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Multi-Scale Multi-Season Land-Based Erosion Modeling and Monitoring for Infrastructure Management

Final Report

Prepared for:

NEW ENGLAND TRANSPORTATION CONSORTIUM

NETC 19-2

February 25, 2022

Prepared by:
GZA GeoEnvironmental, Inc.

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16. Abstract

In the New England region, roadways located within "erosion-prone zones" have been the main sources of erosion-induced road damage, particularly when major storms occur. With recent and continuing climate change influencing weather patterns (specifically causing an increase in high-intensity rainfall events, and rainfall events following snow events), soil erosion and landslides are a major concern for DOTs, roadway planners, and designers, impacting the cost to maintain transportation networks and other critical infrastructure. With limited operational resources and funding available for maintenance and repairs, effective screening tools used for modeling, monitoring, and forecasting erosion can aid in assessing erosion and landslide susceptibility, which is critical for regional operations and planning.

GZA developed a screening-level tool to identify roadways vulnerable to erosion and landslides. The work was performed in collaboration with the New England Transportation Consortium (NETC). The project objective was to develop a multi-scale, multi-season land-based erosion and landslide modeling and monitoring (prototype) toolkit for infrastructure management for all the New England states (including Maine, New Hampshire, Vermont, Massachusetts, Rhode Island and Connecticut).

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic	m^3
	meters NOTE: volumes greater than 1000 L shall be			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inc h	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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ACRONYMS

BFE – Base Flood Elevation

DEM – Digital Elevation Model

DTM – Digital Terrain Model

DOT – Department of Transportation

FEMA – Federal Emergency Management Agency

GIS – Geographic Information System

GZA – GZA GeoEnvironmental, Inc.

LiDAR – Light Detection and Ranging

MGS – Maine Geological Survey

NACCS – North Atlantic Coast Comprehensive Study

NASA – National Aeronautical and Space Administration

NETC – New England Transportation Consortium

NHGS – New Hampshire Geological Survey

NOAA – National Oceanic and Atmospheric Administration

NRCS – Natural Resources Conservation Service

PCF – Pounds per Cubic Foot

PSF – Pounds per Square Foot

SFHA – Special Flood Hazard Area

USACE – United States Army Corps of Engineers

USDA – United States Department of Agriculture

USGS – United States Geological Survey

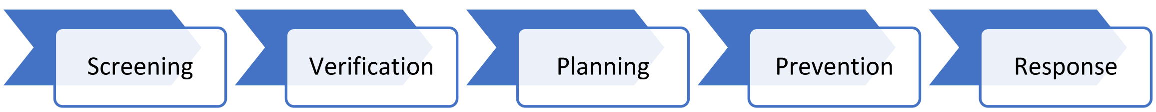
UTM – Universal Transverse Mercator

1.0 INTRODUCTION

Soil erosion and landslides are a major concern for Departments of Transportation (DOTs), roadway planners, and designers, impacting the cost to maintain transportation networks and other critical infrastructure. With limited operational resources and funding available for maintenance and repairs, effective screening tools can aid in assessing erosion and landslide susceptibility, improving the decision-making ability for transportation operations and planning.

GZA GeoEnvironmental, Inc. (GZA) developed a GIS framework to evaluate and screen potential for erosion and slope instability along roadway corridors where instability could impact roadways. The work was performed in collaboration with the New England Transportation Consortium (NETC). The project objective was to develop a multi-scale, multi-season land-based erosion and landslide modeling and monitoring toolkit for infrastructure management for all the New England states (including Maine, New Hampshire, Vermont, Massachusetts, Rhode Island and Connecticut).

The model and toolkit supports a process of:



2.0 LITERATURE REVIEW AND SURVEY

The first step in the development of the model and toolkit was a literature review to collect and compile available information regarding: 1) slope instability susceptibility; and 2) modeling capabilities suitable for the New England region, including means and methods used by others.

Previous studies from New England and other parts of the country were identified, summarized, and cataloged. We also identified information and causative factors that appear to be relevant for this project. GZA focused on studies that appeared to have application to the New England states (i.e., studies done in areas with similar geography, landscapes and climate), and that were conducted by government agencies such as state departments of transportation (DOT), the US Geologic Survey (USGS) and U.S. Army Corps of Engineers (USACE).

We also identified studies that used a Geographic Information System (GIS) based approach for spatial hazard analysis for slope stability (landslide and/or erosion). We also researched available datasets that could be used for the toolkit development.

Tables 1 through **3** summarizes GZA's key references and findings. Three major categories of literature sources were identified and reviewed:

- Slope stability design standards and guidance documents (**Table 1**);
- GIS-based modeling publications on approaches and case studies for slope stability, landslide and/or erosion (**Table 2**); and
- Available datasets including GIS format and other traditional datasets (**Table 3**).

A summary of each reference is provided in the tables. Key findings of the overall Literature Search are summarized below:

- At the national level, U.S. Geological Survey has compiled a landslide inventory and made it available through an ESRI web-based interactive map product (USGS, 2019).
- Three New England states have landslide inventory or geodatabase. There is existing state-wide landslide inventory in the States of Maine, being presented and accessible as a web-based GIS portal. Data is compiled and managed by the Maine Geological Survey (MGS, 2020). The Vermont Geological Survey compiled a preliminary landslide inventory based on historical landslide locations, accessible via a web-based online portal (VGS, 2019). New Hampshire Geological Survey (NHGS) has also compiled a landslide geodatabase (currently not available online for public access; information provided by NHDOT).
- State-wide Landslide Hazard Mapping was developed by University of Massachusetts (UMass) in 2013 (UMass, 2013). The underlying computing engine, SINMAP, is a deterministic model for Stability Index Mapping, which was used to identify areas that may be prone to shallow, translational landslides, assuming an infinite slope geometry. Certain parameters within the model can be assigned with uniform probability distributions, to account for uncertainty and allow model calibration.
- There are a number of research or mapping projects in the New England area focusing on landslides susceptibility based on a set of input parameters such as terrain information, groundwater conditions, land cover type and precipitation (e.g., Tufts, 2013; VGS, 2012). These studies are often for a specific area with unique site characteristics and the results were developed with specific objectives. For example, the Tufts 2013 study was to assess risk imposed by slope failure on transportation network.
- Most of these studies largely rely on GIS spatial datasets such as digital elevation/terrain model (DEM/DTM), surficial geology and land cover data, with the transportation network included as shapefiles.
- Most studies apply decision-based deterministic models to analyze and compute key risk factors such as factor of safety for slope stability, using simplified physics-based methods (e.g., USGS, 2001; NCGS, 2011; Barr, 2017).
- Some studies use a collation of risk factors to determine composite susceptibility factors (MGS, 2009a and MGS, 2009b).
- Final mapping products are often presented spatially in terms of categorized risk/susceptibility levels, typically using a risk factor approach.
- Currently no online GIS portal (in the New England state or at the national level) provides interactive slope stability assessment based on user input. Nor does any site or product provide real-time predictions.
- There is no state-wide or regional erosion/landslide GIS mapping application dedicated to the transportation system in New England, which was also confirmed by the survey results (Section 3.0).
- USGS 3D provides a nation-wide repository of topographic data and some related layers developed using spatial analytics (e.g., slope).
- Most of the existing applications utilize Esri GIS web mapping platforms.

References presented in **Table 2** mostly rely on deterministic approaches to calculate and/or quantify landslide and erosion susceptibility/vulnerability. GZA also reviewed published references using heuristic or probabilistic/statistical approaches (see Error! Reference source not found. at the end of this document). Previous research demonstrated that it is possible to improve landslide prediction accuracy by using regression and machine learning models with refined input data. We explored some of the applicable approaches (heuristic and/or statistical) when developing the toolkit for this project.

2.1 PRE-STUDY SURVEY

GZA collated a list of contacts with the help of the NETC 19-2 committee, including New England state's DOTs and other state agencies. We developed a list of questions, which were provided to the project technical committee for approval prior to the solicitation of responses. Once the list of questions was approved the internet-based survey was developed in Google Forms and was available online during the Task 1 phase of this project in May 2020.

The primary goal of the survey was to identify the current GIS practice, GIS modeling capability, toolkit expectation and available datasets within the State DOTs and GIS offices in New England. The survey consisted of four sections:

- Needs assessment;
- Model use and expectations;
- Policies and procedures (related to GIS); and
- Available datasets

The online survey was distributed to the New England state transportation agencies (CT, MA, ME, NH, RI, VT) in May 2020 for responses. The objective of the survey was stated at the beginning of the questionnaire (below).

Section 1 of 5

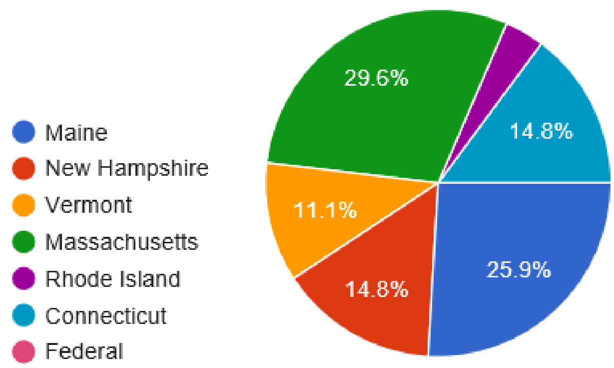
NETC 19-2 Multi-Scale Multi-Season Erosion Modeling/Mapping - Pre-Study Survey

In the New England region, roadways located within "erosion-prone zones" have been the main sources of erosion-induced road damage, particularly when major storms occur. With recent and continuing climate change influencing weather patterns (specifically causing an increase in high-intensity rainfall events, and rainfall events following snow events), soil erosion and landslides are a major concern for DOTs, roadway planners, and designers, impacting the cost to maintain transportation networks and other critical infrastructure. With minimal operational resources and funding available for maintenance and repairs, effective screening tools used for modeling, monitoring, and forecasting erosion can aid in assessing erosion and landslide susceptibility, which is critical for regional operations and planning.

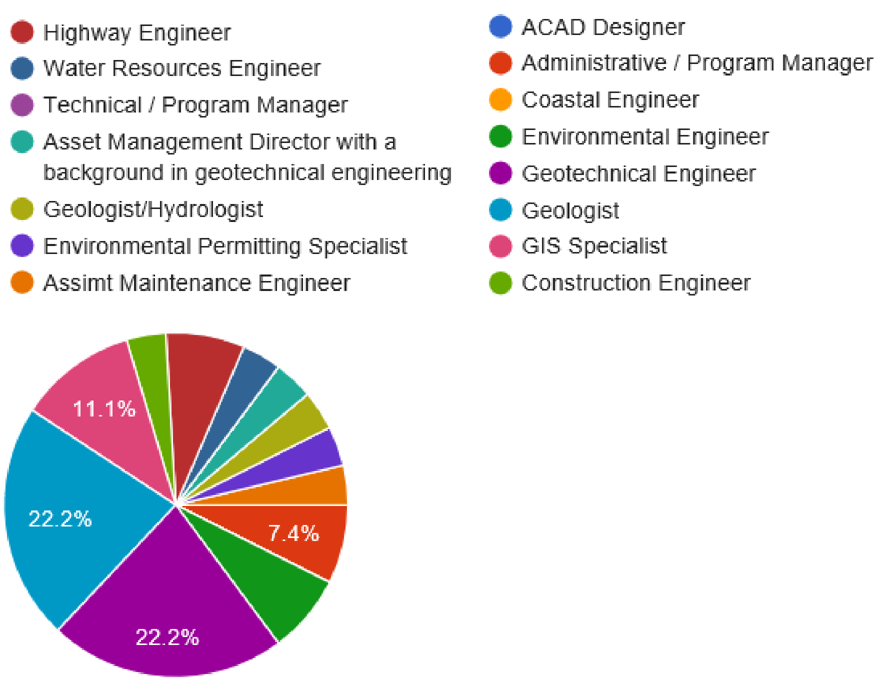
The objective of this research project is to develop a slope stability model that will be used to create an effective multi-scale assessment toolkit that aids in monitoring, forecasting, and prioritizing areas of erosion and slope instability.

Please provide input based on the best knowledge / understanding you have at the moment for this project.

A total of 27 responses were received. All six New England states responded to the survey (below), with particularly good turnouts in Maine and Massachusetts. No federal agency participated in the survey.



The respondents appeared to come from a wide variety of practices, as shown in the chart below.



Key findings from the survey are summarized below:

- Respondents of this survey cover a wide range of technical backgrounds, including geology, geotechnical, hydrology, CAD, GIS and management. Approximately 80% are engineers, scientists and geologists.

- All the respondents (except for one) are from three state offices/departments, namely, DOT, Geological Survey and State GIS.
- Majority of the participants indicate that their work requires the use of GIS and they are familiar with online applications and/or desktop GIS.
- There is a strong preference for using GIS-based technology within the New England state DOTs and ESRI (ArcGIS and ArcMap) appears to be the predominant software package used by the state government agencies.
- Microsoft Office Suite and AutoDesk are also widely used for daily job functions.
- Google products are being widely used, in particular Google Earth/Google Earth Pro.
- Sharepoint, FTP and MS Teams are widely used for data sharing. One respondent indicated that only secure
- Mobile electronic devices are widely used for field data collection, in addition to the traditional hand-written method.
- Two thirds of the respondents think that this toolkit will be useful.
- Most respondents agreed that we need to collaborate with state GIS, state Geological Survey, USGS and USACE. Half of the responses also indicate that some collaboration is needed with National Park Services and Federal Highway Administration.
- The proposed toolkit is expected to be used for emergency response, engineering, maintenance and planning.
- Expectant users largely prefer electronic format of maps that can customized via a web-based portal. Paper format is still being used but not preferred or required. Approximately half of the respondents indicate that smaller sizes (11”x17” and below) of maps are more likely being used and the other half would like to have the option available for large prints (e.g., 34”x22” and above) as well.
- More than half of the respondents expect to use the toolkit both on computer and mobile device. None expects to use the toolkit solely on a mobile device.
- Required dataset as input for the toolkit are topography, surficial geology, groundwater conditions/soil moisture, precipitation, hydrologic information and existing roadway structures (bridges and culverts), per survey responses.
- Respondents provided names and/or hyperlinks to datasets that may be used for the toolkit development including asset database and transportation feature classes.
- Less than 50% of the respondents have knowledge on policy and/or procedure related to GIS standard and protocols existent within each state. This could be due to the fact that most participants are not from the state GIS.
- Most of the respondents are aware that there is some sort of online GIS mapping application developed by their states but there is no application dedicated to erosion and landslide monitoring and modeling.

The full survey output is included as **Appendix A**.

2.2 LITERATURE REVIEW AND SURVEY SUMMARY

The results of both the literature review and project survey indicated that a web-based viewer and a heuristic/deterministic model for slope stability and erosion has been the dominant approach used by others (e.g., research publications and projects). The models developed by others predominantly analyzed topography as the primary variable, with additional variables of surface cover, geology and precipitation-driven change to soil moisture.

3.0 ANALYSIS AND MODELING

Following a comprehensive review of existing literature, available source data, and analytical methods, GZA started to develop our own approach to identify critical parameters, perform analyses, and generate model outputs of soil slope stability and potential erosion areas.

GZA developed model applications to evaluate and screen for erosion and slope stability zones along roadway corridors that have the potential to impact roadways. We understand the predominant characteristics that impact roadway failure include, but are not limited to:

- Surficial geology (i.e., geologic formation and soil material/geotechnical properties);
- Topography; and
- Flood/water-related failure mechanisms such as surface erosion (e.g., overtopping and wave impact), internal erosion (e.g., underseepage and piping); material softening by saturation; pavement failure (seepage and wave loads and flotation); and culvert failure or overtopping.

3.1 METHODOLOGY

GZA considered the following aspects / input parameters:

- Geostatistical analysis of topography, National Elevation Dataset published by U.S. Geological Survey (USGS);
- Geospatial analytics such as roadway segmenting, orientation, site condition and/or proximity queries (MaineDOT roadway inventory);
- Large culverts (MaineDOT);
- MGS 1:250,000 (250k) surficial geological data;
- USGS national hydrography dataset (NHD) with streams and surface water bodies;
- Land cover dataset published by Natural Resources and Conservation Service (NRCS); and
- Flood hazard mapping data published by Federal Emergency Management Agency (FEMA).

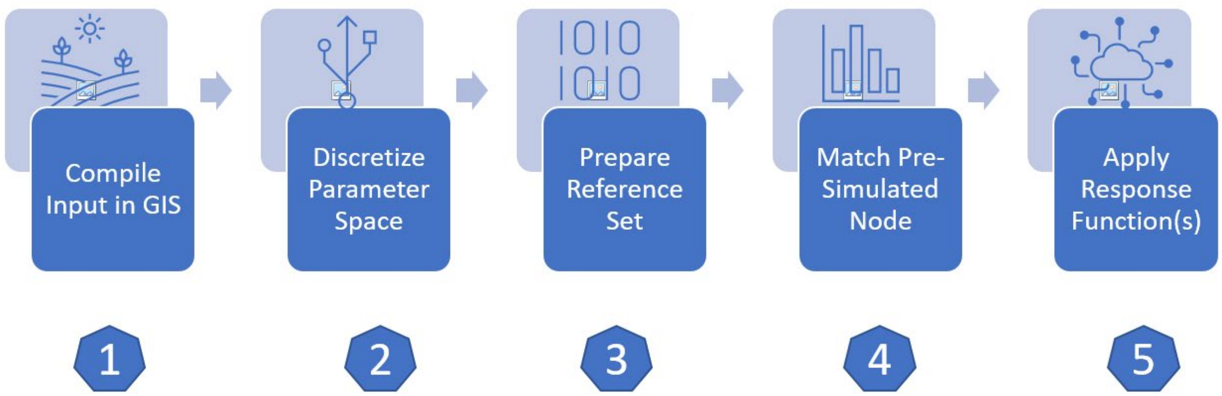
Figure 1 presents a simple schematic of the road-side slopes for this study. We grouped slopes into two main categories: source slopes and support slopes, which are defined by their relative elevation to the nearest roadway segment.

GZA adopted an analytical concept “analogous” to the Response Surface method widely adopted by U.S. Army Corps of Engineers (USACE) and FEMA for their coastal storm surge flood studies (Resio et al., 2009[1], USACE, 2015[2]). GZA’s workflow included the following steps, as summarized in the graphic below:

- Select key input parameters that affect slope stability (Step 1);
- Discretize parameter space per surficial geological information (Step 2);
- Assemble a base parameter combination set for numerical simulations (Step 3);
- Perform numerical slope stability analysis using simplified geotechnical material properties (Step 3);
- Include varying groundwater conditions (Step 3); and

[1] Resio, D.T., J. Irish, and M. Cialone, “A surge response function approach to coastal hazard assessment – part 1: basic concepts“, Natural Hazards, 2009. 51:163–182. DOI 10.1007/s11069-009-9379-y
[2] North Atlantic Coast Comprehensive Study (NACCS) Coastal Storm Hazards from Virginia to Maine, ERDC/CHL TR-15-5, November 2015.

- Establish an interpolation and extrapolation scheme for scenarios that are not directly modeled (Steps 4 and 5).



Complex geometry such as slope length, slope surface curvature and toe undercutting were considered as additional hazard contributing factors and were simulated as part of the sensitivity analysis. External loading, such as surcharge from traffic, was not included in the final toolkit as part of this project but could be considered and incorporated in future development.

3.2 NUMERICAL SLOPE STABILITY ANALYSIS

GZA used SLOPE/W (submodule of GeoStudio v.2018), a widely used commercial slope stability software program for analyzing soil slopes. SLOPE/W can effectively analyze both simple and complex problems for a variety of slip surface shapes, pore-water pressure conditions, soil properties, and loading conditions. **Figure 2** presents a simple schematic of the geometry modeled in SLOPE/W. GZA used the Morgenstern-Price (M-P) method with half-Sine side function (SLOPE/W default). The M-P method, similar to the Spencer method, uses mathematically more rigorous formulations than the earlier Bishop's method, which include all interslice forces and satisfy all equation of statics (**Figure 3**).

GZA carefully examined the surficial geological data available from MGS/USGS and selected the 250k unified state-wide layer as input. The material geological descriptions are presented in **Table 4**. GZA classified the soils into three main categories:

- granular soils with frictional angle (ϕ) as the soil strength parameter;
- cohesive soils with undrained shear strength (s_u) as the soil strength parameter;
- rock – weathered or intact bedrock (not modeled at this stage).

For each soil type (granular or cohesive), GZA divided them into three subgroups, with simplified, representative soil strength properties based on engineering judgment and local knowledge, as presented in **Table 5**. For example, G1, a granular soil with the lowest frictional angle, represents silty sandy materials with relatively low density, whereas G3, with the highest frictional angle, represents gravelly materials or dense sandy soils, such as glacial till. Fine-grained glaciomarine deposits were largely classified as C1, a cohesive soil with very low shear strength (or cohesion value).

Two groundwater conditions (as shown in **Figure 2**) were assumed to represent:

- relatively <u>dry</u> condition with a groundwater table approximately 10 feet below ground surface; and

- relatively wet condition with a groundwater table approximately 3 feet at crest of the slope and exiting the ground surface at the slope toe.

Dry and wet groundwater conditions can be a result of various factors such as precipitation, material types, slope aspect and curvature, local hydrologic setting and seasonal variations. Simulated SLOPE/W results are summarized in **Table 6**. Critical Factor of Safety (FoS) values from the critical slip surface are presented in the table, which are the slip surface that produce the minimum FoS value of all the slip surfaces analyzed by the program in each simulation. In general, a shallower groundwater table tends to lower the FoS in granular soil slopes, whereas the difference is less noticeable in cohesive soils. FoS values are positively correlated with increasing soil strength parameters (**Table 6**). Please note that the predicted FoS values appear to be conservative, when compared to a rule-of-thumb number that a Geotechnical engineer may use. Contributing factors to the overall conservative FoS results include:

- Large size of the slope modeled: the slope is 100 feet long in horizontal distance, which leads to a tall slope when the slope angle is large;
- Deep seated slip surfaces: critical slip surfaces appeared to be deeper than commonly observed, partially due to the size of the slope modeled;
- High groundwater: the slope is essentially saturated in the model, which increases instability for granular soils;
- Stabilizing factors not considered such as suction (i.e., negative pore pressure) in fine-grained materials;

Figure 4 presents an example SLOPE/W geometry used for this study. GZA selected a slope size of 100 feet in horizontal distance from crest to toe. A separate sensitivity analysis indicates that shorter slopes tend to produce larger FoS values with the same input parameters. Therefore, using 100-foot wide slopes in modeling is judged conservative for this study. **Figure 5** presents the SLOPE/W simulation results for the granular soils and **Figure 6** presents the results for the cohesive soils. These curves can be viewed as discrete slices from a 4-dimensional (response) surface, with the response being the factor of safety and the variables being the slope angle, material type and ground conditions. **Figure 7** presents interpolated and extrapolated results for next steps to estimate a FoS value for each grid cell based on its slope in percent (%) up to 120% (steeper slopes will be defaulted to this value). Natural soil slopes, regardless of material types or geometry, becomes inherently unstable when the slope exceeds 100% (i.e., 1-to-1 slope), consistent with our modeling results and general knowledge. Additional material types and/or parameters can be incorporated in the model when needed, under the modular structure of the overall approach. The curves in **Figure 7** are smooth, consistent with the modeled results.

Note that multi-layered geometry is beyond the scope of this screening level analysis. Stratigraphy should be considered for site-specific slope stability studies and engineering design.

Preliminarily, GZA proposed to use the following slope stability hazard index system based on calculated FoS values:

FoS	**Hazard Designation**	**Color Coding**		**Remarks**
>= 1.5	Very Low	Deep Green		Significant destabilizing factors needed to initiate failure
1.3 – 1.5	Low	Green		Moderate destabilizing factors needed to initiate failure
1.1 – 1.3	Moderate	Yellow		Minor destabilizing factors needed to initiate failure
0.9 – 1.1	High	Orange		Stabilizing factors required to prevent failure
< 0.9	Very High	Red		Significant stabilizing factors required to prevent failure

The "Remarks" column was added to highlight possible influence of stabilizing or destabilizing factors.

3.3 GIS MAPPING OF SLOPE STABILITY AND EROSION HAZARD INDEX

GZA assembled the following list of fields to determine the hazard indices for roadway-impacting slopes:

- Easting (X) and Northing (Y) in universal transverse mercator (UTM) zone 19 north (19N) coordinate system;
- Grid cell elevation, slope, aspect and curvature;
- MGS 250k surficial material type;
- NRCS land cover type;
- Roadway surface elevation and roadway segment aspect;
- Distances from grid cell to the nearest roadway segment, hydrographic feature and culvert; and
- FEMA special flood hazard area designations (flood zones and base flood elevation (BFE), if available);

Computations were performed using Python scripts and output results were included in the NETC 19-2 Project Viewer (ESRI ArcGIS web mapping application[3]) developed by GZA and could be displayed as various map layers/attributes.

Selected preliminary output generated in ESRI's ArcMap is shown in **Figure 8**. The hazard presented is generally driven by slope instability. The selected test area is along Route 136 (near Androscoggin River), Auburn, ME. Five hundred (500) feet each side of the road was used as the spatial filter for potential road impact screening zone for slope and erosion hazards. Note that the calculated hazard index value increases with the estimated hazard level. **Figure 9** presents selected key parameters for two representative locations (as shown in **Figure 8**). Pt 1 is located near the bottom of the embankment slope next to the Androscoggin River, with a slope of 117%, which means the natural slope at the toe exceeds one horizontal to one vertical. Pt 2 is located on the other side of the road on a relatively flat parcel, with a gentle slope of 3%. The soil type was the same for both, classified as "201", the weakest cohesive material in this study. The computed factors of safety for slope stability are 0.1 and 2.6 for Pt1 and Pt2, respectively. The Hazard Index for Pt 1 and Pt2 was calculated to be 5 and 1, respectively. As a result, the map in Figure 8 shows a strip of red color along the river bank and large patches of green color on the other side of the road. **Figure 10** presents a close-up view of a pre-existing gully-like feature, where the predicted hazard indices are fairly high. In addition, red shading along the support slopes west of the road also indicates some potential slope instability issues in this area.

Figure 11 presents the areas (in red) that are within 50 feet of hydrographic features such as streams and other surface water bodies. **Figure 12** presents the areas (in magenta) that are within 100 feet of existing culverts. There is some overlapping information between the two plots. It also appears that the existing culvert layer only contains culverts along Route 136 for this example study area.

Figure 13 presents FEMA Special Flood Hazard Areas (in red). FEMA flood zone, proximity to water (hydrographic features such as stream or pond), and proximity to culvert are presented as individual layers as Boolean numbers. GZA proposed to use 100 feet for flagging due to proximity to these types of features. These layers were included in the NETC 19-2 Project Viewer.

3.4 ANALYSIS AND MODELING SUMMARY

GZA's general modeling approach and selected preliminary results of the modeling task are summarized in this section. GZA categorized slopes using key input parameters and used SLOPE/W to quantify soil slope stability hazard levels

[3] Transferrable to other external sites when needed, e.g., MaineDOT's server.

based on factors of safety numerically. The computed factor of safety results are overall conservative due to the simplified approach, assumptions, and conservative input parameters adopted. They are probably lower bound values. We understand that the objective of this study is to identify high hazard slope-failure prone areas and GZA's results will serve as a basis for a high-level hazard screening tool. The presented FoS results are not intended to be adopted for direct use for any specific site. The results should be viewed as approximate accurate to the order of magnitude. Other hazard factors such as flood and wave impacts are adopted as qualitative flags. The web-based viewer (i.e., the NETC 19-2 Project Viewer) developed for this project was interactive and allowed users to selectively display various results regarding slope stability and erosion for a given/selected area or point of interest.

4.0 GROUND TRUTHING AND MONITORING

GZA performed slope stability and erosion modeling under Task 2 of this project. GZA adopted an analytical method similar to the Response Surface method widely adopted by U.S. Army Corps of Engineers (USACE) and FEMA for their coastal storm surge flood studies. GZA used key input parameters (such as surficial geology and topography) that affect slope stability, performed numerical slope stability analysis using representative geotechnical material properties and groundwater conditions, and established an interpolation and extrapolation scheme for scenarios that are not directly modeled. High resolution (3 m x 3 m) digital terrain model (DTM) data was used.

For this "Ground Truthing" task, GZA applied field data and engineering experience from past GZA projects at a number of selected "test sites" to verify and validate the modeled slope stability results. In addition, landslide susceptibility maps produced by MGS were compared to our modeled results as part of the verification and validation process.

4.1 METHODOLOGY

GZA selected a number of "test sites" based on the following criteria:

- Known past slope failure or stability issues;
- Proximity to water bodies (river or ocean);
- Availability of site-specific subsurface exploration geotechnical information;
- Past project experience combined with local knowledge; and
- Coverage of both soil types, cohesive and granular.

Figure 14 presents a location map of the two towns selected, Auburn and Kennebunk, Maine. The following color scale (below) was used for Figures 14 through 26.

Map Color [4]Code	Predicted Stability Zone	Relative Hazard Index Ranking	Estimated Factor of Safety (FoS)	Probability of Instability	Possible Influence of Stabilizing or Destabilizing Factors
(red)	Unstable	Very High (5)	<0.9	90%	Stabilizing factors required to achieve/maintain stability
(orange)	Threshold of instability	High (4)	0.9 – 1.1	>50%	
(yellow)	Nominally stable	Moderate (3)	1.1 – 1.3	10%	Minor destabilizing factors needed to cause failure
(light green)	Moderately stable	Low (2)	1.3 – 1.5	--	Moderate destabilizing factors needed to cause failure
(dark green / blue)	Stable	Very Low (1)	>1.5	--	Significant destabilizing factors needed to cause failure

4.2 GROUND TRUTHING RESULTS AND FINDINGS

4.2.1 Auburn, Maine

The City of Auburn was selected due to its proximity to Lake Auburn and Androscoggin River with varying terrain and land cover types. The surficial material type in Auburn is locally referred to as the Presumpscot Deposit. It consists largely of soft clay, classified by GZA as "C1"[5] characterized as having undrained shear strength of 350 pounds per square foot (psf), with lesser layers of marine deltaic sands and silts. The Presumpscot Deposit is also the source of many if not most Maine landslides. GZA was involved with a previous roadside embankment slope project along Route 136 in 2010. Some natural failures had occurred due to oversteepening of the riverbank adjacent to the roadway. However, the major failure that GZA provided geotechnical services for was triggered by installation of steel sheet piles during proposed reconfiguration of the slope. **Figure 15** presents the predicted slope failure hazard indices along Route 136, adjacent to Androscoggin River. The calculation was based on a LiDAR[6] dataset dated 2009, prior to the major failure incident in Summer 2010. It is clear that the modeled results were able to capture the low factor of safety values at the toe of the slope, which led to predicted high hazard level (red dots). **Figure 16** presents two representative photographs from the site, post-failure and post-construction.

Figure 17 presents high hazard areas along Jordan School Road, largely due to low soil shear strength (soft clay) and steep slopes. GZA confirmed that the predicted instability patterns closely match steeper areas in the shaded topographic relief in the area. These features represent typical steep-sided erosional gullies commonly found cutting into the Presumpscot deposits in Maine. Note that GZA's results may have overestimated the slope instability/landslide hazard due to the overall conservative approach we adopted (e.g., conservative soil strength parameters and the 250K surficial material layer).

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[4] Very Low = Green in Auburn; Blue in Kennebunk
[5] Refer to Table 3-1 for soil classifications.
[6] Light Detection and Ranging (LiDAR)

4.2.2 Kennebunk, Maine

Kennebunk was selected due to its proximity to Kennebunk River, Mousam River, and the Maine coastline. GZA's local knowledge, past project experiences and availability of MGS previously published landslide susceptibility map are all contributing factors for using this area as the ground truthing sites.

4.2.2.1 Downtown

Figure 18 presents the calculated hazard index in the downtown area of Kennebunk. The model results highlight unstable areas along Mousam River, typically riverbanks over-steepened by toe erosion and sloughing and slumping of sand and clay deposits. Many developed areas at the tops of slopes are being encroached on by unstable slopes including a residential neighborhood were identified in the results (as noted on the figure). The Route 1 over Mousam River bridge abutment areas were found to be unstable in prior GZA evaluations and were detected in the model due to steep slopes. These slopes are now constructed of engineered riprap material able to withstand the steep slope angles.

4.2.2.2 North Street / Reid Lane (near Cape Arundel Golf Course, Kennebunkport)

Figure 19 presents predicted unstable areas concurrent with erosional gullies along North Street (similar to the Auburn site), in an area with known slope "sloughing" issues in the past. Same as other highlighted areas in Kennebunk, the underlying cause is the presence of Presumpscot Deposit (or as previously described) and steep terrain.

4.2.2.3 Coastal Marsh/Estuary

The modeled results also identified areas where coastal erosion is apparent based on existing topography and slopes such as near the Kennebunk River mouth area (at the confluence with the Atlantic Ocean), as shown in **Figure 20**. The orange/red pixels highlight drainage channels that are actively eroding and forming the gullied terrain previously described. The area known as Great Hill at the oceanfront of the river mouth is highlighted due to the steep slopes adjacent to the water, even though the area is mapped as dense sand/grave/silt glacial till deposits. By observation, this area has been stabilized repeatedly with a combination of riprap and stone-filled gabion mattresses and continues to actively erode and experience surficial sloughing failures. Note that the hazard index model does not directly consider flood effects such as elevated water levels, waves and resultant erosion. FEMA flood hazard zones will be included in the toolkit as a reference layer.

4.2.2.4 U.S. Route 1/State Route 9 Intersection

Figure 21 presents some apparent instability issues in this area due to manmade structures. For instance, steep embankment along an existing railroad is highlighted as unstable due to its slopes up to 1.5H:1V[7] (67% in slope value) over a mapped cohesive deposit. The surficial material types used in the model do not have the adequate resolution to detect manmade (and typically engineered for stability) embankment fills. The roadside slopes along Route 1 at the railroad crossing are also steep with slopes up to 2H:1V (approximately 50%). This type of embankment and/or manmade slopes is highlighted due to steep terrain (slope values) used as the input parameter. Areas highlighted in orange/red are often associated with the weak cohesive foundation soil type (C1). However, if these embankments were engineered and have been in service for some time, we anticipate that the hazards of instability would be low here at the present, if properly maintained and closely monitored. The figure also shows lower hazard areas in blue/green colors, most frequently due to lesser slope angles and more competent medium dense granular deposits (G2) as the foundation soils. This area highlights the fact that the soil types and strength parameters play a key role in determining the estimated hazard levels by this analytical model.

[7] H:V stands for the ratio between horizontal distance and vertical height difference.

4.2.2.5 Interstate I-95

Similar to the scenarios presented in **Figure 21**, manmade features (including overpass bridge ramps and railroad embankments) stand out as potentially unstable areas based on the modeling results, as shown in **Figure 22**. Granular deposits mostly are mapped as low or very hazard areas.

4.3 COMPARISON WITH MGS LANDSLIDE SUSCEPTIBILITY MAP – KENNEBUNK, MAINE

According to Maine Geological Survey[8], "landslides are one of the most common geologic hazards in Maine, causing damage in both rural and urban areas of the state." What many of the documented landslide incidents had in common was that they occurred in areas underlain by a glaciomarine clay and stratified sand deposit called the Presumpscot Formation, and usually occurred in areas with steep slopes. Rainfall is one of the common triggering factors, in combination with poor drainage. The Presumpscot Formation is a widespread blanket of glaciomarine silt, clay, and sand that covers much of coastal Maine and inland lowlands and has proven to be highly susceptible to slope failure. The MGS produced a series of Landslide Susceptibility Maps for areas in Maine. The maps focused on areas underlain by glaciomarine deposits, and in particular, the marine clay of the Presumpscot Formation.

MGS use the following two categories of risk factors in the study, including:

- Geomorphic Risk Factors (such as slope, curvature, aspect, and slope height); and
- Soil properties (such as surficial geologic materials).

The map used for NETC 19-2 Task 3 is titled "Landslide Sites and Areas of Landslide Susceptibility, Town of Kennebunk, Maine" dated 2009 (Open File No. 09-28). GZA converted this PDF map to a jpeg file and used features such as roads and town lines to georeference the map in GIS so it could be compared to model results. Please note that this series of MGS maps were reviewed as part of Task 1 (Literature Review) and referenced in Section 2.0 and Tables 1 – 3.

Figure 23 presents an image where MGS mapping results and NETC 19-2 modeling results are overlaid on top of each other for comparison. Our study results have a focus on existing roadways, whereas MGS results cover the entire land area. There is, overall, agreement between the MGS predictions and NETC 19-2 modeling results, in terms of where high hazard areas are located (darker/warmer colors). It is apparent that the NETC 19-2 modeling results are significantly higher in resolution (green to red scale), compared to the MGS mapped color blocks (yellow to dark brown color scale; refer to MGS map legend). The MGS results appear to have predicted more "high hazard" areas than this study. GZA's results seems to match the underlying terrain and manmade features more accurately than MGS land-based mapping results, mostly because of the fine resolution (3-meter by 3-meter) and the use of generalized rotational stability analyses as the basis for the current model.

Figure 24 indicates that the NETC 19-2 modeling results are more capable of detecting more detailed potential failure features in general, even if the terrain is generally very gently sloping in the coastal areas. **Figure 25** seems to indicate that the MGS mapping results are strongly correlated with existing water courses, such that predicted high hazard areas closely follow streams alignments. **Figure 26** confirms the same observations described above. Please note the excellent agreement between the two sets of mapping results in the residential area (**Figure 26**). MGS did not predict small/discrete potential failure locations due to the lower resolution of the input terrain data. The NETC 19-2 modeling results identified various small potentially unstable areas especially along roadways.

[8] Landslide Susceptibility Mapping in Maine, Maine Geological Survey, 2010 (available at the Maine Geological Survey Publications site https://digitalmaine.com/mgs_publications/453/)

Note that the ESRI aerial imagery was used as a background as a visual reference (with the MGS map set to 50% transparency).

4.4 ADDITIONAL HAZARD FLAGS

Please note that Figures 11 through 13 presented in Section 3 of this report also presented additional layers that highlight erosion hazards due to proximity to water body, culverts and FEMA mapped flood zones. Those are not repeated in this Section.

4.5 GROUND TRUTHING AND MONITORING SUMMARY

This section presents GZA's ground truthing methodology and results. GZA selected a few areas in Auburn and Kennebunk, Maine as the ground truthing sites. Key findings include:

- The modeling results were able to identify potential failure or high hazard zones based on the selected input parameters (such as topography and surficial geology). The predicted high hazard areas appear to be accurate, compared to historical failures and/or field observations.
- Steep riverbanks (especially at the toe of slope) are often identified as high hazard areas.
- Steep manmade fill slopes such as bridge abutments and roadway fill embankments are often overly mapped due to weak foundation soils (according to the surficial geological data). When this occurs, the areas are detected as potential unstable areas. In many cases these embankments are engineered using stronger materials than the model detects because the surficial maps in Maine typically don't identify artificial fill and the actual hazard of instability is low (i.e., this model produces false positives for certain areas/structures/terrain features).
- Manmade cut slopes adjacent to highways typically consist of the mapped soil type. Consequently, the NETC 19-2 modeling results are expected to be in good agreement there.
- Gullies formed due to long-term "sloughing" (sand / silt / soft cohesive deposits shearing and moving down slope due to changes in moisture and gravity) are apparent from the modeling results.
- The modeling results are also capable of detecting detailed erosion features in flat coastal marsh areas, which conceivably experience regular tidal and/or flood conditions.
- The NETC 19-2 modeling results are in good agreement with the MGS landslide susceptibility mapping results, in terms of overall spatial distribution of the predicted high hazard zones. The results from this study are much finer in resolution and detected more discrete, high hazard areas at various locations, especially along transportation corridors. The MGS results highlight larger areas of landslide susceptibility zones, showing a strong spatial distribution pattern along existing rivers and streams.
- GZA's results are reasonably conservative. For certain areas, the slope instability/landslide hazard may have been overrepresented (i.e., false positives). Our modeling approach adopts conservative assumptions and generic input parameters. The model was refined during the toolkit development phase (Task 4), which is summarized in the next section.

5.0 TOOLKIT DEVELOPMENT

GZA completed slope stability and erosion modeling under Task 2 of this project and applied field data and engineering experience from past GZA projects at a number of selected "test sites" to verify and validate the modeled slope stability results under Task 3.

5.1 METHODOLOGY

For Task 4 (Toolkit Development), GZA selected Aroostook County as the first pilot site, largely due to its low roadway density overall which requires less computational power to generate GIS data layers. Similarly, York County was added to the test county list due to its small footprint. **Figure 27** presents a location map of Aroostook and York Counties on GZA's NETC 19-2 Project Viewer. Example map views from the preliminary toolkit were generated from either York or Aroostook County for this document.

5.2 TOOLKIT DEVELOPMENT PROCESS

In general, GZA started processing data layers by downloading the data from various publicly available sources such as U.S. Geologic Survey (USGS) and Maine Department of Transportation (MaineDOT). Using ESRI ArcMap, data was then clipped to separate sets based on Maine county boundaries for easier data management and processing. GZA developed tools using ESRI ModelBuilder for spatial data analysis/processing. Models will be available to MaineDOT upon completion of this project as part of the technology transfer per project requirement.

GZA produced a total of nine (9) results layers for the toolkit / data viewer. Results are processed and saved in raster format. The base geospatial data is the 300-foot buffer zone from the road features contained in the MaineDOT public roads centerline feature class, as shown in **Figure 28**, based on the assumption that slope instability or erosion beyond 300 feet from the roads has a less significant impact on roadway traffic and safety. Interim layers (also included and presented in the toolkit) served as the necessary input for others. Layers below are presented in the order of our overall workflow.

1. Proximity to Surface Water

To identify and screen erosion hazards due to flooding, such as high water levels, water currents, wave impacts, etc., proximity to surface water was generated as a results layer. The surface water layer used for this analysis was the National Hydrography Dataset (NHD) from USGS. The USGS manages surface water and hydrologic unit mapping for the Nation as geospatial datasets. Of the three main types of surface water features GZA used two for this project:

- NHD Line Features, which represent streams (e.g., mainly rivers and brooks, also including pipeline and canal/ditch);
- NHD Polygon (area/waterbody) Features, which represent surface water bodies (e.g., lakes and ponds, including swamp/marsh, reservoir, etc.);

Point features in the NHD (such as stream gage locations) were not used for this study. **Figure 29** presents the ArcMap ModelBuilder Flow Chart, which highlights the key steps of the geoprocessing model. One-hundred-feet was selected as the screening criteria. As a result, the proximity to surface water layer represents areas that are within 100 feet from water sources (such as perennial streams, ponds, and lakes), as shown in the example image in **Figure 30**.

2. Proximity to Culvert

This layer is to identify potential hazard areas that are prone to erosion and/or wash-out hazard due to the presence of existing culverts, which is a common cause for roadway damage and traffic disruption in Maine following heavy rainfall events. GZA used two MaineDOT sources for this step: (a) cross culverts; and (b) large culverts. Note that the cross culvert data set contains more objects than the large culvert layer. Similar to the proximity to surface water layer, 100-feet was used as the screening criteria. Both culvert types are Point Features in the source format, which leads to circular areas after performing the buffer operation in ArcGIS. As a result, highlighted areas for this layer represent areas that are prone to flooding or high-flow conditions around the culvert locations. **Figure 31** presents the model builder used for performing this step. **Figure 32** presents the calculated results viewable inside the NETC 19-2 Project Viewer.

3. Proximity to FEMA's Special Flood Hazard Areas

Special Flood Hazard Areas (SFHA) are defined as the area that will be inundated by the flood event having a 1-percent chance of being equaled or exceeded in any given year, commonly referred to as the 1% annual chance floodplain (or formerly known as the 100-year floodplain). SFHAs fall under FEMA's jurisdiction. Flood hazards are inherently high within SFHAs. GZA highlighted areas within the 300-feet roadway buffer zone (i.e., the study area) if intersecting with FEMA's mapped SFHAs.

Figure 33 presents the data processing model in ModelBuilder. **Figure 34** presents the identified FEMA 1% annual chance flood zones in the NETC 19-2 Project Viewer.

4. Slope Types

Slope type is one of the factors for slope stability considerations. In this study, we grouped terrain cells along the roads into two categories:

- Support slope, where the elevation of the roadside cell is lower than the nearest roadway elevation (i.e., acting as a support to the roadway embankment structure); and
- Source slope, where the elevation of the roadside cell is higher than the nearest roadway elevation (i.e., when the slope fails or gets eroded, it is the source of fallen materials).

The nearest roadway cell was determined using Euclidian distance. **Figure 35** presents the flowchart in ModelBuilder for developing this data layer. **Figure 36** presents a sample view in the NETC 19-2 Project Viewer.

5. Relative Aspect

GZA recognizes that absolute aspect (slope direction) plays an important role in slope stability, such as surficial sloughing due to freezing and thawing on south facing slopes. For this particular layer, we calculated a relative aspect to determine the relationship between the adjacent slope cells and the nearest roadway segment. Calculations were performed based on the absolute value of their relative aspects:

- Azimuth values for the terrain cells nearest to the MaineDOT public road centerlines were included in the source terrain dataset. Euclidian distance was used for determining the nearest roadway segment for a given terrain cell.
- Azimuth values for the roadway centerlines were calculated in ArcGIS using an azimuth geometry calculation.

- If the acute angle[9] between the nearest roadway centerline and a given slope terrain cell is less than 22.5 degrees (°), we consider the slope as a Parallel Slope to the roadway which typically represents a lower hazard of impacting the roadway safety.
- If the acute angle[10] is greater than 22.5°, the cell is classified as a Perpendicular Slope, which is more likely to impact the roadway structure and safety. **Figure 37** presents the workflow in ModelBuilder. **Figure 38** presents a sample output in the NETC 19-2 Project Viewer.

6. Geotechnical Material Types

GZA grouped and assigned material types with geotechnical properties based on geologic unit descriptions provided on the 250k surficial geology maps published by the MGS and engineering judgment (see Section 3.0 for details). The data processing task for this step is illustrated in **Figure 39**. **Figure 40** presents a sample output with the two main classes of materials: granular and cohesive soils.

7. Factor of Safety

Factor of Safety (FoS) for each terrain cell within the study area is calculated using a lookup table based on Material Type and Slope Value (in percent) in ArcGIS (i.e., "Raster Calculator" module in **Figure 41**). **Figure 42** presents the results view in the NETC 19-2 Project Viewer.

8. Slope Hazard Index

The hazard index layer is a direct translation from the calculated FoS dataset. **Figure 43** and **Figure 44** present the ArcGIS processing workflow and the results layer in the NETC 19-2 Project Viewer, respectively. Warmer colors indicate a greater likelihood for slope failure (including landslide).

9. Culvert Hazard Index

The MaineDOT Cross Culvert dataset contains a large number of attributes, including location. GZA used two key attributes from the MaineDOT Cross Culvert dataset, roadway priority and culvert condition, to assign a hazard index value (low, medium, and high) to each structure. There are a total of six priority values in the dataset, 1 through 6. For example, GZA considered 1 and 2 as high priority roads. There are a total of 4 descriptions for culvert conditions, critical, poor, fair, and good. Note that there are a number of culverts assigned with "unknown" conditions.

- High Hazard: "critical" or "poor" structural conditions crossing roads with high roadway priority, 1 or 2 (i.e., culverts in poor conditions for high priority roads);
- Low Hazard: "good" structural conditions crossing roads with relatively low priority, 4, 5, or 6 (i.e., culverts in good conditions for low priority roads);
- Medium Hazard: in between the High and Low categories (e.g., culverts in "fair" or "good" conditions for high priority roads (1 and 2); and culverts in critical, poor, or fair conditions for low priority roads (3 through 6). All culverts with "unknown" conditions fall within this category.

Figure 45 and **Figure 46** present the ArcGIS processing tool and the results layer in the NETC 19-2 Project Viewer, respectively.

[9] Absolute value between 0° and +22.5° or 157.5° and 180°.
[10] Absolute value between 22.5° and 157.5°

5.3 TOOLKIT DEVELOPMENT SUMMARY

GZA processed results for Aroostook and York Counties and provided access to the NETC 19-2 Project Viewer for the NETC 19-2 Technical Committee members to review the results and provide feedback. A Quick Start Guide was drafted and supplied to NETC 19-2 Technical Committee members to aid them with using the NETC 19-2 Project Viewer. Only minor feedback regarding the use and functionality of the NETC 19-2 Project Viewer were received from members of the NETC 19-2 Technical Committee.

6.0 TOOLKIT REFINEMENT

6.1 TOOLKIT REFINEMENT METHODOLOGY

For Task 5 (Toolkit Refinement), GZA completed processing results layers for all of the Maine counties. GZA made adjustments to the ArcGIS models to handle the variability in the source data for different counties due to geographic size and roadway complexity. GZA processed cross culvert hazard index data based on roadway priority rating and culvert structural conditions, which is a descriptive parameter included in the MaineDOT's inventory.

6.2 TOOLKIT REFINEMENT PROCESS

GZA performed an additional calculation to transcribe terrain-based hazard data to roadway-based risk information as an experiment for potential future improvements. As we understand, it will be beneficial to users if the information contained in the Toolkit is directly associated with roadway segments, which the MaineDOT has already developed. Planning and operation tasks may be easier to perform over roadway segments than the terrain-based data, using direct sorting and filtering functions in GIS, per GZA's current thinking.

Figure 47 presents GZA's experiment at an example intersection. The calculated hazard index data within the 300-foot (') buffer was further clipped down to a 100' wide buffer around the roadway centerline, which GZA considers to be the direct impactful zone to roadway function and safety. The embedded table in **Figure 47** presents the input and output data from the calculation. A total of 9 different segments were involved at this intersection for this example. The road segments vary in length and roadway priority. The land-based hazard index is shown in color, where red denotes the highest hazard category and green denotes the lowest hazard category (consistent with the color scale used in the Toolkit). Standard statistical calculations were performed using ArcGIS's built-in statistics functions and are summarized in the table.

Using Segment No. 8 (Interstate 95 Southbound) as an example, it is apparent that the embankment slope is quite steep and/or the in-situ geologic materials are relatively weak in strength, with large patches of red areas around this particular intersection. However, due to its long segment length, this segment is also surrounded by green cells away from the intersection. As a result, the calculated mean of the hazard index turned out to be relatively low, around 1.8, with a median of 1.0 (as opposed to a value of 4 as we intuitively expected). Sum of the mean and one standard deviation for Segment Nos 3 and 8 surpassed a value of 3.0, which is considered to be a median hazard level and considering this is a Priority Level 1 roadway segment (I-95), we could potentially assign a high risk index (for instance, 5) to this particular roadway segment – if we were to define such a rating system. This is apparently due to the fact that these two segments are adjacent to highly hazardous areas along the roadway segments. However, GZA would need to further refine the calculation by reviewing the statistical distributions to test if additional parameters need to be calculated to make a conclusion before using these descriptive statistics. One thought for future improvement of this approach is that the roadway segments from the MaineDOT inventory will probably need to be further refined to

300- or 500-foot-long segments such that calculated high hazard index results will be more concentrated on problematic areas, without being "diluted" by low hazard zones along a long stretch of a roadway segment. The web application could be further developed to allow the user to specify a roadway segment for analysis and the refined results may be generated upon request through built-in functions and/or widgets. For a future model like this, we conceptually envision that different roadway segments would be assigned with different colors denoting various hazard/risk indices, based on detailed calculations. A database like that could be sorted and filtered based on various parameters, such as spatial extent, highway priority ranking, hazard index, etc. The project goal is to identify potential risks to roadway safety and function. When a small, localized high hazard area fails, it can take part of or the entire section out of service.

Note that the calculation presented in **Figure 47** is an example. GZA did not expand the same calculation to any of the Toolkit county-level data layers.

6.3 TOOLKIT REFINEMENT SUMMARY

Feedback on the interim toolkit, which was shared with the Committee starting July 2021, was limited to an issue with the NETC 19-2 Project Viewer Elevation Profile widget that was demonstrated at the June 17, 2021, Technical Committee meeting. The Elevation Profile widget did not work for individuals outside GZA's internal network. The Elevation Profile widget is available from the ArcGIS Application Builder widget library and can be integrated with mapping applications developed on the ArcGIS platform.

GZA made necessary refinements and adjustments to our processing models and produced data layers for other counties besides York and Aroostook. Other refinements include the addition of a tool that allows the user to display the information associated with each cell in the model results layer. The tool displays information such as soil type, slope, and aspect for use in more detailed assessment of specific locations. Upon completion, GZA transferred data layers for all the Maine counties via a portable storage drive due to the large size of the statewide dataset. GZA anticipates that the MaineDOT GIS technical team will integrate the results onto the existing MaineDOT web-based mapping viewer.

7.0 SUMMARY AND CONCLUSIONS

This erosion and slope stability modeling toolkit is intended to serve as a screening tool for MaineDOT for operation and planning purposes. The high resolution of the source data and results layers made it possible for roadway segment-level assessment. Key take-aways of the study include:

- The study area was set to be a 300-foot buffer zone from roadway centerlines in the MaineDOT public roadway inventory.
- The toolkit congregates GIS source data from various agencies such as USGS, MGS, MaineDOT, FEMA, etc., which are considered relevant to this study.
- This screening tool allows easy navigation of a large area and screening for slope/erosion issues without performing complex numerical modeling or calculations.
- Key slope stability and erosion influencing factors are considered in the model including geology, topography, slope geometry, and proximity to various water conveying features such as culverts and surface water bodies.

- The toolkit highlights high hazard areas spatially in a GIS mapping platform so that areas require additional site-specific analysis can be easily identified. Similarly, the toolkit can be used for maintenance or repair planning.
- For erosion-prone areas, screening level assessment can be performed by turning on various results layers such as proximity to water, culverts, and FEMA Special Flood Hazard Areas.
- For areas with slope instability concerns, the hazard index layer provides a ranked system in terms of stability for terrain cells at 10 feet by 10 feet resolution, based on slope stability modeling results.
- Certain man-made structures such as steep bridge abutments or roadway embankments were captured as high hazard features. They can be screened out if the DOT has site- or project-specific information to support such a decision.
- The screening toolkit captures certain man-made structures such as bridge abutments and steep roadway embankments as high hazard features. For the Maine database, they can be screened out using the surficial geologic type “Artificial fill” where that layer is included on the MGS 1:24,000 surficial geology maps. This layer was added to the toolkit as a separate layer so it can be used to screen out fall positive “high hazards” identified by the screening toolkit. Similarly, where MaineDOT has developed their GIS “retaining walls” layer, it can be used to screen out fall positive “high hazards” identified by the screening toolkit. These screening tools can be developed on a state-by-state basis to incorporate the variable level of available GIS data.
- A high hazard index presented in the toolkit result layer does not mean this location is going to have a slope failure right away. It simply points out that this area has a relatively high potential of experiencing some kind of slope instability or erosion issue, compared with the surrounding areas.
- The prototype toolkit has a user-friendly ESRI GIS interface that allows users to conservatively assess vulnerabilities in the roadway systems in the State of Maine. Users such as the engineers, planners and maintenance personnel from state transportation agencies, municipal public works, and local and regional planners may identify at-risk roadway segments for use in emergency response planning, project planning, and maintenance and repair prioritization. The prototype was developed using available GIS base data layers that vary based on state, regional and national dataset availability. The model can be readily expanded to other states and regions due to the plug and play architecture of the framework.

8.0 PROPOSED FUTURE IMPROVEMENTS AND IMPLEMENTATION

The toolkit was developed by design as a modular geospatial software system utilizing Esri ArcGIS Enterprise and is highly adaptable to incorporate future modification. Opportunities for modification include:

- Compilation of the base data and development of the screening stability calculation for other states. This would require identification of the available state-wide base data sets, geotechnical material type categorizing of the surficial material types, and inputting the required data and parameters into the data processing model. The model relies heavily on the geotechnical interpretation of the surficial geology and must be catered to each state’s surficial geology mapping. The modular nature of the toolkit allows for integration with the mapping data available in each state.

- Incorporation of an Esri ArcGIS Dashboard for information access and management, such as could be used for roadway maintenance and planning.

- Incorporation of additional, layer modules for other natural hazard data (e.g., seismic, flood).

- Incorporation of real time monitoring and sensor data (such as slope displacement sensors).

- Incorporation of widgets for added functionality (e.g., printing and data export) and analysis capability.

9.0 REFERENCES

Huang et al., 2020. "Comparisons of heuristic, general statistical and machine learning models for landslide susceptibility prediction and mapping", CATENA (Elsevier), Vol 191. https://doi.org/10.1016/j.catena.2020.104580

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Ruff and Czurda, 2008. "Landslide susceptibility analysis with a heuristic approach in the Eastern Alps (Vorarlberg, Austria), Geomorphology 94(3): 314-324.

Stanley and Kirschbaun, 2017. "A heuristic approach to global landslide susceptibility mapping", Natural Hazards (Springer), 87:145-164. DOI 10.1007/s11069-017-2757-y.

TABLES

Table 1: Summary of Literature Search on Design Guidance Documents

Category	Content Summary	Reference
Guidance Document	This circular outlines the key elements of a comprehensive and effective national strategy for reducing losses from landslides nationwide and provides an assessment of the status, needs, and associated costs of this strategy. The framework envisions a society that is fully aware of landslide hazards and routinely takes action to reduce both the risks and costs associated with those hazards. The strategy envisions bringing together relevant scientific, engineering, construction, planning, and policy capabilities of the Nation to eliminate losses from landslides and other ground-failure hazards nationwide.	USGS, 2003. Circular 1244 "National Landslide Hazards Mitigation Strategy— A Framework for Loss Reduction".
Guidance Document	This handbook gives a brief overview of precautions and actions that can be adopted to at least ensure an individual's immediate safety. We strongly suggest that, where possible, the assistance of professional engineers/geologists or those experienced in the successful mitigation of unstable slopes be consulted before actions are taken. This handbook helps home-owners, community and emergency managers, and decisionmakers to take the positive step of encouraging awareness of available options and recourse in regard to landslide hazard.	USGS, 2008. Circular 1325 "The Landslide Handbook— A Guide to Understanding Landslides".
Design Guide	Slope Stability – Engineer Manual provides guidance for analyzing the static stability of slopes of earth and rock-fill dams, slopes of other types of embankments, excavated slopes, and natural slopes in soil and soft rock. The criteria in this EM are to be used with methods of stability analysis that satisfy all conditions of equilibrium.	USACE Engineering and Design EM 1110-2-1920, October 2003.
Design Guide	New England State DOT Highway Design Manuals/Standards	CTDOT, MaineDOT, MassDOT, RIDOT, NHDOT, and VTrans; dates vary.

Table 2: Summary of Literature Search on Examples and Modeling Approaches

Category	Content Summary	Reference
Example	This online ESRI web-based interactive map provides landslide sites at the national scale. The database provides centralized access to information about landslide occurrence and a starting point for the public, land managers, emergency planners and researchers interested in landslide hazards.	USGS, 2019. U.S. Landslide Inventory
Example	The Story Map is a website dedicated for providing information on historical landslides, causes of landslides in Maine, and other related information on landslides in Maine.	MGS, 2020. Landslides in Maine – An Introductory Guide.
Example	Vermont Landslides Inventory compiles various datasets including existing county-wide landslide inventories, Vermont Geological Survey surficial geologic maps and publications, and sites from Vermont Agency of Natural Resources Stream Geomorphic Assessment.	State of Vermont, 2020. "Vermont Open Geodata Portal"
Modeling Approach	This is the companion document for the story map (above). The purpose of this guide is to provide introductory information about the types of mass wasting that may occur in Maine and their causative factors.	MGS, 2020. "Maine Landslide Guide" by L. J. Spigel, Open file No. 20-9, March 2020
Modeling Approach	This map product presents landslide susceptibility/vulnerability based on terrain information, such as slope, curvature (shape) and local relief (slope height), and surficial material type (e.g., fine grained versus coarse grained soils).	MGS, 2009a. "Landslide Sites and Areas of Landslide Susceptibility, Town of Kennebunk, Maine", by Maine Geological Survey, Open File No. 09-28. MGS, 2009b. "Landslide Sites and Areas of Landslide Susceptibility, Town of Kittery, Maine", by Maine Geological Survey, Open File No. 09-30.
Modeling Approach	The New Hampshire Department of Transportation (NHDOT) now incorporates 380 rock cuts and four different Rock Fall Hazard Rating Systems, through Rock Cut Hazard Survey since 1975. This research project was initiated to investigate combining new rock cut data with pre-existing data into a Geographical Information System (GIS). Rock cut point features were collected for every rock cut with a Global Positioning System (GPS) and were added as a data layer on top of existing data coverage available through the Department's GIS server. A relational database was developed which would store all the rock cut data and be linked to the GIS through a structured query language (SQL) connect statement. Collected data included rock cut structural data, photographs, and two-dimensional profiles.	NHDOT, 2002. "GIS and the New Hampshire Rock Cut Management System" Final Report, New Hampshire DOT Research Record.

Category	Content Summary	Reference
Modeling Approach	This study developed and tested a protocol to map potential hazard areas to advance the state of landslide mapping and landslide hazard assessment in Vermont. Used seven site areas in an attempt to represent conditions throughout Vermont. As a bare-earth lidar digital elevation model (DEM) was envisioned as being a key part of any resulting protocol (and the distribution of lidar data in Vermont was more limited when this study was conceived) the study sites are mostly within Chittenden County. Other considerations in site area selection included map coverage, geology, elevation, types of terrain, urban disturbance, and types of landslides expected. Fourteen potential parameters were considered as to their effect on landslide hazard, including: location with respect to the marine limit of the Champlain Sea, aspect, distance to stream, elevation, hydrologic group, NDVI, profile curvature, roughness, slope angle, slope height, soil type, stream power index, surficial geology, and topographic wetness index.	Vermont Geological Survey, 2012. "Protocol for Identification of Areas Sensitive to Landslide Hazards in Vermont" prepared by Clift and Springton, University of Norwich.
Modeling Approach	The purpose of this project is to prepare an updated map of potential landslide hazards for the Commonwealth of Massachusetts. The intent is to provide the public, local government and local and state emergency management agencies with a map showing the location of areas where slope movements have occurred or may possibly occur in the future under the right conditions of prolonged antecedent moisture and high intensity rainfall. The information is useful for planning upgrades and improvements to culverts and drainage along roadways in the future. In additional to printable maps, data are also available as ESRI ArcGIS data files.	MEMA, 2013. "Slope Stability Map of Massachusetts" by UMass Geosciences.
Modeling Approach	This study is to develop an assessment of the risk posed to transportation networks in southern New Hampshire by slope failure, including parameters to assess slope failure risk; GIS raster calculations to assess slope failure risk for the area of interests, GIS raster calculations to assess slope failure hazard risk in regards to the transportation networks in the area of interest. Parameters include slope of the land surface; surficial geology characteristics, soil drainage and land cover.	Tufts, 2013. "Slope Failure Hazard Risk Assessment – An Analysis of the Hazard Risk Posed by Slope Failure to Transportation Networks in Southern New Hampshire" by Tufts University.
Modeling Approach	Washington Department of Natural Resource GIS Open Data – Slope Stability – provides a predictive data layer of shallow-rapid slope stability using one or more calibrated GIS-based models and covers all forested watersheds of western Washington State, to be a screening tool for determining shallow-rapid landslide potential. It is intended to be used for pre-classification screening of forest practices applications and screening for slope stability concerns on managed timberlands. This data layer is derived from calibrated	Washington DOT, 2018. "Washington Department of Natural Resource GIS Open Data – Slope Stability"

Category	Content Summary	Reference
	algorithms (models) that use DEMs to generate slope and curvature information.	
Modeling Approach	The intent is to provide the public, local government, and local and state emergency agencies with a description and location of areas where slope movements have occurred, or are likely to occur, and the general areas at risk from these slope movements. The map was produced using SINMAP (Stability Index MAPping) software, an ArcViewTM 3.x extension developed by Pack and others (1998) for use in a GIS. SINMAP then assigns a stability index based on computed factors of safety. The six stability zones are assigned relative hazard rankings (high, moderate, and low) based on the calculated stability index ranges and known slope movement occurrences. Model input parameters include upper and lower bounded values for recharge to the shallow groundwater system, soil transmissivity (soil permeability or hydraulic conductivity multiplied by soil thickness), and other soil properties (i.e., unit weight, thickness, effective internal friction angle, and effective cohesion). To account for the variability and uncertainty inherent within the natural system, SINMAP randomly samples the bounded input parameter values using a uniform probability distribution.	NCGS, 2011. "Stability Index Map of Henderson County, North Carolina for Shallow Translational Slope Movement Susceptibility during a 5-inch Recharge Event" by North Carolina Geological Survey.
Modeling Approach	This paper evaluated and compared the approaches of SINMAP, LISA, and Iverson's (2000) transient response model for slope stability analysis by applying each model to a historical landslide incident in Madison County, Virginia. Of these three stability models, Iverson's model would be the preferred method of the three models to evaluate landslide hazards on a regional scale in areas prone to rain-induced landslides as it considers both the transient and spatial response of pore pressure in its calculation of slope stability. The stability calculation used in SINMAP and LISA is similar and utilizes probability distribution functions for certain parameters. SINMAP only considers soil cohesion, internal friction angle and rainfall-rate distributions. LISA allows the use of distributed data for all parameters.	USGS, 2001. "A Comparative Analysis of Hazard Models for Predicting Debris Flows in Madison County, Virginia", by Meghan M. Morrissey, Gerald F. Wieczorek, and Benjamin A. Morgan, Open-File Report 01-0067, 2001.
Model	Landslide responses to rainfall involve transient processes with different intrinsic timescales. A new model of these transient processes links slope failure and landslide motion to groundwater pressure heads that change in response to rainfall. This paper tries to examine relationships between these timescales to develop a mathematical model that uses reduced forms of Richards equation to evaluate effects of rainfall infiltration on landslide occurrence, timing, depth, and acceleration in diverse situations. The model adds realism to current models that predict landsliding as a function of steady state hydrology with a minimum	Iverson, 2000. "Landslide Triggering by Infiltration", R. M. Iverson, Water Resources Research, Vol. 36, No. 7, 1897-1910, July 2000

Category	Content Summary	Reference
	of added data requirements. The model also provides information for assessing rates of postfailure landslide motion, thereby refining hazard forecasts. The model neglects important factors such as soil strength evolution (contractile strain weakening, dilatant strain hardening, and fabric development). It also neglects mechanical effects of three-dimensional landslide geometries.	
Model	SINMAP 2.0 (Stability Index MAPping) is an ArcGIS (9+) plug-in that implements the computation and mapping of a slope stability index based upon geographic information, primarily digital elevation data. SINMAP assumes an infinite plane slope stability model with wetness (pore pressures) obtained from a topographically based steady state model of hydrology. Digital elevation model (DEM) methods are used to obtain the necessary input information (slope and specific catchment area). Parameters are allowed to be uncertain following uniform distributions between specified limits. These may be adjusted (and calibrated) for geographic "calibration regions" based upon soil, vegetation or geologic data. The methodology includes an interactive visual calibration that adjusts parameters while referring to observed landslides. The calibration involves adjustment of parameters so that the stability map "captures" a high proportion of observed landslides in regions with low stability index, while minimizing the extent of low stability regions and consequent alienation of terrain to regions where landslides have not been observed. This calibration is done while simultaneously referring to the stability index map, a specific catchment area and slope plot (of landslide and non landslide points) where lines distinguish the zones categorized into the different stability classes and a table giving summary statistics. SINMAP is grid based, requiring ArcGIS version 9.0 or higher.	Pack et al., 2005. SINMAP User's Manual "SINMAP 2, A Stability Index Approach to Terrain Stability Hazard Mapping", R.T. Pack, D.G., Tarboton, C.N. Goodwin and A. Prasad (Utah State University).
Modeling Approach	Slope stability studies in the USDA Forest Service in accordance with a three-level concept: • Leve 1 – generally for watershed analysis, ecosystem management support, etc.; • Level 2 – intermediate level for evaluation of slope stability along road corridors and other routes; • Leve 3 – detailed (site-specific) level for design of stabilization measures. Use XSTABL interactive program for soil and Federal Highway Administration's rock slope stability analysis method for rock slopes.	United States Department of Agriculture (USDA), 1994. "Slope Stability Reference Guide for national Forests in the United States".
Modeling Approach	Physics-based combined with GIS-based approach for slope failure modeling; identified the following major causative factors: slope angle, soil type and geology; vegetation; land use and drainage density; antecedent precipitation/soil moisture; rainfall intensity and duration. Infinite slope approach used for simplicity for application in conjunction with GIS source data.	Barr, 2017. "Slope-Failure Risk Analysis Mapping | Pilot Project" for Minnesota's Local Road Research Board (LRRB) in 2017.

Category	Content Summary	Reference
Modeling Approach	Developed a GIS-based computer program (in ESRI's ArcGIS platform) for spatial infinite slope landslide hazard analysis, based on calculated factors of safety. Used an underlying probabilistic infinite slope analysis model which processes normally-distributed soil properties.	J. Sanders, 2017. "Developing a GIS Tool for Infinite Slope Stability Analysis (GIS-TISSA), Michigan Technological University MS Thesis.
Modeling Approach	Presented a landslides case study in Nepal. Developed a GIS tool which is able to calculate safety factor of the slopes within ArcGIS. Input included soil test data, geological distribution, hydrological information and topographical information with automated algorithm to estimate realistic slope instability coefficient. Prepared roadside maintenance priority map.	Bhattarai, et al. "Quantitative Slope Stability Mapping With ArcGIS: Prioritize Highway Maintenance", ESRI User Conference.
Modeling Approach	Developed and tested a GIS-based 3-D slope stability model in terms of computing time and model results. The model was developed as a C- and Python-based raster module of the open source software GRASS GIS and considers the 3-D geometry of the sliding surface. The model is able to calculate factor of safety and probability of slope failure for a number of randomly selected potential slip surfaces, ellipsoidal or truncated in shape. This is a deterministic-probabilistic model.	Mergili et al., 2014. "A strategy for GIS-based 3-D slope stability modelling over large areas", Geoscientific Model Development conference proceedings.
Modeling Approach	Presented an early warning system developed for Maryland, using a GIS database and a collective overlay of maps that highlight highway slopes susceptible to soil slides or slope failures in advance through spatial and statistical analysis. Considered six major factors, including event precipitation, geological formation, land cover, slope history, slope angle, and elevation. Precipitation and poor surface or subsurface drainage conditions are principal factors causing slope failures.	Ramandathan, et al., 2015. "Development of a GIS-based failure investigation system for highway soil slopes", Frontiers of Earth Science.

Table 3: Summary of Available GIS Data Inventory

Category	Content Summary	Reference / Source
Inventory	Landslide Hazards Program: - Debris flow hazards; - U.S. Landslide Inventory – web-based interactive map with landslide data. The searchable map includes contributions from many local, state, and federal agencies and provides links to the original digital inventory files for further information. - Earthquake-triggered ground failure	USGS landslide hazards
Inventory	Maine Landslide – landslide inventory	Maine Geological Survey
Inventory	New Hampshire Landslide Geodatabase	New Hampshire Geological Survey
Inventory	Vermont Landslides Inventory	State of Vermont, 2020. "Vermont Open Geodata Portal" with downloadable attribute data
Source Data	National Flood Hazard Layer	FEMA "Flood Insurance Rate Maps", date varies.
Source Data	National 3D Elevation Program	3DEP Data
Source Data	State-wide DOT Roadway Inventory (Maine, NH, VT, MA, RI and CT)	Available online (mostly through state GIS office); date varies;
Source Data	State-wide LiDAR (Maine, NH, VT, MA, RI and CT)	Available online (mostly through state GIS office); date varies;
Source Data	National precipitation frequency data	National Oceanic and Atmospheric Administration (NOAA) Atlas 14
Source Data	National soil information database	SSURGO data provided/served by the USDA-NRCS: 1. Vermont Center for Geographic Information (VCGI) 2. USDA / NRCS
Source Data	Global Landslide Catalog including (point data, polygons and csv files associated with the map data)	National Aeronautical and Space Administration (NASA) provides collated downloadable data
Source Data	Connecticut Erosion Susceptibility	Connecticut Department of Energy and Environmental Protection

Note: Table 3 lists key datasets that the model development likely requires. Additional data source will be identified and obtained during the modeling development process.

Table 4: GZA Classification for 1:250,000-Scale Surficial Geology Maps

Symbol	Geologic Unit	Materials	Topography	Origin	GZA Classification
a	Stream alluvium (includes Holocene flood plain, stream terrace, and alluvial fan deposits)	Sand, gravel, and silt.	Flat to gently sloping on flood plains and stream terraces; gently to moderately sloping on alluvial fans.	Deposited on flood plains and stream beds by postglacial streams.	G1
s	Swamp, marsh, and bog deposits (includes both fresh-water and salt-water marshes)	Peat, muck, clay, silt, and sand.	Flat.	Formed by accumulation of sediments and organic material in depressions and other poorly drained areas.	C1
b	Beach deposits	Sand and gravel.	Gently to moderately sloping, with low ridges and mounds.	Includes beach sediments formed by wave and current action, and sand dunes derived from these deposits.	G2
eb	Emerged beach deposits	Sand and gravel.	Low ridges or sloping surfaces. May be associated with wave-cut benches on hillsides.	Formed by wave erosion of till or other materials during the late-glacial marine submergence of parts of southern Maine.	G2
e	Eolian deposits	Sand.	Dune ridges and mounds, or blanket deposit that conforms to surface of underlying unit.	Windblown sand. Derived from wind erosion of glacial sediments and deposited in late-glacial to postglacial time.	G2
L	Lake-bottom deposits	Silt, clay, and sand. Commonly well stratified, and may be rhythmically bedded.	Flat to gently sloping except where dissected by modern streams.	Composed of sediments that washed out of late Wisconsinan glacial ice and accumulated on the floors of glacial lakes. Map unit may also include a few non-glacial lake deposits.	C2

Symbol	Geologic Unit	Materials	Topography	Origin	GZA Classification
m	Glaciomarine deposits (fine-grained facies)	Silt, clay, sand, and minor amounts of gravel. Commonly a clayey silt (the Presumpscot Formation). Sand is dominant in some places, but may be underlain by finer grained sediments. Locally fossiliferous. Map unit includes small areas of till and other units that are not completely covered by marine sediments.	Flat to gently sloping except where dissected by modern streams. Commonly has a branching network of steep-walled stream gullies.	Composed of glacial sediments that accumulated on the ocean floor. Formed during the late-glacial marine submergence of lowland areas in southern Maine.	C1
ms	Glaciomarine deposits (coarse-grained facies)	Sand, gravel, and minor amounts of silt.	Flat to moderately sloping. Steeper on ice-contact slopes and delta fronts. May be kettled where deposited over stagnant ice blocks.	Deposited where glacial meltwater streams and currents entered the sea. Includes glaciomarine deltas, subaqueous kames and fans (subaqueous outwash), and outwash that prograded into shallow marine waters and locally covered earlier glaciomarine silt and clay deposits.	G2
go	Glacial outwash deposits	Sand and gravel.	Flat to gently sloping. Steeper on ice-contact slopes and delta fronts. May be kettled where deposited over stagnant ice blocks.	Deposited by meltwater streams in front of the receding late Wisconsinan ice margin. Includes non-marine outwash plains, deltas, and fans.	G2
g	Ice-contact glaciofluvial deposits (exclusive of eskers)	Sand, gravel, and silt.	Flat-topped kame terraces and deltas which are locally kettled and bounded by steep sides, or hummocky terrain with numerous kames and kettles.	Deposited by meltwater streams adjacent to stagnant glacial ice.	G2

Symbol	Geologic Unit	Materials	Topography	Origin	GZA Classification
ge	Eskers	Gravel and sand. May include minor amounts of till. Portions of many eskers below the marine limit are partly or entirely buried by glaciomarine deposits.	Individual or multiple ridges. Complex eskers may have anastomosing patterns and be gradational with other types of ice-contact deposits.	Chiefly deposited by meltwater streams flowing in tunnels within or beneath the late Wisconsinan ice sheet. Map unit also includes small undifferentiated areas of units "g" and "go".	G3
sm	Stagnation moraine	Mostly till, but also includes variable percentages of undifferentiated sand and gravel.	Undulating topography with local hummocks and ridges.	Deposited during the dissipation of stagnant glacial ice.	G3
em	End moraines	Till or sand and gravel. May be very bouldery. Commonly interbedded with or overlain by glaciomarine sediments in areas that experienced late-glacial marine submergence. Only the largest end moraines and some dense clusters of smaller ones are shown here as a separate unit (em). Elsewhere, short lines mark the crests of moraine ridges, which are locally so numerous that only selected individuals are represented.	Ridges. Commonly arcuate, discontinuous, and in groups. May be multi-crested and hummocky. Size range: 1-30 m high, 5-200 m wide, and 30 m to over 10 km long.	Deposited in the marginal zone of the late Wisconsinan ice sheet, by glacial ice and/or meltwater flowing out of the ice.	G3
rm	Ribbed moraine	Till is the principal constituent, but stratified sediments are present in some of the deposits.	Numerous hummocks and short sub-parallel ridges which typically occur in lake basins and other lowland areas.	Origin uncertain. Deposited either at the margin of or beneath the late Wisconsinan ice sheet.	G3

Symbol	Geologic Unit	Materials	Topography	Origin	GZA Classification
t	Till	Heterogeneous mixture of sand, silt, clay, and stones. May include many boulders. Generally massive, but in many places contains beds and lenses of variably washed and stratified sediments.	Generally a blanket deposit that conforms to the underlying bedrock topography. Also forms drumlins and other glacially streamlined hills.	Deposited directly by glacial ice.	G3
n/a	Thin drift	Area of many bedrock outcrops and/or thin surficial deposits (generally less than 3 m thick). The type of surficial material is known or inferred.	Topography of these areas reflects the configuration of the bedrock surface and ranges from smooth undulating hills to knobby terrain and high mountains.	Commonly the result of non-deposition of glacial sediments, but the surficial materials in some coastal areas have been largely removed by marine erosion in late-glacial time.	G3
n/a	Thin drift, undifferentiated	Area of many bedrock outcrops and/or near-surface bedrock where the surficial materials have not been mapped.	Same as other thin-drift areas.	Same as other thin-drift areas.	G2
rk	Bedrock	Area of extensive bedrock outcrop, or where the bedrock has only a thin cover of soil and vegetation. Surficial deposits are essentially absent. Particularly common on the ridge crests and steeper slopes of mountainous areas.	Hilly to mountainous terrain.	Same as the thin-drift areas.	R

Notes:

1. Source table downloaded from https://www.maine.gov/dacf/mgs/pubs/mapuse/series/surf-250/surf-exp.htm.
2. G denotes granular soil; C denotes cohesive soil; and R denotes rock.
3. Numeric values 1 through 3 denote increasing density and/or shear strength.

Table 5: Summary of Material Properties for SLOPE/W Runs

	Granular Soil			**Cohesive Soil**			**Rock**
Parameter	G1	G2	G3	C1	C2	C3	R
Material Code in GIS *	101	102	103	201	202	203	300
Unit Weight (pcf)	118	125	135	120	120	120	150 - 170
Friction Angle (°)	28	32	38	0	0	0	--
Undrained Shear Strength (psf)	0	0	0	350	750	1,250	--

Note: * code (integer) assigned by GZA for identification purposes during computations. No computation performed for rock at this stage.

pcf = Pounds per Cubic Foot

psf = Pounds per Square Foot

Table 6: Summary of SLOPE/W-calculated Factors of Safety

Row ID	Soil Type	Key Parameter	Slope (H:V)	Slope (%)	FoS (wet)	FoS (dry)
1	G1	ϕ = 28°	6:1	17%	1.85	3.07
2			4:1	25%	1.23	2.05
3			3:1	33%	0.90	1.53
4			2:1	50%	0.53	0.96
5			1.5:1	67%	0.33	0.66
6			1:1	100%	0.10	0.34
7	G2	ϕ = 32°	6:1	17%	2.28	3.69
8			4:1	25%	1.52	2.48
9			3:1	33%	1.11	1.85
10			2:1	50%	0.66	1.16
11			1.5:1	67%	0.42	0.80
12			1:1	100%	0.12	0.43
13	G3	ϕ = 38°	6:1	17%	3.00	4.60
14			4:1	25%	2.00	3.13
15			3:1	33%	1.48	2.33
16			2:1	50%	0.89	1.47
17			1.5:1	67%	0.58	1.02
18			1:1	100%	0.21	0.55
19	C1	Su = 350 psf	6:1	17%	1.09	1.09
20			4:1	25%	0.72	0.72
21			3:1	33%	0.53	0.53
22			2:1	50%	0.34	0.34
23			1.5:1	67%	0.22	0.22
24			1:1	100%	0.10	0.14
25	C2	Su = 750 psf	6:1	17%	2.34	2.33
26			4:1	25%	1.64	1.64
27			3:1	33%	1.15	1.15
28			2:1	50%	0.72	0.72
29			1.5:1	67%	0.48	0.49
30			1:1	100%	0.13	0.23
31	C3	Su = 1,250 psf	6:1	17%	3.89	3.89
32			4:1	25%	2.58	2.57
33			3:1	33%	1.92	1.91
34			2:1	50%	1.21	1.20
35			1.5:1	67%	0.83	0.82
36			1:1	100%	0.49	0.49
37	R	Rock	----- Not modeled -----			

Notes:

1. Table 3-3 lists the factor safety value of the "critical slip surface", i.e., the one with the lowest FoS value among all slip surfaces evaluated by the program.
2. Red indicates FoS value less than 1.0 (i.e., instability).
3. "wet" denotes the shallow groundwater table case and "dry" denotes the 10-foot deep groundwater table case (Figure 2).

FIGURES

Figure 1: Schematic of Road-side Slopes

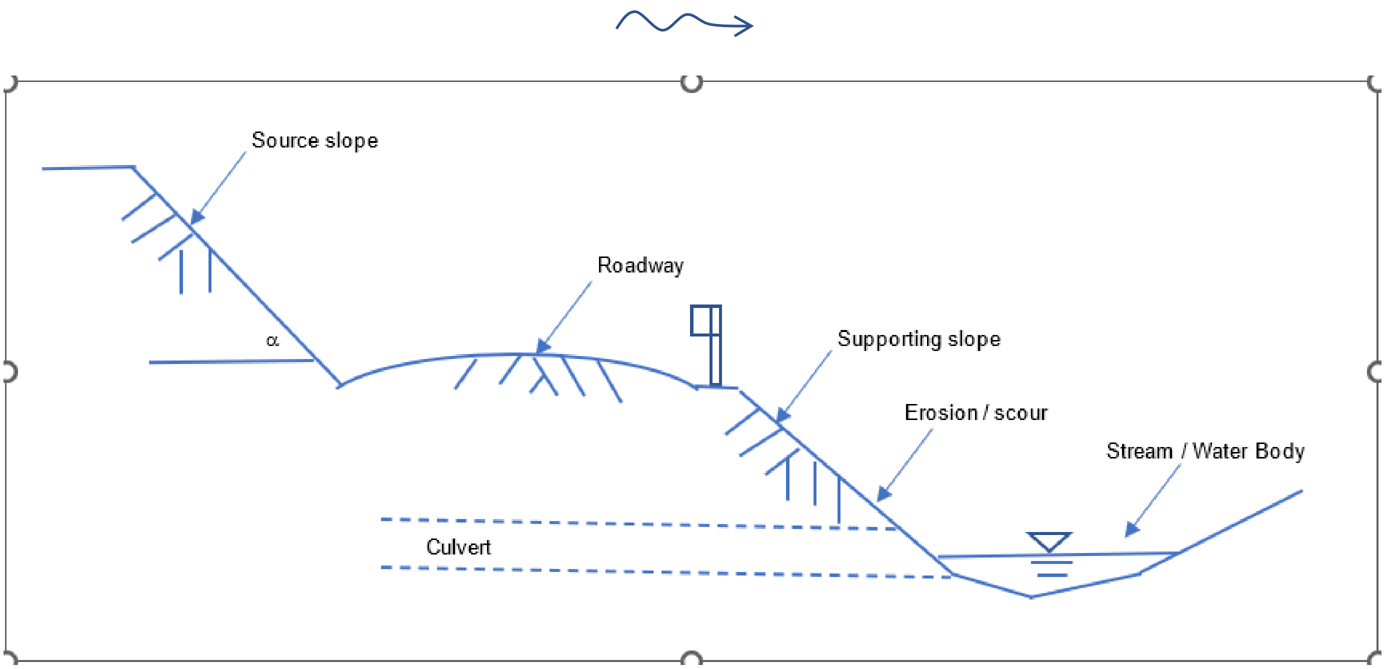


Figure 2: Schematic of SLOPE/W Model

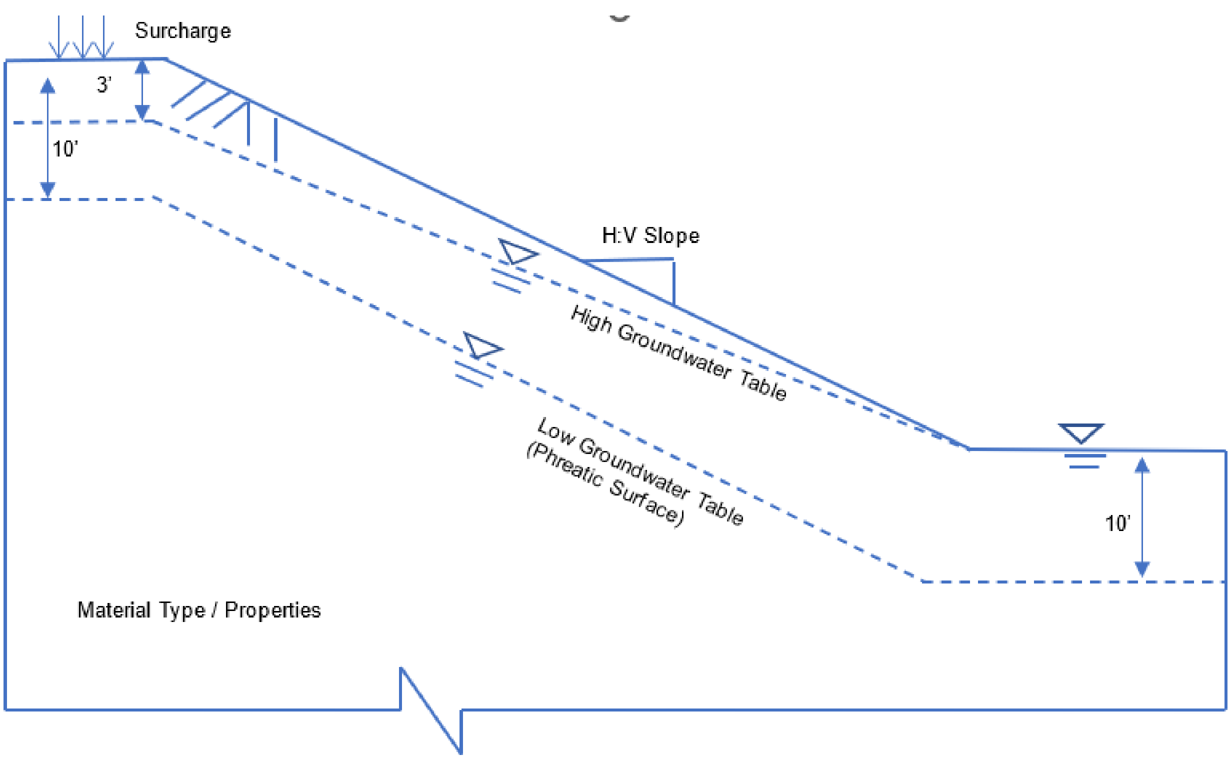
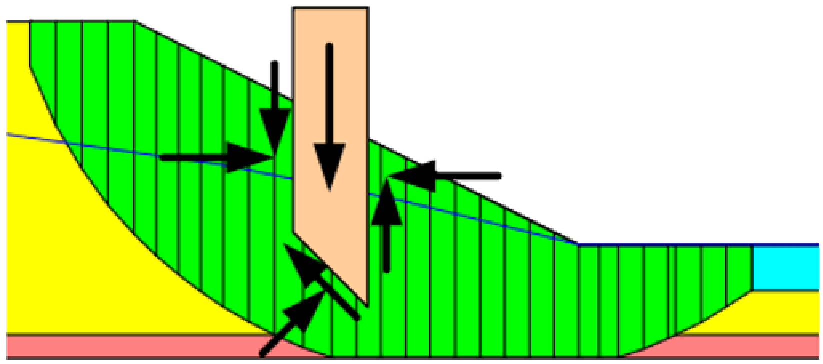
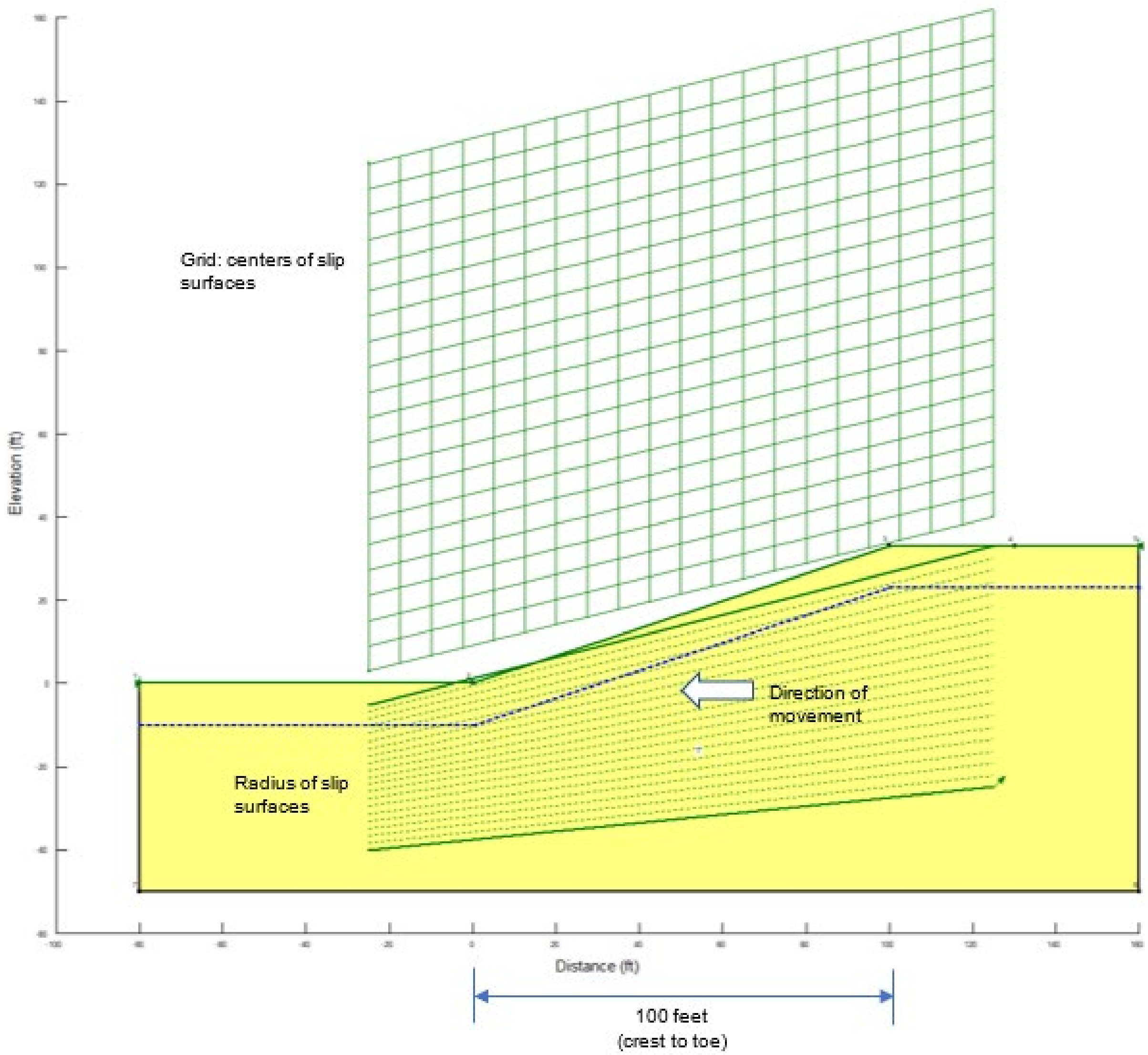


Figure 3: Schematic of Slice Discretization and Slice Forces in SLOPE/W



Source: Figure 2-1 of SLOPE/W Manual "Stability Modeling w/ SLOPE/W - An Engineering Methodology" GEO-SLOPE International, Ltd., November 2012 Edition.

Figure 4: SLOPE/W Model – Example



Note: Example shows a 3H:1V slope with one uniform material. Grid and radius method used for Grid and radius for circular slip surfaces.

Figure 5: SLOPE/W-calculated Factors of Safety – Granular Soils

Notes:
1. See Table 4 for granular soil descriptions (G1 – G3).
2. Groundwater depth is noted in parentheses.

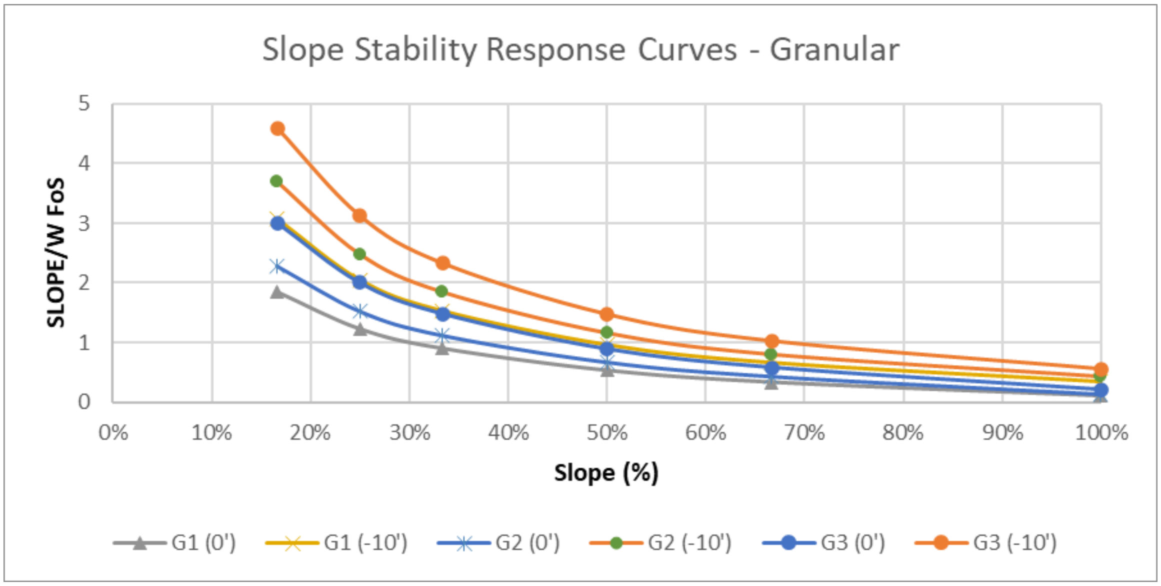


Figure 6: SLOPE/W-calculated Factors of Safety – Cohesive Soils

Notes:
1. See Table 4 for cohesive soil descriptions (C1 – C3).
2. Groundwater depth is noted in parentheses.

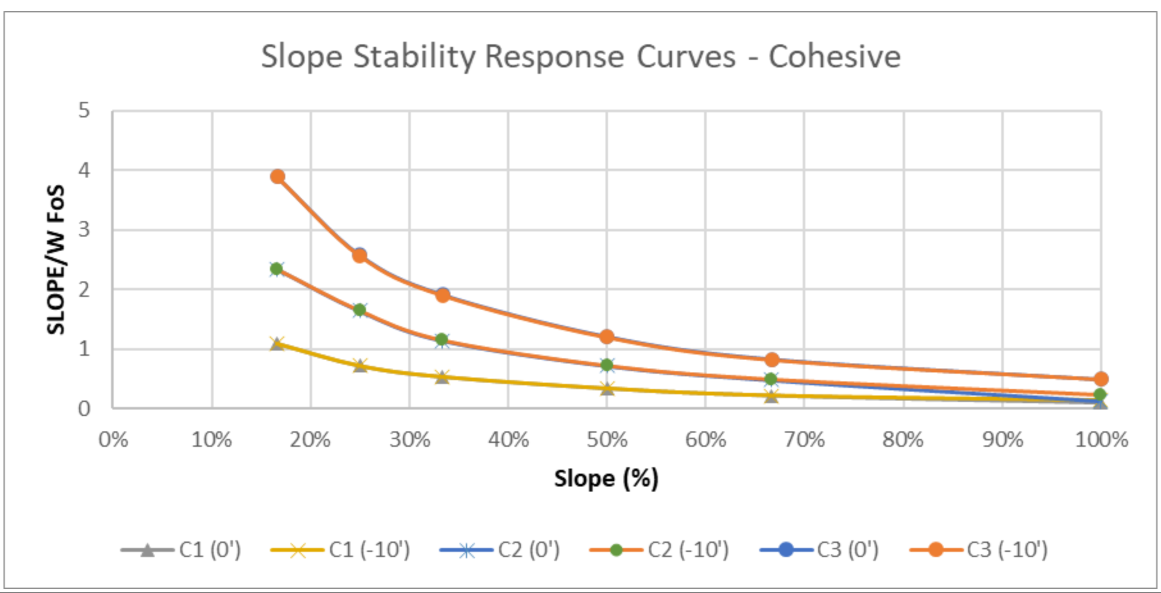
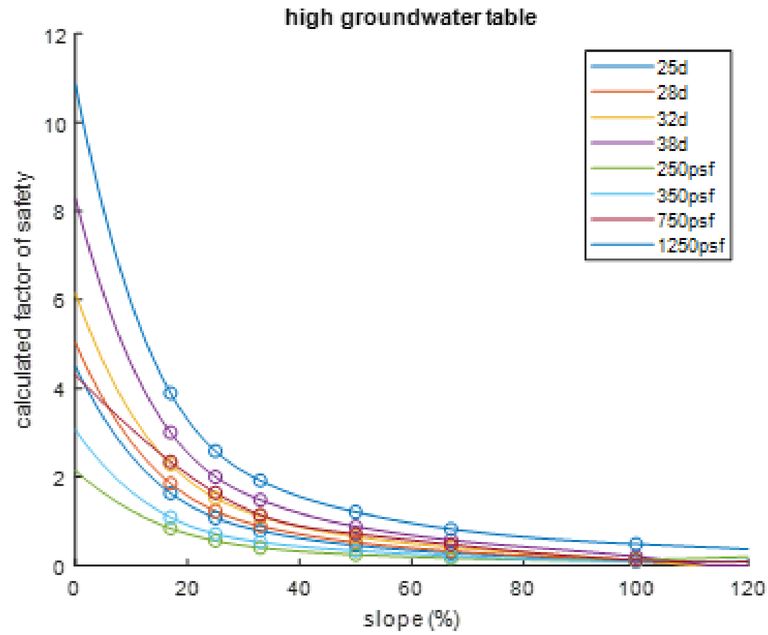
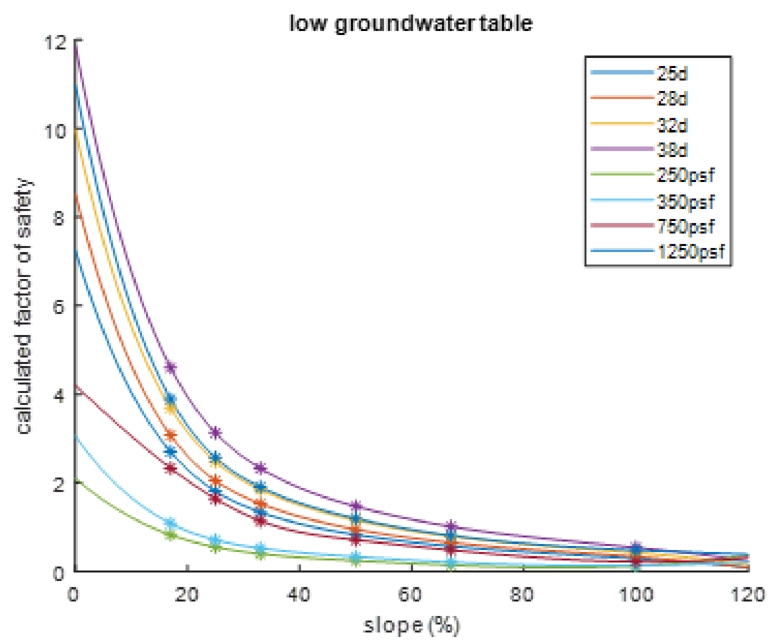


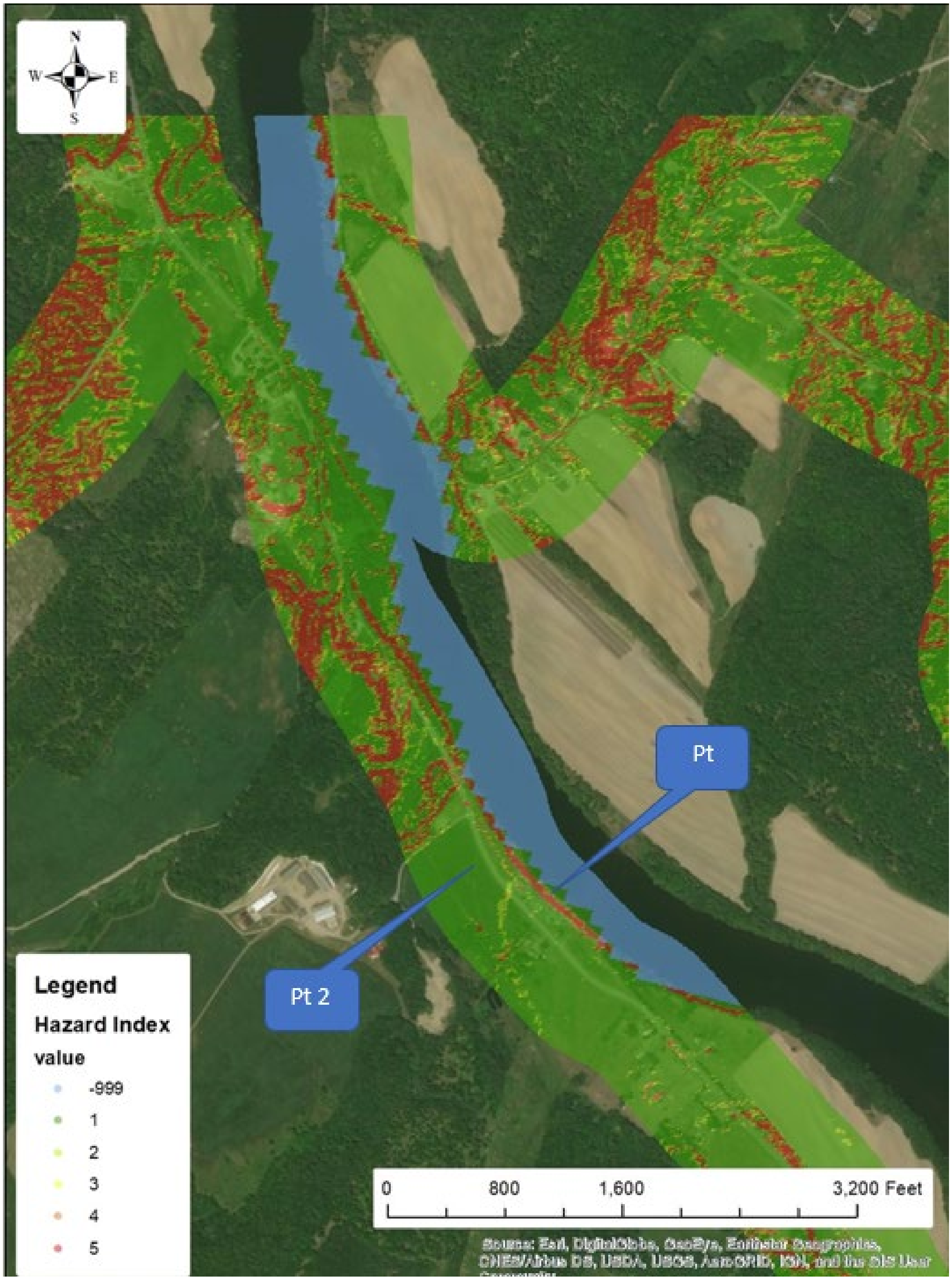
Figure 7: Interpolated FoS Values – Various Scenarios





Note: Open circle or asterisk denotes SLOPE/W calculated values for both high and low groundwater conditions; curve denotes MATLAB spline-interpolated values at 1% intervals.

Figure 8: Example Slope Stability Hazard Index Map, Route 136, Auburn, ME



Note: Index values of 4 and 5 indicate marginal stability and instability per GZA's modeling results. "-999" denotes area covered by water. Key parameters for Point locations Pt1 and Pt2 shown in Figure 9.

Figure 9: Key Parameters for Points Pt1 and Pt2

a) Pt 1

Location: 405,559.415 4,875,111.025

Field	Value
FID	201682
Shape	Point ZM
F__ID	543366
x	405551
y	4875119
z	34
lc	21
mat	201
slp	117
fos	0.1
asprel	1
slptype	0
risk	5
flag	1

b) Pt 2

Location: 405,454.398 4,875,153.032

Field	Value
FID	198390
Shape	Point ZM
F__ID	528631
x	405444
y	4875162
z	38
lc	81
mat	201
slp	3
fos	2.56
asprel	1
slptype	1
risk	1
flag	0

Figure 10: Example Close-up View of Computed Hazard Index Map

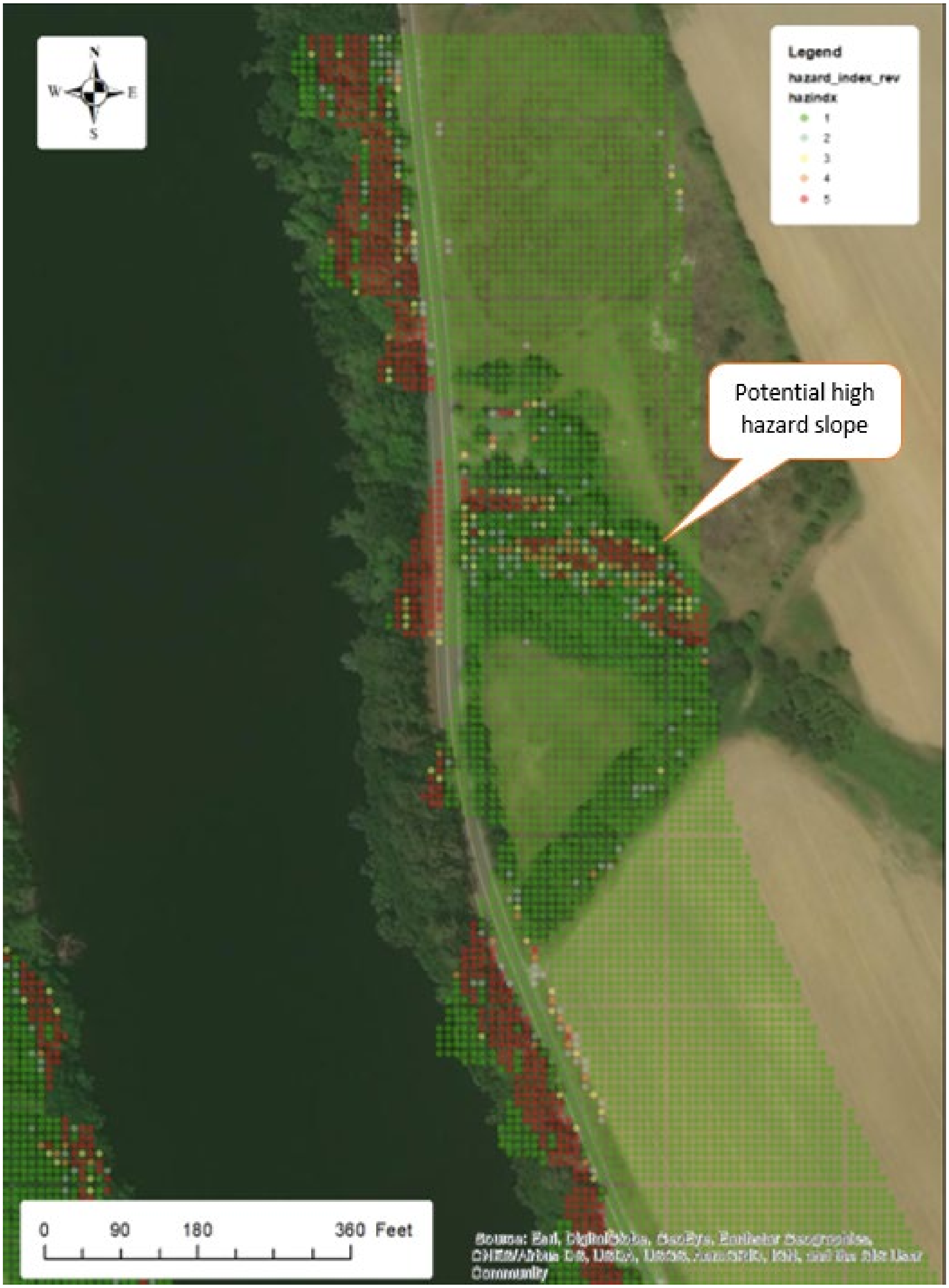


Figure 11: Example Proximity Flag to Hydrographic Features

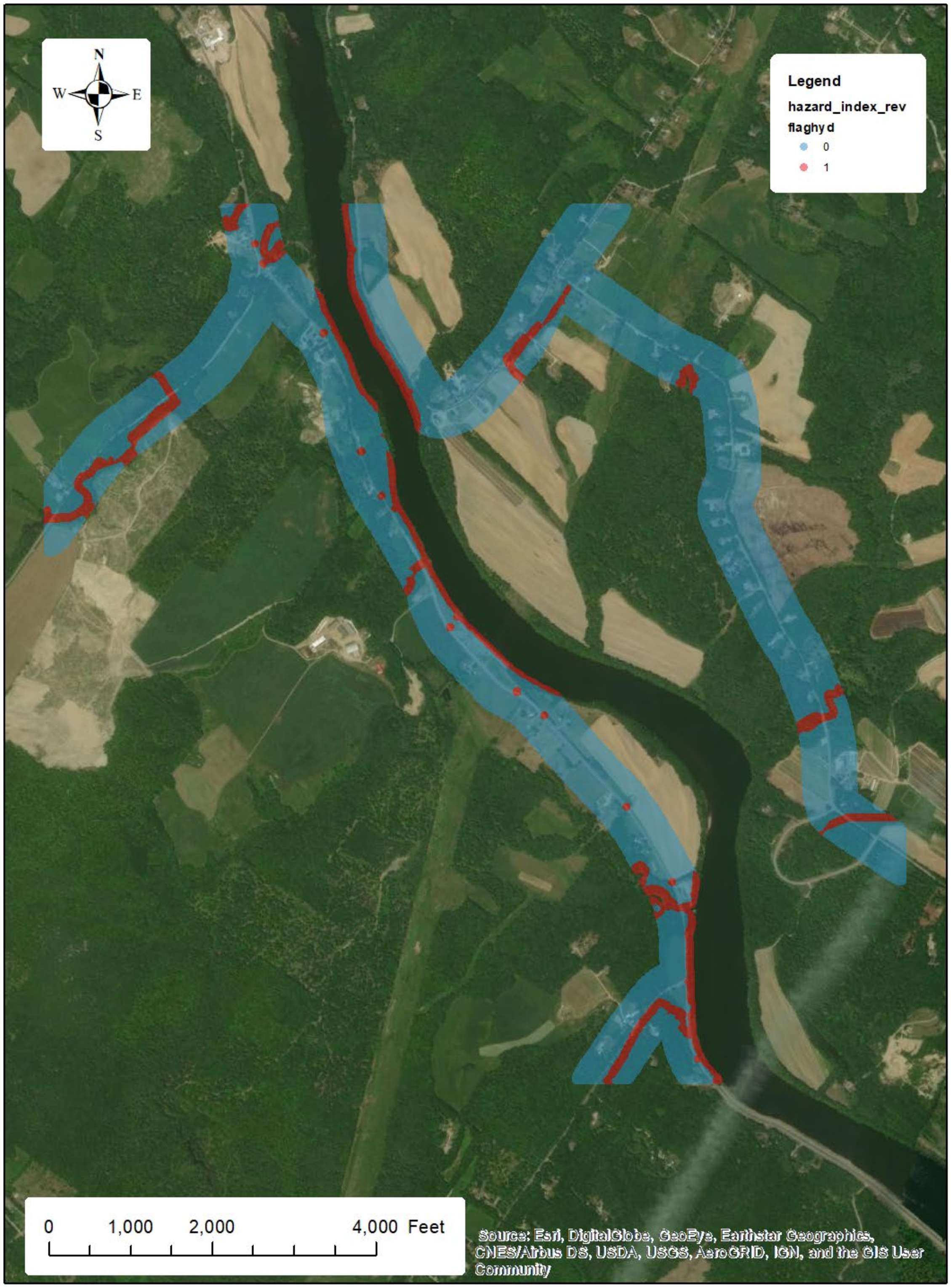
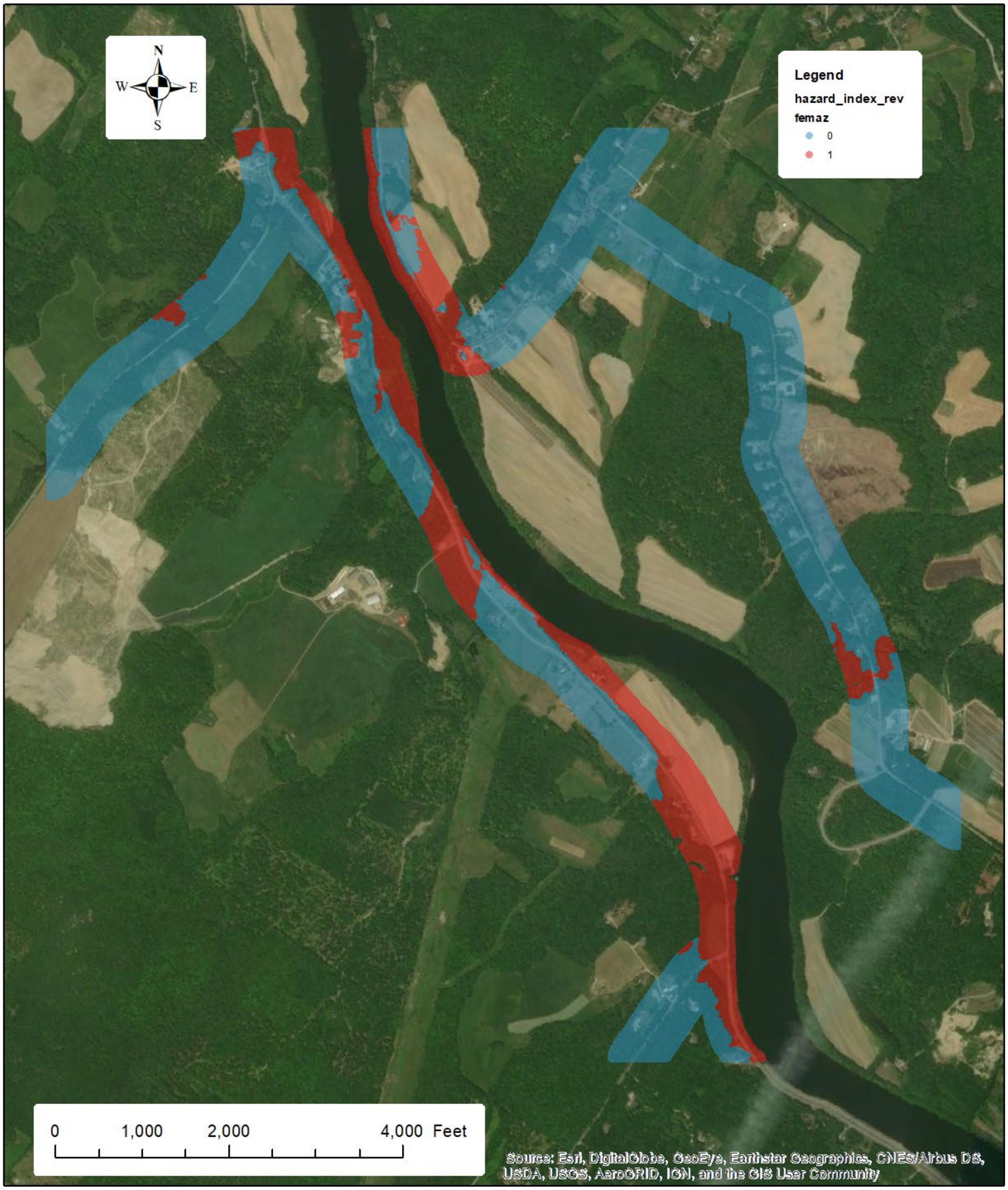


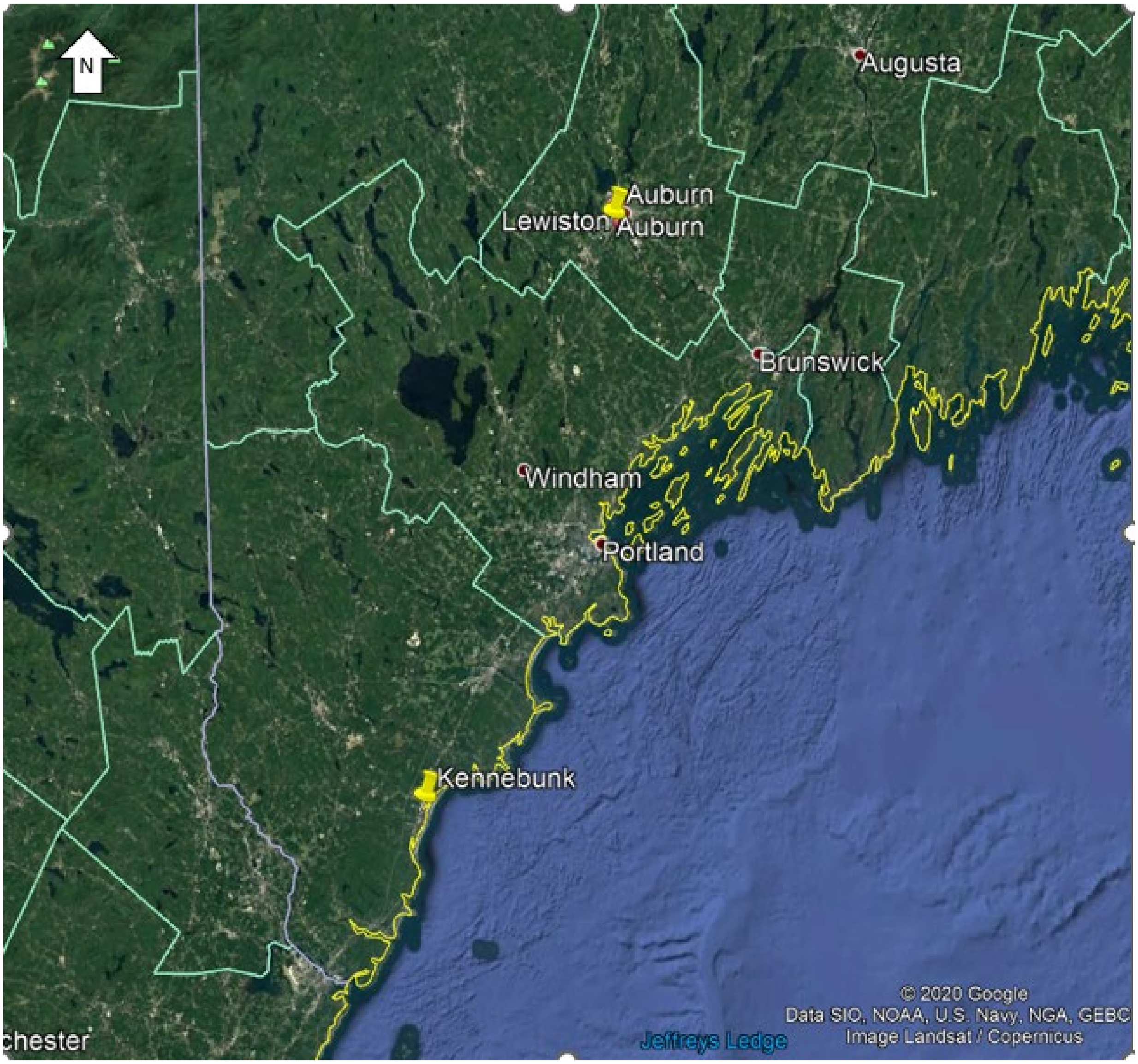
Figure 12: Example Proximity Flag to Culverts

Figure 13: FEMA Special Flood Hazard Area



Note: "1" denotes Zone A/AE (1-percent annual chance floodplain); "0" denotes Zone X (outside 1-percent annual chance floodplain).

Figure 14: Location Map of Ground Truthing Sites – Auburn and Kennebunk, ME



Note: Based on Google Earth image.

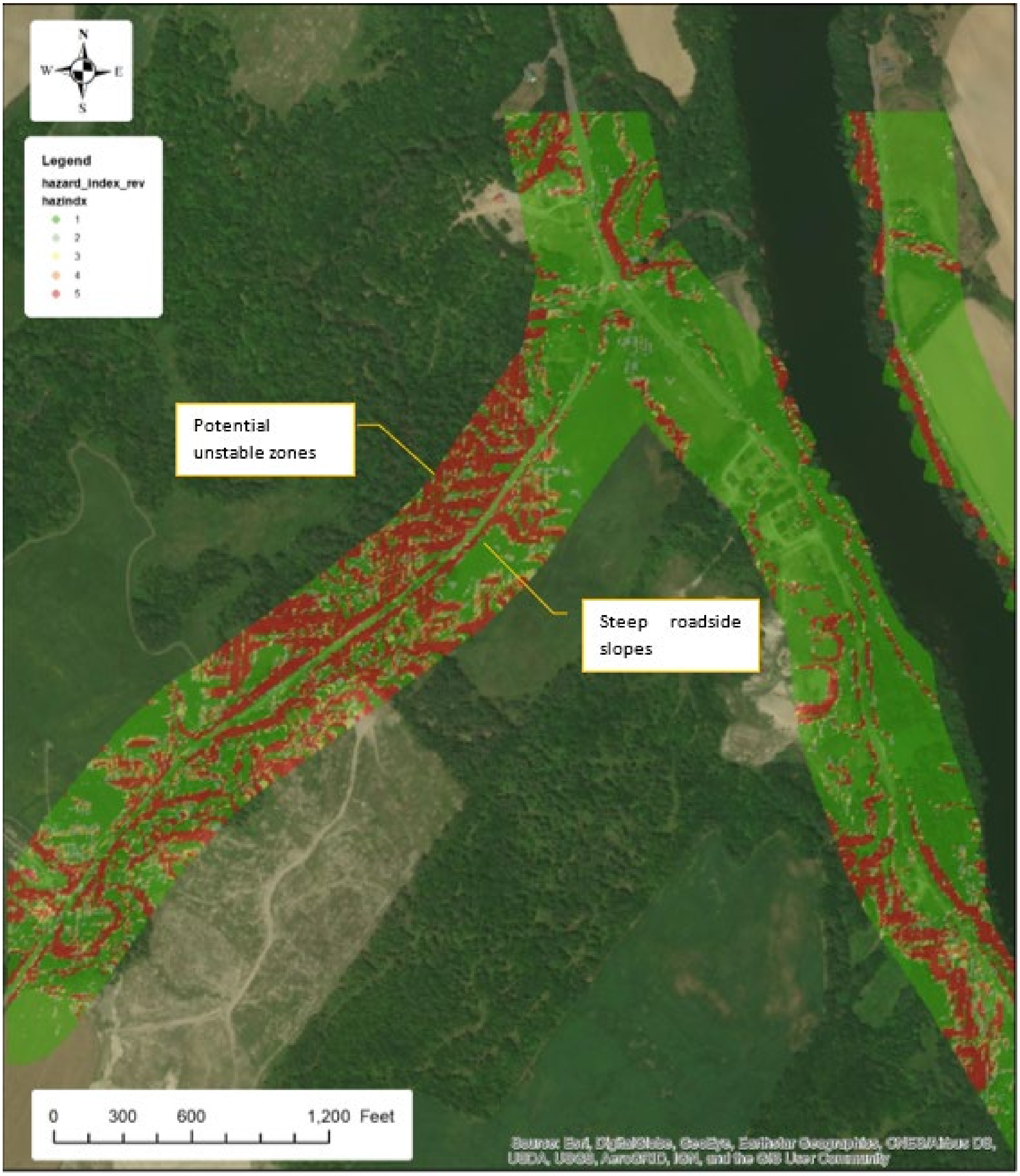
Figure 15: Slope Failure Site at Route 136

Note: Aerial image more recent than 2010; topography LiDAR from 2009. Failure occurred in Summer 2010.

Figure 16: Project Photographs for Route 136 Slope Failure

Note: Top image after failure incident in September 2010; bottom image after construction/remediation completed in December 2010.

Figure 17: Terrain-driven Slope Instability



Note: red indicates low factor of safety values due to steep slopes.

Figure 18: Downtown Kennebunk, Maine

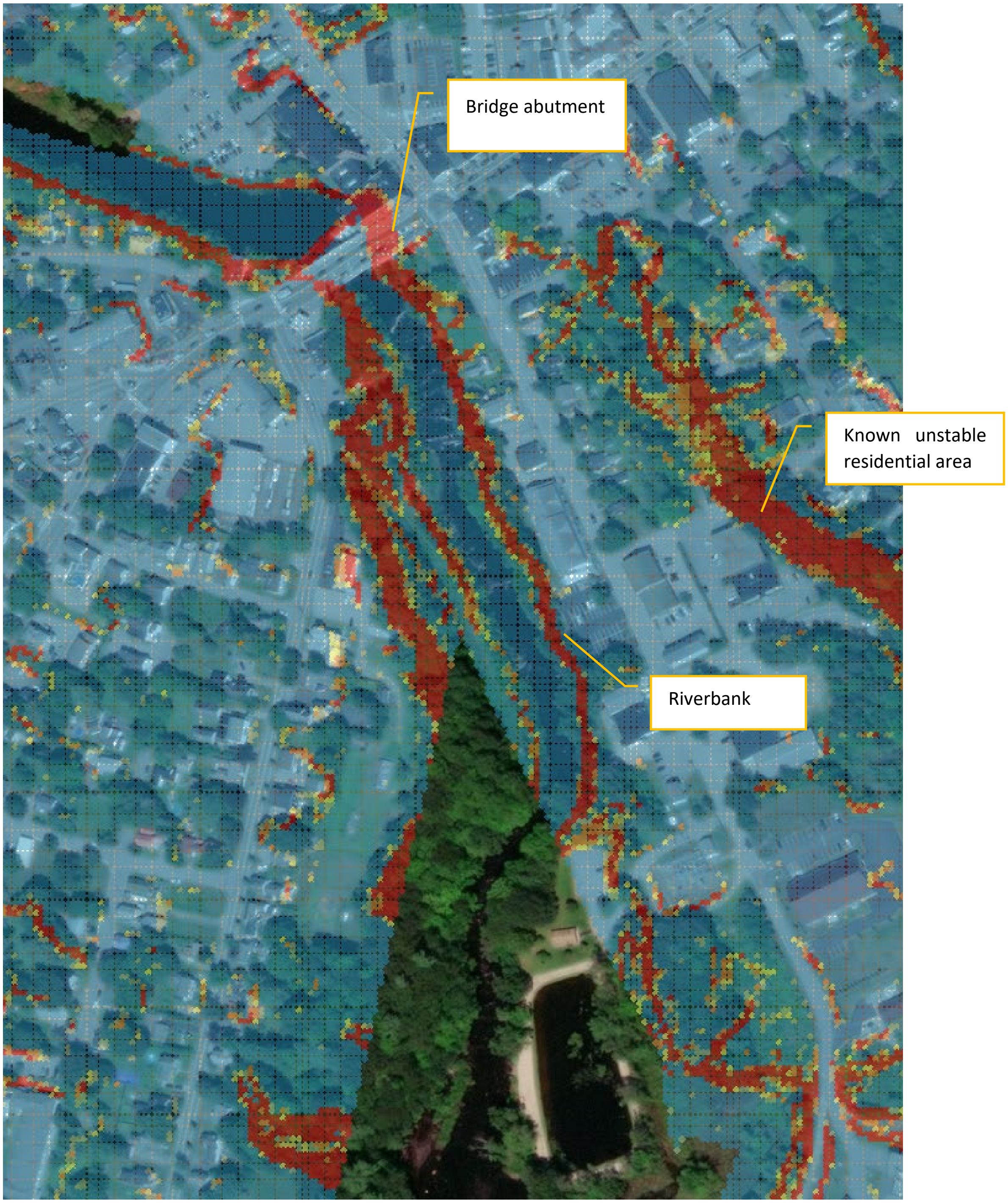


Figure 19: North Street, Kennebunkport, Maine

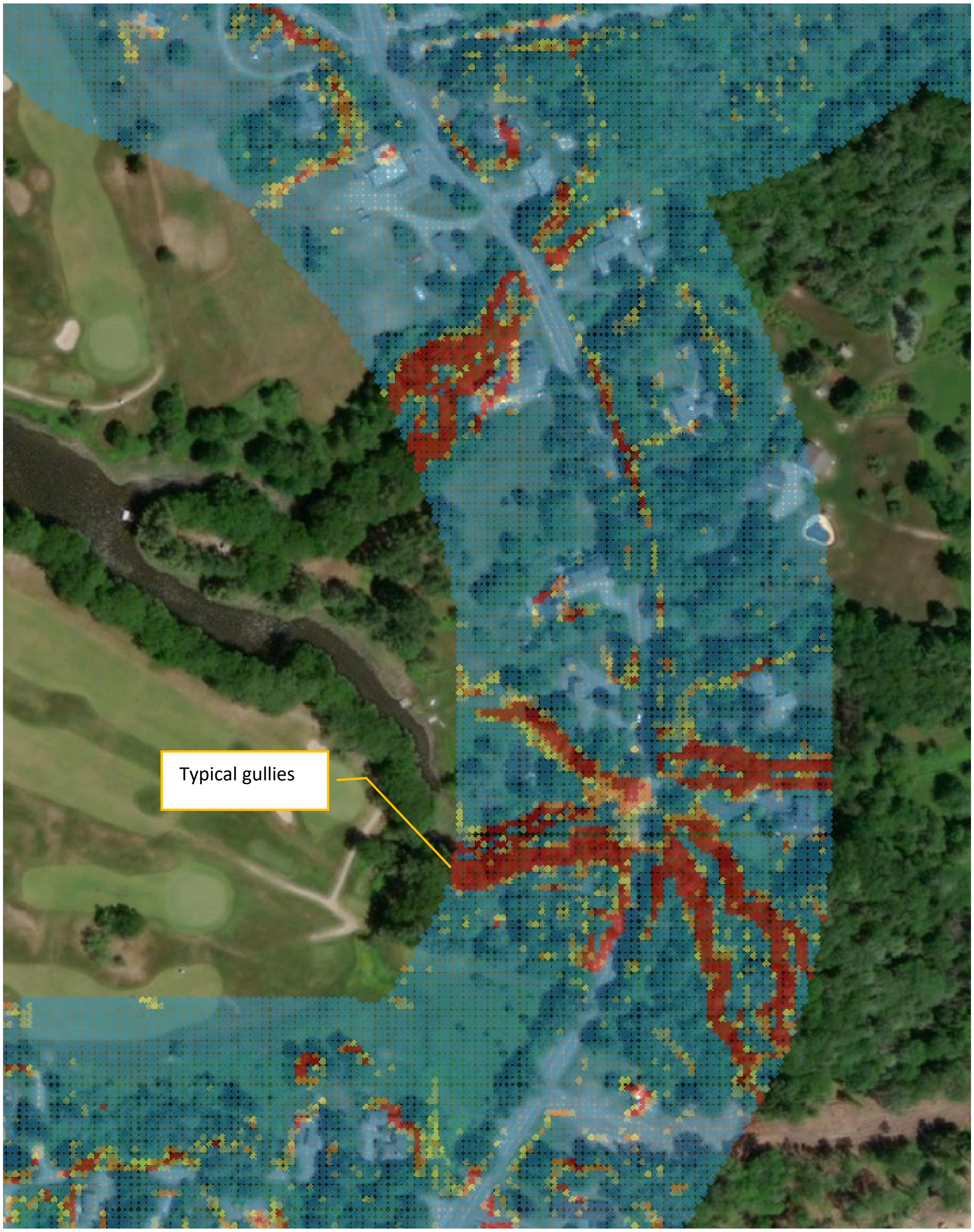
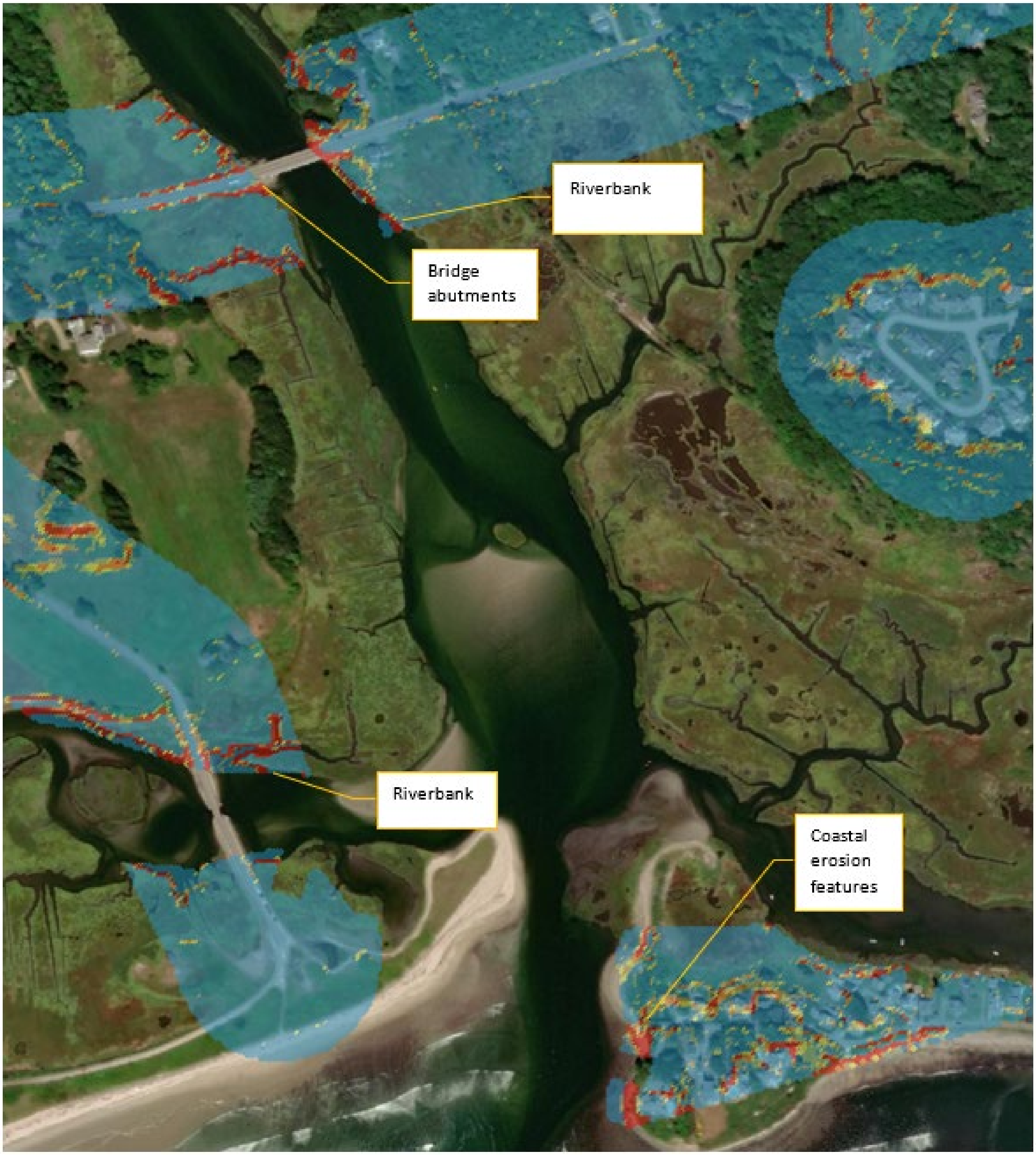
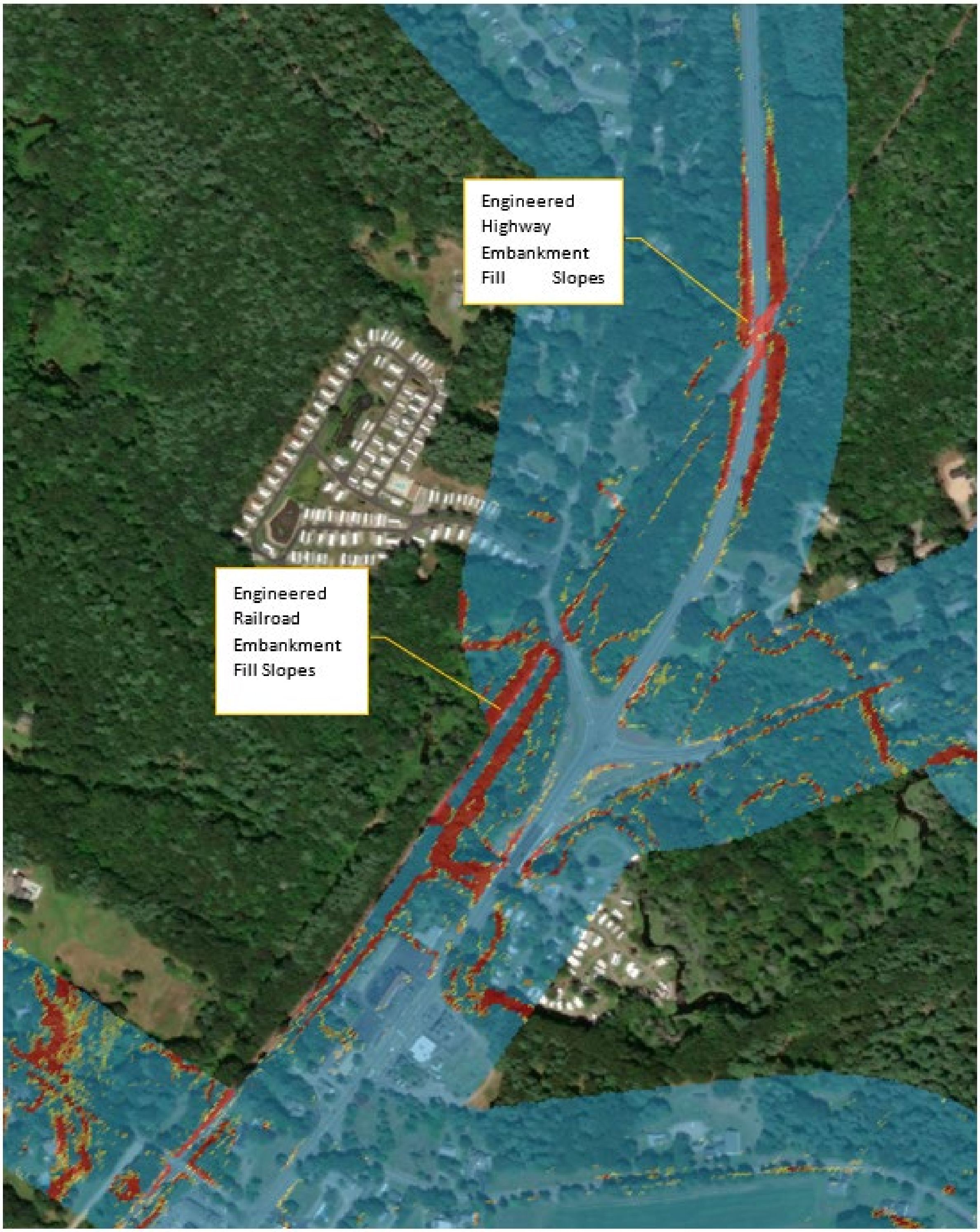


Figure 20: Coastal Erosion and Instability, Kennebunk, Maine



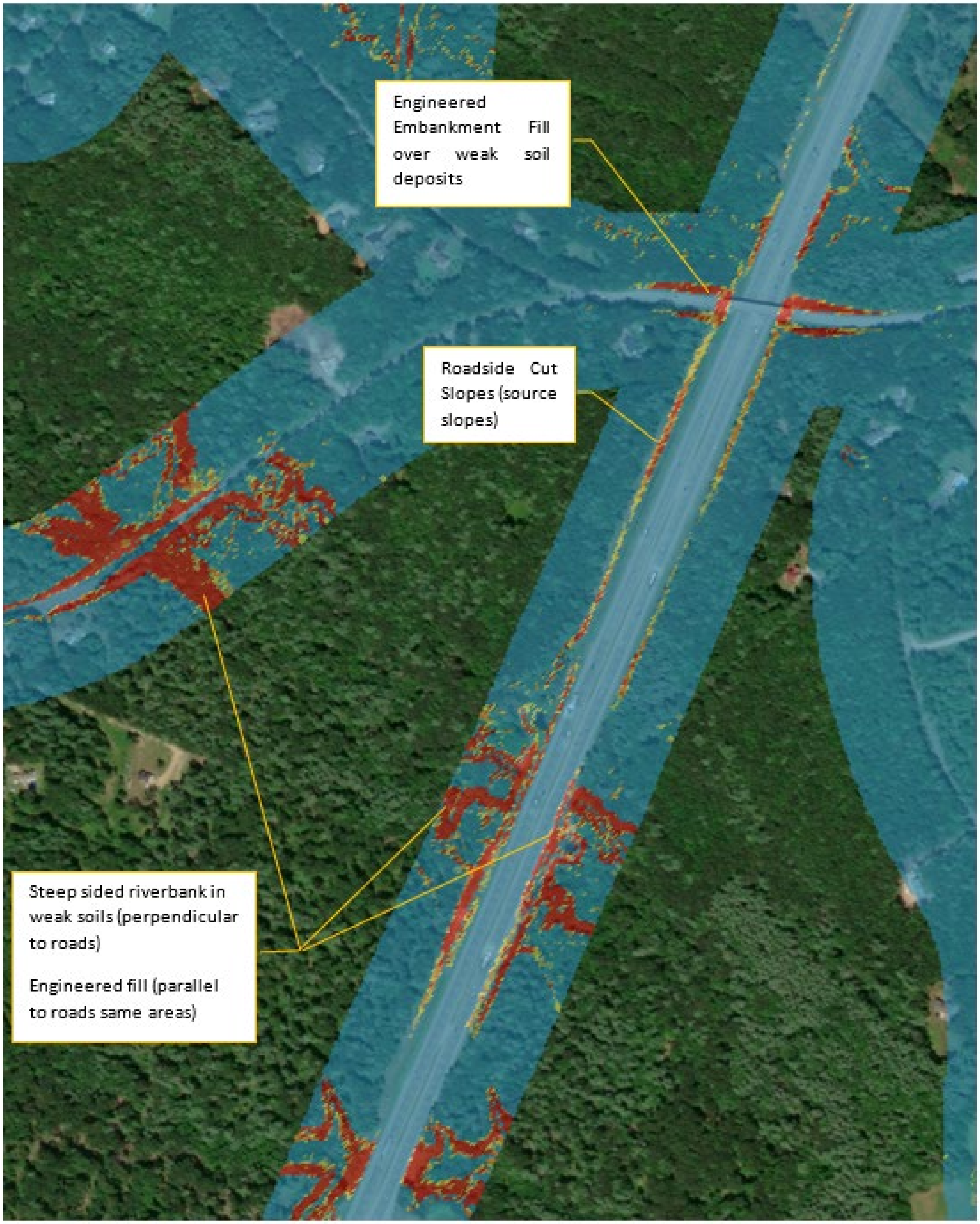
Note: Various erosion / stability issues in a coastal setting.

Figure 21: Route 1, Kennebunk, Maine



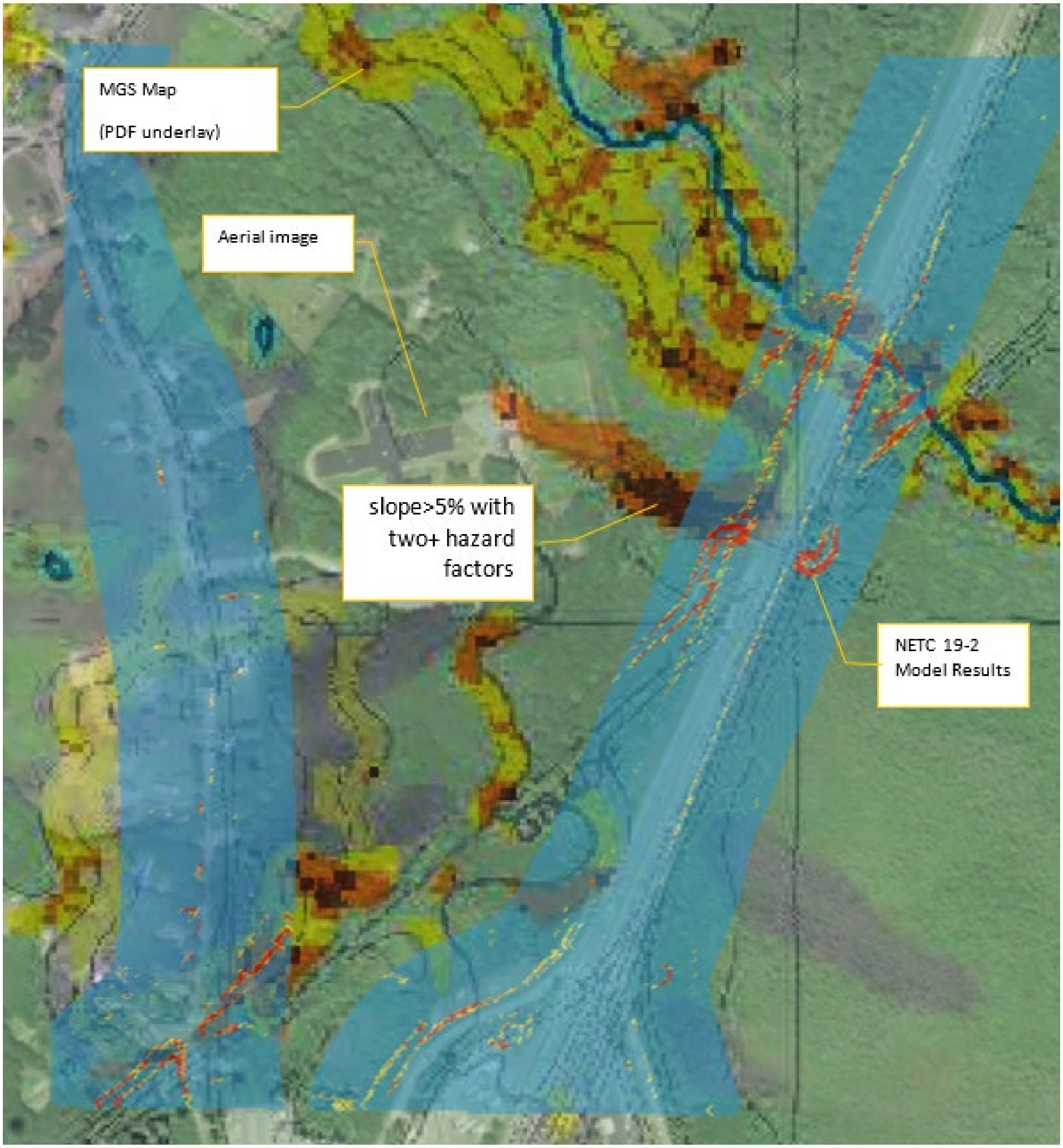
Note: Manmade slopes not part of underlying surficial geology layer used as model input.

Figure 22: Interstate I-95, Kennebunk, Maine



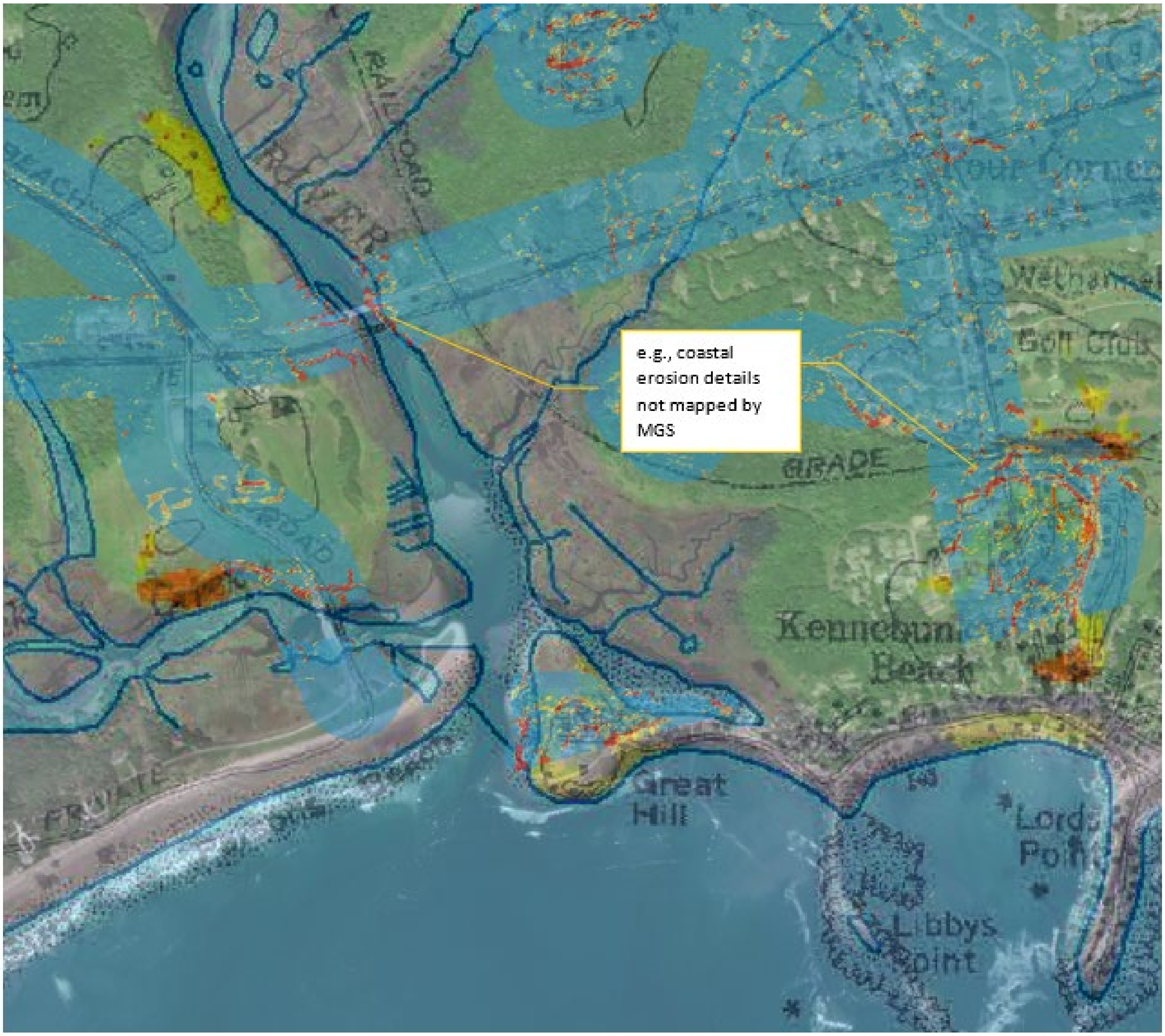
Note: Manmade slopes not part of underlying surficial geology layer used as model input.

Figure 23: Comparison of NETC 19-2 Modeling Results and MGS Landslide Susceptibility Map – I-95



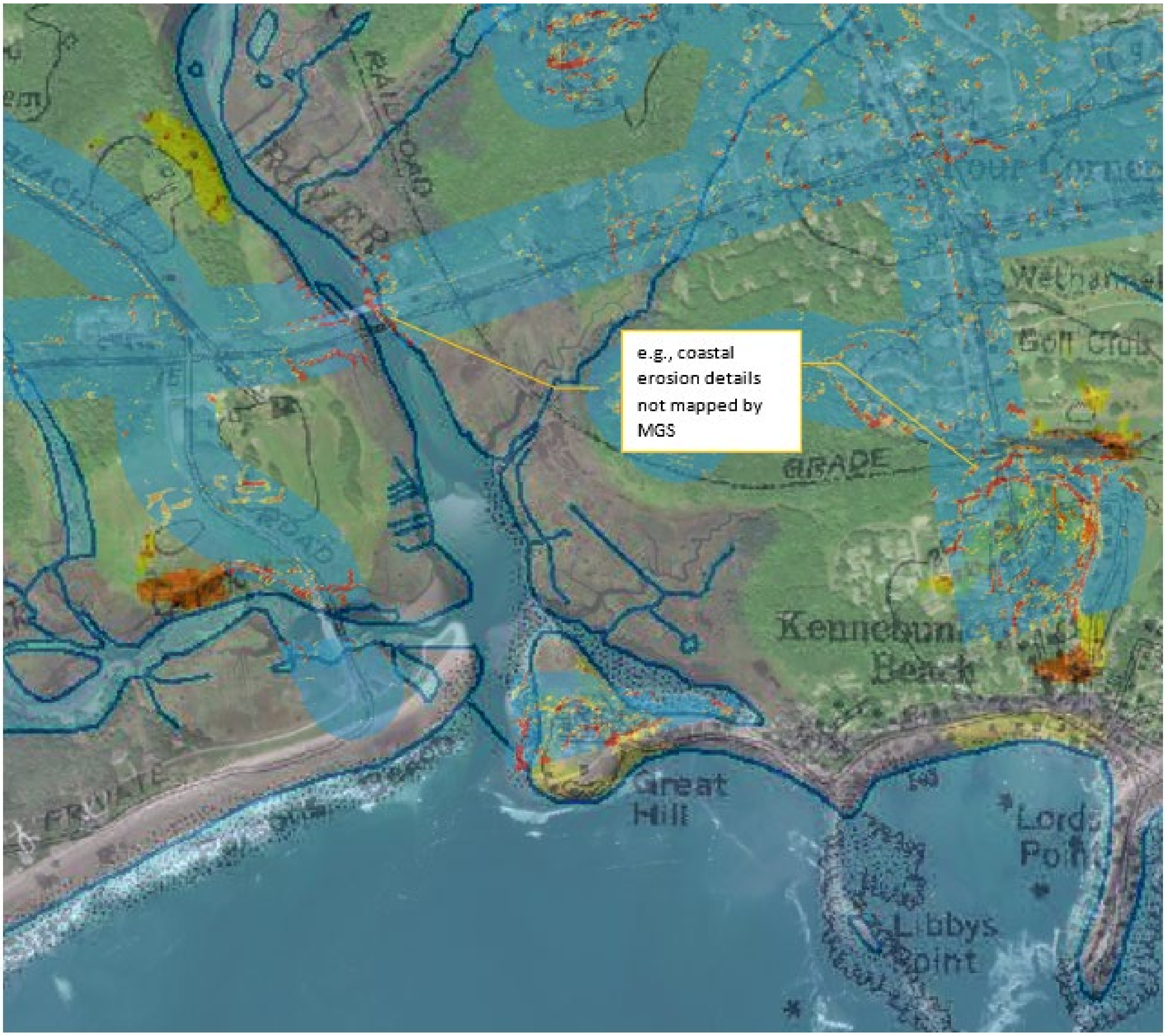
Note: Aerial image and MGS landslide susceptibility map overlaid with NETC 19-2 computed slope stability hazard index. PDF is slightly offset due to projection.

Figure 24: Comparison of NETC 19-2 Modeling Results and MGS Landslide Susceptibility Map – Coast



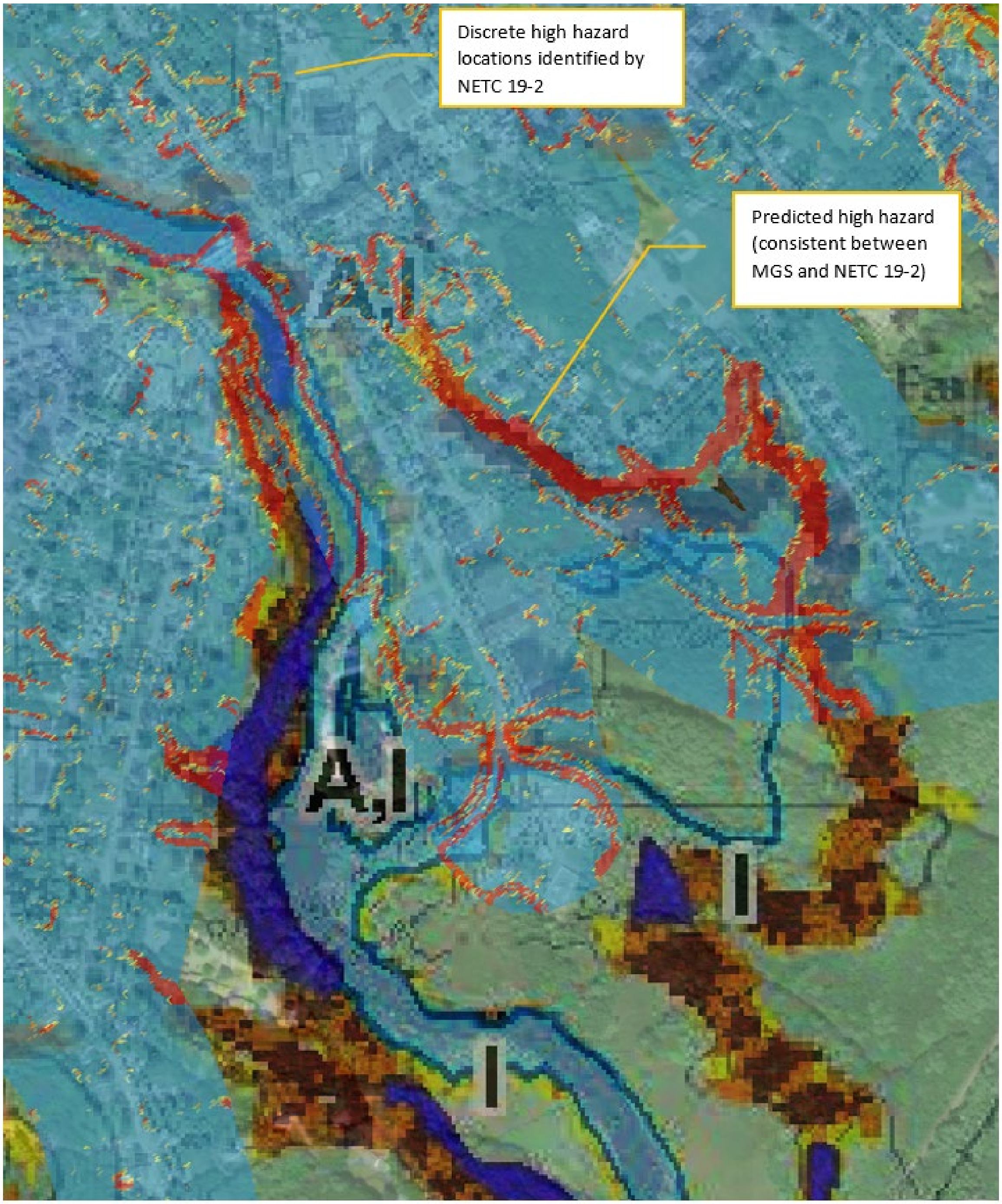
Note: Aerial image and MGS landslide susceptibility map overlaid with GZA computed slope stability hazard index. PDF is slightly offset due to projection.

Figure 25: Comparison of NETC 19-2 Modeling Results and MGS Landslide Susceptibility Map – North Street



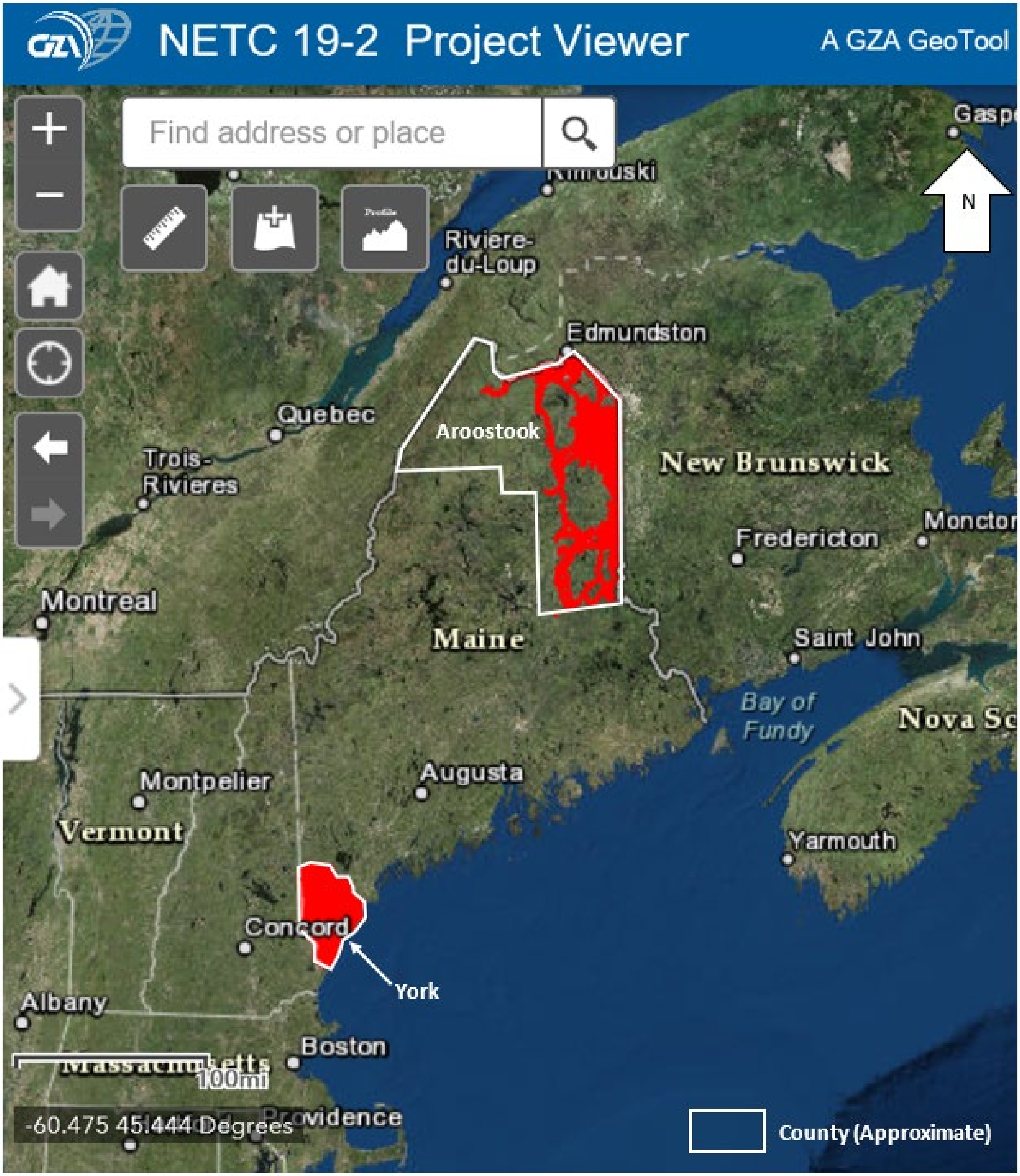
Note: Aerial image and MGS landslide susceptibility map overlaid with GZA computed slope stability hazard index. PDF is slightly offset due to projection.

Figure 26: Comparison of NETC 19-2 Modeling Results and MGS Landslide Susceptibility Map – Downtown



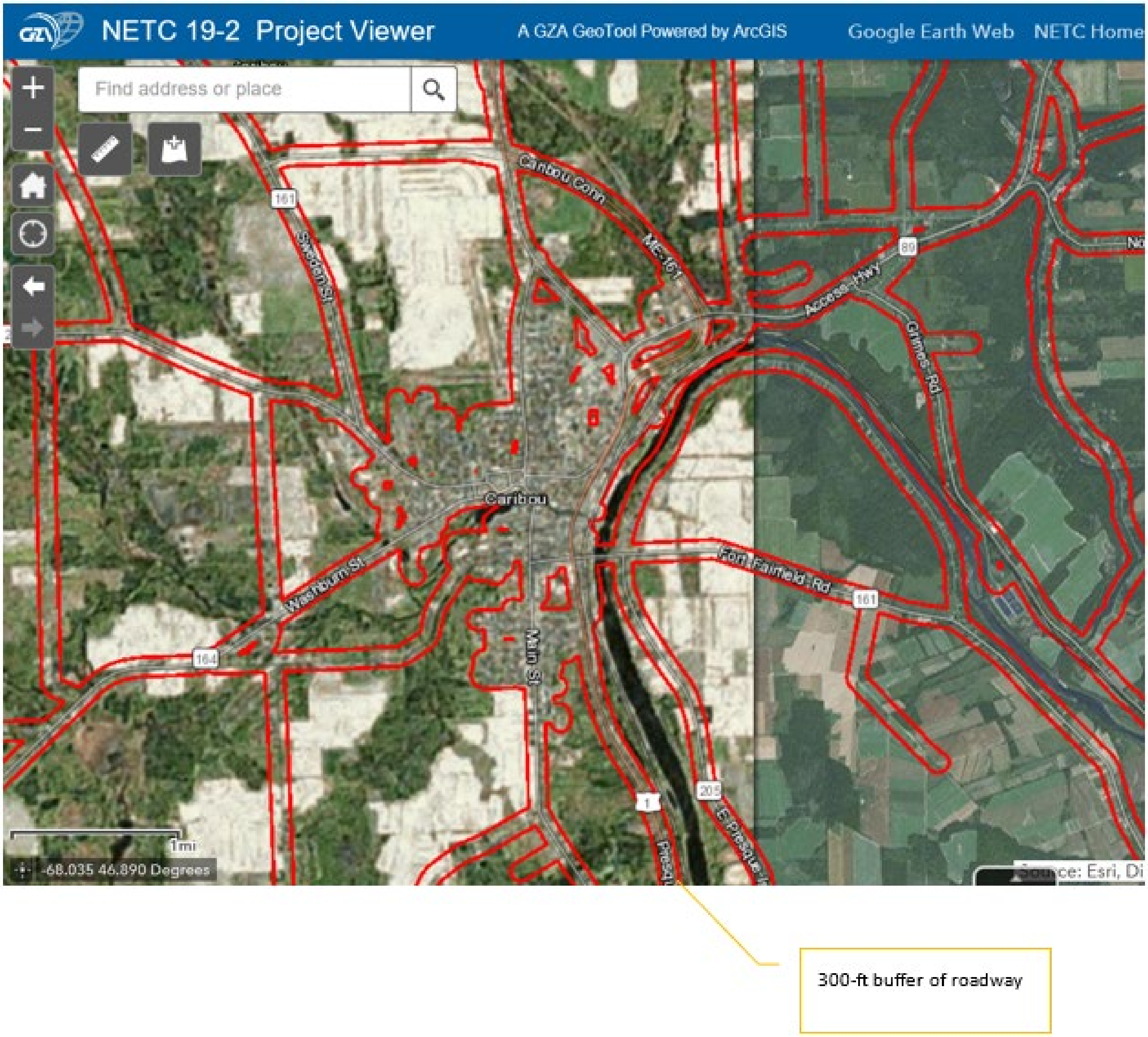
Note: Aerial image and MGS landslide susceptibility map overlaid with GZA computed slope stability hazard index. PDF is slightly offset due to projection.

Figure 27: Pilot Counties for Toolkit Development – Aroostook and York



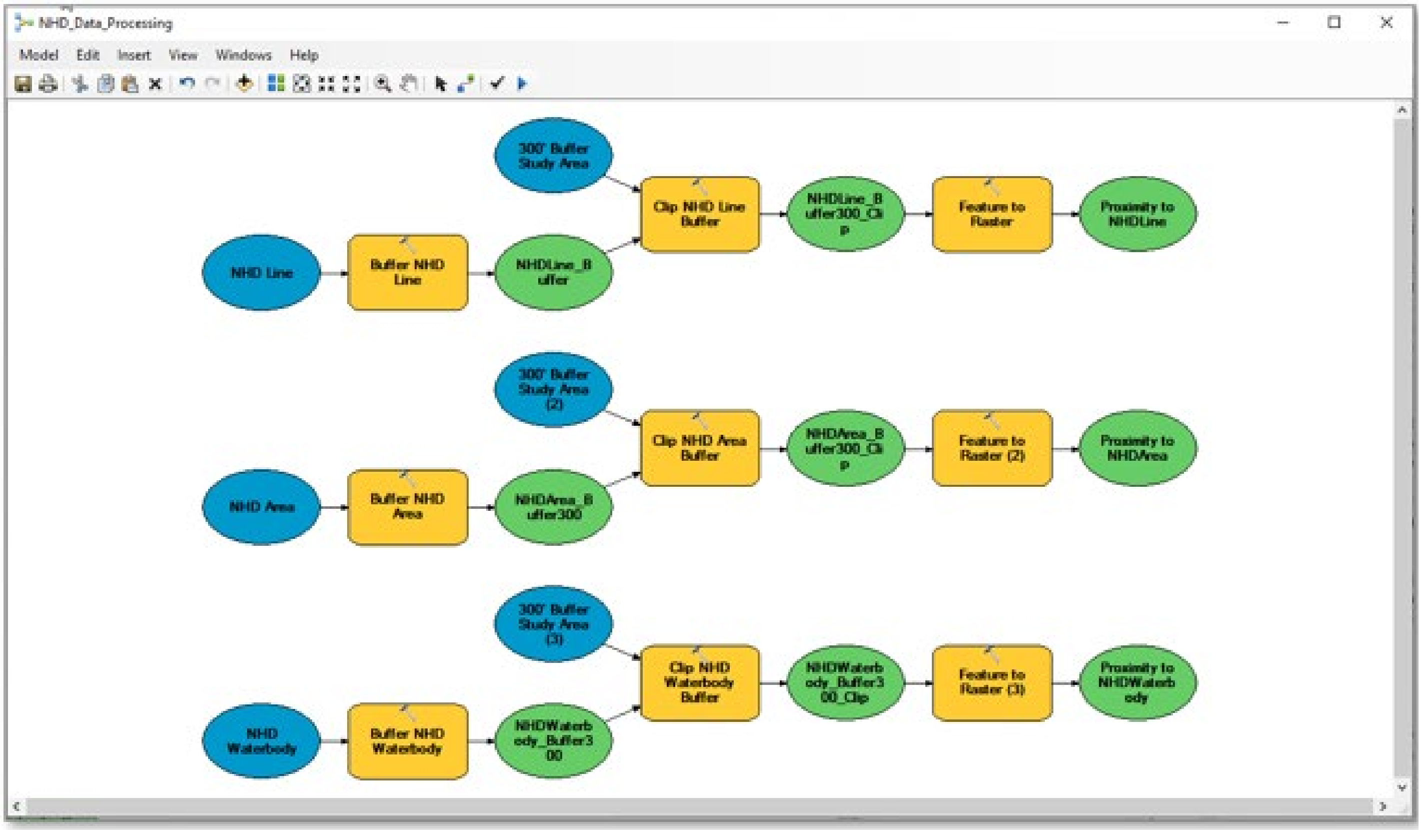
Note: red lines represent 300-feet buffer from existing roadway (per MaineDOT's roadway inventory)

Figure 28: NETC 19-2 Study Area – 300 feet Buffer along Public Roadways



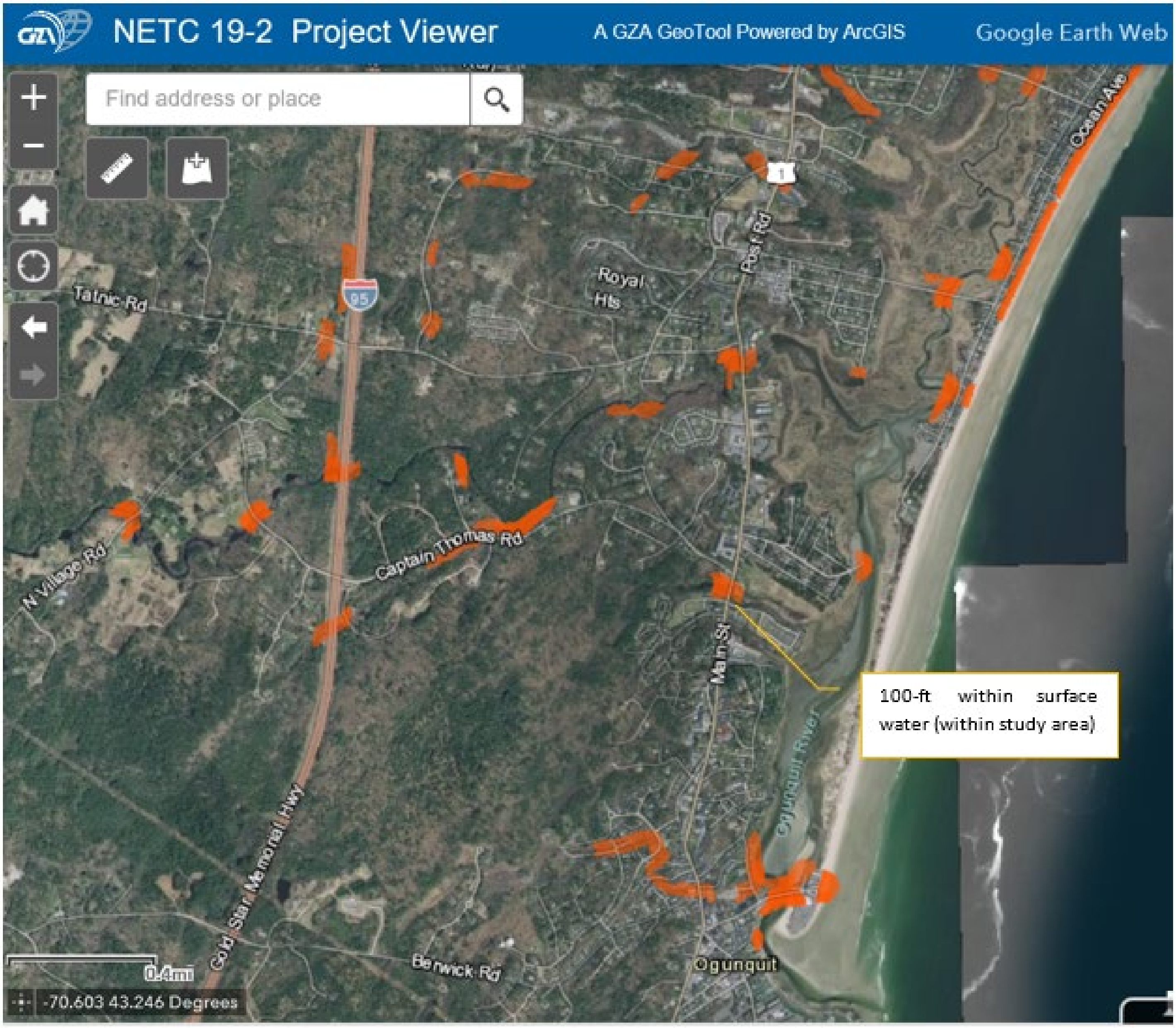
Note: Note: Red outlines represent the study area.

Figure 29: Model for Processing NHD Data



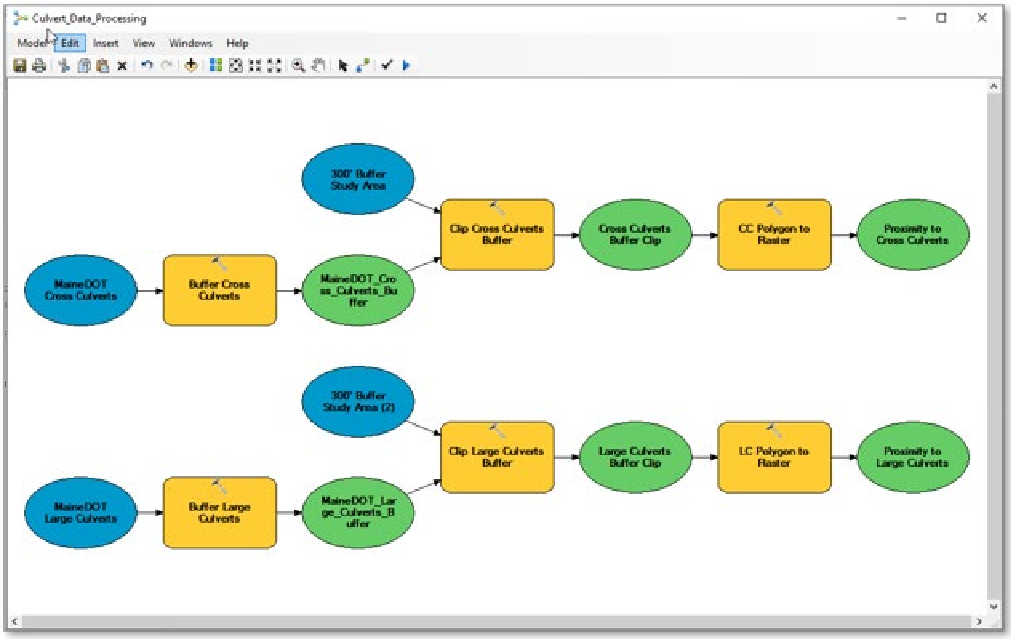
Note: ModelBuilder view

Figure 30: Example View of Proximity to Surface Water



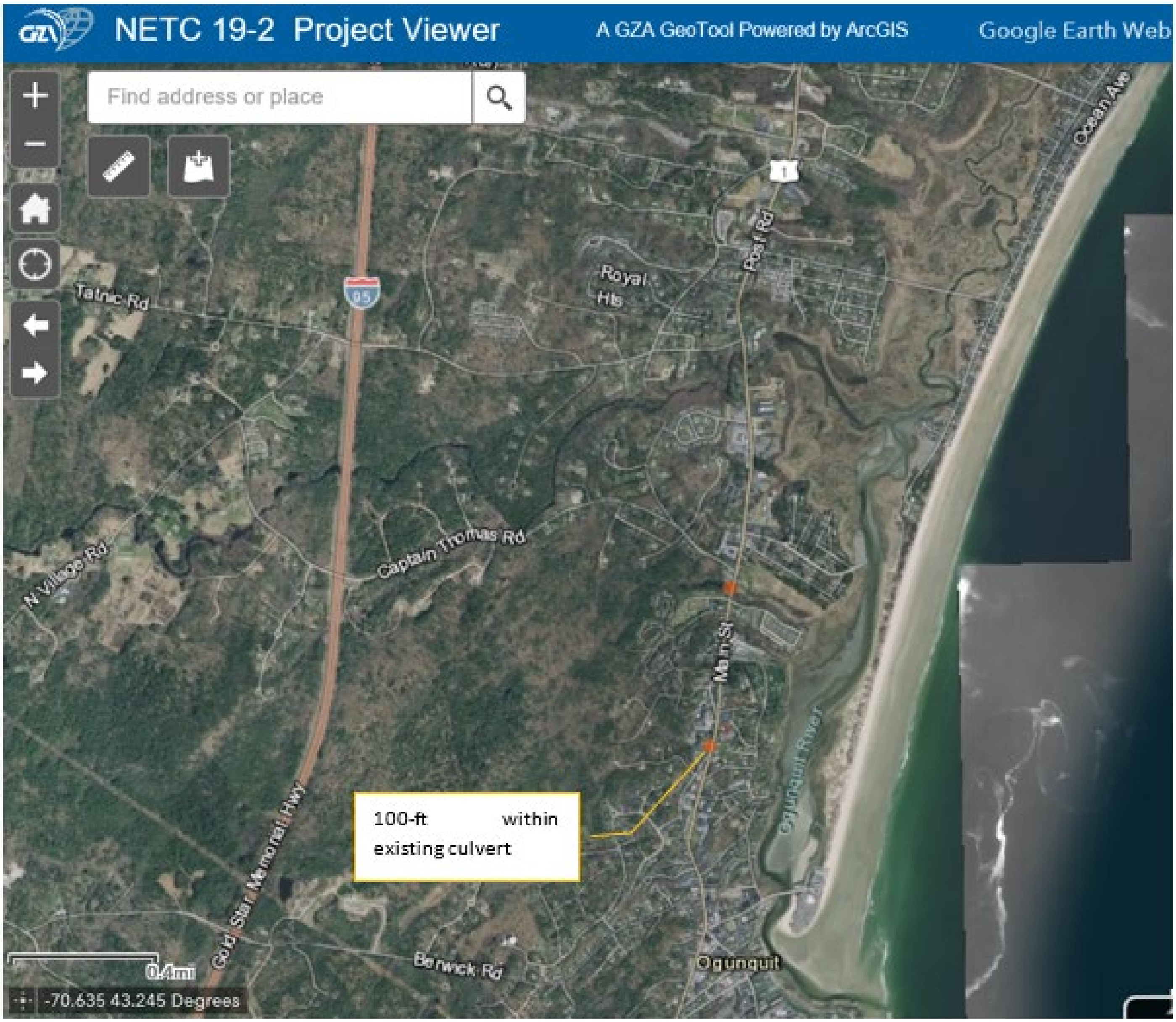
Note: Orange indicate surface water within 100 feet in distance.

Figure 31: Model for Processing Culvert Data



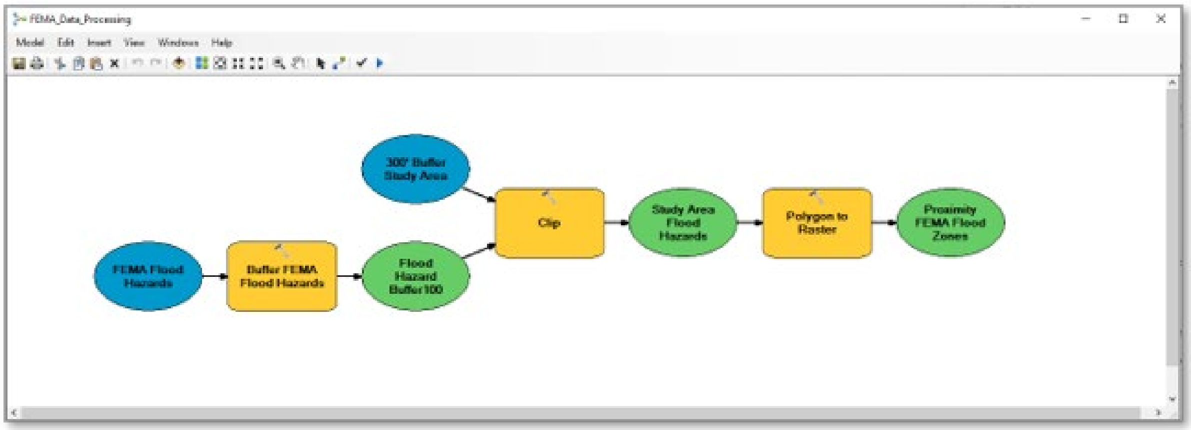
Note: ModelBuilder view

Figure 32: Example View of Proximity to Culverts



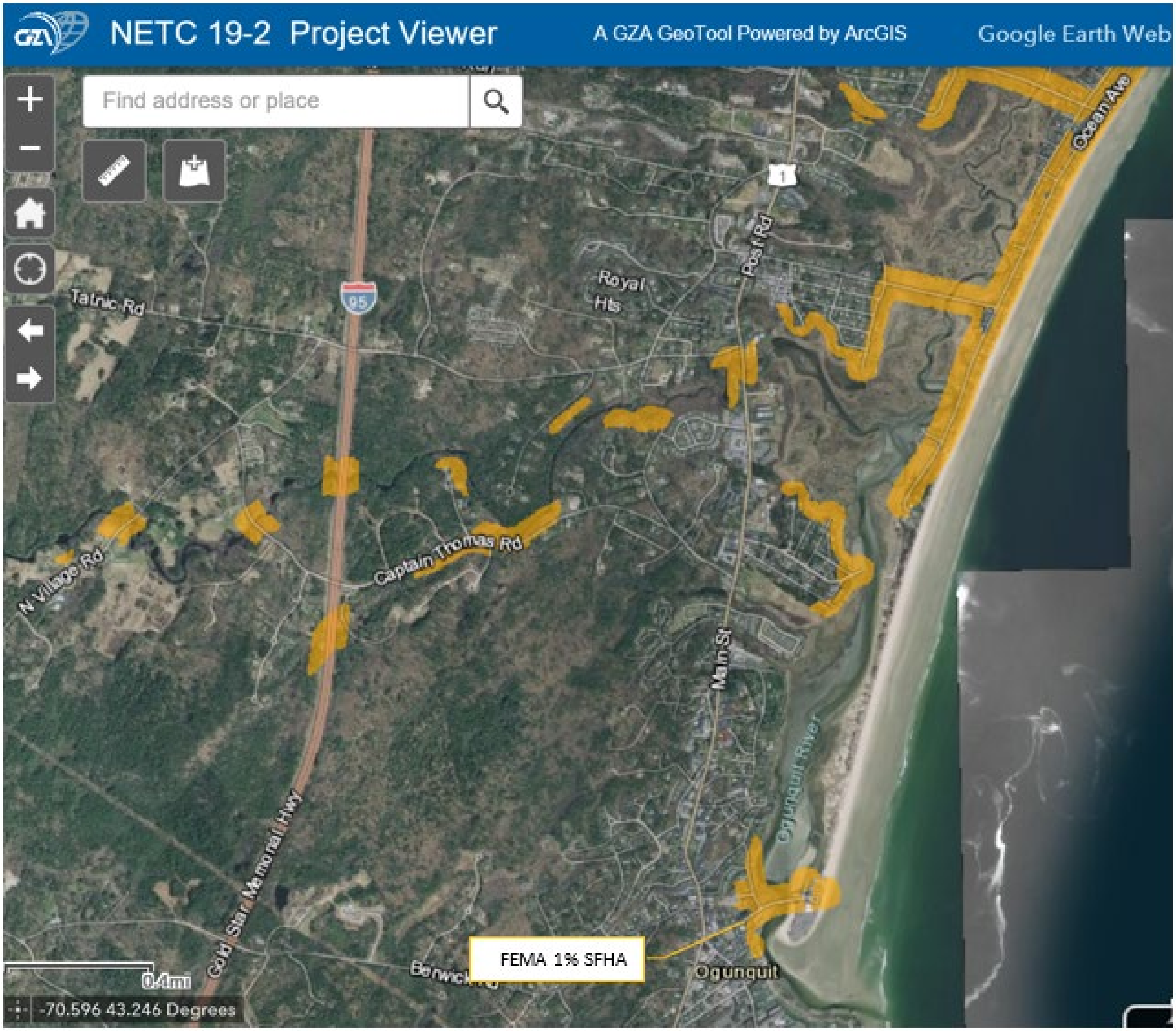
Note: include cross and large culverts

Figure 33: Model for Processing FEMA Special Flood Hazard Area Data



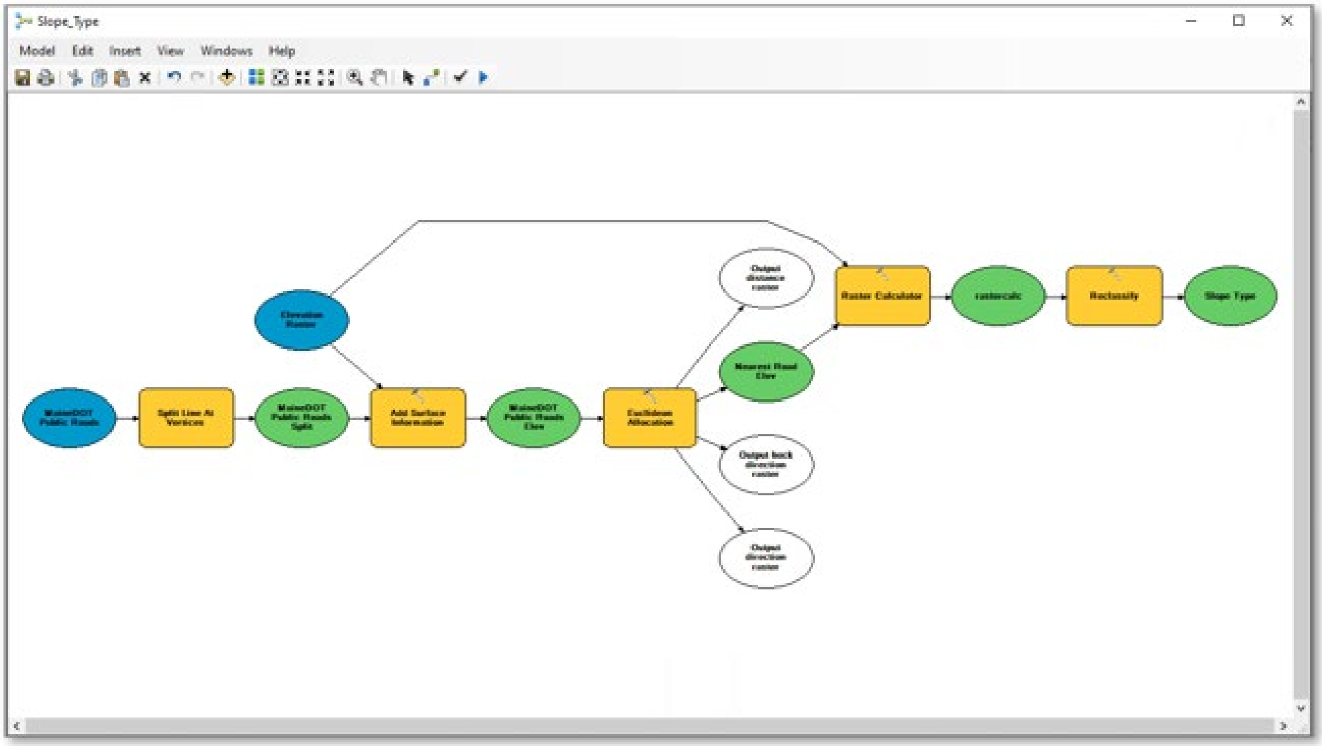
Note: ModelBuilder view

Figure 34: Example View of Proximity to FEMA's Special Flood Hazard Area



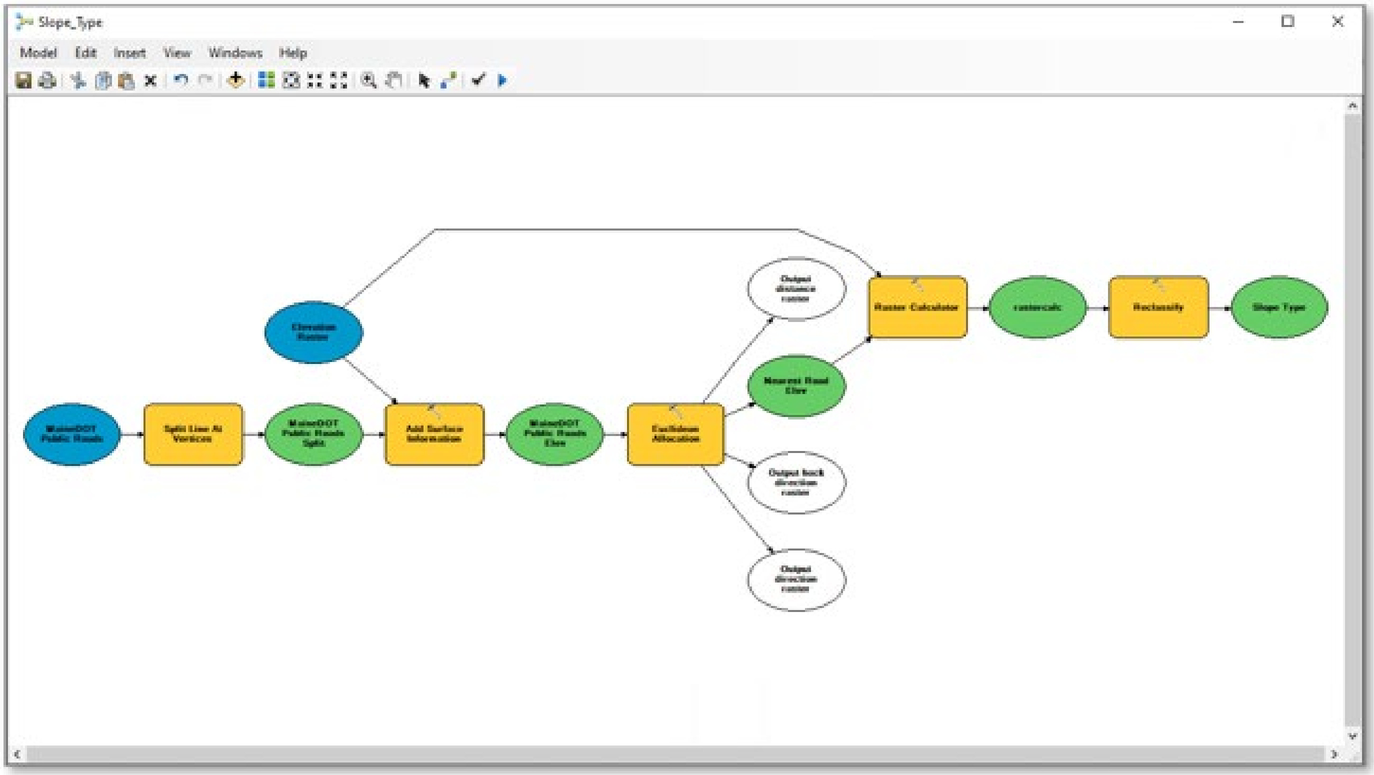
Note: SFHA due to both riverine and coastal flood sources.

Figure 35: Model for Calculating Slope Types



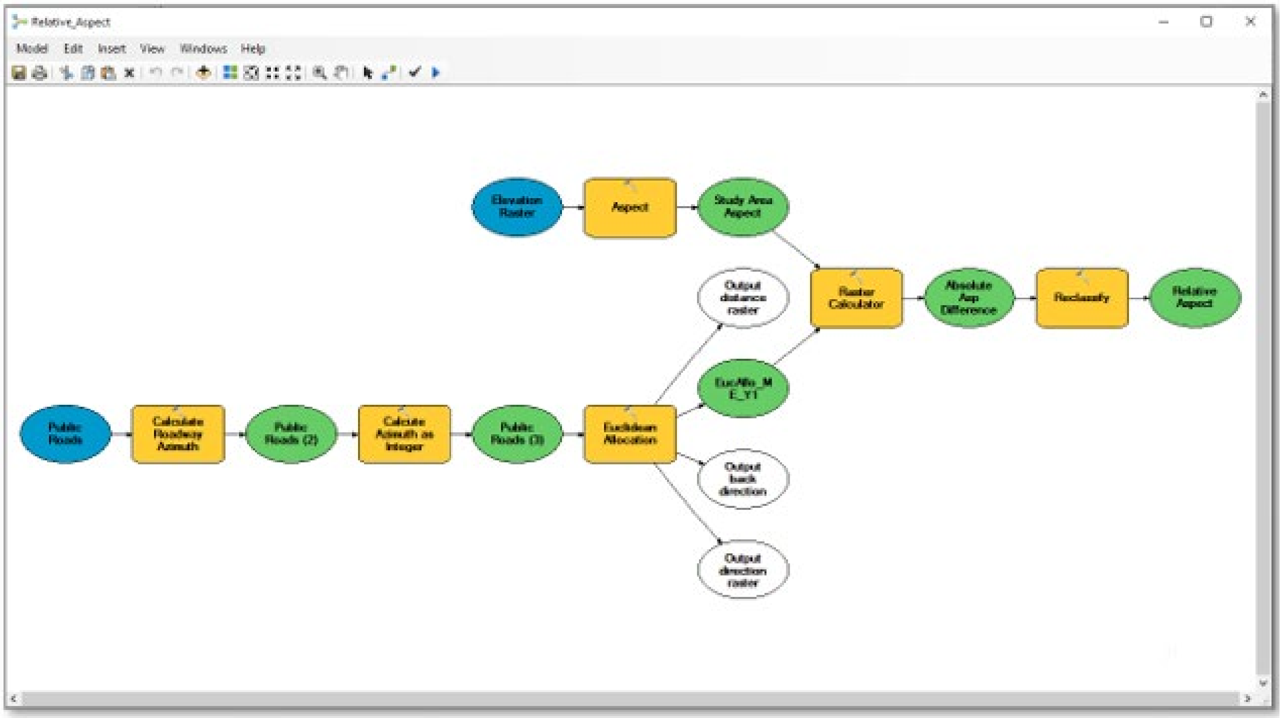
Note: ModelBuilder view.

Figure 36: Example View of Slope Types



Note: ModelBuilder view.

Figure 37: Model for Calculating Relative Aspect



Note:. ModelBuilder view.

Figure 38: Example View of Relative Aspects Layer

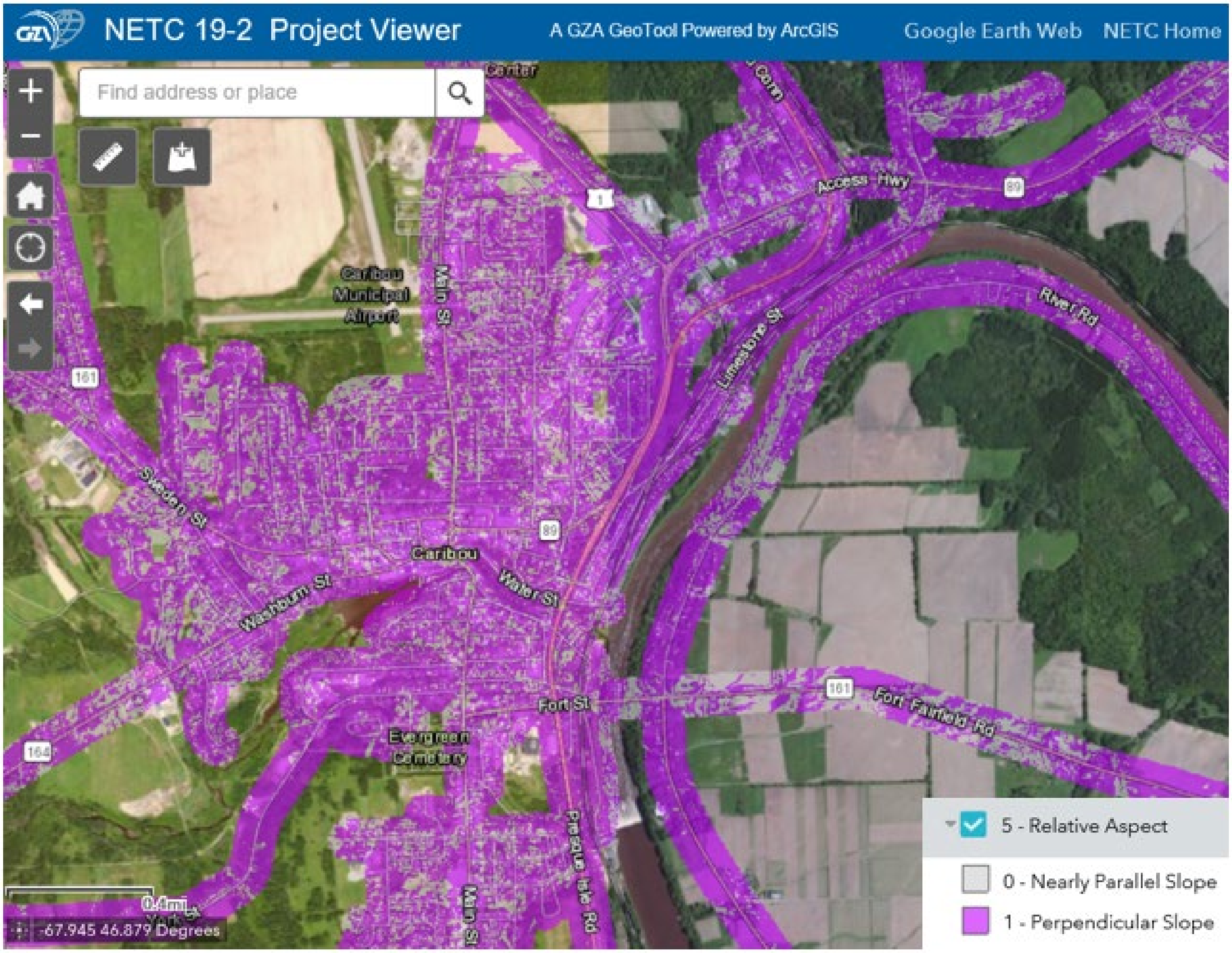
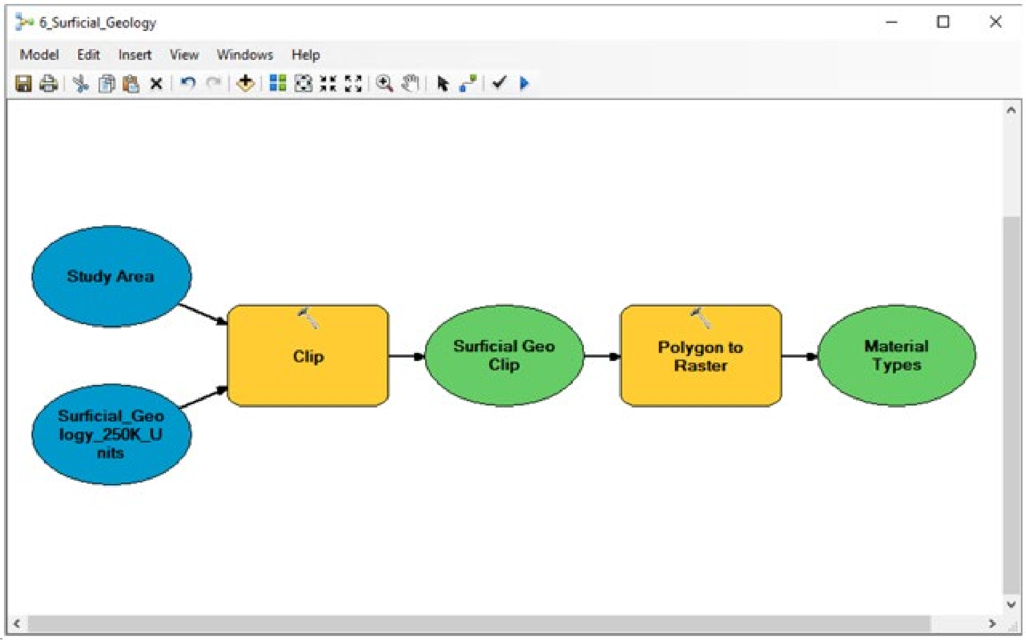
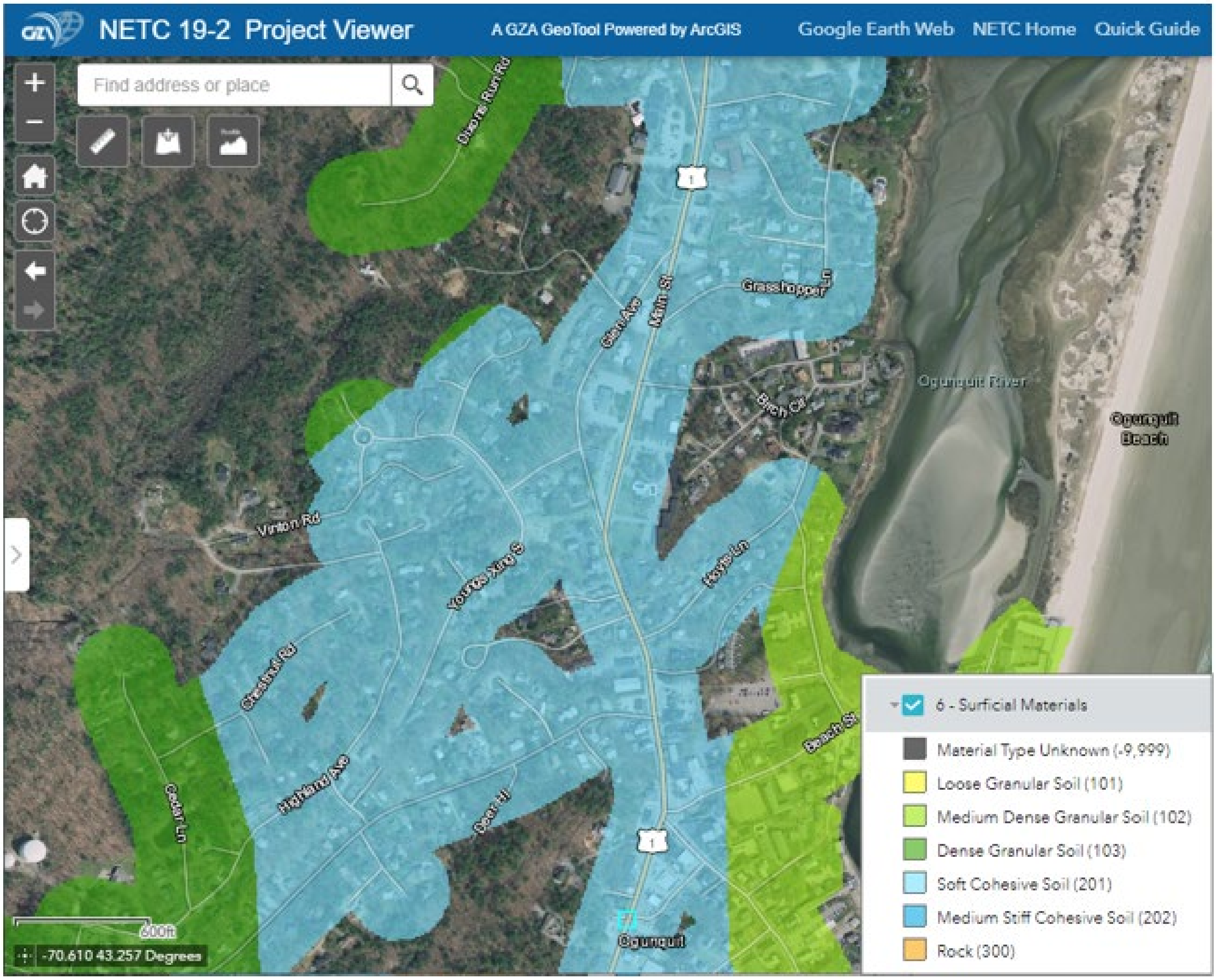


Figure 39: Model for Assigning Surficial Material Types



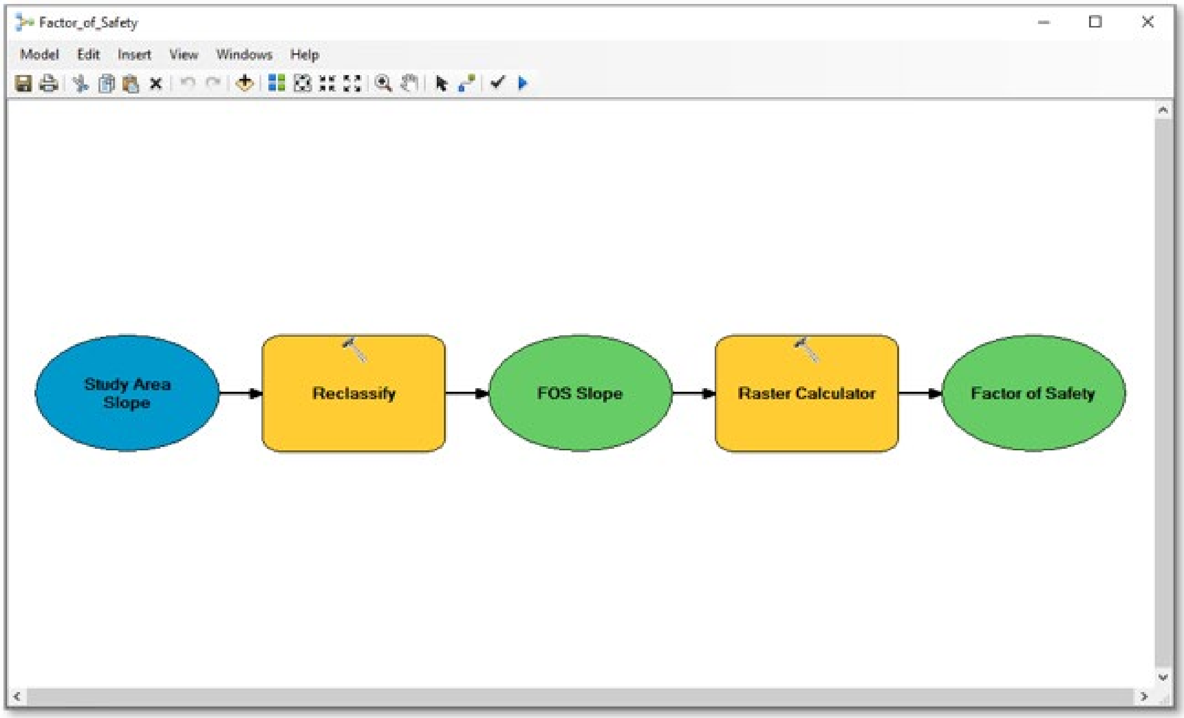
Note: ModelBuilder view.

Figure 40: Example View of Material Types



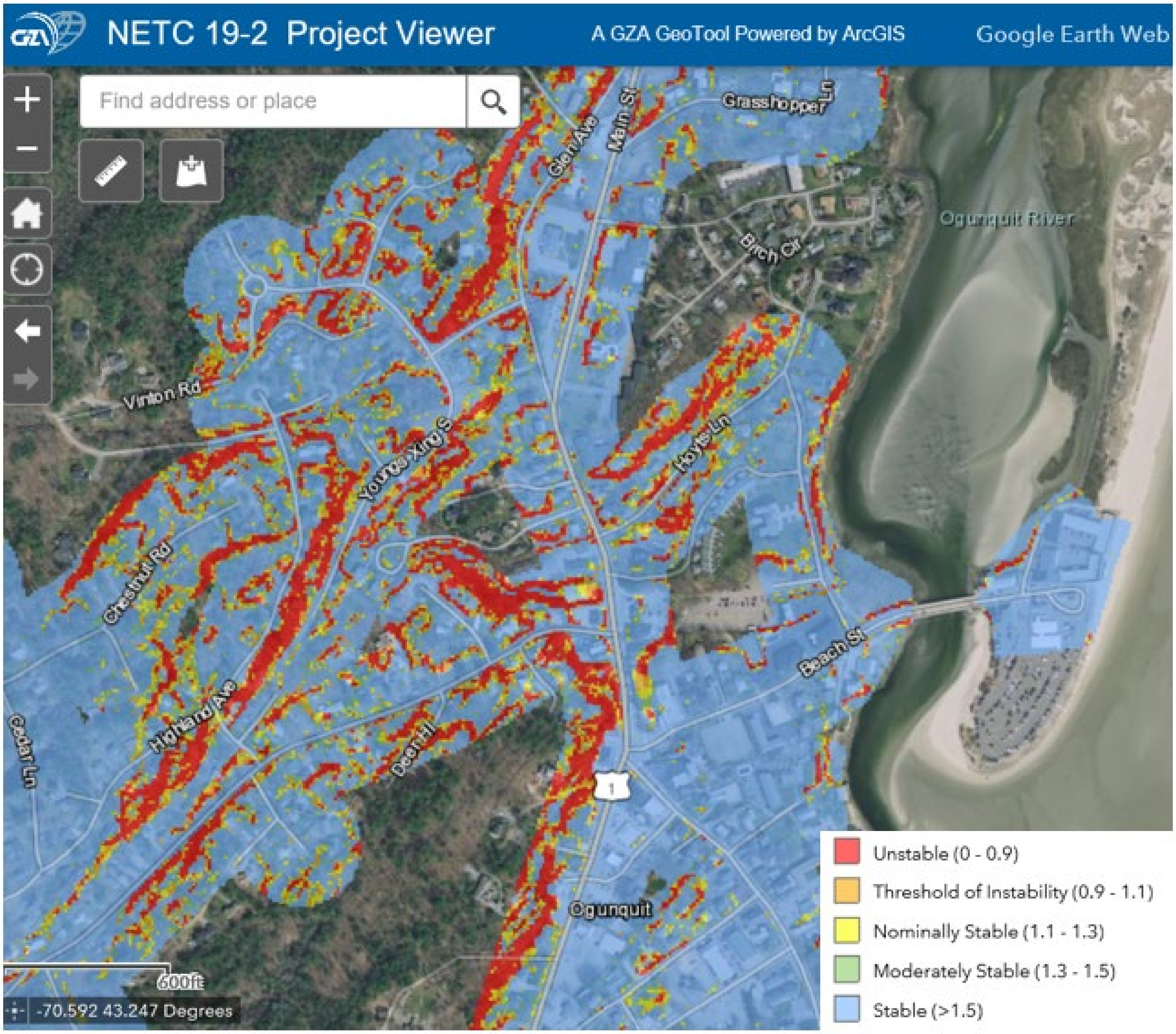
Note: Soil types only. Rock not present in this area.

Figure 41: Model for Calculating Factor of Safety



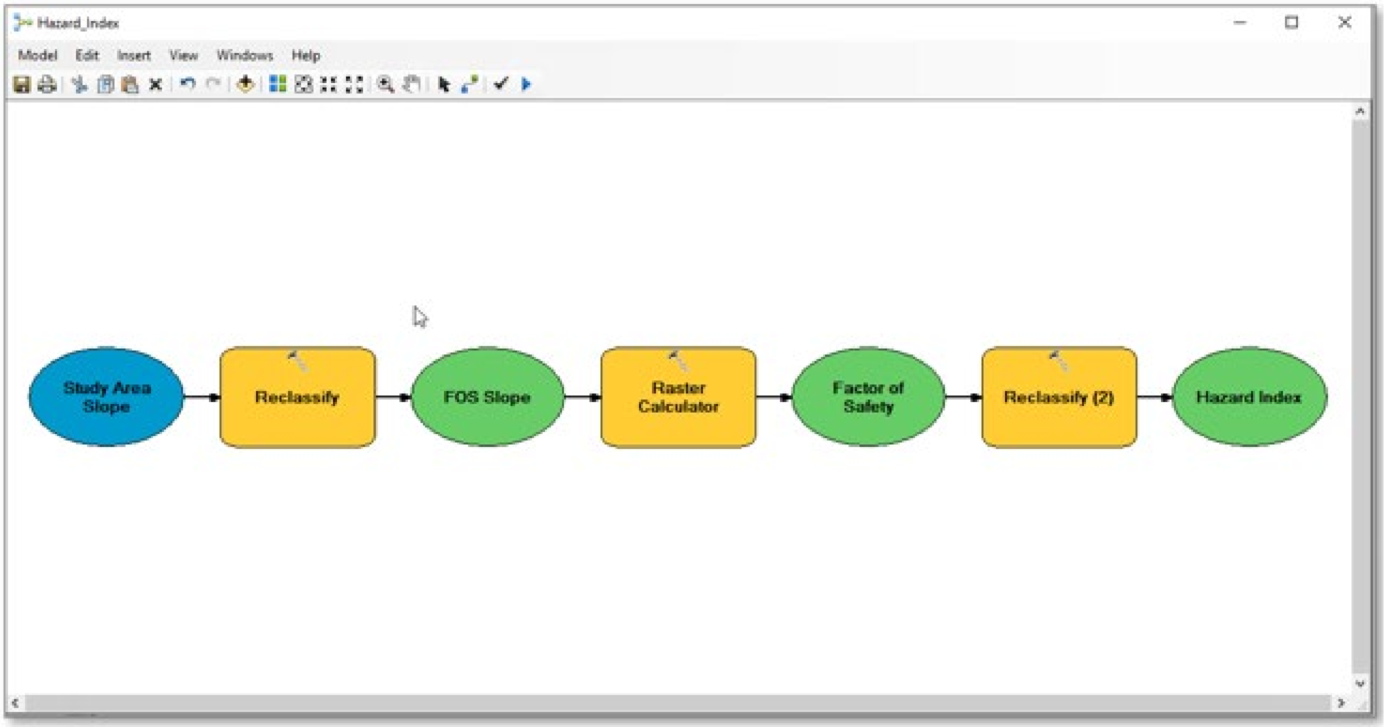
Note: ModelBuilder view.

Figure 42: Example View of Factor of Safety



Note: Calculated factor of safety based on material types and slope.

Figure 43: Model for Calculating Hazard Index



Note: ModelBuilder view.

Figure 44: Example View of Hazard Index

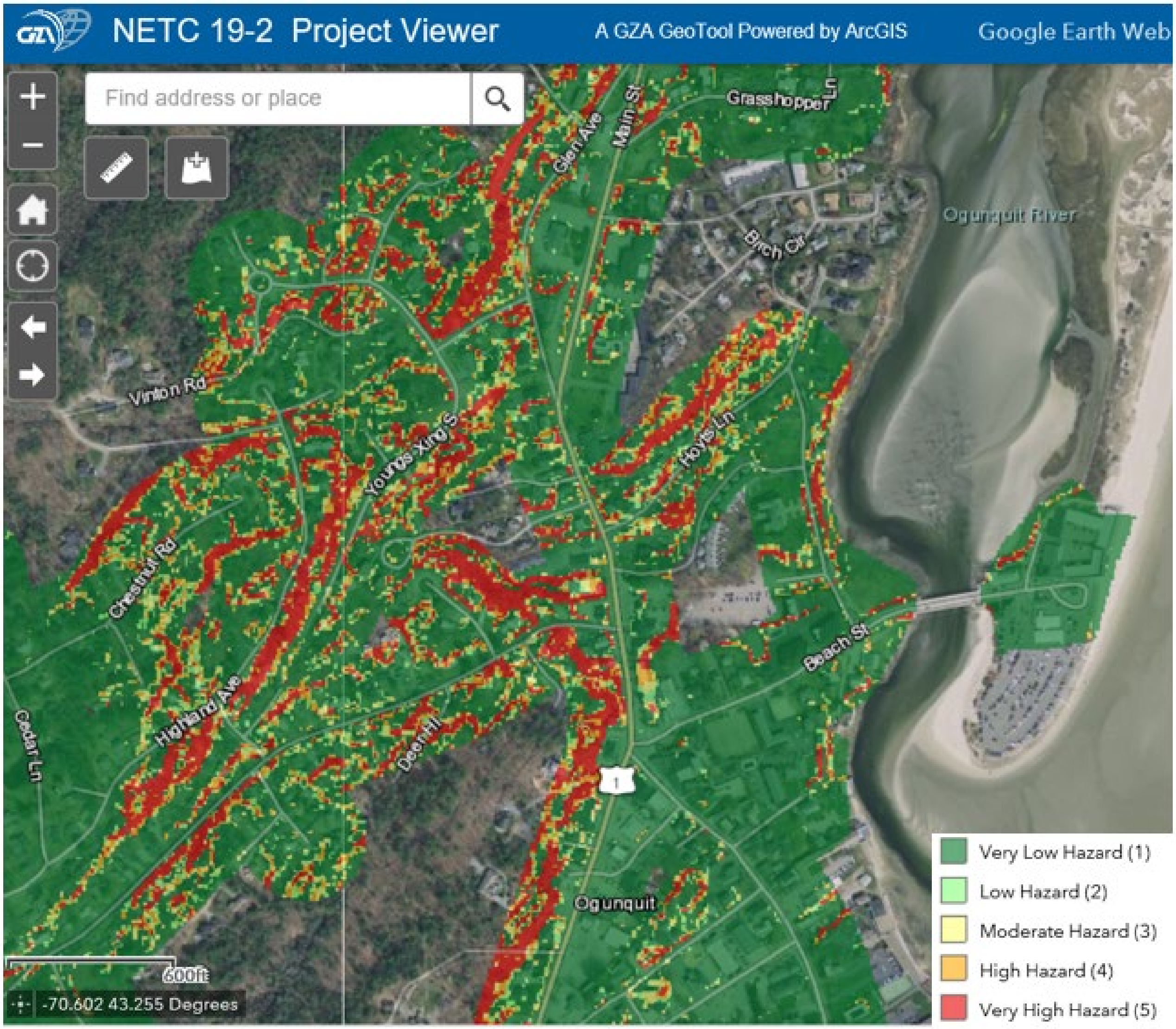


Figure 45: Model for Calculating Culvert Hazard Index

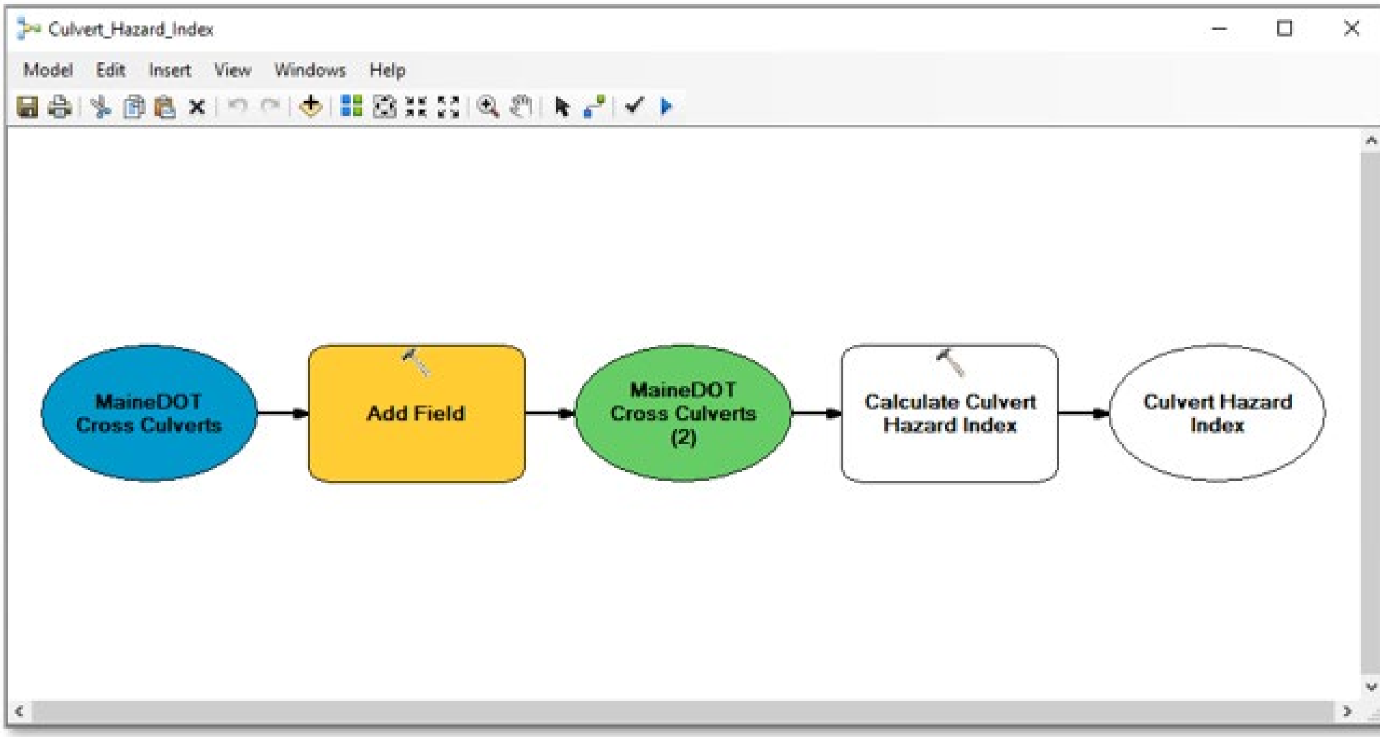


Figure 46: Example View of Culvert Hazard Index

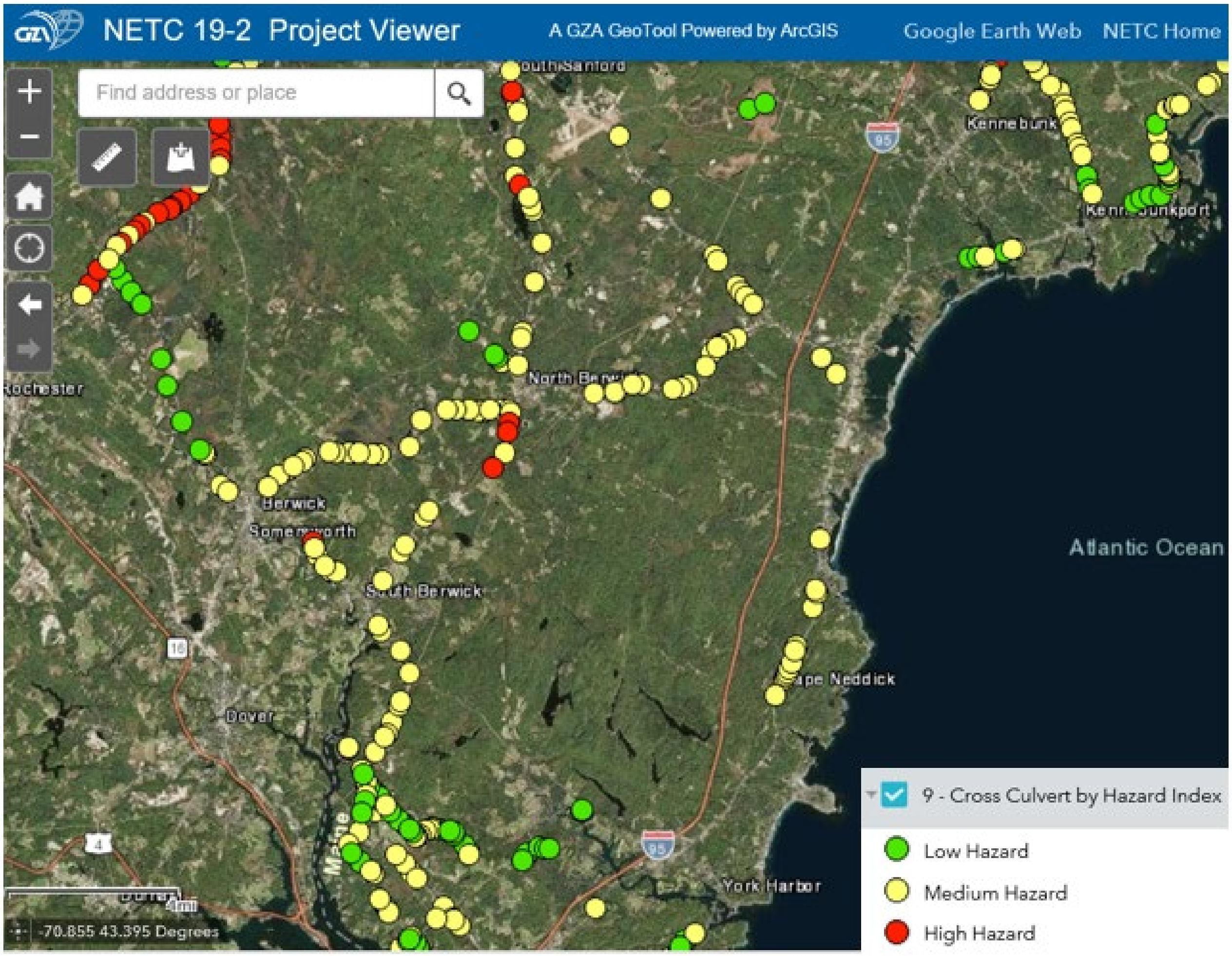
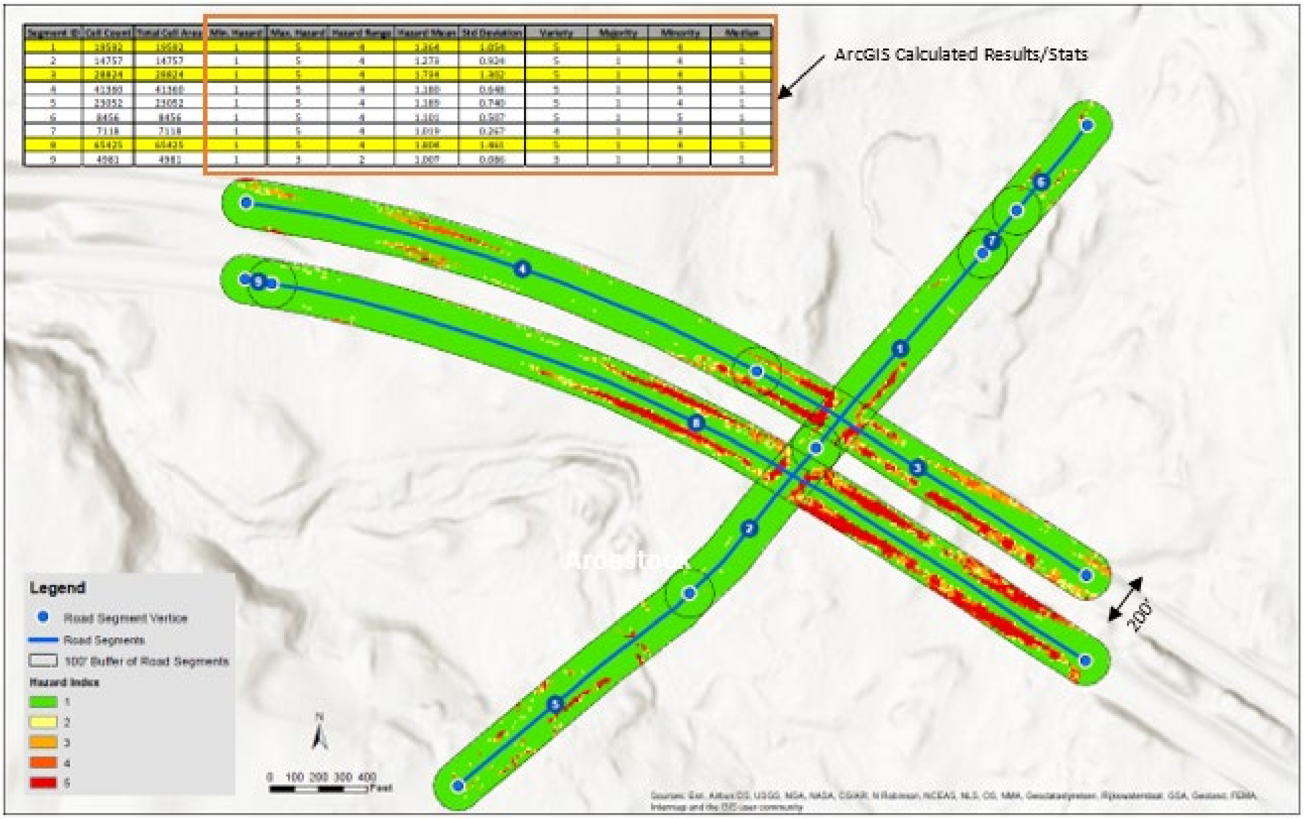


Figure 47: Experimental Roadway-based Hazard/Risk Calculation



Note: areas represent a 100-foot buffer from existing roadway centerlines (per MaineDOT's roadway inventory)

APPENDIX A – PRE-STUDY SURVEY RESULTS