2,875 feet in the north, and 960 feet in the south (Figure 4-9, inset a). While the roadway itself is not within a FEMA flood zone, the adjacent dunes are partially within both VE (waves >3 feet) and AE flood zones (Figure 4-9, inset b).

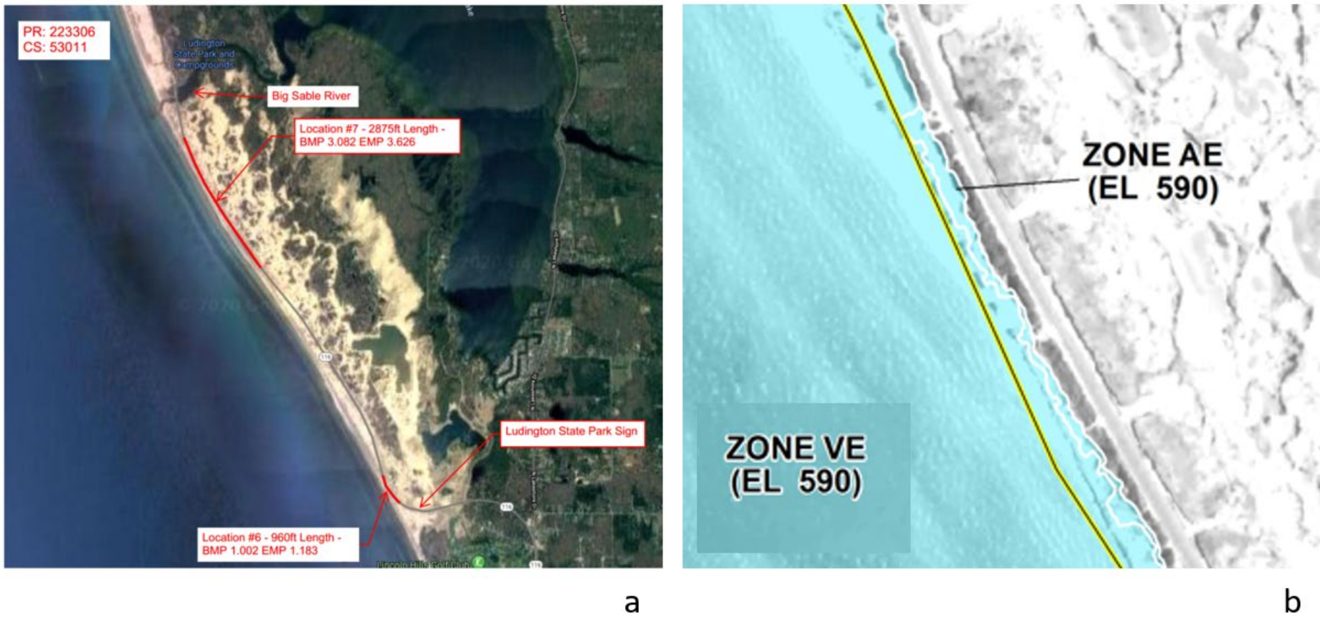


Figure 4-9. Site context for M-116. a) aerial showing two areas of interest b) close up of FEMA flood map showing adjacency of VE and AE zones to the dunes and roadway.

Beach and dune erosion has reduced the width of the beach between the lake and the road and has exposed groins along the shoreline (Figure 4-10, inset a, d). Based on regional interviews, groins had been installed at two points in time along this stretch. The first was in 1953 (now quite dilapidated), and a second series was installed in 1986 during the last cycle of high water (Figure 4-10, inset c). Additionally in 1986, stone was placed along the base or side of the then current slope (Figure 4-10, inset b). Since the 1980s, these groins and stones had since been covered by sand, only to again be uncovered in 2019 and 2020. During the 2019 and 2020 seasons, the State Geotechnical Engineer performed monitoring on this site, however no road closures were experienced.

Key considerations for the assessment are summarized in Table 4-17.

a b c d

Figure 4-10. Imagery of past mitigation measures at M-116. a) groins in the south b) rip rap in the south c) groins in the north, with both 1953 installation (underwater) and 1986 installations visible d) groins in the north.

Table 4-17. Summary of M-116 St. John's Marsh site considerations.

Metric	Description
Asset Classification	Roadway (2-lane)
Begin Extent	500 feet East of Piney Ridge Road: DMS: 43º59'36.0 N, 86º28'12.10" W Decimal Degrees: 43.993333, -86.470028
Suspend Work	1330 feet South of park rest area: DMS: 43º59'56" N, 86º28'48" W Decimal Degrees: (43.998889, -86.480)
Resume Work	1 mile south of Big Sable River DMS: 44º 01'02" N, 86º29'48" W Decimal Degrees: 44. 017222, -86.496667
End Extent	50 feet South of Big Sable River: DMS: 44º01'49" N, 44º30'19" W Decimal Degrees: 44.030278, -86.505278
Approximate Length	2,875 feet in the north 960 feet in the south
Distance from roadway to shoreline	Varies, 60 feet to 100 feet
Damages to Date	No road closures have occurred No direct costs captured to date
Past Mitigation Efforts	Groins in place from previous mitigation efforts and were exposed during high water period Monitoring by State Geotechnical engineering
FEMA FIS Data	10 percent Annual Chance Stillwater Elevation: 581.9 feet NAVD88 1 percent Annual Chance Stillwater Elevation: 582.6 feet NAVD88 1 percent Annual Chance Total Water Elevation 590.1 feet NAVD88 Wave Runup: VE 590
Exposure and Critical Elevations	Toe of Slope: 586-588 feet NAVD88 Asset Elevation: 597 feet NAVD88

Metric	Description
Consequence	AADT: 1,162 (Seasonal: 1.5 Multiplier) CAADT: 42 Detour: None available.

Notes:

AADT = annual average daily traffic

CAADT = commercial annual average daily traffic

FEMA = Federal Emergency Management Agency

FIS = Flood Insurance Study

NAVD88 = North American Vertical Datum of 1988

4.2.1.2 Engineering Analysis and Preferred Mitigation Alternative

MDOT is concerned that the combination of beach and dune erosion plus rising lake levels may lead to shoreline erosion becoming a threat to M-116. Therefore, the intent of studying M-116 near Ludington State Park is to evaluate 1) shoreline and dune erosion mitigation options and 2) explore realignment options for M-116 in the subject location.

M-116 is considered a major collector with AADT of 3,500 vehicles per day and starts in the City of Ludington and ends at the entrance/ exit to the Ludington State Park. It is the only access to the state park which sees an estimated 800,000 visitors per year. The M-116 project site is located mostly within the state park, and the roadway corridor consists of a 200 feet wide right-of-way that parallels the coast of Lake Michigan. Of particular interest are the more northern and southern portions which only have a minimum setback of 50 feet to the existing shoreline at various locations. This engineering analysis reviewed the entire 3.30-mile (17,400 feet) corridor section within the state park for possible engineering solutions to the erosion threat.

Several alternatives were considered including raising the roadway, adding additional erosion protection measures along the shoreline, and building up the dunes to provide more protection to the roadway. However, it was determined that the most the most economical and least impacting long-term engineering solution is to relocate the roadway at both the northern and southern entrances/ exits to the park as these areas were experiencing the most erosion and had the least protection. Additionally, given the recreational nature of this site, Arcadis felt that additional erosion protection would diminish the natural value of the site. Relocating the roadway agrees with MDOT's internal engineering review of the issue completed last year. In fact, survey was obtained at the north and south extremes of the park in preparation for design phase. However, for the purposes of this study Light Detection and Ranging (LiDAR) data was solely used for the engineering design due to the need for more data and the need to convert between datums (that is, NAVD88 and IGLD).

From review of the historic lake levels and FEMA flood maps, it was determined to use a critical design elevation of 590.00 feet NAVD88 which nearly equates to the 1 percent annual chance wave generated water surface elevation of 590.10 (or Total Water Level). Also, to comply with MDOT criteria, a minimum of 1.5 feet of freeboard was provided from this surface to the proposed edge of pavement for the relocated section of the roadway. As such, the proposed section is between 75 feet and 100 feet inland from the 590.0 feet water surface elevation contour. A design speed of 60 mph was used for determining the limiting horizontal and vertical alignment design parameters. See *Appendix G: M-116 Ludington State Park Expanded Documentation* for a summary of the design criteria used for the roadway design. To meet the minimum setback from the 100-year flood requirement, the proposed relocated roadway alignment went outside of the existing right-of-way at two locations. Acquisition of a wide swath will be required for the southern relocation, while a 2,200 feet length of a 30-foot width will be required for the northern section. A conservative estimate of 6.0 acres of additional right-of-way will be required to construct and maintain this alternative, with no total takes being required.

From reviewing the recent traffic data, it was noted that the traffic tends to be seasonal, and not much growth is expected for this area. Therefore, the proposed roadway typical section is the same as the existing section which complies with all MDOT roadway criteria (Figure 4-11). A calculation for the pavement buildup assuming the current traffic indicated that 7 inches of asphalt over 6 inches of aggregate will be sufficient. See *Appendix G: M-116 Ludington State Park Expanded Documentation* for the schematic drawings.

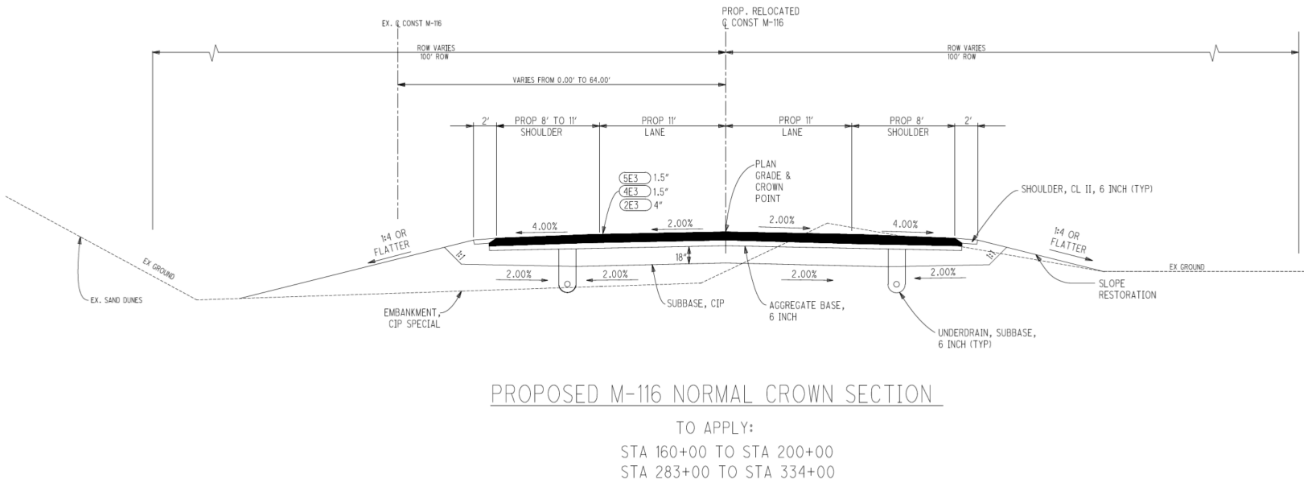


Figure 4-11. Proposed M-116 Ludington State Park typical roadway section.

From our literature review, it was noted that the MDNR has a future goal of expanding services within the park, including wider shoulders and parking for increased visitors. It is recommended that MDOT and MDNR coordinate and combine funding sources to provide the desired facilities. Besides the need for additional right of way within the state park, the corridor will experience other impacts including environmental impacts with the removal and/ or relocation of existing sand dunes, endangered species impacts, and economic impacts with less visitors during construction. However, because most of the relocated roadway can be built off-line, the latter impact can be minimized.

Lastly, the total estimated construction cost is **$9.26 million.** It is based on MDOT's most recent bid tabs for work done in the region and includes a 30 percent contingency to cover any incidentals not noted in the estimate. See *Appendix G: M-116 Ludington State Park Expanded Documentation* for the schematic cost estimate.

4.2.1.3 BCA Results

The following BCA provides a mixed qualitative and quantitative approach, to help structure the decision-making process for MDOT as they review whether to invest in relocating the roadway at M-116 Ludington State Park.

First, the geotechnical engineer reviewed the likelihood of 1) the slope failing, and 2) the asset failing, based on wholistically looking at the erosion decision making matrix. Classifications by key measure are shown in Table 4-18.

Key inputs and considerations for weighing the costs, benefits, and risks are shown in Table 4-19. As no detour exists, a maximum value of 720 minutes was used to as a proxy to calculate the expected loss of function, based on the value of travel time savings methodology presented in *Section 3*. This method is per FEMA standard guidance (FEMA, 2021). The potential losses from lost tourism were not directly captured. Informally, MDOT has noted that even though no detour exists if erosion were to lead to loss of roadway function at this site a temporary roadway would likely be put in place.

Table 4-18. Geotechnical evaluation of erosion matrix for M-116 Ludington State Park

Parameter	Risk Ranking	Description / Notes
Groundwater Outflow, Seepage	Low	Trace, isolated dripping water
Bluff Makeup / Strength *(Includes consideration of soil type, stratification, strength [angle of internal friction and cohesion], and unit weight)*	Moderate	Moderate / Sand
Surface erosion / sensitivity to surface runoff	High	Presence of gullies created by surface runoff
Bluff Slope / Average Angle	Low	> 3H:1V
Wave Exposure *(Water Elevation = Total Water Level Elevation - Toe Elevation)*	High	> 7 feet difference between Total Water Level Elevation and Toe Elevation; *590.1 feet NAVD88 = Total Water Level* *581.9 feet NAVD88 = 10 percent annual chance Stillwater elev.* *Difference = 8.2 feet*
Existing Manmade Toe Protection Quality *(Includes manmade structures - groins, riprap, etc.)*	High	No protection, or protection is highly degraded
Existing Natural Toe Protection *(Includes natural materials only, for example, trees from previous failure)*	High	No natural toe protection
Vegetation	High	Lightly covered/rooted (ex. grass and brush). Trees show strong curvature.
Previous Failures	Low	No nearby failures, or recent failure stabilized the site

Parameter	Risk Ranking	Description / Notes
Bluff Height	Low	Low (<25 feet); *Approximately 10 feet*
Rapidity of Failure	Low	Warning signals apparent in advance, slow onset
Ability to Intervene	Moderate	Intervention is possible with some challenges
Horizontal Distance to MDOT Assett	High	Majority of asset is < 100 feet away; *For two key sections of interest, approximately 50 feet minimum*

Table 4-19. Mixed Qualitative and Quantitative Costs, Benefits, and Risks for M-116 Ludington State Park

Category	Metric	No Action	Mitigation (Relocate Roadway)
What are the damages if slope failure occurs? (Quantitative and Qualitative)	AADT	1,743	1,743
	Detour Length	0 miles	0 miles
	Detour Time	720 minutes	720 minutes
	Economic Loss Per Day of Loss of Function	$726,000	$726,000
	Expected Duration of Loss Over Project Useful Life	30 – 60 days	0 days
	Estimate of Potential Costs	$22 – 44 million	$0
	Life Safety Risk	None	None
	Other Property Risk (non-MDOT Assets)	Medium-High: Beaches are at risk (low value, but generate high revenues)	Medium-High: Beaches are at risk (low value, but generate high revenues)
What are the expected cost over the analysis duration? (Semi-Quantitative)	Construction Costs	-	$$$
	Maintenance Costs	$$	$
	Repair Costs	$$	-

Category	Metric	No Action	Mitigation (Relocate Roadway)
What is the likelihood of failure for first, the slope, and second, the asset? (Qualitative, per geotechnical evaluation of erosion matrix)	Likelihood of **slope** failure based on physical site conditions and mitigation measures	Likely	Likely
	Likelihood of **asset** failure based on slope distance to MDOT asset	Highly Likely	Unlikely

The following two options must be weighted by MDOT decision makers:

- **No Action.** If no action is taken, eventual slope failure is **likely**, at which point, damage to the roadway is **highly likely** due to the roadway proximity to water and waves. As there is no detour available, this translates to high economic loss if there is loss of roadway function.
- **Mitigation.** Relocating the roadway will preserve the only access to a high revenue-generating locations; however, right-of-way and environmental considerations will complicate the feasible alternative.

MDOT must weigh the above considerations against competing priorities across the state. Given the low chance of catastrophic risk at this erosion site (bluff height is low, and failure will likely have warning signs apparent in advance with a slow onset) MDOT may choose to prioritize other sites around the state that have a higher life safety risk.

4.2.2 I-94BL St. Joseph

The I-94 BL site was chosen due to the potential catastrophic nature of a future slope failure.

4.2.2.1 Site Description and Problem Statement

The shoreline west of I-94BL St Joseph (Lakeshore Drive) in St. Joseph, Michigan, has been studied extensively due to a long history of erosion issues south of the jetties at the mouth of the St. Joseph River. The project site is in this area south of the existing jetties and has experienced persistent erosion issues. Many types of shoreline protection measures in widely varying states of repair have been installed within the project limits.

Figure 4-12 provides overview visuals including a site map (inset a) and FEMA flood map (inset b). Figure 4-13 provides drone imagery of the site as of May 2021, depicting the relationship of the roadway to the water (inset a), as well as ongoing impacts including lake water landside of existing mitigation measures (inset b) and loss of vegetation (inset c). A summary of additional site overview metrics is presented in Table 4-20.

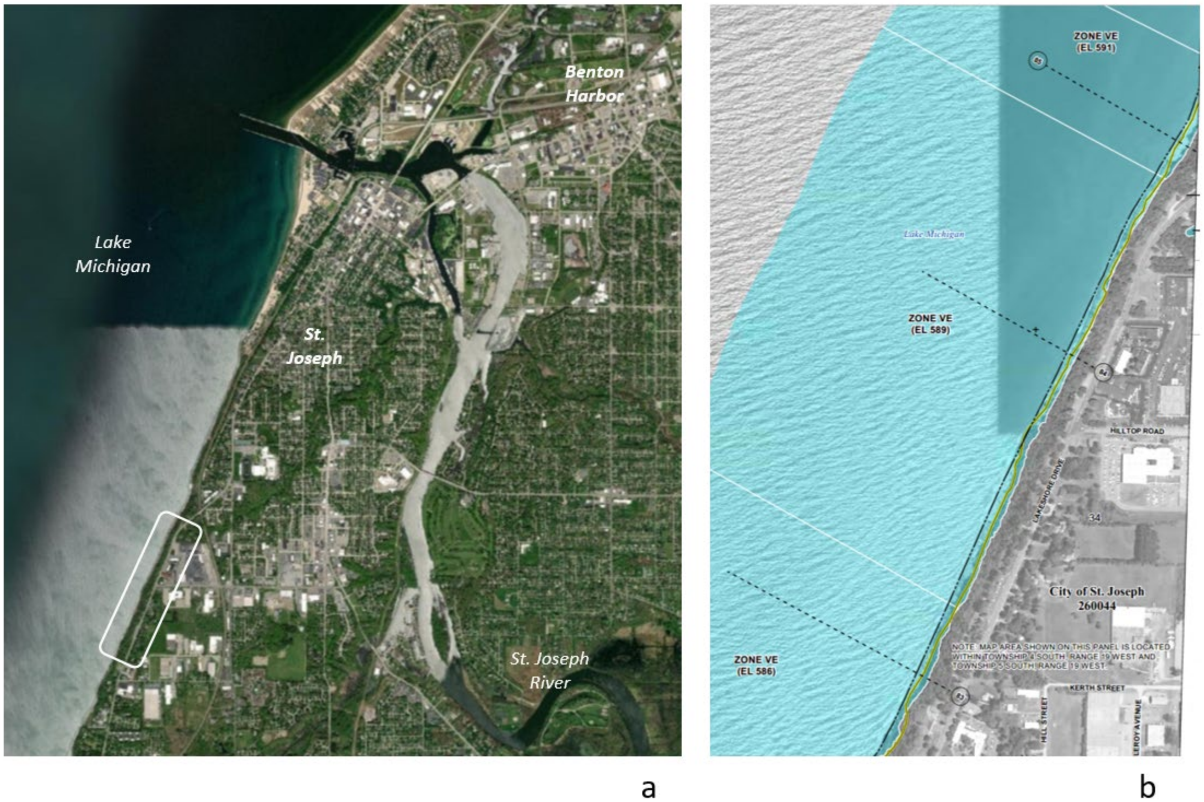


Figure 4-12. I-94BL Site overview, including a) site map showing the relation of the jetties at the mouth of the St. Joseph River to area of interest, and b) FEMA VE flood zone in relation to the toe of slope.

Figure 4-13. Drone imagery of I-94 BL St. Joseph, May 2021, showing a) the roadway in relation to the bluff and exiting mitigation measures, b) existing state of rip-rap mitigation measures, and c) evidence of slope failure.

Table 4-20. Summary of I-94BL St. Joseph site considerations.

Metric	Description
Area of Interest	Shoreline lakeward of the intersections of I-94BL and Lakeshore Road (northern extent) and I-94BL and Hawthorne Avenue (southern extent) in Saint Joseph, Michigan.
Northern Extent	DMS: (42°05'08.4804", -086°29'54.7764") Decimal degrees: (42.085689°, -86.498549°)
Southern Extent	DMS: (42°04.32366', -086°30.43326') Decimal degrees: (42.072061°, -86.507221°)

Metric	Description
Approximate Length	4,800 feet
Distance from roadway (I-94BL) to shoreline	Varies, 200 feet (north) to 400 feet (south)
Damages to Date	No road closures to date. Monitoring during 2019/2020 seasons. No direct costs captured
Past Mitigation Efforts	Revetment berm offset from shoreline installed on southern half in 70s. Protections installed on northern half in the 80s, including gabions and rip-rap Monitoring by State Geotechnical Engineer
FEMA FIS Data	10 percent Annual Chance Stillwater Elevation: 582.6 feet NAVD88 1 percent Annual Chance Stillwater Elevation: 583.6 feet NAVD88 Wave Runup: VE 586-589 feet NAVD88
Exposure and Critical Elevations	Toe of Slope: 582.03 feet NAVD88 Asset Elevation: 663 -678 feet NAVD88
Consequence	AADT: 14,519 CAADT: 298 Not seasonal traffic Detour: 2.3 miles, 5 min

Notes:

AADT = annual average daily traffic

CAADT = commercial annual average daily traffic

FEMA = Federal Emergency Management Agency

FIS = Flood Insurance Study

NAVD88 = North American Vertical Datum of 1988

The following references that describe conditions at the site and provide site-specific information, analyses, assessments, and recommendations:

- Parson and Smith, 1995, *Assessment of Native Beach Characteristics for St. Joseph, Michigan, Southeastern Lake Michigan*, Miscellaneous Paper CERC-95-2, United States Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

- Parson, et al., 1996, *Geologic Effects on Behavior of Beach Fill and Shoreline Stability for Southeast Lake Michigan,* Technical Report CERC-96-10, United States Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.
- Nairn, et al., 1997, *Effectiveness of Beach Nourishment on Cohesive Shores, St. Joseph, Lake Michigan*, United States Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.
- Edgewater Resources, LLC, 2012, *City of St. Joseph, Michigan, Coastal Engineering Study*, St. Joseph, Michigan.
- Bergmann Associates, 2017, *Rock Revetment Design for Shoreline Protection – City of St. Joseph, Berrien County, Michigan, USA*, St. Joseph, Michigan.
- Chris Jonecheck (MDOT) site reconnaissance summary email. Site visit December 11, 2019. Summary email sent December 13, 2019.
- David Gerdeman (Arcadis) site reconnaissance summary email. Site visit and summary email on May 14, 2021.

4.2.2.1.1 **Key Issues**

The greatest factor in beach loss south of the jetties at the mouth of the St. Joseph River is the effect of the jetties. We often think of beaches as static systems with sand that moves landward and beachward normal to the shoreline. However, beaches are dynamic systems and the mass balance of sediment in a “stable” beach means that the amount of sediment being removed from the beach system is about equal to the amount of sediment that is being deposited. Longshore (or littoral) transport is the movement of beach sand parallel to the shoreline, and longshore transport at St. Joseph, Michigan, is generally from north to south. Because of the presence of the jetties, the natural migration of sediment along the shoreline is interrupted. As a result, the beach north of the jetties grows while the beaches south of the jetties erode and regress due to a lack of sediment supply. Nair, et al. (1997) recognized that during the study period from 1945 to 1995, the shoreline north of the jetties gained an average of about 8,000 cubic meters of sediment per year, while the shoreline south of the jetties lost between approximately 20,000 and 40,000 cubic meters of sediment per year. The following points emphasize the significance of the jetties and the subsequent impact to shorelines south of the jetties at St. Joseph:

- Shabica, et al. (2011) state “The earliest and most disruptive human-made structures affecting Great Lakes beaches are harbor entrance breakwaters and jetties.”
- Nairn, et al. (1997) say “The net alongshore sediment transport direction [at St. Joseph, Michigan] is from north to south. The harbor jetties act as partial to full littoral transport barriers.”

- In Michigan State Distinguished Professor of Geography Dr. Randall Schaetzl's publicly available notes on Great Lakes coastal erosion, he uses photos of the jetties at St. Joseph as *the* example for the effects of the disruption of longshore transport and erosion and beach loss on the leeward side of the jetties (Schaetzl, date unknown).

The coastline at St. Joseph is atypical for Michigan, as the underlying soil layers are fine-grained, cohesive material. This is important because the mechanisms of erosion for shorelines comprising cohesive materials are different than the mechanisms of erosion for non-cohesive shorelines. Nairn, et al. (1997) describe "A cohesive shore erodes and recedes because of the permanent removal and loss of the cohesive sediment (both from the bluff and the lakebed). The sand cover may come and go (depending on the season, water level, and storm activity), but the erosion of the cohesive layer is irreversible...".

Nairn, et al. (1997) recognize that beach nourishment practices greatly impacted the rate of beach loss in the study area. The beach in the study area was nourished with both hydraulically dredged sand from the St. Joseph River and with sand that was trucked to the site. Figure 4-14 summarizes dredging quantities during the study period. Some important findings from the dredging assessment include:

- Nourishing the beach reduced the average annual rate of beach loss.
- Hydraulically dredged sand from the St. Joseph River was finer (smaller diameter) than the beach sand in the study area, and sand that was trucked to the site was coarser (larger diameter) than the beach sand. The finer sand will erode more quickly than native beach sand, and the coarser sand will erode a bit slower. However, the nuances of grain size are not as important for erosion reduction as quantity of nourishment. Nairn, et al. (1997) state "One significant difference between [time periods in the study] was the annual average volume of beach nourishment. Annual placement volumes have been reduced by approximately 50 percent to 40,000 m3 [in the last 5 years of the study]. The reduced level of beach feeding may at least partly explain the accelerated erosion rates."
- As much as 50 percent of the sand placed on the beach just south of the jetties ends up back in the navigation channel from which it was dredged.

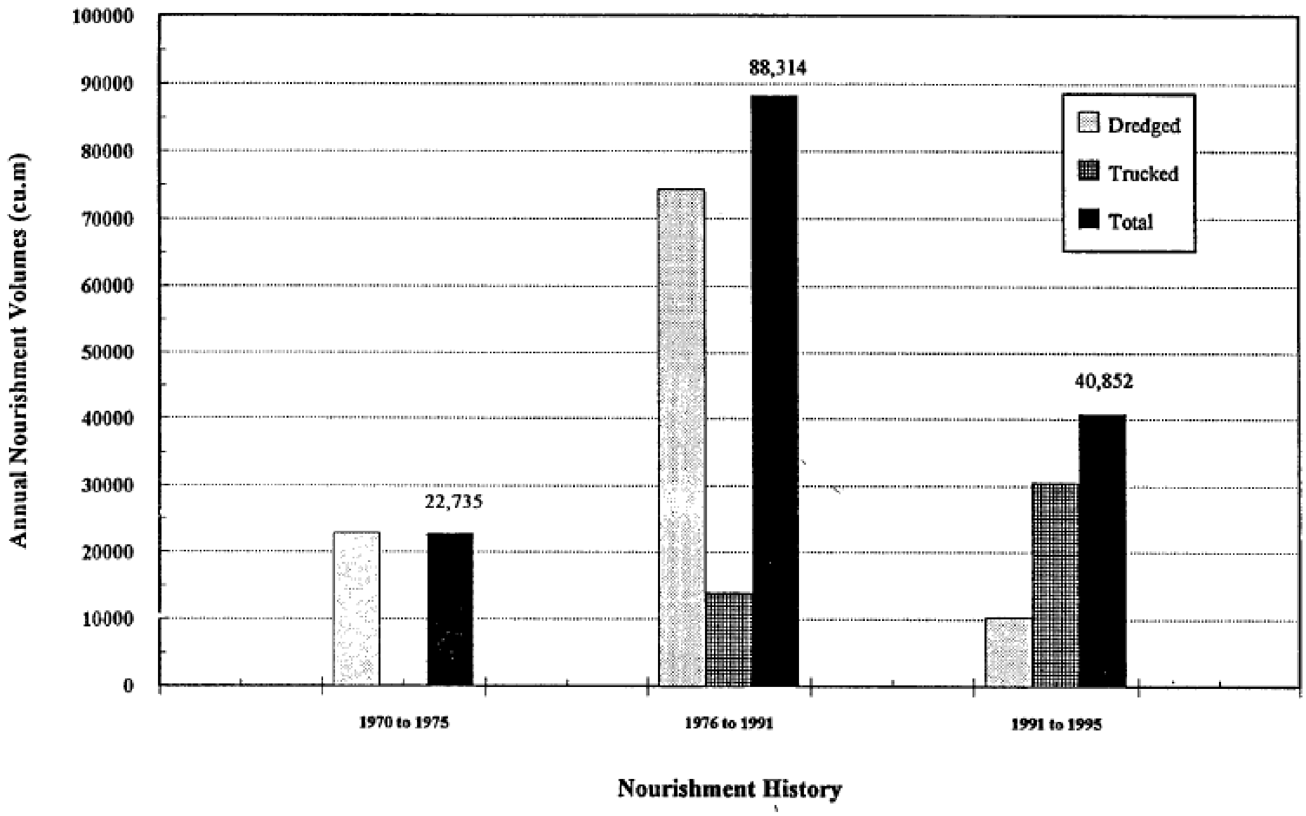


Figure 4-14. Summary of average annual beach nourishment volumes from 1970 to 1995 (from Nairn, et al., 1997).

4.2.2.2 Engineering Analysis and Recommendations

The engineering analysis first presents remediation options, followed by Arcadis' recommended path forward. Finally, costing information is summarized.

4.2.2.2.1 Remediation Options

Potential paths forward include doing nothing, decommissioning and deconstructing the jetties to restore natural longshore (or littoral) transport processes, regularly nourishing the beach, and/or constructing shoreline protection structures to mitigate additional erosion.

Doing nothing would be a judgment call by MDOT. Hands (1976) quantified the average 120-year bluff recession rate in Berrien as approximately 2 feet/year, although "short-term and local [bluff recession] rates can be much higher, particularly during periods of high lake levels" (Nairn, et al., 1997). Doing nothing may be an acceptable alternative because although shorelines comprising cohesive materials are prone to small, localized slope failures that are generally induced by undermining, shorelines comprising cohesive materials are less prone to major, catastrophic failures (like the failure at Petoskey) than non-cohesive shorelines.

Although deconstructing the jetties may be the most beneficial alternative to mitigate beach loss in the project area, it may not be a viable alternative for MDOT because 1) the jetties are not owned by MDOT and deconstruction will likely be opposed by jetty stakeholders, and 2) the Port of St. Joseph, whose operation depends on the jetties, provides over $21 million in personal income in the region (Southwest Michigan Planning Commission, 2015).

Nourishing the beach is a practical alternative. However, beach nourishment may be outside of the purview of MDOT. We should note that according to Nairn, et al. (1997), previous beach nourishment has been minimally successful due to incompatibility of the grain size of placed material to the native beach and improper placement of dredged material, so any beach nourishment mitigation should be appropriately planned and engineered by a qualified team of coastal, geotechnical, and geological engineers.

Shoreline protection structures could be constructed, for example, riprap revetment, seawalls, groins, nearshore stone breakwaters, or protected headlands. As shown in Figure 4-15, seawalls and groins are generally more costly than riprap revetments, and we should note that groins are becoming less common erosion mitigation solutions because they can disrupt longshore transport patterns, much like the jetties at St. Joseph. Shabica, et al. (2011) reinforce this concern with groins noting that “Toward the end of the 20th century, coastal scientists and engineers, recognizing the reduced effectiveness of groins on sediment-starved coasts, began designing and constructing nearshore stone breakwaters and headlands.”

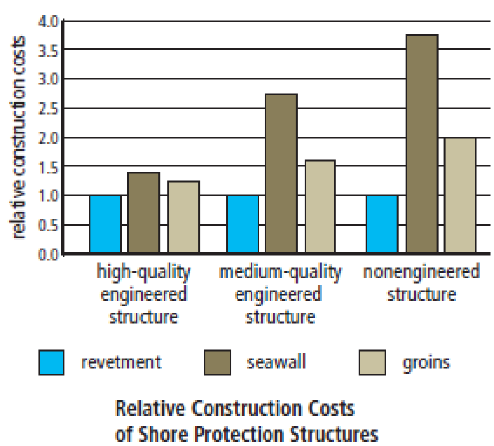


Figure 4-15. Relative cost of seawalls and groins, as compared to riprap revetments (from: Keillor, and White, 2003)

4.2.2.2.2 Recommendations

The appropriate solution for erosion mitigation at the St. Joseph area of interest should address site-specific characteristics including the presence of the St. Joseph jetties and cohesive shoreline materials. We expect that decisions regarding the approach to erosion mitigation at the area of interest will include other area stakeholders, including the USACE, who oversees the dredging of St. Joseph Harbor.

MDOT has plans to install riprap revetment at the area of interest; however, we also understand that EGLE has concerns about the plan to install riprap revetment at this site. Thus, EGLE will also be an interested stakeholder in developing the erosion mitigation approach at St. Joseph.

Arcadis anticipates that the most comprehensive and effective solution for mitigating erosion within the area of interest will be a combination of beach nourishment and shoreline protection.

4.2.2.2.3 Costing Information

The best information for estimating the cost of the shoreline protection at St. Joseph is the existing estimate for the planned riprap revetment. Estimated cost is approximately $13.4 million, or approximately $4,600 per linear foot.

Developing a dredging and beach nourishment plan is outside of the scope of this study. However, the Southwest Michigan Planning Commission (2015) cites that hydraulic dredging in the navigation channel cost approximately $8.25 per cubic yard, and in 2014 approximately 54,000 cubic yards of material were dredged from the outer harbor.

4.2.2.3 BCA Results

The following BCA provides a mixed qualitative and quantitative approach to help structure the decision-making process for MDOT as they review whether to invest in installation of additional shoreline protections at the toe of the bluff slope adjacent to I-94BL (Lakeshore Drive) on the south side of St. Joseph, Michigan.

The site was first analyzed by a geotechnical engineer to examine 1) the risk of slope failure, and 2) the likelihood of that failure causing a failure of the asset. Classification by key metrics are shown below in Table 4-21. The site sits on top of a high bluff with a moderate strength and a steep slope. Existing toe protection is highly degraded, and signs of small failures indicate risk of future failure. The asset is over 200-feet from the shoreline offering some protection, and the ability to intervene exists with some challenges, including some concerns raised by EGLE.

Table 4-21. Geotechnical evaluation of erosion matrix for I-94BL St. Joseph, Michigan

Parameter	Risk Ranking	Description / Notes
Groundwater Outflow, Seepage	Moderate	Slight, wet cliff face with drips, point-source seeps
Bluff Makeup / Strength *(Includes consideration of soil type, stratification, strength [angle of interal friction and cohesion], and unit weight)*	Moderate	Moderate / Sand
Surface erosion / sensitivity to surface runoff	Not ranked	-
Bluff Slope / Average Angle	High	< 2H:1V
Wave Exposure *(Water Elevation = Total Water Level Elevation - Toe Elevation)*	Moderate	3 to 7 feet difference between Total Water Level Elevation and Toe Elevation; *587.5 feet NAVD88 = average of transect 83 and 84 for Total Water Level* *582.6 feet NAVD88 = 10% annual chance Stillwater elevation* *Difference = 4.9 feet*
Existing Manmade Toe Protection Quality *(Includes manmade structures - groins, riprap, etc.)*	High	No protection, or protection is highly degraded; *One section is somewhat degraded (medium), another is highly degraded (low). Chose low.*
Existing Natural Toe Protection *(Includes natural materials only, for example, trees from previous failure)*	Not ranked	-

Parameter	Risk Ranking	Description / Notes
Vegetation	Moderate	Covered, moderately developed, moderately rooted (ex. brush and small trees). Trees show some curvature
Previous Failures	Moderate	Small failures may indicate some risk of future failure
Bluff Height	Moderate	Medium (25 to 75 feet); *Approximately 50 feet*
Rapidity of Failure	Not ranked	-
Ability to Intervene	Moderate	Intervention is possible with some challenges
Horizontal Distance to MDOT Assett	Low	Majority of asset is >200 feet away; *225-250 feet average, 175 minimum*

Key inputs and considerations including costs, benefits, and risks are summarized in Table 4-22.

The detour time anticipated for this site is relatively low at five minutes and 2.3 miles, but a high AADT means that the daily economic loss from loss of function of the assets is still estimated to be $60,709 per day. Assuming a 60-to-90-day duration for loss of function, the overall estimated cost of a slope failure impacting the asset is between $3.6 and $5.5 million dollars.

The height of the bluff and high traffic contributes to a high level of life safety risk which is moderated by the distance from the shoreline. Presence of residential properties south of the area and the Kiesel Overlook under MDOT jurisdiction contribute to a moderate to high level of risk to other properties for the site.

Anticipated cost to implement mitigation at the site are relatively high, however the cost of repair given slope failure is anticipated to be very high. Additionally, without mitigation, maintenance costs at the site will likely be higher than they will be if mitigation is to take place. Leveraging dredging activities that occur in the St. Joseph River to the north for beach nourishment may be one option for reducing these costs, however as discussed above the finer grain size of that material will erode more quickly than that of the native beach.

Based on the characteristics of the slope it is likely that failure will occur at some point in the future, although given the characteristics of the asset, namely its distance from the shoreline, it is not likely that a failure will impact the roadway. Doing nothing may be an acceptable alternative because although the site's characteristics make it prone to small, localized slope failures, they are less prone to major, catastrophic failures. In the near term continued monitoring of the site may be sufficient, but the high benefits of avoiding slope failure should be considered if conditions continue to deteriorate.

Table 4-22. Mixed Qualitative and Quantitative Costs, Benefits, and Risks for I-94BL St. Joseph, Michigan

Category	Metric	No Action	Mitigation (Relocate Roadway)
What are the damages if slope failure occurs? (Quantitative and Qualitative)	AADT	14,519	14,519
	Detour Length	2.3 miles	2.3 miles
	Detour Time	5 minutes	5 minutes
	Economic Loss Per Day of Loss of Function	$60,709	$60,709
	Expected Duration of Loss Over Project Useful Life	60 – 90 days	0 days
	Estimate of Potential Costs	$3.6 – 5.5 million	$0
	Life Safety Risk	Medium-High: Life safety risks to a small number of people	Low: No life safety risks
	Other Property Risk (non-MDOT Assets)	Medium-High: Lower value assets at risk (park structures) and several homes	Low: No other assets at risk
What are the expected cost over the analysis duration? (Semi-Quantitative)	Construction Costs	-	$$$
	Maintenance Costs	$$	$
	Repair Costs	$$$$	-
What is the likelihood of failure for first, the slope, and second, the asset? (Qualitative, per	Likelihood of slope failure based on physical site conditions and mitigation measures	Likely	Not Likely

Category	Metric	No Action	Mitigation (Relocate Roadway)
geotechnical evaluation of erosion matrix)	Likelihood of asset failure based on slope distance to MDOT asset	Not Likely	Not Likely

4.2.3 US-31 Petoskey

This section evaluates monitoring and remediation alternatives for cost-effectively addressing the 2020 slope failure near western Petoskey, Michigan, and to applies lessons learned and remedial and monitoring estimates for the Petoskey slope failure to use as guidance for addressing similar issues throughout Michigan.

4.2.3.1 Site Description and Problem Statement

On April 13, 2020, a section of the coastal bluff near western Petoskey, Michigan, and adjacent to Little Traverse Bay catastrophically failed into the bay. At the crest of the failed bluff is US-31, and mid-slope between US-31 and the bay is the Little Traverse Wheelway, a paved bicycle and pedestrian path. The April 2020 failure did not damage the highway; however, the failure destroyed approximately 150 feet of the Little Traverse Wheelway. Figure 4-16 shows an aerial view of the catastrophic 2020 slope failure, and Figure 4-17 shows drone imagery of the large failure (inset a) and an adjacent, smaller failure (inset b).

Figure 4-16. Aerial view of the catastrophic 2020 slope failure near western Petoskey, Michigan (from Baird, 2020)

a b

Figure 4-17. Aerial view of the catastrophic 2020 slope failure near western Petoskey, Michigan (from Baird, 2020)

Prior to the April 2020 slope failure, several smaller, shallow_slope slides were observed, and the City of Petoskey, Emmet County, and Resort Township retained W.F. Baird & Associates Ltd. (Baird) and OHM Advisors (OHM) to evaluate the stability of the slopes between East Park and Magnus Park and to provide conceptual design alternatives to mitigate these minor slope failures. Baird evaluated both the catastrophic slope failure and minor slope failures, and MDOT provided the Arcadis project team with Baird's draft report dated August 26, 2020. In addition to reviewing Baird's draft report and publicly available geologic maps, Arcadis looked for but did not find additional relevant studies in the area.

Table 4-23. Summary of US-31 Petoskey site considerations.

Metric	Description
Area of Interest	Southern limit of US-31 right of way to Little Traverse Bay Shoreline between Resort Pike and Aspen Way.
Eastern Extent	DMS: (45°22'11.9748", -84°58'57.5220") Decimal degrees: (45.369993°, -84.982645°)
Western Extent	DMS: (45°22'01.6824°, -84°59'37.6224°) Decimal degrees: (45.367134°, -84.993784°)
Approximate Length	2,700 feet
Distance from roadway (US-31) to shoreline	Varies, 220 feet (east end) to 320 feet (west end)
Damages to Date	No closure to date No direct costs captured to date Monitoring by State Geotech Failure of slope resulting in coincident failure of City/County asset (Little Traverse Wheelway) located below M-31
Past Mitigation Efforts	Little Traverse Wheelway rerouted to the shoulder of M-31, with barrels put in place to delineate pedestrian from car traffic Crossings added to facilitate bike/ped access Advisory speed signs put in place but resulted in conflict with State Police
FEMA FIS Data	10 percent Annual Chance Stillwater Elevation: 582.1 feet NAVD88 1 percent Annual Chance Stillwater Elevation: 583.2 feet NAVD88 1 percent Annual Chance Total Water Elevation: 592.5 Wave Runup VE 593
Exposure and Critical Elevations	Toe of Slope: 582 ft NAVD88 Asset Elevation: 679 – 696 feet NAVD88

Metric	Description
Consequence	AADT: 16,538 CAADT: 547

Notes:

AADT = annual average daily traffic

CAADT = commercial annual average daily traffic

FEMA = Federal Emergency Management Agency

FIS = Flood Insurance Study

NAVD88 = North American Vertical Datum of 1988

4.2.3.1.1 Key Issues

There are multiple key issues that likely contributed to the April 2020 catastrophic slope failure including 1) previous slope failures in the area, 2) erosion of beach sediment at the toe of the bluff, 3) groundwater conditions and 4) potentially inadequate groundwater drainage from the uphill side of the Little Traverse Wheelway to the downhill side. These issues are discussed below.

1) **Previous slope failures in the area.** The Baird report cites a major coastal bluff failure circa 1913 in the same vicinity as the catastrophic 2020 slope failure. The exact location of the 1913 failure is unknown. However, Eppler Road that runs north-south and is just east of the 2020 failure was formerly known as “Washout Road,” in reference to the major 1913 slide. In addition to the major 1913 slope failure, local newspaper articles describe other major slope/bluff failures in the vicinity in 1916, 1957, 1959, and 1985. Aerial imagery of the Susan Creek Nature Preserve just west of Bay Shore, Michigan, shows coastal geomorphological features that appear to be like the post-failure geometry of the catastrophic 2020 Petoskey bluff failure. The presence of these features coupled with recent major slope failures indicate that the coastal bluffs on the south shore of Little Traverse Bay are sensitive to slope instability and may be marginally stable. Figure 4-18 shows many V-shaped land protrusions into Little Traverse Bay west of Bay Shore, Michigan, that may be evidence of previous slope/bluff failures on the southern shore of Little Traverse Bay.

Figure 4-18. V-shaped land protrusions into Little Traverse Bay west of Bay Shore, Michigan, that may be evidence of previous slope/bluff failures on the southern shore of Little Traverse Bay (image modified from Google).

2) **Erosion of beach sediment at the toe of the bluff.** Baird coastal erosion analyses aptly characterized loss of beach sediment at the toe of the bluff due to coastal erosion and beach processes. Sediment at the toe of the bluff acts to resist downhill slope displacement. Thus, when toe material is removed, forces resisting slope failure are reduced, increasing the likelihood for slope failure. Baird slope stability models confirmed that erosion of toe material contributed to the catastrophic 2020 Petoskey slope failure.
3) **Groundwater conditions**. Elevated groundwater levels encourage slope instability by increasing pore water pressure and reducing the effective strength of the soil. We understand that both the catastrophic 2020 failure and the major 1913 failure were preceded by large precipitation events. These precipitation events may have elevated groundwater levels within the slopes. Elevated groundwater levels combined with removal of sediment at the toe ultimately resulted in major slope failures. Baird slope stability analyses confirmed that elevated groundwater levels in the slope increased the likelihood for slope failure.
4) **Potentially inadequate groundwater drainage from the uphill side of the Little Traverse Wheelway to the downhill side.** One observer noted after the catastrophic 2020 failure that sand in the failed soil mass near the Wheelway was saturated. This is a significant observation because it indicates that groundwater in the slope may have mounded within the slope due to inadequate slope drainage or that surficial soils may have become over saturated and flowed like a dense liquid downslope.

4.2.3.2 Engineering Analysis and Recommendations

4.2.3.2.1 **Remediation Options**

Arcadis identified the following mitigation options for the US-31 Petosky site:

- Do nothing and monitor.
- Construct remediation Option 1 presented in Baird's draft slope failure study. Option 1 consists of a riprap revetment along the shoreline along with regrading and drainage improvements.
- Construct remediation Option 2 presented in Baird's draft slope failure study. Option 2 consists of a cobble beach along the shoreline and similar regrading and drainage improvements as Option 1.
- Construct remediation Option 1 or Option 2 from Baird's draft slope failure study and install additional slope reinforcement to achieve greater slope stability factors of safety.
- Relocate MDOT assets.

4.2.3.2.2 **Recommendations**

Currently, we do not recommend rebuilding the Little Traverse Wheelway back to its pre-failure configuration. The Baird report assumed groundwater conditions for two-dimensional slope stability modeling and subsequent conceptual remediation alternatives, and we agree that this is a reasonable approach for concept-level evaluations. However, groundwater conditions are critically important for slope stability, and all remediation design must be based on a more complete understanding of ground and surface water conditions at the site.

To that end, we recommend that a thorough ground and surface water investigation be completed prior to remediation design. The intent of the recommended study is to understand the sources of groundwater in the bluff, the contribution of ground and surface water (runoff) conditions to the catastrophic 2020 slope failure, and to determine methods to control groundwater levels in the bluff and surface water on the slope. The Baird report makes a similar recommendation by saying:

> We suggest that a hydrogeologic study may be of benefit as long term solutions to stabilizing the slope are explored. The goal of a detailed hydrological study would be to understand if there is a relationship between regional hydrology (including precipitation) and local ground water levels… The goal of this study is to better understand the issues causing high ground water levels in the slope (that is, whether it is a regional or local phenomenon) as our slope stability modeling indicates the overall stability of the slope is very sensitive to ground water elevation.

MDOT's most critical asset at the Petoskey site is US-31. The threats to US-31 are headcutting of the existing scarp and progressive slope failure. Headcutting can be mitigated by preventing excessive runoff into the head of the scarp. Because additional slope failures will likely be preceded by large precipitation events, MDOT should have crews ready to divert runoff away from the head of the scarp whenever large precipitation events are forecasted. Crews should exercise care with diverted runoff discharge locations and should avoid discharging diverted runoff onto the slope.

In general, slopes like this should have a target factor of safety against slope failure of at least 1.5. Baird remediation Option 1 and Option 2 each result in factors of safety of approximately 1.3, which is less than commonly accepted guidance for critical infrastructure such as US-31. Because Options 1 and 2 may not provide desired levels of slope stability, selection of an appropriate slope remediation alternative should be based on the results of additional groundwater investigations. In addition, MDOT may want to consider input from other stakeholders before selecting a slope remediation alternative.

4.2.3.2.3 Costing Information

Baird estimated that Option 1 remediation would be approximately $5-8 million, and Option 2 remediation would be approximately $8-10 million. We should, again, note that the Option 1 and Option 2 remediation alternatives assume that a slope stability factor of safety of 1.3 is acceptable to MDOT and other stakeholders.

Additional remediation to improve drainage within the slope or to increase slope stability factor of safety will likely push the repair to the higher end of that range. Other alternatives, including roadway relocation or constructing a retaining wall, will likely increase the construction cost relative to the Option 1 and Option 2 alternatives. However, we recommend gaining a comprehensive understanding of ground and surface water conditions at the site to provide a more thorough basis for selecting appropriate remediation alternative.

4.2.3.3 BCA Results

The following BCA provides a mixed qualitative and quantitative approach to help structure the decision-making process for MDOT as they coordinate with local jurisdiction stakholders on options to invest in installation of additional shoreline protections at the toe of the bluff slope adjacent to US-31 on the west of Petoskey, Michigan.

The site was first analyzed by a geotechnical engineer to examine 1) the risk of slope failure, and 2) the likelihood of that failure causing a failure of the asset. Classification by key metrics are shown below in Table 4-24. The site sits on top of a high bluff with a moderate strength, a moderate quality of vegetation, and a steep slope. The site lacks adequate toe protection, and the clear presence of ground water outflow is a major risk factor. A catastrophic slope failure and signs of previous failures indicate a high likelihood of future failure and should be considered carefully. The asset is over 200-feet from the shoreline offering some protection, and the ability to intervene exists with some challenges as indicated by the information provided in the Baird report, but the area of intervention is not within MDOT's jurisdiction posing a major challenge.

Table 4-24. Geotechnical evaluation of erosion matrix for US-31 Petoskey, Michigan

Parameter	Risk Ranking	Description/Notes
Groundwater Outflow, Seepage	High	Moderate, point-source seeps with flowing water
Bluff Makeup / Strength *(Includes consideration of soil type, stratification, strength [angle of interal friction and cohesion], and unit weight)*	Moderate	Moderate / Sand
Surface erosion / sensitivity to surface runoff	High	Presence of gullies created by surface runoff
Bluff Slope / Average Angle	High	< 2H:1V; *Petosky is a 1:1 slope*
Wave Exposure *(Water Elevation = Total Water Level Elevation - Toe Elevation)*	High	> 7 feet difference between Total Water Level Elevation and Toe Elevation; *592.5 feet NAVD88 = Total Water Level* *582.9 feet NAVD88 = 10% annual chance Stillwater elevation* *Difference = 9.6 feet*
Existing Manmade Toe Protection Quality *(Includes manmade structures - groins, riprap, etc.)*	High	No protection, or protection is highly degraded; No toe protection
Existing Natural Toe Protection *(Includes natural materials only, for example, trees from previous failure)*	Not ranked	-
Vegetation	Moderate	Covered, moderately developed, moderately rooted (ex. brush and small trees). Trees show some curvature

Parameter	Risk Ranking	Description/Notes
Previous Failures	High	Significant nearby failure(s) indicate another failure is highly likely
Bluff Height	High	High (>75 feet); *Approximately 100 feet*
Rapidity of Failure	High	No warning, sudden onset
Ability to Intervene	Moderate	Intervention is possible with some challenges
Horizontal Distance to MDOT Asset	Low	Majority of asset is >200 feet away; *Approximately 250 feet on average, with around 200 feet minimum*

Key inputs and considerations as MDOT weighs the costs, benefits, and risks are shown in Table 4-25.

The detour time anticipated for this site is moderate at 14 minutes and 8.6 miles; and a high AADT means that the daily economic loss from loss of function of the assets is estimated to be $267,040 per day. Assuming a 60-to-90-day duration for loss of function, the overall estimated cost of a slope failure impacting the asset is between $16 and $24 million dollars.

The height of the bluff and high traffic contributes to a high level of life safety risk which is moderated by the distance from the shoreline. Presence of the Little Travers Wheelway on the slope below the asset contribute to an elevate level of risk to other properties for the site.

Anticipated cost to implement mitigation at the site are relatively high, however the cost of repair given slope failure impacting the asset is anticipated to be very high. Notably, the area that would receive mitigation is not under the jurisdiction of MDOT, and MDOT would not bear the full cost implementing those activities, if at all.

Based on the characteristics of the slope, and the history of failure, it is highly likely that failure will occur at some point in the future, although given the characteristics of the asset, namely its distance from the shoreline, it is not likely that a failure will impact the roadway. Considering the recent failure, some remedial action is warranted, however, again that is not fully under the purview of MDOT.

Taking no action is a low-cost option in the near term but with potentially very high cost in the long term. Mitigation will have a high upfront cost but will return high benefits from avoided loss of function due to a failure impacting the asset. Further incidence of slope failure is likely and MDOT should continue to monitor slope conditions carefully. Continued close coordination with local jurisdiction holders is also a high priority as all options proposed for the site have some bearing on the MDOT asset, including potential re-routing of the Little Traverse Wheelway within MDOT right-of-way. As the ability to intervene is not fully in MDOT's hands, MDOT should look to take an advisory role supporting local stakeholders while continuing to monitor the slope's impact on the asset.

Table 4-25. Mixed Qualitative and Quantitative Costs, Benefits, and Risks for US-31 Petoskey, Michigan

Category	Metric	No Action	Mitigation (Relocate Roadway)
What are the damages if slope failure occurs? (Quantitative and Qualitative)	AADT	20,673	20,673
	Detour Length	8.6 miles	8.6 miles
	Detour Time	14 minutes	14 minutes
	Economic Loss Per Day of Loss of Function	$267,040	$267,040
	Expected Duration of Loss Over Project Useful Life	60 – 90 days	0 days
	Estimate of Potential Costs	$16 – 24 million	$0
	Life Safety Risk	Medium: Life safety risks to a small number of people	Low: No life safety risks
	Other Property Risk (non-MDOT Assets)	Medium: Lower value asset at risk (bike path)	Low: No other assets at risk
What are the expected cost over the analysis duration? (Semi-Quantitative)	Construction Costs	-	$$$
	Maintenance Costs	$$	$
	Repair Costs	$$$$	-
What is the likelihood of failure for first, the slope, and second, the asset? (Qualitative, per	Likelihood of **slope** failure based on physical site conditions and mitigation measures	Highly Likely	Not Likely

Category	Metric	No Action	Mitigation (Relocate Roadway)
geotechnical evaluation of erosion matrix)	Likelihood of **asset** failure based on slope distance to MDOT asset	Not Likely	Not Likely

5 Statewide Assessment

As a final step of analyzing coastal hazards from high lake levels for MDOT assets, a statewide analysis of 53 sites identified by regional leaders was conducted. Drawing on methods developed as a part of the detailed 5-site analysis, sites were categorized by asset type, classified by hazard, and measured based on a suite of critically and consequence, risk, and qualitative metrics to develop a prioritized list of sites to investigate mitigation actions.

The excel tool referenced herein is included as *Appendix H: Statewide Matrix.*

5.1 Statewide Decision-Making Matrix

The statewide decision-making matrix is a classification of risk for the 53 sites identified by MDOT regional leaders. The excel matrix uses publicly available data, data provided by MDOT through a data sharing agreement and regional interviews, and expert knowledge to measure each site based on a suite of risk metrics developed by the engineering team in coordination with MDOT personnel. Sites were scored based on metrics measuring the risk faced by the asset, criticality of the asset, and the consequence of a failure of the asset. This quantitative score is supplemented by qualitative notes and findings to help MDOT best serve their State, protect their infrastructure, and allocate resources.

The analysis can be summarized in the following steps:

1) Analyze criticality/consequence for each site of interest, and score.
2) Analyze flood risk for each site, and score.
3) Add criticality/consequence score with flood risk score for a final score for flood hazard sites.
4) Establish if erosion risk exists for a site (and flag for subsequent analysis).
5) Identify qualitative considerations for each site.

Criticality/consequence for the asset measures its importance within the larger context of the road network and the areas that are served by them. Criticality was scored using AADT and CAADT, access to critical facilities, and access to community facilities. Access to critical and community facilities was measured through a desktop analysis using Geographic Information System (GIS) and data about locations of hospitals, fire stations, and emergency medical services for critical facilities, and schools, universities, recreational facilities, and other identified interests for community facilities. GIS data was supplemented and verified with Google Maps to capture additional context about businesses and neighborhoods served by each road. Access to the two types of facilities was scored based on a low, medium, high (one, two, three) point scale according to the impact closure or failure of the road would have on the ability to reach or be reached by such services. Similarly, the consequence of failure was quantified through the expected detour and mileage that would be required to circumnavigate an inoperable roadway.

Sites were then divided by their hazard classification, flood, erosion, or a mix of both; and those identified as flood or inundation sites were measured by another suite of risk metrics. Flood risk metrics include presence and location of a FEMA SFHA or flood zone, and site elevation relative to the max historic lake elevation.

Flood zone risk was classified as minimal if the nearest flood zone was greater than 75-feet away, low if the nearest flood zone was less than 75-feet but not touching the shoulder, and high if the flood zone was touching the shoulder for more than 100 linear feet or if the asset was located withing the designated flood zone.

Elevation of the site was determined using 3DEP DEMs from the U.S. Geological Survey (USGS), and the MDOT 2020 Linear Reference System shapefile filtered to the identified sites. Site elevation was determined by generating points every 200 feet along the Linear Reference System line and using the Add Surface Information tool in ArcGIS Pro which assigns elevation values from DEM raster pixels to the multipoint feature representing the road. This elevation was then compared to the maximum historic water level elevation for the respective body of water associated with the site to determine a rough measure of free-board or inundation depth. The free-board/depth measurement was then scored low (one) for free-board of greater than 10 feet, moderate (two) for free-board greater than one but less than 10 feet, and high (three) for free-board of less than one foot or a negative value indicating inundation. One limitation of this method is the availability and resolution of elevation data. USGS currently hosts full coverage of the State at a resolution of 1/3 arc-second (10 meters), but only scattered coverage at a resolution of 1/9 arc-second (3.4 meters) and one meter. Best available data was used for each site, however, for those sites located in an area of lower resolution coverage, raster pixel values were sometimes skewed by lower or higher elevation areas around the site and anomalies of the survey data. Arcadis first dropped all values below 571 feet (the lowest point in Michigan) before further verifying outlier elevations. To ground truth data elevation was verified manually using GIS, Google Street View, and the USGS National Map viewer tools for point elevation and elevation profiles. Following verification, the elevation was either manually entered or the median of the site elevation points was used.

A final score for flood risk sites was calculated by multiplying the Criticality/Consequence scores by one another to produce an overall score for that category and by doing the same for the flood risk scores. These two scores were added together to produces a ranking of sites across the state. Results are discussed below.

For those sites classified as facing an erosion hazard, a two-part Erosion Matrix was developed as a supplement to the statewide assessment and as a tool that can be used independently to measure erosion risk at a site. The erosion risk matrix was created drawing from a mix of literature and guidance on erosion risk, and expert engineering opinion. This matrix aggregates multiple risk factors into a scoring table that roughly estimate the likelihood of failure of a slope and a second table measures the likelihood that failure will impact the asset. The first part of the matrix is to be used to analyze a list of mostly physical characteristic to determine a high, moderate, or low contribution to the likelihood of failure for the slope or bluff in question. These characteristics include groundwater presence, bluff makeup/strength, surface erosion/sensitivity to surface runoff, bluff slope/average angle, wave exposure, existing manmade protection, existing natural protection, vegetation, previous failures, bluff height, and the rapidity of failure. This table is intended to be used by a geotechnical expert to examine the site and develop an opinion of risk for each site of interest. Table 5-1 shows the matrix and the parameters used to score erosion while Table 5-2 shows the additional site characteristics for erosion sites not captured elsewhere in the criticality/consequence section of the Statewide Matrix.

Table 5-1. Erosion Matrix Part 1– Likelihood of Slope Failure

Parameter	Low Risk	Moderate Risk	High Risk
Groundwater Outflow, Seepage	Trace, isolated dripping water	Slight, wet cliff face with drips, point-source seeps	Moderate, point-source seeps with flowing water
Bluff Makeup / Strength *(Includes consideration of soil type, stratification, strength [angle of interal friction and cohesion], and unit weight)*	Strong / Rock	Moderate / Sand	Weak
Surface erosion / sensitivity to surface runoff	No evidence of surface erosion	Evidence of erosion due to surface runoff	Presence of gullies created by surface runoff
Bluff Slope / Average Angle	> 3H:1V	>2H:1V	< 2H:1V

Parameter	Low Risk	Moderate Risk	High Risk
Wave Exposure *(Water Elevation = Total Water Level Elevation - Toe Elevation)*	< 3 feet difference between Total Water Level Elevation and Toe Elevation	3 to 7 feet difference between Total Water Level Elevation and Toe Elevation	> 7 feet difference between Total Water Level Elevation and Toe Elevation
Existing Manmade Toe Protection Quality *(Includes manmade structures - groins, riprap, etc.)*	High level of protection (no degradation)	Moderate level of protection (some degradation)	No protection, or protection is highly degraded
Existing Natural Toe Protection *(Includes natural materials only, for example, trees from previous failure)*	Large amounts of natural toe protection	Moderate amounts of natural toe protection	No natural toe protection
Vegetation	Covered, highly developed, deep rooted (ex. large trees)	Covered, moderately developed, moderately rooted (ex. brush and small trees)	Lightly covered/rooted (ex. grass and brush). Trees show strong curvature.
Previous Failures	No nearby failures, or recent failure stabilized the site	Small failures may indicate some risk of future failure	Significant nearby failure(s) indicate another failure is highly likely
Bluff Height	Low (<25 feet)	Medium (25 to 75 feet)	High (>75 feet)
Rapidity of Failure	Warning signals apparent in advance, slow onset	Some warning signals before failure, could be slow or sudden onset	No warning, sudden onset

Table 5-2. Erosion Matrix Part 2– Likelihood of MDOT Asset Failure

Parameter	Low Risk	Moderate Risk	High Risk
Horizontal Distance to MDOT Asset	Majority of asset is >200 feet away	Majority of asset is between 75 and 200 feet away	Majority of asset is < 75 feet away

Parameter	Low Risk	Moderate Risk	High Risk
Ability to Intervene *(Existence of mitigation options and the ability to implement)*	Site is accessible and several intervention options exist	Intervention is possible with some challenges	Intervention is not possible due to site characteristics

The second part of the table of the erosion matrix measures the likelihood of MDOT asset failure based on the distance between the asset and the slope at risk, the ability to intervene, and the estimated impact/cost of making permanent repairs. The ability to intervene is intended to capture the feasibility of implementing an intervention. Factors that should be considered are the existence and viability of mitigation options, the ability to access the site and conduct work, the political context of intervention, including regulatory and local stakeholder concerns, and jurisdictional challenges among others.

Due to the complex nature of erosion risk and availability of data it is beyond the scope of this assessment to score each erosion site. It is recommended that MDOT prioritize further study of erosion risk sites based on their criticality score and supplementing that with any local knowledge of developing erosion issues. The erosion score can then be added to the criticality score to rank the erosion risk sites as has been done for inundation risk sites.

5.2 Summary of Findings and Next Steps

The statewide assessment resulted in an assessment of 53 sites statewide with 16 inundation sites, 27 erosion sites, and 10 sites with characteristics of both and erosion and inundation risk. Among the sites, there are 3 sites represented by multiple segments/entries in the matrix for a total of 48 distinct sites.

Criticality/consequence was scored for all sites within the assessment and scores ranged from 2 to 90. The highest scores were often seen by those sites which had no realistic detour route available, requiring detour times that exceeded 45 minutes with some as high as 87 additional minutes. Other sites that ranked at the top of the list for criticality were those that provide key access to both critical and community facilities and had detour times that exceeded 15 minutes.

Each site was also classified by their flood risk, including erosion sites, although flood risk for these sites should be considered more of a proxy for factors influencing risk of slope failure, as opposed to direct risk to the asset. For those sites classified as facing inundation risk, flood risk scores were determined with a range from 2 to 9. Those sites scoring highest among the inundation sites were those that were within the limits of a FEMA Special Flood Hazard Area, and at or near an elevation that corresponded to the maximum historic lake level for the site.

Finally, a combined score was produced for the inundation sites by adding the criticality/consequence score to the flood risk score. Values for this score ranged from 5 to 96 and included those sites that were classified as facing both inundation and erosion risk. Ranking was largely driven by the criticality/consequence score and differentiated through the flood risk score. A summary of the statewide assessment ranking is shown in Table 5-3 below.

Table 5-3. State-wide Assessment Inundation Site Rankings

Unique Id TSC Description	Physical Reference #	Traffic Flow	Critical Facilities	Community Facilities	Detour Time	Criticality/Consequence	Free Board/Depth	Flood Zone	Flood Risk	Flood Risk + Criticality/ Consequence
SUP.009 - Newberry - At Nunn's Creek	1143604	1	1	1	3	**3**	1	2	**2**	**5**
SUP.011a - Newberry - East of Cedarville	1143604	1	1	1	3	**3**	1	2	**2**	**5**
SUP.011d - Newberry - East of Cedarville	1464605	1	1	1	3	**3**	2	2	**4**	**7**
SUP.011c - Newberry - East of Cedarville	1144106	1	1	1	3	**3**	2	2	**4**	**7**
U.001 - Brighton - State Line to I-275	1226910	3	1	1	2	**6**	1	2	**2**	**8**
SUP.011b - Newberry - East of Cedarville	1467210	1	1	1	3	**3**	2	3	**6**	**9**
SUP.001 - Ishpeming - Head of Keweenaw Bay	1189907	3	1	1	1	**3**	3	2	**6**	**9**
SUP.015 - Newberry - Manistique	1199903	3	1	1	1	**3**	2	3	**6**	**9**
N.010 - Gaylord - MDOT Roadside Park, 1400' west of Burgess Road	1244001	3	1	1	1	**3**	2	3	**6**	**9**
B.007 - St. Clair - Ice Jams near Downtown Algonac	4502633	2	3	1	1	**6**	1	3	**3**	**9**
SW.001 - Kalamazoo - St. Joe River to 6th St	1363303	3	2	2	1	**12**	2	3	**6**	**18**
G.001 - Muskegon - Various locations within the corridor, Village of Pentwater.	1541508	2	2	2	2	**16**	1	2	**2**	**18**
B.006 - St. Clair - St. John's Marsh	4502633	2	2	2	2	**16**	1	3	**3**	**19**
SUP.017 - Ishpeming - East of Silver City	1271205	1	3	2	2	**12**	3	3	**9**	**21**
G.002 - Muskegon - Downtown Whitehall and Montague	859301	3	2	2	2	**24**	1	3	**3**	**27**
SUP.005 - Crystal Falls - From Menominee northerly to Escanaba	1322610	3	2	2	2	**24**	2	3	**6**	**30**
SUP.012 - Newberry - Manistique Scenic Turnout	1199707	3	2	2	2	**24**	3	2	**6**	**30**

Unique Id TSC Description	Physical Reference #	Traffic Flow	Critical Facilities	Community Facilities	Detour Time	Criticality/Consequence	Free Board/Depth	Flood Zone	Flood Risk	Flood Risk + Criticality/ Consequence
SUP.002 - Crystal Falls - Big Fish Dam & Little Fish Dam Bridges	1349006	3	1	2	5	**30**	2	3	**6**	**36**
SUP.008 - Newberry - At Tahquamenon River	3170009	1	3	2	5	**30**	3	3	**9**	**39**
SUP.007 - Ishpeming - Between Carp River and the Marquette Welcome Center	1562009	3	3	2	2	**36**	3	0	**3**	**39**
G.004 - Muskegon - West of School St. - Village of Spring Lake	754007	2	2	3	3	**36**	2	3	**6**	**42**
B.008.2 - St. Clair - Harson's Island Drainage Issues	967504	1	3	3	5	**45**	1	3	**3**	**48**
B.008.1 - St. Clair - Harson's Island Drainage Issues	967507	1	3	3	5	**45**	1	3	**3**	**48**
N.009 - Traverse - Causeway near Elberta	1073009	2	3	3	3	**54**	1	3	**3**	**57**
N.011 - Grand Traverse/Lellanau - Traverse City Area	N/A - see comments	3	3	3	3	**81**	2	3	**6**	**87**
SUP.016 - Ishpeming - Between Plains Cut-off Road and Superior Avenue	1189907	3	2	3	5	**90**	3	2	**6**	**96**

The highest-ranking site was in the Upper Peninsula along Lake Superior with a score of 96. US-41 between Baraga and L'Anse scored highly for traffic count, access to critical facilities, and scored moderately for access to community facilities due to their availability in each of the respective villages. The route had no realistic detour option with detour time estimated to be 47 minutes and even then, it would involve travelling on sections of unpaved road, and likely not feasible for commercial travel.

The second highest ranking site with a score of 87 was the site located at the south end of each of Little Travers Bay. This site was identified as an additional site and added to the statewide assessment. The site scored highly on all measures of criticality/consequence and serves as a main thoroughfare through Traverse City and a key connection to destinations around the Ctiy. The site is characterized by a low elevation, and a roadway that is very near the flood zone and bay that would drive flooding. This site was identified in two sections and extends most of the way up the coast of the West Arm of Little Traverse Bay. This site has been identified as a high priority site, however due to the extent given it is recommended that further study be done to identify problem hotspots for more focused mitigation.

The ranking from the statewide assessment should serve as a filtering mechanism for prioritizing high water level mitigation projects, however it is still recommended that criticality/consequence and flood risk should be confirmed with on the ground stakeholders and by regional leaders as impacts tend to be very site specific.

One limitation of the assessment is the accuracy of elevation data as has been discussed above. It is recommended that MDOT recreate the exercise for elevations when the Michigan Statewide Authoritative Imagery & LiDAR (MiSAIL) program concludes its collection of higher resolution data, especially for sites in the Upper Peninsula. All but eight counties in the state have been surveyed, passed USGS QA/QC, and been accepted into the 3DEP program, although not all of those have been published to date. The remaining counties have been surveyed and are undergoing USGS review. The option to do site specific surveying should also be considered.

For erosion sites the criticality/consequence score should be used to determine priorities for completing the full erosion matrix. As these assessments are done, they should then be added to the criticality/consequence score to determine a ranking for erosion sites.

Overall, the assessment maps out the highest priority sites based on use and site characteristics. Qualitative inputs and cost of mitigation will inevitably play a factor in actual prioritization; however this assessment serves as a framework for making those decisions.

6 Conclusions and Future Recommendations

The mechanisms that govern Great Lake water levels are quite complex. On top of this, many coastal processes such as erosion do not present in a linear fashion. In terms of planning, this means that many times, answers are less straightforward than on the ocean coasts, where sea level rise projections can be clearly tied to a timeframe for action. Decision makers at MDOT must weigh an uncertain level of risk as they make decisions about where to invest, with many competing priorities for funds.

6.1 Comparison of Inundation Sites

The duration analysis performed provides a historic look at the past water levels at the two inundation sites, based on proxy NOAA guage stations. In comparing the number of exceedances since 1970 seen at the edge of pavement for both M-22 Elberta/Frankfort and M-29 St. John's Marsh, M-22 Elberta/Frankfort saw higher impacts across the years (Table 6-1). For example, in 1985 M-22 Elberta/Frankfort saw 56 exceedances, while M-29 St. John's Marsh only saw 6. The number of exceedances also translates into longer total duration of inundation (Table 6-2). Over the course of five decades, the area M-22 Elberta/Frankfort area was likely inundated for a total of 3.6 years, while M-29 St. John's Marsh saw only 1.6 total years of inundation. However, these timeframes are both significant considering roadway function and safety. Additionally, the duration analysis shows that lake levels have equaled or exceeded the assumed subgrade of both sites has almost continuously, totaling 37.5 years for M-22 Elberta/Frankfort and 40 years for M-29 St. John's Marsh.

Table 6-1. Comparison of Inundation Sites Edge of Pavement Incidence of Exceedance

Year	Ludington Station (M -22 Elberta/Frankfort)	Algonac Station (M-29 St. John's Marsh)
1973	10	2
1974	10	2
1975	4	0
1976	4	0
1985	56	6
1986	22	21
1987	10	5

Year	Ludington Station (M -22 Elberta/Frankfort)	Algonac Station (M-29 St. John's Marsh)
1997	10	1
2019	5	17
2020	15	11
2021*	2	1

* Only partial data was available for 2021.

Table 6-2. Summary of Duration Analysis Results for Inundation Sites

Station	Threshold	Threshold Elevation (feet, IGLD)	Number of Exceedance Events	Total Duration, hours (days), *years*
Ludington Station (M -22 Elberta/Frankfort)	Edge of Pavement (At Shoulder)	581.2	159	31354 (1306) *3.6*
	Bottom of Subgrade	578.2	210	328757 (13698) *37.5*
	Design Elevation	582.9	0	0
Algonac Station (M-29 St. John's Marsh)	Edge of Pavement (At Shoulder)	577.3	66	13970 (582) *1.6*
	Bottom of Subgrade	574.5	229	347452 (14477) *40*
	Design Elevation	579.8	0	0

Based on the duration analysis, M-22 Elberta/Frankfort appears to have greater need for a mitigation solution. However, when monetizing the potential loss of function, M-29 St. John's Marsh shows significantly higher losses due to it being a higher use roadway. Both sites have significant detours, however M-29 St. John's Marsh is about twice the added time. If no action were to happen and water levels were to peak high enough to close the roadway for a total of 60 days across 2 years, M-22 Elberta/Frankfort would see $2.1 million dollars in loss of function base on the value of travel time savings, while M-29 St. John's Marsh would see $9.0 million. Comparatively, construction costs for raising the roadway and bridge at M-22

Elberta/Frankfort is estimated at $1.625 million, while raising the roadway at M-29 St. John’s Marsh is estimated at $4.956 million.

For both sites, the low-cost temporary mitigation of sandbags provides flexibility of installation, and potential savings if water levels do not reach levels greater than those seen in 2019 and 2020. However, if they are deployed at least once over a ten-year planning horizon (2-years of high-water scenario), total costs assuming roadway elevation in year 9 are on par with investing in the preferred mitigation alternative early in the planning cycle. Costs of temporary mitigation measures become significantly more costly if they need to be deployed twice (5-years of high-water scenario) (Table 6-3). These results assume a large capital project for each of these sites based on the provided asset lifespan by MDOT. If a capital improvement project were to be delayed, these results would change.

While Arcadis suggests MDOT consider mitigation at both sites, when interpreting quantified losses with the duration analysis above, MDOT may choose to give priority to M-22 Elberta/Frankfort due to relatively greater risk of future long-term inundation high enough to close the roadway (based on historic levels) combined with a lower project cost for mitigation. However, if water levels were to be severe M-29 could see significantly higher loss of function costs associated with closure.

Table 6-3. Comparison of Costs between Mitigation Alternatives for Inundation Sites, Discounted

Scenario	Cost	M -22 Elberta/Frankfort)		M-29 St. John's Marsh	
		2-Years of 1 Month High Water	5-Years of 4 Months High Water	2-Years of 1 Month High Water	5-Years of 4 Months High Water
No Action	Construction Costs	$950,000	$950,000	$2,900,000	$2,900,000
	Maintenance Costs	$1,300,000	$1,300,000	$2,900,000	$2,900,000
	Loss of Function Costs	$2,100,000	$20,000,000	$9,000,000	$83,000,000
	Total	**$4,300,000**	**$22,000,000**	**$15,000,000**	**$89,000,000**
Temporary Mitigation	Construction Costs	$1,200,000	$1,400,000	$4,300,000	$5,400,000
	Maintenance Costs	$1,500,000	$1,900,000	$4,200,000	$5,300,000
	Loss of Function Costs	$71,000	$130,000	$300,000	$540,000
	Total	**$2,800,000**	**$3,400,000**	**$8,800,000**	**$11,000,000**
Permanent Mitigation	Construction Costs	$1,500,000	$1,500,000	$4,600,000	$4,600,000
	Maintenance Costs	$1,200,000	$1,200,000	$2,800,000	$2,800,000
	Loss of Function Costs	-	-	-	-
	Total	**$2,700,000**	**$2,700,000**	**$7,400,000**	**$7,400,000**

Notes:

Results are rounded to two significant digits. The totals represent the sum of the damages prior to rounding to avoid rounding assumptions.

Results represent a 7 percent discount rate over a 10-year planning horizon.

6.2 Comparison of Erosion Sites

While ideally mitigation action is taken at all sites that exhibit erosion risk, MDOT will need to prioritize where they begin mitigation. Table 6-4 below summarizes the key findings of the erosion BCA, providing a structured view for decision makers. As cost is only one decision factor, life safety and duration of loss of function are also highlighted.

Table 6-4. Summary of key qualitative and quantitative benefits, cost, and risk for erosion sites.

Considerations	M-116 Ludington		I-94 St. Joseph		US-31 Petosky	
	No Action	Mitigation	No Action	Mitigation	No Action	Mitigation
Estimate of duration of loss of function if slope were to fail	30 – 60 days	0 days	60 – 90 days	0 days	60 – 90 days	0 days
Estimate of potential costs from loss of function after a slope failure	$22 – 44 million	$0	$3.6 – 5.5 million	$0	$16 – 24 million	$0
Life safety risk of asset failure	None	None	Medium-High	None	Medium	None
Likelihood of **slope** failure based on physical site conditions and mitigation measures	Likely	Likely	Likely	Not Likely	Highly Likely	Not Likely
Likelihood of **asset** failure based on slope distance to MDOT asset	Highly Likely	Unlikely	Not Likely	Not Likely	Not Likely	Not Likely

Slope failure is likely or highly likely across all the erosion sites prioritized. However, based on varying asset locations in relation to the shoreline, this may or may not lead to actual MDOT asset failure. Based on geotechnical expert judgment, M-116 Ludington is likely to see roadway failure if the slope fails. As both 1-94 St. Joseph and US-31 Petosky are further from the shoreline, it is less likely the roadways would experience failure if the slope itself fails in the next few decades. However, the risk of failure still exists. If a failure were to occur, these two sites pose higher life safety threats than if M-116 Ludington were to fail, due to significantly higher bluff height.

Ideally, all three sites should see mitigation. However, if that is not realistic due to budget considerations, MDOT must weigh the small, but real risk associated with life-safety concerns present at US-31 Petosky and I-94 St. Joseph against the less catastrophic, but more likely failure of M-116 Ludington.

6.3 Recommendations for Further Research and Implementation

As this was a multi-faceted research project, MDOT may choose to implement all or some of the key findings. Arcadis has summarized the highest priority needs in Table 6.5 below. They cover the next steps for each of the five sites, as well as more general statewide considerations around planning and policy, financing, adaptive management/monitoring, and partnerships. [19]

Additionally, while this study looked at high water levels, low water levels present their own risks and challenges. As the Great Lakes will inevitably see both highs and lows in the future, a similar risk assessment should be done for low water levels. While there will be some overlap in coastal sites, the mechanisms for asset failure and potential solutions may differ.

[19] Some of the recommendations listed below may already be in initial stages by MDOT or conducted on an informal basis, however, it is always beneficial to formalize processes. For example, when dealing with staff turnover institutional knowledge may be lost.

Table 6-5. Recommendations for Further Research and Implementation

#	Type	Task	Description
1	Capital Project	M-22 Elberta/Frankfort – implement preferred alternative	Arcadis recommends implementing raising the causeway and bridge. To refine and finalize the schematic design proposed here, Arcadis suggests a H&H study for the site, given its location at the mouth of the Betsie River. Prior to moving forward with the design, MDOT should coordinate with MDNR and other relevant stakeholders. Additionally, it is recommended that the current bridge be inspected every 24 months.
2	Engineering Study / Capital Project	M-29 St. John's Marsh – H&H study to refine preferred alternative	Given development with the floodplain near this site, including neighborhoods to the north and south of the project, additional H&H study is warranted to determine the necessary quantity and size of openings along this route, prior to proceeding with just raising the roadway. During regional interviews, it was noted that citizens are quite active in this area, so due diligence in showing no additonal neighborhood flooding will occur. Additionally, coordination with MDNR may highlight additional environmental concerns.
3	Capital Project	M-116 Ludington – implement preferred alternative	Arcadis recommends implementing relocation of the roadway. Priority may be given to higher-consequence sites.
4	Engineering Study/Design	I-94BL St. Joseph – Coastal analysis and Design of Combined Beach Nourishment and Shoreline Protection	As the fundamental driver of erosion at this particular location is a disruption of longshore (or littoral) transport due to the presence of jetties along the shoreline. It is anticipated that the most effective solution for mitigating erosion at the I-94BL St Joseph site will be a combination of beach nourishment and shoreline protection, A design for beach nourishment was beyond the scope of this project and will need the engagement of a coastal engineer. MDOT should consider continued engagement with stakeholder agencies including USACE and EGLE.

#	Type	Task	Description
5	Engineering Study	US-31 Petoskey Ground and Surface Water Investigation and Runoff Diversion Plan	Before determining a mitigation option or rebuilding the Little Traverse Wheelway, it is first recommended that a thorough ground and surface water investigation take place to better understand conditions that currently exist and those that lead to the 2020 slope failure. It is also recommended that MDOT address the risk of headcutting of the existing scarp, potentially by having a plan to divert excessive runoff when intense precipitation is expected. Additionally, a target factor of safety against slope failure of 1.5 should be considered for the any future remediation design.
6	Engineering Study/Policy	Develop coastal design standards, including procedures around hydraulics in coastal areas. Outreach to lawmakers to codify these standards as regulations statewide.	With the great length of shorelines in Michigan, it is recommended that MDOT develop coastal design standards, similar to the Ohio Coastal Design Manual and AASHTO's Drainage Manual (Current Edition). While Arcadis has provided draft standards in *Appendix B: Proposed Coastal Design Criteria*, this topic deserves a level of analysis that is outside the scope of this study, including considerations specific to Michigan's coastal features and climate. Considerations should include setbacks, maximum design water levels, erosion protection guidelines, etc. Procedures around hydraulics in coastal areas should be outlined. These standards would be applicable to sites with risks of coastal flooding, wave impacts, or erosion and would be in addition to riverine flooding standards. At a minimum, frequency and elevation data should be prescribed (such as design elevation of the road needs to have at least 3 feet of freeboard above the 1 percent AEP for coastal flooding).
7	Planning/policy	Set up a capital improvement program for shoreline flooding and erosion control. Expand the Statewide Matrix into a full capital improvement plan.	Instead of having regions rely on their yearly maintenance budget, MDOT should consider setting up a capital improvement program explicitly for shoreline flooding and erosion control. The capital improvement budget can also include coordinated purchasing of temporary mitigation measures (that is, sandbags) at a statewide level. MDOT can leverage the statewide matrix as a modifiable tool to finalize the project ranking as a basis for the capital improvement plan.

#	Type	Task	Description
8	Planning/policy	Ongoing coordination with USACE	The USACE is probably the greatest resource for MDOT. MDOT should consider formalizing at least twice-yearly check-ins to discuss planned projects, available funding, and updated water level forecasting (both the Great Lakes Water Level Future Scenarios (not regulatory) and Coordinated 6-month Forecast Bulletin (regulatory) forecasts)
9	Planning/policy	Implement inspection program for monitoring shoreline erosion	Arcadis recommends implementing an inspection program to monitor high risk areas on a biennial term to monitor the erosion along the shorelines. This should be done on an ongoing basis, not just when water levels begin to rise.
10	Planning/policy	Develop a funding strategy for leveraging federal grant and load opportunities	There are many federal funding sources, with more passing of the Infrastructure Investment and Jobs Act (November 2021). MDOT should consider developing a funding strategy where they match projects with appropriate funding sources (such as FHWA, FEMA, USACE, etc.). Grant and no or low interest loan opportunities should be monitored on an ongoing basis. This could be done in conjunction with the capital improvement plan, or as a separate effort.
11	Research/pilot project	Elevation data for high priority/at risk assets, and potentially statewide	MDOT should continue to work to streamline elevation data into existing asset databases and prioritize gathering survey data for priority at-risk sites where it does not exist. While Michigan's state-wide lidar collection program (MiSAIL) provides a starting point, for ongoing monitoring of high water levels, elevation data at a higher resolution for critical assets would be beneficial going forward.

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Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AADT	annual average daily traffic
AEP	annual exceedance probability
BCA	benefit cost analysis
BFE	base flood elevation
CAADT	commercial annual average daily traffic
CPI	Consumer Price Index
DEM	digital elevation model
EGLE	Michigan Department of Environment, Great Lakes, and Energy
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
HERA	High Erosion Risk Area
H&H	hydrologic and hydraulic
GLERL	Great Lakes Environmental Research Laboratory
GIS	Geographic Information System
LiDAR	Light Detection and Ranging
IGLD	International Great Lakes Datum
MDOT	Michigan Department of Transportation
MDNR	Michigan Department of Natural Resources
MiSAIL	Michigan Statewide Authoritative Imagery & LiDAR
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
SFHA	Special Flood Hazard Area
TSC	Transportation Service Center
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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