USER GUIDE FOR THE VERMONT TRANSPORTATION RESILIENCE PLANNING TOOL (TRPT)

(Version 2.0)

Prepared for:

Vermont Agency of Transportation

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global **environmental** and **advisory** solutions

USER GUIDE FOR THE
VERMONT TRANSPORTATION RESILIENCE PLANNING TOOL (TRPT)

(Version 2.0)

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- SLR (formerly Milone & MacBroom): Roy Schiff, Jessica Louisos, Alexandra Marcucci, Doug Osborne, Brian Cote, Lauren Weston, Claire Nauman, James MacBroom, Tony Ciriello
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1.0 INTRODUCTION

This document contains concepts and key assumptions for users of the Vermont Transportation Resilience Planning Tool (TRPT) to understand the origin of the data and how to interpret results. Concept details and variable recipes are contained in the appendices.

Resources exist for TRPT users that are not as familiar with river science and road conflicts. The three-tier Vermont Rivers and Roads Training can be attended to learn more about the concepts that are used in the TRPT. Tier 1, the introductory online training, may be accessed on the internet (https://anrweb.vt.gov/DEC/RoadsTraining/Default.aspx). Tier 2 trainings are offered by the Vermont Rivers Program and build on Tier 1 concepts. Tier 3 advanced trainings are offered by a collaboration between VTrans and the Vermont Rivers Program and facilitate design.

1.1 Background

The goal of the TRPT is to improve the resilience of Vermont's highway network to floods and erosion by providing data and tools to inform planning and investment decisions. The TRPT consists of the following components.

- A method to systematically identify road segments, bridges, and culverts that are vulnerable to flood and erosion damages
- A screening tool to pinpoint the most critical locations and identify mitigation options on the transportation network
- A web-based application to display risk and mitigation information

The project was led by the Vermont Agency of Transportation with funding from a Federal Emergency Management Agency (FEMA) Hazard Mitigation Grant, federal funds through the VTrans State Planning and Research work program, and match from state transportation dollars. Project partners included the Vermont Department of Environmental Conservation, Vermont Emergency Management, Vermont Agency of Commerce and Community Development, the University of Vermont, regional planning commissions in Vermont, Vermont non-profit organizations, and other watershed stakeholders. A multidisciplinary consultant team was selected by VTrans to create the vulnerability analysis (SLR Consulting and Fitzgerald Environmental), criticality modeling (Smart Mobility), mitigation selection methods (SLR Consulting, Fitzgerald Environmental, and Dubois & King), watershed case studies (Dubois & King and SLR Consulting), and web-based application (Stone Environmental).

The TRPT was originally developed in 2018 for three pilot watersheds – Upper White River, North Branch Deerfield River, and Whetstone Brook (~4% of the state complete) (Table 1). The TRPT was built out by VTrans and several regional planning commissions during a second phase of data development (~20% of the state complete). The TRPT was completed by the developing consulting team in collaboration with University of Vermont in 2022 (100% of the state complete).

Table 1 TRPT Phased Buildout

Project Phase	Watershed	Developer
1	Whetstone Brook	Consultant Team
1	Upper White River	Consultant Team
1	North Branch Deerfield River	Consultant Team
2	Missisquoi River	VTrans and UVM
2	Huntington River, Joiner Brook, Snipe Island Brook	Chittenden County RPC and UVM
2	Stevens Branch	Central Vermont Regional Planning Commission and UVM
2	Headwaters of Otter Creek	Rutland Regional Planning Commission and UVM
2	Headwaters of the Batten Kill	Bennington Regional Commission and UVM
2	Williams River	Windham Regional Commission and UVM
2	Portions of several watersheds listed above	Two Rivers Ottauquechee Regional Commission and UVM
3	Remainder of State – Portions of most of the Vermont Planning Basins	Consultant Team and UVM

1.2 Brief Overview of the TRPT

The TRPT combines river science, hydraulics, and transportation planning methods and is applied at a watershed scale (see Appendix A for a glossary of relevant terms and acronym definitions). The TRPT has been developed and tested across Vermont to inform project scoping, capital programming, and hazard mitigation planning at the state, regional, and local levels. The need for the TRPT became apparent following the widespread damage to state and local roadways caused by flooding from Tropical Storm Irene in August 2011 and due to the increase in ongoing local damages that take place each year. Much of the agency's effort following Tropical Storm Irene focused on improving its emergency response and recovery capabilities to restore transportation functionality faster after a disaster. The TRPT's purpose is to identify vulnerabilities in a proactive manner to avoid or minimize the impacts of future damages in the most critical, highest risk locations.

The TRPT has identified risk levels for roads, bridges, and culverts due the consequences of failures associated with erosion, inundation, and deposition. A vulnerability (V) scoring system was created and linked to different levels of transportation failures. Low levels of vulnerability may lead to small-scale damages due to inundation or minor erosion/deposition while high levels of vulnerability may indicate that asset failure is likely due to severe erosion or deposition.

The TRPT web application, User Guide, and training videos may be accessed at http://roadfloodresilience.vermont.gov.

1.3 Accuracy

Field checking was performed to fine-tune TRPT results and check on the accuracy of predictions at a sub-set of roads, bridges, and culverts across the state. The TRPT was found to be 90% accurate in its predictions of risk, vulnerability, and criticality (Figure 1 and Appendix B). Field review was performed in each Vermont Planning Basin, on state and local roads, and over a range of risk, vulnerability, and criticality rankings. Approximately 10% of the Vermont road network was visited for field review.

Figure 1 TRPT Accuracy

1.4 Audience

The TRPT can be used by anyone with access to the internet. The following people are the intended primary user groups:

- Vermont Agency of Transportation
    - Planner
    - Bridge and Highway Engineers
    - Asset Manager
    - Hydraulic Engineer
- Vermont Department of Environmental Conservation
    - River Management Engineer
    - Floodplain Manager
    - River Scientist
- Regional Planning Commissions
    - Regional Planner
    - Transportation Planner
    - Emergency Management Planners
- Vermont Emergency Management
    - Hazard Mitigation Planner
    - Hazard Mitigation Grant Program Project Coordinator
    - Emergency Operation Center Watchstander

The following people are the intended co-beneficiary user groups:

- Vermont Agency of Transportation
    - District Manager
    - District Technician
    - Project Manager
- Vermont Agency of Commerce and Community Development
    - Economic Development Specialist
    - Community Planner
- Municipal Officials
    - Emergency responders to support transportation recovery (State Support Function 1)
    - Planner
    - Emergency management
    - Road Foreman
- Vermont Emergency Management
    - Emergency Operation Center GIS Analyst
- Researchers
    - Academia
    - Agency
    - NGO
    - Private
- Consultant
    - Planner
    - Engineer

1.5 Uses

The results of this project may be used for project identification and planning, project prioritization, budgeting, resource and asset management, initial site assessment, starting the scoping and design alternatives analysis, emergency preparedness, hazard mitigation planning, conservation planning, and planning for continuity of business and future housing.

1.6 How to Use this Guide

Chapters 2.0 through 6.0 of this User Guide are intended for all users and describe in more general terms the data, methods, and concepts behind the flooding and erosion vulnerability, transportation criticality, risk, and mitigation screening results presented in the TRPT.

Chapter 7.0 provides instructions on how to use and navigate the online TRPT application. While the controls and results in the TRPT are mostly intuitive, it is recommended that users become familiar with the data sources and concepts presented in Chapters 2.0 through 6.0 before applying the results.

Case studies from the pilot watersheds are provided in the appendices to demonstrate broadly applicable planning strategies that can be used on a wide range of mitigation projects and describe the diverse group of stakeholders often required to implement projects and reduce risks.

The appendices provide detailed technical documentation on the data and methods and are intended for use by Geographic Information System (GIS) specialists and travel demand modelers that will perform the vulnerability, criticality, and risk analyses for additional watersheds. Data development cheat sheets used during phase 2 data development by the regional planning commissions are also included in the appendices.

2.0 PRIMARY DATA

2.1 Primary Data

A variety of data were used for exploratory purposes, vulnerability screening, risk assessment, and display in the web application (Tables 2 to 5). The data include spatial information and reports describing roads, structures, Tropical Storm Irene damages, and river corridor variables. **Bolded datasets** indicate "backbone" datasets in the analysis – road and river segments from statewide databases. The typical road segment in the analysis is 0.5 to 1.0 miles long, and the typical river segment is 0.25 to 0.5 miles long (Appendix C). Availability of data such as Light Detection and Ranging (LiDAR) and stream geomorphic assessment (SGA) varied in the pilot watersheds (Appendix C).

Variables were calculated from the original datasets for vulnerability screening in the pilot watersheds (e.g., 100-year flood depth above the road, length of road in the river corridor, roadway-river relief, etc.). These calculated datasets are unique to the resiliency project and are described in detail in the following sections and appendices.

All vulnerability, criticality, and risk data are displayed at the road and structure scale. River variables were associated with the road segments by relating the nearest stream segment(s). Structures were associated with the nearest road-stream intersections, joining the road and stream segment variables for the intersection.

2.1.1 Roads

Table 2 Road Network Original Datasets

Data	Source and Format	Web Service	Data Use±	Comments
VTrans AllRoads/AOT Master Road Centerline	**VTrans - Shapefile**	**Yes**	**E, V, C, R, A**	**Principal dataset for assessment and display of vulnerability data. Available statewide.**
Automatic Road Analyzer (ARAN)	VTrans - Spreadsheet	No	E, V	Available on VTrans highways; years vary
LiDAR Digital Elevation Model	VTrans - ASCII Raster	No	E, V	At the time of the pilot analysis, LiDAR was available for parts of Routes 9, 100, and 107. Today it is available statewide.
Critical Closeness Accessibility (CCA)	UVM - Shapefile	No	C, R	Available statewide. On E911 roads layer.

± E = exploratory, V = vulnerability, C = criticality, R = risk assessment, A = viewable in application

2.1.2 Bridges and Culverts

Table 3 Structures Original Datasets

Data (Source)	Source and Format	Web Service	Data Use±	Comments
Structex (Phase 2 SGA)	VTANR - Spreadsheet	No	E, V, R, A*	Available where Phase 2 SGA have been conducted
VTrans Structures data	VTrans - Shapefile	Yes	E, V, R, A*	Long (>20-foot span) and short structures (6- to 20-foot span). Available on VTrans highways and for town long structures.
VTCulverts.org Structures data	Towns - Shapefile	Yes	E, V, R, A*	Town bridges and culvert inventories available statewide.
VTrans Small Culvert Inventory (Ultrashorts)	VTrans - Shapefile	Yes	E, V, R, A*	Less than 6-foot span. Available statewide for VTrans highways.

* Datasets may be modified from original source for the app.

± E = exploratory, V = vulnerability, R = risk assessment, A = viewable in application

2.1.3 Tropical Storm Irene Damages

Table 4 Damages Original Datasets

Data (Source)	Source and Format	Web Service	Data Use±	Comments
Detailed Damage Inspection Reports (DDIR)	VTrans - Shapefile and Scanned Reports	No	E, V	DDIR available on VTrans highways.
RPC Damage Sites	RPCs - Shapefile	No	E, V	Available by region statewide. May have limited information on damage details.
Public Assistance Project	FEMA - Shapefile	No	E, V	Available statewide; limited information on damage details.
Stakeholder Input	Public Meeting Notes	No	E, V	Locally available.

± E = exploratory, V = vulnerability, R = risk assessment, A = viewable in application

2.1.4 Rivers

Table 5 River Corridor Original Datasets

Data	Source and Format	Web Service	Data Use±	Comments
VHD SGA Network - Assessment	**VTANR - Shapefile**	**Yes; needs update**	**E, V, R, A***	**Principal dataset for assessment and display of vulnerability data. Associated with road segments for scoring and display. Available statewide.**
VT River Sensitivity Coarse Screen	MMI; VLT - Shapefile	No	E, V	Available statewide.
SGA Data: Phases 1 and 2	VTANR - Spreadsheet	No	E, V	Available for select watersheds.
VT River Corridor	VTANR - Shapefile	Yes; needs update	E, V	Available statewide for drainages over 2 square miles.
VT Meander Centerlines	VTANR - Shapefile	No	E, V	Available statewide for drainages over 2 square miles. Produced by VTANR for statewide river corridor mapping.
VHD SGA Network - FIT	VTANR - Shapefile	Yes	E, V	Available in select locations.
Valley Walls	VTANR and TNC - Shapefile	No	E, V	Available statewide for drainages over 2 square miles. Produced by VTANR for statewide river corridor mapping.
SSURGO	USDA - Shapefile	Yes	E, V	Available statewide.
DFIRM Floodplains and Cross Sections	FEMA - Shapefile	Yes; needs update	E, V	Available where flood insurance rate mapping has been conducted.

* Datasets may be modified from original source for the app.
± E = exploratory, V = vulnerability, R = risk assessment, A = viewable in application

3.0 VULNERABILITY (V)

3.1 Overview/Definition

During flooding events, transportation infrastructure may be vulnerable to damages from inundation, erosion, or depositional processes. The severity of these damages will vary based on the magnitude of the flood. Vulnerability to inundation, erosion, and deposition damages in the 10-, 50-, and 100-year floods was evaluated for roads, bridges, and culverts in the three pilot watersheds. Vulnerability was evaluated using variables measured at the river reach, structure, and road segment scales combined in a scoring system that assigned a vulnerability value of 0 to 10 for each road, bridge, and culvert.

3.2 Scoring Overview

For roads and structures vulnerable to damages, the type of flood vulnerability (i.e., inundation, erosion, or deposition) will affect the severity of damages (Figure 2 and Table 6). Inundation may cause temporary road segment closures but rarely causes long-term disruption of travel; therefore, the inundation prioritization scores were capped at 5 (moderate vulnerability). However, the severity of erosion and deposition damage may range from debris removal or minor shoulder repairs to replacement of a critical bridge or long stretch of completely washed out road embankment.

Erosion and deposition scores range from 1 (low vulnerability) to 10 (high vulnerability). Previously damaged sites were scored based on the failure mode of the asset as documented in the Federal Highway Administration (FHWA) Detailed Damage Inspection Reports (DDIR) and FEMA Public Assistance Worksheets (Appendix D and Appendix E). Road segments were assigned a vulnerability score of 0 if they were not within 100 feet of a low-order stream or valley wall, and structures were only scored if they were near a road-stream intersection (Appendix F and Appendix G). Aside from the sites with damage records, the probability of failure is not 100% for assets given a score of 10. Due to uncertainties in the data and the stochasticity associated with a storm event, the probability of failure is approximately 30% to 40% (on average) for sites with a vulnerability of 9 or 10 based on past Vermont flood damage records.

Table 6 Summary of Vulnerability Scoring

Vulnerability Score	Vulnerability Rank	Likely Failure Mode	Transportation Influence	Distance (miles)	Vulnerability Type
0	Low	None	Road far from river such that vulnerability is unlikely	N/A	N/A
1, 2, 3	Low	Partial Closure	Single-lane closure, reduced capacity with some allowable travel, <24 hours	<0.25	Temporary inundation, minor erosion or deposition
4, 5	Medium	Full Closure	Multilane closure, detour required, 24 hours to several days	0.25 – 1	Large-scale inundation, localized erosion, localized deposition
6, 7, 8	Medium	Temporary Failure	Partial destruction of facility, several days to 1 week for recovery	0.25 – 1	Severe inundation, erosion, deposition
9, 10	High	Complete Failure	Complete destruction of facility, 1 week to months for recovery	Varies	Severe erosion or deposition

$$V_{ROAD\ EMBANKMENT} = MAX(V_{I,ROAD}; V_{E,ROAD}; V_{D,ROAD})$$
$$V_{BRIDGES} = MAX(V_{I,\ BRIDGES}; V_{E,BRIDGES}; V_{D,BRIDGES})$$
$$V_{CULVERTS} = MAX(V_{I,CULVERTS}; V_{E,CULVERTS}; V_{D,CULVERTS})$$

where I = inundation, E = erosion and D = deposition

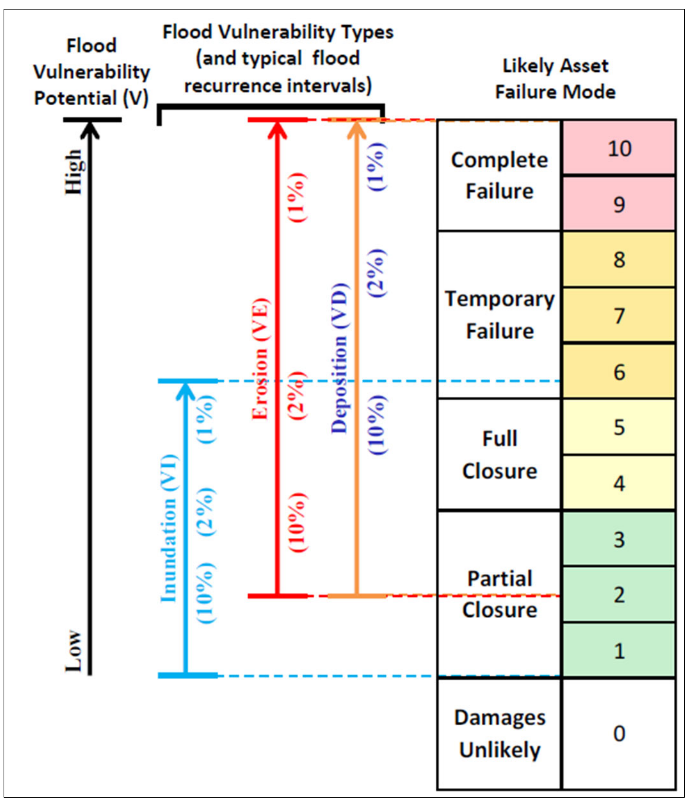


Figure 2 Vulnerability screen by process and failure mode

3.3 Vulnerability Processes

Vulnerability was estimated for three processes: inundation, erosion, and deposition (Table 7). The type and severity of damages associated with each process is expected to vary, and thus, the set of variables to predict vulnerability associated with each process differs. For instance, low stream power will be associated with deposition of sediments while moderate to high stream power will be associated with erosion (see Appendix F and G).

Table 7 Flood Vulnerability Types

Vulnerability Process	Other Names	Definition	Photograph
Inundation *Example: Flooding of an Elm Street parking lot in Brattleboro along Whetstone Brook (Photo courtesy Town of Brattleboro)*	Flooding Submergence Ponding	Submergence of a crossing or low spot in the road due to rising floodwaters where road closures take place, yet the facility is typically not damaged or is operating shortly or immediately after the floodwaters recede.	
Erosion *Example: Washout of U.S. Route 4 in Mendon (Photo courtesy of J. Louisos)*	Undercutting Scour Washout Downcutting	Erosion of the banks, channel bed, road embankment, and structure abutments/footings due to high-velocity moving material downstream. Undercutting results in high-impact events such as bank erosion, structure failure, and road embankment washout that requires immediate repairs prior to reopening roads. Widespread road embankment failure can take weeks to restore.	
Deposition *Example: Deposition along Route 100 from Money Brook in Plymouth, VT (Photo courtesy of M. Tucker)*	Debris buildup Clogging Accumulation	The deposition of sediment or large wood that can clog structures and reduce the space in a channel to carry floodwaters. Deposition typically leads to washout of the road fill near a structure, bank erosion and channel widening, or rapid channel relocation (i.e., avulsion).	

3.4 Flood Sizes

Vulnerability was estimated for three flood scenarios (Table 8) – one moderate flood (10% chance of occurring in a given year) and two large floods (2% and 1% chance of occurring in a given year). By examining a range of flood magnitudes, overall flood vulnerability of road segments and structures to varying failure modes from inundation, erosion, and deposition was assessed (Table 8).

The effects of climate change on flood magnitude were not explicitly considered in this analysis as future flood prediction and detailed hydrologic-hydraulic modeling were a step beyond the scope of this screening tool. However, the evaluation of each asset's vulnerability to a range of flood severity allows the user to understand relative vulnerability at each site (i.e., the effects of climate change flood damage potential are implicit through the evaluation of moderate to extreme floods). Using these flood magnitudes facilitated the calibration of the model with recent flood damage data. The vast majority of the damage data available for the pilot watersheds describes damages sustained in 2011 during Tropical Storm Irene, which was a regional flood approximating (or exceeding) the 100-year flood.

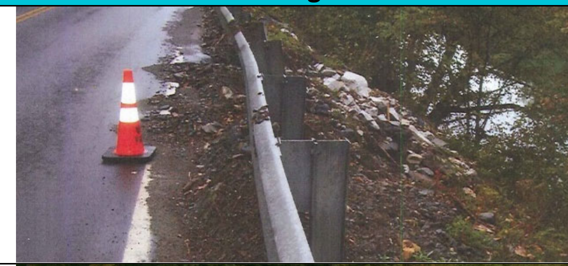
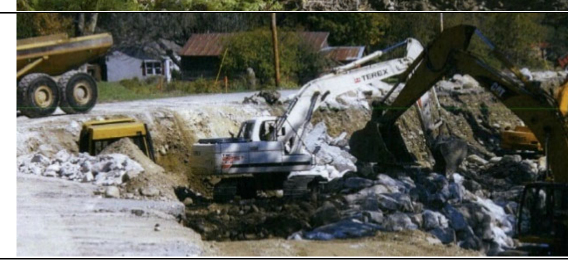
Table 8 Summary of Flood Recurrence Intervals Assessed in Vulnerability Scoring

Recurrence Interval (years)	Annual Exceedance Probability (AEP; %)	Typical Scenario
10	10%	High-intensity, short-duration summer thunder burst
50	2%	Local floods from repetitive thunderstorms in one or more watersheds in short periods of times (i.e., training storms) resulting in localized loss of structures and road segments
100	1%	Regional floods such as nor'easters and tropical storms that impact large areas of the state with major road and infrastructure loss

3.5 Failure Types

Damage data from Tropical Storm Irene were compiled for the subwatersheds from FEMA Public Assistance Projects shapefiles, VTrans DDIR shapefiles and photographs, and Regional Planning Commission shapefiles (see Appendix D and Appendix E). Failure modes were assigned to each damage record (Table 9).

Table 9 Failure Definitions and DDIR Images of Each Failure Mode

Failure Mode	Influence	Image
Partial Closure *Example: Shoulder damage along Route 100 in Stockbridge*	Single-lane closure resulting in brief disruptions (<24 hours) over short distances (100 feet or less) of travel due to temporary inundation with lower-velocity floodwaters or small-scale deposition or erosion events in smaller channels or near undersized structures. Shoulder repair, culvert replacement, or minor sediment and debris removal from roadway may be needed after floodwaters recede. Alternate routes are not required but may be sought out by travelers.	
Full Closure *Example: Embankment washout and some shoulder damage along Route 100 in Rochester*	Closure of all lanes (24 hours to several days, hundreds of feet) due to inundation during large floods or localized damages associated with erosion or deposition typically during the 10% chance flood or larger. Sediment and debris removal from roadway may be needed after floodwaters recede. Work on drainage ditches, culverts, and road shoulders may also be required for the recovery. Alternate routes are required, so the disruption to local traffic can be substantial.	
Temporary Failure *Example: Route 107 washout due to a plugged culvert in Stockbridge*	Partial asset damage resulting in temporary disruption (typically days to a week, hundreds to thousands of feet) typically caused by river erosion or deposition, leading to culvert failure or partial roadway embankment failure. Roadway is typically closed during and immediately following the disruption, but one travel lane may be rapidly restored during the emergency recovery period. Reduced access to destinations as alternate routes is required during the disruption. Utilities may be damaged.	
Complete Failure *Example: Route 73 washout due to a plugged bridge in Rochester*	Complete asset damage resulting in long-term disruption (weeks/months, thousands of feet) of travel typically caused by river erosion or deposition, leading to complete roadway embankment failure, bridge failure, or large culvert failure. The roadway is closed during the emergency recovery period, and long-term travel disruptions take place. Utilities damaged, and commerce is reduced.	

3.6 Variables

The variables used for the inundation, erosion, and deposition vulnerability screens (Table 10) were selected and scored based on geomorphic process, scientific literature (e.g., Dunne and Leopold, 1978; Nanson and Croke, 1992; Knighton, 1999), and professional judgment based on flood mitigation and recovery work in Vermont and the region. The TRPT development team was familiar with the existence and availability of these variables from past work, performing stream geomorphic assessments, aquatic organism passage, and geomorphic compatibility screens on structures, assisting with Tropical Storm Irene recovery efforts, and developing the Vermont River Sensitivity Coarse Screen (Schiff et al., 2015).

Variables were classified as high, moderate, or low based on their categorical or numerical values (Appendix G). The classification for each variable was entered into a screen using logical combinations to assign a vulnerability score for inundation, erosion, and deposition to each structure and road segment. Classifications made using the raw data were used for the 2% (50-year) annual exceedance probability (AEP) scenario and scaled for the 10% (10-year) and 1% (100-year) floods. The vulnerability scoring system was created for bridges, culverts, and highway segments to inundation, erosion, and deposition (Figure 3, Appendix G, and Appendix H).

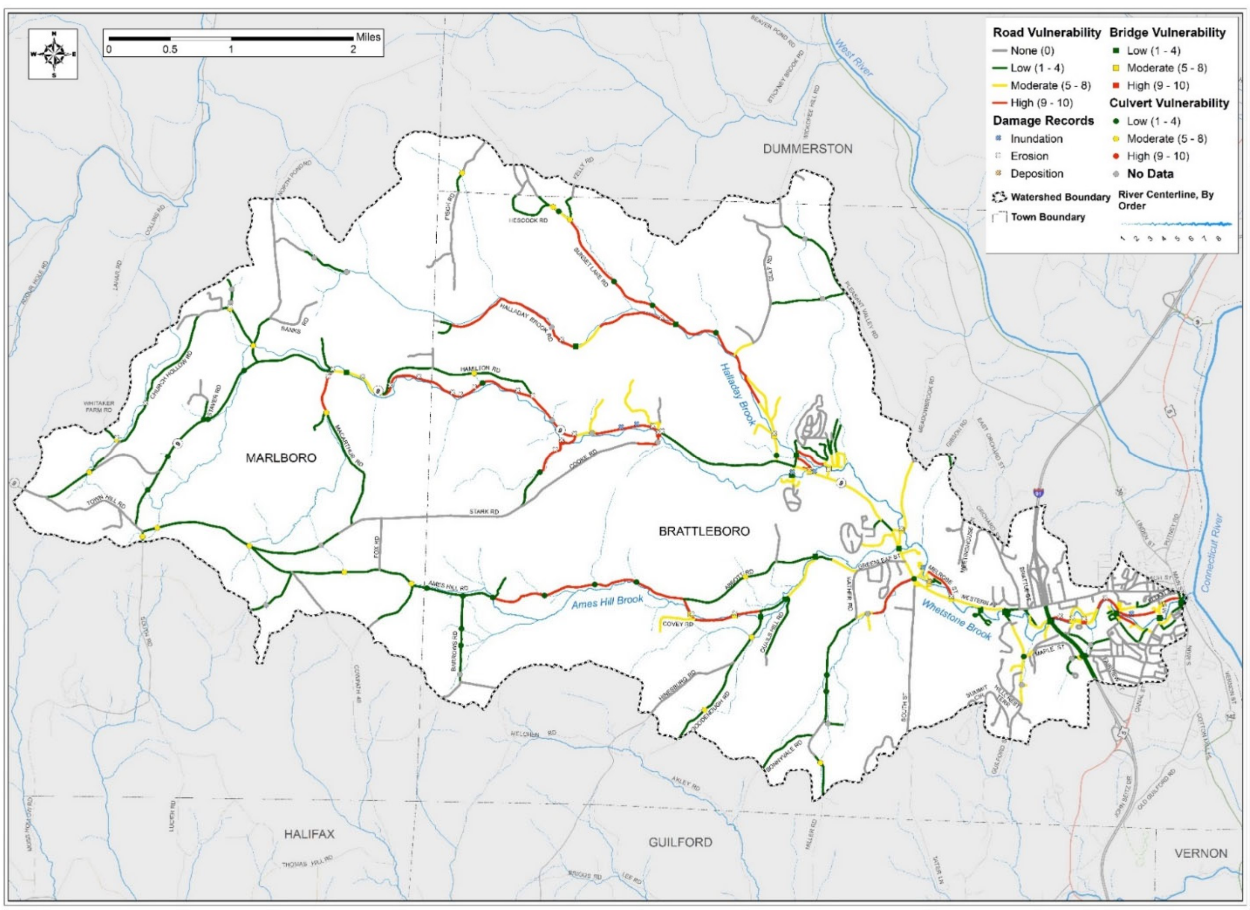


Figure 3 Example map of vulnerability scores for Whetstone Brook watershed

Table 10 Variables Used in Vulnerability Screens for Inundation, Erosion, and Deposition

	VARIABLES			SCALE		
More Detailed Variables	**Inundation**	**Erosion**	**Deposition**	**Road Segments**	**Structures**	**River Segments**
Documented Past Damages	√	√	√	√	√	
River-Roadway Relief (feet)	√			√		
Incision Ratio and Entrenchment Ratio	√	√				√
FEMA 100-Year Flood Depth Above Road (feet)	√			√		
Length of Road in 100-Year Floodplain (feet)	√			√		
Bridge/Culvert Invert-Roadway Relief (feet)	√				√	
Structure Width vs. Bankfull Channel Width (%) (HGR-based)	√	√	√		√	
Specific Stream Power (W/m^2)		√	√			√
Dominant Substrate Size		√				√
Valley Confinement		√				√
Remaining River Corridor Width where the ROW or Development Confine River (%)		√		√		
Length of ROW in River Corridor (feet)		√	√	√		
Erosion (SGA Data, GC Screen)		√			√	
Armoring (SGA Data, GC Screen)		√			√	
Culvert Slope (SGA Data, GC Screen)		√			√	
5% or Larger Slope Decrease Areas (count)			√			√
Third Order or Larger Confluences (count)			√			√
Change in Confinement Ratio from Upstream Reach			√			√
Road Crossings (count)			√	√		
Mass Failures in Upstream Reach (feet)			√			√
Bank Erosion in Upstream Reach (% of Channel Length)			√			√
Channel Slope (SGA Data)			√			√
Sediment Discontinuity (SGA Data, GC Screen)			√		√	
Approach Angle (SGA Data, GC Screen)			√		√	
Less detailed variables (to replace more detailed variables when they do not exist)						
Valley Slope	√					√
Surficial Landform in Corridor Area		√				√
Steep Slopes in Upstream or First Order Reach (feet)			√			√

[1] Refer to Appendix F for detailed information on the data sources and methods used to develop the variables.

4.0 CRITICALITY (C)

4.1 Overview/Definition

Criticality (C) scores are a relative metric of the consequences of the failure of an individual road segment. For this project, C was calculated as a composite index of the following three components:

1. Network Criticality Index (NCI) – The impact on local and regional travel due to failed trips and delays associated with simulated flood damages
2. The importance of a link to access critical facilities such as hospitals
3. The importance of a road for local use as reported by residents

4.2 Refinement of the Statewide Travel Demand Model

VTrans maintains a statewide transportation model (Sullivan and Conger, 2013). The base statewide model includes only major roadways and little detail about the locations of different land uses. An enhanced version of the statewide transportation model was developed for this project, which supports detailed subarea modeling for an individual watershed. As part of this project, all local roads were added to the model in each of the three pilot watersheds. Within the watershed and a buffer area extending around the three pilot watersheds, all roadways are modeled, and the locations of individual buildings are modeled based on E911 data (Figure 4).

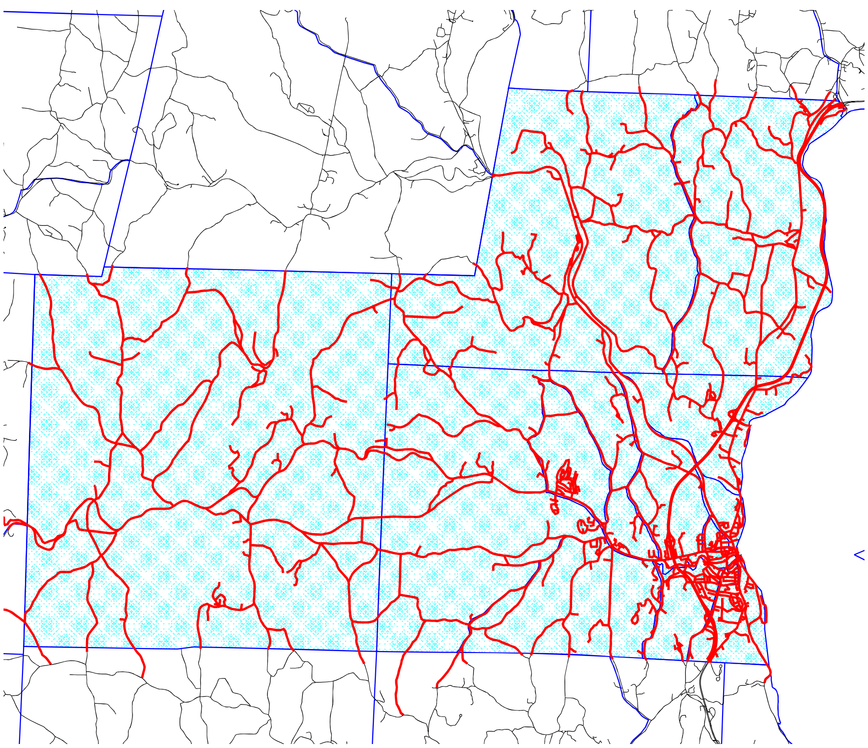


Figure 4 Whetstone Brook subarea model including all state and local roads

4.3 Network Criticality Index (NCI)

The NCI (Appendix I) modeling builds on the Network Robustness Index (NRI) developed by the University of Vermont Transportation Research Center (Sullivan and Novak, 2015). The NCI modeling requires access to and a good understanding of *TransCAD*, the commercial software that is used for the Vermont travel demand model (Caliper, 1990). The NCI extends the NRI work in two important ways. First, the NCI considers scenarios with multiple roadway segment failures through simulations while the NRI considers only one road segment at a time. The NCI can thus identify secondary routes as critical in cases where both primary and secondary routes are vulnerable (Figure 5). Second, the NCI modeling uses vulnerability scores to calculate both delay and failure probabilities for different storm events (Figure 6). The NRI assumes that trips can be delayed but not prevented. In summary, the NCI builds on the NRI to provide a more realistic flood damage simulation based on vulnerability to identify local and regional changes to the road network during floods and recovery.

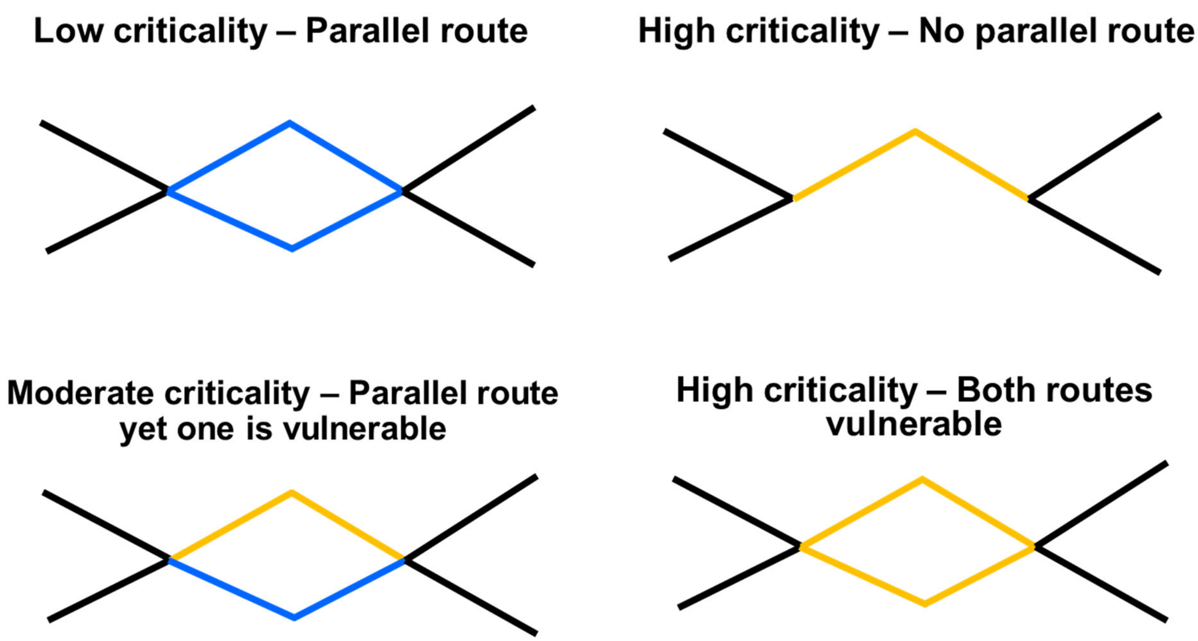


Figure 5 Schematic of vulnerability-based criticality showing low (blue) and high (orange) criticality scenarios

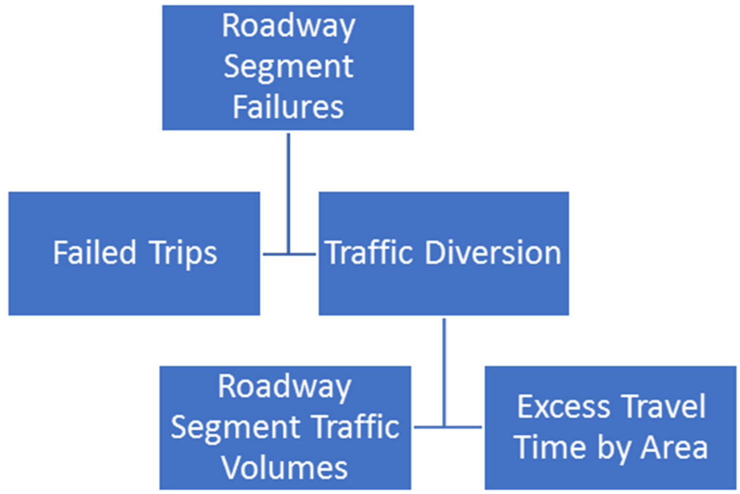


Figure 6 **NCI captures trips that cannot be completed and delayed trips**

The vulnerability scores determine the probability of failure or delay for each roadway segment. The NCI estimates were calculated using the output of 1,000 model runs. Each model run represents a scenario of a different combination of multiple road failures, selected randomly based on their vulnerability and associated failure probability.

While it is important that all users understand the concept of the NCI, its calculation will be provided by transportation professionals with expertise in travel demand modeling. VTrans will ensure NCI values are available for future watersheds through its ongoing cooperative agreement with the University of Vermont to maintain and operate the statewide travel demand model. In some cases, consultants with travel demand modeling expertise may also be utilized.

4.4 Critical Closeness Accessibility Index (CCA)

The CCA used the Vermont statewide transportation model to score the relative importance of roadway segments that provide critical access to critical facilities including hospitals, police departments, ambulance dispatch stations, and fire stations (Sullivan et al., 2014). This index has been calculated for all major roadway segments in the State of Vermont and is available in a typical GIS file format.

4.5 Locally Identified Important Roads

The final criticality component allows users, potentially working with other stakeholders in a watershed, to manually identify the most critical roadways for reasons that may not be captured in the NCI and CCA modelling such as local detour routes, access to a town highway maintenance facility, or an emergency shelter that would support response and recovery operations. This stakeholder-driven method of establishing criticality is regularly used in resiliency work sponsored by the FHWA (e.g., FHWA, 2014b, a; Nelson et al., 2015).

4.6 Scoring

The NCI and CCA components of the C score are categorized as high, medium, or low based on their data distributions (Appendix I). The local importance variable is given a yes or no based on stakeholder input. The combination of the three C components is scored 0 (low) to 10 (maximum) (Table 11) (Appendix I). A high criticality score (i.e., $\geq$ 5) indicates that failure of the link could lead to many failed trips or long delays, that access to critical facilities could be reduced, and that a local detour route may be cut off.

Table 11 Variables and Scoring for the Criticality Screen

SCORE	Network Criticality Index		Critical Closeness Accessibility		Locally Important	Combined Criticality
10=	High or Medium	AND	High	AND	y	HIGH (RED)
9=	High or Medium	AND	Medium	AND	y	
8=	High or Medium	AND	High or Medium	AND	n	
7=	High or Medium	AND	Low	AND	y	
6=	Low	AND	High	AND	y	
5=	Low	AND	Medium	AND	y	
4=	High or Medium	AND	Low	AND	n	MEDIUM (YELLOW)
3=	Low	AND	High or Medium	AND	n	
2=	Low	AND	Low	AND	y	
1=	Low	AND	Low	AND	n	LOW (GREEN)

5.0 RISK (R)

5.1 Overview/Definition

Risk is the intersection of vulnerability and the consequence of failure, or criticality. For this project, risk was calculated as the average of V and C, and thus, has a 0 to 10 (maximum) score.

5.2 Scoring

Risk is displayed in the TRPT spatially by showing an asset's location on a plot of V versus C and color coding (Figure 7). High-risk (R > 5) roads, bridges, and culverts are red; medium risk assets are yellow (5 ≥ R ≥ 2); and low-risk sites (R < 2) are green. Risk is the initial view when opening the TRPT.

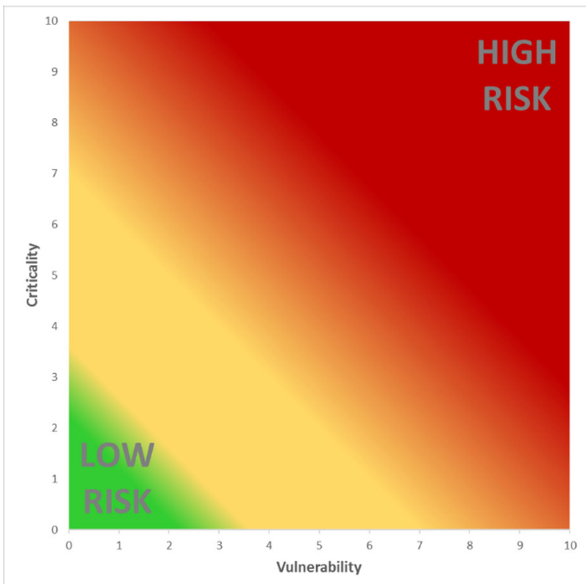


Figure 7 Generic risk plot of V versus C (left) and clip from the TRPT showing asset risk

6.0 MITIGATION (M)

6.1 Overview/Definition

A list of initial mitigation strategies to support broad planning and to begin an alternatives analysis to reduce vulnerability is provided in the TRPT. Mitigation recommendations were established based on the characteristics that contribute to vulnerability and criticality for each location (Appendix J). Planning strategies (Appendix K) are also helpful to mitigate risk yet are not explicitly covered in the TRPT.

The mitigation strategies are organized and presented in four groups as follows:

1. River and Road Stabilization – In general, the purpose of this group of strategies is to fortify road embankments, bridges, or culverts to resist erosion. River and road stabilization tend to be applied in high-risk settings where damages due to erosion and deposition are likely. Examples of river and road stabilization practices include armoring eroding riverbanks with a riprap slope or wall, installing rock veins or riffles to stabilize a downcutting riverbed, or installing stone around scourprone structures to protect foundations.

2. Conveyance of Flood Flows – In general, the purpose of this group of strategies is to increase space for passing (i.e., conveying) water, sediment, large wood, and ice downstream during flooding. An increase in application of this group of practices has taken place over the last decade to remove encroachments and give the river more space to reduce infrastructure conflicts. Examples of practices to improve conveyance of flood flows include restoring local flood benches in erosionprone, confined settings to reduce flood velocities and restoring floodplains to create more flood storage in a watershed to reduce local erosion potential and downstream flooding.

3. Floodplain Protection/Relocate Roads – In general, the purpose of this group of strategies is to protect the space in floodplains and river corridors to keep permanent infrastructure and private property out of areas where inundation, erosion, and deposition are taking place. This strategy group reduces rover-road conflicts in the future. Examples of floodplain protection/ relocate roads practices include adjusting the road alignment, conserving river corridors, and buying out floodprone properties individually served by floodprone roads.

4. Improve Vegetation – In general, the purpose of this group of strategies is to naturalize the riverbanks and riparian corridor to provide the many benefits of vegetation such as increasing bank stability, creating near-stream habitat for birds and insects, and filtering stormwater runoff. Although not applicable alone at sites with high flood velocities that are prone to excessive erosion, vegetative practices are universally applied to naturalize river and road stabilization projects in high-risk settings and to stand alone in less erosive environments.

Typically, more than one practice in more than one mitigation strategy group will be applicable at a project site. For example, a project may include armoring a riverbank with a placed riprap wall (river and road stabilization), creating a flood bench (conveyance of flood flows), and protecting the river corridor (floodplain protection/relocate roads). Clicking on the "Strategies" button for a road or structure in the TRPT will illustrate how many practices within each of the four categories may be used in an area to reduce vulnerability, and thus, what class of strategies is likely to be the most applicable (Figure 8).

Strategies		Overall Count: 20
Display: Initial River Impact		
Conveyance of flood flows		Count: 5
River & Road Stabilization		Count: 9
Armor riverbank slope (with joint plantings)	M	$70 CY
Armor road embankment	M	$70 CY
Install rock toe	M	$100 CY
Weirs/vanes	M	$100 CY
Increase local armoring size to resist increased shear	M	$100 CY
Install surficial scour protection	M	$100 CY
Armored riffles	H	$100 CY
Bed Armoring	H	$100 CY
Placed riprap wall	H	$100 CY
Floodplain protection/Relocate road		Count: 3
Improve Vegetation		Count: 3
Install bank vegetation	L	$1 SF
Revegetate embankment	L	$1 SF
Riparian buffer plantings	L	$1 SF

Figure 8 Clip from the TRPT showing groups and counts of mitigation strategies for a specific location sorted by Initial River Impact

In the TRPT, the practices within each of the four strategy groups can be ordered by one of four filters – Initial River Impact, Transportation Network Impact, Implementation Time Frame, and Project Application Scale (Table 12). Filtering helps the TRPT user with planning to answer questions such as "Which practice will have the least environmental impact?"; "Which practice will have the smallest impact on the transportation network?"; and "Which practice may cost the least?" The default filter is Initial River Impact (see Figure 8).

Table 12 Practice Filtering Available on the TRPT

Filter (TRPT Name)	Options (Listed in Order of Presentation)	Definition
Initial River Impact	Low (L)	None/Low impacts, return to nature
(Initial River Impact)	Moderate (M)	Moderate intensity and impacts
	High (H)	High intensity and impacts
Transportation Network Impact	Low (L)	None to small footprint change
(Network Impact)	Moderate (M)	Some changes to network
	High (H)	Large changes to network such as relocations and ROW issues
Implementation Time Frame	Short-term (S)	Short-term repair to get/keep road open
(Short or Long Term)	Long-term (L)	Permanent change to setting, > 5-year implementation time
Project Application Scale	Point (P)	
(Application Scale)	Road segment (RS)	Less than 0.5 miles long
	River reach (RR)	0.5 to 1 mile long
	Watershed (W)	

An order-of-magnitude unit cost is provided with each strategy, which consists of the average rounded cost per unit length, area, volume, or item.

6.2 Watershed Resiliency Planning Case Studies

A watershed resiliency case study was prepared for each of the three pilot watersheds using the TRPT (Appendix L). Each case study contains a watershed overview, transportation flood resiliency mapping and prioritization from the TRPT, potential mitigation strategies/projects to reduce flood risk, broadly applicable mitigation and planning strategies to reduce risks (Appendix J and Appendix K), and site examples.

7.0 THE TRPT APP

7.1 Overview

The TRPT is a web-based application (app) located at http://roadfloodresilience.vermont.gov, which identifies bridges, culverts, and road embankments within a watershed that are vulnerable to damage from floods; estimates risk based on the vulnerability and criticality of roadway segments; and identifies potential mitigation measures based on the factors driving the vulnerability and criticality. The TRPT was developed by VTrans with consultant assistance and with significant input from regional, local, and state agency partners. The TRPT is hosted by VTrans (see Appendix M for details on the hosting environment).

The app displays the results of vulnerability, criticality/transportation modeling, risk, and mitigation strategies assessments in the three pilot watersheds. Additional watersheds will be added in the future. Users have the option to review these data for three flood sizes (10-year, 50-year, and 100-year; or 10%, 2%, and 1% chance annual recurrence interval) and three processes (inundation, erosion, and deposition). Key features include a map service for viewing spatial datasets, graphical data for summary analyses, and tabular display of mitigation alternatives for at-risk transportation assets.

The app is available for use by anyone connected to the internet and is compatible with multiple internet browsers and devices. It provides a centralized repository and display for all users without requiring any specialized desktop software or internet browser plug-ins. This tool is for planning purposes only, and findings must be confirmed in the field prior to seeking funding and initiating design.

If users would like to use the TRPT data for analysis outside of the app, the data may be downloaded in five spreadsheets. The data can be connected to the river and road segment GIS shapefiles through the ID codes of each segment (see Appendix M for data package file names and contents).

A full list of application features is provided in the following section.

7.2 TRPT Instructions

The following graphics describe the features and functions of the TRPT app for the Main Menu, Utility Menu, Asset Risk Chart, and Asset Details.

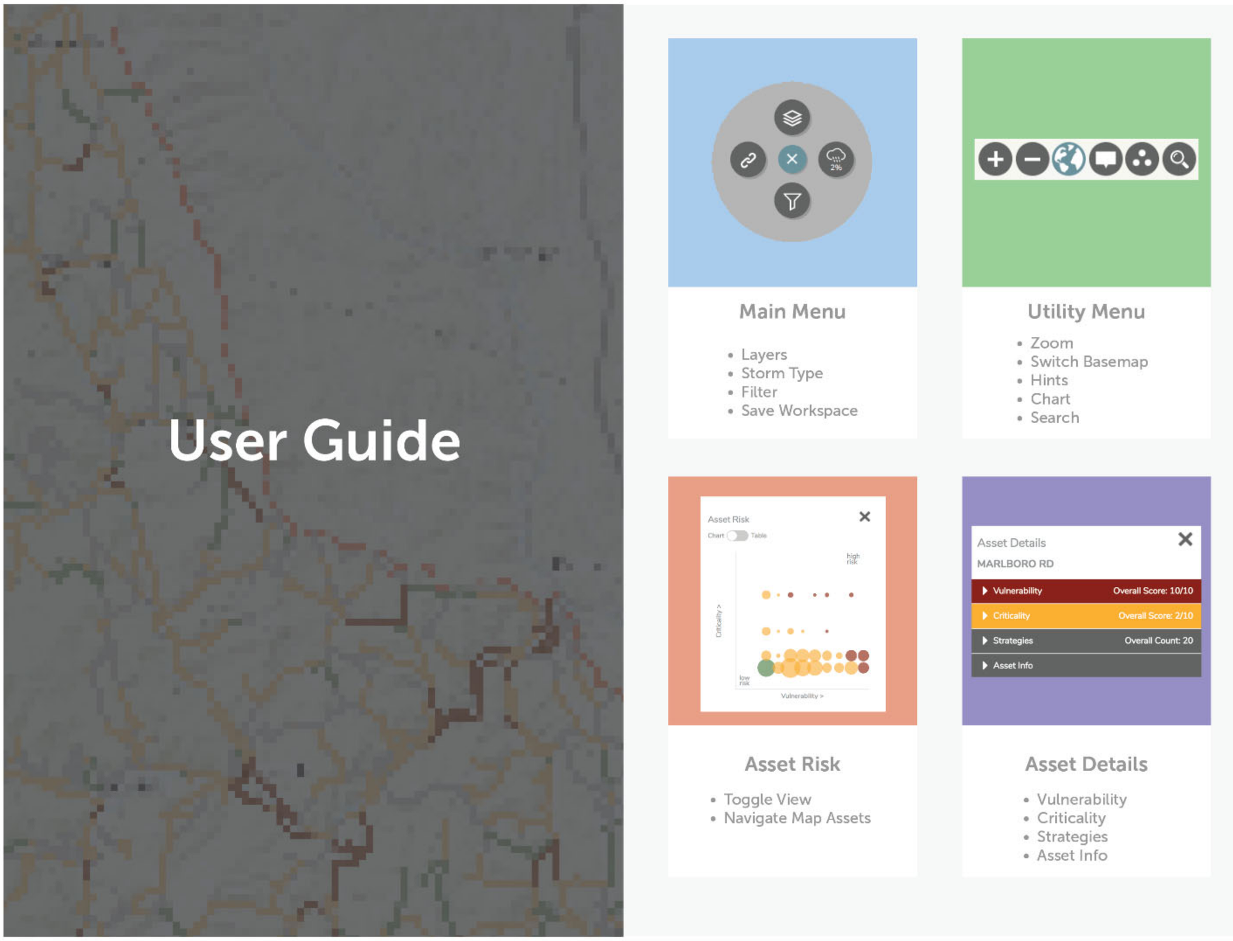


Figure 9 TRPT Web Application Menus

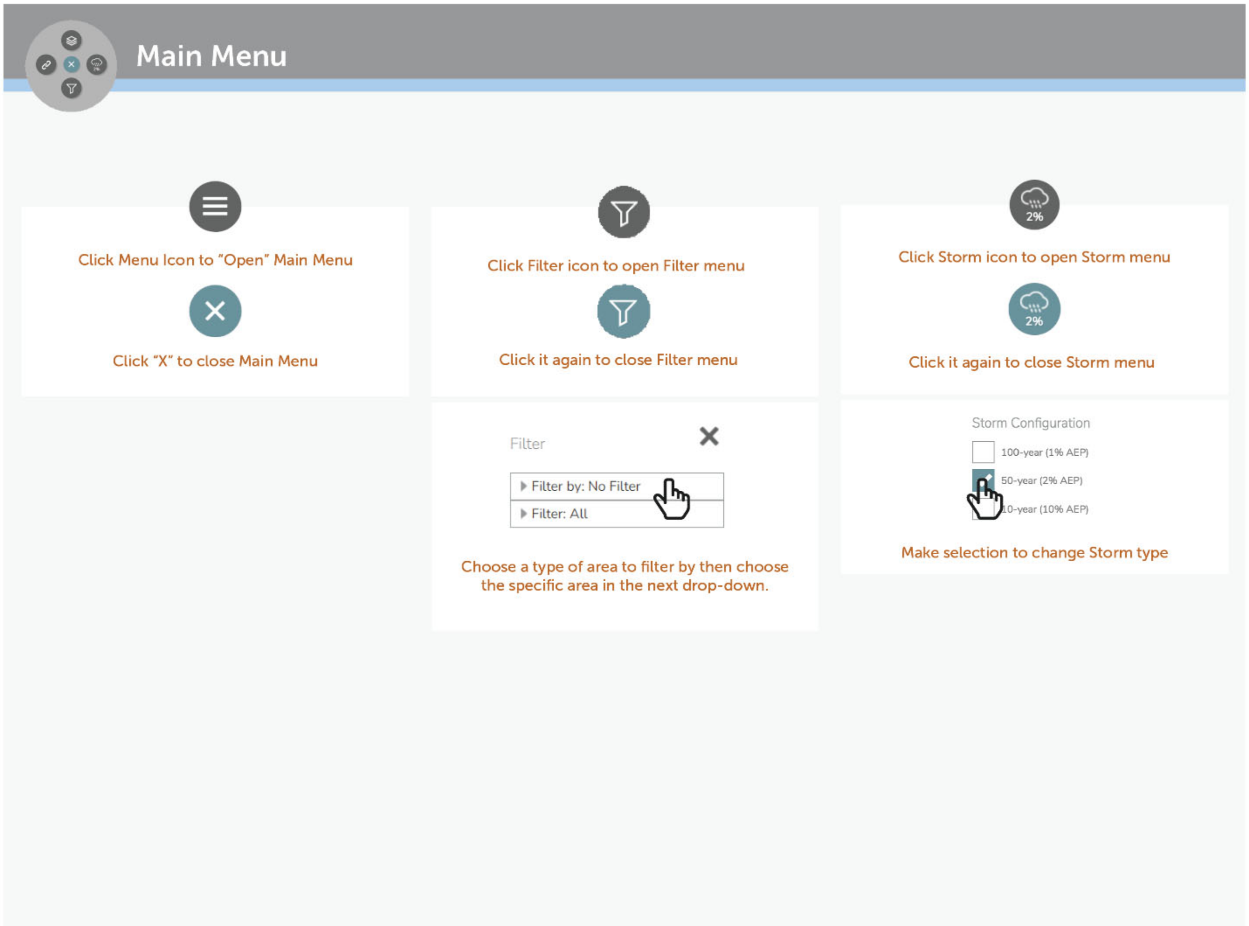


Figure 10 TRPT Main Menu

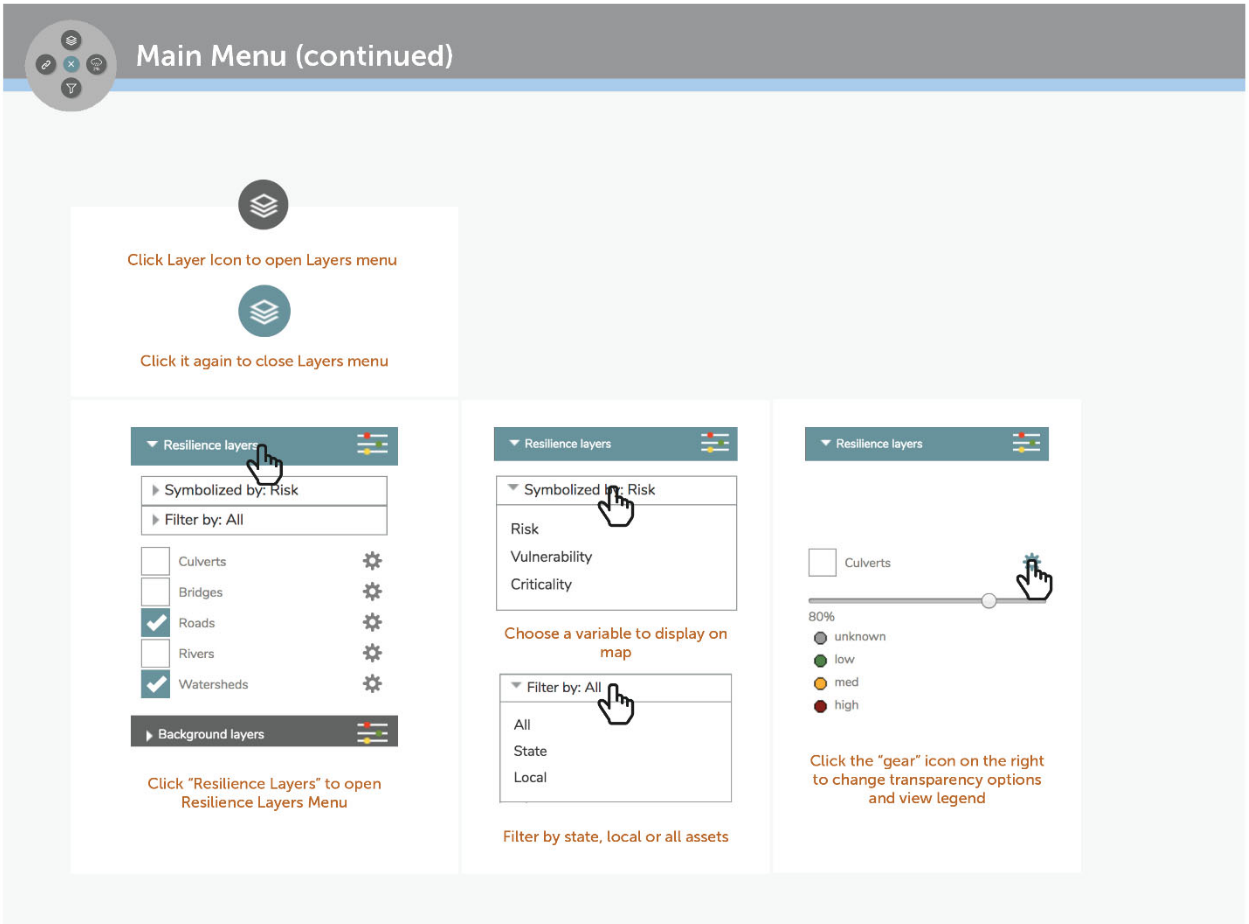


Figure 11 TRPT Main Menu (Continued)

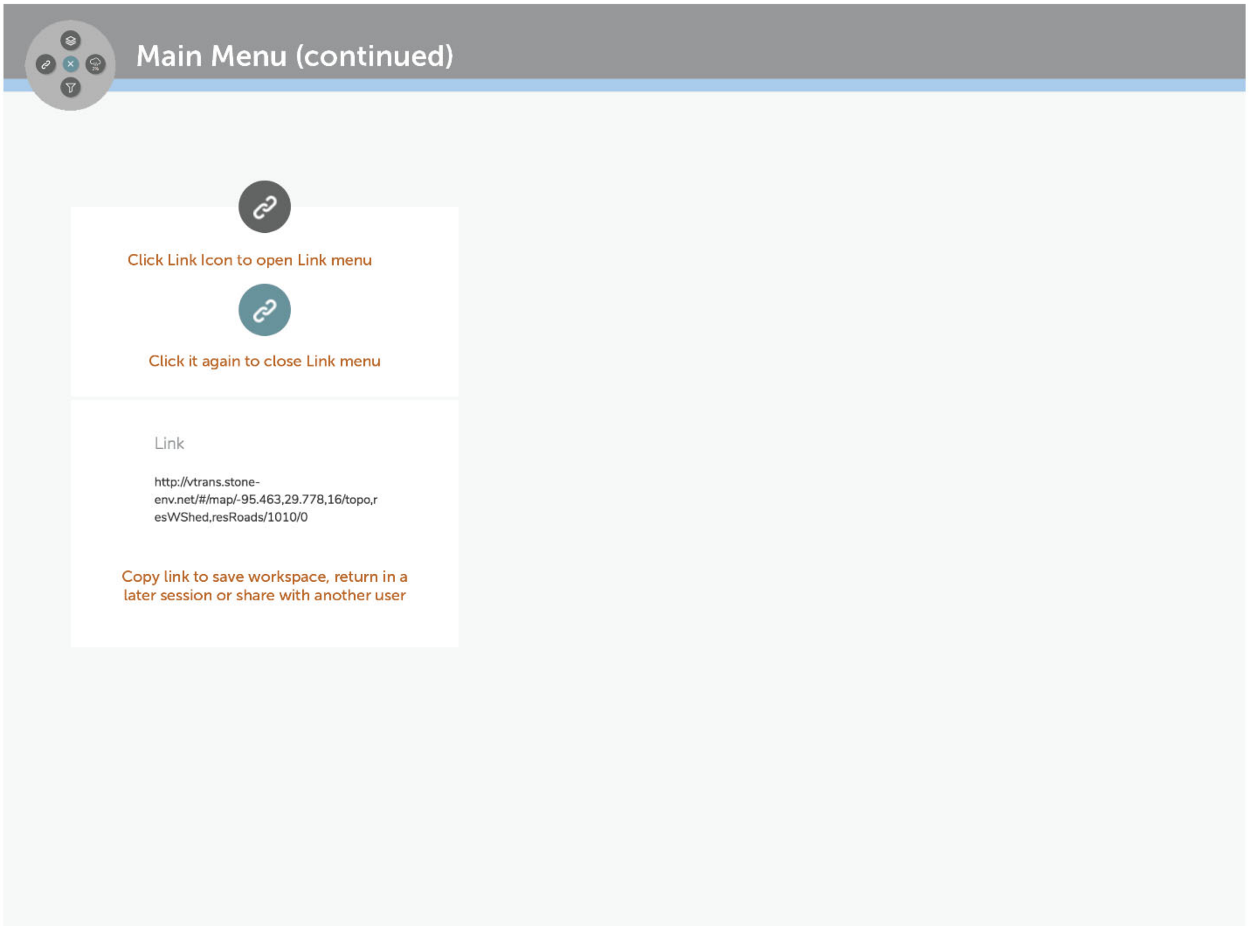


Figure 12 TRPT Main Menu (Continued)

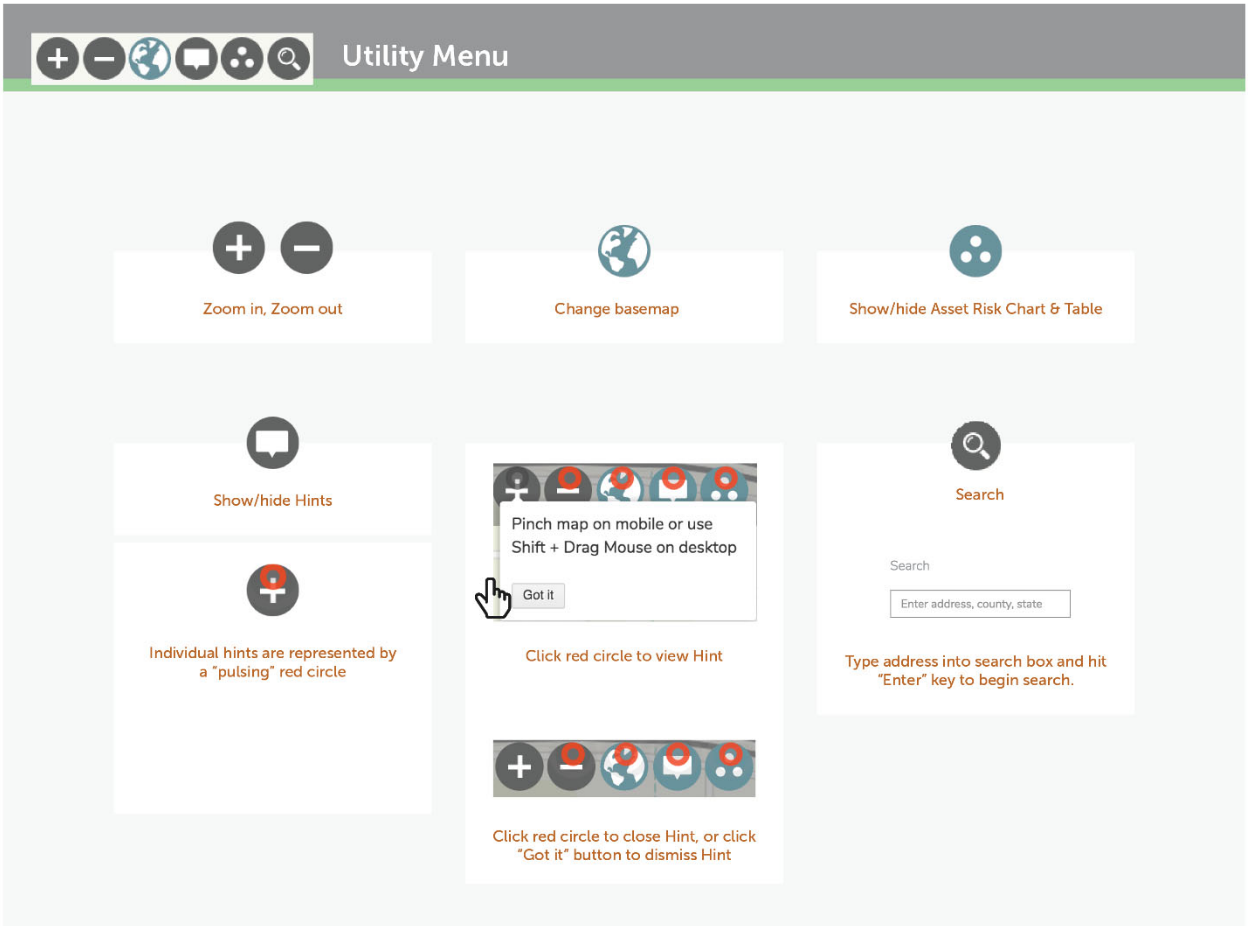


Figure 13 TRPT Utility Menu

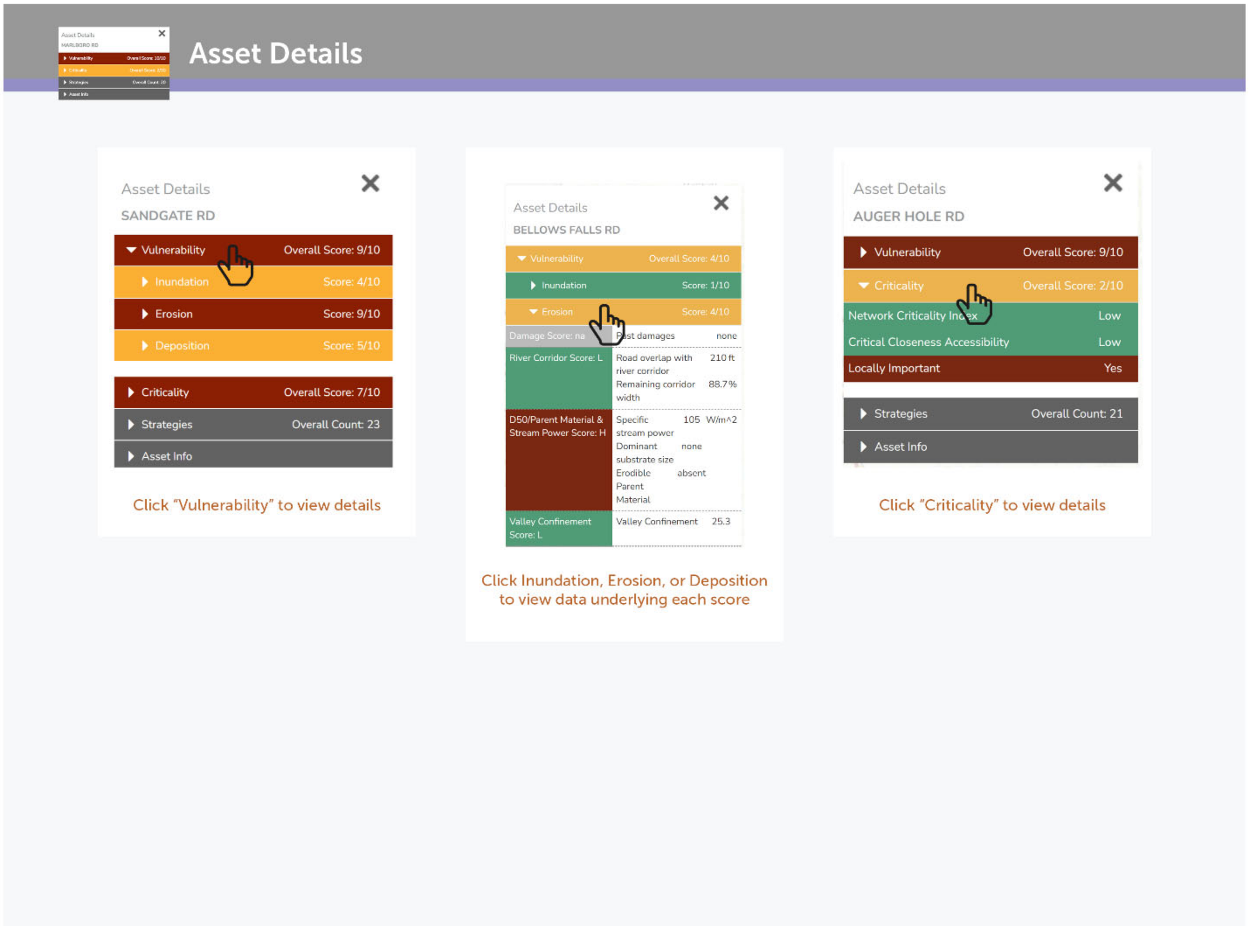


Figure 14 TRPT Asset Details

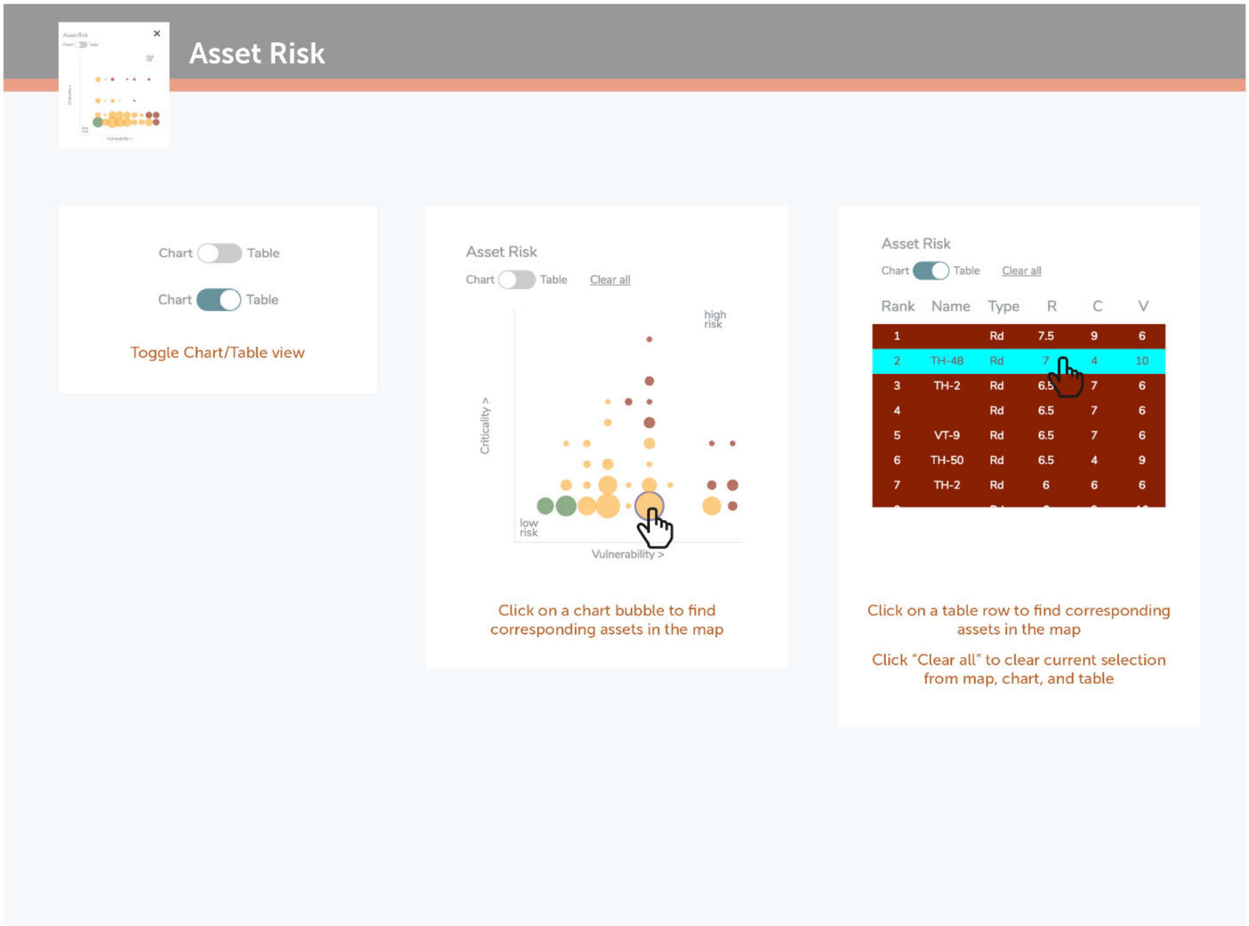


Figure 15 TRPT Asset Risk

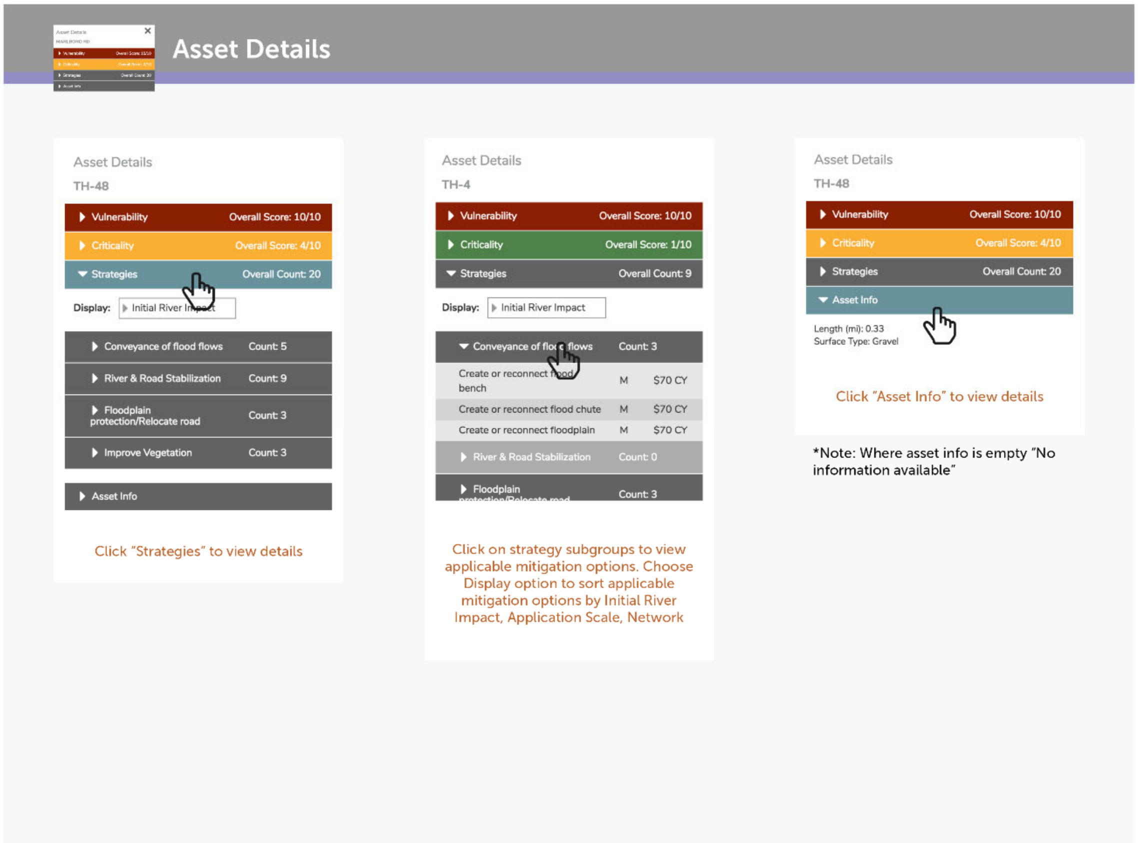


Figure 16 TRPT Asset Details

7.3 Flood Damage Case Study

Using the Tweed River Valley within the Upper White River Pilot Watershed, this case study demonstrates how to apply the TRPT to identify flood vulnerability and mitigation options.

The Tweed River Valley in Killington and Pittsfield is mostly narrow due to the mountainous setting and additional confinement by the road embankment. In many cases, the small natural floodplains in the narrow valley have been disconnected from the river channel as the river has cut down (i.e., incised) due to erosion. The Tweed River along Vermont Route 100 is very erosive as it has a lot of (stream) power to move sediment and is overly confined.

During Tropical Storm Irene, the erosive nature of the Tweed River led to loss of several sections of the Vermont Route 100 road embankment. High-velocity flows that could not spread into a floodplain gouged holes in the road embankment to make new floodplain (Figure 17). Small culverts and bridges were washed out.

The TRPT shows high and moderate risk sections of Vermont Route 100 along the Tweed River (Figure 18). The vulnerability due to erosion is high (10 out of 10). Stream power is high (123 watts per square meter), and a long portion of the road segment is in the river corridor (1,464 feet). More than 10% of the floodplain is filled by the road embankment, which is leading to high vulnerability. Road sections near Stage Road and Hadley Lane are the most constricted (V = 9 out of 10), lead to severe transportation consequences if damaged (C = 7 out of 10), and thus, have the highest risk in the area (R = 8 out of 10). Refer to the vulnerability definitions (Appendix F) to learn more about each parameter including the numeric thresholds for high, medium, and low vulnerability.

Figure 17 Failure of the Vermont Route 100 road embankment due to erosion during Tropical Storm Irene in Pittsfield (Source: Mansfield Heliflight, 2011)

The reader is encouraged to open the TRPT, select the Upper White River watershed, and pan to the road segment being described in the case study. Keep the 50-year flood (default) selected. Open each of the drop-down menus for vulnerability, criticality, and strategies.

Due to the high power and erosive setting along Vermont Route 100 identified in the TRPT, the mitigation strategies that can protect the road, bridges, and culverts require rigid stabilization using large rock. Although vegetative practices are preferred to naturalize the river, the high flood velocity in the area will erode roots and soils, so rock is needed to protect the road. Practices such as armoring all or part of the riverbanks while maintaining the channel bankfull width; armoring the bed with weirs, stone riffles, or full bed armoring; or installing local scour protection at bridges and culverts are needed to protect the transportation network (see the "Strategies" drop-down menu in the TRPT). A truly resilient design approach will address the root problem in the area – reducing confinement and reconnecting floodplain. This last practice is the top recommendation to improve conveyance of flood flows and reduce the process of erosion. A review of these strategies before flood damages take place will allow for proactive alternatives analysis and design to reduce vulnerability.

Emergency bank armoring took place along several sections of Vermont Route 100 following Tropical Storm Irene as short-term, temporary repairs to get the road open. The armoring allowed for rebuilding of the road embankment and provided temporary stabilization. Unfortunately, this approach also narrowed the river channel below the bankfull channel width, which led to a higher potential for erosion. Many river channel stabilization practices inadvertently increase future risk yet do not rectify the primary problem such as incision (Figure 19). A proper understanding of river and road conflict areas coupled with use of the TRPT will lead to more appropriate design, less flood damages, and elimination of flood recovery, which increases risk.

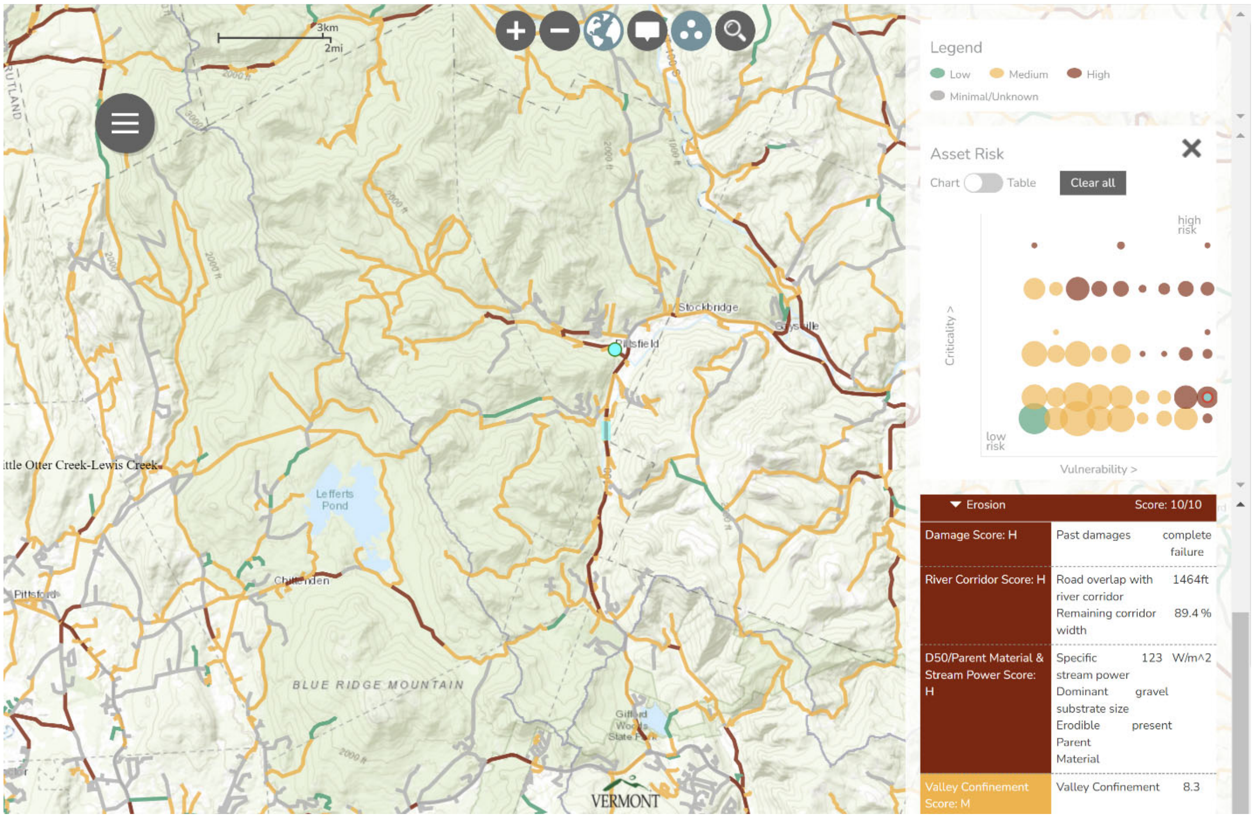


Figure 18 Screen shot of the TRPT, which shows high risk along Vermont Route 100 road embankment due to erosion in Pittsfield. See inset for project area south of Pittsfield. (Source: Vermont Transportation Resilience Planning Tool, exported 2/14/2018)

With the understanding of the driving processes behind the vulnerability, a mitigation project was designed to both protect the road and reduce erosion. Bed armoring was installed to elevate the channel to preflood levels and reconnect floodplain (Figure 20). The oversteepened bank armoring that spilled into the river channel was pulled back to restore the bankfull channel width. The bank armoring was reinstalled at a shallower slope, and the lower portion was covered with grubbings and then seeded to restore riparian vegetation. Proper sediment and erosion controls were used during installation of this aggressive alternative to minimize construction impacts. The practice has been installed for nearly 4 years and is stable. The reconnected floodplain has been accessed several times.

Figure 19 **Incision and floodplain disconnection due to confinement on Tweed River following Tropical Storm Irene in Killington, Vermont (Source: MMI, 2012)**

Figure 20 Elevated channel via bed armoring right after construction. Note the reconnected floodplain and the gentler side slope of the road embankment. (Source: Fitzgerald Environmental, 2013)

7.4 Planning Case Study

The following describes an example workflow for a transportation planner seeking to prioritize road projects based on flood risk. The user locates their area of interest from the map and browses the road segments that are displayed by risk category, making note of segments that are high risk (red) at different flood recurrence probabilities by toggling the storm selection options (Figure 21). In Whetstone Brook, the user investigates four segments that are high risk at all three storm probabilities and focuses on the highest risk segment based on its position in the risk chart – Western Avenue (VT Route 9) between Garfield Drive and Meadowbrook Road (Figure 22). Clicking on this segment, the user notes that the vulnerability is moderate (4/10) for the 10-year storm recurrence because of moderate erosion vulnerability but that the segment is highly critical (9/10), which is the factor driving the high-risk score. Vulnerability is higher for larger floods as expected. This segment is locally important for detours and accessing services in Brattleboro (Figure 23). The user turns on the bridge and culvert map layers and finds a bridge that intersects this segment and is a factor in the risk level. To mitigate flood risks, the user examines river and road stabilization strategies, focusing on strategies with low transportation network impact given the road's high criticality (Figure 24). Implementing weirs/vanes rises to the top of the list for the road segment in terms of low network impact to achieve moderate initial river impact. For the bridge, conveyance of flood flow projects is recommended to achieve moderate initial river impact with low network impact. By changing the strategy display list from Transportation Network Impact to Initial River Impact, it is possible to see how possible strategies influence the river and the road, and thus, tradeoffs can be considered.

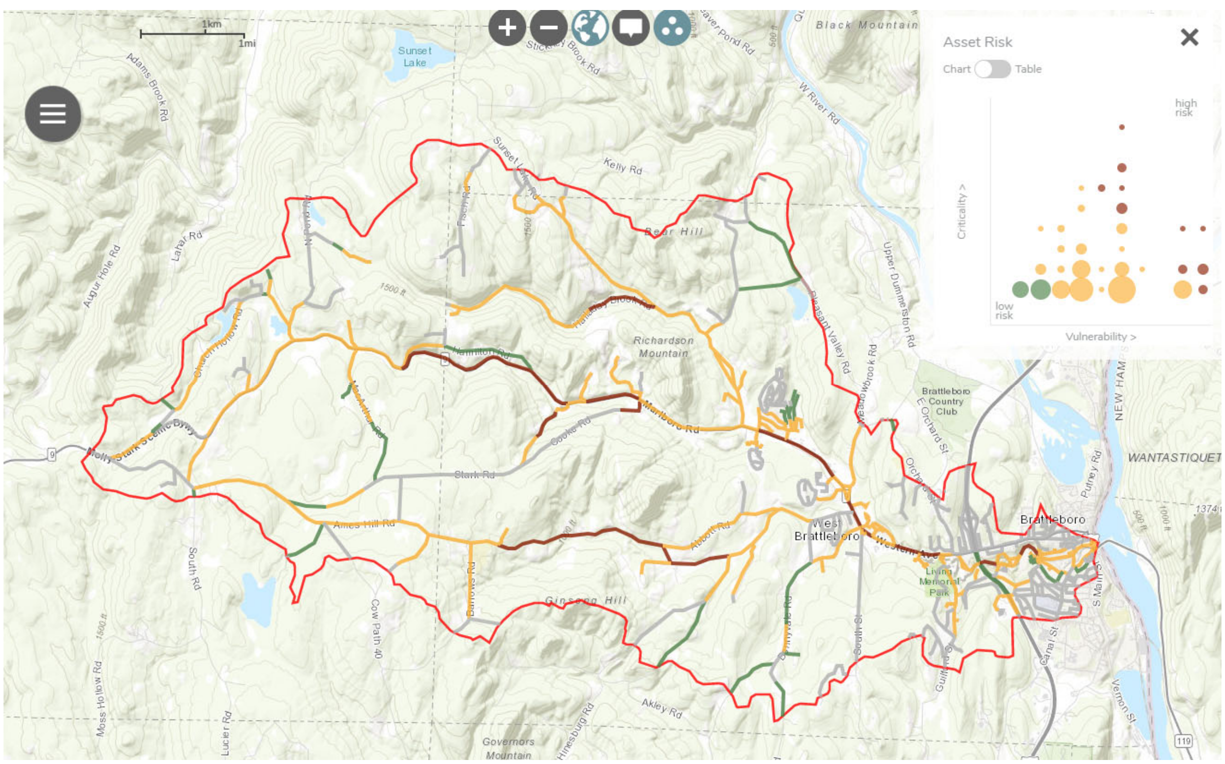


Figure 21 Road risk in the Whetstone Brook watershed

Figure 22 High-risk road segment on VT Route 9

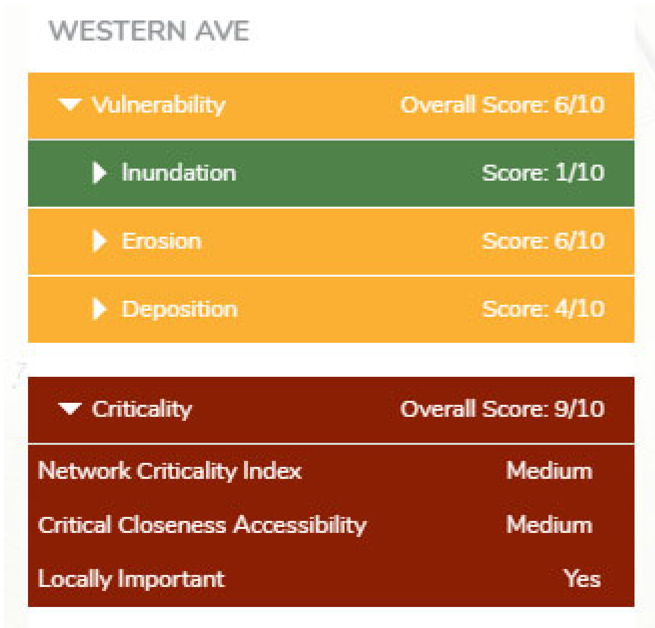


Figure 23 Vulnerability and criticality score details

Strategies		Overall Count: 14
Display: Initial River Impact		
River & Road Stabilization		**Count: 5**
Armor riverbank slope (with joint plantings)	M	$70 CY
Armor road embankment	M	$70 CY
Install rock toe	M	$100 CY
Install surficial scour protection	M	$100 CY
Weirs/Vanes	M	$100 CY
Conveyance of flood flows		**Count: 4**
Create or reconnect flood bench	M	$70 CY
Create or reconnect flood chute	M	$70 CY
Create or reconnect floodplain	M	$70 CY
Reduce space behind guard rail	M	$100 CY
Floodplain protection/Relocate road		**Count: 2**
River corridor conservation	L	$3000 AC
Adjust road alignment	M	$350 LF
Improve Vegetation		**Count: 3**
Install bank vegetation	L	$1 SF
Revegetate embankment	L	$1 SF
Riparian buffer plantings	L	$1 SF

Figure 24 Potential mitigation strategies

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APPENDIX A

GLOSSARY

Acronyms

ARAN – Automatic Road Analyzer

BGS – Buildings and General Service

BMP – Best Management Practice

CCA – Critical Closeness Accessibility Index

CCRPC – Chittenden County Regional Planning Commission

CFS – cubic feet per second

CVRPC – Central Vermont Regional Planning Commission

D&K – DuBois & King, Inc.

DDIR – Detailed Damage Inspection Reports

DEC – Department of Environmental Conservation

DFIRM – Digital Flood Insurance Rate Map

DMS – Data Management System

FAID – FIPS Arc ID

FEMA – Federal Emergency Management Agency

FEA – Fitzgerald Environmental Associates, LLC

FHWA – Federal Highway Administration

FID – Feature IDentification

FIT – Feature Indexing Tool

GDB – Geodatabase

GIS – Geographic Information System

HGR – Hydraulic Geometry Regression Equation

HUC – Hydrologic Unit Code

LHMP – Local Hazard Mitigation Plans

LiDAR – Light Detection and Ranging

LWD – Large woody debris

MMI – Milone & MacBroom, Inc.

NCI – Network Criticality Index

NFIP – National Flood Insurance Program

NRI – Network Robustness Index

PA – Public Assistance

ROW – right-of-way

RPC – Regional Planning Commission

SEI – Stone Environmental, Inc.

SMI – Smart Mobility, Inc.

SGA – Stream Geomorphic Assessment

SGAT – Stream Geomorphic Assessment Tool

SSP – Specific stream power

SSURGO – Soil Survey Geographic Database

TNC – The Nature Conservancy

TRORC – Two Rivers-Ottaquechee Regional Commission

TRPT – Vermont Transportation Resilience Planning Tool

TSI – Tropical Storm Irene (August 28, 2011)

UVM TRC – University of Vermont Transportation Research Center

USGS – United States Geological Survey

VCGI – Vermont Center for Geographic Information

VEM – Vermont Emergency Management

VHD – Vermont Hydrography Dataset

VLT – Vermont Land Trust

VTACCD – Vermont Agency of Commerce and Community Development

VTANR – Vermont Agency of Natural Resources

VTrans – Vermont Agency of Transportation

WRP – White River Partnership

WRC – Windham Regional Planning Commission

Glossary of Terms

Aggradation – A progressive buildup or raising of the channel bed and floodplain due to sediment deposition. The geologic process by which streambeds are raised in elevation and floodplains are formed. Aggradation indicates that stream discharge and/or bed load characteristics are changing. Opposite of degradation.

Alluvial – Deposited by running water

Approach – The roadway or stream channel directly adjacent to or upstream of a structure

Natural Bed Armoring – A river process where smaller sediment particles are removed over time, leaving an erosion-resistant layer of larger particles. A naturally armored streambed generally resists movement of bed material at discharges up to approximately 3/4 bankfull depth. Natural bed armoring is replicated through bed armoring to control the grade of the river, typically in confined locations surrounded by infrastructure where river channels tend to cut down.

Avulsion – A change in channel course that occurs when a stream suddenly breaks through its banks, typically bisecting an overextended meander arc. An avulsion is often triggered by excessive deposition during a flood that reduces the channel area where floodwater can be carried, leading to a rapid channel relocation. Avulsions are often hazardous, damaging infrastructure and properties by excessive erosion.

Bank stability – The ability of a stream bank to counteract erosion or gravity forces

Bankfull discharge – The stream discharge corresponding to the water stage that overtops the natural banks. This flow occurs on average about once every 1 to 2 years and, given its frequency and magnitude, is responsible for the shaping of most stream or river channels and effectively transporting a large amount of sediment over the long term.

Bankfull width – The width of a river or stream channel between the highest banks on either side of a stream in a nonincised setting, typically containing the 1.5- to 2-year flood

Bar – An accumulation of alluvium (usually gravel or sand) caused by a decrease in sediment transport capacity on the inside of meander bends or in the center of an overwide channel

Base flow – The portion of stream flow that is drawn from a natural watershed storage source and not runoff following precipitation

Channel slope – The inclination of the channel bottom, measured as the elevation drop per unit length of channel or percent

Berms – Constructed mounds of dirt, earth, gravel, or other fill built parallel to the stream banks and designed to keep flood flows from entering the adjacent floodplain. Berms were historically used to protect property near channels but are now not allowed as we know that they confine flood flows, actually increase risk, and create a false sense of safety.

Boundary resistance – The ability of a stream bed or bank to withstand the erosional forces of the flowing water at varying intensities. Under natural conditions, boundary resistance is increased due to larger sediment sizes and vegetation (roots).

Braided – A stream channel pattern characterized by flow in several channels, typically made of coarse sediments that are dynamic and regularly change course during flooding. Braiding often occurs when sediment loading is too large to be carried by a single channel for the given flow and channel slope.

Buffer – A strip of vegetation, such as forest or unmowed perennials, between waterways and land uses, such as agriculture or urban development, designed to slow runoff and filter pollution before it reaches the surface water resource. Buffers tend to be static and equal width such as 50 feet on either side of the channel.

Catchment – A small watershed typically consisting of a local drainage network in the headwaters or a stream reach with a length around 0.5 miles

Channel – An area that contains continuously or periodically flowing water that is confined by banks and a streambed

Channelization – The process of changing the natural path of a waterway, usually through straightening and armoring with rock or walls

Confluence – The meeting or junction of two or more streams; also, the place where these streams meet

Conservation – The preservation of lands to protect the process or means of achieving recovery of viable populations

Criticality – The importance of an asset to the transportation network

Culvert – A structure that conveys a stream under a road that has fill over it. Culverts are typically closed pipes, closed boxes, open boxes, or open arches. Culverts have historically been sized through hydraulic modeling of water and are now sized through both hydraulic modeling and bankfull width of the channel to be able to pass sediment and wood during floods.

Degradation – A progressive lowering of the channel bed due to scour. Degradation is an indicator that the stream's discharge and/or sediment load is changing.

Deposition – The accumulation of sediment and wood that leads to the formation of bars and can clog structures in extreme cases

Drainage area – The total surface area upstream of a point on a stream that drains toward that point

Drainage basin – The total area of land from which water drains into a specific river

Dredging – Removing sediment from wetlands or waterways, usually to make them deeper or wider

Embankment – Fill material that is raised above the natural surface of the land to contain, divert, or store water, support roads or railways, or for other similar purposes

Entrenchment Ratio – The width of the floodprone area divided by the bankfull width that indicates how broad the floodplain is

Equilibrium Condition – The state of a river reach in which the input of energy (flow of water and slope of channel) is in balance with the resistance of the riverbed (sediment size). Natural river reaches in equilibrium without human impacts tend toward a most stable state where predictable channel forms are maintained over the long term under varying flow conditions.

Erosion – Wearing away of the banks, channel bed, road embankment, and structure abutments/ footings due to high-velocity flows moving material downstream

FAID – A concatenation of the FIPS8 and ARCID fields to give a unique ID for road segments.

Failure – Damage from severe inundation, erosion, or deposition causing partial or complete destruction of a transportation asset, resulting in temporary or long-term travel disruptions

Flash flood – A sudden flood of great volume, usually caused by a heavy rain in a short period of time that is often characterized by high velocity

Floodplain – Land adjacent to a river that is regularly flooded. The 100-year floodplain that is often regulated by FEMA is the floodplain that has a 1% chance in a given year of being inundated or is typically flooded once in 100 years.

Floodprone Width – The width of flooding at two times the bankfull depth, typically assumed to be about the 50-year flood depth that is used for calculating entrenchment ratio

Floodplain Function – Floodwater access of floodplains that spreads flood width and decreases flood velocity and stream power. Floodplain access reduces erosion, increases sediment deposition and storage, and allows for nutrient uptake.

Flow – The measure of the volume of water passing a point in a stream over a given time, usually expressed in cubic feet per second (cfs)

Fluvial Geomorphology – The study of river form and processes and how rivers and their landforms interact over time

Ford – A shallow place in a body of water, such as a stream, where one can cross by foot, horse, or truck. Fords are usually hardened with large stone.

Geographic Information System (GIS) – A computer program that stores spatial data, facilitates spatial analysis, and allows for data presentation in maps and tables

Geomorphology – A branch of physiography and geology that deals with the form of the earth, the general configuration of its surface, and the changes that take place due to erosion of the primary elements and the buildup of erosional debris

Grade Control – A fixed feature on the streambed that controls the bed elevation at that point, effectively fixing the bed elevation from potential incision. Natural grade control consists of bedrock or large wood spanning the channel. Man-made grade control consists of weirs and bed armoring.

Gradient – The slope, or vertical drop per unit of horizontal distance, typically measured in % or foot/foot

Headcut – A sharp change in slope, almost vertical, where the streambed is being eroded from downstream to upstream

Headwater – Referring to the source of a stream or river. Often used to describe small channels with stream order 2 or lower.

High-Gradient Streams – Steeper streams that may have cascade, step/pool, or riffle/pool bedforms. Most of the streams in Vermont are high-gradient streams.

Hydraulic Radius – The cross-sectional area of a stream divided by the wetted perimeter

Hydrograph – A curve showing stream flow over time. Hydrographs are used to show the rise, peak, and decline of a flood.

Hydrologic Unit Code (HUC) – A numeric code that defines a distinct watershed or river basin. The more digits in the HUC, the smaller the drainage.

Hydrology – The study of the water of the earth; its occurrence, circulation, and distribution; its chemical and physical properties; and its interaction with its environment, including its relationship to living things.

Incised River – A river that erodes its channel and cuts down, reducing its connection to its floodplain. Incised rivers tend to be excessively erosive and prone to causing flood damage.

Incision Ratio – The low bank height divided by the bankfull maximum depth that indicates the level of vertical floodplain connection. An incision ration of 1 indicates a good connection while an incision ratio larger than 1.5 indicates loss of connection.

Intermittent Stream – Any nonpermanent flowing drainage feature having a definable channel and evidence of scour or deposition

Inundation – Submergence of a crossing or low spot in the road due to rising floodwaters.

Large Wood – Also known as large woody debris (LWD). Pieces of trees at least 6 feet long and 1 foot wide contained, at least partially, within the bankfull area of a channel.

Low-Gradient Streams – Streams that have low slope and typically appear slow moving and winding

Mainstem – The principal channel of a drainage system into which other smaller streams or rivers flow

Mass Failure – The downslope movement of earth caused by gravity. Includes but is not limited to landslides, rock falls, debris avalanches, and creep. It does not, however, include surface erosion by running water. It may be caused by natural erosional processes or by natural disturbances (e.g., earthquakes or fire events) or human disturbances (e.g., mining or road construction).

Meander – The bend or winding of a stream channel, usually in an erodible alluvial valley

Median Grain Size (D50) – The median grain size of a sediment sample that falls in the middle of the distribution of size or mass of particles

Mitigation – Practices to reduce the risk of inundation, erosion, and deposition damages to the transportation network

MMIGRID – A unique alpha-numeric identification code for each stream segment in the merged VHD – SGA data set used in the TRPT. The letters indicate major basin in Vermont and the segments are numbered.

Natural Flow – The flow past a specified point on a natural stream that is unaffected by stream diversion, storage, import, export, return flow, or change in use caused by modifications in land use

Outfall – The mouth or outlet of a river, stream, lake, drain, or sewer

Perennial Streams – Streams that flow continuously

Probability of Exceedance – The probability that a random flood will exceed a specified magnitude in a given period of time

Reach – A section of stream having relatively uniform physical attributes, such as valley confinement, valley slope, sinuosity, dominant bed material, and bed form, as determined in geomorphic assessment. An individual stretch of stream that has beginning and ending points defined by identifiable features such as where a tributary confluence changes the channel character or order.

Recurrence Interval – An estimation of the probability of a flood event of a given size occurring based on measurements of the historic flow record, expressed in years or exceedance probability (percentage)

Reference Stream Type – Observations of the natural channel form and process that would be present in the absence of anthropogenic impacts to the channel and the surrounding watershed

Relief – Elevation difference between two or more features

Resilience – The resistance of the transportation network to maintain function even when vulnerable assets are closed or fail

Restoration – The return of an ecosystem to a close approximation of its condition prior to disturbance.

Riparian – Located on the banks of a stream or other body of water.

Riparian Buffer – Riparian buffer is the width of naturally vegetated land adjacent to the stream between the top of the bank (or top of slope, depending on site characteristics) and the edge of other land uses. The buffer is often designated by a direct setback from the top of the bank. A buffer is largely undisturbed and consists of the trees, shrubs, groundcover plants, duff layer, and naturally uneven ground surface. The buffer serves to protect the water body from the impacts of adjacent land uses.

Riparian Vegetation -- The plants that grow adjacent to a wetland area, such as a river, stream, reservoir, pond, spring, marsh, bog, meadow, etc., and that rely upon the hydrology of the associated water body

Riprap – Rock or other material with a specific mixture of sizes referred to as a "gradation," used to stabilize stream banks or riverbanks from erosion or to create habitat features in a stream

Risk – An overall measure of the probability of asset damage due to flooding (vulnerability) and the importance of the asset to the transportation network (criticality). In this study, the risk is the average of the vulnerability and criticality.

River Corridor – The space required by a river to maintain natural dynamic equilibrium with stable stream dimension, pattern, profile, and sediment regime through meandering down a valley. In Vermont, this includes the meander belt that is a function of the geomorphic stream type (e.g., six bankfull channel widths for riffle-pool channels) plus a 50-foot buffer.

River Stage – The elevation of the water surface above a known or arbitrary datum

Riverine – Relating to, formed by, or resembling a river including tributaries, streams, brooks, etc.

Road Closure – Damage causing temporary single-lane or multilane closure, resulting in travel disruptions ranging from a brief period of time to several days in length

Roads – Includes private, town, and state travelways that can be dirt, gravel, or paved

Runoff – Water that flows over the ground and reaches a stream because of rainfall or snowmelt. River flow is runoff in terms of the hydrologic cycle where water travels from mountains to ocean.

Scour – The erosive action of running water in streams that excavates and carries away material from the bed and banks. Scour may occur in both earth and solid rock material and can be classed as general, contraction, or local scour.

Sediment – Soil or mineral material transported by water or wind and deposited in streams or other bodies of water

Sediment Discontinuity – When a gap in sediment transport exists, such as through a structure, causing deposition upstream of the structure and scour downstream of the structure

Sedimentation – Deposition of sediment

Siltation – The deposition or accumulation of fine soil particles

Sinuosity – The ratio of channel length to direct down-valley distance. Also may be expressed as the ratio of down-valley slope to channel slope.

Slope – The ratio of the change in elevation over distance

Slope Stability – The resistance of a natural or artificial slope or other inclined surface to failure by mass movement, geotechnical forces, or hydraulic forces.

Specific Stream Power – Stream power divided by the bankfull channel width to normalize by unit length of channel. See Stream Power definition. A specific stream power range of 100 to 300 watts per square meter is where the most erosion damages tend to occur when resistance is not very high.

Stone – Rock or rock fragments used for construction

Straightening – The removal of meander bends, often done in towns and along roadways, railroads, and agricultural fields for increased use of land or for historic log drives

Stream Banks – The top of bank is the point where an abrupt change in slope is evident and where the stream is generally able to overflow the banks and enter the adjacent floodplain during flows at or exceeding the average annual high water.

Stream Channel – Water flowing in a natural, small channel that is normally wetted and provides a substrate that supports aquatic organisms

Stream Order – A hydrologic system of stream classification where each small unbranched perennial tributary is a first-order stream. Two first-order streams join to make a second-order stream. A third-order stream has only first- and second-order tributaries and so forth.

Stream Power – The ability of a stream to do work as it flows downgradient, causing the environment to be erosional or depositional. The power works on the bed and banks that resist the erosion.

Streambank Armoring – The installation of concrete walls, gabions, stone riprap, and other large erosion-resistant material along stream banks

Streambank Erosion – The removal of soil from stream banks by flowing water

Streambank Stabilization – The lining of stream banks with riprap, matting, vegetation, or other measures intended to control erosion

Streamflow – The rate at which water passes a given point in a stream or river, usually expressed in cfs

Structure Invert – The elevation of the bottom of a structure

Structure Length – Bridge: The opening of a structure measured parallel to the roadway. Culvert: The structure size measured perpendicular to the roadway.

Structure Span – The length of the roadway that is supported by a bridge

Structure Width – Bridge: The structure size measured perpendicular to the roadway. Culvert: The structure opening measured parallel to the roadway.

Surface Water – All waters whose surface is naturally exposed to the atmosphere; for example, rivers, lakes, reservoirs, ponds, streams, impoundments, seas, estuaries, etc.

Transportation Network – The roads and structures used for travel and their arrangement and connectivity

Tributary – A stream that flows into another stream, river, or lake

Valley – A large geologic feature that contains a river channel and floodplains and that dictates geomorphic stream type, expected channel stability, and habitat

Valley Confinement – The ratio of valley width to channel width. Unconfined channels (confinement of 4 or greater) flow through broader valleys and typically have higher sinuosity and area for floodplain. Confined channels (confinement of less than 4) typically flow through narrower valleys.

Valley Wall – The side of a valley that begins where the topography transitions from the gentle-sloped valley floor to steep terrain. The distance between valley walls is used to calculate the valley confinement.

Vulnerability – The likelihood of damage resulting from inundation, erosion, or deposition

Washout – Erosion of a relatively soft surface, such as a roadbed, by an intense flood

Water Quality – The chemical, physical, and biological characteristics of water, usually in respect to its suitability for a particular purpose

Watershed – An area of land whose total surface drainage flows to a single point in a stream

Wetland – Areas adjacent to a stream with sufficient hydrology to have hydric soils and hydrophytic vegetation (e.g., cattails, sedges, rushes, willows, or alders)

APPENDIX B

FIELD QA/QC OF TRPT SCORES

A desktop review of each basin was conducted prior to the completion of quality assurance (QA) field work. Scientists mapped out a route within each basin to visit in the field. An effort was made to include a mix of types of roads (i.e., State, Town, private) as well as a range of vulnerability rankings. ArcGIS Online was used on a tablet and the ArcGIS Field Maps app to view basin-wide road segment vulnerability data in the field. Road segments were driven for their entire length where possible and reviewed for accuracy of scoring. Characteristics of road segments and adjacent lands and resources were observed in order to assess field vulnerability. Adjustments were made, as needed, to variable scores (inundation, deposition, erosion) as well as overall vulnerability scores. Each road segment was either assigned no change or a new vulnerability score.

Following the completion of field work, data were reviewed in the office. Scoring changes were compiled and manual edits made to the databases housing the road segment vulnerability data. Percent accuracy of vulnerability scoring was estimated by basin and statewide as part of the quality assurance review. The number of unchanged segments that were field reviewed was compared to the total number of segments field reviewed to determine an accuracy percentage. The breakdown of scoring changes was evaluated to determine the relative proportion of vulnerability scoring change type by basin (i.e., vulnerability increase, no change to overall vulnerability score but change to the component scores, and vulnerability decrease).

Based on field QA efforts, statewide scoring accuracy is predicted to be 90%. Accuracy varied by basin with the highest reported accuracy for the Lamoille River and Lake Memphremagog basins, both at 97%. The White River basin had the lowest reported accuracy at 78%. The White River watershed contains many small, steep streams in confined valley settings where it may be more difficult to predict vulnerability through desktop analysis such as the TRPT.

The field QA data were evaluated to identify qualitative trends in scoring accuracy. In general, basins with a high proportion of lowlands and low slope streams had the fewest changes made to vulnerability scoring data. By contrast, basins with a greater proportion of steep upland streams and more varied mountainous terrain appeared to have more scoring changes made in the field.

Field QA review was conducted for 1,974 miles of road across the state. This represents ten percent of the approximately 20,000 miles of roads mapped in Vermont. A total of 5,618 individual road segments was visited of the 76,121 segments included in the TRPT roads layer.

Field QA - Estimated Scoring Accuracy

Transportation Resilience Planning Tool

Vermont Agency of Transportation

Map prepared July 29, 2022.

0 2.5 5 10 15 20 25
Miles
1 in = 12 miles

N

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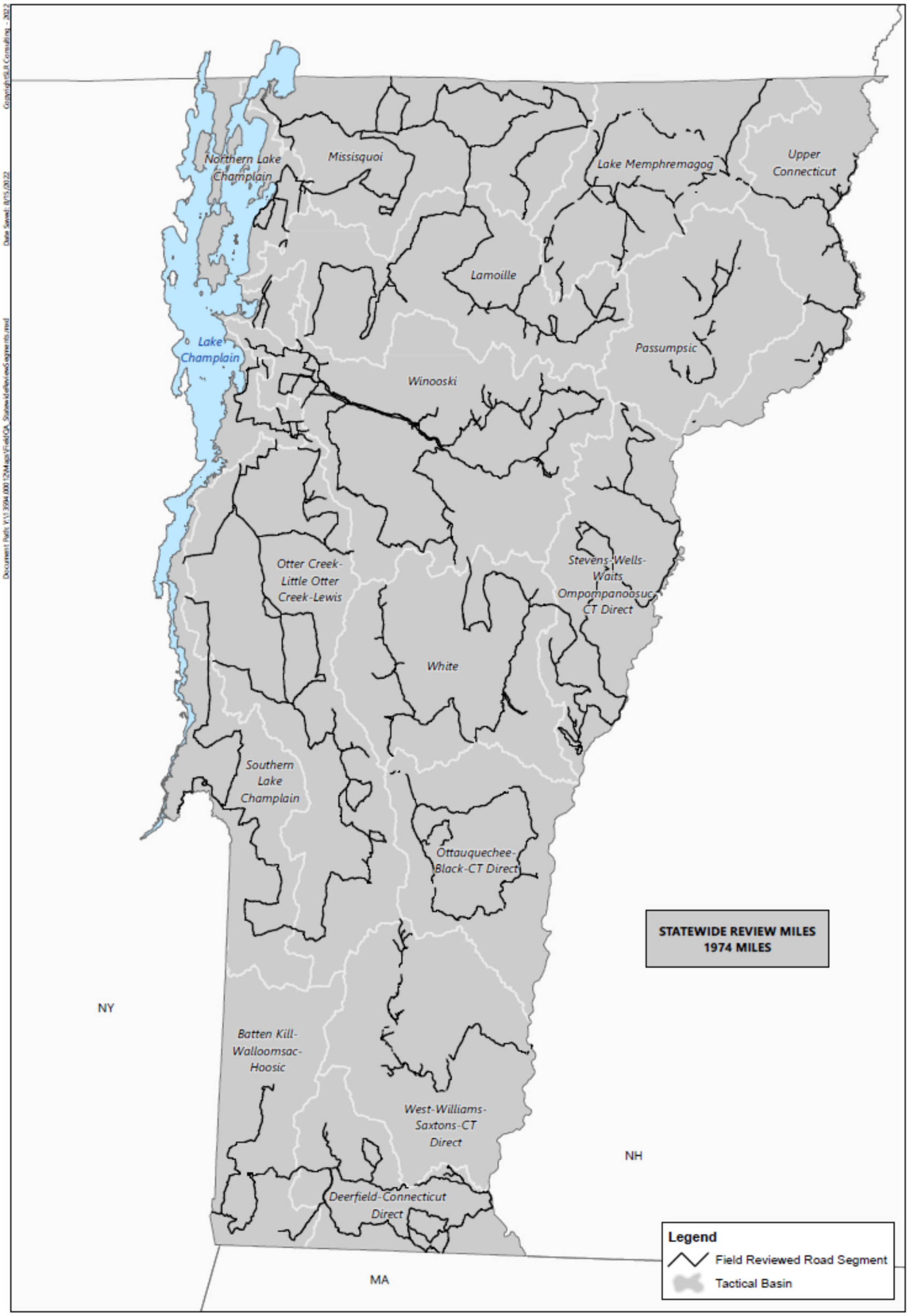
1 SOUTH MAIN ST
WATERBURY, VT 05676
802.882.8335

Vermont Transportation Resilience Planning Tool
Field Quality Assurance Review
Vulnerability Scoring Accuracy

Basin	Number of Segments Assessed	Length of Segments Assessed (mi)	Number of Segments with Score Change	Percent Change	Percent Accuracy
Batten Kill - Walloomsac - Hoosic	280	74	46	16%	84%
Deerfield - Connecticut Direct	310	118	38	12%	88%
Lake Memphremagog	294	160	8	3%	97%
Lamoille	491	148	15	3%	97%
Missisquoi	443	177	39	9%	91%
Northern Lake Champlain	380	95	20	5%	95%
Ottauquechee - Black - CT Direct	288	84	20	7%	93%
Otter Creek - Little Otter Creek - Lewis	691	207	68	10%	90%
Passumpsic	118	75	15	13%	87%
Southern Lake Champlain	212	88	16	8%	92%
Stevens - Wells - Waits - Ompompanoosuc - CT Direct	471	163	42	9%	91%
Upper Connecticut	82	100	6	7%	93%
West - Williams - Saxons - CT Direct	228	75	11	5%	95%
White	351	127	77	22%	78%
Winooski	979	283	137	14%	86%
STATEWIDE TOTAL	**5618**	**1974**	**558**	**10%**	**90%**



Field Reviewed Road Segments

Transportation Resilience Planning Tool
Vermont Agency of Transportation

Map prepared August 15, 2022.

0 2.5 5 10 15 20 25
Miles
1 in = 12 miles

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APPENDIX C

DATA DETAILS

The data presented below are specific to the three pilot watersheds from the original TRPT study – Whetstone Brook, North Branch Deerfield River, and Upper White River. The data plots provide a representative sample of roads and rivers data across Vermont. Since the TRPT pilot study, LiDAR has become available statewide and all subsequent watersheds evaluated with the TRPT methods had the benefit of full LiDAR coverage. The availability of FEMA Flood Hazard Data and Stream Geomorphic Assessment Data varies widely across Vermont.

Roads Data

Road segments were adopted from the existing VTrans Roadway Master Centerline data. Segments in the pilot watersheds ranged in length from 8 feet (a short segment on I-91 in Brattleboro) to 15,914 feet (a 3-mile legal trail in Chittenden) (Figure C-1). Longer segments are more likely to be vulnerable to multiple damage modes. Each unique road and river segment pairing was scored, and the maximum score was selected to assign the highest (most conservative) vulnerability value to the entire road segment.

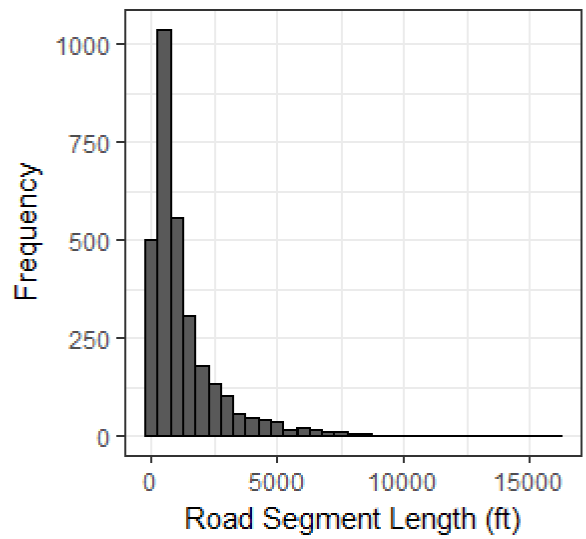


Figure C-1: Distribution of road segment lengths in the pilot watersheds (median = 755 feet, mean = 1,304 feet)

River Segments

River segments were established within the existing VT ANR SGA Network. In the pilot watersheds, segments ranged in length from 15 feet (first-order stream in the Whetstone Brook watershed) to 15,762 feet (a portion of the Upper White River mainstem) (Figure C-2). Any road within 100 feet of a valley wall or stream centerline was considered vulnerable to stream damages. This includes both roads parallel to streams and roads with stream crossings.

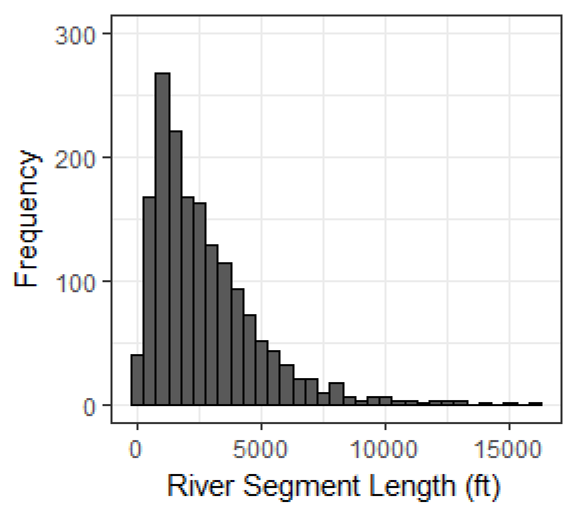
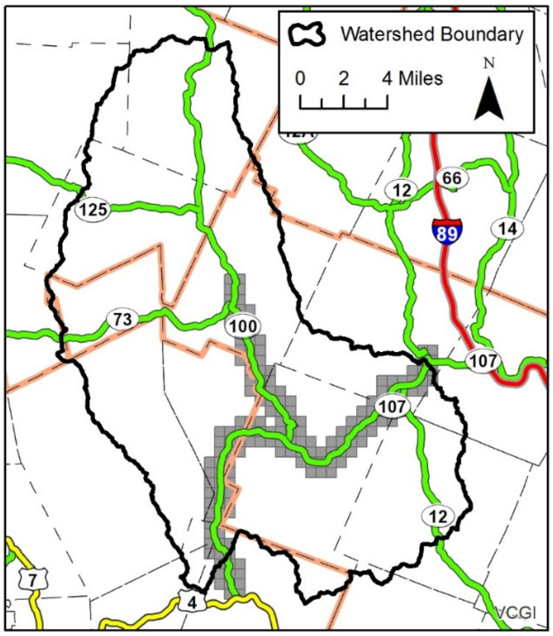


Figure C-2: Distribution of river segment lengths in the pilot watersheds (median = 2,180 feet, mean = 2,741 feet)

Elevation Data

LiDAR data were available from VTrans for portions of Vermont Routes 9, 100, and 107 in the Upper White River and Whetstone Brook watersheds (Figure C-3). No LiDAR data were available within the North Branch Deerfield River watershed at the time of analysis. Due to the LiDAR availability constraints, road-river relief was evaluated for 14% of the road segments within 100 feet of a valley wall or centerline of smaller drainages, broken out as 9% of the Whetstone Brook (25/280) segments, 23% of the Upper White River segments (190/836), and 0% of the North Branch Deerfield segments (0/386).

LiDAR data were not available for most of the roads to be screened for flooding vulnerability. Therefore, ARAN data were used for road elevation values for portions of this analysis because it was available for parts of the North Branch Deerfield River watershed and overlapped more with areas that had Digital Flood Insurance Rate Map (DFIRM) cross sections than LiDAR data (Figure C-4). LiDAR digital elevation models are now available statewide for Vermont and are recommended for analyses requiring elevation data.



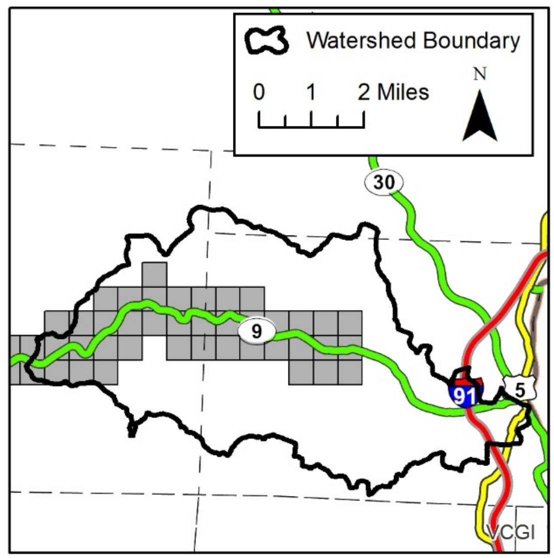


Figure C-3: LiDAR extent in the Upper White River (left) and Whetstone Brook (right) watersheds

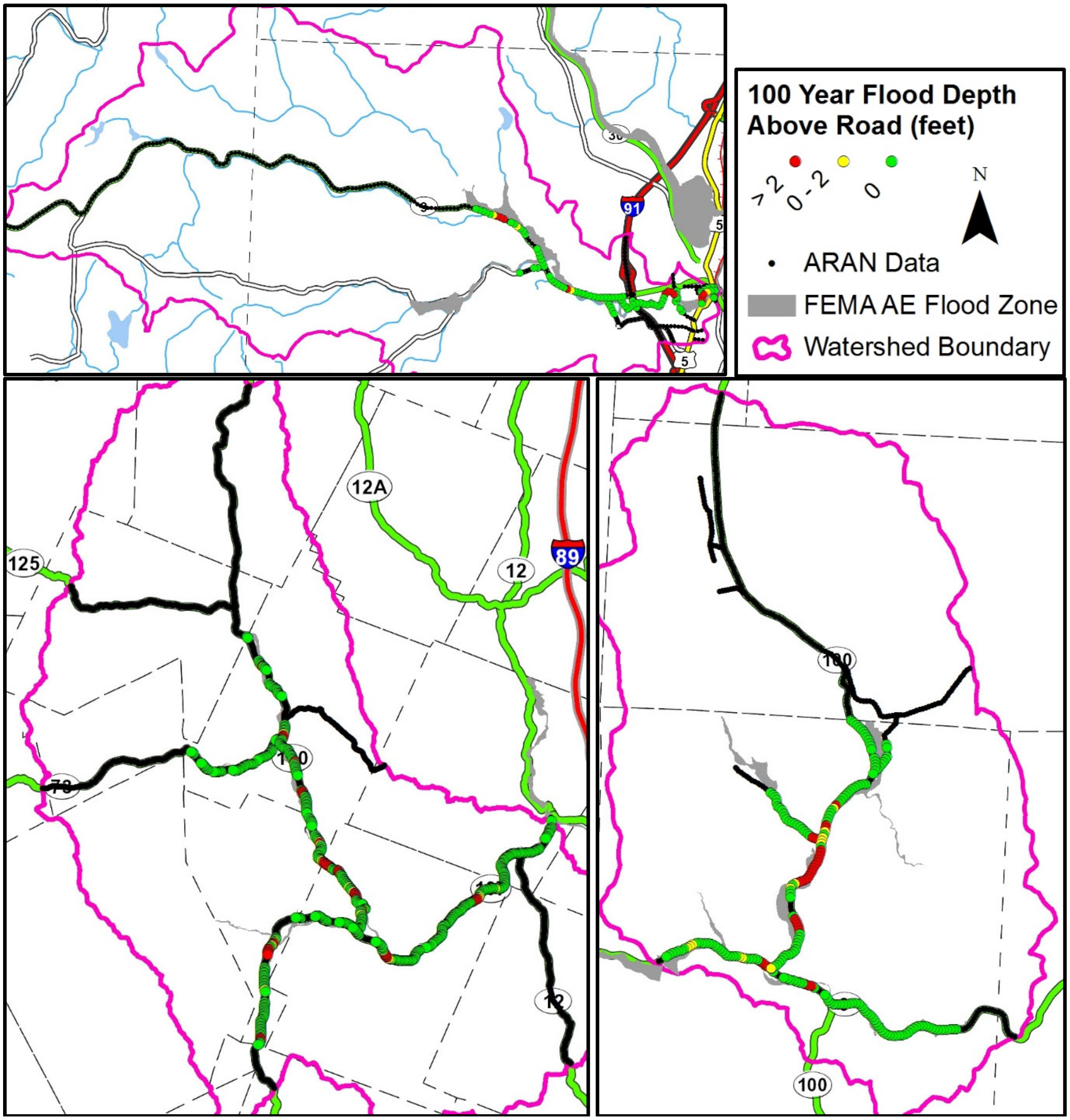


Figure C-4: ARAN and DFIRM data availability in the three pilot watersheds: Whetstone Brook (upper left). Upper White River (lower left), and North Branch Deerfield River (lower right)

Stream Geomorphic Assessment (SGA) Data

SGA data are available for download from the SGA Data Management System (DMS; https://anrweb.vt.gov/DEC/SGA/default.aspx). Reach names correspond to the MMIGRID field in the VHD SGA Network primary data layer, allowing these variables to be joined from tables downloaded from the DMS. SGA data were available on most of the mainstem and main tributaries for each of the pilot watersheds (Figure C-5 and Table C-1). More information on SGA data processing follows (Appendix F).

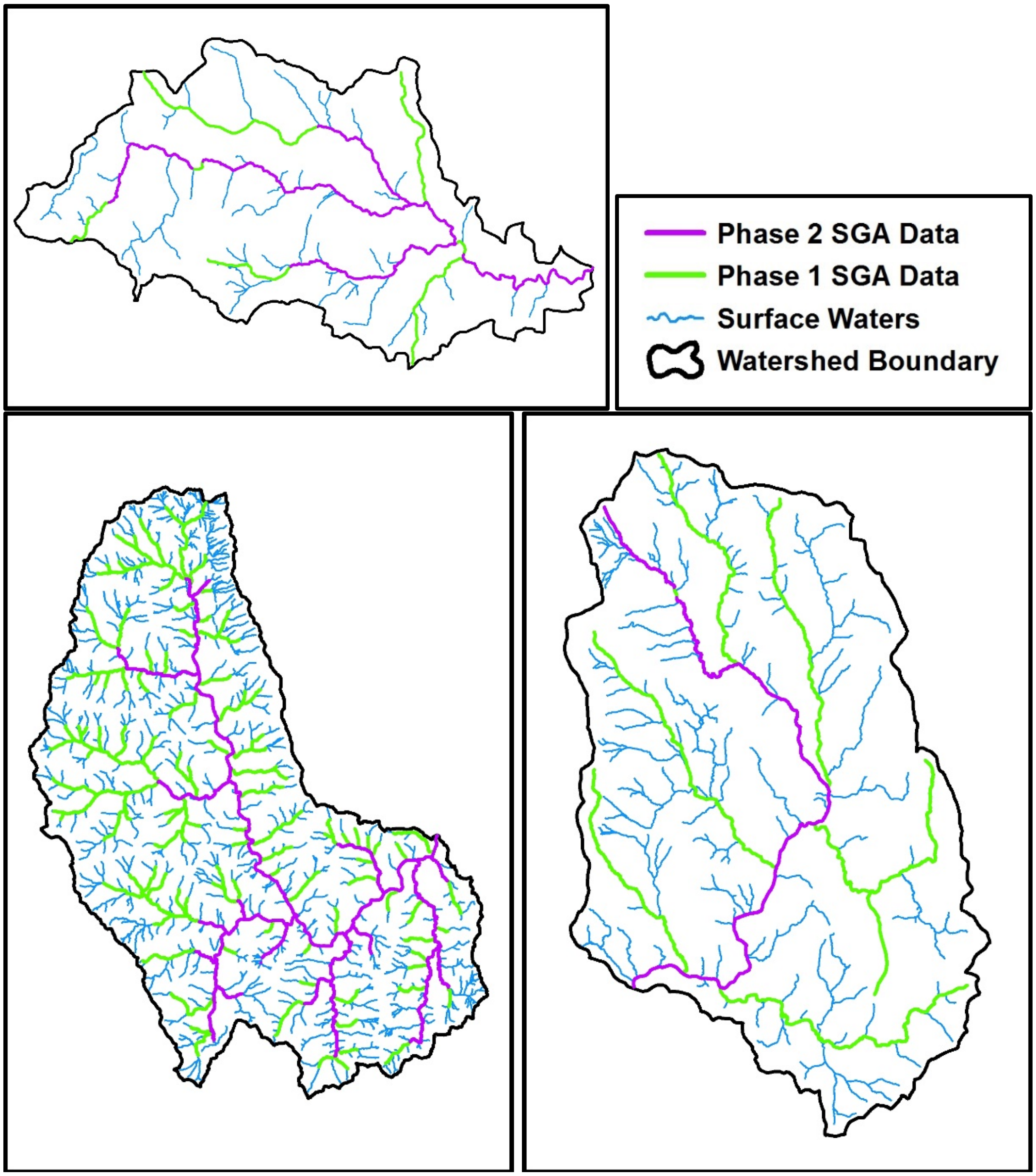


Figure C-5: Stream Geomorphic Assessment (SGA) data availability in the three pilot watersheds: Whetstone Brook (upper left), Upper White River (lower left), and North Branch Deerfield River (lower right)

TABLE C-1
SGA Data Availability in the Three Pilot Subwatersheds

Watershed	Phase 1 SGA Segments (%)	Phase 2 SGA Segments (%)	River Segments
Whetstone Brook	59 (42%)	47 (34%)	139
North Branch Deerfield River	62 (20%)	22 (7%)	310
Upper White River	257 (21%)	115 (9%)	1230
Total	378 (23%)	184 (11%)	1679

APPENDIX D

FAILURE MODE DETAILS

TABLE D-1
Failure Definitions Applied to Embankments, Bridges, and Culverts

Failure Mode	Road Embankments	Bridges	Culverts
Partial Closure	Small-scale embankment erosion, resulting in brief and local single-lane closure (< 1 day, < 100 feet) due to inundation or minor deposition or erosion in smaller channels	Scour around footings, abutments, and slopes of road embankments approaching bridge. Roadway overtopping and inundation. Brief single-lane closure (~1 day) for repairs including debris removal and shoulder reconstruction.	Erosion of slopes of road embankment approaching culvert or roadway overtopping. Brief single-lane closure (~1 day) for repairs including debris removal and shoulder reconstruction.
Full Closure	Road embankment washout for hundreds of feet, resulting in closure of both lanes. Temporary repairs within 1 to 2 days allow both lanes to reopen to traffic. Inundation or sediment/debris deposition, leading to full closure. Minor repair of road shoulder may be needed to reopen both travel lanes.	Overtopping of undersized bridges. Sediment and debris deposited on roadway adjacent to bridge, leading to full road closure. Road reopened following removal of material within 1-2 days.	Overtopping of undersized culverts. Sediment and debris deposited on roadway adjacent to culvert, leading to full road closure. Debris blocking culvert inlet, resulting in temporary inundation. Road reopened following removal of material within 1-2 days.
Temporary Failure	Road embankment washout, resulting in closure of both lanes for hundreds to thousands of feet. One lane may be reopened during emergency repairs.	Undermining of abutments or piers or bridge approach washed out due to deposition or erosion and outflanking. Road closed for several days to weeks while bridge repairs take place.	Small to medium-size culvert and roadway approaches washed out due to deposition/erosion and outflanking. Headwall damage due to scour. Temporary repairs needed, and road closed for several days.
Complete Failure	Complete road embankment washout resulting in closure of both lanes. Direct roadway damages on the order of thousands of feet. Both lanes closed for long periods during emergency recovery.	Bridge destroyed often accompanying road embankment washout. Temporary bridge likely in place within 1 to 2 weeks as needed. Permanent bridge repair to take months or years.	Large culvert and roadway approaches washed out due to deposition/erosion and outflanking. Temporary repairs require road closing for > 1 week.

APPENDIX E

PAST DAMAGE DATA ASSIGNMENTS

River Process	Road	Bridge	Culvert
Inundation	√	√	√
Erosion	√	√	√
Deposition	√	√	√

Low Vulnerability	Moderate Vulnerability		High Vulnerability	
No Damage Record	Partial Closure	Full Closure	Temporary Failure	Complete Failure

Definition: Documented damages from Tropical Storm Irene. VTrans DDIR included a GIS shapefile and documentation about the repair and approximate costs as well as site photographs in many cases. FEMA Public Assistance (PA) project locations were available as a shapefile. Shapefiles provided by Regional Planning Commissions (RPC) were included for assessing roads maintained by towns. Local accounts, such as those gathered from public meetings and news reports, were also used for classifying the extent of damages.

Application: The presence of a past damage indicates a high degree of vulnerability for that road-river corridor setting. The detailed analysis in the three pilot watersheds included an assessment of the severity of damage (e.g., temporary road closure versus failure).

Data Development: DDIR PDF files with a summary of the damage, work done, and photographs were inspected to classify the damage as road or structure damage. Damages that were not stream related (e.g., landslides or road ditch erosion) were discarded. The remaining records were classified as primarily inundation, erosion, or deposition damage. Damage records were spatially joined to the nearest road segments to link the damage record to the road network (VTrans AllRoads, 2017). For bridges and culverts, all potential crossing locations were first identified in GIS through an intersection between the road and river networks. Then the intersected points were spatially joined with all available structure datasets.

GIS Methods:

Files	Data Type	Unique ID Field
VTrans DDIR	Point Shapefiles, PDF Reports, Photographs	REPORT_NUM
RPC Damage Sites	Point and Line	N/A - Varies
FEMA PA Project	Point	PW_NUMBER (for a given disaster)
Stakeholder Input	Point	N/A
VTRANS AllRoads (Road Centerlines)	Line	FAID
Rivers (VHD/SGA composite channel network)	Line	MMIGRID
VTrans Long Structures	Point	StructureN
VTrans Short Structures	Point	StructureN
VTrans Small Culvert Inventory (Ultrashorts)	Line	Asset_Sys_
SGA Structex Structures Database	Point	SgaID

1. Create "Stream Crossings" layer.
   a. Open the "Intersect" tool.
   b. Add the VLT rivers and the VTrans road centerlines files and specify the desired name and destination for the output file.
   c. Under "Output Type" specify "POINT" features.
   d. Create a unique ID field by concatenating the MMIGRID, FAID, and the FID. Including the FID makes sure that a stream crossing the same road segment multiple times has a unique ID for each crossing.

2. Associate damage layers with stream and road IDs.
   a. Convert RPC damage lines into a point shapefile using the coordinates of the line centroids.
   b. Open the "Merge" tool and add the DDIR, RPC, and PA Project point files as input datasets to create a feature class of all damage records.
   c. Open the "Spatial Join" tool.
   d. Add the DDIR file for the "Target Features" and the VTrans road centerlines file for the "Join Features." Specify the desired name and destination for the output feature class. Select "CLOSEST" from the "Match Option" drop-down. Keep all other defaults.
      - Optional: In the "Field Map of Join Features" box, remove extra fields from the road centerlines layer, keeping the unique ID field, road name, and route number. This makes the attribute table easier to work with in later steps.
   e. Repeat step 2b with the output file created in step 2b for the "Target Features" and the VLT rivers layer for the "Join Features" to create a file of damage locations with the unique IDs for the nearest road and stream. Specify a name in the "Distance Field Name" box to obtain a field with the distance from the damage point to the nearest stream to help rule out damages not related to perennial streams.
      - Optional: In the "Field Map of Join Features" box, remove extra fields from the streams layer, keeping the unique ID field, stream name, and stream order. This makes the attribute table easier to work with in later steps.
   f. Repeat step 2b with the output file created in step 2c for the "Target Features" and the "Stream Crossings" layer for the "Join Features" to create a file of damage locations with the unique IDs for the nearest road-stream intersection. Specify a name in the "Distance Field Name" box to obtain a field with the distance from the DDIR point to the nearest crossing to help distinguish between damages likely to have affected a structure (located at a stream crossing) and structures affecting only the road.
      - Optional: In the "Field Map of Join Features" box, remove extra fields from the streams layer, keeping the unique ID field, stream name, and road name. This makes the attribute table easier to work with in later steps.

3. Classify damage data.
   a. Add the following fields to the attribute table of the DDIR layer created in step 2c.
      - [STruc_D]: Text. In this field, specify whether the damage is to a structure ("Y"), road ("N"), both ("Both"), or neither ("Neither").
      - [SV_Type]: Text. If the damage was to a structure or both the road and a structure, specify whether the damage was primarily due to inundation ("I"), erosion ("E"), or deposition ("D").

- [RV_Type]: Text. If the damage was to a structure or both the road and a structure, specify whether the damage was primarily due to inundation ("I"), erosion ("E"), or deposition ("D").
- [SF_Mode]: Text. Failure mode of the structure (see Appendix C for detailed descriptions of each failure mode). Specify whether the failure mode was a partial closure ("PC"), full closure ("FC"), temporary failure ("TF"), or complete failure ("CF").
- [RF_Type]: Text. Failure mode of the road segment (see Appendix C for detailed descriptions of each failure mode). Specify whether the failure mode was a partial closure ("PC"), full closure ("FC"), temporary failure ("TF"), or complete failure ("CF").

b. Go through each damage record, filling in the newly added fields for each record.

- Eliminate duplicate damage records as much as possible by examining the point locations and damage descriptions.
- Examine proximity to blue line streams and the damage descriptions in the reports to limit the inclusion of damages from stormwater runoff from impervious surfaces (e.g., rilling and ditch erosion along gravel roads) or landslides from saturated soils on steep slopes.
- Examine the reports to determine whether the damage was to a bridge, culvert, or both. Damage descriptions, line items for repair, and photographs are especially useful. Ancillary information from VCGI imagery, Google Earth, Google Maps, Google Street View, news articles, etc. can help with this determination. Use the stream crossing distance field to help determine if the damage was to the road, structure, or both. The structures database assembled for vulnerability screening can help distinguish between bridges and culverts. For FEMA PA Projects, filter out damages to public buildings, utilities, and recreational and other infrastructure that are not associated with a road, bridge, or culvert.
- Examine the reports to specify the primary damage mode for road and structure damages. For inundation damages, look at the proximity of the points to the 100-year floodplain boundaries where available and look for mentions of flooding and pavement bubbling. For deposition damages, look for mentions of debris or erosion resulting from a bridge or culvert plugged with debris. Most significant damages were from erosion, and descriptions often mentioned washouts. The ancillary information described above is also useful for this determination. If multiple damage modes seem likely, choose the one that was the root cause of the damage (e.g., deposition plugging a culvert and causing inundation or erosion at the structure). If no root cause is clear, choose the damage mode with the costliest repairs (e.g., >$10,000 for rock and pavement to fix an eroded embankment versus <$1,000 in debris removal would be classified as erosion damage). If no other information is available, choose the damage type that was most extensive at the site.
    1. For damages with limited descriptions, such as the PA Projects, scan imagery and the setting of the river in the valley to determine the most likely damage type. Search for applicable news articles and ask stakeholders for more information.
- Assign a failure mode to each damage record (in order of increasing severity: partial closure, full closure, temporary failure, complete failure). See Table 4-4 and Appendix C for more detailed information on the criteria used to distinguish failure mode. Criteria include the duration of travel disruption and extent of damage. Incorporate prior knowledge as well as stakeholder input from public meetings and personal

correspondence. For PA projects without a description of the extent of damage, use aerial imagery and consult stakeholders for more information. PA projects tend to be less urgent from a transportation perspective and therefore will mainly be classified as partial and full closure. Incorporate prior knowledge as well as stakeholder input from public meetings and personal correspondence.

1. Evaluation of failure mode during field visits can be accomplished by observing repairs made (e.g., extent of new armoring or recently replaced structures) or lack of evidence of extensive repairs. Where applicable, classification of damage type or failure mode can be revised following field visits.

- Check MMIGRID and FAID values for damages, especially stream crossing IDs matched to structure damages to verify damages are being matched with the most affected road segment and crossing.

4. Check for spelling errors and consistency in the attribute fields for a seamless input to the scoring spreadsheet.

TABLE E-1
Damage Data Used in Vulnerability Scoring for the Pilot Watersheds

Name	Source	Description and Limitations
PA Projects	FEMA	Point locations, limited description of damages, damage categories (e.g., debris removal, protective measures, roads, and bridges)
DDIR	VTrans	Point locations, description of damages, image(s), cost to repair
Regional Planning Commissions	Two Rivers-Ottaquechee Regional Commission (TRORC), Rutland Regional Planning Commission (RRPC), Windham Regional Commission (WRC)	Point and line locations, variable level of detail describing damages in comments fields of shapefiles

APPENDIX F

VULNERABILITY PARAMETER CALCULATION DETAILS

The following sections detail each variable used in the vulnerability screen and the processes used to assign these to a road, structure, or river segment.

Variables for each road segment include the following:

1. River-Roadway Relief
2. 100-Year Flood Depth Above Road
3. Length of Road in FEMA 100-Year Floodplain
4. Length of Road in River Corridor

Variables for each structure include the following:

- Start with Structure Database Assembly
1. Invert-Roadway Relief
2. Structure Width vs. Bankfull Channel Width (%)
3. Structure SGA and Geomorphic Compatibility Screen Variables

Variables for each river (corridor) segment include the following:

- Start with Defining Upstream-Downstream Relationships for river segments
1. River Stream Geomorphic Assessment data
2. VT River Sensitivity Coarse Screen Variables
3. Nearby Steep Slopes

Road Segments

Variable Descriptions and Methods

River-Roadway Relief

River Process	Road	Bridge	Culvert
Inundation	√		
Erosion			
Deposition			

Low Vulnerability	Moderate Vulnerability	High Vulnerability
<5 ft	5 – 10 ft	>10 ft

Definition: The elevation difference (ft) between the GIS river and road segments (VTrans, 2016)

Application: The lower the relief between rivers and roads, the higher the vulnerability to roads due to inundation. High vulnerability occurs when the road segment is less than 5 feet above the river. Road segments greater than 10 feet above the river tend to have low inundation vulnerability.

Data Development: Relief was assessed by creating lines perpendicular to the segment and sampling river and road elevations where the perpendicular lines intersected the road and river lines. High-resolution LiDAR digital elevation models are recommended for this analysis.

GIS Methods:

Files	Type	Unique ID Field
VTRANS AllRoads (Road Centerlines)	Line	FAID
VT Meander Centerlines	Line	MMIGRID
Rivers (VHD/SGA composite channel network)	Line	MMIGRID
LiDAR Digital Elevation Model	Raster	N/A

1. Create "Perpendicular Lines" layer (Figure F-1).

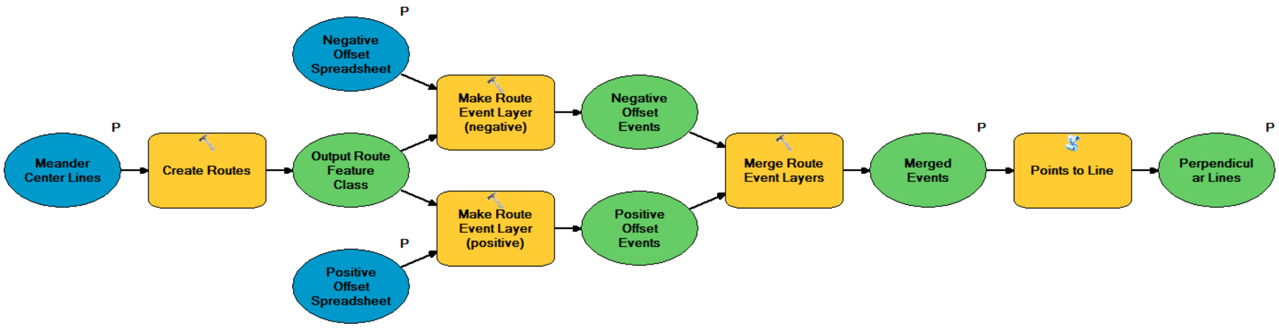


Figure F-1: Overview of the steps to create perpendicular lines

a. Clip the "VT Meander Centerlines" to the area of interest. Where no meander centerline is available, use the VHD stream centerline. Add a field named [RouteID] to the "VT Meander Centerlines" for the watershed of interest. Set all entries in the table equal to 1.
    - Note: Perpendicular lines created using the VHD stream centerline may require more manual adjustment due to the curvature of the line.
b. Open the "Create Routes" tool.
c. Convert river networks into routes using the "VT Meander Centerlines" as the input lines. Set the "Route Identifier" field to [RouteID], "Measure Source" field to "LENGTH," and "Measure Factor Offset" to 1.
d. Create an *Excel* format spreadsheet with two tabs, "neg" and "pos," each with the fields [Location], [Offset], and [Route]. Begin the [Location] field with 1 in the first cell and increase in 150-meter increments until it matches the length of the river route in meters. Set all values in [Offset] to 300 meters in the "pos" tab and -300 meters in the "neg" tab. Set all value [for Route] equal to 1. Save the spreadsheet.
e. Open the "Make Route Event Layer" tool.
f. For "Input Route Features," select the meander centerline route created in step 1b. Set the "Route Identifier" field to [RouteID]. Select the "pos" tab of the *Excel* spreadsheet created in step 1c for the "Event Input Table." Set the "Route Identifier Field" to [Route], the "Measure Field" to [Location], "Layer Name or Table View" to "$pos," and the "Offset Field" to [Offset].
g. Repeat step 1f for the "neg" tab of the spreadsheet.
h. Use the "Merge" tool to merge the negative and positive offset layers.

i. To draw perpendicular transects across the river network, use the "Points to Line" tool with the merged layer as input. Select [Location] for the "Line Field."
j. Select perpendicular transects that do not intersect roads and delete from the shapefile.
k. Add a field to the perpendicular transect shapefile named [PLineID] and set it equal to the FID + 1 to give each line a unique ID.

2. Extract elevation data.
   a. Open the "Intersect" tool.
   b. Intersect the VHD/SGA composite channel network shapefile with the perpendicular lines shapefile. Use the "Multipart to Singlepart" tool to split points that fall on the same perpendicular line into separate features. Manually delete extra points where a perpendicular line intersects two streams or a single stream multiple times.
   c. Repeat steps 2a and 2b to intersect the VTrans AllRoads Centerlines with the perpendicular lines, but do not delete any of the resulting points.
   d. Open the "Extract Multi Values to Points" tool.
   e. Input the stream-perpendicular line intersection points as the "Input point features" and the LiDAR DEM as the "Input raster."
   f. Repeat steps 2d and 2e for the road-perpendicular line intersection points.

3. Join road and stream elevations.
   a. Open the "Spatial Join" tool.
   b. Input the road-perpendicular line intersects for the "Target Features" and the stream-perpendicular line intersects for the "Join Features." Select "WITHIN_A_DISTANCE" for the "Match Option." Specify a "Search Radius" of 300 meters.
   c. Examine the output and remove points where the [PLineID] created in step 1k do not match to ensure road and stream elevations along the same perpendicular line are compared.

4. Calculate relief.
   a. Create a new field. Subtract stream elevations from road elevations. Convert to feet.
   b. Examine results for 0 or negative values. Examples of when this may occur include roads that are far from streams (>150 meters) and potentially in another drainage basin, stream points that fall on bridge crossings not burned into the LiDAR DEM, or areas where the road or stream line geometry does not match the LiDAR DEM. Small forested stream centerlines are especially likely to have geometry that differs from the channel centerline as measured in the LiDAR.
   c. Manually delete negative and 0 relief point. Perform QA/WC of relief values less than 1.5 meters and delete or correct as necessary.
   d. Use the "Dissolve" tool with [FAID] as the "Dissolve_Field." Calculate the minimum relief as a "Statistics Field."

Note: This method may select multiple roads along the same perpendicular line. This allows the line to select roads on either side of the stream that may be vulnerable. It may also select multiple parallel roads on the same side of the stream, especially in areas of high road density. Through visual examination of the pilot data, it was determined that the road further away usually has a higher elevation than the road closer to the stream except near watershed boundaries. If the transect crosses a watershed boundary, it may pick up a road in the next basin over that has a lower elevation than the closer road segment. This method may be improved by drawing perpendicular lines separately for each side of the stream segment and performing the spatial join of the closest points using those lines.

100-Year Flood Depth Above Road

River Process	Road	Bridge	Culvert
Inundation	√		
Erosion			
Deposition			

Low Vulnerability	Moderate Vulnerability	High Vulnerability
0 ft	0-2 ft	>2 ft

Definition: The elevation difference (ft) between interpolated FEMA flood depths and GIS road segments (VTrans, 2016)

Application: The higher the projected 100-year flood elevation based on FEMA models is compared to the road elevation, the higher the vulnerability to roads due to inundation. High vulnerability occurs when the road segment is more than 2 feet below the projected flood elevation. Road segments above the projected flood elevation tend to have low inundation vulnerability.

Data Development: Flood depth above the road was assessed interpolating flood elevations from FEMA cross section data and comparing it to road elevations. ARAN elevation data were used for the pilot watershed road elevations due to its broader coverage at the time. However, statewide LiDAR data is now available for Vermont and is recommended for future analyses due to the extent of coverage available.

GIS Methods:

Files	Type	Unique ID Field
VTRANS AllRoads (Road Centerlines)	Line	FAID
FEMA DFIRM Cross Sections	Line	MMIGRID
Automatic Road Analyzer (ARAN)	Point	N/A
LiDAR Digital Elevation Model	Raster	N/A

1. Interpolate cross sections into a digital elevation model (DEM).
   a. Open the "Create TIN" tool.
   b. For the "Input Feature Class," choose the FEMA DFIRM cross sections where available for the area of interest. For the "Height Field," choose the 100-year flood elevation. Use the river corridor layer with a 100-meter buffer as a "hardclip" for the DEM. Flood depths are not calculated for road segments outside this buffer.
   c. Open the "TIN to Raster" tool.

2. Extract elevation and calculate flood depth.
   a. Open the "Extract Multi Values to Points" tool.

- Note: As ARAN points were used for the pilot watersheds, no preprocessing was necessary to obtain points along the roads, and the points were spatially joined to the VTrans AllRoads centerlines after the calculation. To sample LIDAR elevation data, the "Make Route Event Layer" can be used as described in the River-Roadway Relief section with the roads as the route layer to create evenly spaced points along the road network for sampling elevation.

b. Specify points along the road network for the "Input point features" and both the LiDAR DEM and the 100-year flood DEM created in step 1 for the "Input rasters."
c. Calculate the difference between road elevation and flood elevation by subtracting the flood elevation from the road elevation converted to feet. Negative values indicate inundation. Convert the road elevation to feet.
d. Use the "Dissolve" tool, with FAID as the dissolve field and flood depth as a statistics field to select the greatest flood depth along the segment (the minimum value due to negative values indicating inundation).

Length of Road in FEMA 100-Year Floodplain

River Process	Road	Bridge	Culvert
Inundation	√		
Erosion			
Deposition			

Low Vulnerability	Moderate Vulnerability	High Vulnerability
<50 ft	50 – 100 ft	>100 ft

Definition: The length of the GIS road segment (VTrans, 2016) right-of-way (ROW) located in digitized FEMA floodplains (accessed from VTANR) and approximate floodplains based on soil characteristics (Adpated after Sangwan and Merwade, 2015). A standard 3-rod (49.5 feet) ROW centered on the road centerline was used for the analysis. The floodplains used in this analysis are a combination of officially digitized DFIRMS and rough/nonofficial data from a variety of sources and done to a variety of specifications.

Application: The more road in the floodplain, the higher the vulnerability to roads, bridges, and culverts due to inundation. High vulnerability occurs when more than 200 feet are in the floodplain. Low vulnerability tends to be present when less than 50 feet of the road is in the floodplain.

Data Development: The ROW, rather than just the road centerline, was used to be sure that the overlap between the two polygon layers was maximized. The ROW was developed by offsetting the road centerline 1.5 rods (24.75 feet) in each direction. The ROW lines and the floodplains were clipped and had their lengths measured to determine the overlap (Figure F-2). The maximum total overlapping length of the ROW lines was used as the overlap between the road segment ROW and the floodplain (Figure F-3).

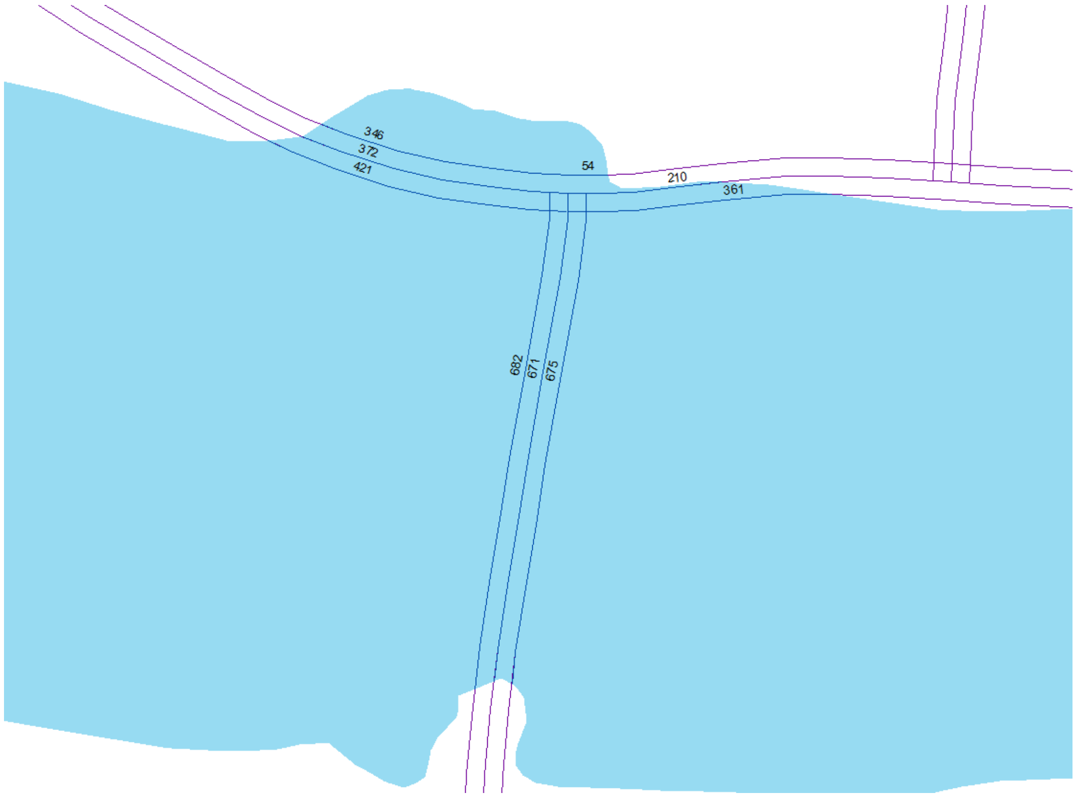


Figure F-2: Example of lengths of road segment ROW in floodplain

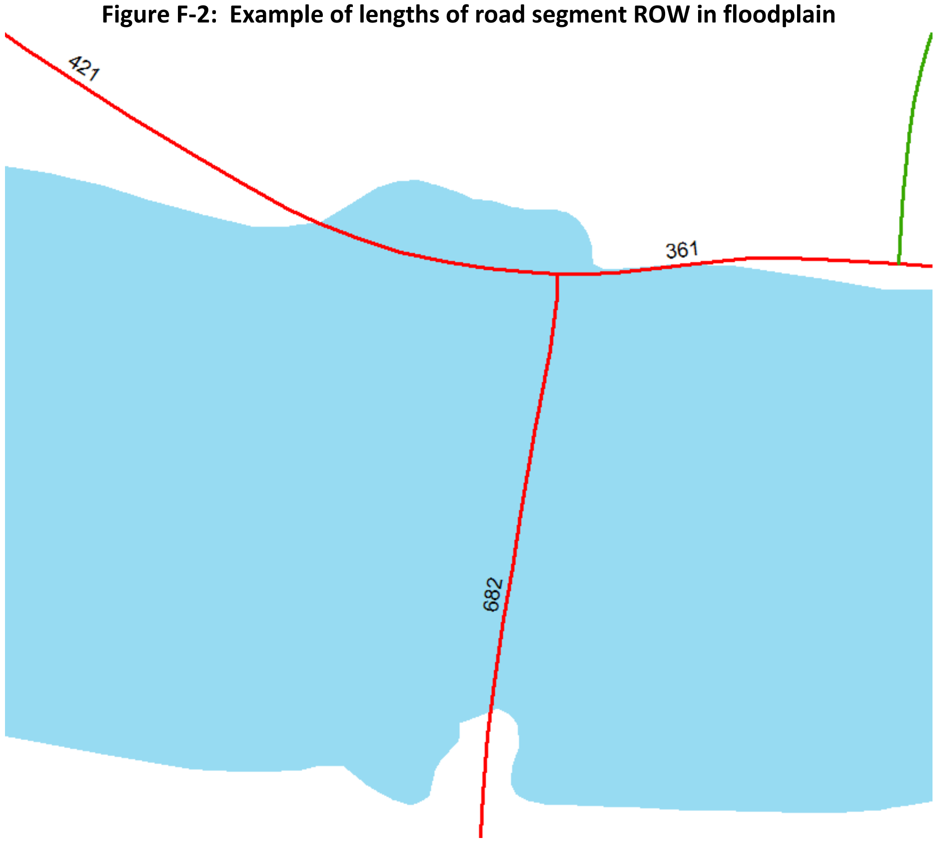


Figure F-3: Example of maximum length of road segment ROW in floodplain

GIS Methods:

Files	Type	Unique ID Field
VTRANS AllRoads (Road Centerlines)	Line	FAID
ROW Roads (copy saved from Appendix B)	Line	FAID
Flood Hazard Areas	Polygon	N/A
SSURGO Floodplain Soils (method adapted from Sangwan & Merwade (2015))	Polygon	N/A

1. Create file.
   a. Open the "Merge" tool.
   b. Input the "Flood Hazard Areas" file and the "SSURGO Floodplain Soils" file; specify the desired name and destination for the output file.
   c. Open the "Dissolve" tool.
   d. Input the file created in step 1b above; specify the desired name and destination for the output file.

2. Determine maximum length of ROW.
   a. Open "Clip" tool. Input "ROW Roads" file. Under "Clip Features," specify the file created in step 1d. Specify the desired name and destination for the output file.
   b. Open the "Attribute Table" for the clipped file created in step 2a above. "Add Field" for segment length values; specify "Double." "Calculate Geometry" of this field; specify "Length," "Feet." Right click on "FAID," select "Summarize." Under 1, specify "FAID." Under 2, specify the segment length field just created, and select all variables. Under 3, name the summary table as desired, save as type "Text."

3. Classify data
   a. Open the VTRANS AllRoads Attribute Table. "Add Field" for maximum segment length values, specify "Double." Join the summary table to the AllRoads table based on "FAID." Use Field Calculator on the maximum segment length value field and set it equal to the maximum length field from the summary table.
   b. Score the maximum lengths by Categories of Vulnerability. In the VTRANS AllRoads Attribute Table, "Add Field" for scoring, specify "Text."
   c. Select by Attributes all road segments that are <50 feet; in "Field Calculator" for the new text field, specify "LOW."
   d. Repeat step 3c. between 50 and 200 = "MODERATE" and >200 = "HIGH."

Length of Road in River Corridor

River Process	Road	Bridge	Culvert
Inundation			
Erosion	√		
Deposition	√		

Low Vulnerability	Moderate Vulnerability	High Vulnerability
<660 ft	660 – 1,320 ft	>1,320 ft

Definition: The length of the GIS road segment (VTrans AllRoads, 2017) ROW located in the approximate Vermont River Corridor (VTANR, 2015). A standard 3-rod (49.5 feet) ROW centered on the road centerline was used for the analysis. The river corridor used in this analysis includes the unmapped 100-foot corridor – 50 feet on each side – that ANR has identified for small streams with watershed areas less than 2 square miles.

Application: The more road in the river corridor, the higher the vulnerability to roads, bridges, and culverts due to erosion and deposition. High vulnerability occurs when more than 1,320 feet (0.25 miles) are in the corridor. Low vulnerability tends to be present when less than 660 feet of the road is in the corridor.

Data Development: The ROW, rather than just the road centerline, was used to be sure that the overlap between the two polygon layers was maximized since in some locations the river corridor is clipped at the edge of major roads. The ROW was developed by offsetting the road centerline 1.5 rods in each direction. The ROW lines and the river corridor were unioned to determine the overlap. The maximum total overlapping length of the two ROW lines was used as the overlap between the road segment ROW and the river corridor (Figure F-4).

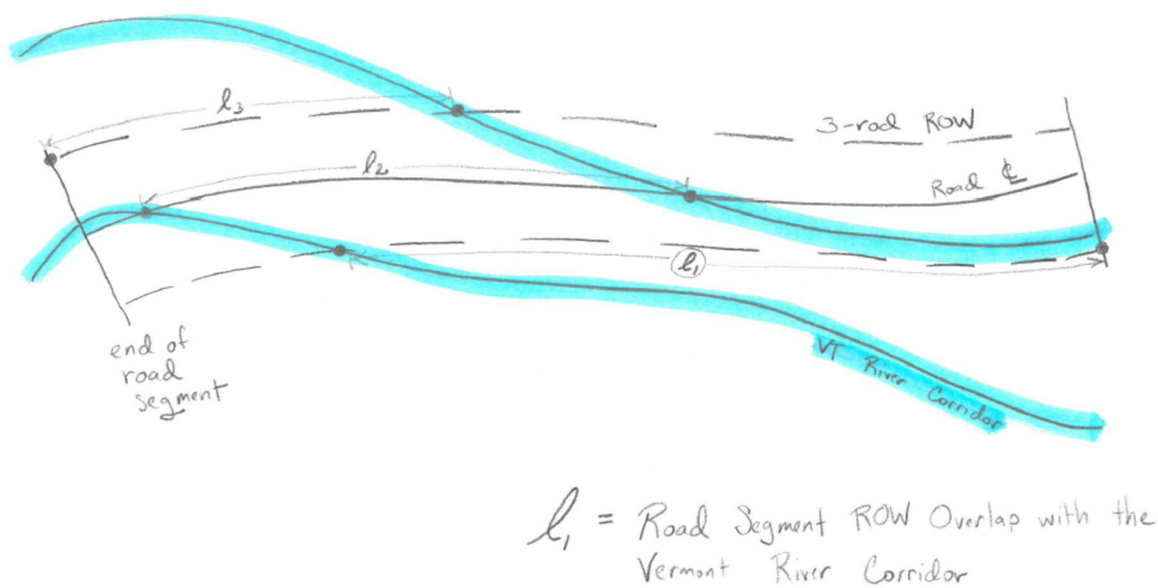


Figure F-4: Sketch of length of road segment ROW in river corridor

GIS Methods:

Files	Type	Unique ID Field
VTRANS AllRoads (Road Centerlines)	Line	FAID
VTRANS River Corridors	Line	N/A
Rivers (VHD/SGA composite channel network)	Line	N/A

1. Create "ROW Roads" file.
    a. Make a copy of the "VTRANS AllRoads" file and specify the desired name and destination for the output file.
    b. Click on the "Editor" toolbar and select "Start Editing."
    c. Select the copy of the VTRANS AllRoads layer to edit.
    d. Click on the "Editor" toolbar again and select "Copy Parallel."
    e. Under "Distance," specify "24.75."
    f. Under "Side," specify "Both."
    g. Under "Corners," specify "Mitered."
    h. Uncheck "Remove self-intersecting loops."
    i. Click on the "Editor" toolbar and select "Save Edits" and "Stop Editing."
    j. Make a copy of this "ROW Roads" file and save it in a different location to use during the ROW in Floodplain Analysis below.

2. Create "Buffered Rivers" file.
    a. Open the "Buffer" tool.
    b. Input the "Rivers (VHD/SGA composite channel network)" layer and select the desired name and destination for the output file.
    c. Under "Distance," select "Linear unit," specify "50" feet.

3. Create combined file.
    a. Open the "Merge" tool.
    b. Input the "Buffered Rivers" and "VTRANS River Corridors" files and specify the desired name and destination for the output file.
    c. Open the "Dissolve" tool.
    d. Input the file created in step 3c above and specify the desired name and destination for the output file.
        - This step requires a 64-bit geoprocessing, available in ArcGIS Pro or as a supplementary installation to ArcGIS Desktop.

4. Determine maximum length of ROW.
    a. Open "Clip" tool. Input "ROW Roads" file. Under "Clip Features," specify the file created in step 3d. Specify the desired name and destination for the output file.
    b. Open the "Attribute Table" for the clipped file created in step 4a above. "Add Field" for segment length values; specify "Double." "Calculate Geometry" of this field; specify "Length," "Feet." Right click on "FAID," select "Summarize." Under 1, specify "FAID." Under 2, specify the segment length field just created, and select all variables. Under 3, name the summary table as desired, save as type "Text."

5. Classify data.
   a. Open the VTRANS AllRoads Attribute Table. "Add Field" for maximum segment length values, specify "Double." Join the summary table to the AllRoads table based on "FAID." Use Field Calculator on the maximum segment length value field and set it equal to the maximum length field from the summary table.
   b. Score the maximum lengths by Categories of Vulnerability. In the VTRANS AllRoads Attribute Table, "Add Field" for scoring, specify "Text."
   c. Select by Attributes all road segments that are <660 feet, and in "Field Calculator" for the new text field, specify "LOW."
   d. Repeat step 5c. between 660 and 1,320 = "MODERATE" and >1,320 = "HIGH."

Bridges and Culverts

Structure Database Assembly

GIS Methods:

Files	Type	Unique ID Field
VTRANS AllRoads (Road Centerlines)	Line	FAID
Rivers (VHD/SGA composite channel network)	Line	MMIGRID
VTrans Long Structures	Point	StructureN
VTrans Short Structures	Point	StructureN
VTrans Small Culvert Inventory (Ultrashorts)	Line	Asset_Sys_
SGA Structex Structures Database	Point	SgaID
VOBCIT Bridges	Point	id
VOBCIT Culverts	Point	id

1. Create point layer from Small Culvert Inventory Lines.
   a. Open the "Add Geometry Attributes" tool and add the Small Culvert Inventory to the "Input Features" box. Check the "LINE_START_MID_END" box in the "Geometry Properties" window.
   b. Open the "Make XY Event Layer" tool. Add the Small Culvert Inventory layer to the "XY Table" box. Specify the newly created midpoint coordinates for the X and Y fields, choose a layer name, and make sure the spatial reference corresponds to the units and coordinate system used to calculate the midpoint locations.
   c. Right click on the newly created event layer and export to a shapefile.

2. Create "Stream Crossings" layer.
   a. Open the "Intersect" tool.
   b. Add the VLT rivers and the VTrans road centerlines files, and specify the desired name and destination for the output file.
   c. Under "Output Type," specify "POINT" features.
   d. Use the "Multipart to Singlepart" tool to convert multiple structures on the same river and stream segment into unique point features.

e. Create a unique ID field by concatenating the MMIGRID, FAID, and the FID. Including the FID makes sure that a stream crossing the same road segment multiple times has a unique ID for each crossing.

3. Associate stream crossing points with structure IDs.
   a. Condition the structure data layers using the "Feature Class to Feature Class" tool to export a new version of each structure layer. Reduce the number of columns in each attribute table by removing unnecessary fields. Keep the unique ID and structure width fields. Add a prefix to the fields that is unique to each layer by renaming them. This makes sure no information is removed when the layers are merged from matching column names.
      - The structure width fields are as follows:

Files	Unique ID Field	Width Field	Units
SGA Structex Structures Database	SgaID	StructureW	Feet
VTrans Long Structures	StructureN	StructureL	Feet
VTrans Short Structures	StructureN	StructureL	Feet
VOBCIT Bridges	id	Overall_w	Feet
VOBCIT Culverts	id	Width	Inches
VTrans Small Culvert Inventory (Ultrashorts)	Asset_Sys_	Width	Inches

   b. Open the "Spatial Join" tool. Perform six one-to-one joins, selecting the "CLOSEST" match option and specifying a unique distance field name for each join.

Target Features	Join Features	Output Layer	Unique ID Field	Width Field	Units
"Stream Crossings"	SGA Structex Structures Database	"Structex_Join_1"	SgaID	StructureW	Feet
"Structex_Join_1"	VTrans Long Structures	"VTLong_Join2"	StructureN	StructureL	Feet
"VTLong_Join2"	VTrans Short Structures	"VTShort_Join3"	StructureN	StructureL	Feet
"VTShort_Join3"	VOBCIT Culverts	"VOBCIT_C_Join4"	id	Width	Inches
"VOBCIT_C_Join4"	VOBCIT Bridges	"VOBCIT_B_Join5"	id	Overall_w	Feet
"VOBCIT_B_Join5"	VTrans Small Culvert Inventory (Ultrashorts)	"VTUltraShorts_Join6"	Asset_Sys_	Width	Inches

4. Apply filters to the joined crossing and structures data.
    a. Apply the distance filters developed using the pilot watershed data. The selection uses the following distance layers and cutoffs: Structex (≤70m S_Dist), VTrans Long (≤30m L_Dist), VTrans Short (≤30m S_Dist), VOBCIT Bridges (≤20m B_Dist), VOBCIT Culverts (≤20m C_Dist), Small Culvert Inventory (≤20m U_Dist).
        - Select by Attributes VBSCRIPT:
          ("U_Dist" >-1 AND "U_Dist" <= 20) OR ("B_Dist" > -1 AND "B_Dist" <= 20) OR ("C_Dist" > -1 AND "C_Dist" <= 20) OR ("S_Dist" > -1 AND "S_Dist" <= 30) OR ("L_Dist" > -1 AND "L_Dist" <= 30) OR ("X_Dist" >-1 AND "X_Dist" <= 70)
    b. Filter the structure width data for each layer. Examine the datasets to look for structure widths that are outside the range of expected values or likely do not match the road-stream intersection they were joined to.
        - Filter out widths that are negative, zero, or less than 1 foot.
        - Filter out widths of 999, 9,999, and greater than 9,999.

5. Identify whether the structure is a bridge or culvert.
    a. The following rules were applied to assign structure type to intersections between roads and rivers described above:
        - Structex [StructureT] assigned either Arch, Bridge, or Culvert. Assumed Arch = Bridge
        - BCVtransLong [CulvertRat] if N= Bridge
        - BCVtransShort[CulvertRat_1] if N= Bridge
        - VOBCIT culvert – assume all culverts
        - VOBCIT bridge – assume all bridges, unless classified as culvert in Structex
        - VTrans Small Culvert – assume all culverts
    b. Create a new field and assign all structures with some data = "Culvert." Then, select by attributes using the logic above to identify bridges.
    c. Refine with damage record descriptions as needed. Display structures without enough information to classify structure type as culverts and score using the culvert screen if sufficient data do exist.

Structure Variable Descriptions and Methods

Invert-Roadway Relief

River Process	Road	Bridge	Culvert
Inundation		√	√
Erosion			
Deposition			

Low Vulnerability	Moderate Vulnerability	High Vulnerability
>10 feet	5 – 10 feet	<5 feet

Definition: The elevation difference (ft) between the GIS road elevation in the low point of the stream where it crosses the road

Application: The lower the relief between structure inverts and roads, the higher the vulnerability to roads due to inundation. High vulnerability occurs when the road segment is less than 5 feet above the structure invert. Road segments greater than 10 feet above the structure invert tend to have low inundation vulnerability.

Data Development: Relief was assessed by finding the average of upstream and downstream low points at stream crossings and comparing the elevation to the road elevation sampled at the stream crossing. High-resolution LiDAR digital elevation models are recommended for this analysis.

GIS Methods:

Files	Type	Unique ID Field
VTRANS AllRoads (Road Centerlines)	Line	FAID
Rivers (VHD/SGA composite channel network)	Line	MMIGRID
LiDAR DEM	Raster	N/A

1. Create stream crossing buffers.
   a. Use the "Buffer" tool on the structures database compiled in the previous section. Specify a 15-meter buffer for town roads and a 20-meter buffer for state and federal highways. Highways are assumed to be wider than town roads in most cases.
   b. Use the ArcGIS Modelbuilder tool "Split Polygons with Lines" (available at: http://www.arcgis.com/home/item.html?id=cd6b2d45df654245b7806a896670a431) to generate an upstream and downstream semi-circle buffer for each crossing.
      - Note: In areas with higher road density, the buffers will be split into more than two parts. In these instances, merge buffers manually so there are single upstream and downstream polygons for each structure.
2. Calculate relief.
   a. Use the Zonal Statistics 2 tool in the Spatial Analyst Supplemental Tools toolbox (available here: https://www.arcgis.com/home/item.html?id=3528bd72847c439f88190a137a1d0e67), which supports analysis involving overlapping polygons, to calculate the minimum and maximum elevations in each polygon. Use table joins to add the upstream and downstream elevations for each structure to the polygon layer.
      - Note: Because the stream elevation is artificially high near the road in the LiDAR digital elevation, the lowest point in the DEM was usually a few meters above the bridge or culvert rather than at the structure inlet. This results in calculated reliefs that tended to be ~1 ft lower than the size of the structure when the lowest upstream elevation was compared to the maximum (road) elevation. By taking the average of the upstream and downstream minimum elevations and comparing that to the road elevation, the relief values are more reasonable in respect to culvert size.
   b. Perform a Q/A check and manually sample LiDAR where necessary.
      - Note: In pilot watersheds, negative relief was observed where a bridge was washed out and not replaced. Low relief was observed in some cases where the stream or structure layer was off by more than 15 to 20 meters. The road elevation adjacent to the bridge was manually assigned to the bridge for a more accurate relief estimate. Structures located in areas that had inaccurate stream centerlines had elevations that did not approximate invert-roadway relief and needed to be manually relocated to a road-stream intersection before the analysis.

Structure Width vs. Bankfull Channel Width (%)

River Process	Road	Bridge	Culvert
Inundation		√	√
Erosion		√	√
Deposition		√	√

Low Vulnerability	Moderate Vulnerability	High Vulnerability
>100%	50 – 100%	<50%

Definition: Bankfull channel width in feet was calculated using the hydraulic geometry relationships (HGR) equation for each river segment (VTDEC, 2006). These data were calculated using the following HGR equation:

$$13.1 * DA^{0.44}$$

Where DA is the drainage area of the catchment in square miles, derived from watershed delineations for each of the reaches included in the screen

Structure width is the width of a bridge or culvert extracted from a combination of different statewide structure datasets. Percent bankfull width is calculated by dividing structure width by bankfull width and multiplying by 100.

Application: The smaller a structure is in comparison to the bankfull channel, the more likely it is to be overtopped, eroded, or clogged with debris.

Data Development: Structure points were spatially joined to the nearest stream crossing of a road segment, with threshold search distances developed in the pilot watersheds applied for each different structure dataset joined. Different structure datasets were joined sequentially to preferentially select width data from datasets found to be the most accurate in the pilot watersheds. Filters were applied to select structures maintained by the state and to otherwise clean up the final structure width dataset.

GIS Methods:

Files	Type	Unique ID Field
VTRANS AllRoads (Road Centerlines)	Line	FAID
Rivers (VHD/SGA composite channel network)	Line	MMIGRID
VTrans Long Structures	Point	StructureN
VTrans Short Structures	Point	StructureN
VTrans Small Culvert Inventory (Ultrashorts)	Line	Asset_Sys_
SGA Structex Structures Database	Point	SgaID
VOBCIT Bridges	Point	id
VOBCIT Culverts	Point	id

1. Compile structure width data.
   a. Convert all structure width fields to feet.
   b. In the structure database described in the "Structure Database Assembly," create a field for structure width. Select the nearest joined structure with a value for width for each crossing using the distance fields in the attribute table and set the compiled structure width field equal to the selected value.

2. Calculate bankfull width/structure width.
   a. The bankfull width field from the VHD/SGA composite channel network, [Wbk_HGR_ft], is in the attribute table from the initial road-stream intersect. Add a field and divide the compiled structure width field by the bankfull width and multiply by 100 to get structure width vs. bankfull channel width as a percentage.

Structure SGA (VTANR, 2009) and Geomorphic Compatibility Screen Variables (Schiff et al., 2008)

River Process	Road	Bridge	Culvert
Inundation			
Erosion		√	√
Deposition		√	√

GIS Methods:

Files	Type	Unique ID Field
Structures Database (See "Structure Database Assembly" Section)	Point	Concatenated MMIGRID, FAID, and FID
Structex (Phase 2 SGA) Structure Data	Spreadsheet	SgaID

1. Use the "SgaID" column in the structures database described in the "Structure Database Assembly" section to join SGA data for structures.

2. The following variables are processed as described below for use in the structure vulnerability scoring:
   a. *Erosion Screen Variables*
      - *Bridge and Culvert Erosion:* Structex variables describing upstream and downstream bank erosion with possible values of 'None,' 'Low,' or 'High.' This variable is given a high vulnerability classification if upstream OR downstream bank erosion is 'High' and is given a low vulnerability classification if upstream AND downstream bank erosion are 'None.' Classify all other records with SGA data as moderate.
      - *Bridge and Culvert Armoring:* Structex variables describing upstream and downstream bank armoring with possible values of 'Failing,' 'Intact,' 'None,' or 'Unknown.' The variable is given a high vulnerability classification if upstream OR downstream bank armoring are 'Failing' and is given a low vulnerability classification if upstream AND downstream bank erosion are 'None.' Classify all other records with SGA data as moderate.
      - *Culvert Slope:* Structex variable describing culvert slope as compared to channel slope with possible values of 'Same,' 'Lower,' 'Higher,' or 'Blank.' This variable is given a high

vulnerability classification if culvert slope as compared to channel slope is 'Higher' and a low vulnerability classification if culvert slope as compared to channel slope is 'Same' OR 'Lower.' All null values, 'Blank,' and bridge or arch entries are not scored.

b. *Deposition Screen Variables*

- *Bridge Channel Slope:* Structex variable describing whether the structure is located at a break in valley slope with possible values of 'Yes,' 'No,' or 'Unsure.' This variable is given a high vulnerability classification if the structure is located at a break in valley slope ('Yes') and a low vulnerability classification if the structure is not located at a break in valley slope ('No'). All null values, 'Unsure,' and culvert entries are not scored.
- *Culvert Slope and Channel Slope:* Structex variables describing culvert slope as compared to channel slope with possible values of 'Same,' 'Lower,' 'Higher,' or 'Blank' and whether the structure is located at a break in valley slope with possible values of 'Yes,' 'No,' or 'Unsure.' This variable is given a high vulnerability classification if the culvert slope as compared to the channel slope is 'Lower' OR if the structure is located at a break in valley slope ('Yes'). The variable is given a low vulnerability classification if the culvert slope as compared to the channel slope is 'Same' AND the structure is not located at a break in valley slope ('No'). Classify all other records with SGA data as moderate if the structure type is "Culvert."
    - *Bridge and Culvert Approach Angle:* Structex variables describing the approach angle of the upstream channel with possible values of 'Sharp Bend,' 'Channelized Straight,' 'Mild Bend,' or 'Naturally Straight.' This variable is given a high vulnerability classification if the approach angle is a 'Sharp Bend' or 'Channelized Straight,' a moderate vulnerability classification if the approach is a 'Mild Bend,' and a low vulnerability classification if the approach angle is 'Naturally Straight.'
    - *Sediment Discontinuity:* This variable uses the Structex variables for upstream sediment deposit types, upstream sediment deposit elevations, downstream bank heights, and downstream scour. Upstream sediment deposits include possible values of 'None,' 'Delta,' 'Side,' 'Point,' 'Mid-Channel,' or a combination of the sediment deposit types where present. The upstream sediment deposit elevation variable describes whether the elevation of any deposit is greater than or equal to ½ of bankfull elevation with possible values of 'Yes' or 'No.' The downstream bank heights variable describes whether downstream bank heights are substantially higher than upstream bank heights with possible values of 'Yes' or 'No.' The downstream scour variable describes any streambed scour causing undermining under or around the structure outlet with possible values of 'None,' 'Culvert,' 'Footer,' 'Wing Walls,' or a combination of the scour types where present. The sediment discontinuity variable is given a high vulnerability classification if upstream deposits elevations are greater than or equal to ½ bankfull elevation ('Yes') AND downstream banks heights are substantially higher than upstream bank heights ('Yes'). The variable is given a low vulnerability classification if there are no upstream sediment deposits ('None') and no downstream scour ('None'). The variable is given a moderate classification if any upstream sediment deposits OR downstream scour are present OR if downstream bank heights are substantially higher than upstream bank heights.

Rivers and Corridors
Variable Descriptions and Methods

Defining Upstream-Downstream Relationships

GIS Methods:

Files	Type	Unique ID Field
Rivers (VHD/SGA composite channel network)	Line	MMIGRID

1. Create start and end points for each river segment.
   a. Open the "Add Geometry Attributes" tool and add the master rivers dataset to the "Input Features" box. Check the "LINE_START_MID_END" box in the "Geometry Properties" window.
   b. Use the "Create XY Event Layer" to create start points for each river segment using the geometry attributes calculated above.
   c. Repeat step 1b with the geometry for the line end points.

2. Associate upstream and downstream river segments.
   a. Open the "Spatial Join" tool. Select the downstream points layer (line end) for the target features and the upstream points layer (line end) for the join features. Specify "WITHIN_A_DISTANCE" for the "Match Option" and a 100-meter "Search Radius."
      - Note: Multiple upstream segments joined to a single downstream segment were common at stream confluences. First-order headwater reaches will not join to any upstream reaches.
   b. Remove any instances where the start and end points both have the same MMIGRID unique ID (i.e., rare cases of stream segments less than 100 meters long).

River SGA (VTANR, 2009)

River Process	Road	Bridge	Culvert
Inundation	√		
Erosion	√		
Deposition	√		

GIS Methods:

Files	Type	Unique ID Field
Rivers (VHD/SGA composite channel network)	Line	MMIGRID
SGA Data: Phases 1 and 2	Spreadsheet	PH2SEGID

1. Use the "PH2SEGID" column in Rivers and SGA data to join SGA data for rivers.
   a. Note: Phase 2 SGA work that has been conducted since the creation of the MMI/VLT river segments may subdivide segments in the master Rivers dataset. These segments must be split by the new Phase 2 reach break with the MMIGRID and segment ID manually updated

to reflect the new segment names. The valley and river corridor layers may also need to be split by hand. In the pilot watersheds, the following VT River Sensitivity Coarse Screen variables were recalculated: the number of third-order or larger confluence areas upstream, number of slope decrease areas, number of road crossings, valley area, river length, and natural confinement. The following VT River Sensitivity Coarse Screen variables were not recalculated: bankfull width and recalculated HGR stream power (described below).

2. The following river SGA variables are processed as described below for use in the vulnerability scoring:
   a. *Entrenchment/Incision Ratio (Inundation and Erosion):* Entrenchment and incision ratios are assigned to reaches where Phase 2 SGA assessments had been conducted and a cross section describing typical channel dimensions for the reach was collected.
   b. *Valley Slope (Inundation):* Valley slope (%) is assigned to reaches where Phase 1 SGA assessments had been conducted. This provides surrogate information for incision and entrenchment ratio due to more extensive Phase 1 SGA data availability.
   c. *Dominant Substrate Size (Erosion):* Dominant substrate size is assigned to reaches where Phase 2 SGA assessments have been conducted and a pebble count describing the typical substrate size distribution has been performed. Use this information in conjunction with stream power estimates (described in the VT River Sensitivity Coarse Screen variables section) as a key variable in determining erosion vulnerability potential. As a surrogate for dominant substrate size in reaches without SGA data, the presence or absence of erodible parent materials ("Alluvial" or "Outwash") from SSURGO soils within the valley walls of each segment can be used.
   d. *Upstream Mass Failures (Deposition):* Mass failures are catalogued using the Feature Indexing Tool (FIT) GIS plugin that is part of VTANR's Stream Geomorphic Assessment Tool (SGAT). While Phase 1 SGA reaches have limited FIT information, this dataset is most complete in reaches that have had Phase 2 geomorphic assessments. To use this information in the vulnerability screen, use table joins between (1) the master rivers layer, (2) the upstream-downstream relationships table, and (3) the FIT data joined to the upstream reach MMIGRID. This joins the length of mass failures in upstream reaches for river segments with upstream Phase 2 SGA assessments. To account for instances where more than one reach is directly upstream (e.g., a confluence), use the "Dissolve" tool with MMIGRID as the dissolve field and the mass failure length as a statistics field, selecting the maximum length.
   e. *Upstream Bank Erosion (Deposition):* Like with mass failures, bank erosion is catalogued via FIT and most complete for reaches with Phase 2 geomorphic assessments. Divide the length of bank erosion per reach in feet by the channel length in miles multiplied by two, to account for left and right banks. Join bank erosion values (ft/mi) to river segments with upstream Phase 2 SGA data as described above for mass failures, and use the "Dissolve" tool to choose the maximum bank erosion value if two reaches are upstream.

VT River Sensitivity Coarse Screen Variables

River Process	Road	Bridge	Culvert
Inundation			
Erosion	√		
Deposition	√		

GIS Methods:

Files	Type	Unique ID Field
Rivers (VHD/SGA composite channel network)	Line	MMIGRID
VT River Sensitivity Coarse Screen	Line	MMIGRID
Valley Walls	Polygon	MMIGRID

1. The following river variables are included in the VT River Sensitivity Coarse Screen (Schiff et al., 2015) and are processed as described below for use in the vulnerability scoring:

    - *Valley Confinement (Erosion) and Change in Valley Confinement (Deposition):* Join valley confinement (the ratio of valley width to channel width) from the VT River Sensitivity Coarse Screen results (Schiff et al., 2015). The raw values are used in the erosion screen. In the deposition screen, use sequential table joins of (1) the master rivers layer, (2) the upstream-downstream relationships, and (3) the valley confinement of any upstream reaches. For reaches with a confinement value less than 10, subtract upstream confinement from the confinement of the reach it is joined to obtain change in valley confinement. Segments with higher deposition risk are presumed to be those that have narrower valleys upstream and open into broader downstream valleys.
        - Note: The assumptions for scoring this variable were made based on prior knowledge of valley confinement as it relates to stream typing. However, valley confinement is calculated in the valley walls layer by dividing the valley area by the length of the stream segment within it to estimate valley width. This roughly approximates confinement but can be problematic, especially in areas with confluences where merged buffers from multiple stream segments can inflate valley area and lead to inflated estimates of valley width.
    - *Specific Stream Power (Erosion and Deposition):* Join stream power per unit area of channel bed (Knighton, 1999) in watts per square meter to the VHD/SGA composite channel network from the VT River Sensitivity Coarse Screen (Schiff et al., 2015). It can be updated as necessary with the HGR method using the following formula:

    $$\left(\frac{40.57DA}{35.315} * \frac{Slope}{100} * 9810\right) \div WBK$$

    Where DA is the drainage area in square miles, Slope is percent slope, and WBK is the bankfull width. Stream power is used as a stand-alone variable in the deposition screen, with lower stream power indicating higher deposition vulnerability. In the erosion screen, stream power is used in conjunction with dominant substrate size or erodible parent materials. Channels with stream power between 100 and 300 watts per square meter and smaller dominant substrate or more erodible parent materials are presumed to be more vulnerable to erosion than channels with higher or lower stream power and larger substrate or less erodible parent materials.
    - *Number of Slope Breaks in Channel (Deposition):* Join the number of reaches where second-order or larger channels with slopes of <5% decreases by 5% or more from the VT River Sensitivity Coarse Screen results (Schiff et al., 2015). These can be updated as needed for the new SGA segments.

- *Number of Confluences (Deposition):* Join the number of third-order or larger confluences within each river segment from the VT River Sensitivity Coarse Screen results (Schiff et al., 2015). These can be updated as needed for the new SGA segments.
- *Number of Road Crossings (Deposition):* Join the number of road crossings per segment from the VT River Sensitivity Coarse Screen results (Schiff et al., 2015). These can be updated as needed for the new SGA segments.

Nearby Steep Slopes

River Process	Road	Bridge	Culvert
Inundation			
Erosion			
Deposition	√		

Low Vulnerability	Moderate Vulnerability	High Vulnerability
<50 feet	50 – 200 feet	> 200 feet

Definition: Slopes greater than 50% on either side of the channel were intersected with a 50-foot buffer beyond channel bankfull width. The presence of steep slopes in upstream reaches may indicate a sediment source resulting in downstream deposition.

Application: Greater length of steep slopes in upstream reaches may result in more vulnerability to deposition in downstream reaches.

Data Development: A buffer off of the bankfull channel width was created and intersected with a slope raster. For the pilot watersheds, the VT HydoDEM raster of elevations was used to create the slope raster due to the absence of statewide LiDAR during method development. However, statewide LiDAR data is now available for Vermont and is recommended for future analyses due to the extent of coverage available.

GIS Methods:

Files	Type	Unique ID Field
Rivers (VHD/SGA composite channel network)	Line	MMIGRID
VT HydroDEM	Raster	N/A
LiDAR DEM	Raster	N/A

1. Create a buffer 50 feet beyond bankfull width.
   a. Open the "Buffer" tool.
   b. Create a bankfull buffer using the master rivers layer for the "Input Features" and the [Wbk_HGR_ft] field for the "Distance." If available, use the "FLAT" end type to minimize the extension of lines upstream and downstream.
   c. Create a new line shapefile and start editing.

d. Select the bankfull buffer polygons created in step 1b, and the use the "Buffer" tool on the editing toolbar with the new line shapefile as a template. Specify a 50-foot distance to a polyline buffer 50 feet beyond bankfull width.

2. Obtain length of steep valley slopes.
   a. Use the "Slope" tool to create a slope raster (%) from the DEM.
   b. Use the "Reclassify" tool on the slope raster, setting "Old Values" less than 50 to "NULL" and "Old Values" greater than 50 to 1.
   c. Use the "Raster to Polygon" tool to convert the reclassified raster to polygons.
   d. Use the "Intersect" tool with the stream buffer lines created in step 1d with the steep slope polygons created in step 2c.
   e. Use the "Dissolve" tool to merge the lines by [MMIGRID], the unique stream segment ID.
   f. Create a length field and calculate the length of steep valley slopes in feet.

3. Associate upstream valley slopes with downstream reaches.
   a. Use sequential table joins of (1) the master rivers layer, (2) the upstream-downstream relationships, and (3) the length of steep valley slopes calculated in step 2f. Match 1 and 2 using [MMIGRID] and the upstream MMIGRID. Match 2 and 3 using the downstream MMIGRID and [MMIGRID].
   b. For first-order reaches with no upstream counterpart, use the length of steep valley slopes immediately adjacent to the stream segment.

Damage Data Preparation

1. Acquire Damage Data

- Download DDIR Damage Data from TRPT ftp site. Folders with DDIR damages are organized by watershed.
- Additional DDIR data for your watershed may be available in the dataset organized by VTrans Mapping – see “Part667_For_TRPT.zip” on ftp. Compare the two datasets.
- Other damage data collected by the RPCs may also be available.
- A list of damage data sources from the TRPT User Guide is provided below.

TABLE D-1
Damage Data Used in Vulnerability Scoring for the Pilot Watersheds

Name	Source	Description and Limitations
PA Projects	FEMA	Point locations, limited description of damages, damage categories (e.g., debris removal, protective measures, roads, and bridges)
DDIR	VTrans	Point locations, description of damages, image(s), cost to repair
Regional Planning Commissions	Two Rivers-Ottaquechee Regional Commission (TRORC), Rutland Regional Planning Commission (RRPC), Windham Regional Commission (WRC)	Point and line locations, variable level of detail describing damages in comments fields of shapefiles

2. Evaluate Damages and Assign Failure Mode and Flood Vulnerability Process

- Evaluate damages using criteria in Table 1 on page 5, and Tables 3-2 and 3-4 from the User Guide which are included below on pages 7 and 8. **Ultimately the following two (2) determinations are needed:**
  - Determine Vulnerability Process of Inundation, Erosion, or Deposition (determines which column to populate in RE_VC and BC_VC)

Vulnerability Process	RE_VC Column	BC_VC Column
Inundation	VE_I_Damages_Val	VB_I_Damages_Val VC_I_Damages_Val
Erosion	VE_E_Damages_Val	VB_E_Damages_Val VC_E_Damages_Val
Deposition	VE_D_Damages_Val	VB_D_Damages_Val VC_D_Damages_Val

  - Determine Failure Mode (value to populate in RE_VC and BC_VC damage columns)
    - Partial Closure, Full Closure, Temporary Failure, Complete Failure

- Examples of Populated RE_VC and BC_VC Tables:

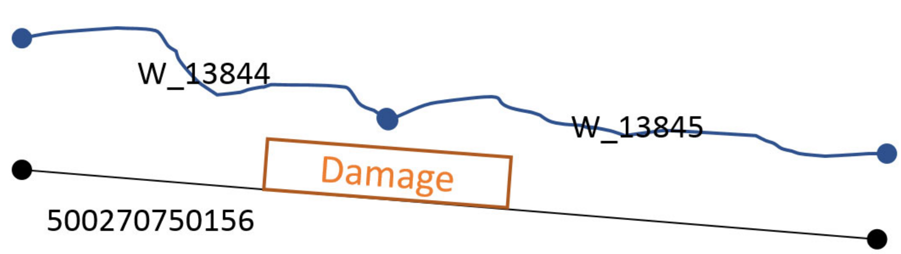
RE_VC

FAID	MMIGRID	VE_I_Damages_Val	VE_E_Damages_Val	VE_D_Damages_Val
500010200103	O_1775	<Null>	<Null>	<Null>
500010200103	O_1776	<Null>	<Null>	<Null>
500010200109	O_1735	<Null>	<Null>	Partial Closure
500010200109	O_1736	<Null>	Full Closure	<Null>
500010200113	O_2681	<Null>	Complete Failure	<Null>

BC_VC

strucid	VB_I_Damages_Val	VB_E_Damages_Val	VB_D_Damages_Val	VC_I_Damages_Val	VC_E_Damages_Val	VC_D_Damages_Val
O_3987_500011100021_23765	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
O_2727_500010550364_23969	<Null>	<Null>	<Null>	<Null>	<Null>	Complete Failure
O_4275_500010650212_23720	Full Closure	<Null>	<Null>	<Null>	<Null>	<Null>

- Key Steps/Notes in Damage Data Research
  - Merging the attribute tables for damage shapefiles in the watershed can be used to create a lookup table with all damage records in the watershed.
    - See Table 2 on page 6 for a sample lookup table used to keep track of notes on damages in a pilot watershed. These fields were added as columns to a merged damage record shapefile.
    - Spatial joins can be used as a first cut for joining FAID and structure ID to nearby damage records.
  - Add a structure ID column for keeping track of bridges and culverts. Use FAID and structure ID to join relevant damages to inundation, erosion, and deposition damage columns in RE_VC and BC_VC.
  - Structure IDs in BC_VC are unique. The joins are 1:1.
  - Often there are multiple records (rows) of FAID in RE_VC repeats since each road segment may be considered proximate to multiple stream segments (denoted by MMIGRID), and these unique combinations are factored into the scoring. Use the damage lookup table to populate damages associated with all instances of a given FAID, unless the specific stream segment for the damage is known. See example figure below with two (2) stream segments in blue and one (1) road segment in black. In this instance there would be two (2) records of FAID, one for each road-stream segment combination, and the damage assignment should be applied to both records with FAID 500270750156.



- Other Damage Evaluation Tips
    - Damages may be assigned to both a road segment and structure, or just one of the two.
    - Eliminate duplicate damage records as much as possible by examining the point locations and damage descriptions.
    - Examine proximity to blue line streams and the damage descriptions in the reports to exclude non-fluvial damages such as stormwater runoff from impervious surfaces (e.g. rilling and ditch erosion along gravel roads) or landslides from saturated soils on steep slopes.
    - Examine the reports to determine whether the damage was to a bridge, culvert, or both. Damage descriptions, line items for repair, and photographs are especially useful. Ancillary information from VCGI imagery, Google Earth, Google Maps, Google Street View, news articles, etc. can help with this determination. Use the stream crossing distance field to help determine if the damage was to the road, structure, or both. The structures database assembled for vulnerability screening can help distinguish between bridges and culverts. For FEMA PA Projects, filter out damages to public buildings, utilities, recreational and other infrastructure that are not associated with a road, bridge, or culvert.
    - Examine the reports to specify the primary damage mode for road and structure damages.
        - For inundation damages, look at the proximity of the points to the 100-year floodplain boundaries where available and look for mentions of flooding and pavement bubbling.
        - For deposition damages, look for mentions of debris or erosion resulting from a bridge or culvert plugged with debris.
        - Most significant damages were from erosion and descriptions often mentioned washouts.
        - The ancillary information described above is also useful for this determination. If multiple damage modes seem likely, choose the one was the root cause of the damage (e.g. deposition plugging a culvert and causing inundation or erosion at the structure). If no root cause is clear, choose the damage mode with the costliest repairs (e.g. >$10,000 for rock and pavement to fix an eroded embankment vs. <$1,000 in debris removal would be classified as erosion damage. If no other information is available, choose the damage type that was most extensive at the site.
        - For damages with limited descriptions, such as the PA Projects, scan imagery and the setting of the river in the valley to determine the most likely damage type. Search for applicable news articles and ask stakeholders for more information.
    - Assign a failure mode to each damage record (in order of increasing severity: partial closure, full closure, temporary failure, complete failure). See Table 4-4 and Appendix C for more detailed information on the criteria used to distinguish failure mode. Criteria include the duration of travel disruption and extent of damage. Incorporate prior knowledge as well as stakeholder input from public meetings and personal correspondence. For PA projects without description of the extent of damage, use aerial imagery and consult stakeholders for more information. PA projects tend to be less urgent

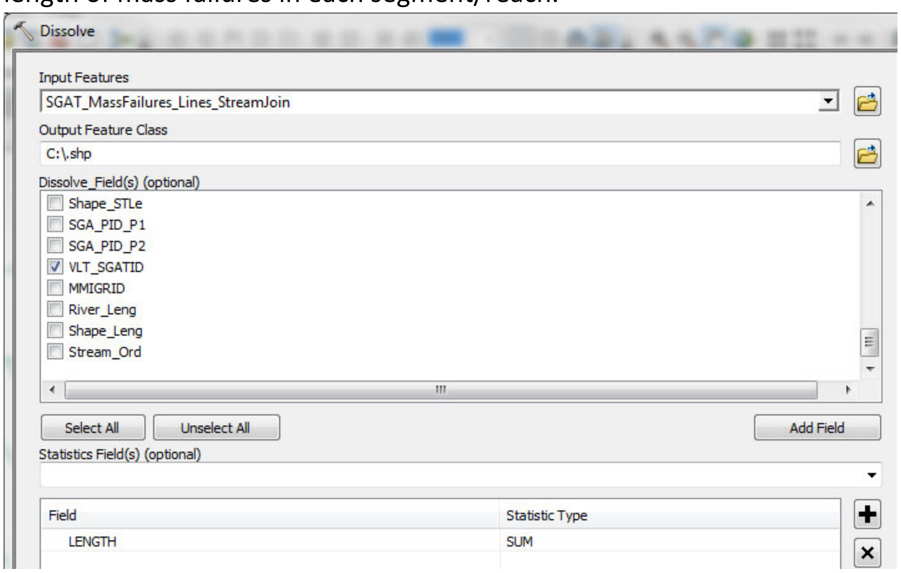
from a transportation perspective and therefore will mainly be classified as partial and full closure. Incorporate prior knowledge as well as stakeholder input from public meetings and personal correspondence.

  - Evaluation of failure mode during field visits can be accomplished by observing repairs made (e.g. extent of new armoring or recently replaced structures) or lack of evidence of extensive repairs. Where applicable, classification of damage type or failure mode can be revised following field visits.

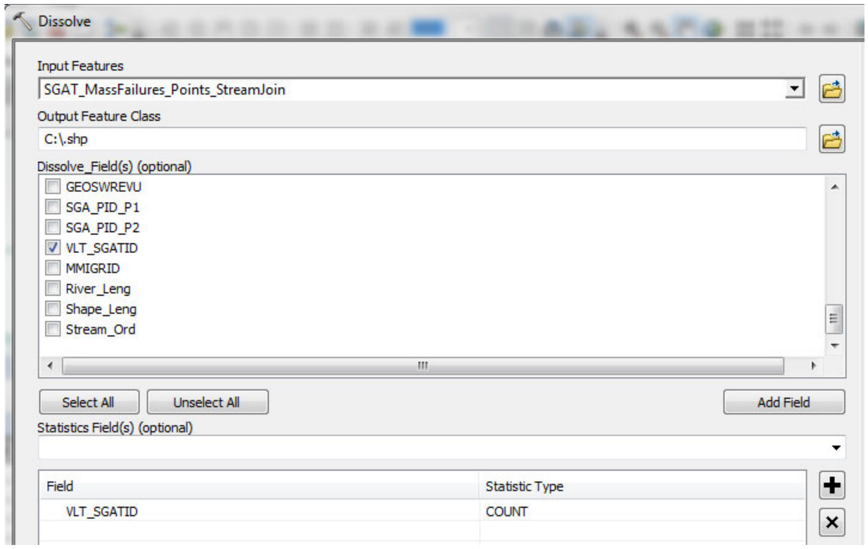
- Check MMIGRID and FAID values for damages, especially stream crossing IDs matched to structure damages to verify damages are being matched with the most affected road segment and crossing.
- Check for spelling errors and consistency in the attribute fields for a seamless input to the scoring spreadsheet.

Mass Failures Data Preparation

1. Download SGA Input Data - See FTP for 'massfailures_stream_id_join' for SGA reaches tagged with SGA project (spatial join from stream centerlines).
2. Extract data for your watershed (clip or select).
3. Process Input Data
   a. SGA Feature Indexing Tool (FIT) Lines
      i. [LENGTH] is the length of the line in feet
      ii. Dissolve by [VLT_SGATID] with [LENGTH] as a statistics field (SUM) to get the length of mass failures in each segment/reach.



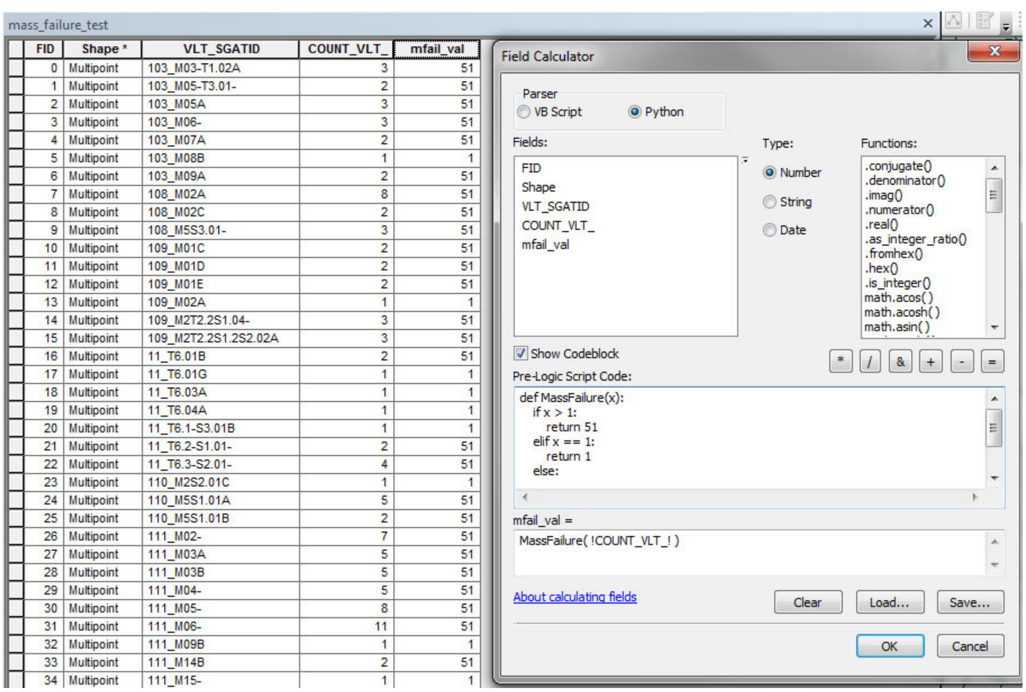
   b. SGA Feature Indexing Tool (FIT) Points
      i. You can add a length field based on notes in the data, field measurements, or measurements from imagery/LiDAR and dissolve as shown above.
      ii. Otherwise, dissolve by [VLT_SGATID] with [LENGTH] as a statistics field (COUNT) to get the number of mass failures in each segment/reach.



iii. Add a field to the dissolved feature class and set the mass failure values as follows for scoring.

	Mass Failures in Upstream Reach (Abundance)		
COUNT	>1 (Multiple)	1	0
Value for Scoring	51	1	0

The following is an example of the fields and calculation.



FID	Shape *	VLT_SGATID	COUNT_VLT_	mfail_val
0	Multipoint	103_M03-T1.02A	3	51
1	Multipoint	103_M05-T3.01-	2	51
2	Multipoint	103_M05A	3	51
3	Multipoint	103_M06-	3	51
4	Multipoint	103_M07A	2	51
5	Multipoint	103_M08B	1	1
6	Multipoint	103_M09A	2	51
7	Multipoint	108_M02A	8	51
8	Multipoint	108_M02C	2	51
9	Multipoint	108_M5S3.01-	3	51
10	Multipoint	109_M01C	2	51
11	Multipoint	109_M01D	2	51
12	Multipoint	109_M01E	2	51
13	Multipoint	109_M02A	1	1
14	Multipoint	109_M2T2.2S1.04-	3	51
15	Multipoint	109_M2T2.2S1.2S2.02A	3	51
16	Multipoint	11_T6.01B	2	51
17	Multipoint	11_T6.01G	1	1
18	Multipoint	11_T6.03A	1	1
19	Multipoint	11_T6.04A	1	1
20	Multipoint	11_T6.1-S3.01B	1	1
21	Multipoint	11_T6.2-S1.01-	2	51
22	Multipoint	11_T6.3-S2.01-	4	51
23	Multipoint	110_M2S2.01C	1	1
24	Multipoint	110_M5S1.01A	5	51
25	Multipoint	110_M5S1.01B	2	51
26	Multipoint	111_M02-	7	51
27	Multipoint	111_M03A	5	51
28	Multipoint	111_M03B	5	51
29	Multipoint	111_M04-	5	51
30	Multipoint	111_M05-	8	51
31	Multipoint	111_M06-	11	51
32	Multipoint	111_M09B	1	1
33	Multipoint	111_M14B	2	51
34	Multipoint	111_M15-	1	1

Full Pre-Logic Script Code - Note the Python Parser is Checked in the Calculator

```
def MassFailure(x):
if x > 1:
   return 51
elif x == 1:
   return 1
else:
   return 0
```

c. No SGA Data

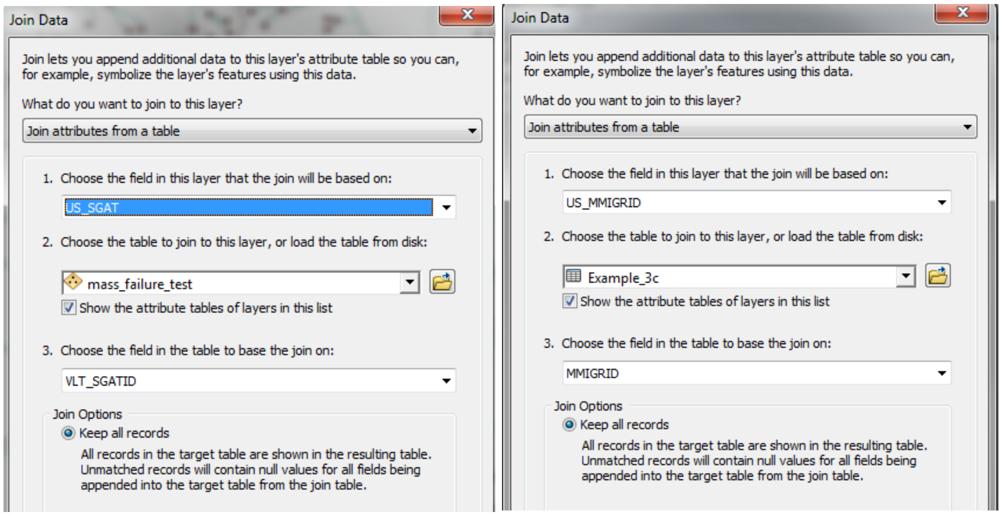
i. Create a blank lookup table with fields for MMIGRID and mass failure length. The MMIGRID in this table will correspond to [US_MMIGRID] in the Stream_Upstream_Segs point file.

ii. Add mass failure records to the table on a case-by-case basis. Use landslide data, desktop examination of imagery and the LiDAR hillshade, and/or field measurements of known mass failures. If there is more than one mass failure per segment (in this case each segment will have a unique MMIGRID ID), sum the mass failure lengths over the segment.

Example_3c

OID	MMIGRID	mfail_ft
0	O_1140	20
1	O_1141	19
2	O_1142	2019

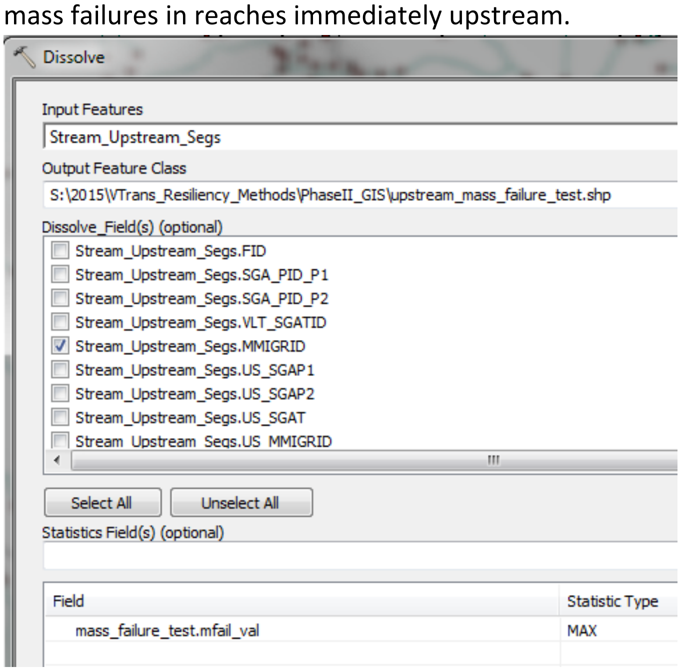
4. Join Data to Downstream Reaches - Steps 1-3 calculate the length of mass failures in SGA reaches. These are the upstream reaches in the deposition analysis. For this variable, we are interested in the length of mass failures upstream of a given reach where the eroded material might be deposited.
   a. If joining mass failure data from multiple tables (i.e. lines, points, and manual entries), create a field in the Stream_Upstream_Segs layer for mass failure length.
   b. Join the mass failure data from Steps 3a - 3b to the Stream_Upstream_Segs point file using the [US_SGAT] field (TRPT_Supplemental Folder). If applicable, join mass failure data from step 3c using the [US_MMIGRID] field in the Stream_Upstream_Segs point file. If joining mass failure Compile mass failure data from multiple sources by populating the field created in Step 4a using the field calculator.



c. If joining mass failure data from multiple tables (i.e. lines, points, and manual entries), compile the mass failure length data from the joined tables by populating the field created in Step 4a using the field calculator.

d. Select from Stream_Upstream_Segs the records where [US_SGAP2] is not blank. This prevents underestimating mass failure data where no assessment has occurred. If your watershed has mass failure data where there is no [US_SGAP2] record (e.g. it was added manually by your group in step 3c, or was part of a Phase 1 SGA), add these records to your selection.

e. Dissolve by [MMIGRID] (this is the ID for the downstream segment/reach) with the length (lines) or value (points) as a statistics field (MAX) to get the maximum length of mass failures in reaches immediately upstream.



Note: Do not use [US_MMIGRID]

5. Populate RE_VC

a. Use [MMIGRID] to join the dissolved mass failure data (step 4c) to RE_VC. MMIGRID is not a unique ID in the RE_VC table as one stream segment can be associated with multiple road segments. Calculate [VE_D_MassFailures_Val] to equal the field from step 4c with the maximum length of mass failures in the upstream reach. Remove the join. **Note: Most values will likely be <Null> as this variable depends on SGA data coverage for your watershed.**

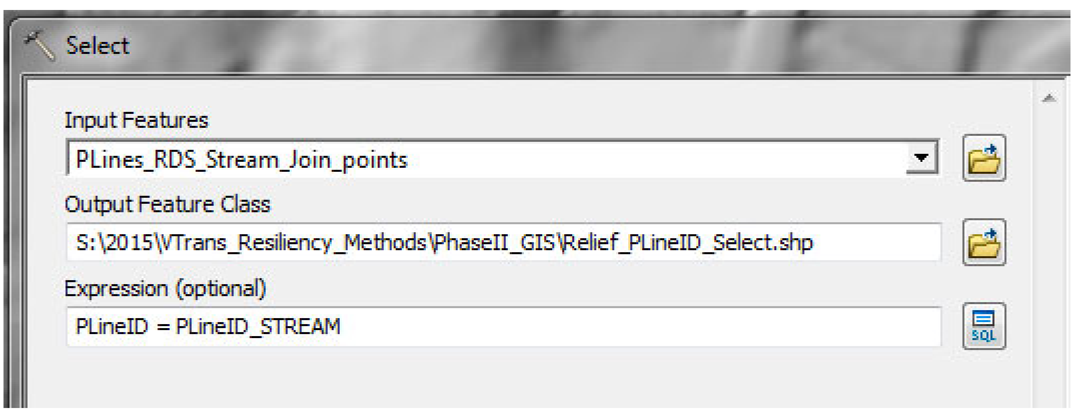
	Mass Failure Length in Upstream Reach (feet)			
Value	>200	50-200	<50	0
Score (50-Year)	H	H	M	L

Roadway-River Relief Data Preparation

1. Download 'TRPT_Base.gdb' sent by Johnathan (10/1/2019 version).

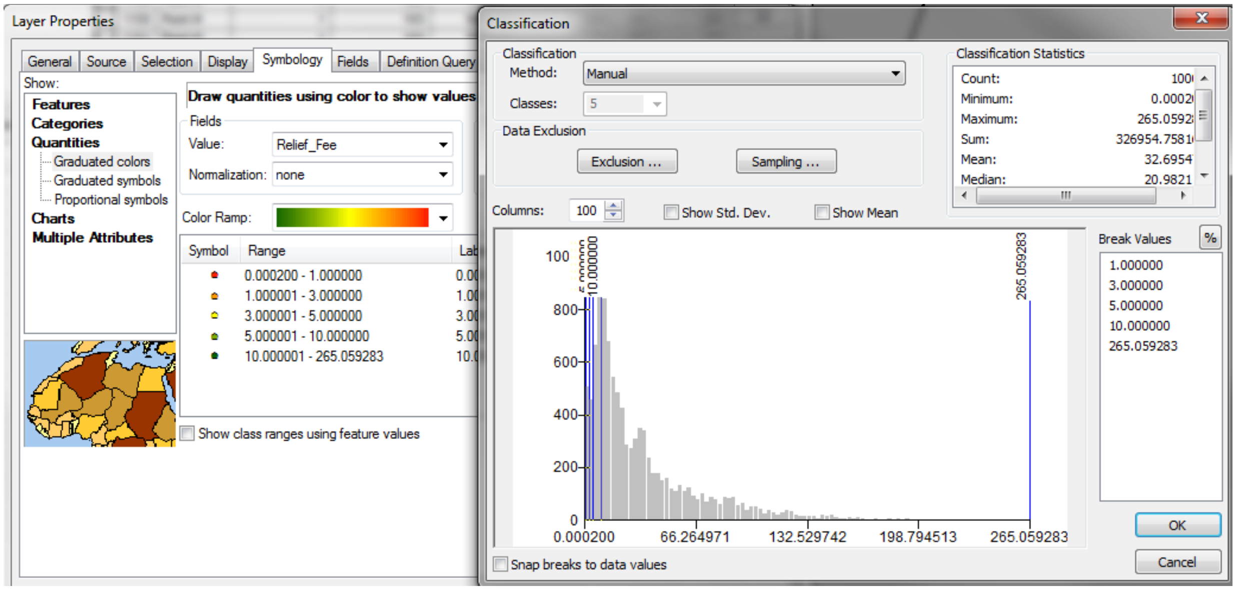
2. Extract data for your watershed (clip or select).

3. Run 'Select' tool or perform select by attributes to choose points on matching perpendicular lines.



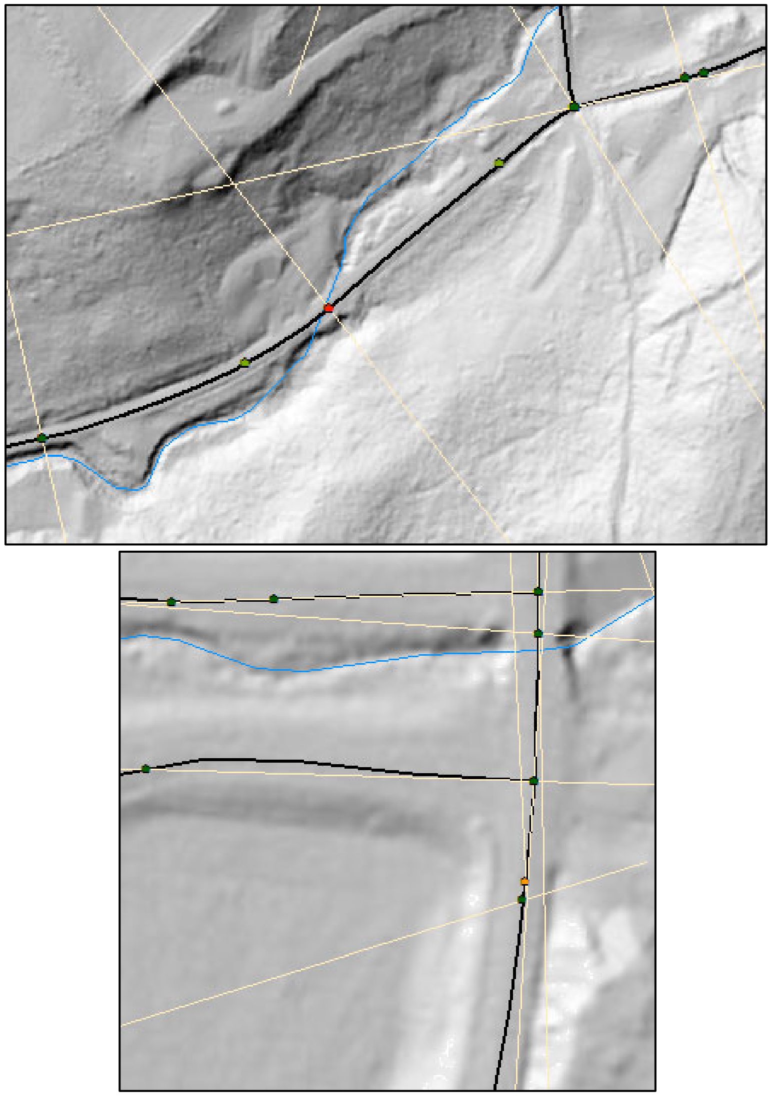
Method Note: Road and stream elevations are joined for relief calculations by performing the spatial join with a 300 m search radius. Therefore, road elevations are pairing with stream elevations up to 300 meters up/downstream. This leads to some artificially low relief values in the dataset (e.g. a stream with 1% slope will be ~10 feet higher 300 meters upstream). By performing a selection after this join to keep only joins where the road and stream perpendicular line ID's match, relief will be consistently evaluated along the same transect.

4. QA/QC of Relief Data. The QA check is performed on the points with matching perpendicular line IDs selected in Step 3.
   a. Set up symbology with manual breaks to visualize relief values. This can help identify whether a point is an outlier or consistent with the surrounding values.



b. Start editing, select and delete all points where [Relief_Feet] is less than 2 ft. If there are any areas in the watershed where you know there is very low relief, pan to these areas before you delete and spot check to make sure the 2 ft threshold does not remove any real values. In this instance, a lower threshold (1 or 1.5 feet) might make sense for your geographic region. If you determine through panning around to points with values in the 2-3 foot range that a higher threshold makes sense for your geographic region, delete values below this threshold.

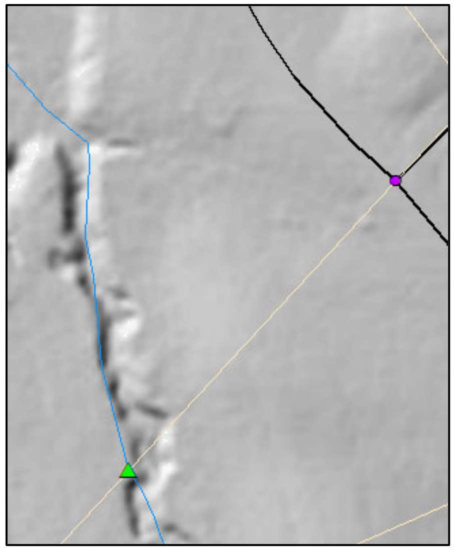
c. Pan around your watershed. Prioritize checking relief values that are very low (< 5 ft). Of these low relief values, focus on points that are outliers compared to others on the segment.



Road points classified by relief. In these examples, the points with erroneous values stand out as a low outliers compared to other points along the road segment. Both errors in this example are due to stream elevation being sampled at a road crossing.

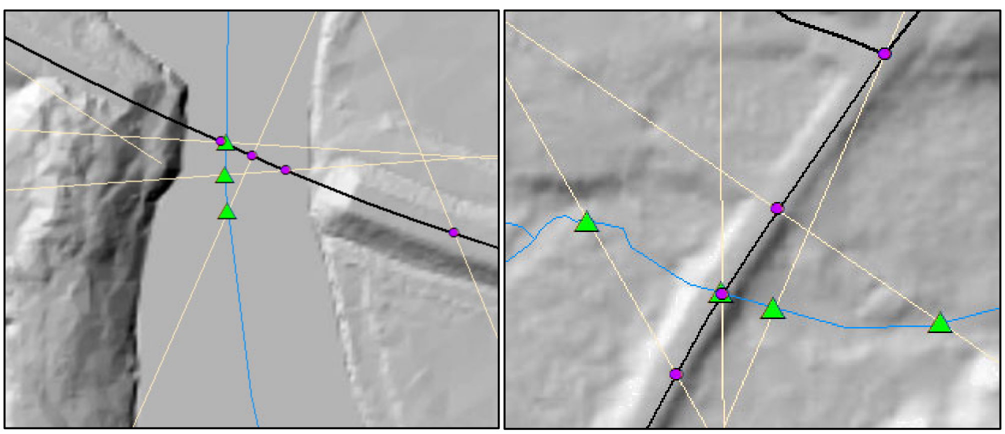
d. Recommended background layers for this process:
   i. VCGI hillshade and DEM for visualizing stream and road locations and sampling elevation if manual updates are needed. The DEM is in meters, so convert values to feet for relief calculations.
   ii. 'Perpendicular_Lines', 'Perpendicular_Lines_Test', 'Plines_Intersect_RDS_points'', and 'Plines_Intersect_Streams_points' from Johnathan's TRPT_Base.gdb. These provide the locations sampled for the calculation and can be used to identify the location of the sampled elevations.

e. Relief values tend to be less accurate in headwater streams, especially in forested settings, where errors in the stream centerline geometry lead to sampling elevation in an area other than the stream channel.



Stream (green triangle) and road (purple circle) elevation samples along perpendicular lines for relief calculations. In this example, inaccuracy in the stream centerline causes sampling on the top of bank, rather than the stream channel.

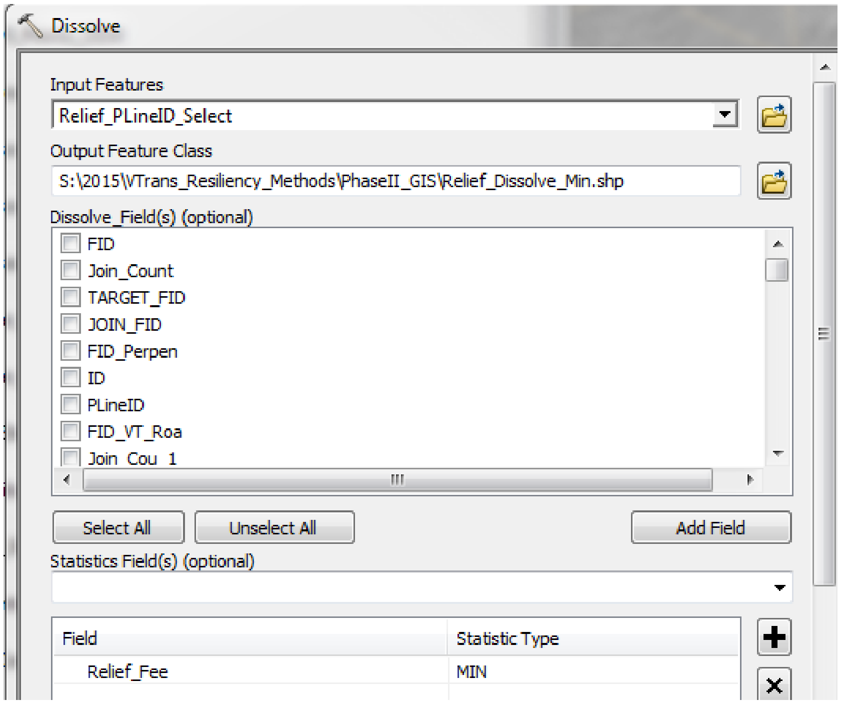
f. Relief values can also be less accurate at road crossings (see screenshots below). The hydroflattening process may affect the road elevation values around bridges if the bridge deck gets removed from the DEM. Additionally, if the stream elevation is sampled at a road crossing, it can be artificially high compared to the road elevation.



Stream (green triangle) and road (purple circle) elevation samples along perpendicular lines for relief calculations. On the left, the bridge deck has been removed from the LiDAR causing both the road and stream elevation to be sampled from the water surface. On the right, the road and stream points overlap at the crossing, causing both the road and stream elevation to be sampled on the road.

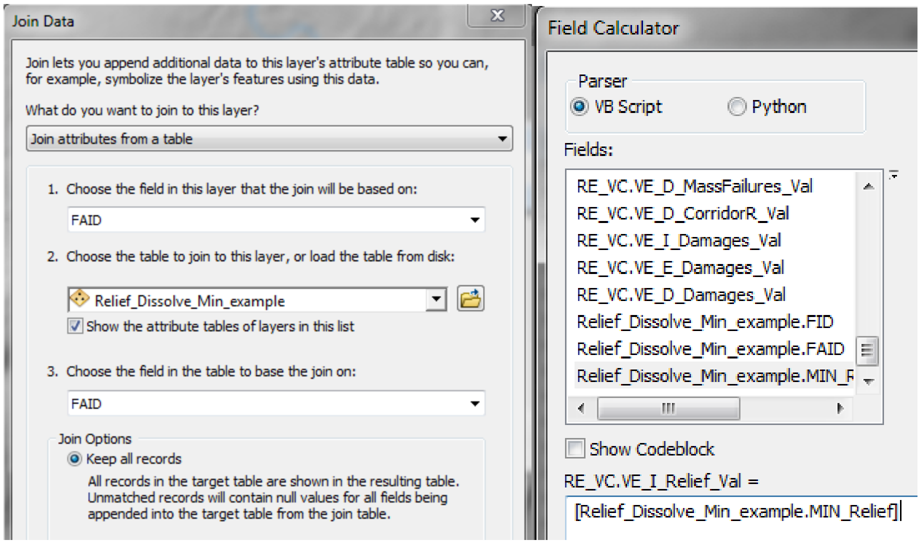
g. Manually update the [Relief_Feet] field or delete points with inaccuracies. Ideally, you would have at least one good relief measurement for each road segment (same FAID). Therefore, deleting inaccurate points at road crossings is fine if transects on the same segment are producing good data. However, if a long stretch of the VHD is inaccurate because it does not follow the actual stream centerline in the LiDAR, it is recommended you manually update at least one of the relief values per road segment.

5. After QA, dissolve by FAID and keep the minimum relief value.



6. Use [FAID] to join the dissolved relief data (Step 5) to RE_VC. FAID is not a unique ID in the RE_VC table as one stream segment can be associated with multiple road segments. Calculate [VE_I_Relief_Val] to equal the field from step 5 equal to the minimum relief value. Remove the join.

	Roadway-River Relief (feet)		
Value	< 5	5 - 10	> 10
Score (50-Year)	H	M	L



Structure Data Preparation

Notes on Data Generation

The VT_Crossings points were generated through the intersection of the road and river centerlines. The structure width and SGA variables were populated based on spatial joins from the following layers if they fell within the specified distance threshold. Since the SGA data is so integral to the scoring, and the spatial data collection historically varied in accuracy, we wanted to cast a wide net to capture the data.

Order of Width Application	**Joined Data**	**Threshold**	**Crossings Fields Prefix**
1 – Assume most accurate/ complete	VTrans Long Structures	30 m	L_
2	VTrans Short Structures	30 m	S_
3	SGA Structex Structures Database	70 m	X_
4	VOBCIT Culverts	20 m	C_
5	VTrans Small Culvert Inventory (Ultrashorts)	20 m	U_
6	VOBCIT Bridges	20 m	B_

Structure type (Bridge/Culvert) was assigned using the following hierarchy

Order of Type Application	**Joined Data**	**Field/Logic**
1 – Assume most accurate/ complete	SGA Structex Structures Database	[StructureT] Bridge (Arch/Bridge) or Culvert
2	VTrans Long Structures	If [CulvertRat] N=Bridge
3	VTrans Short Structures	If [CulvertRat_1] N=Bridge
4	VOBCIT Culverts	Assume all culverts

5	VOBCIT Bridges	Assume all bridges unless classified as culvert in Structex
6	VTrans Small Culverts	Assume all culverts

Structure QA/QC

1. Examine join distances in the VT_Crossings feature class (Fields [U_Dist], [B_Dist], [C_Dist], [S_Dist], and [L_Dist]). Prioritize checking joins close to the distance threshold. Values of -1 indicate no structure was joined.

U_Dist	B_Dist	C_Dist	S_Dist	L_Dist
-1	-1	-1	-1	16.375697
-1	-1	-1	6.226327	-1
15.466329	-1	16.055559	-1	-1
-1	-1	-1	-1	10.81366
-1	-1	7.293423	-1	-1
-1	-1	-1	-1	-1
-1	-1	17.348728	-1	-1
-1	-1	18.253674	-1	-1
-1	-1	3.766171	-1	-1
-1	-1	3.823165	-1	-1
-1	-1	3.026751	-1	-1
-1	-1	14.478968	-1	-1

2. Compare structure width and bankfull width measurements. Are these relatively close? Look for width values that seem disproportionately large or small compared to the channel width. Prioritize checking these joins.

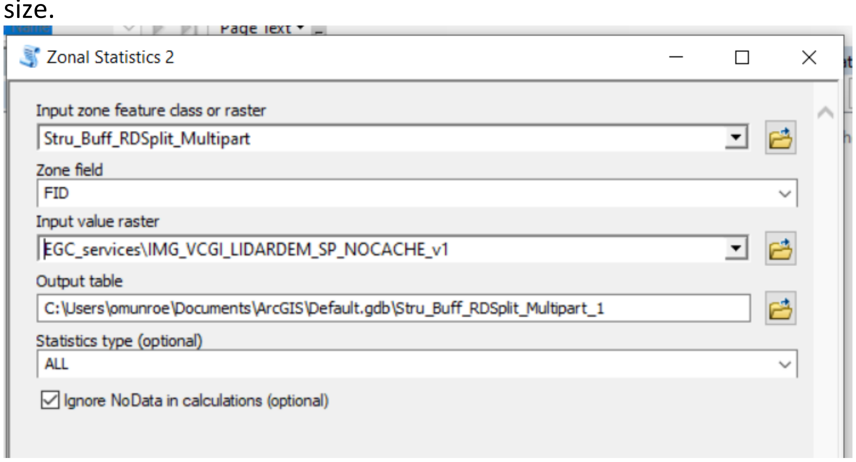
Wbk_HGR_ft	AOTCLASS	RDFLNAME	FAID	U_Height	U_Width	U_Culv_Len	U_StrucLyr
133.067993	Interstate Highway - South Bound	INTERSTATE 91 S	500050350126	18	18	72	UltraShorts

3. Editing Data
    a. Don't change the Struc_ID. Any of the other fields in the crossing feature classes/tables (MMIGRID, FAID, etc.) can be updated. In a case like this, you would update the prepopulated portions of the BC_VC table. Keep notes for your records of any updates.
    b. If adding or removing data, the prepopulated fields that will be updated are: (a) the structure width/bankfull width variable and (b) the SGA variables (see TRPT_GDB_Metadata_2019-07-10 for the variable codes).
        i. Bankfull width is in the VT_Crossings layer and is unlikely to change much unless you're moving the point from a tributary to a mainstem or vice versa. Divide the updated structure width (in feet) by the bankfull width (in feet) and multiply by 100 to get the new value.
        ii. If you move the structure and there are SGA data for the new location, use the TRPT_GDB_Metadata_2019-07-10 table to match up the SGA data with the respective fields in the BC_VC table. If the SGA fields were filled in before you moved the crossing and you think they should be cleared, set these values to null.
        iii. If a crossing doesn't exist or there is no data for a structure, leave all data fields blank.

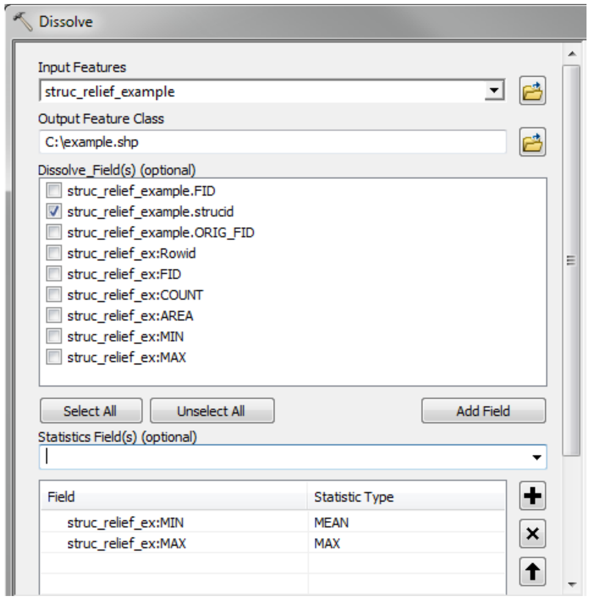
c. To change structure type, switch entries in the BC_VC table between B_ and C_ columns.
d. Regenerate & split relief buffers (15 m for Town Roads, 20 m for State/Federal Highways) or move and edit existing buffer to align the buffer split along the road centerline.

River-Structure Relief

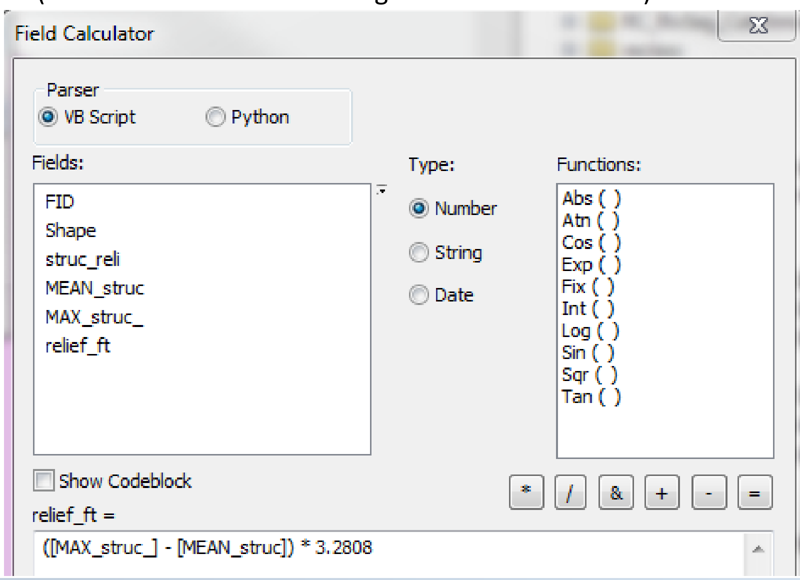
1. Structure buffers were split on roads to generate upstream and downstream zones (Stru_Buff_RDSplit_Multipart). Check for instances of more than 2 polygons per structure ID and merge/delete polygon slivers to leave two zones.
2. Calculate relief.
   a. Use the Zonal Statistics 2 tool in the Spatial Analyst Supplemental Tools toolbox (available here: https://www.arcgis.com/home/item.html?id=3528bd72847c439f88190a137a1d0e67), which supports analysis involving overlapping polygons, to calculate the minimum and maximum elevations in each polygon. Use table joins to add the upstream and downstream elevations for each structure to the polygon layer.
      - Note: Because the stream elevation is artificially high near the road in the LiDAR digital elevation, the lowest point in the DEM was usually a few meters upstream of the bridge or culvert rather than at the structure inlet. This results in calculated reliefs that tended to be ~1 ft lower than the size of the structure when the lowest upstream elevation was compared to the maximum (road) elevation. By taking the average of the upstream and downstream minimum elevations and comparing that to the road elevation, the relief values are more reasonable in respect to culvert size.



   b. Join the results back to the Stru_Buff_RDSplit_Multipart layer using the FID. Then, dissolve by the STRUCID, taking the average of the upstream and downstream minimum elevation and keeping the maximum elevation.



c. Calculate relief (Maximum Elevation - Average Minimum Elevation). Convert to feet.



struc_relief_example_dissolve

FID	Shape *	struc_reli	MEAN_struc	MAX_struc_	relief_ft
0	Polygon	LCTD_11118_500270550412_9	215.497368	220.322159	15.8292

d. Perform a Q/A check and manually sample LiDAR where necessary. Cases where this may be needed include instances when the crossing location was not representative of the structure or the relief value is <5, 0, and/or negative.

- Note: In pilot watersheds, negative relief was observed where a bridge was washed out and not replaced. Low relief was observed in some cases where the stream or structure layer was off by more than 15 – 20 meters. The road elevation adjacent to the bridge was manually to the bridge for a more accurate relief estimate. Structures located in areas that had inaccurate stream centerlines had elevations that did not approximate invert-roadway relief and needed to be manually relocated to a road-stream intersection before the analysis.

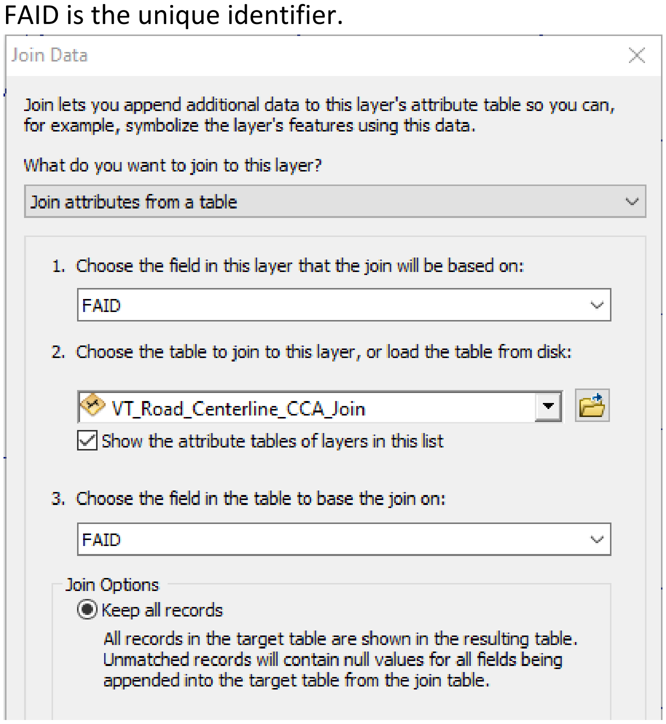
	River - Structure Relief (feet)		
Value	<5	5-10	>10
Score (50-Year)	H	M	L

Criticality Data Table Preparation

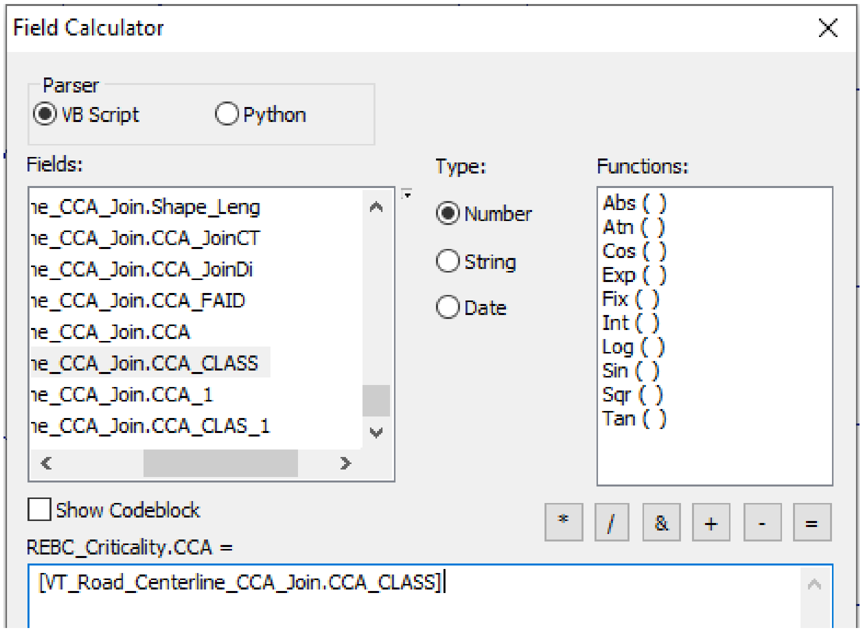
Criticality is calculated at the road scale with FAID as a unique identifier. Road and structure vulnerability have been consolidated into one score for the CCA analysis performed by UVM.

Summary of Criticality Fields and Acceptable Values		
Variable	**Field**	**Acceptable Values (Lower/Upper case does not matter)**
Network Criticality Index	NCI	Low, Medium, High, NA
Critical Closeness Accessibility Index	CCA	Low, Medium, High, NA
Locally Identified Important Roads	LI	Yes, No

1. Join VT_Road_Centerline_CCA_Join (download from the FTP) with the REBC_Criticality table. FAID is the unique identifier.



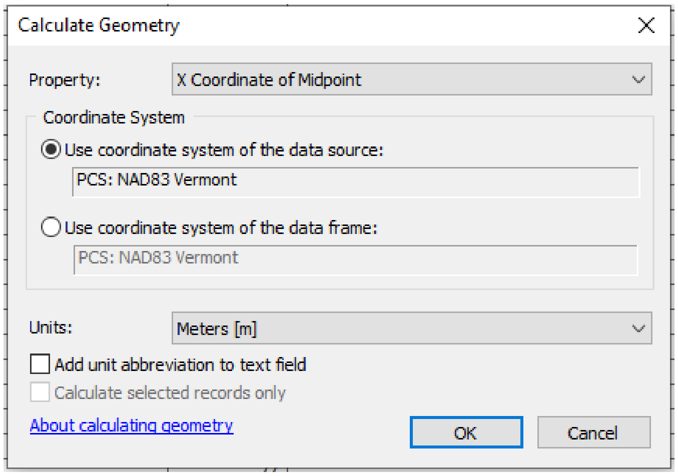
2. Use the field calculator to set the REBC_Criticality [CCA] field equal to the VT_Road_Centerline_CCA_Join [CCA_CLASS] field. The values in the field should be Low, Medium, or High. Any missing data should be the text entry “NA”.



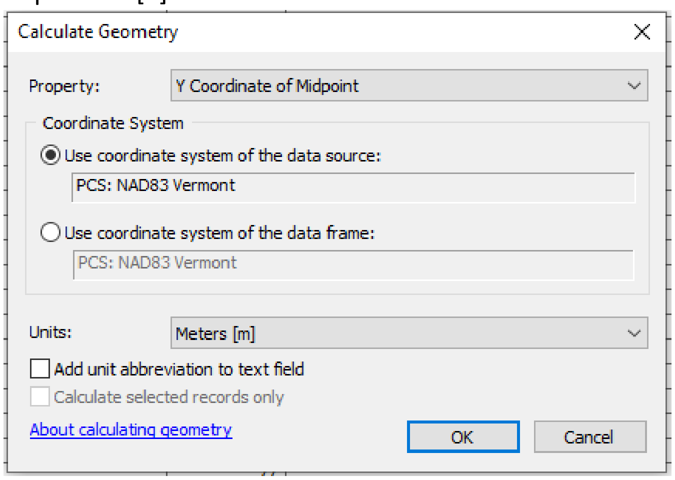
3. Remove CCA table join.

4. The output of the NCI process from UVM may not match the road segment layer exactly. If you join the NCI shapefile from UVM with the REBC_Criticality using FAID there may be missing records. Below is a suggested workflow, but the results received from UVM will vary.
    a. Examine the NCI results shapefile.
    b. If the number/geometry of road segments in the file received matches the shapefile you sent to UVM, join the NCI shapefile from UVM with the REBC_Criticality table as you did for the CCA data using FAID as the unique identifier. Use the field calculator to set the REBC_Criticality [NCI] field equal to the field of the shapefile classifying the NCI data. The values in the field should be Low, Medium, or High. Any missing data should be the text entry “NA”.
    c. If the number of road segments in the file received is very close (i.e. number of road segments is within 5%) to the shapefile you sent to UVM, join the NCI shapefile from UVM with the REBC_Criticality table as you did for the CCA data using FAID as the unique identifier. Use the field calculator to set the REBC_Criticality [NCI] field equal to the field of the shapefile classifying the NCI data. The few missing segments can be filled in manually with NCI data of the overlapping segment. The values in the field should be Low, Medium, or High. Any missing data should be the text entry “NA”.
    d. If the number/geometry of road segments in the file received is fairly different (i.e. number of road segments is more than 5% different) from the shapefile you sent to UVM:
        i. Add fields [X] and [Y] to the the VT_Road_Centerline shapefile for your watershed.

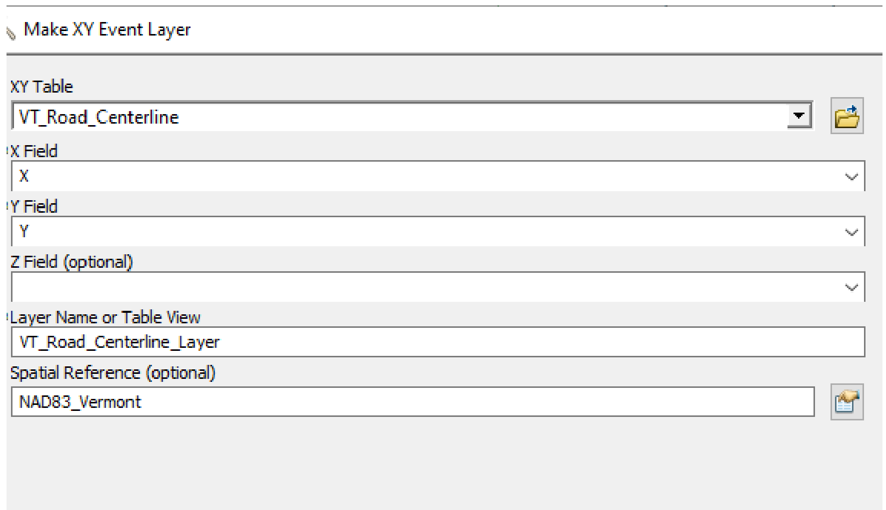
ii. Right click on [X] and select Calculate Geometry. Complete the dialogue to calculate the X coordinate of the line midpoint. Make sure to calculate the midpoint rather than the centroid, which may not be on the line segment.



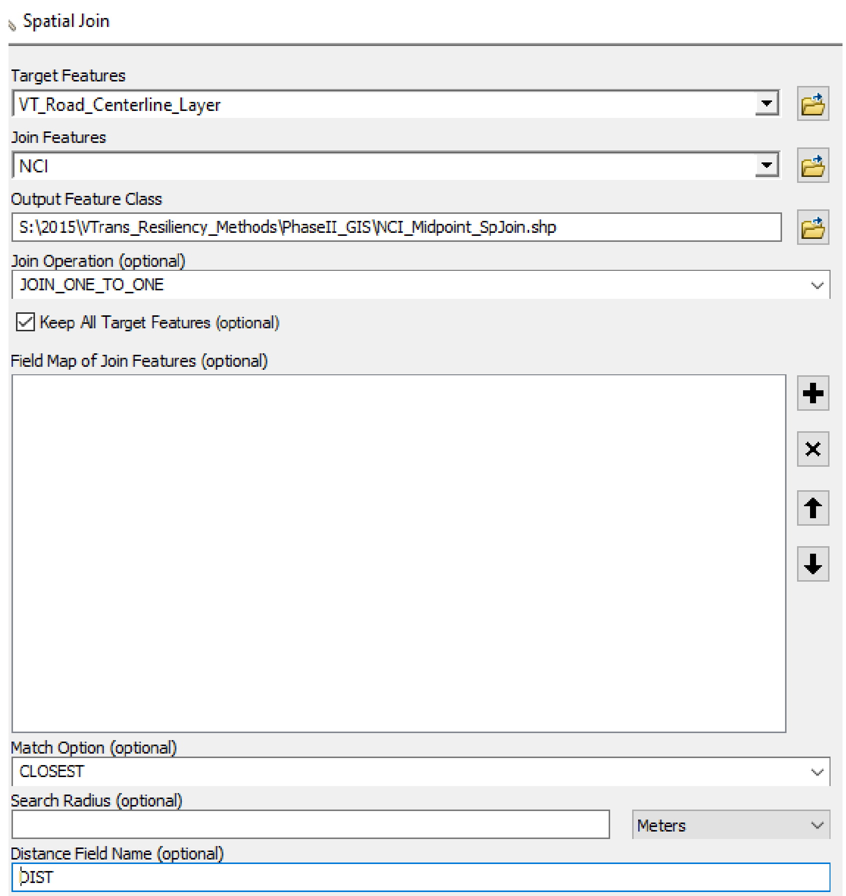
iii. Repeat for [Y]



iv. Open the Make XY Event Layer Tool. Use this to create a points layer of segment midpoints. Make sure to match the Spatial Reference to the coordinate system used to calculate [X] and [Y] above. Export the resulting points to a feature class in your database.



v. Perform a spatial join between your road midpoints and the NCI shapefile. Examine the output for any large join distances that may signal an incorrect join.



vi. Join the table created from the spatial join with the REBC_Criticality table using FAID as the unique identifier. Use the field calculator to set the REBC_Criticality [NCI] field equal to the field of the shapefile classifying the NCI data. The values in the field should be Low, Medium, or High. Any missing data should be the text entry "NA".

5. Remove NCI table join.

6. Start an edit session and set REBC_Criticality [LI] field equal to "yes" or "no". From p. 18 of the TRPT User Guide 1.0:
   "The Final criticality component allows users, potentially working with other stakeholders in a watershed, to manually identify the most critical roadways for reasons that may not be captured in the NCI and CCA modeling such as local detour routes, access to a town highway maintenance facility or an emergency shelter that would support response and recovery operations."

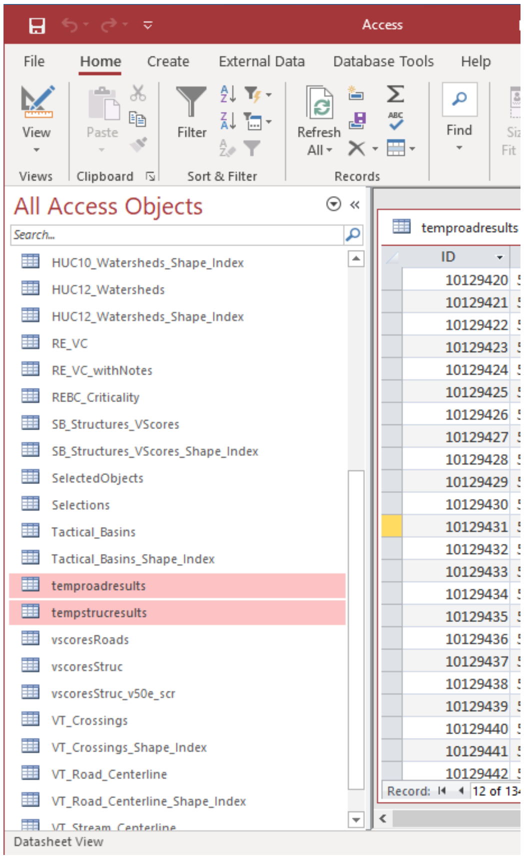
7. When the REBC_Criticality table is complete, run the scoring tool to check the data and calculate the criticality score.

Final Scoring Overrides and Updates

In some cases, actual site conditions affecting vulnerability scores may not be captured by scoring logic. For instance, vulnerability may be overestimated in cases where the road elevation is high above the river such that the likelihood flood damage is relatively low. In other cases, Town staff may identify areas of known erosion or flooding that were not identified in the remote scoring approach. After field visits and discussions, the stakeholders to confirm the site conditions, users may make manual updates to the final vulnerability scores. The following instructions outline how to make updates to the vulnerability scores that will be used to calculate the Network Criticality Index (NCI) and the final vulnerability scores that will be displayed on the web application and used to calculate overall risk.

Manual Database Changes

1. Manual updates to vulnerability scores should first be made to the v50e_scr, v50b_scr, or v50c_scr variable in the vscoresRoads and/or vscoresStructures shapefiles sent to Jim Sullivan for the Network Criticality Index analysis. Changing the vulnerability score will increase or decrease the probability of a network link breaking for the criticality analysis.
2. Manual updates for display on the web application can be made to the v10e_scr, v50e_scr, v100e_scr, v10b_scr, v50b_scr, v100b_scr, v10c_scr, v50c_scr, or v100c_scr. The manual update can be completed in ArcMap, ArcCatalog, or Microsoft Access. This update is intended for the final database that will be uploaded to the web application. Navigate to your database **after running the criticality scoring tool (mainRpc_CriticalityTool.exe)**.
3. Open the temproadresults and/or tempstrucresults table that was added to your database by the criticality scoring tool.


Access
File
Home
Create
External Data
Database Tools
Help
View
Paste
Filter
Refresh All
Find
Views
Clipboard
Sort & Filter
Records
All Access Objects
Search...
HUC10_Watersheds_Shape_Index
HUC12_Watersheds
HUC12_Watersheds_Shape_Index
RE_VC
RE_VC_withNotes
REBC_Criticality
SB_Structures_VScores
SB_Structures_VScores_Shape_Index
SelectedObjects
Selections
Tactical_Basins
Tactical_Basins_Shape_Index
temproadresults
tempstrucresults
vscoresRoads
vscoresStruc
vscoresStruc_v50e_scr
VT_Crossings
VT_Crossings_Shape_Index
VT_Road_Centerline
VT_Road_Centerline_Shape_Index
temproadresults
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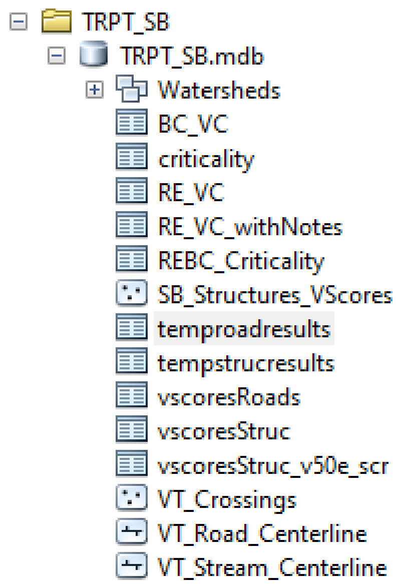
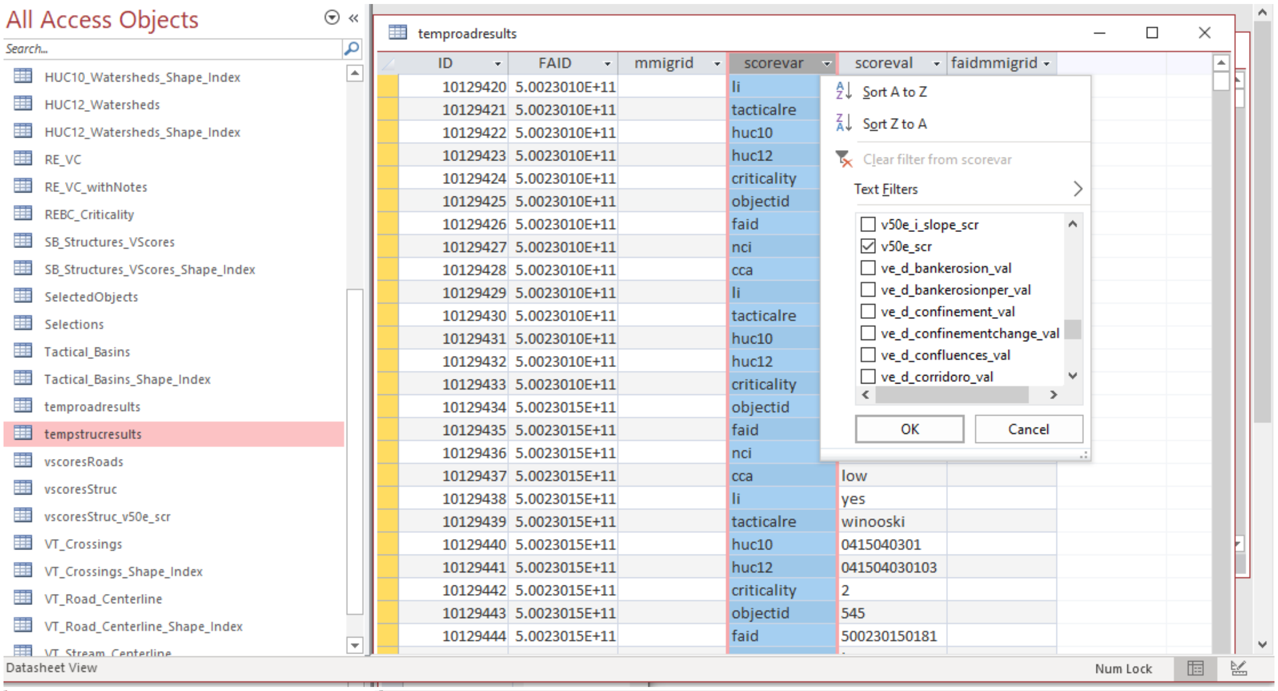
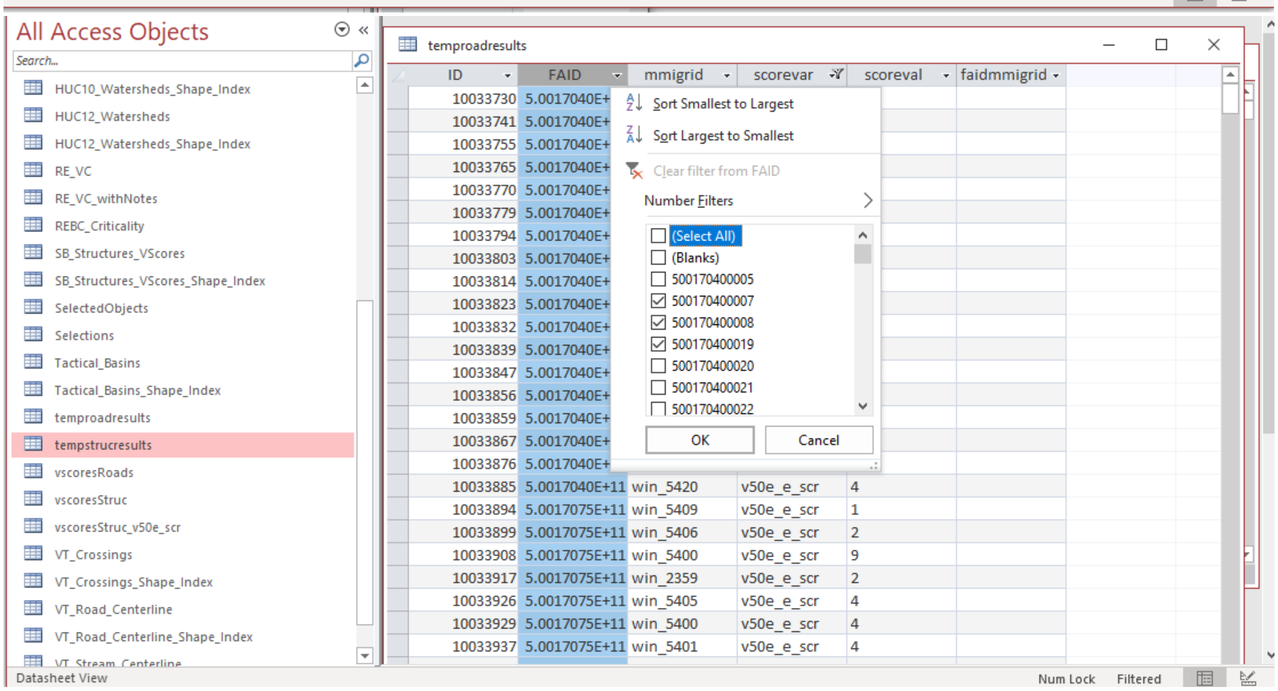
Record:
Datasheet View


TRPT_SB
TRPT_SB.mdb
Watersheds
BC_VC
criticality
RE_VC
RE_VC_withNotes
REBC_Criticality
SB_Structures_VScores
temproadresults
tempstrucresults
vscoresRoads
vscoresStruc
vscoresStruc_v50e_scr
VT_Crossings
VT_Road_Centerline
VT_Stream_Centerline

4. Filter or select the final vulnerability scores you will make the manual updates to. These should be v10e_scr, v50e_scr, v100e_scr, v10b_scr, v50b_scr, v100b_scr, v10c_scr, v50c_scr, or v100c_scr only.





5. Change the scoreval variable to reflect the manual vulnerability update. Valid vulnerability values are integers from 1 (lowest vulnerability) to 10 (highest vulnerability).

temproadresults

	ID	FAID	mmigrid	scorevar	scoreval	faidmmigrid
	10092558	5.0017040E+11	win_5427	v50e_e_scr	1	
	10098190	5.0017040E+11	win_5427	v100e_scr	1	
	10098191	5.0017040E+11	win_5427	v10e_scr	1	
*	(New)					

6. Save the revised database.

R-Functions for Database Changes

These functions were created to update one database or all databases after the vulnerability and criticality scoring tools have been run on them with a lookup table of manual updates.

Required Input Data

1. A lookup table of manual updates with the fields [basin], [FAID], [strucid], [scorevar], and [manual_score].

basin	FAID	strucid	scorevar	manual_score
Ottauquechee-Black-CT Direct (5)	500271200794		v50e_scr	4
Ottauquechee-Black-CT Direct (5)	500271200794		v100e_scr	4
Ottauquechee-Black-CT Direct (5)	500271200794		v10e_scr	4
Ottauquechee-Black-CT Direct (5)	500271200663		v50e_scr	3
Ottauquechee-Black-CT Direct (5)	500271200663		v100e_scr	3
Ottauquechee-Black-CT Direct (5)	500271200663		v10e_scr	3
Ottauquechee-Black-CT Direct (5)	500271200580		v50e_scr	3
Ottauquechee-Black-CT Direct (5)	500271200580		v100e_scr	3
Ottauquechee-Black-CT Direct (5)	500271200580		v10e_scr	3

2. If updating multiple basins, a lookup table with the fields [basin] and [db_path].

basin	db_path
Batten Kill-Walloomsac-Hoosic (1)	S:/2020/20070_MMI_TRPT_Ph3/GIS/Final_Databases/Test/Battenkill_Scored.mdb
Northern Lake Champlain (13)	S:/2020/20070_MMI_TRPT_Ph3/GIS/Final_Databases/Test/Champlain_North_Scored.mdb

Manual Update Functions

Required packages: tidyverse, RODBC, readxl, writexl

1. Run the *manual_update* and *bulk_update* function definitions.
2. Define the path to the manual updates spreadsheet and database or database dictionary

```
#path to updates spreadsheet
updates <- "S:/2020/20070_MMI_TRPT_Ph3/GIS/Final_Databases/Test/test_updates.xlsx"

#path to database (if only updating one basin)
db <- "S:/2020/20070_MMI_TRPT_Ph3/GIS/Final_Databases/Working/BattenKill/Battenkill_test.mdb"

#path to masterlist (if updatiing all basins from masterlist)
path_dict <- "S:/2020/20070_MMI_TRPT_Ph3/GIS/Final_Databases/Test/test_dict.xlsx"
```

3. Run functions to update databases.

```
#updating single basin
manual_update(updates, db)

#updating all basins from a masterlist
bulk_update(updates, path_dict)
```

APPENDIX G

VULNERABILITY SCORING DETAILS

The following scoring data are detailed below:

1. Selecting Road Segments and Structures to Score
2. Assigning Road-Stream Segment Relationships
3. Vulnerability (V) scoring
    a. Individual V scores for Inundation, Erosion, and Deposition for Road Embankments, Bridges, and Culverts
    b. Composite V scores for Road Embankments, Bridges, and Culverts
    c. Final (maximum) V scores
    d. Combining road and structure V
    e. QA/QC

Data Conditioning

Selecting Road Segments and Structures to Score

GIS Methods:

Files	Type	Unique ID Field
VTRANS AllRoads (Road Centerlines)	Line	FAID
Rivers (VHD/SGA composite channel network)	Line	MMIGRID
Valley Walls	Polygon	N/A

1. Select road segments potentially vulnerable to stream damages.
    a. Use the "Select by Location" dialogue to select all road segments within the VT ANR Valley Walls layer, using a 100-foot search radius.
    b. Use the "Select by Location" dialogue and 100-foot search radius to add all road segments 100 feet of the VHD stream centerline to the selected features. This selects roads near small streams with no mapped valley walls.
    c. Any road segments not selected by this logic are assigned a vulnerability value of 0 for planning purposes.

2. Select structures potentially vulnerable to stream damages.
    a. See instructions for estimating the locations of stream crossings, assigning a unique ID, and compiling bridge and culvert data to join to the nearest road/stream intersections in the "Structure Database Assembly" section of Appendix F.
    b. All road-stream intersections with structure data in each pilot watershed were selected for scoring.

Data Development Notes: In the Whetstone Brook watershed, 43% of segments were selected for scoring (Figure G-1; 280/648); 60% of segments in the Upper White watershed were scored (836/1384); and 36% of segments in the North Branch Deerfield were scored (386/1086).

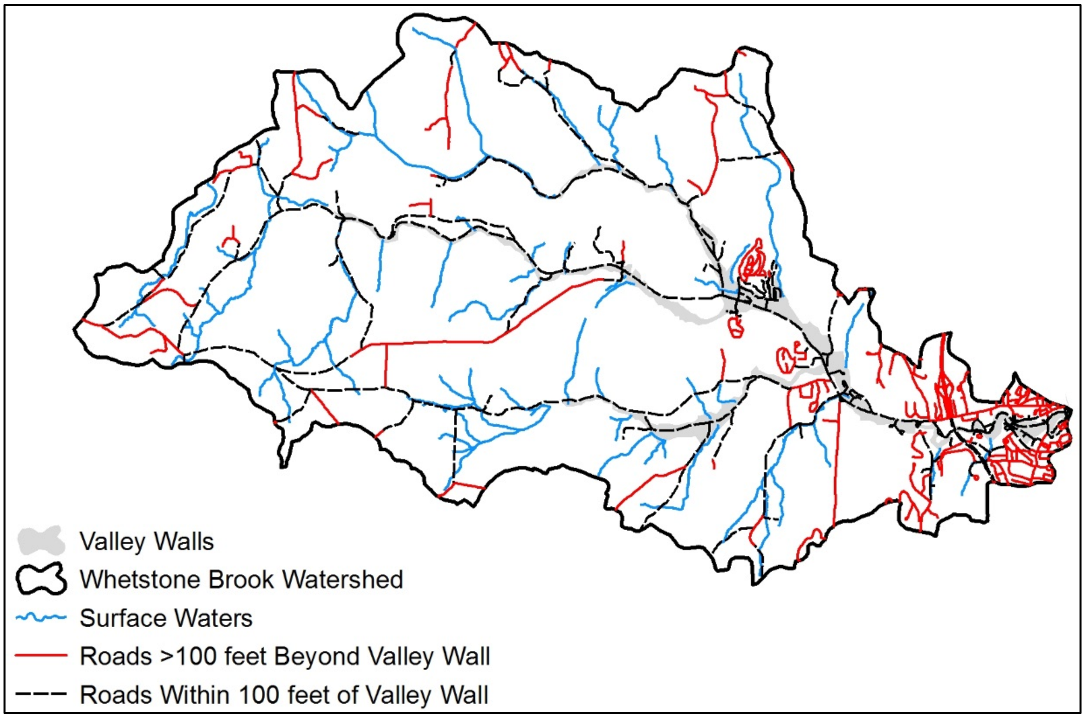


Figure G-1: Roads 100 feet beyond a valley wall or low-order stream were assigned 0 vulnerability (red)

Assigning Road-Stream Segment Relationships

GIS Methods:

Files	Type	Unique ID Field
VTRANS AllRoads (Road Centerlines)	Line	FAID
Rivers (VHD/SGA composite channel network)	Line	MMIGRID
Catchments (VHD/SGA watersheds)	Polygon	MMIGRID
Valley Walls	Polygon	N/A

1. Divide valley walls by stream segment.
    a. Use the "Intersect" tool with the VT ANR mapped valley walls and MMI catchments corresponding to river segments in the VHD/SGA composite channel network, retaining the MMIGRID of the catchments.
        - Note: For river segments manually divided to reflect new SGA segment breaks, the valley walls will need to be manually divided perpendicular to the stream centerline. Alternatively, new catchments can be delineated to intersect with the valley walls layer.

2. Intersect road segments with buffered valley walls.
    a. Use the "Buffer" tool to create a 100-foot buffer off the split valley walls layer.
    b. Use the "Intersect" tool with the buffered split valley walls layer and the master roads layer as inputs.

3. Intersect road segments with buffered streams.
    a. Use the "Buffer" tool to create a 100-foot buffer off of streams outside the valley walls layer. Select a "FLAT" end type if possible. The flat buffer will prevent relating road segments to small downstream stream segments.
    b. Use the "Intersect" tool with the buffered split valley walls layer and the master roads layer as inputs.

4. Compile road-stream relationships.
    a. Use the "Merge" tool to combine the layers created in steps 2b and 3b.
    b. Use the "Dissolve" tool with [MMIGRID] and [FAID] as the dissolve fields to eliminate any duplicate river-road segment combinations identified in this analysis.
    c. Many-to-one and one-to-many relationships between road and stream segments are common. To deal with this, each road segment-river segment pairing is scored separately for vulnerability and then the highest (most conservative) score for the vulnerability screen was selected in the screening spreadsheet.

Vulnerability Scoring

<u>Application:</u>

Qualitative variable values or quantitative variable ranges related to road segments and structures are classified by their likelihood to correspond with vulnerability to inundation, erosion, and deposition. Based on the value of the variable, this vulnerability was classified as "High," "Moderate," or "Low." The variables used in the scoring system for each of the three vulnerability types and the values/ranges used to classify them are detailed in the tables below. These variables classifications are scaled from the 50-year flood values for the 10- and 100-year floods (e.g., a "Moderate" vulnerability may scale to "High" in the 100-year flood and may scale to "Low" in the 10-year flood). Based on logical combinations of the variables detailed in the tables below, vulnerability was scored on a scale of 1 to 5 for inundation (presumed to cause less damage) and 1 to 10 erosion and deposition.

<u>Spreadsheet Methods:</u>

See the Microsoft *Excel* spreadsheet for data input formatting and logic statements to perform the vulnerability scoring outlined in Table F-1. The vulnerability scoring spreadsheet has tabs for each flood and each asset type (road and structure). The following is an overview of the scoring process:

1. Score road segments for vulnerability in the 10-, 50-, and 100-year floods (see the Microsoft *Excel* spreadsheet attachment).

    a. Compile road vulnerability parameters. Merge damage data (Appendix D) and vulnerability parameters (Appendix E) with the stream-road pairings developed in the "Data Conditioning" section of this Appendix.
    b. Insert compiled data into the scoring spreadsheet, which performs vulnerability scoring for inundation, erosion, and deposition in the 10-, 50-, and 100-year floods using the Road Embankment logic shown in Table F-1.
    c. Update the PivotTable data source range and refresh the PivotTable to aggregate the maximum inundation, erosion, and deposition scores by [FAID]. For "Rows," choose [FAID], and for values,

choose the maximum of each score. These dissolved scores are used to calculate the NCI (Appendix H).

2. Score structures for vulnerability in the 10-, 50-, and 100-year floods (see the Microsoft *Excel* spreadsheet attachment).

    a. Compile structure vulnerability parameters. Merge damage data (Appendix E) and vulnerability parameters (Appendix F) with the structure IDs developed in the "Structure Database Assembly" section of Appendix F.
    b. Insert compiled data into the scoring spreadsheet, which performs vulnerability scoring for inundation, erosion, and deposition in the 10-, 50-, and 100-year floods using the Bridge and Culvert logic shown in Table F-1. As each crossing has a unique ID, the data does not need to be further dissolved. These scores are used to calculate the NCI (Appendix I).

<u>Data Display and Compatibility:</u> Each road segment and structure are tied to a unique ID corresponding to spatial data. Scoring and data display are both performed at the road segment and structure scales. The road segments scored for vulnerability correspond in their unique ID ([FAID]) and spatial extent to those scored for criticality to allow for seamless integration of the scores.

TABLE G-1

Vulnerability Scoring for Inundation, Erosion, and Deposition for Road Embankments, Bridges, and Culverts

BRIDGE AND CULVERT INUNDATION VARIABLE SCORING

Flood	**Past Inundation Damages[1]**				**Structure Opening Invert-Roadway Relief (feet)[2]**			**Structure Width vs. Bankfull Channel Width (%)[2]**		
% AEP	Complete Failure	Temporary Failure	Full Closure	Partial Closure	<5	5-10	>10	<25%	25-50%	>50%
10%	FC	FC	N/A	N/A	M	L	L	M	L	L
2%	CF	TF	FC	PC	H	M	L	H	M	L
1%	CF	TF	FC	PC	H	H	M	H	H	M

OVERALL BRIDGE AND CULVERT INUNDATION SCORING

Score	**Past Inundation Damages**	**Structure Opening Invert-Roadway Relief (feet)**	**Structure Width vs. Bankfull Channel Width (%)**
5=	Complete or temporary failure	L, M, H, null	L, M, H, null
4=	Full or partial closure	L, M, H, null	L, M, H, null
4=	null	H	H
3=	null	M	M
3=	null	L, M, null	H
3=	null	H	L, M, null
2=	null	L, null	M
2=	null	M	L, null
1=	null	L, null	null, L
0=	null	N/A	N/A

In the following tables, the superscript on each variable indicates data detail level where 1 = high and 3 = low.

CF = Complete Failure
TF = Temporary Failure
FC = Full Closure
PC = Partial Closure

H = High Vulnerability
M = Moderate Vulnerability
L = Low Vulnerability

ROAD EMBANKMENT INUNDATION VARIABLE SCORING

Flood	**Past Inundation Damages[1]**				**River-Roadway Relief (feet)[1]**			**Entrenchment Ratio / Incision Ratio[2]**						
								ER<3		ER=3-5		ER>5		
(% AEP)	Complete Failure	Temporary Failure	Full Closure	Partial Closure	<5	5-10	>10	IR<1.5	IR≥1.5	IR<1.5	IR≥1.5	IR<1.3	IR=1.3-1.5	IR≥1.5
10%	FC	FC	N/A	N/A	M	L	L	L	L	L	L	M	M	L
2%	CF	TF	FC	PC	H	M	L	M	L	M	L	H	M	M
1%	CF	TF	FC	PC	H	H	M	M	L	H	M	H	H	M

Flood	**Valley Slope (Replaces ER/IR)[3]**			**FEMA 100-Year Floodplain[1] = Length in Floodplains (ft) and Depth of 100-Year Flood Over Road**								
				Length in floodplains = 0-50 ft			Length in floodplains = 50-200 ft			Length in floodplains >200 ft		
(% AEP)	<0.5	0.5-1.5	>1.5	null, D=0'	D=0-2'	D>2'	null, D=0'	D=0-2'	D>2'	null, D=0	D=0-2'	D>2'
10%	M	L	L	L	L	L	L	L	M	L	M	M
2%	H	M	L	L	L	M	L	M	H	M	H	H
1%	H	H	M	L	M	H	M	H	H	H	H	H

OVERALL ROAD EMBANKMENT INUNDATION SCORING

SCORE	**Past Inundation Damages**	**River-Roadway Relief (feet)**	**Entrenchment Ratio / Incision Ratio**	**Valley Slope (Replaces ER/IR)**	**FEMA 100-Year Floodplain**
5=	Complete or temporary failure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
5=	null	H	L, M, H, null	L, M, H, null	H
4=	Full closure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
4=	null	H, M	L, M, H, null	L, M, H, null	M, H
3=	Partial closure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
3=	null	M	H	L, M, H, null	M
3=	null	L, M, H, null	L, M, H, null	L, M, H, null	H
3=	null	H	L, M, H, null	L, M, H, null	L, M, H, null
2=	null	M, null	L, M, H, null	L, M, H, null	M, null
1=	null	L, null	L, null	L, null	L, null
0=	N/A	N/A	N/A	N/A	N/A

VTrans Working to Get You There

BRIDGE EROSION VARIABLE SCORING

Flood	Past Erosion Damages[1]				Structure Width vs. Bankfull Channel Width (%)[2]					Erosion[3]			Armoring[3]		
(% AEP)	Complete Failure	Temp. Failure	Full Closure	Partial Closure	<25	25-50	50-75	75-100	>100	Severe	Low	None	Failing	Intact	None
10%	FC	FC	N/A	N/A	H	M	L	L	L	H	M	L	M	L	L
2%	CF	TF	FC	PC	H	H	M	M	L	H	M	L	H	M	L
1%	CF	TF	FC	PC	H	H	H	M	M	H	H	M	H	H	M

OVERALL BRIDGE EROSION SCORING

SCORE	Past Erosion Damages	Structure Width vs. Bankfull Channel Width (%)	Erosion	Armoring
10=	Complete failure	L, M, H, null	L, M, H, null	L, M, H, null
9=	Temporary failure	H	H	H
8=	Temporary failure	L, M, H, null	L, M, H, null	L, M, H, null
7=	Full or partial closure	H	H	H
6=	Full or partial closure	L, M, H, null	L, M, H, null	L, M, H, null
6=	null	H	H	H
5=	null	H	L, M, H, null	L, M, H, null
4=	null	M	H	H
3=	null	M	M, H	M, H
2=	null	M	M, L, null	M, L, null
2=	null	L, null	M, H	M, H
1=	null	All other combinations	All other combinations	All other combinations
0=	N/A	N/A	N/A	N/A

CULVERT EROSION VARIABLE SCORING

Flood	Past Erosion Damages[1]				Structure Width vs. Bankfull Channel Width (%)[2]					Culvert Slope[3]		Erosion[3]			Armoring[3]		
(% AEP)	Complete Failure	Temp. Failure	Full Closure	Partial Closure	<25	25-50	50-75	75-100	>100	Steeper	Same, Lower	Severe	Low	None	Failing	Intact	None
10%	FC	FC	N/A	N/A	H	M	L	L	L	M	L	H	M	L	M	L	L
2%	CF	TF	FC	PC	H	H	M	M	L	H	L	H	M	L	H	M	L
1%	CF	TF	FC	PC	H	H	H	M	M	H	M	H	H	M	H	H	M

OVERALL CULVERT EROSION SCORING

SCORE	Past Erosion Damages	Structure Width vs. Bankfull Channel Width (%)	Culvert Slope	Erosion	Armoring
10=	Complete failure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
9=	Temporary failure	H	L, M, H, null	H	H
8=	Temporary failure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
7=	Full or partial closure	H	L, M, H, null	H	H
6=	Full or partial closure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
6=	null	H	H	H	H
5=	null	H	L, M, H, null	L, M, H, null	L, M, H, null
4=	null	M	H	H	H
3=	null	M	M, H	M, H	M, H
2=	null	M	M, L, null	M, L, null	M, L, null
2=	null	L, null	M, H	M, H	M, H
1=	null	All other combinations	All other combinations	All other combinations	All other combinations
0=	N/A	N/A	N/A	N/A	N/A

ROAD EMBANKMENT EROSION VARIABLE SCORING

Flood	Past Erosion Damages[1]				Specific Stream Power and Dominant Substrate Size[2]						Entrenchment Ratio / Incision Ratio[3]									Valley Confinement[3]			River Corridor[2] = Length in Corridor (ft) and Remaining Width (%)								
					SSP = 100 to 300		SSP > 300		SSP < 100		ER<2			ER=2-5			ER>5						0-660 ft			660-1,320 ft			>1,320 ft		
(% AEP)	CF	TF	FC	PC	Gravel OR Alluvium	Cobble or Larger OR No Alluvium	Gravel/ Cobble OR Outwash	Larger than Cobble OR No Outwash	Gravel	Larger than Gravel	IR <1.5	IR= 1.5-2.0	IR ≥2.0	IR <1.5	IR= 1.5-2.0	IR ≥2.0	IR <1.5	IR= 1.5-2.0	IR ≥2.0	<6	6-10	>10	null, >90%	75-90%	<75%	null, >90%	75-90%	<75%	null, >90%	75-90%	<75%
10%	FC	FC	N/A	N/A	H	M	M	L	L	L	L	M	H	L	L	M	L	L	L	M	L	L	L	L	L	L	L	L	L	L	M
2%	CF	TF	FC	PC	H	H	M	M	L	L	M	H	H	L	M	H	L	L	M	H	M	L	L	L	M	L	M	H	M	H	H
1%	CF	TF	FC	PC	H	H	H	M	M	L	H	H	H	M	H	H	L	M	H	H	H	M	L	M	H	M	H	H	H	H	H

OVERALL ROAD EMBANKMENT EROSION SCORING

SCORE	Past Erosion Damages	Specific Stream Power and Dominant Substrate Size	Entrenchment Ratio / Incision Ratio	Valley Confinement	River Corridor
10=	Complete failure	L, M, H	L, M, H, null	L, M, H, null	L, M, H, null
10=	Temporary failure	H	L, M, H, null	L, M, H, null	H
9=	Temporary failure	H, M	L, M, H, null	L, M, H, null	H, M
9=	null	H	L, M, H, null	L, M, H, null	H
8=	Temporary failure	L, M, H	L, M, H, null	L, M, H, null	L, M, H, null
7=	null	M	L, M, H, null	L, M, H, null	H
7=	Full closure	M, H	L, M, H, null	L, M, H, null	M, H
6=	null	H	L, M, H, null	L, M, H, null	M
5=	Full closure	L, M, H	L, M, H, null	L, M, H, null	L, M, H, null
5=	null	H	H, M	H, M	L
5=	null	L	H, M	H, M	H
4=	null	M	H, M	H, M	M
4=	null	H	H, M, L, null	H, M, L, null	L
4=	null	L	H, M, L, null	H, M, L, null	H
4=	null	M	H, M	H, M	M
3=	Partial closure	L, M, H	L, M, H, null	L, M, H, null	L, M, H, null
3=	null	M	H, M, L, null	H, M, L, null	M
3=	null	L	H, M	H, M	M
3=	null	M	H, M	H, M	L
3=	null	L	H, M	H, M	M
2=	null	M	L, null	L, null	L
2=	null	L	L, null	L, null	M
1=	null	All other combinations	All other combinations	All other combinations	All other combinations
0=	N/A	N/A	N/A	N/A	N/A

BRIDGE DEPOSITION VARIABLE SCORING

Flood	Past Damages[1]	Structure Width vs. Bankfull Channel Width (%)[2]	Channel Slope[3]	Sediment Discontinuity[3]	Approach Angle[3]

(% AEP)	CF	TF	FC	PC	<25	25-50	50-75	75-100	>100	Local break	No break	Large US deposit AND tall DS banks	US deposits OR DS tall banks OR DS scour	No US deposits and DS scour	Sharp bend, channelized straight	Mild bend	Naturally straight
10%	FC	FC	N/A	N/A	H	M	L	L	L	M	L	H	M	L	M	L	L
2%	CF	TF	FC	PC	H	H	M	M	L	H	L	H	M	L	H	M	L
1%	CF	TF	FC	PC	H	H	H	M	M	H	M	H	H	L	H	H	L

OVERALL BRIDGE DEPOSITION SCORING

SCORE	Past Deposition Damages	Structure Width vs. Bankfull Channel Width (%)	Channel Slope	Sediment Discontinuity	Approach Angle
10=	Complete failure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
9=	Temporary failure	H	L, M, H, null	H	H
8=	Temporary failure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
7=	Full or partial closure	H	L, M, H, null	H	H
6=	Full or partial closure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
6=	null	H	H	H	H
5=	null	H	L, M, H, null	L, M, H, null	L, M, H, null
4=	null	M	H	H	H
3=	null	M	M, H	M, H	M, H
2=	null	M	M, L, null	M, L, null	M, L, null
2=	null	L, null	M, H	M, H	M, H
1=	null	All other combinations	All other combinations	All other combinations	All other combinations
0=	N/A	N/A	N/A	N/A	N/A

CULVERT DEPOSITION VARIABLE SCORING

Flood	Past Damages[1]				Structure Width vs. Bankfull Channel Width (%)[2]					Culvert and Channel Slope[3]			Sediment Discontinuity[3]			Approach Angle[3]		
(% AEP)	CF	TF	FC	PC	<25	25-50	50-75	75-100	>100	Lower or local break	Equal and local break	Equal and no break	Large US deposit AND tall DS banks	US deposits OR DS tall banks OR DS scour	No US deposits and DS scour	Sharp bend, channelized straight	Mild bend	Naturally straight
10%	FC	FC	N/A	N/A	H	M	L	L	L	M	M	L	H	M	L	M	L	L
2%	CF	TF	FC	PC	H	H	M	M	L	H	M	L	H	M	L	H	M	L
1%	CF	TF	FC	PC	H	H	H	M	M	H	H	L	H	H	L	H	H	L

OVERALL CULVERT DEPOSITION SCORING

SCORE	Past Deposition Damages	Structure Width vs. Bankfull Channel Width (%)	Channel Slope	Sediment Discontinuity	Approach Angle
10=	Complete failure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
9=	Temporary failure	H	L, M, H, null	H	H
8=	Temporary failure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
7=	Full or partial closure	H	L, M, H, null	H	H
6=	Full or partial closure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
6=	null	H	H	H	H
5=	null	H	L, M, H, null	L, M, H, null	L, M, H, null
4=	null	M	H	H	H
3=	null	M	M, H	M, H	M, H
2=	null	M	M, L, null	M, L, null	M, L, null
2=	null	L, null	M, H	M, H	M, H
1=	null	All other combinations	All other combinations	All other combinations	All other combinations
0=	N/A	N/A	N/A	N/A	N/A

ROAD EMBANKMENT DEPOSITION VARIABLE SCORING

River Corridor[2] Length in Corridor (ft) and Remaining Width (%)

Flood	Past Damages[1]				Specific Stream Power[2]			Number of Slope Breaks[3]			Number of Confluences[3]			Change in Confinement[4]			Number of Crossings[3]			Mass Failures (ft)[4]			Bank Erosion (% Length)[4]			Nearby Steep Slopes (feet)[4]			0-660 ft			660-1,320 ft			>1,320 ft		
(% AEP)	CF	TF	FC	PC	<60	60-300	>300	> 2	1-2	0	>1	1	0	>4	2-4	<2	>2	1-2	0	>200	50-200	<50	>25	10-25	<10	>200	50-200	<50	null, >90%	75-90%	<75%	null, >90%	75-90%	<75%	null, >90%	75-90%	<75%
10%	FC	FC	N/A	N/A	M	L	L	M	L	L	M	L	L	M	L	L	M	L	L	H	M	L	M	L	L	M	L	L	L	L	L	L	L	L	L	L	M
2%	CF	TF	FC	PC	M	M	L	H	M	L	H	M	L	H	M	L	H	M	L	H	H	M	H	M	L	H	M	L	L	L	M	L	M	H	M	H	H
1%	CF	TF	FC	PC	H	M	M	H	H	M	H	H	M	H	H	M	H	H	M	H	H	H	H	H	M	H	H	M	L	M	H	M	H	H	H	H	H

OVERALL ROAD EMBANKMENT DEPOSITION SCORING

SCORE	Past Damages	Specific Stream Power	Number of Slope Breaks in Channel	Number of Confluences	Change in Confinement	Number of Crossings	Mass Failures (ft)	Bank Erosion (% Length)	Nearby Steep Slopes (feet)	River Corridor
10=	Complete failure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
10=	Temporary failure	H	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	H
9=	Temporary failure	H, M	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	H, M
8=	Temporary failure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
7=	Full or partial closure	H, M	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	H, M
7=	null	H	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	H
6=	Full or partial closure	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null
6=	null	M	H	H	L, M, H, null	H	L, M, H, null	L, M, H, null	L, M, H, null	M
5=	null	H, M	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	L, M, H, null	H, M
5=	null	H	H	H	L, M, H, null	H	L, M, H, null	L, M, H, null	L, M, H, null	L
5=	null	L, null	H	H	L, M, H, null	H	L, M, H, null	L, M, H, null	L, M, H, null	H
5=	null	H	M, H	M, H	H, M, null	M, H	H, M, null	H, M, null	H, M, null	L
5=	null	L, null	M, H	M, H	H, M, null	M, H	H, M, null	H, M, null	H, M, null	H
5=	null	M	M, H	M, H	L, M, H, null	M, H	L, M, H, null	L, M, H, null	L, M, H, null	M
4=	null	H	L, M, H	L, M, H	L, M, H, null	L, M, H	L, M, H, null	L, M, H, null	L, M, H, null	L
4=	null	L, null	L, M, H	L, M, H	L, M, H, null	L, M, H	L, M, H, null	L, M, H, null	L, M, H, null	H
4=	null	M	L, M, H	L, M, H	L, M, H, null	L, M, H	L, M, H, null	L, M, H, null	L, M, H, null	M
3=	null	M	H	H	L, M, H, null	H	L, M, H, null	L, M, H, null	L, M, H, null	L
3=	null	L, null	H	H	L, M, H, null	H	L, M, H, null	L, M, H, null	L, M, H, null	M
3=	null	M	M, H	M, H	H, null	M, H	H, null	H, null	H, null	L
3=	null	L, null	M, H	M, H	H, null	M, H	H, null	H, null	H, null	M
2=	null	M	L, M, H	L, M, H	L, M, H, null	L, M, H	L, M, H, null	L, M, H, null	L, M, H, null	L
2=	null	L, null	L, M, H	L, M, H	L, M, H, null	L, M, H	L, M, H, null	L, M, H, null	L, M, H, null	M
1=	null	All other combinations	All other combinations	All other combinations	All other combinations	All other combinations	All other combinations	All other combinations	All other combinations	All other combinations
0=	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

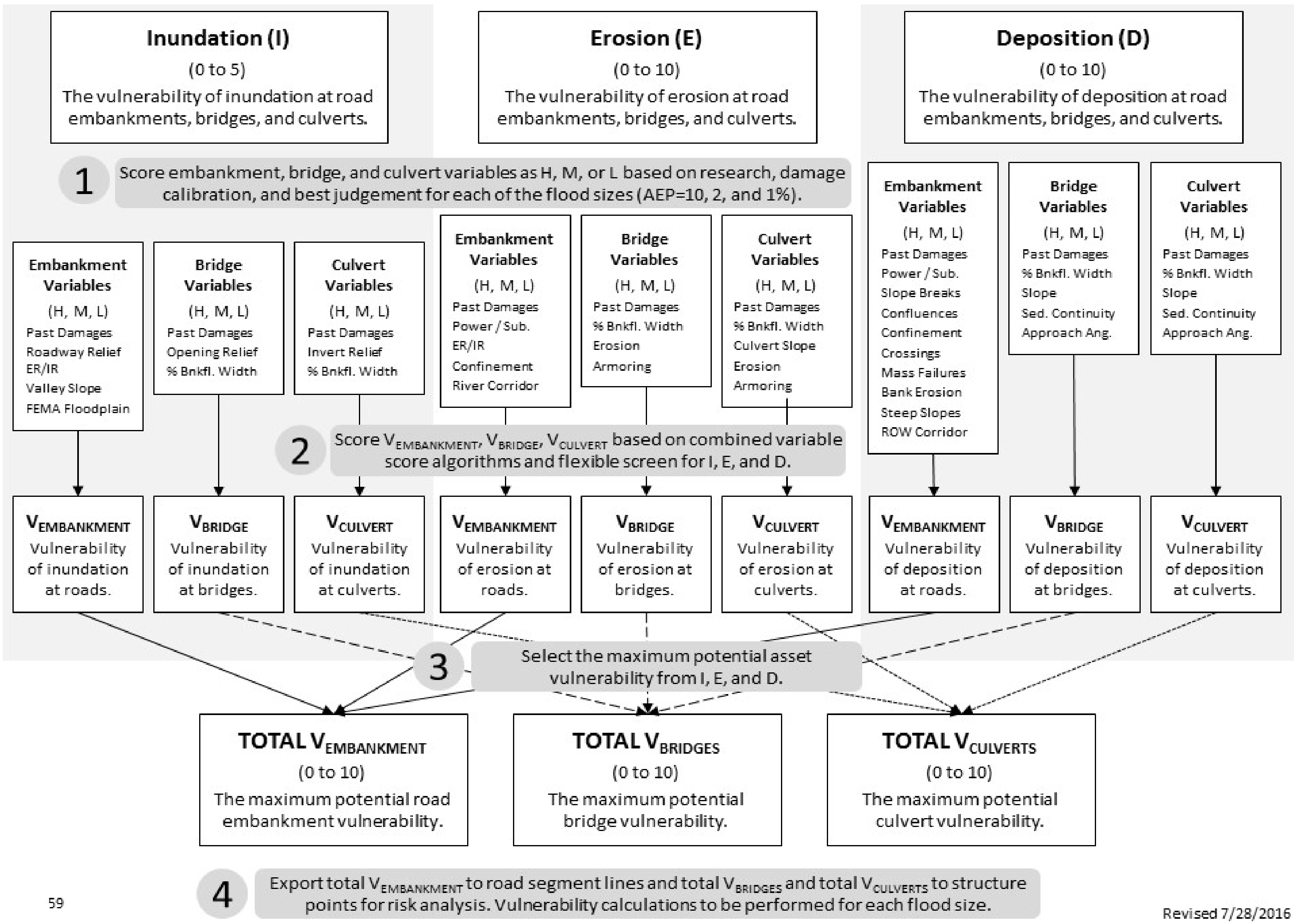


Figure G-2: Overview of the Vulnerability Screen

Final V Scoring

Composite scores were determined by summarizing the maximum of inundation, erosion, and deposition for each river-road segment pairing with a pivot table in the spreadsheet. A single road segment vulnerability score for map and app display was determined by choosing the maximum vulnerability across all three categories (Figure G-2). Overall, erosion scores tended to drive the overall vulnerability score. In the app, the raw data for the road-river relationship yielding the maximum vulnerability score is displayed.

Combining Road and Structure V

A combined vulnerability score for roads, bridges, and culverts was determined through a joint probability calculation whereby the failure probability of each asset is considered independent. The maximum vulnerability scores for each asset in each flood scenario were used for the joint probability calculation. This is explained in more detail in Appendix H and shown below in Table G-2. Where P_s is the probability of a structure (bridge or culvert) failure for a particular road segment and P_r is the probability of the road segment failing, the general formula for the joint probability is:

- Joint probability of failure: $P_f = 1-((1-P_s)*(1-P_r))$

TABLE G-2
Joint Probability Calculation for Roads and Structures

$P_s \backslash P_r$	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
0.1	0.10	0.19	0.28	0.37	0.46	0.55	0.64	0.73	0.82	0.91	1.00
0.2	0.20	0.28	0.36	0.44	0.52	0.60	0.68	0.76	0.84	0.92	1.00
0.3	0.30	0.37	0.44	0.51	0.58	0.65	0.72	0.79	0.86	0.93	1.00
0.4	0.40	0.46	0.52	0.58	0.64	0.70	0.76	0.82	0.88	0.94	1.00
0.5	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
0.6	0.60	0.64	0.68	0.72	0.76	0.80	0.84	0.88	0.92	0.96	1.00
0.7	0.70	0.73	0.76	0.79	0.82	0.85	0.88	0.91	0.94	0.97	1.00
0.8	0.80	0.82	0.84	0.86	0.88	0.90	0.92	0.94	0.96	0.98	1.00
0.9	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00
1.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Estimating Failure Rate Based on Road and Structure V

The estimated failure rate for each vulnerability level was determined through a review of past flood damages as documented by VTrans, Regional Planning Commissions, and FEMA (see Appendix D). This included 160 Tropical Storm Irene flood damage records in the three pilot watersheds. The number of road segments in the pilot subwatersheds were grouped by vulnerability score (1 to 10) from the 50-year flood and compared to the number of damages observed on segments in the pilot subwatersheds, grouped by failure modes. The percentage of segments with damage records for each failure mode was used to develop a table of estimated rates of failures and delays (Table G-3).

TABLE G-3
Estimated Failure Rate for Each Vulnerability Level

Likely Asset Failure Mode		Estimated Number of Road Segment Failures out of 100	Estimated Number of Road Delays out of 100	Estimated Segment Delay (minutes)
Complete Failure	10	40	0	NA
	9	35	0	NA
Temporary Failure	8	30	0	NA
	7	25	0	NA
	6	20	0	NA
Full Closure	5	10	10	10
	4	5	8	10
Partial Closure	3	0	5	5
	2	0	3	2
	1	0	0	0
Damages Unlikely	0	0	0	0

QA/QC

To initially check the vulnerability spreadsheet, 30 road segments were chosen (10 per pilot watershed), and all formulas were reviewed in the scoring spreadsheets for individual variables, variable scaling between floods, and composite scoring. Overall spreadsheet checks as well as examination of variable and score distributions and scoring maps were used for additional QA/QC. An error scaling stream power from the 50- to 100-year flood was noticed, and approximately 10% of segments in each watershed experienced a decrease in maximum vulnerability for the 100-year storm as a result of the correction.

Further checks on the scores were incorporated into an iterative scoring process that incorporated observations from stakeholder input at public meetings and field validation of scores. Stakeholder input assisted in damage mode and severity classifications as well as setting target scores for calibration of the screening method. Field validation trips also identified damage records for revision-based observations of repair extents and landscape setting, especially at sites that had little information for making the damage mode and severity determinations (e.g., PA Project shapefile records) (Figure F-3). Additionally, some road segments outside the LiDAR coverage area received high scores but in the field were observed to have high road-river relief. In cases where the road was high above the river (e.g., I-89 near Brattleboro), road vulnerability was manually lowered by overriding the scores from the spreadsheet (Figure G-4).

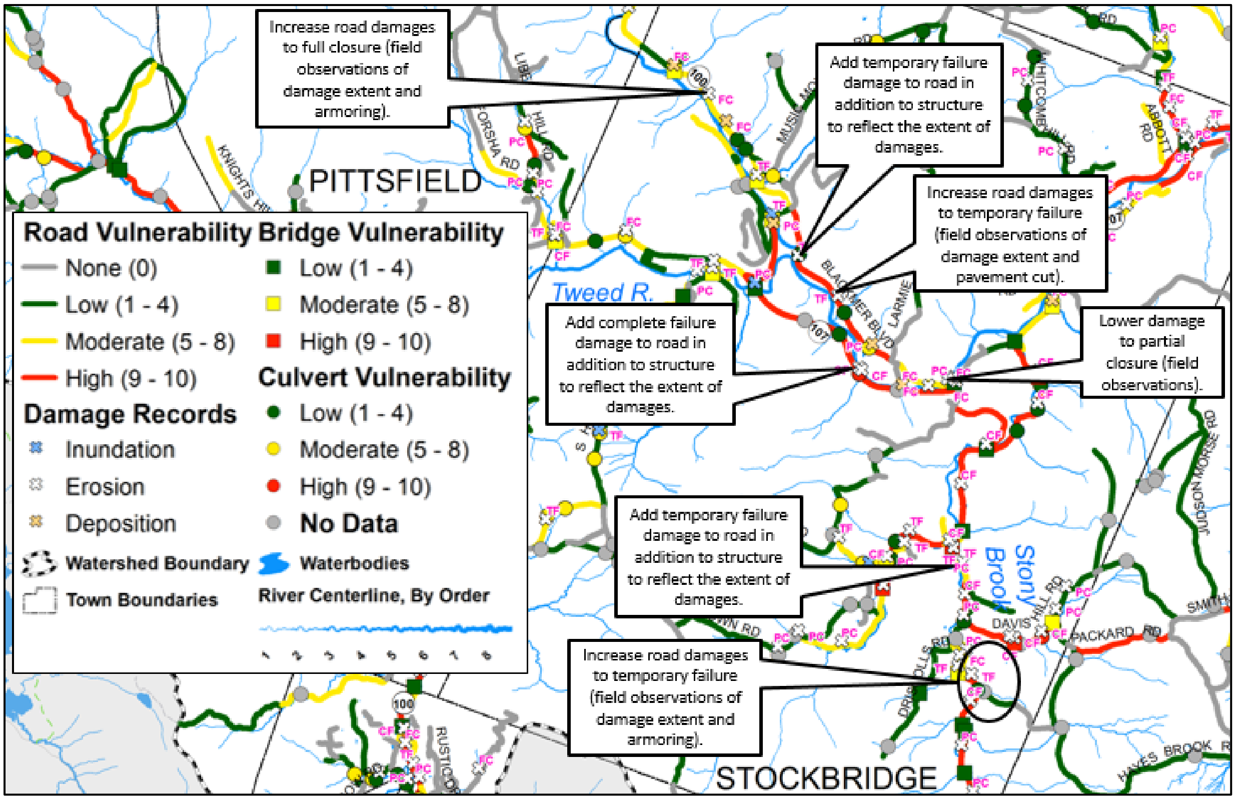


Figure G-3: Example map of observations from field review of Upper White overall vulnerability scores

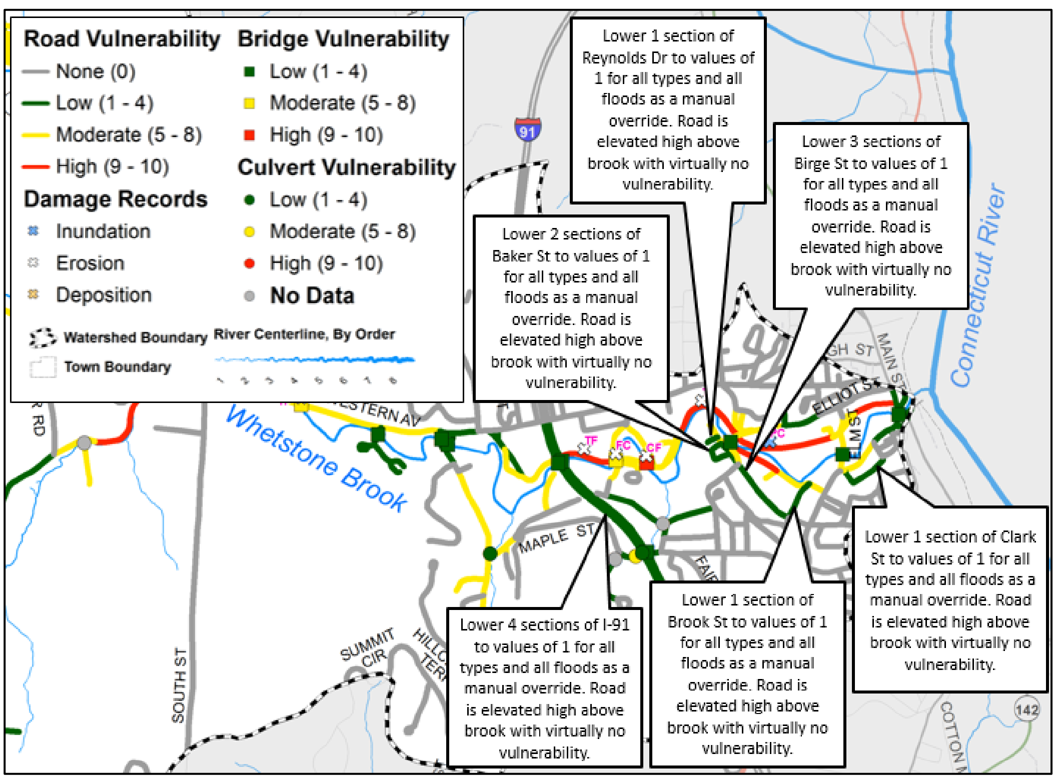


Figure G-4: Manual scoring changes in Brattleboro due to field observations of road-river relief in an area without LiDAR coverage

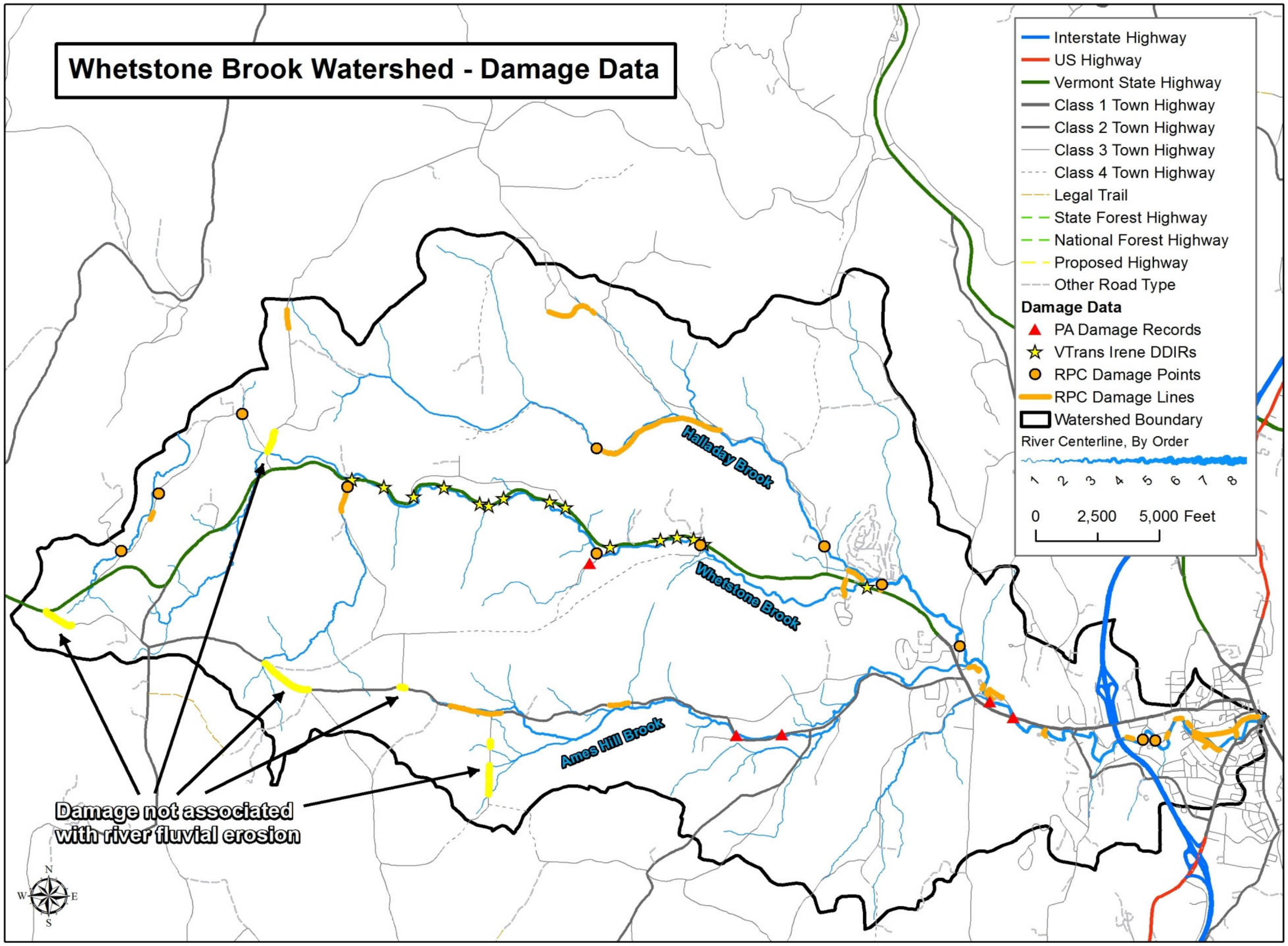


Figure G-5: Damage records in the Whetstone Brook watershed

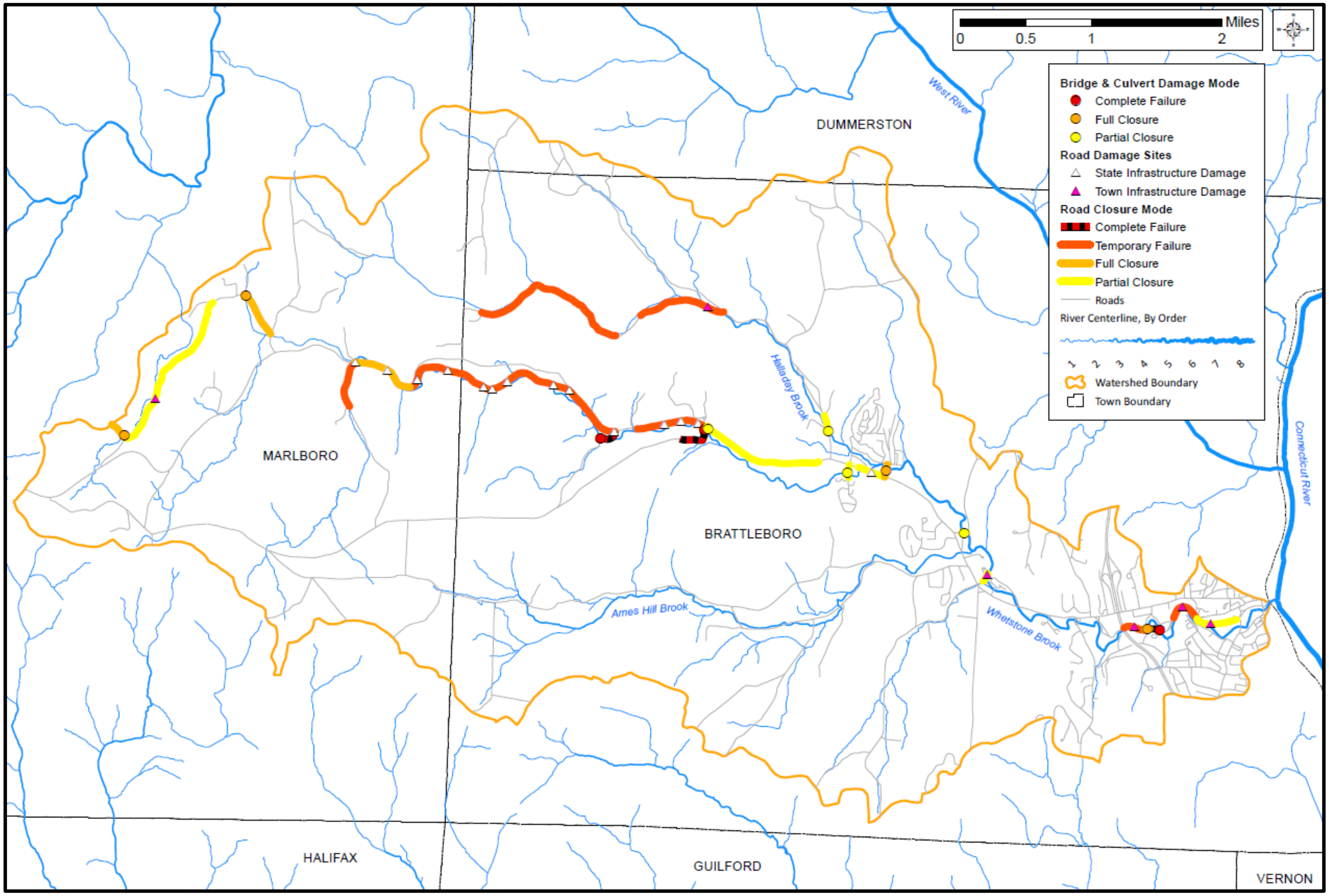


Figure G-6: Damage mode for structures and road segments in the Whetstone Brook watershed

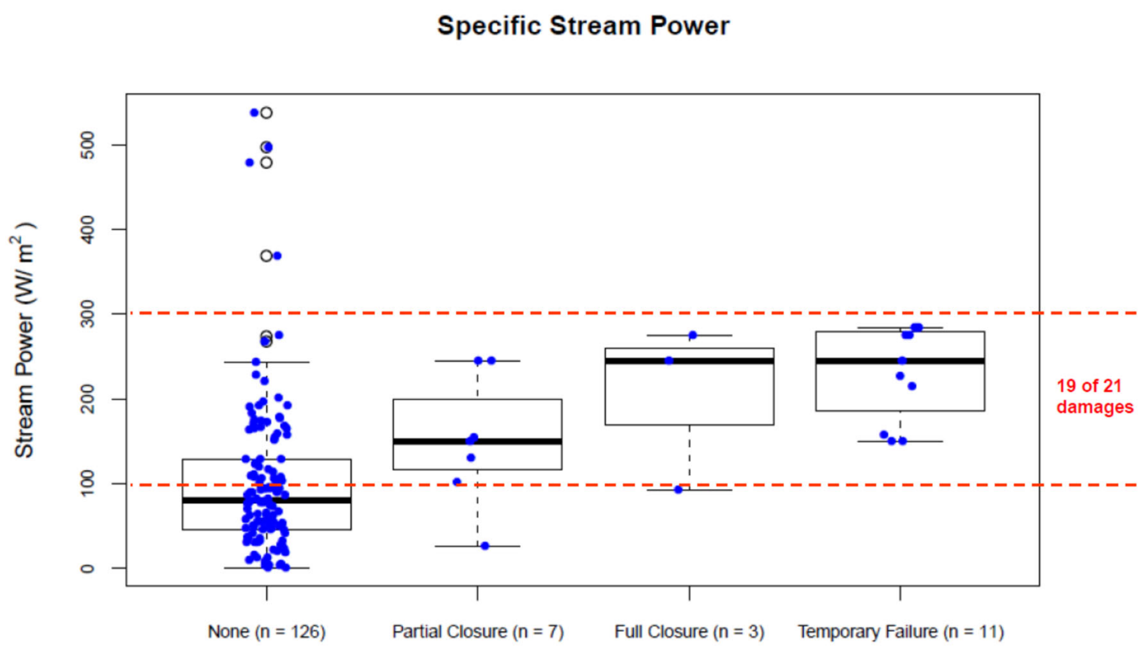
APPENDIX H

INITIAL VULNERABILITY VALIDATION

Quality Control Check
A quality control check of the dataset was performed by examining distributions for individual variables and scores, mapped scores, and spreadsheet review. Field verification was performed by taking several iterations of results and verifying scoring based on current and past field observations. Individual variables were checked and updated as needed. No more than 5% of sites in each pilot watershed needed score adjustments.

Variable Range Exploration
Variables were selected based on prior knowledge of data sources and the literature. Individual variables were classified as high, moderate, or low based on their categorical or numerical values. The scoring ranges were selected based on values from the literature (e.g., incision and entrenchment ratios associated with erosional or depositional channels) and examination of the ranges observed for damaged road segments in the pilot watersheds (Figure H-1).

a)



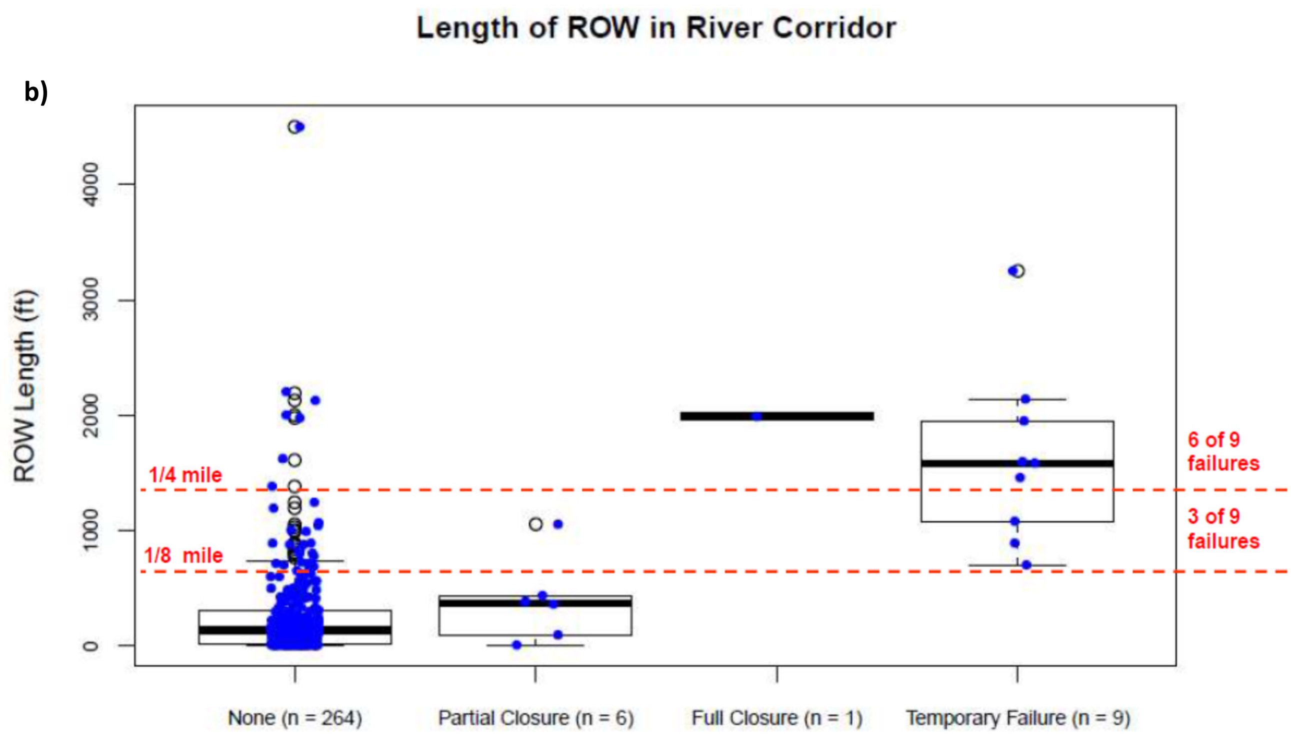
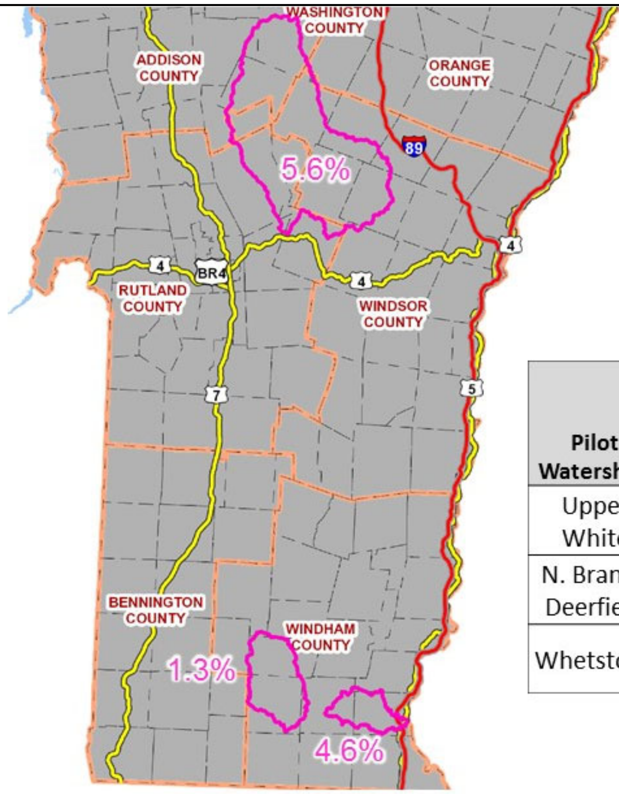


Figure H-1: Boxplots of (a) stream power (W/m^2) and (b) length of the ROW in the river corridor (ft) in pilot watershed reaches associated with road segments for vulnerability screening by damage record failure mode

The final dataset assembled facilitated an examination of how variables potentially related to flood vulnerability compared to recorded damages. This information was used to confirm ranges of the variable that may be associated with elevated vulnerability potential (e.g., stream power of 100-300 W/m^2 for vulnerability to erosion). Thus, the damage records were used to calibrate classifications of individual variables as well as the overall vulnerability score.

Validation and Refinement

An iterative scoring process incorporating both stakeholder input and field observations was used to refine the vulnerability screen and overall scores. Stakeholder input was solicited in three meetings, one for each pilot watershed. Vulnerability scores were discussed, and the scoring system was refined to match the observations and recollections of the group. Each watershed was visited for further evaluation of the vulnerability of road segments and structures as well as the type and severity of damage records in the pilot watersheds (Figure H-2).



Pilot Watershed	Total # Scored Road Segments	Manual Changes	Damage Record Changes	% of Road Segments Changed
Upper White	836	2	45	5.6%
N. Branch Deerfield	386	0	5	1.3%
Whetstone	280	12	1	4.6%

Figure H-2: Summary of vulnerability scoring calibration statistics for the pilot watersheds

APPENDIX I

THE NETWORK CRITICALITY INDEX (NCI) AND FINAL CRITICALITY SCORING

The Network Criticality Index Model

Norman L. Marshall
President

June 2018

DRAFT

Prepared for the
Vermont Agency of Transportation

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Overview

The Vermont Resiliency Travel Model (VRTM) extends the Vermont Travel Model (VTM) to represent more geographic detail, and to adds new capabilities. The VTRM has been developed for application in the VTrans Vermont Transportation Flood Resiliency Planning Tool (TRPT). For more information about this project refer to this User Guide and see https://roadfloodresilience.vermont.gov/#/map .

The VRTM includes four submodels as illustrated in Figure 1.

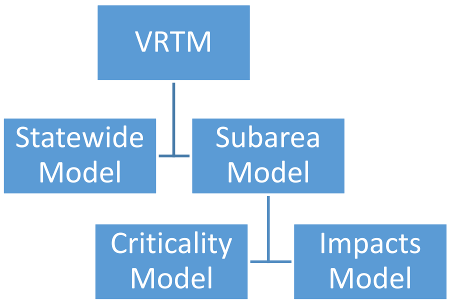

Figure 1. Overview of Vermont Resiliency Travel Model.

The four submodels are:

- *Statewide Model*: Produces comparable traffic assignments to VTM and primarily included for quality assurance.
- *Subarea Model*: Includes all relevant roadways in Vermont. Within a designated subarea, the VRTM disaggregates the VTM down to very small areas centered around roadway intersections. The *Subarea Model* must be run prior to running either the *Criticality Model* or *Impacts Model.* The *Subarea Model* also is useful for transportation analysis in detailed corridor and area studies.
- *Criticality Model*: Within a subarea, calculates the relative importance of every roadway segment in terms of excess travel time and incomplete trips if the segment were removed from the network.
- *Impacts Model*: Evaluates the traffic impacts of different storms within a subarea through Monte Carlo simulations based on roadway segment vulnerability estimates.

VTRM Software and Data Distribution

TransCAD

The Vermont Travel Impacts Model (VTRM) requires TransCAD 6.0.[1] and an experienced TransCAD user.

The TransCAD GISDK scripts are all in a single file, VermontResiliencyModel#.rsc, where # represents the version date expressed as an integer. This file may be placed anywhere on the computer. Appendix H1 documents the GISDK scripts.

The VTRM interface includes a VTrans logo graphic called VTRM.bmp. For this graphic to load, place VTRM.bmp in the TransCAD software directory, e.g. c:\Program Files\TransCAD 6.0\. Note that the VTRM will work without the graphic.

Essential Data Sets

The essential data sets are listed in Table 1. These files should all be placed in the same folder, but this folder can be anywhere on the computer.

Table 1. *TransCAD Essential Data Sets*

Data Set Type	File Names
Road network database	Vermont_Roads_Resiliency.* plus Vermont_Statewide_Resiliency_.* (total of 21 files)
Turn penalty files	TurnPenalties.bin and TurnPenalties.dcb
2015 trip table matrix file	Gravity_RawFY.mtx
Transportation Analysis Zones (TAZ) database	2010 Vermont TAZs.* (total of 17 files)
TAZ-node correspondence files	TAZNodesShares.bin and TAZNodeShares.dcb

The *Impacts Model* requires additional input files which are described in the *Impacts Model* section.

Road network database: This collection of files was created during this project by integrating the Vermont Travel Model network and the VTrans TransRoad_RDS GIS layer. Separate node and link layers are included, and some additional data fields have been added. Information about the integration work and documentation for the data fields are included in Appendix H2.

Turn penalty: Some link-to-link movements are prohibited by roadway geometry. This is especially common in grade-separated interchanges. Coding these prohibitions in a turn penalty file is standard travel modeling practice. These files are network-specific and were created for this project.

2015 trip tables: This file was developed by the University of Vermont Transportation Research Center (UVMTRC) and includes TAZ-TAZ daily person and vehicle trips for several different trip types.

Transportation Analysis Zones (TAZ): From the Vermont Travel Model and provided by UVMTRC

[1] In consultation with Jim Sullivan of the University of Vermont Transportation Research Center, it was decided to use TransCAD Version 6 for consistency with the existing Vermont Travel Model rather than Version 7 which has different data structures.

TAZ-node correspondence: Developed for this project to allocate travel origins and destinations at a much finer geographic detail than TAZs. This was done using E911 data as discussed in Appendix H3.

Vermont Transportation Resiliency Models Menu

The Vermont Models menu has six options:

- Statewide Model
- Subarea Model
- Criticality Model
- Impacts Model
- About
- Close

The first four are the models which are launched when chosen in the Vermont Models Window. *About* includes some information about the package, and C*lose* removes Vermont Models from the toolbar options.

Overview of the Four Applications

All four applications assign traffic to the roadway network. It is assumed that there is little or no need to include feedback for congested travel times for average weekday conditions due to low population density in most areas of Vermont. Therefore "All or Nothing" assignment is used as it is the simplest, and fastest[2]. This assignment assumes that every traveler takes the fastest route as computed without congestion. The four applications use standard "hard-coded" output names. Therefore, *a separate folder should be created for each modeling scenario to avoid writing over outputs from other scenarios.* Each application is explained a bit more below.

Statewide Model assigns the same TAZ-to-TAZ trip tables as in the Vermont Travel Model, and does so on the same network links, except that the links have more geographic detail due to upgrades in the TransRoad_RDS network (Appendix H2). This option is provided primarily for purposes of testing and checking the data. The *Statewide Model* flow diagram is shown in Figure 2.

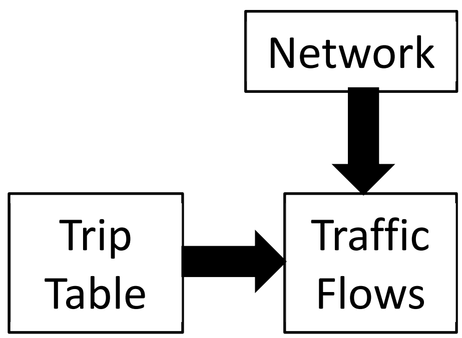

Figure 2. *Statewide Model Flow Diagram.*

[2] The Statewide and Subarea models could be reworked to feed back congested traveled times. The Criticality and Impacts Models already have long simulation times, and treatment of congestion at the same time is impractical.

The *Subarea Model* takes a user-specified subarea, coded as any combination of TAZs. Within this subarea, the trip table is expanded and assigned to the full roadway network including local roads. In addition to traffic flows, a TAZ-TAZ travel time matrix also is output. The *Subarea Model* flow diagram is shown in Figure 3.

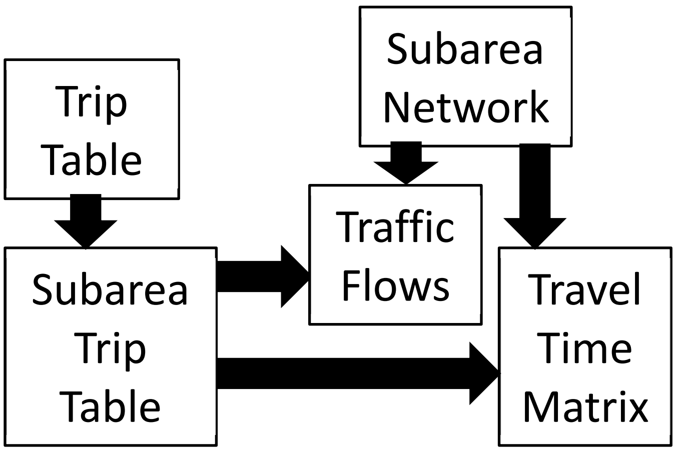

Figure 3. *Subarea Model* Flow Diagram.

The *Criticality Model and impacts Model* are extensions of the *Subarea Model*. The *Subarea Model* must be run first with the same output folder designated. The *Criticality Model* estimates the relative importance of every roadway segment. As shown in the flow diagram (Figure 4), it does this by iterating through every roadway segment in the subarea, and calculating the impacts on travel, including trips that cannot be completed and excess travel time for trips that can be completed.

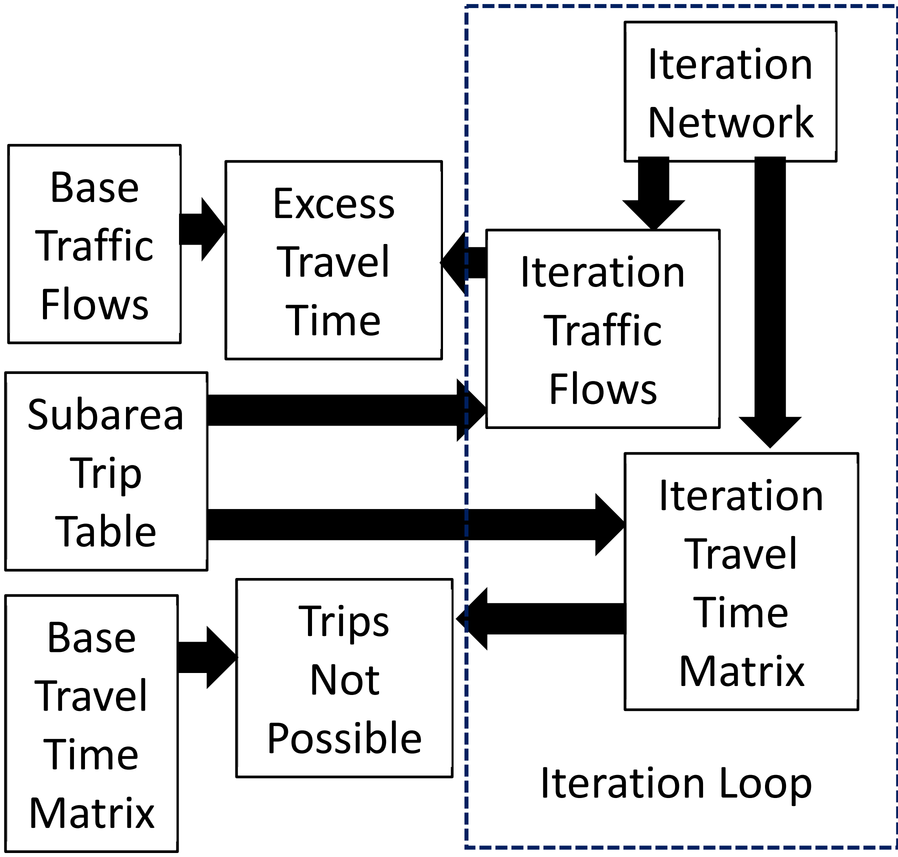

Figure 4. *Criticality Model Flow Diagram*.

Storm events almost always will result in the failure of multiple roadway segments. The *Impacts Model* simulates the travel impacts of different storm events using Monte Carlo simulations. Each Monte Carlo iteration includes a different set of roadway segments failing. Overall risk is calculated by averaging the results from all iterations. Figure 5 shows the *Impacts Model* flow diagram.

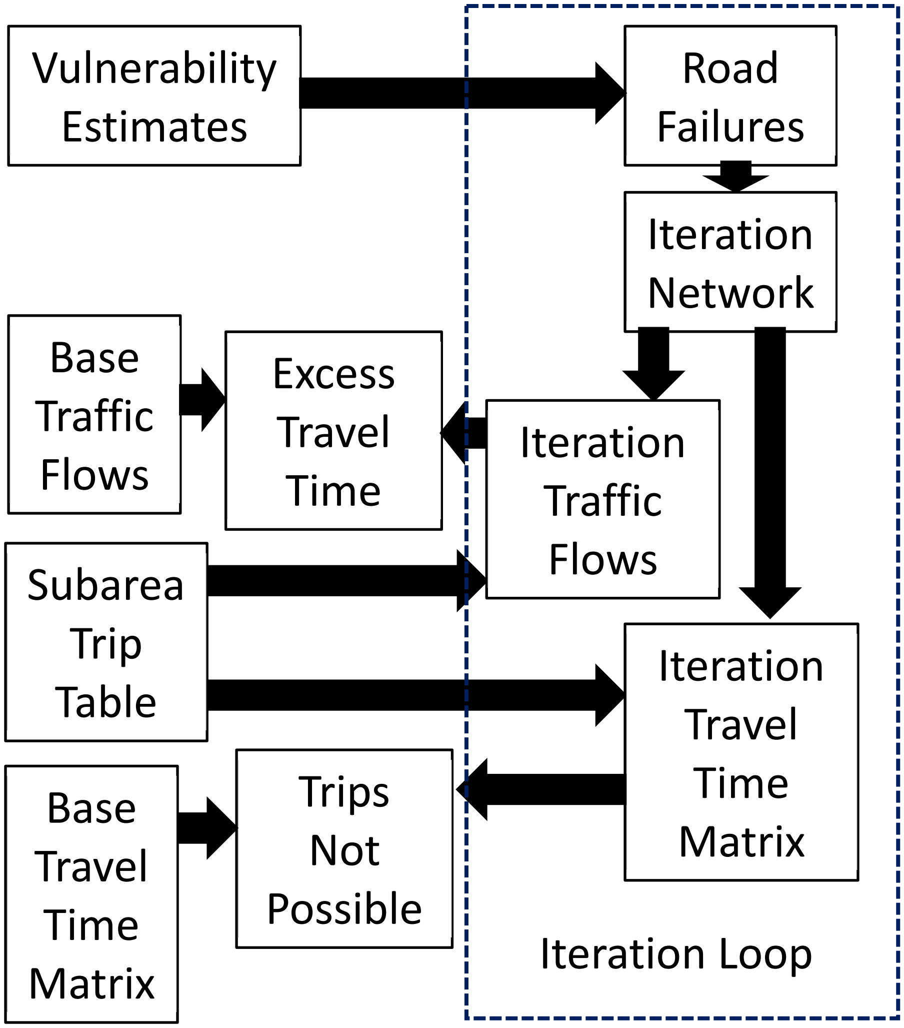

Figure 5. Impacts Model Flow Diagram**.**

Installing the Model

The VTRM is installed using the TransCAD GIS Developer's Kit. If this toolbar is not already active, activate it by checking GIS Developer's Kit from the Tools menu. The GIS Developer's Kit toolbar is highlighted in Figure 6 with a warning to the reader that the toolbars in TransCAD often move around.

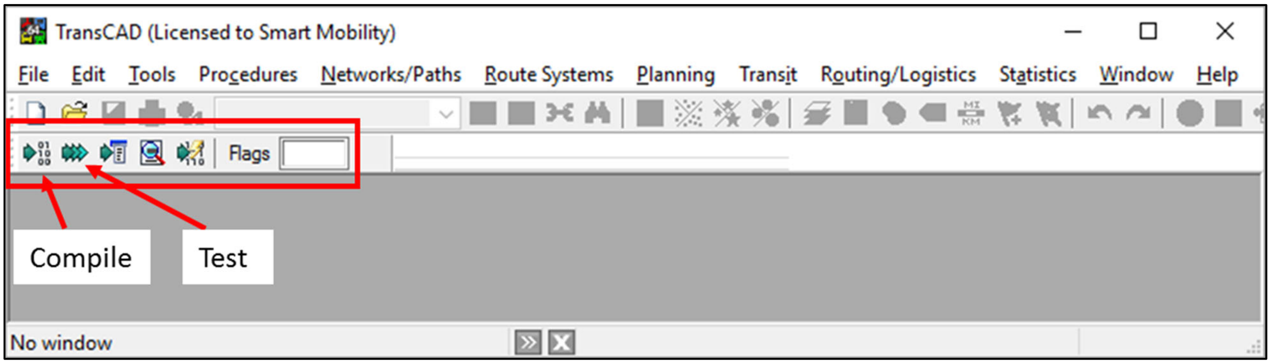

Figure 6. *TransCAD GIS Developer's Kit Toolbar.*
*Note: Toolbar may appear in different position on screen. TransCAD toolbars can be repositioned***.**

The VTRM is accessed through a custom toolbar. Installing the VTRM toolbar requires two steps:

1) *Compile*: click the Compile button (Figure 6) and choose the VTRM script VermontResiliencyModel#.rsc where # represents the current version number

2) *Test*: click the Test button (Figure 6), keep the default Macro type, and type in the name ModelMenu as shown in Figure 7. Click OK. This adds a Vermont Models menu to the left of the Window menu as highlighted by the red box shown in Figure 8.

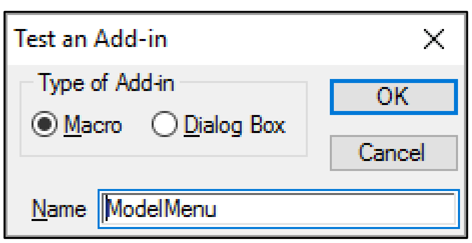

Figure 7. *Test an Add-in Dialog Box***.**

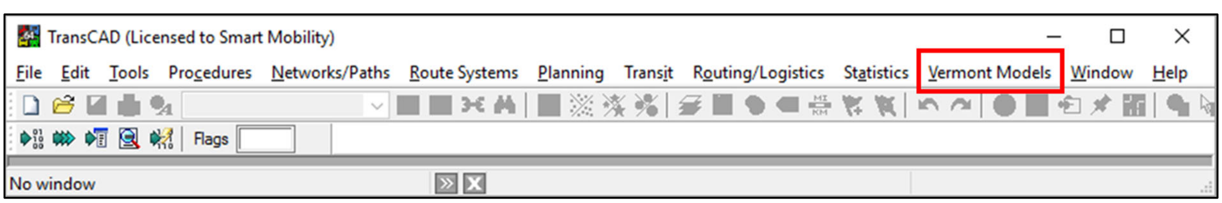

Figure 8. *Vermont Models Menu***.**

Statewide Model – Inputs

The *Statewide Model* dialog window is shown in Figure 9.

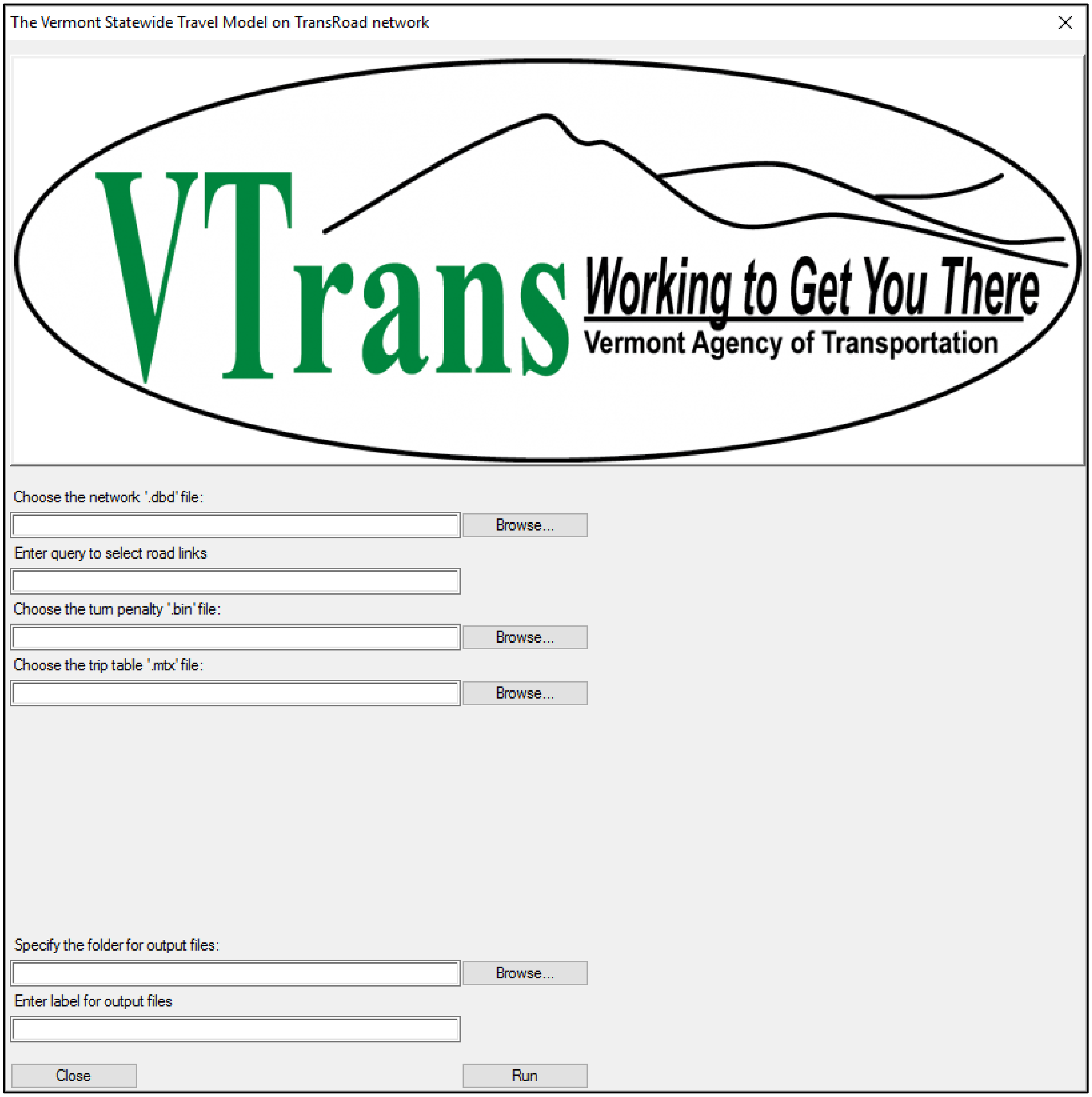

Figure 9. *Statewide Model Dialog Window***.**

There are six inputs which include three of the input files from the essential data sets (Table 1). These files are selected using the standard Windows Browse buttons. Similarly, the output folder is selected using a Browse button. The other two entries require typing in the following text:

- For "Enter query to select road links" select the statewide model links by entering: **SW15=1**
- For "Enter label for output files" type in short scenario-specific prefix for beginning of output file names (left blank if no prefix is desired)

Note: If the VTrans graphics does not appear, check to make sure that the VTRM.bmp is placed in the TransCAD software directory, e.g. c:\Program Files\TransCAD 6.0\. Also recall that a separate folder should be created for each modeling scenario to avoid writing over outputs from other scenarios.

Statewide Model - Outputs

After entering inputs, click *Run* to execute the model. Once complete, a *Done* button appears. Clicking either the *Close* or *Done* buttons closes the window. *Statewide Model* inputs are listed in Table 2.

Table 2. Statewide Model Outputs

Description	File Names (with input prefix added to front)
Simulation network	<user supplied prefix>_net.net
Output traffic flow	<user supplied prefix>_flow.bin and <user supplied prefix>_flow.dcb

Simulation network: Before assigning traffic, TransCAD makes a *.net file which includes the required fields from the full roadway network fields, along with some settings. Typically, the user will not use this file although it sometimes can be helpful in debugging problems.

Output traffic flow: This is standard TransCAD output and includes traffic flow by trip type and direction. Output fields include:

- Home-Based-Work: AB_Flow_HBW-VTs/BA_Flow_HBW-VTs
- Home-Based-Shopping AB_Flow_HBSHOP-VTs/BA_Flow_HBSHOP-VTs
- Home-Based-Other AB_Flow_HBO-VTs/BA_Flow_HBO-VTs
- Nonhome-Based AB_Flow_NHB-VTs/BA_Flow_NHB-VTs
- Truck AB_Flow_TRUCK-VTs/BA_Flow_TRUCK-VTs
- Total traffic AB_Flow/BA_Flow/Tot_Flow

To view the results, open the roadway network *.dbd file. Then use menu option ***Dataview-Join*** to join the newly output _flow.bin data to the road network (Figure 10).

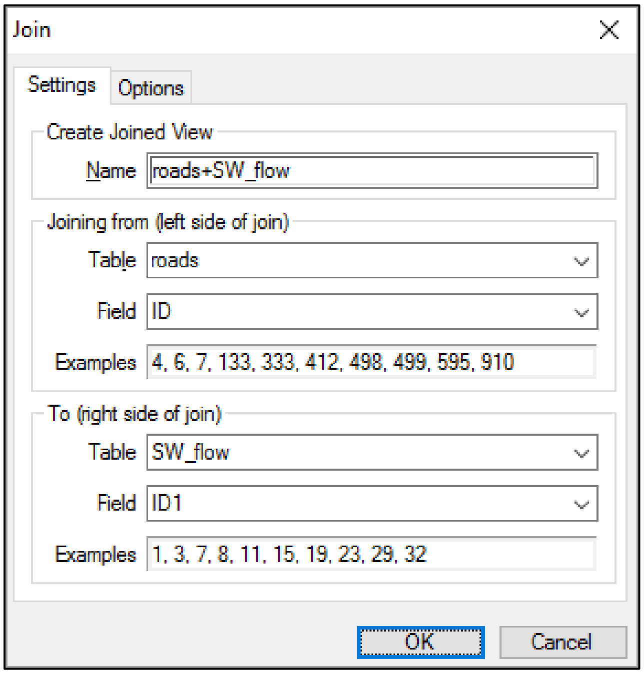

Figure 250. *TransCAD Dataview Join example*.

TransCAD includes a number of tools for viewing the flow data including:

- Illustrating relative volumes with scaled symbol widths
- Labeling road segments with volumes
- Selecting flows within certain ranges and illustrating with color and/or width

Refer to TransCAD Help for more information.

Subarea Model - Inputs

Prior to running the Subarea Model, the subarea must be defined in the TAZ layer. If the subarea of interest is not yet defined, do so with these steps:

1) In TransCAD, open the TAZ (*.dbd) layer from the Vermont database
2) Select menu Dataview-Modify Table
3) Click the *Add Field* button and add an integer field with the desired subarea name (examples in base data are UpperWR, Whetstone, and NBDeerfield). Click OK when done.
4) Activate Selection toolbar if not already active using menu Tools-Selection
5) Select Subarea TAZs (Figure 6) using the Pointing (or Selection) tool in TransCAD
6) Open *New Dataview* using button shown in Figure 11
7) The newly opened dataview shows "All Records" on the toolbar. Change this dataview option to the "Selection" window (Figure 12).
8) In the dataview, select the column labeled with the subarea field (e.g., Whetstone)
9) Right click on the field name header and ***Fill…*** with ***Single Value*** set to 1. Click OK when done.
10) Close all of the windows
11) Under the Vermont Models Toolbar, select *Subarea Model* and fill out following Figure 13.

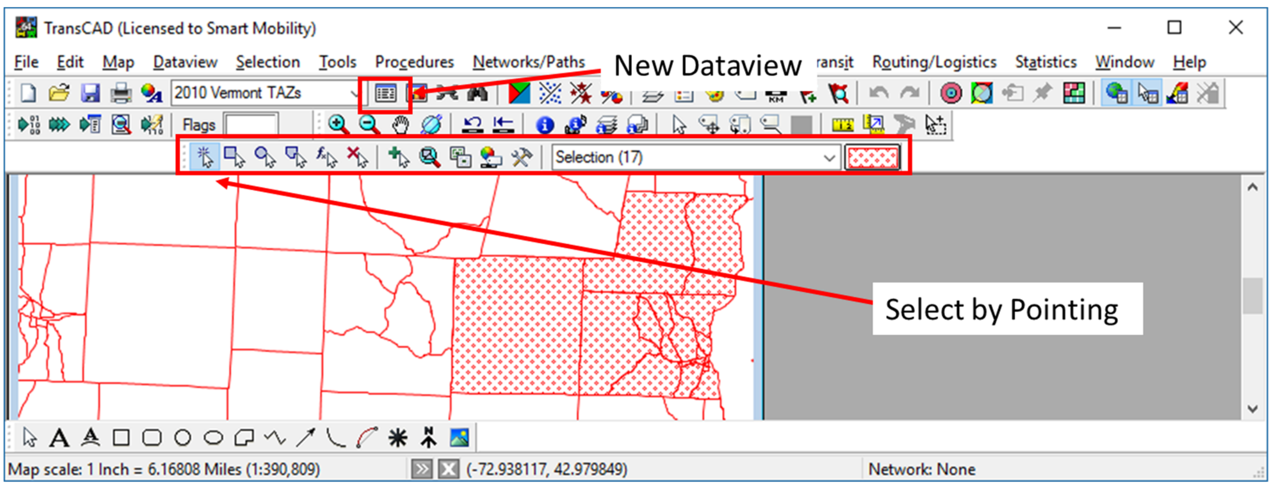

Figure 261. *Graphically isolating a subarea.*

Use the TransCAD Selection Toolbar's *Select by Pointing* tool to define the geography of the subarea in Figure 11.

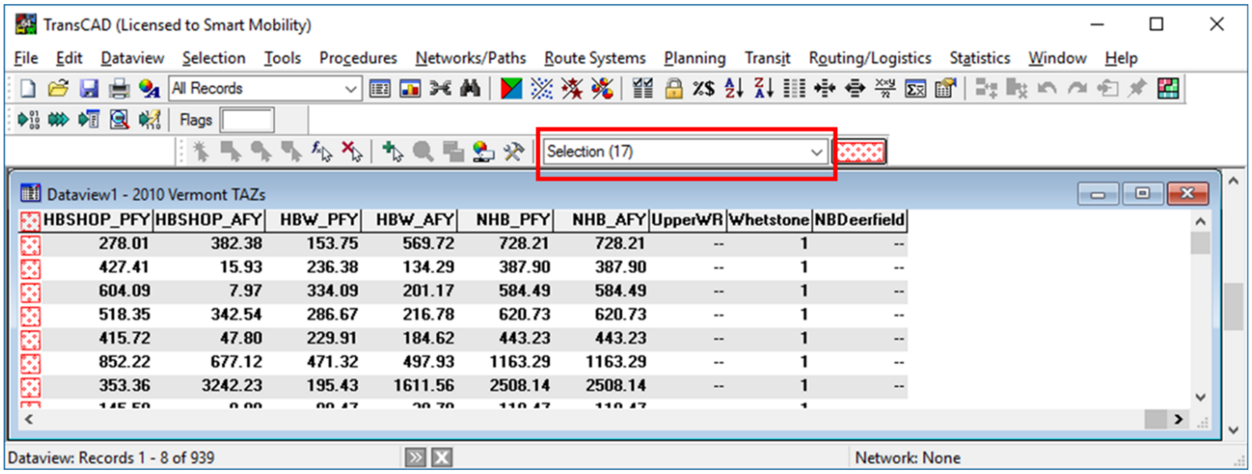

Figure 272. *Numerically flag a selected subarea***.**

Use TransCAD ***Dataview*** and the ***Selection*** of the subarea to isolate the needed rows of data and numerically populate these selected rows by filling them with an integer value of 1.

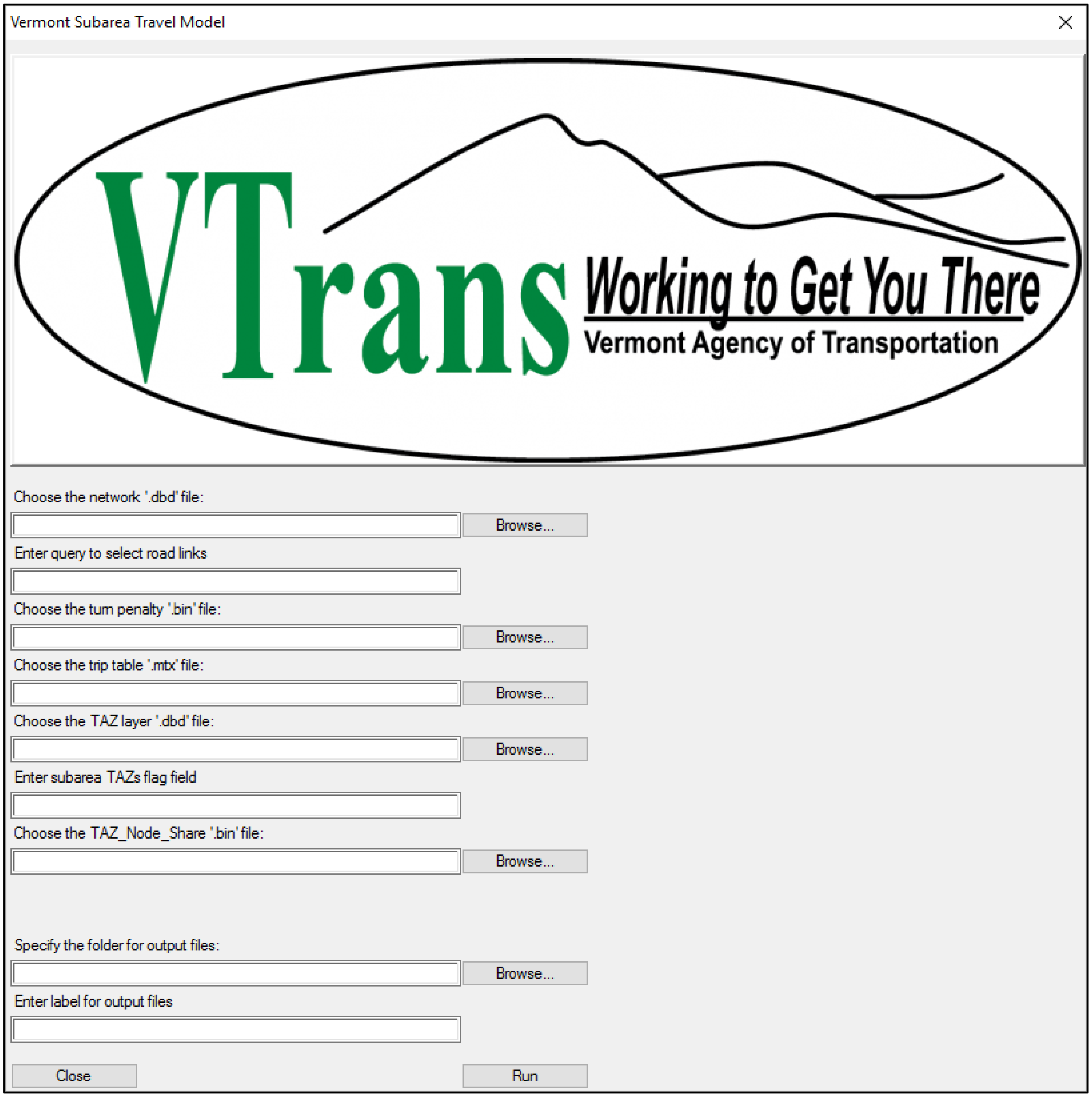

Figure 283. *Subarea Model Dialog Window***.**

There are nine inputs in this model's main interface tool. These include the input and output requests from the Statewide model (Figure 9) plus the three TAZ entries. Most entries use the browse button with the three requiring typed text as follows.

- For "Enter query to select road links", select all model links[3] by entering **Full15=1**
- For "Enter subarea TAZs flag field", enter the subarea field name (e.g., Whetstone)
- For "Enter label for output files", enter short scenario-specific prefix for beginning of output file names (blank is allowed if no prefix is desired)

[3] In the essential data sets (Table 1), private roads are excluded (Appendix H1). If certain private roads should be included, another field can be coded using the same general approach outline in designating the subarea, i.e. adding a new field for which links should be included and populating it with 1 for the appropriate links.

Subarea Model – Outputs and Sample Graphics

After entering inputs, the *Run* button executes the model. After model completion, a *Done* button appears. Clicking either *Close* or *Done* buttons to close the window. Outputs are given in Table 3.

Table 3. Subarea Model Outputs

Description	File Names (with user input prefix added to front)
Simulation network	<user supplied prefix>_net.net
Output traffic flow	<user supplied prefix>_flow.bin and <user supplied prefix>_flow.dcb
TAZ-node correspondence table	<user supplied prefix>_TAZNode.bin
Expanded trip tables	<user supplied prefix>_expTT.mtx
Subarea travel time matrix	<user supplied prefix>_skim.mtx
Subarea nodes file	<user supplied prefix>_NodeOut.bin and <user supplied prefix>_NodeOut.dcb

The simulation network and output traffic flow files are described in the *Statewide Model* section.

TAZ node correspondence table: This is an intermediate file to expand the trip tables that could be useful in debugging certain cases.

Expanded trip tables: This file has the same internal matrices as the input trip tables, but disaggregated to the subarea expanded TAZ structure.

Subarea travel time matrix: TAZ-TAZ travel times.

Subarea nodes file: Includes one record for each traffic loading node in the Subarea Model. Also includes empty fields as preparation for the Impacts Model runs.

Criticality Model - Inputs

The *Criticality Model* computes the relative importance of each roadway segment in a subarea. It does this by iteratively removing each roadway segment at a time and recalculating travel times. This can take many hours of computation time, depending on the number of roadway segments in the subarea.

The *Criticality Model* dialog window is shown in Figure 14.

Figure 294. Criticality Model Dialog Window**.**

There are seven inputs. These include the four browsed selections of 1) the preprocessed Statewide geodatabase that has been augmented to include the storm probabilities for each subarea, 2) the turn penalty input files from Table 1, 3) the TAZ .dbd file augmented in the *Subarea Model* run to include a flagged column identifying each TAZ node within the Subarea (e.g., UpperWR) and 4) the output folder name that matches the Subarea model outputs. The remaining three entries require typing as follows:

- For "Enter query to select road links" select all model links[4] by entering **Full15=1**
- For "Enter subarea TAZs flag field enter the appropriate field name (e.g., UpperWR)

[4] In the essential data sets, private roads are excluded as discussed in Appendix H1. If certain private roads should be included, another field can be coded using the same general approach outlined when designating the subarea, i.e. add a new field where links should be included and populate these appropriate links with a value of 1.

- For "Enter label for output files" use the same entry as the Subarea model prefix.

Criticality Model – Outputs

The critical roadway segments model output files are listed in Table 4.

Table 4. Criticality Model Outputs

Description	File Names (with input prefix added to front)
Link output data	LinkOut.bin and LinkOut.dcb

For each roadway segment in the study area, these variables are calculated:

- *FailTrips* – the number of daily trips that cannot be completed
- *ExcessTime* – Additional daily travel time in minutes compared to base case
- *CritTotal* – *ExcessTime* + 100 * *FailTrips*
- *CritIndex* – *CritTotal* normalized so that maximum value is 1.0

Figure 15 illustrates *CritIndex* in the Whetstone Brook Watershed.

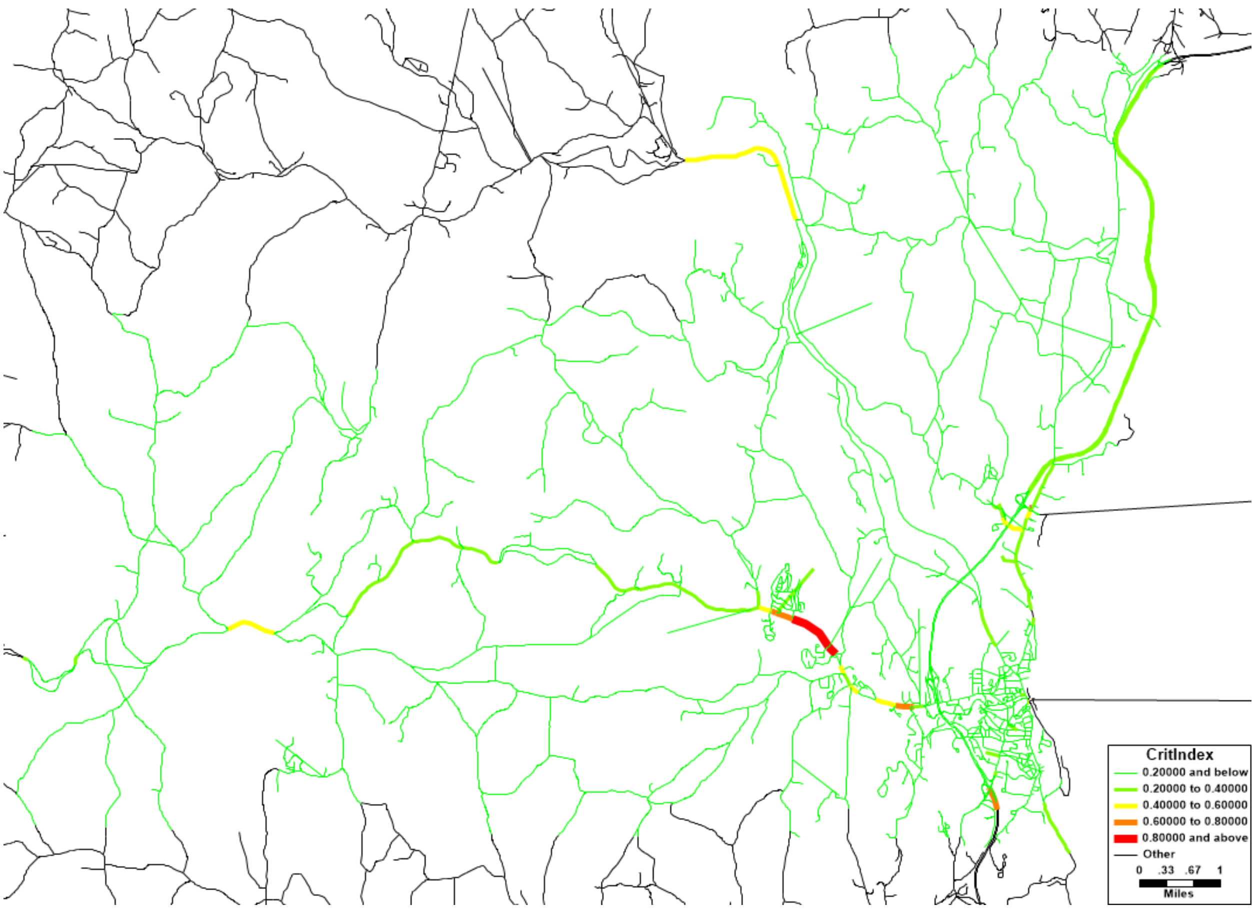

Figure 305. *Critical Links in the Whetstone Brook Watershed*.

Impacts Model - Inputs

The Impacts Model takes vulnerability estimates for each roadway segment and does multiple iterations to estimate the consequences of failures on travel.

The Impacts Model requires that two vulnerability fields be created in the roadway network field and populated with probabilities between 0.0 and 1.0. One field is for bridges and culverts on each roadway segment and the other field is for segment vulnerability separate from bridges and culverts. These fields can be added to the roadway layer using the same TransCAD tools that are described above in subarea definition.

In general, the Impacts Model assumes that all of these probabilities are independent. Therefore, if two roadway segments along the same path each has a failure probability of 50%, there will be a 75% chance of at least one of the segments failing. Similarly, it a single segment has a 50% chance of structural failure and a 50% of segment failure, the segment will have a 75% chance of failure. If P_s is the probability of a structure failure for a particularly road segment, and P_r is the probability of the road segment failing, the general formula for the joint probability is:

- Joint probability of failure: $P_f = 1-((1-P_s)*(1-P_r))$

The joint probability is illustrated in Figure 16

$P_s \backslash P_r$	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
0.1	0.10	0.19	0.28	0.37	0.46	0.55	0.64	0.73	0.82	0.91	1.00
0.2	0.20	0.28	0.36	0.44	0.52	0.60	0.68	0.76	0.84	0.92	1.00
0.3	0.30	0.37	0.44	0.51	0.58	0.65	0.72	0.79	0.86	0.93	1.00
0.4	0.40	0.46	0.52	0.58	0.64	0.70	0.76	0.82	0.88	0.94	1.00
0.5	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
0.6	0.60	0.64	0.68	0.72	0.76	0.80	0.84	0.88	0.92	0.96	1.00
0.7	0.70	0.73	0.76	0.79	0.82	0.85	0.88	0.91	0.94	0.97	1.00
0.8	0.80	0.82	0.84	0.86	0.88	0.90	0.92	0.94	0.96	0.98	1.00
0.9	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00
1.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Figure 316. *Joint Probability from Structures Vulnerability and Road Segment Vulnerability***.**

The TransRoad_RDS layer has many very short links as is discussed in Appendix H2. Many paths include multiple short segments, and if each segment is considered independent, the likelihood of failure would be very high. In order to compensate for short segments, the Impacts Model adjusts the segment probabilities for segments of less than 1.0 mile by multiplying the input probabilities by the segment length. For example, if a path includes ten roadway segments each 0.1 miles long and with a failure probability of 50%, the Impacts Model converts the failure probability for each segment to 50% x 0.1 = 5%.[5] The general formula is:

[5] In this example, the probability of failure for the 1.0-mile path is 1.0 – ((1.0 – 0.005) ^ 10) = 40%.

Adjusted P_r = minimum(length, 1.0) * Input P_r

The Impacts Model requires outputs from the Subarea Model and a pre-processed Statewide geodatabase which is augmented (through a series of join commands) to include storm probability outcomes. Therefore, the Subarea Model must be run prior to the Impacts Model with the same output folder and file prefix.

If the probability of a certain road segment failing is 0.5 (50%), the situation is just like flipping a coin. Over a large number of iterations, the average failure rate will be close to 50%. The precision of the model in matching the input probabilities is a function of the number of iterations. Figure 17 illustrates the 95% confidence intervals for different numbers of iterations.

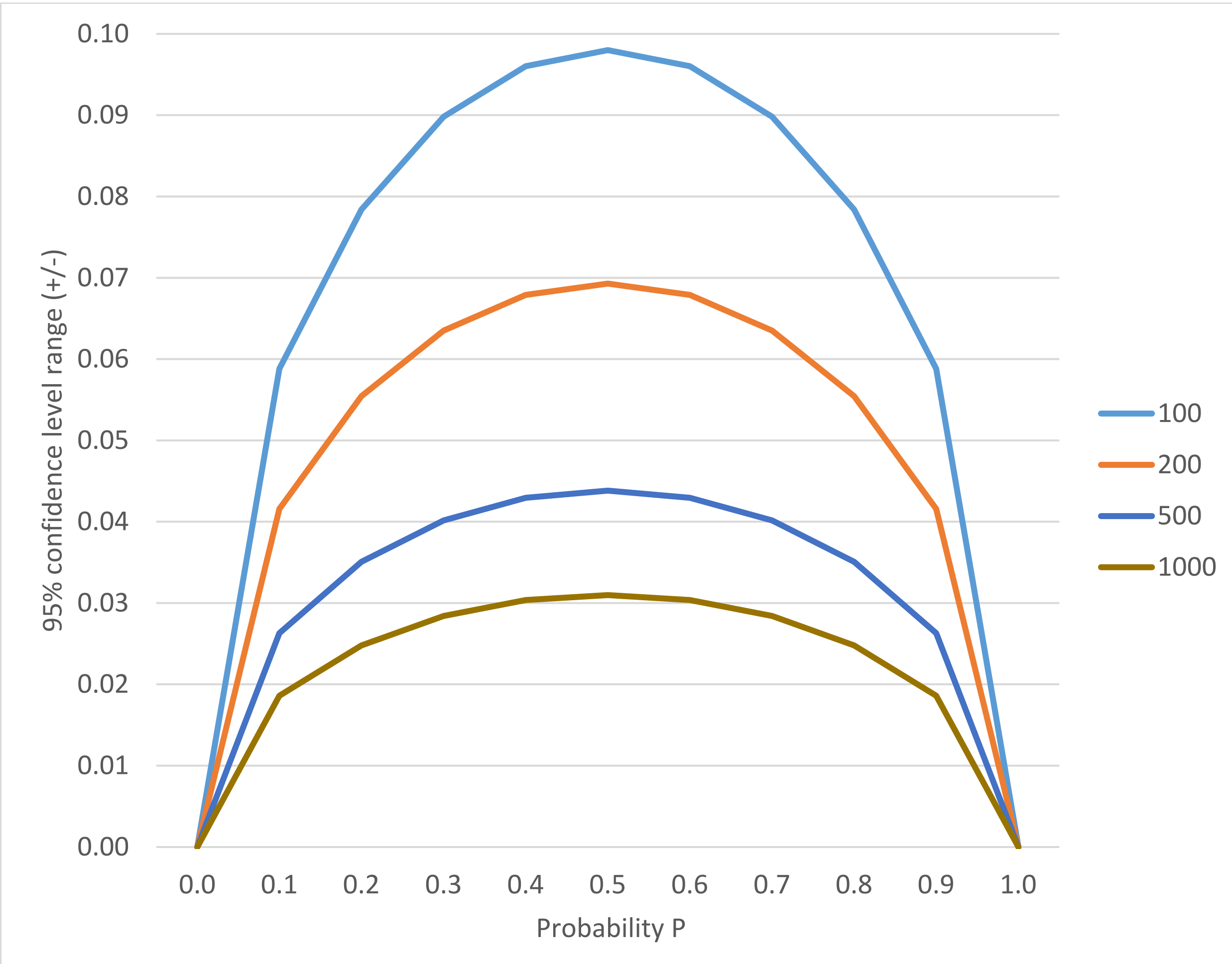

Figure 327. *95% Confidence Interval (+/-) for Average Failure as a function of probability P.*

At P=0, there are no failures. At P=1.0, there always are failures. In these cases, there is no probabilistic error. The probabilistic error is greatest at P=0.5. As shown in Figure 17, the 95% confidence interval for P=1 is approximately +/- 0.1, i.e. the 95 percent confidence range is from 0.4 to 0.6.

Running 100 iterations is sufficient for model testing, but 500-1000 iterations are recommended for final analyses.

The *Impacts Model* dialog window is shown in Figure 18.

Figure 338. *Impacts Model Dialog Window***.**

There are eight inputs. These include the three browsed selections of 1) the preprocessed Statewide geodatabase that has been augmented to include the storm probabilities for each subarea, 2) the turn penalty input files from the essential data set (Table 1), and 3) the output folder name that matches the Subarea model outputs. The other five entries require typing:

- For "Enter query to select road links" select all model links by entering **Full15=1**
- For "Enter the structure vulnerability field name" enter the header name in (1) containing the structural storm probabilities from the subarea of interest at a given storm level (e.g., UW_struct_Q50max)

- For "Enter the segment vulnerability field name" enter the header name in (1) containing the storm probabilities for each road in the subarea of interest at a given storm level (e.g., UW_road_Q50max)
- For "Enter the number of Monte Carlo iterations" enter an integer (first test with a small number, i.e. less than ten; the computation time is approximately proportional to the number of iterations)
- Label for the output prefix which must match the Subarea model prefix.

Impacts Model – Outputs

Figure 19 is an overview of how the Impacts Model generates different types of model metrics:

- Roadway segments fail.
- These roadway segment fails cause some areas to be cut off completely, and cause traffic diversion.
- The traffic diversion increases travel times.

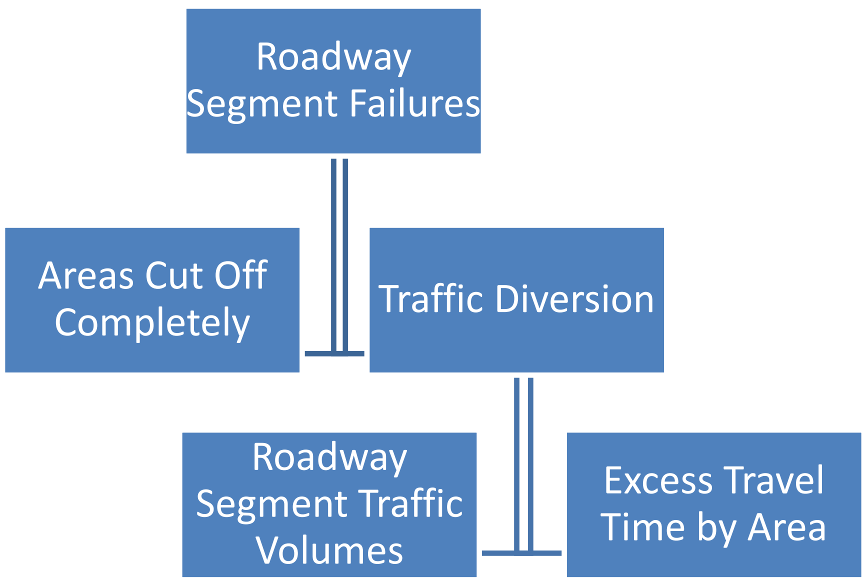

Figure 19: *Impacts Model Flow and Metrics*

After entering inputs, the *Run* button executes the model. After model completion, a *Done* button appears. Clicking either *Close* or *Done* buttons closes the window. Outputs are given in Table 4.

Table 5. Impacts Model Outputs

Description	File Names (with input prefix added to front)
Node output data	NodeOut.bin and NodeOut.dcb
Link output data	LinkOut.bin and LinkOut.dcb

<u>Link output data</u>: The file has one record for each Subarea roadway segment. The fields include:

- ID1: roadway link layer ID
- Vulnerability inputs copied from the roadway layer: VStruct and VSeg

- Failures for the last iteration (not important): FailStruct, FailSeg and NetFail
- Average failures: AvFailStruct, AvFailSeg and AvFail
- Base volume from the Subarea Model: AB_Base_Vol, BA_Base_Vol and Tot_Base_Vol
- Average volumes across the iterations: AB_AvVol, BA_AvVol and Tot_Av_Vol

Node output data: The file has one record for each Subarea intersection. The fields include:

- ID1: roadway node layer ID
- Base average travel time for trips from node: BaseTime
- Average travel time for trips from node in this scenario: AvTime
- AvTime – BaseTime: TimeDiff
- Number of daily trips from this node: Trips
- Trips * TimeDiff: TotTime

Figures 20-23 illustrate some of the many ways that *Impacts Model* output can be portrayed on maps.

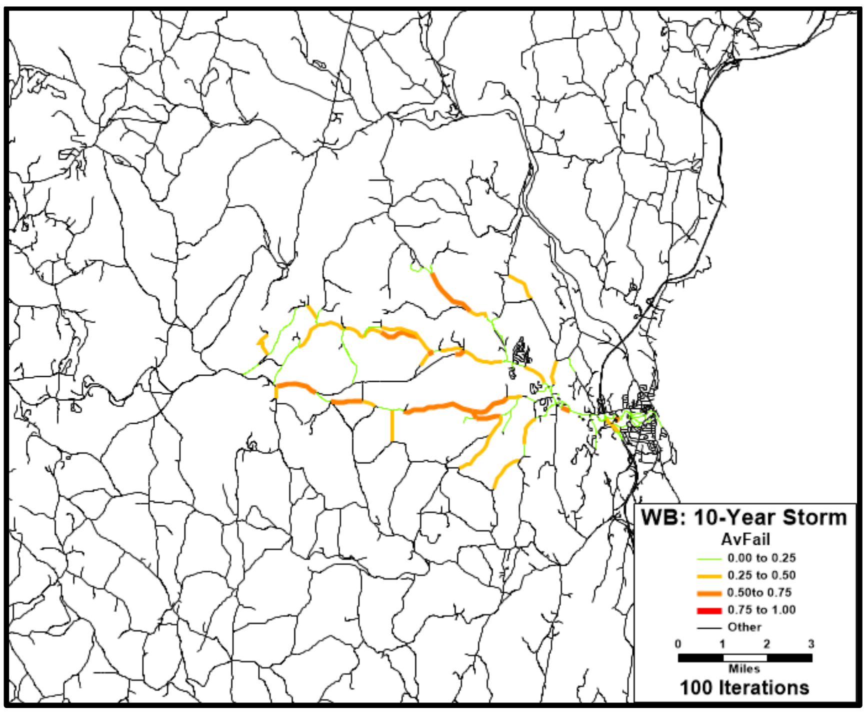

Figure 340. *Road Segment Failures Example*

The *Road Segment Failures* example was created by:

- Opening the road layer
- Joining the road layer to ID to the LinkOut ID1
- Select *TransCAD's Color Theme MapWizard*
- Select field AvFail
- Define classes and styles and apply

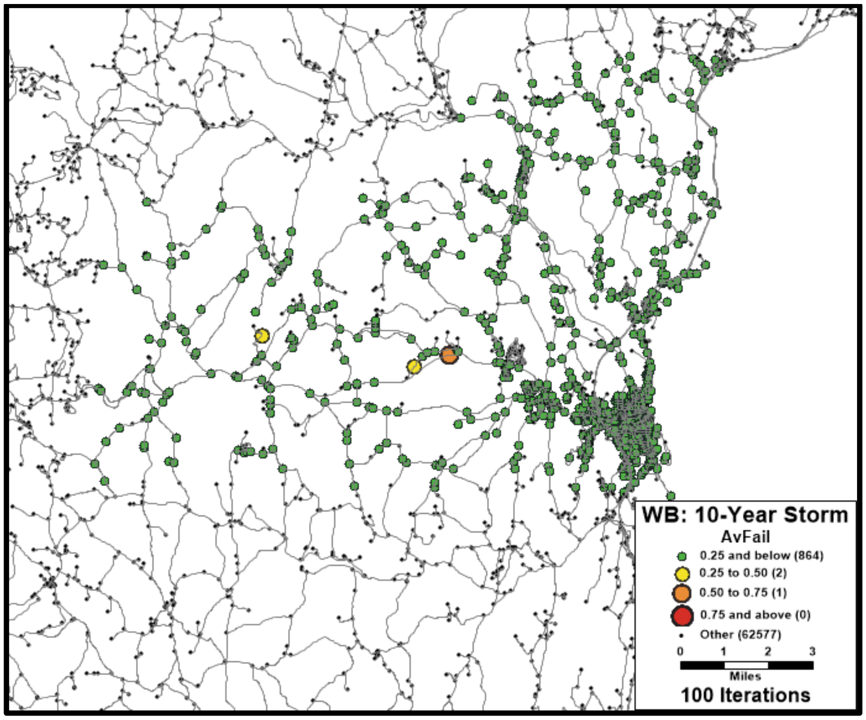

Figure 351. *Areas Cut Off Example*

The *Areas Cut Off* example was created by:

- Opening the road layer
- Showing the node layer
- Joining the node layer to ID to the NodeOut ID1
- Select *TransCAD's Color Theme MapWizard*
- Select field AvFail
- Define classes and styles and apply

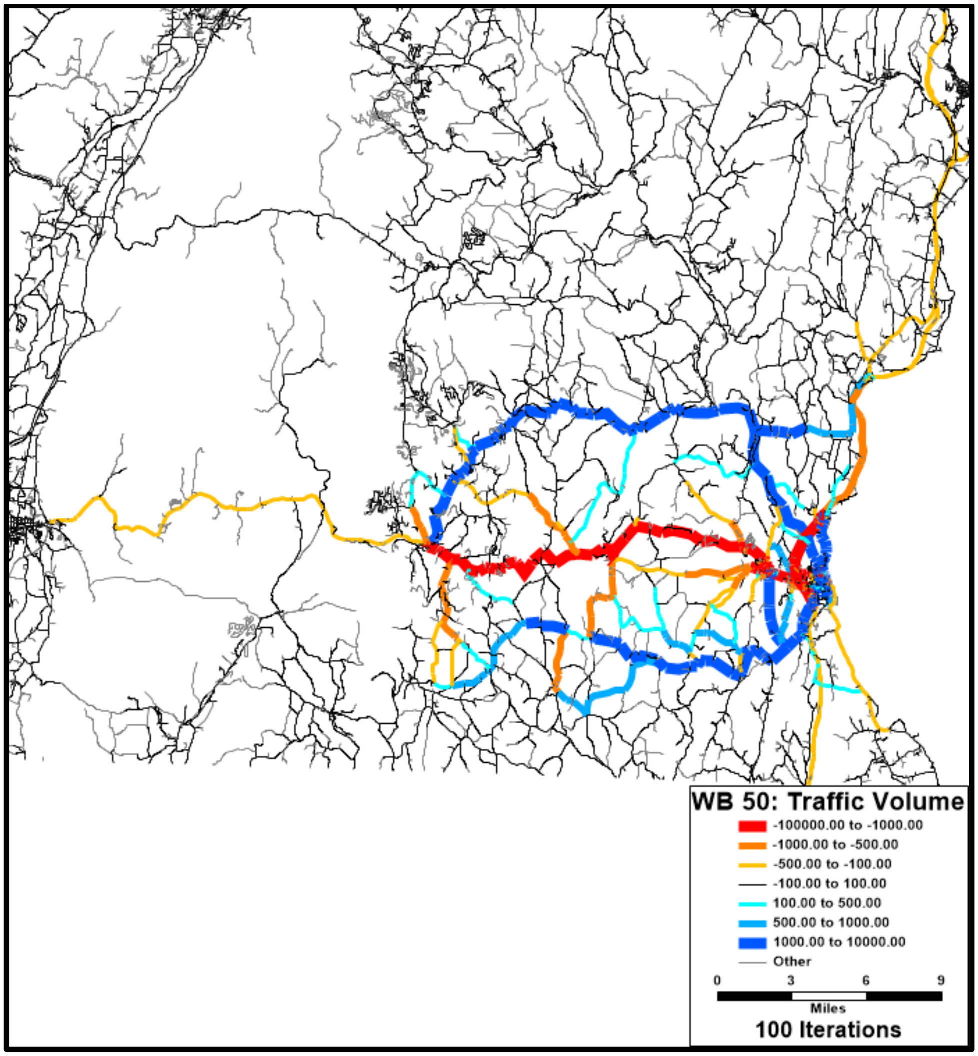

Figure 362. ***Traffic Diversion Example***

The *Traffic Diversion* example was created by:

- Opening the road layer
- Joining the road layer to ID to the LinkOut ID1
- Select *TransCAD's Color Theme MapWizard*
- Select field *Tot_Vol_Diff*
- Define classes and styles and apply

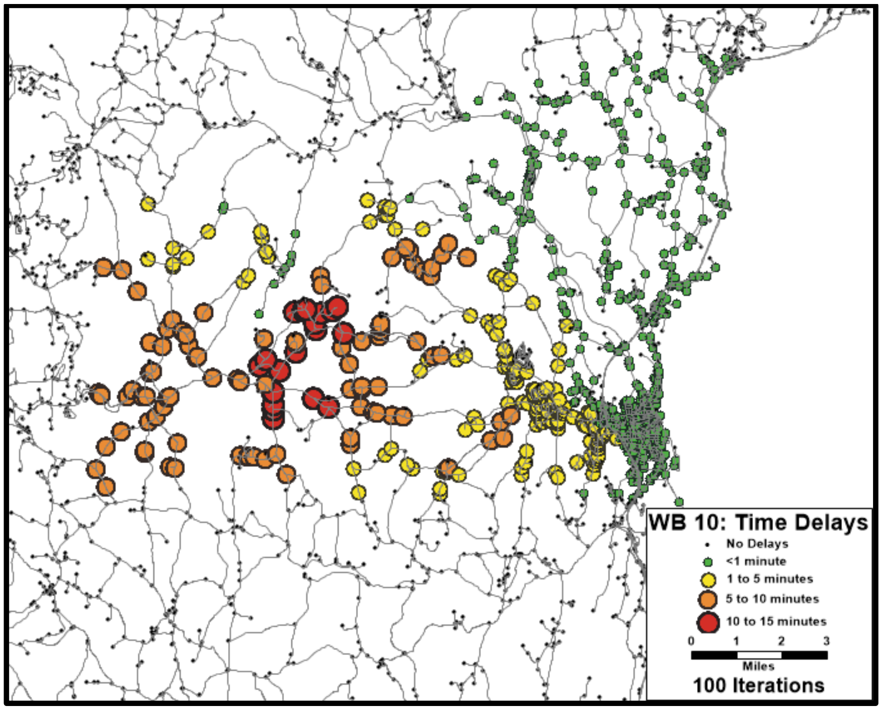

Figure 373. *Excess Time Example*

The *Excess Time* example was created by:

- Opening the road layer
- Showing the node layer
- Joining the node layer to ID to the NodeOut ID1
- Select *TransCAD's Color Theme MapWizard*
- Select field *TimeDiff*
- Define classes and styles and apply

Note: Alternatively, *TotTime* could be mapped to show excess time weighted by the number of trips.

Appendix H1: TransCAD Scripts

The Vermont Resiliency Travel Model (VRTC) is coded within a single TransCAD GISDK script: VermontResiliencyModelv#.rsc where # is the version number.

The first part of the script is the Graphical User Interface (GUI). This includes

- Macro "ModelMenu" which adds a menu within TransCAD
- Menu "VermontModels"
- Five dialog boxes called from the menu
  - "About"
  - "Statewide"
  - "Subrea"
  - ""Criticality"
  - "Impacts"

There also is a "Close" option.

The GUI scripts are all standard TransCAD coding and mostly handle the input-output described in the model documentation.

The following sections provide an overview of the scripts that perform the calculations for the four model applications.

Statewide Model

The "Run" button in the *Statewide Model* application executes this code:

```
HideItem("Done")
RunMacro("Clear Workspace")
RunMacro("Build Network", dbd_name, qLinks, tp_name, out_path, out_label, 0)
index = "TRID"
RunMacro("Assignment by Type", dbd_name, qLinks, tt_name, index, out_path, out_label, 0)
ShowItem("Done")
```

In the script, the HideItem and ShowItem statements are self-explanatory. The "Clear Workspace" Macro initializes conditions by closing any maps and dataviews that the user may have opened.

The other two macros are:

- "Build Network": passes input data and outputs a TransCAD *.net file
- "Assignment by Type" passes input data and returns a loaded flow *.bin file

The "0" parameter passed to these macros indicates that the macros are run once rather than multiple times. The "TRID" index refers to the Transportation Analysis Zone (TAZ) centroids in the node layer.

Subarea Model

The "Run" button in the *Subarea Model* application executes this code:

```
HideItem("Done")
RunMacro("Clear Workspace")
RunMacro("Expand Trip Table", dbd_name, tt_name, TAZ_name, qTAZ, Shares_name, out_path,
    out_label)
RunMacro("Build Network", dbd_name, qLinks, tp_name, out_path, out_label, 0)
tt_name = out_path + "\\" + out_label + "_expTT.mtx"
index = "Node"
RunMacro("Assignment by Type", dbd_name, qLinks, tt_name, index, out_path, out_label, 0)
RunMacro("Travel Time Matrix", dbd_name, out_path, out_label, 0)
RunMacro("Node Travel Times", out_path, out_label)
ShowItem("Done")
```

Most of this code is identical to the Statewide Model code. Differences include:

- Macro "Expand Trip Table" takes TAZ-to-TAZ input trip table and expands the subarea TAZs to node-to-node based on the TAZ_Node_Share file as described in Appendix H3
- The output trip table is assigned to tt_name in the script and the matrix index is "Node"
- Macro "Travel Time Matrix" calculates Node-to-Node travel times, with "0" again used as a flag that the macro is being run a single time.
- Macro "Node Travel Times" calculates average travel times for all travel from a Node (zone). This creates baseline conditions for the *Impacts Model* calculations.

Criticality Model

The *Criticality Model* takes as inputs several *Subarea Model* outputs including:

- Expanded trip table
- Base assigned flows
- Baseline Node-to-Node travel times
- Baseline average travel times from subarea Nodes

The "Run" button in the *Criticality Model application* executes this code:

```
HideItem("Done")
RunMacro("Clear Workspace")
RunMacro("Criticality", dbd_name, qLinks, tp_name, TAZ_name, qTAZ, out_path, out_label)
ShowItem("Done")
```

The *Criticality Model* is considerably more complicated than the *Statewide* or *Subarea* models, and a separate "Criticality" macro has been developed rather than reusing the other macros. The application iterates through every roadway segment in the subarea. As this can involve several thousand links, this application can take many hours of computer time.

In each iteration, a single subarea model roadway segment is marked as failed. A network without that link is created, the subarea trip table is assigned, and a subarea travel time matrix is calculated. Three metrics are calculated for each link: the number of trips that cannot be completed, excess travel time, and an index combining the other two methrics.

Impacts Model

The *Impacts Model* takes as inputs several *Subarea Model* outputs including:

- Expanded trip table
- Base assigned flows
- Baseline Node-to-Node travel times
- Baseline average travel times from subarea Nodes

The "Run" button in the *Impacts Model* executes this code:

```
HideItem("Done")
RunMacro("Clear Workspace")
RunMacro("Resiliency", dbd_name, qLinks, tp_name, VStruct, VSeg, nMC, out_path, out_label)
ShowItem("Done")
```

The Impacts Model is coded in the "Resiliency" macro. This macro relies on vulnerability inputs VSTruct and VSeg. These vulnerability estimates are used to calculate a set of roadway segment failures in each Monte Carlo iteration. An Iteration Network is created that excludes the failed roadway segments. The Subarea Trip Table is assigned to the Iteration Network. The "Link Statistics" section sums the number of times that roadway links fail, calculates average traffic flows, and computes the difference between these average traffic flows and the base traffic flows with the intact network.

The "Node Statistics" and "Iteration Travel Times" components are the most complicated part of the Resiliency script. Within each *Impacts Model* iteration, an initial attempt is made to calculate a full travel time matrix from every subarea node/TAZ to every other subarea node/TAZ. However, in many cases some of the nodes may be unreachable in the network due to roadway segment failures. In these cases, TransCAD generates an error and produces a selection set of nodes called "Nodes Not Found". The Resiliency script eliminates these nodes and calculates a reduced travel time matrix without these nodes. The script totals failures across iterations for each "Node Not Found", and calculates average travel times to all destinations for the nodes that are on the network.

Appendix H2: Network Preparation

Network Layers – Standard Nomenclature

The TransRoad_RDS Network is maintained by VTrans as an ESRI geodatabase. The TransRoad_RDS data fields have been maintained in the TransCAD network. Fields of particular interest include:

- Unique identifier FAID_S or FAID_N (redundant columns most likely due to previous join event)
- Route Name - RTNAME (e.g. VT-113, TH-200)
- Agency of Transportation Function Class - AOTCLASS
    - 1 -4 Class 1-4 town highway, undivided roads (see 11-19, 21-29)
    - 5 State forest highway
    - 6 US Forest Service (USFS) Forest Road
    - 7 Legal trail
    - 8 Private road, but not for display on local maps. Some municipalities may prefer not to show certain private roads on their maps, but the roads may need to be maintained in the data for emergency response or other purposes.
    - 9 Private road, for display on local maps
    - 10 Not used; use AOTCLASS = 1 for undivided Class 1 Town Highway
    - 11 North bound (for divided centerlines)
    - 12 South bound
    - 13 East bound
    - 14 West bound
    - 15 Entrance/Exit ramp, Approach, Jughandle
    - 16 Emergency U-turn
    - 17 Rest Area
    - 18 Currently not used
    - 19 Other Class 1 Town Highway (weigh stations, maintenance areas, etc.)
    - 20 Not used; use AOTCLASS = 2 for undivided Class 2 Town Highway
    - 21-29 Class 2 Town Highway; same road types as for 11-19
    - 30 Vermont State Highway, undivided centerline (most Vermont Highways)
    - 31-39 Vermont State Highway; same road types as for 11 -19
    - US Highway, undivided centerline (most US Highways)
    - 41-49 US Highway; same road types as for 11 -19
    - 50 Interstate, undivided centerline (not currently used)
    - 51-59 Interstate, same road types as for 11 -1
    - 81-83 Proposed Class 1-3 Town Highway
    - 84 Proposed State Highway
    - 85 Proposed US Highway
    - 86 Proposed Interstate
    - 87 Proposed ramp: Interstate
    - 88 Proposed ramp: Non-interstate
    - 89 Proposed private road
    - 91 (code no longer used)
    - 92 Military road, no public access
    - 93 Public road from VTrans map, for which the class could not be determined.

- 95 Road class under special review, usually temporary
-

- Rural/ FUNCL Urban Functional Class
  - 0 Not part of Functional Classification System
  - 1 Rural Principal Arterial - Interstate
  - 2 Rural Principal Arterial
  - 4 Rural Principal Arterial - Other (not other freeway); not a standard federal code
  - 6 Rural Minor Arterial
  - 7 Rural Major Collector
  - 8 Rural Minor Collector
  - 9 Rural Local
  - 11 Urban Principal Arterial - Interstate
  - 12 Urban Principal Arterial - Other Freeway
  - 14 Urban Principal Arterial - Other
  - 16 Urban Minor Arterial
  - 17 Urban Collector
  - 19 Urban Local
- SURFACE
  - 1 Hard surface (pavement)
  - 2 Gravel/hard pack
  - 3 Soil or graded and drained earth
  - 5 Unimproved/Primitive
  - 6 Impassable or untraveled
  - 9 Unknown surface

More information about the TransRoad_RDS database can be found at http://maps.vcgi.org/gisdata/metadata/TransRoad_RDS.htm

Network Layers – New Merged Product

Extensive GIS work was done to merge the TransRoad_RDS with the Vermont Travel Model road layer, and to modify the merge layer for use in this project. The first step was to integrate TransRoad_RDS (Figure 24) with the Vermont Travel Model files (Figure 25).

Figure 384. *TransRoad_RDS Network in Bennington Area.*

TransRoad_RDS includes all roadway segments, including some that have not been constructed. In contrast, the Vermont Travel Model are far sparser (Figure 25).

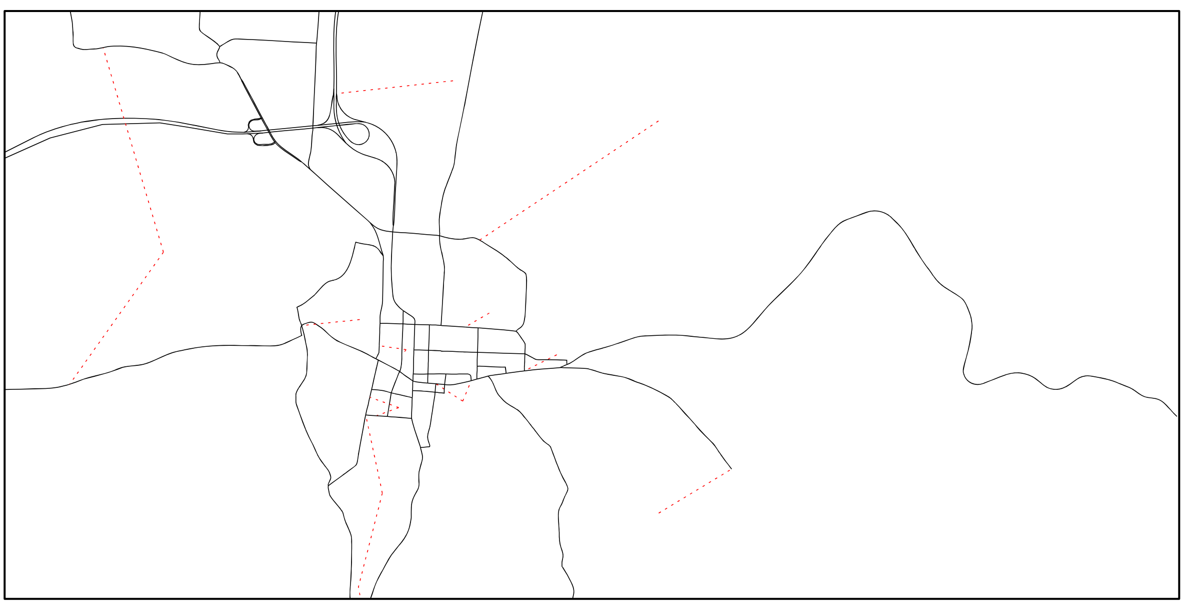

Figure 395. *Vermont Travel Model Network in Bennington Area.*

The dashed red lines are artificial traffic loading links called "centroid connectors."

Moving the information from the Vermont Travel Model to the TransRoad_RDS layer involved the steps listed below with the merged network product illustrated in Figure 26.

- Tagging TransRoad_RDS segments with Vermont Travel Demand IDs
- Manually cleaning up areas where automatic tagging did not work properly
- Extracting Vermont Travel Model centroid connectors and merging with TransRoad_RDS
- Manually cleaning up areas where centroid connectors did not link properly
- Transferring model parameters to new layer (particularly speed)
- TransCAD programming to resolve one-way directionality

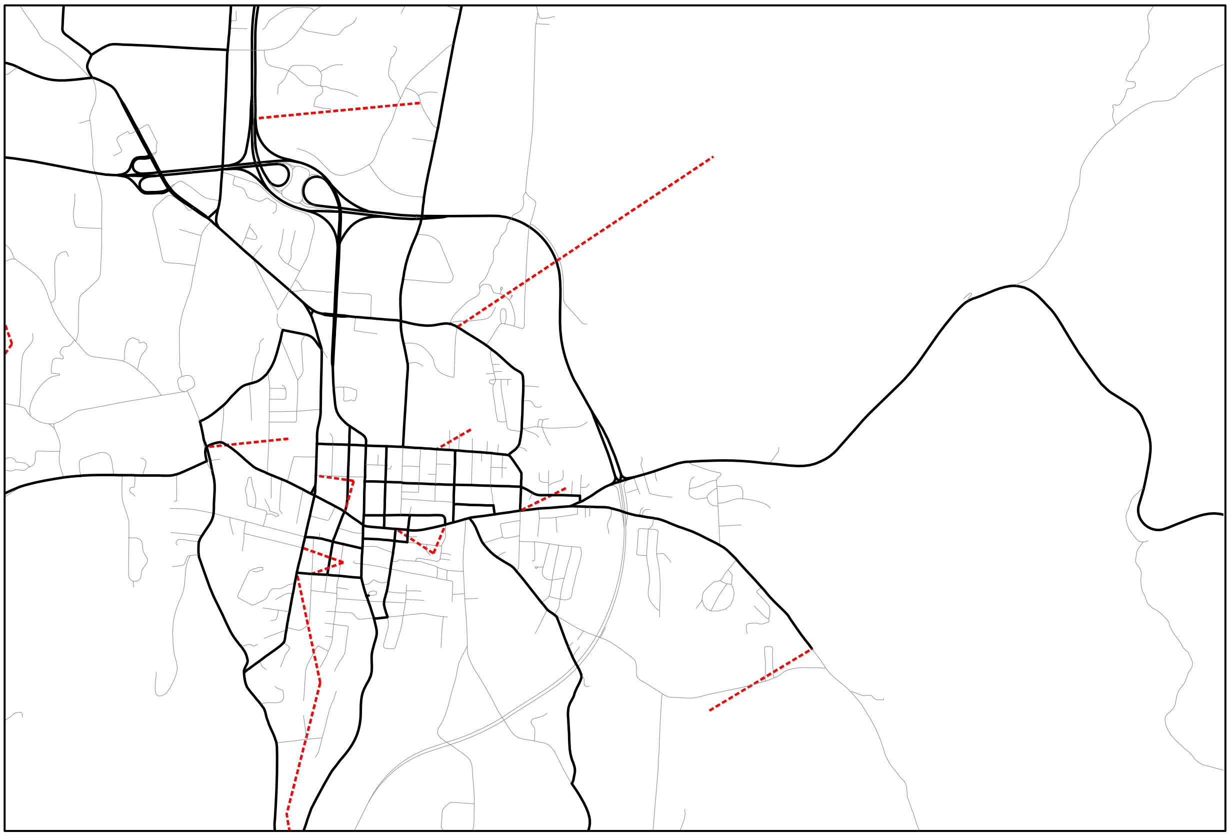

Figure 406. *Merged TransRoad_RDS + Vermont Travel Model Network in Bennington Area.*

Many very short TransRoad_RDS roadway segments did not tag correctly and required manual correction. Also, the TransRoad_RDS layer does not completely represent one-way road segments including the separate directions of divided highways. These needed further coding using TransCAD (Figures 27 and 28).

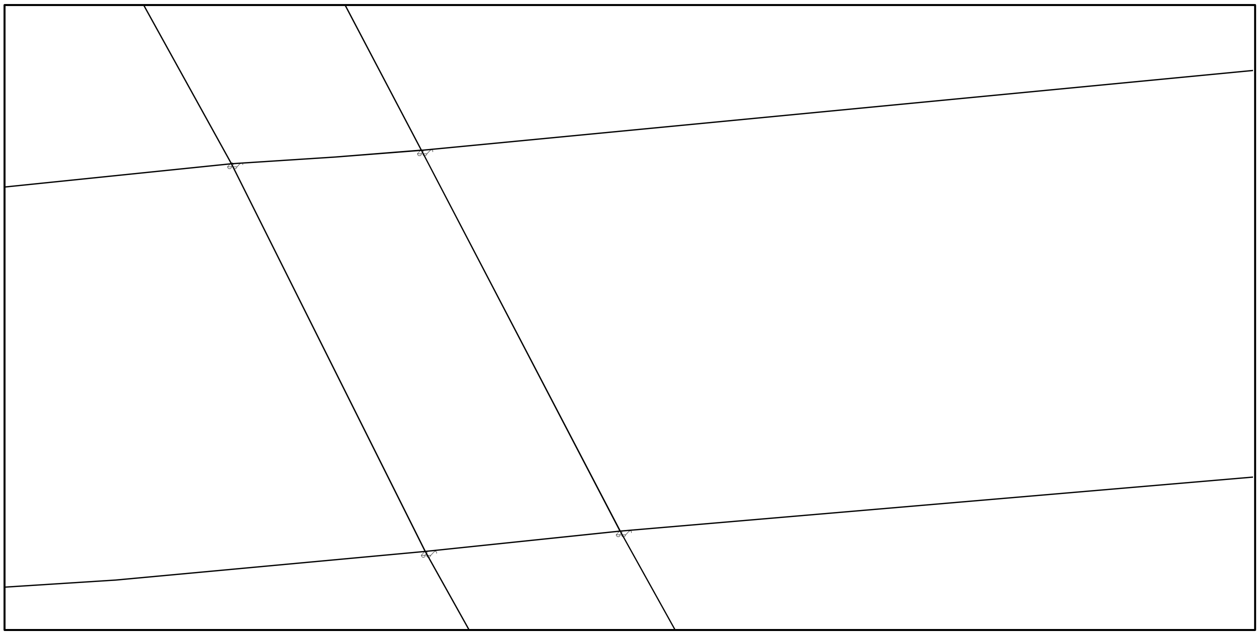

Figure 417 *Lack of Grade Separations in TransRoad_RDS (Before).*

The TransRoad_RDS layer also does not include grade separations, e.g. underpasses and overpasses of other roadways with freeways. These grade separations were added to the TransCAD network. To maintain a one-to-one relationship with the TransRoad_RDS layers, the end points for the road segments were shifted slightly to include directionality (Figures A2-5).

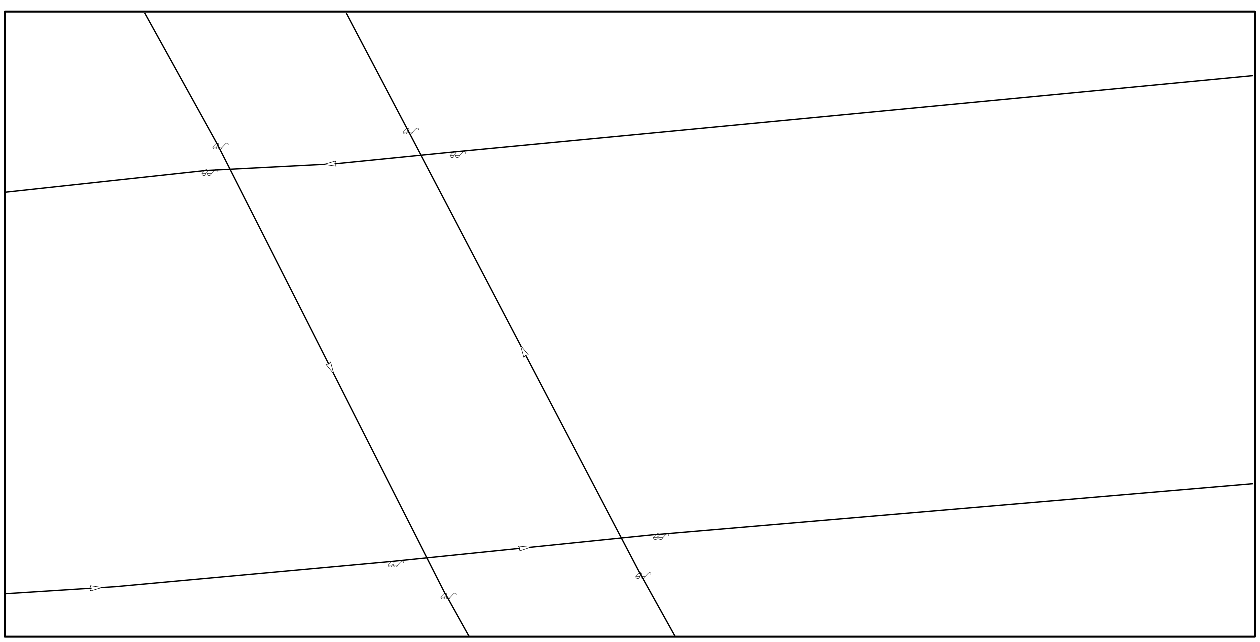

Figure 428. *Grade Separations in TransCAD following road segment shifts and inclusion of directionality***.**

Additional fields added to the TransCAD data within this project:

- *Count, Year, Count Type*, and *Count ID* for segments where traffic counts are available
- *CC* – to denote Centroid Connectors – to match the statewide model
- *SWMod*, *SWID* and *SW15* to designate roadway segments also in original Vermont Travel Model
- *Full15* to designate model links that are included in the subarea applications (e.g., previously excluded segments now include Vermont Class 4 roads and private roads which the user may want to activate as roadway segments in a particular subarea study)
- *Speed* taken from Vermont Travel Model or otherwise conservatively set from TransRoad_RDS attribute – these can be changed in subarea studies
    - Rural paved 30 m.p.h. (same speed as many minor roads in Vermont Travel Model)
    - Rural unpaged 25 m.p.h.
    - Urban paved 25 m.p.h.
    - Urban unpaved 20 m.p.h.
- *Time* calculated from *Speed* and *Length*
- *Fail* field used by model to store intermediate values
- Subarea-specific/scenario-specific vulnerability probability values, with separate values for roadway segments and for structures (bridges and culverts)

Appendix H3: Transportation Analysis Zone (TAZ) to Node Correspondence

The TAZNodesShares.bin and TAZNodeShares.dcb files used in the subarea applications store the fraction of E911 data points at each roadway intersection point in every TAZ. In the subarea, these intersections become new TAZs.

The essential data sets (Table 1) are based on the 2015 roadway network and E911 data files. It is not expected that these files will be updated frequently. However, the user may want to copy the files and adjust some values within a specific subarea based on local knowledge, e.g. increasing the fractions for intersections adjacent to large traffic generators. In this case, the upward adjustments should be balanced by downward adjustments so that the total fraction is conserved (i.e., always balance the sum to 1.0 within each TAZ).

The following steps were taken to calculate the fractions:

1) Open roadway *.dbd file in TransCAD
2) Select roads in network (e.g. Full15=1)
3) Show intersection (node) layer
4) Select nodes that are connected to selected roads (e.g., select by Location features that are connected)
5) Export selected nodes to new *.dbd (e.g. ActiveNodes.dbd) and add to map
6) Add "TAZ" field to ActiveNodes.dbd if it doesn't exist
7) Add TAZ *.dbd layer to map
8) Reactivate active nodes layer, open dataview and Fill TAZ field with [TAZ ID]
9) Select untagged nodes and manually fill in TAZ ID (many along boundary and a few in gores)
10) Add E911 layer to map
11) Add TAZ field to E911 layer and tag E911 points to TAZ
12) Close dataview and map
13) Edit GISDK script E911 nodes.rsc to correct paths and filenames
14) Run script E911 nodes.rsc to tag E911 points to TAZ-Node (runs for several hours)
15) Open E911 table in TransCAD and save to *.csv using option to save field headers
16) Open *.csv in Excel and save as *.xls (for example E911.xls)
17) See SampleE911.xlsx for examples of Excel pivot tables and formulae
18) Insert pivot table that counts points in each TAZ (e.g. count of ID)
19) Copy pivot table and paste special values, leaving off Grand Total line
20) Re-label headers "TAZ" and "Count"
21) Give this table a name in Name Manager (e.g. Count)
22) Make 2nd pivot table that counts points by Node and that also shows TAZ
23) Use PivotTable Options Display: Classic PivotTable layout to put TAZ and Node in columns
24) Again, copy and paste special without Grand Total
25) Use formulas from example spreadsheet to calculate shares (columns I,J,K)
26) Copy calculations section and paste special values
27) Data: Sort result by TAZ and Node_ID to flush out lines with null totals
28) Copy and paste sorted results (without null lines) into new workbook
29) Save Workbook
30) Close Excel
31) Open resultant workbook in TransCAD and save (e.g. TAZ_Node_Share.bin)

Final Criticality Scoring

Criticality Combined Scoring Method

SCORE	Network Criticality Index		Critical Closeness Accessibility		Locally Important	Combined Criticality
10=	High or Medium	AND	High	AND	y	HIGH (RED)
9=	High or Medium	AND	Medium	AND	y	
8=	High or Medium	AND	High or Medium	AND	n	
7=	High or Medium	AND	Low	AND	y	
6=	Low	AND	High	AND	y	
5=	Low	AND	Medium	AND	y	
4=	High or Medium	AND	Low	AND	n	MEDIUM (YELLOW)
3=	Low	AND	High or Medium	AND	n	
2=	Low	AND	Low	AND	y	
1=	Low	AND	Low	AND	n	LOW (GREEN)

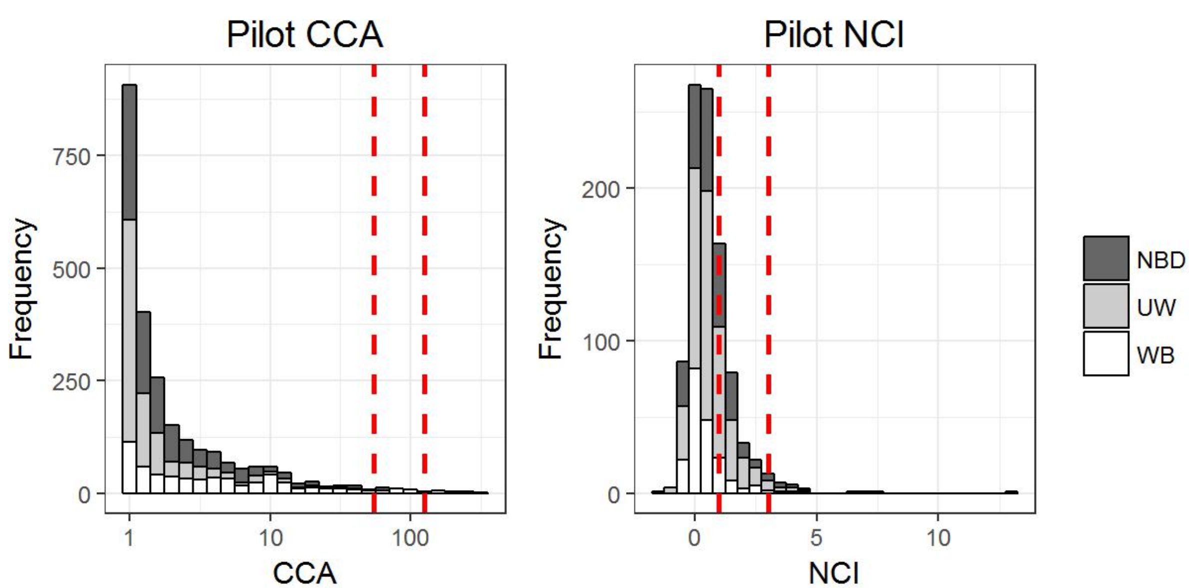

Figure 29: *Distribution of CCA (left) and NCI (right) with low, medium, and high scoring breaks indicated by dashed red lines. Scoring breaks for CCA are Low < 55< Medium < 126< High, and for NCI are Low < 1< Medium < 3 < High. Shaded bars indicate pilot watersheds.*

APPENDIX J

MITIGATION STRATEGIES

Last updated on: November 27, 2017
Last updated by: Roy

(SHORT LIST OF ACTIVE PROJECTS)

MITIGATION OPTIONS

				SORTING OPTIONS				BALLPARK UNIT COST		APPLICABILITY±					
ID	STRATEGY	PROJECT	GROUP§	RIVER IMPACT*	NETWORK IMPACT**	REPAIR TERM‡	PROJECT SCALE***	Cost ($USD)†	Unit	Inundation	Erosion	Deposition	Road	Bridge	Culvert
M1	Fortify	**Bed armoring**	S	H	L	L	RS	100	CY	○	●	●	●	●	●
M2	Fortify	**Engineered structures to resist deep scour (piles, piers, footings, abutments)**	S	H	M	L	P	20,000	PER	○	●	●	○	●	●
M3	Fortify	**Armored riffles**	S	H	L	L	RS	100	CY	○	●	●	●	◑	◑
M4	Fortify	**Placed riprap wall**	S	H	M	L	RS	100	CY	◑	●	●	●	●	●
M5	Address resiliency	**Install larger structures with bankfull width sizing**	F	H	M	L	P	100	LF	●	◑	◑	○	●	●
M6	Fortify	**Weirs/Vanes**	S	M	L	L	RS	100	CY	○	●	●	●	◑	◑
M7	Fortify	**Armor riverbank slope (with joint plantings)**	S	M	M	L	RS	70	CY	○	●	●	●	◑	◑
M8	Fortify	**Install rock toe**	S	M	M	S	RS	100	CY	○	●	●	●	◑	◑
M9	Address resiliency	**Lower road elevation, armor embankment slopes, protect travel surface, plan for closures**	F	M	H	L	RS	230	LF	●	◑	◑	●	○	○
M10	Address resiliency	**Increase local armoring size to resist increased shear**	S	M	L	S	RS	100	CY	◑	◑	○	●	●	●
M11	Fortify	**Install surficial scour protection**	S	M	M	S	P	100	CY	●	◑	◑	○	●	●
M12	Fortify	**Armor road embankment**	S	M	M	L	RS	70	CY	◑	●	●	●	◑	◑
M13	Fortify	**Fill and rebuild road**	S	M	M	L	RS	15	SF	●	○	○	●	○	○
M14	Address resiliency	**Lower structure approach, plan for closures**	F	M	H	L	P	15	CY	●	◑	◑	○	●	●
M15	Address resiliency	**Adjust road alignment**	FP	M	M	L	RS	350	LF	○	●	●	●	○	○
M16	Address resiliency	**Reduce space behind guard rail**	F	M	M	L	RS	100	CY	○	◑	◑	●	○	○
M17	Restoration	**Create or reconnect flood bench**	F	M	L	L	RS	70	CY	◑	●	●	●	●	●
M18	Restoration	**Create or reconnect flood chute**	F	M	L	L	RS	70	CY	●	●	●	●	●	●
M19	Restoration	**Create or reconnect floodplain**	F	M	M	L	RR	70	CY	●	●	●	●	●	●
M20	Fortify	**Install new roadbase**	S	L	L	L	RS	95	LF	●	○	○	●	○	○
M21	Fortify	**Concrete top for scour resistance**	S	L	M	S	RS	700	CY	●	○	○	●	○	○
M22	Fortify	**Pave gravel road**	S	L	M	L	RS	15	CY	●	○	○	●	○	○
M23	Fortify	**Road reclamation**	S	L	M	S	RS	15	CY	●	○	○	●	○	○
M24	Fortify	**Install bank vegetation**	V	L	L	L	RR	1	SF	◑	◑	◑	◑	○	○
M25	Fortify	**Revegetate embankment**	V	L	L	L	RS	1	SF	○	◑	◑	●	○	○
M26	Restoration	**Riparian buffer plantings**	V	L	L	L	RR	1	SF	◑	◑	◑	◑	○	○
M27	Relocate	**Eliminate road / bridge**	FP	L	H	L	RS	0	N/A	●	◑	◑	●	●	●
M28	Relocate	**Relocate road out of floodplain or river corridor**	FP	L	H	L	RS	15	CY	●	◑	◑	●	●	●
M29	Relocate	**Relocate road out of valley bottom**	FP	L	H	L	RR	15	CY	●	◑	◑	●	●	●
M30	Restoration	**Buyout properties served by road**	FP	L	L	L	RS	3,000	AC	●	●	●	●	●	●
M31	Change land use	**River corridor conservation**	FP	L	L	L	RR	3,000	AC	●	●	●	●	●	●
M32	N/A	**No Action**	N/A	L	N/A	L	N/A	N/A	N/A						

NOTES

§ Display groups for App (listed in preferred order for erosion): River and Road Stabilization (S); Conveyance of Flood Flow (F); Floodplain Protection / Relocate Road (FP); Improve Vegetation (V). Preferred list order for inundation and deposition is F, S, FP, V.

* L = No/Low impacts, return to nature; M = Moderate intensity and impacts; H = High intensity and impacts. Initial order should be low to high impacts within each display group category.

** Network impacts = Impacts to the transportation infrastructure. L = Low impact, none to small footprint change; M = Moderate impact, some changes to network; H = Large changes to network such as relocations and ROW issues.

‡ L = Long-term, change setting, >5-year; S = Repair, keep road open

*** P = Point; RS = Road segment (<0.5 mi); RR = River reach (0.5-1 mi); W = Watershed

† Costs are rounded

± ○ = Not applicable; ◑ = Partially applicable; ● = Fully applicable

APPENDIX K

PLANNING STRATEGIES

Improved policy and planning initiatives are essential parts of promoting flood resiliency and are not explicitly part of the TRPT. State agencies, regional organizations, and municipalities are all expected to take an active role in planning for future flood protection to reduce the risk during future floods and to improve the statewide response to flood damages.

There are many planning actions that municipalities can take to promote flood resiliency. Some of these can address impacts at specific sites, and others can foster adaptation to and quick recovery from flooding events, thereby improving the resiliency of the community. The following are some approaches that involve broader planning approaches and will involve municipalities, regional planning commissions, and other partners to implement.

STRATEGIES TO REDUCE IMPACTS OR DAMAGE FROM FLOODING AT SITES

The following strategies are for municipalities to consider as they adopt policies and develop priorities for increasing the resiliency of their infrastructure.

STRATEGY	APPROACH	PROJECT(S)
Protect against erosion and deposition hazards	Increase the size of bridges and culverts	Ensure space for sediment and large wood during design flood; with co-benefits of improving fish passage. https://environment.transportation.org/environmental_issues/construct_maint_prac/compendium/manual/3_5.aspx
Improve drainage	Upgrade stormwater infrastructure	There are numerous ways that municipalities can engage in long-term planning to improve stormwater infrastructure and reduce damages from flooding. The link below provides a comprehensive guide on possible approaches. https://www.epa.gov/sites/production/files/2016-10/documents/draftlongtermstormwaterguide_508.pdf
Restoration	Wetland restoration	Improve wetland hydrology so that they are able to contribute environmental services of floodwater absorption, thereby mitigating flooding. See link below for information and resources: https://dec.vermont.gov/watershed/wetlands/protect/restore

STRATEGIES TO REDUCE CONSEQUENCES OF FLOODING EVENTS TO COMMUNITIES

STRATEGY	APPROACH	PROJECT
Detour	Develop or improve temporary detours	Temporary detour routes during road closures can be used to maintain road network connectivity. Depending on the roadway network, the detour may require simple temporary signage or potentially a new temporary structure on an alternate route to provide network connectivity until the damaged infrastructure can be repaired.
Detour	Develop or improve alternative permanent routes	Develop alternate routes or emergency detours. Local temporary detours can be used to maintain the road network connectivity around highly vulnerable roadway segments. This may require upgrades of local roads or new bridge or culverts to connect local roads to create a detour route.
Detour	Develop or improve alternative permanent routes	Develop alternate bicycle and pedestrian routes. In some cases, providing a vehicular detour is not feasible, but a bicycle and pedestrian connection is possible. This would be particularly of value in a more densely settled area where providing the connectivity to make short trips would reduce the impact of road closures.
Preparedness	Inform/communicate	Develop emergency communication plan, continuity of operations plan, or traffic management plan to be implemented during flood emergencies. These may require cross-jurisdictional agreements with neighboring municipalities or regional planning commissions.
Preparedness	ITS/roadway communications/ monitoring	Communities can be more aware of potential flooding and therefore more prepared to take actions to reduce the consequences of flooding by having timely information on flooding. Techniques such as mounting video cameras on bridges to monitor flood levels, water level alerts on intelligent roadway signs, or other types of flood early warning systems can be included in their local hazard mitigation planning.
Change land use	Naturalize the floodplain and river corridor	Buyouts and demolitions. Communities should inventory floodprone properties and prioritize them based on their public benefit as it relates to transportation infrastructure and landowner interest. This will make them eligible for funding for buyouts.
Change land use	Naturalize the floodplain and river corridor	Protect river corridors from development. The Vermont Department of Environmental Conservation encourages municipalities to adopt river corridor protection zoning, which can eventually lead to more stable river systems and reduce impacts to the transportation system. More information is available at the link below. https://dec.vermont.gov/watershed/rivers/river-corridor-and-floodplain-protection/river-corridor-planning-and-protection

OTHER APPROACHES TO INCREASING COMMUNITY RESILIENCY

In addition to the above strategies, municipalities can adopt the following current programs and policies to promote resiliency. Brief descriptions are provided below for awareness, and readers are encouraged to seek additional information.

Town Road and Bridge Standards
Municipalities should adopt VTrans current recommended town road and bridge standards (VTRB), which include a suite of practical and cost-effective Best Management Practices (BMPs) for the construction, maintenance, and repair of all existing and future town highways in order to address pollution caused by transportation-related stormwater runoff. VTRB Standards are minimum standards that represent best minimum practices to address transportation safety, design, construction, and maintenance. Additionally, by design, these standards are intended to help minimize roadway runoff, protect water quality, and address future bridge and culvert flood resilience. The standards can be found at https://vtrans.vermont.gov/sites/aot/files/operations/TheOrangeBook.pdf.

River Corridor Regulations
Many of the locations that are prone to severe flood and erosion damages are located outside of mapped floodplains. Municipalities are enabled and encouraged to adopt River Corridor Protections as part of their zoning regulations to protect these areas and the development located within. River Corridors have been identified by the Agency of Natural Resources; they include both the river/stream channel and the adjacent land area needed for the river to establish and maintain "equilibrium" conditions. For a map of the Vermont River Corridor visit https://anrmaps.vermont.gov/websites/ANRA5/default.html, and for more information, visit the Vermont River Corridor and Floodplain Protection page at https://dec.vermont.gov/watershed/rivers/river-corridor-and-floodplain-protection.

Hazard Mitigation Plan
Communities are encouraged to adopt Local Hazard Mitigation Plans (LHMP), a broad-based plan for each town that assesses hazards (including flooding) and proposes mitigation measures to lessen their vulnerability to those with the most impact. Communities that have a FEMA-approved LHMP are eligible to apply to Vermont Emergency Management for a Hazard Mitigation Grant Program grant administered by FEMA. LHMPs expire every 5 years, and RPCs are available to help towns update these plans. Additionally, mitigation plans are eligible for points under the National Flood Insurance Program's Community Rating System.

National Flood Insurance Program (NFIP)
Unconstrained development in flood hazard areas can exacerbate the impacts of flooding, cause damages to property and infrastructure, and potentially put lives at risk. Communities that adopt and enforce FEMA's NFIP standards can control the types and design of development that occur within the floodplains. Visit Flood Ready Vermont to see floodplain mapping at https://floodready.vermont.gov/assessment/vt_floodready_atlas.

Municipal Roads Stormwater General Permit
Municipalities are required to develop a Road Stormwater Management Plan, which is administered by the Vermont Department of Environmental Conservation and includes a comprehensive Road Erosion Inventory and an implementation plan. Compliance with the Municipal Roads General Permit presents communities with a way to improve water quality mostly along the dirt road network but also to address some flood resiliency issues. While inventorying roads for water quality problems, municipalities can also assess resiliency needs and infrastructure improvements. For more information visit the VTDEC Municipal Roads Program at https://dec.vermont.gov/watershed/stormwater/permit-information-applications-fees/municipal-roads-program.

APPENDIX L

TRPT PILOT WATERSHED CASE STUDIES – WHETSTONE BROOK, UPPER WHITE RIVER, AND NORTH BRANCH DEERFIELD RIVER

The Whetstone Brook Watershed Resiliency Case Study

May 29, 2018

Introduction

The Transportation Flood Resilience Planning Tool (TRPT) (Schiff et al., 2018) is a web-based application that identifies bridges, culverts and road embankments within a watershed that are vulnerable to damage from floods; estimates risk based on the vulnerability and criticality of roadway segments; and identifies potential mitigation measures based on the factors driving the vulnerability. The TRPT was developed by the Vermont Agency of Transportation (VTrans) with consultant assistance and with significant input from regional, local and state agency partners.

The Whetstone Brook Watershed is one of three pilot watersheds used to develop and validate the TRPT. This case study provides an overview of the Whetstone Brook Watershed, summarizes the vulnerability, criticality and risk concepts in the TRPT, demonstrates how the TRPT can be used to rank needs, and presents three site specific examples that demonstrate how the TRPT can be used to inform decisions to improve the resilience of the transportation system to flooding.

Watershed Overview

Whetstone Brook's headwaters are located at Hidden Lake in the town of Marlboro, and the river travels east through Brattleboro, eventually flowing into the Connecticut River (Figure 1). The watershed (area ~ 28 square miles) covers three communities – Brattleboro, Dummerston and Marlboro. The vast majority (over 90%) of the area is forested or agriculture land, with only 2% developed. The most concentrated development is located in downtown Brattleboro.

The communities in the Whetstone Brook Watershed have a combined population of 14,741[1]. The majority of the population in the watershed is located in Brattleboro. There are 815 established businesses located in the watershed that employ roughly 11,850 people. The largest employer, C&S Wholesale Grocers, is located outside of the Whetstone Brook River Watershed.

A significant number of residents are employed in downtown Brattleboro that means that flood mitigation within the watershed is vital so workers can commute to their jobs and businesses can keep operating during floods. Watershed residents are also employed outside of the watershed, such as at the recreational facilities at nearby Mt. Snow and Stratton Mountain Resort to the west. Access to major transportation routes (Table 1), such as Vermont Route 9, is essential for businesses to operate.

Vermont Route 9 is the only major east-west corridor between Route 4 (roughly 60 miles to the north) and the Massachusetts border. This corridor is used for local travel, trucking to ports in the Hudson River drainage, and tourism. The Brattleboro Hazard Mitigation Plan (Brattleboro, 2015) recognizes the potential for flood and erosion damage along Vermont Route 9 and the potential for a flood to quickly impact east-west travel in the southern half of Vermont. This route is a priority for mitigation to protect the road embankment, bridges and culverts from flood damage.

[1] US American Community Survey, 2012-2016

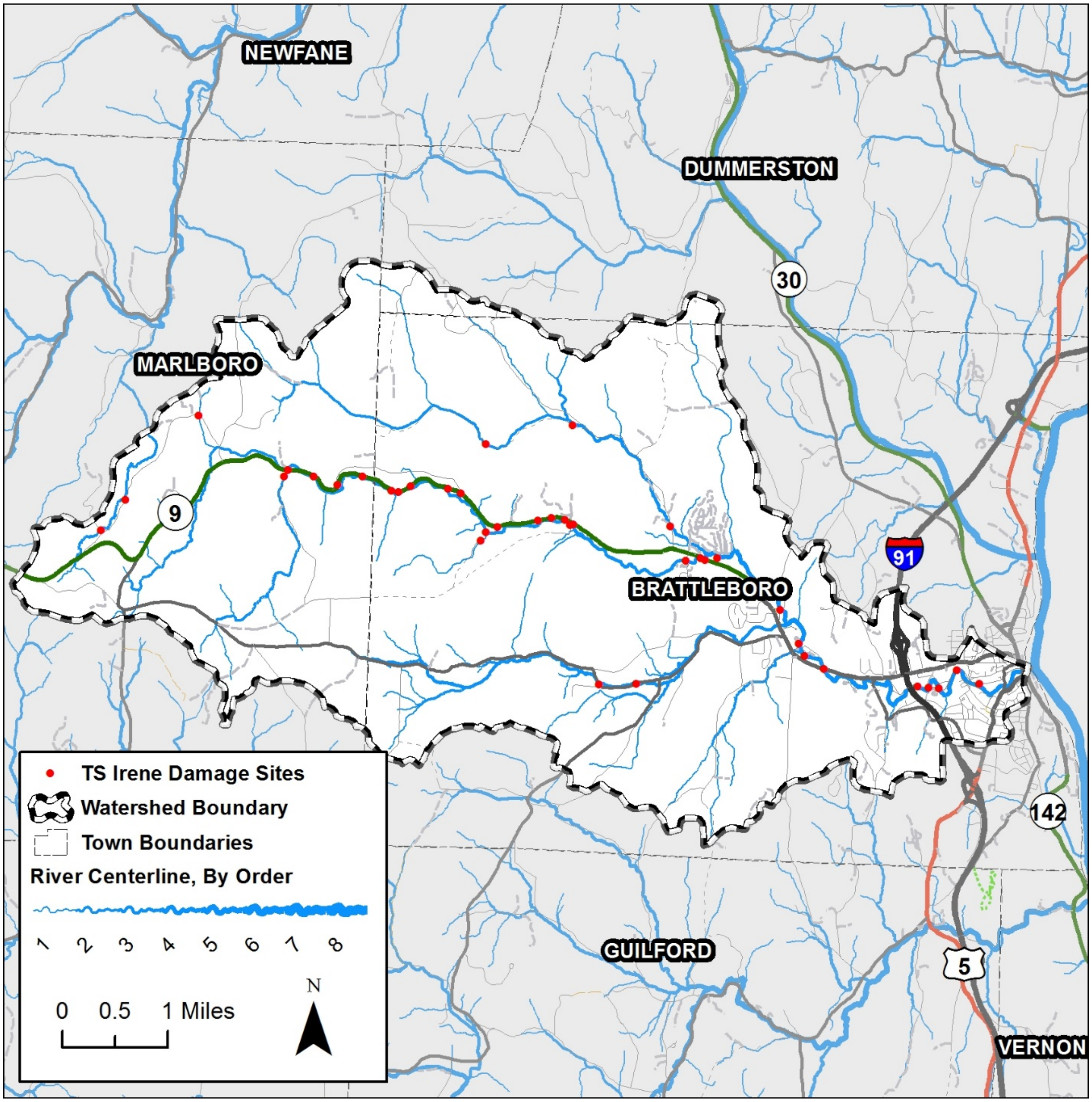

Figure 1: Whetstone Brook Watershed

Significant Transportation Routes - Deer River Watershed				
Road ID	**Owner**	**Classification**	**AADT**	**Importance**
VT 100	State	Minor Arterial	1,300-5,300	Primary north/south route in study area
VT 9	State	Principal Arterial	4,900-9,900	Important east/west connector from I-91 to Bennington
Local Roads	Town	Local		

Table 1- Significant transportation routes in the Whetstone Brook Watershed

The Whetstone Brook and its tributaries have a length of over 63 miles. Coupled with over 111 miles of roads, there are inevitably areas where waterways and roadways will be in conflict during floods. This was no more apparent than on August 28, 2011 when the State of Vermont found itself in the path of Tropical Storm Irene. The storm caused power outages statewide for approximately 50,000 households and widespread flooding that resulted in six deaths. Record amounts of rain fell in a short period of time resulting in widespread flood and erosion damages. Rainfall totals were between 4 and 7 inches with some locally higher amounts up to 10 inches concentrated during a 6-8 hour period.

The Otter Creek reached an historic crest (nearly 4 feet over the previous record in 1938) and the Mad, Winooski and White Rivers were very close to records established in 1927. Those mainstem rivers were fed by many smaller tributaries that caused damaging flash flooding and erosion throughout the central and southern parts of the state. More than 1,500 Vermont families were displaced and transportation and public infrastructure was severely damaged in many towns. Of Vermont's 251 municipalities, 223 were impacted by Irene causing household damage, infrastructure damage or both. Forty-five (45) municipalities were considered severely impacted, including Marlboro and Brattleboro in the Whetstone Brook Watershed.

Hundreds of state and local roads were closed for extended periods of time completely isolating numerous towns and limiting access to others. This resulted in State and National Guard missions to deliver emergency supplies by ground and air. The flooding also caused the first-ever evacuation of the State Emergency Operations Center due to access challenges and the impact to the buildings and support mechanism in the state office complex in Waterbury, which has since been replaced with a more flood-resilient structure.

Several towns found themselves completely isolated geographically and technologically. Electrical services to the towns had been broken. Telephone and cellular communications were predominantly down.

Some of the most severe damage from Irene took place along the Vermont Route 9 corridor. Near the Marlboro-Brattleboro town line the road embankment was eroded and one or more lanes were washed away (Figure 2). The road was closed for weeks.

Figure 2 - Erosion damage of Vermont Route 9 during Tropical Storm Irene at the Marlboro-Brattleboro. Photo Source: VTrans

The need for increased flood resiliency throughout Vermont's communities and along the transportation system was obvious after Irene. Since 2000, Vermont has had twenty-four (24) federally declared disasters related to severe storms and flooding. Although not as widespread as during Tropical Storm Irene, the ongoing local damages are often severe, disrupting, and costly.

Watershed Partners

The Whetstone Brook Watershed includes several important partners who work together to implement flood mitigation and watershed protection strategies. Watershed protection requires effort from multiple partners in order to increase flood resiliency of infrastructure and protect private property. This work must be done across municipal jurisdictions and in a coordinated way.

Vermont Agency of Transportation (VTrans)

VTrans manages and maintains State highways, bridges, and culverts in the Whetstone Brook Watershed primarily along Route 9. Including a section of US Interstate 91 maintained by the State of Vermont, 62 miles of state roads, twenty-four (24) bridges, approximately forty-five (45) large culverts (short structures that have widths between 6 and 20 feet), and approximately 157 small culverts (ultrashort structure that have widths less than 6 feet) owned and operated by VTrans in the Whetstone Brook watershed. VTrans supports the backbone of the transportation network on which the 92-mile long local road network is built. In addition to managing the state system, VTrans provides funding and technical assistance to municipalities to support bridge, culvert and roadway improvements. VTrans works with regional planning commissions on planning, outreach and project prioritization (VTrans, 2017), and will now use the TRPT to assist with this work.

Agency of Natural Resources (ANR)

All of the departments and divisions within ANR work collaboratively on a range of watershed assessment, restoration and protection projects. The Department of Environmental Conservation (DEC) is responsible for the development of a Tactical Basin Plan for Whetstone Brook (VTANR, 2014). DEC also helped establish river corridor easements and zoning across the watershed. A 216-acre easement exists to give the brooks and streams of the Whetstone Brook watershed room to move in their floodplains.

Windham Regional Commission

WRC is a political subdivision of the state whose region is comprised of twenty-seven municipalities in southeastern Vermont, governed by a Commission whose members are appointed by each member town. The Commission provides technical assistance to municipalities, coordinates the Region's planning and policy with local, state and federal levels of government and collaborates with the Region's non-profits and businesses, including watershed related programs. Its regional plan has standing in state land use permitting processes.

- Disaster reporting and recovery assistance to municipalities
- Emergency Management Planning
- GIS Services
- Land Use Planning
- Transportation Planning
- Project Development

Municipalities

Municipalities within the Whetstone Brook Watershed play an important role in watershed protection and in improving the resilience of the transportation system to floods. Through municipal land use planning and regulation, they can determine where development can and cannot occur, or how it can be planned to minimize flood vulnerability in the watershed. Additionally, towns are responsible for the maintenance of significant road networks, drainage ditches and bridges and culverts at stream crossings. Most towns receive assistance from the regional commission in the development of Local Hazard Mitigation Plans, which identify specific hazards and mitigation actions. Towns can also take specific actions to qualify for the maximum possible non-federal match assistance through the Vermont Emergency Relief and Assistance Fund.

Windham County Natural Resource Conservation District (NRCD)

The NRCD is a local-led and operated organization that promotes and supports soil and water conservation. The mission of the district is to 'help provide conservation assistance to the people living in the area through education programs and partnerships with federal, state, and local entities involved in natural resource management." NRCDs are often involved in tree plantings along river banks and floodplains, and other land conservation efforts related to flood resiliency.

Watershed Nonprofit Organizations

Both local and statewide nonprofit organizations can be important partners in flood resiliency efforts in the Whetstone watershed. Currently, the Vermont River Conservancy is working with the Town of Brattleboro to purchase a 12-acre parcel along the Whetstone in downtown Brattleboro, and restore this impacted area to its natural floodplain functioning. While primarily working with riparian conservation easements, the VRC is an important partner in stream restoration and protection. Similarly, the Connecticut River Conservancy participates in advocacy for river health policy and planning, and participates in restoration and flood resilience efforts throughout the Connecticut River watershed.

We are working with Brattleboro Housing Partnerships (BHP) to move residents out of the floodplain at Melrose Terrace and restore floodplain access. This project, in part, involves the demolition of 11 flood prone structures and the removal of 34,000 cubic yards of fill along the Whetstone in West Brattleboro. This will allow for restored access to floodplain in this stretch and lower flood levels between 1 and 4 feet.

BHP is in the process of having Federal Emergency Management Agency mapping updated to reflect proposed changes to the terrain around Melrose Terrace. If the new map is accepted, FEMA is expected to kick in about $3.2 million for the removal and restoration project.

Transportation Flood Resiliency Mapping and Prioritization

The Vermont Transportation Flood Resilience Planning Tool (TRPT) (Schiff et al., 2018) developed through the *Methods and Tools for Transportation Resilience Planning Project* has identified risk levels within the Whetstone Brook Watershed for roads, bridges and culverts due the consequences of failures associated with erosion, inundation and deposition. A vulnerability (V) scoring system was created and linked to different levels of transportation failures (Table 2 and Figure 3). Low levels of vulnerability may lead to small-scale damages due to inundation or minor erosion/deposition, while high levels of vulnerability may indicate that asset failure is likely due to severe erosion or deposition. The vulnerability methods were vetted with towns, field-verified, and found to be accurate predictors of potential damage locations.

Vulnerability Score	Vulnerability Rank	Likely Failure Mode	Transportation Influence	Distance (miles)	Vulnerability Type
0	Low	None	Road far from river such that vulnerability is unlikely.	N/A	N/A
1, 2	Low	Partial Closure	Single lane closure, reduced capacity with some allowable travel, <24 hours	<0.25	Temporary inundation, minor erosion or deposition
3, 4	Low	Full Closure	Multi-lane closure, detour required, 24 hours to several days	0.25 – 1	Large-scale inundation, localized erosion, localized deposition
5, 6, 7	Medium	Temporary Operational Failure	Partial destruction of facility. Several days to a 1 week for recovery.	0.25 – 1	Severe inundation, erosion, deposition
8, 9, 10	Medium, High	Complete Failure	Complete destruction of facility. 1 week to months for recovery.	Varies	Severe erosion or deposition

Table 2: Vulnerability Screen Scoring

A criticality (C) score was assembled to represent the consequence of a transportation link failure, the importance of a link to access critical facilities such as a hospital, and how important the road is for local detour use. Simulations were performed to identify the links in the transportation network where failure due to flooding would cause the longest delays or the most number of trip reductions. The probability of failure in the model was derived from the vulnerability score. A high criticality score (i.e., >5) indicates that failure of the link could lead to many failed trips or long delays, access to critical facilities could be reduced, and a local detour route may be cut off.

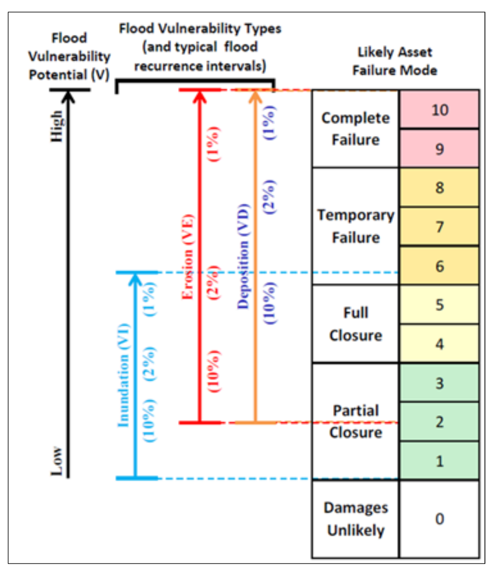

Figure 3 - Flood Vulnerability Screen by Vulnerability Type

The vulnerability and criticality scores were averaged to develop a risk (R) score that can be used to help prioritize actions. High risk locations (i.e., R > 5) may be vulnerable to damages and important for efficient travel. High-risk locations should be prioritized for mitigation and justify greater investment. Low-risk locations (i.e., R < 2) means that V and C are low and the resiliency will not be the primary driver of the need for improvements.

The TRPT identifies mitigation recommendations based on the characteristics that contribute to vulnerability and criticality for each location in the pilot watersheds. A list of initial recommendations is provided to begin an alternatives analysis to reduce vulnerability. Mitigation options include vegetative practices in low risk locations and hard armor stabilization practices in high risk locations. Floodplain reconnection and river corridor conservation are also considered to reduce long-term vulnerability to transportation infrastructure.

The TRPT has been created to display results and improve transportation planning. The web-based application is available for use by anyone connected to the internet. Maps show the vulnerability, criticality and risk results. Variable scores for each road segment or structure may also be viewed to understand what is driving the level of risk. The list of possible mitigation strategies is also provided.

The primary threat to roads in the Whetstone Brook watershed is erosion due to close proximity of roads to steep and erosive river channels. The following roads in the watershed ranked highest in terms of overall risk (Table 3).

Roads

Rank	Risk	Town	Road Name	Jurisdiction	V	C	Location
1	7.5	Brattleboro	Route 9	State	6	9	Route 9 from Meadow Brook Rd. (west end) to Garfield Dr. (east end)
2	7	Brattleboro	TH - 48	Town	10	4	Stark Rd.
3	6.5	Brattleboro	Route 9	State	6	7	Route 9/Western Ave. between the northern and southern ends of South St.
4	6.5	Brattleboro	Route 9	State	6	7	Route 9 from Brookwood Dr. (west end) to Dettman Dr. (east end)
5	6.5	Brattleboro	Route 9	State	6	7	Route 9 from Winding Hill Rd. (west end) to Brookwood Dr. (east end)
6	6.5	Brattleboro	TH-50	Town	9	4	Cook Rd. north to junction of Marlboro Rd. (Route 9)
7	6	Brattleboro	Route 9	State	6	6	Western Ave./Route 9 from southern South St. entrance (west end) to George Miller Dr. (east end)
8	6	Brattleboro	Route 9	State	10	2	Route 9 from Olson Dr. (west end) to Cider Mill Hl. (east end)
9	6	Brattleboro	Route 9	State	10	2	Route 9 from Hamilton Rd. (west end) to Stark Rd. (east end)
10	6	Brattleboro	Route 9	State	10	2	Route 9 from town line (west end) to Hamilton Rd. (east end)

Table 3: Whetstone Brook watershed high-risk roads

Bridges

The primary threat to bridges in the Whetstone Brook watershed is erosion and deposition. Bridges on steep channels and bends in the river can be prone to scour. In lower stream power settings where the slope of the channel is flatter, sediment and large wood can accumulate leading to bridge clogging. In extreme deposition cases the pre-flood channel can fill with sediment and the river will carve a new path during the flood. This depositional setting can be extremely damaging to nearby infrastructure and has led to many of the previous road and bridge failures in the State. The following bridges in the Whetstone Brook Watershed ranked highest in terms of overall risk (T**able 4).**

Rank	Risk	Town	Jurisdiction	BR#	V	C	Location
1	7	Brattleboro	Town	00021	10	4	Cook Rd. over Whetstone Brook
2	6.5	Brattleboro	State	00051	6	7	Route 9 over Whetstone Brook
3	5.5	Brattleboro	City	00035	10	1	Williams St. over Whetstone Brook
4	5.5	Brattleboro	City	00052	2	9	Western Ave/Route 9 over Ames Hill Brook
5	5.5	Brattleboro	Town	00018	10	1	Stark Rd. over Whetstone Brook
6	5	Brattleboro	City	00054	8	2	Western Ave/Route 9 over Whetstone Brook
7	5	Brattleboro	Town	00005	8	2	Ames Hill Rd. over Ames Hill Brook
8	5	Brattleboro	Town	00007	6	4	Sunset Lake Rd. over Halladay Brook
9	5	Brattleboro	Town	00001	8	2	Ames Hill Rd. over Ames Hill Brook
10	4.5	Brattleboro	Town	00058	8	1	Melrose St. over Whetstone Brook

Table 4: Whetstone Brook watershed high-risk bridges

Culverts

The primary threat to culverts in the Whetstone Brook watershed is erosion and deposition. Culverts on steep channels with large fills across a floodplain are prone to scour due to strong contractions in flood flows. Many culverts are prone to accumulating sediment and large wood due to their small size relative to the channel and floodplain width. Many culverts clog during floods. New standards requiring larger culverts are allowing new culverts to pass flood flows. The following culverts in the Whetstone Brook Watershed ranked highest in terms of overall risk (Table 5).

Rank	Risk	Town	V	C	Location
1	4	Brattleboro	5	3	Maple Street
2	3.5	Marlboro	5	2	Ames Hill Rd.
3	3.5	Marlboro	5	2	Ames Hill Rd.
4	3.5	Marlboro	5	2	Ames Hill Rd.
5	3.5	Marlboro	6	1	Whitaker Farm Rd.
6	3.5	Marlboro	5	2	Ames Hill Rd.
7	3.5	Marlboro	5	2	Route 9
8	3.5	Marlboro	6	1	Church Hollow Rd.
9	3	Brattleboro	2	4	Bonneyvale Rd.
10	3	Brattleboro	5	1	Goodenough Rd.

Table 5: Whetstone Brook watershed high risk culverts

Reducing Flood Risk

Reducing Risk through Mitigation

A list of possible mitigation strategies is provided in the TRPT to begin the alternatives analysis of solutions to improve resiliency. The strategies are grouped in the following categories.

- **Fortify infrastructure or river channel**
  - **Bank stabilization** – For high risk locations where river-road conflicts cannot be avoided, innovative rip rap solutions such as stacked toe walls may be necessary to protect infrastructure while maintaining bankfull channel width to avoid increasing erosion.
  - **Riparian buffer plantings** – Planting native tree and shrub species to restore riparian habitat, provide floodplain roughness and cover along banks, and stabilize the upper banks. This method is particularly useful in lower risk settings.
  - **Improve channel roughness** – By adding woody debris and vegetation in the channel and on the floodplain, stream flow energy can be reduced due to increased roughness and friction that leads to less erosion.
- **Address resiliency**
  - **Bridge & Culvert Replacement** – Improperly sized bridges and culverts are often unable to handle flood waters, sediment, large wood, and ice. When partially full or clogged, flood waters run around or undermine the structures that can lead to a failure. By upgrading undersized structures the potential for damage is reduced.
- **Restoration**
  - **The creation of new floodplain** - Improved flood access provides more space for flood storage and sediment deposition. This practice restored natural flood reduction.
  - **Wetland restoration** – By repairing wetlands lost to “ditch and drain” practices, floodwater and sediment storage is improved.
- **Relocate or remove**
  - **Road relocation** – Relocating vulnerable infrastructure reduces the potential for conflicts between man-made development and the river’s natural need to move.
  - **Bridge & Culvert Removal** – Removing abandoned bridges and culverts can improve channel stability and overall water quality.
- **Change land use**
  - **Easements (Conservation and ANR River Corridor)** – By preserving large tracts of land and restricting future encroachments, rivers are provided with room to reach equilibrium.

Reducing Risk through Mitigation Policy and Planning

In addition to active mitigation projects, improved policy and planning initiatives are essential parts of promoting flood resiliency. State agencies, regional organizations and municipalities are all expected to take an active role in improving the statewide response to severe flooding events and planning for future flood protection.

As an incentive to encourage good mitigation policy and planning, the state has created the Emergency Relief and Assistance Fund (ERAF) that provides State funding to match FEMA Public Assistance funding after federally-declared disasters. Eligible public costs are reimbursed by federal taxpayers at 75%. For disasters after October 23, 2014, the State of Vermont will contribute an additional 7.5% toward the costs. For communities that take specific mitigation planning and policy related steps to reduce flood damage the State will contribute 12.5% or 17.5% of the total cost. This additional match can reduce the municipal financial burden of flood recovery in the event of a federally-declared disaster (Table 6).

	7.5% ERAF Rate	12.5% ERAF Rate	17.5% ERAF Rate
Federal Share	$750,000	$750,000	$750,000
State Share	$75,000	$125,000	$175,000
Municipal Share	**$175,000**	**$125,000**	**$75,000**
Total Damages	$1,000,000	$1,000,000	$1,000,000

Table 6: ERAF rates and Municipal Cost Share based on $1,000,000 in damages from a federally declared disaster

Communities have several tools at their disposal such as adoption and adherence to Road and Bridge Standards that improve flood resilience, the adoption of River Corridor protections in their zoning bylaws, maintaining an up-to-date Local Hazard Mitigation Plan, and participation in the National Flood Insurance Program (Table 7).

	12.5% ERAF Rate (must adopt all four)				17.5% ERAF Rate
Town	**NFIP Standards**	**Road & Bridge Standards**	**Local Emergency Operations Plan**	**Local Hazard Mitigation Plan**	**River Corridor Protection**
Brattleboro	Yes	Yes	Yes	Yes	No
Dummerston	Yes	Yes	Yes	Yes	No
Marlboro	Yes	Yes	Yes	Yes	No

Table 7: Status of Mitigation policy and planning in Whetstone Brook watershed communities, 2017

Vermont Town Road & Bridge Standards (VTRB)

Act 110 of the 2009-2010 Legislative session required that VTrans work with municipal representatives to "revise the Agency's current recommended town road and bridge standards to include a suite of practical and cost-effective Best Management Practices (BMPs) for the construction, maintenance, and repair of all existing and future town highways in order to address pollution caused by transportation-related stormwater runoff." VTRB Standards are minimum standards that represent best minimum practices to address transportation safety, design, construction and maintenance. Additionally, by design, these standards are intended to help minimize roadway runoff, protect water quality and address future bridge and culvert flood resilience. Adoption of the VTRB and an annual letter of certification signed by the Town, ensures that FEMA will provide funding to upgrade existing sub-standard roads, bridges or culverts that are damaged in a federally declared disaster.[2]

River Corridor Protections

Many of the locations damaged during Tropical Storm Irene were well outside of mapped Flood Hazard Areas based on inundation alone. Many streams experienced erosion and deposition damage due to

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[2] The standards within the VTRB that address water quality are being superseded by standards within the Municipal Roads General Permit required by Act 64, the Vermont Clean Water Act. Municipalities must apply for the MRGP by July 31, 2018. More information on the MRGP is provided below. Adoption and compliance with the VTRB, which will continue to provide flood resilience standards, will still be required to ensure FEMA funding can be used to upgrade sub-standard roads, bridges and culverts damaged by a flood.

confined flow with high velocity. The Legislature created the ability for communities to limit development within the River Corridor Area. The River Corridor includes both the river/stream channel and the adjacent land area needed for the river to establish and maintain "equilibrium" conditions. Some communities have adopted River Corridor protections that prohibit, or limit new development in this highly dynamic and vulnerable location on the landscape.

Hazard Mitigation Plans

To ensure that communities are actively planning for future flood events (and other significant hazards), communities maintain Local Hazard Mitigation Plans (LHMPs) (Brattleboro, 2015). The LHMP is a broad-based plan for each town that assesses hazards (including flooding) and proposes mitigation measures to lessen their vulnerability to those with the most impact. Communities that have a FEMA approved LHMP are eligible to apply to Vermont Emergency Management for a Hazard Mitigation Grant Program (HMGP) grant administered by FEMA. LHMPs expire every five years and RPCs are available to help towns update these plans. Additionally, mitigation plans are eligible for points under the National Flood Insurance Program's Community Rating System (CRS). The TRPT could help municipalities identify bridges, culverts and road embankments for funding through FEMA grants.

National Flood Insurance Standards

Unconstrained development in flood hazard areas can exacerbate the impacts of flooding; cause damages to property and infrastructure and potentially put lives at risk. Communities that adopt and enforce FEMA's NFIP standards can control the types and design of development that occur within the floodplains.

Water Quality Planning and Project Identification

Municipal Roads Stormwater General Permit

In 2016 the Vermont Legislature passed a law specifically focused on reducing the environmental impacts of stormwater runoff. A primary component of this law is the Municipal Roads Stormwater General Permit (MRGP) that is administered by the Vermont Department of Environmental Conservation. As a requirement of the MRGP Municipalities must develop a Road Stormwater Management Plan (Road SWMP). The Road SWMPs include two components; a comprehensive Road Erosion Inventory (REI) of "hydrologically-connected" road segments and associated Implementation Plan. The purpose of the Implementation Plan is to bring non-complying road segments up to MRGP Standards as soon as possible, but no later than December 31, 2036.

Hydrologically Connected Roads

The criteria that defines a road as "hydrologically connected" are:

- Municipal roads within 100' of a water resource
- Municipal road that crosses and drains into a water source
- Municipal road located within the mapped River Corridor area
- Catch basin outfalls within 500' of a water resource and those segments associated with those outfalls.

Compliance with the MRGP presents communities with a way to improve water quality mostly along the dirt road network, but also to address some flood resiliency issues. While inventorying roads for water quality problems, municipalities can also assess resiliency needs.

The MRGP will require replacement or stabilization retrofits for eroding road drainage culverts, intermittent stream culverts, and driveway culverts located within municipal right-of-ways. Upsizing culverts, improving culvert headwalls/headers, stabilizing drainage ditches and culvert outlets and mitigating catch basin outfall erosion will be among the tasks required to meet MRGP standards. Communities can utilize a prioritized list of necessary repairs that can be integrated into municipal planning and budgeting. The prioritization of infrastructure investments should be part of a locally adopted Municipal Plan. For communities with an adopted Capital Budget and Program, a prioritized plan for road improvements can be incorporated and budgeted for.

Investments in transportation infrastructure will improve water quality, and reduce the potential for severe damage and loss during a severe flooding event. In turn, improved flood resiliency will reduce future costs for repair, and limit the potential for loss of life and property throughout the watershed.

Buyouts and Infrastructure Protection

One way to reduce the risk of damage to transportation infrastructure is to identify properties that are prone to damage that may have a direct impact on roads, bridges and culverts (Figure 4). A house that is located too close to a river, for example, can be swept into the floodwaters, traveling downstream until it meets a bridge or culvert. The effect of a large mass plugging a bridge inlet can result in bridge or road failure.

Figure 4 - Example of a floodprone property that puts infrastructure at risk. East Orange Branch of the Waits River in West Topsham. Source: Google Maps.

The Federal Emergency Management Agency (FEMA) maintains a program through which flood-prone properties in the mapped FEMA floodplain can be purchased to remove the structure and conserve the property in the event of a federally declared disaster. FEMA pays 75% of the value of the flood-prone property, and the remaining 25% is handled by the landowner or possibly through other federal and state funding such as a Community Development Block Grant through the US Department of Housing and Urban Development and the Vermont Housing and Conservation Board.

To prepare for future buyouts, communities should inventory flood-prone properties and prioritize them based on their public benefit as it relates to transportation infrastructure and landowner interest. Priority should be given to:

- Buildings that could cause damage to transportation infrastructure during catastrophic failure; and
- Buildings that are located on a road segment that only serves the flood-prone structures.

Communities may also want to consider developing a contingency fund for the purpose of providing the necessary level of match to complete a buyout following a flood. Because flood-prone properties outside of the mapped floodplain are not covered under FEMA's buyout program, communities or the state may want to consider allocating enough funding to conduct their own buyouts if landowners would prefer to rebuild in a safer location. While bearing the full cost of a buyout might not be preferred, it is important to weigh the benefit of the buyout versus the cost of repeated repairs or reconstructing infrastructure that fails due to the flood-prone property.

A local or state program can eliminate much of the paperwork required by the federal government and prioritize sites outside of the mapped floodplain that may impact infrastructure. An average FEMA buyout from TSI Irene cost $10,000 in administrative costs (personal communication from the TRORC TSI State Buyout Manager). The TRPT could help municipalities identify buyouts that would improve bridges, culverts and road embankments flood resiliency.

Removing Vulnerable Infrastructure

Many communities have damage-prone road segments that regularly require repair due to inundation, erosion or deposition. To address these problem areas, communities should consider discontinuing or moving a road segment where feasible. If a damage-prone road serves a limited number of floodprone homes and has very low traffic volume, it may be financially sound to buy out the floodprone homes and discontinue the road. Communities should also consider if there is adequate access through alternative safer routes to properties.

In some instances, it is possible to move a road segment away from a river or stream. Moving roads is expensive (Table 8), and thus careful planning and analysis is necessary.

Gilman Rd. Relocation, Royalton	
Administration & Engineering	$103,464
Stream Bank Stabilization	$408,059
Moving Road	$226,609
Total	$738,132

Table 8 - Costs for moving an 850 feet (1/6mile) segment of Gilman Road 40 feet in Royalton. Does not include procurement of adjacent property.

Communities may want to proactively identify road segments that have the potential to be moved. Look for areas where the adjacent topography would allow for moving a road segment with minimal ground work to minimize costs. In areas where the landscape makes it feasible to move a road, communities should identify ownership of adjacent properties and determine what reasonable compensation would be for the land necessary to accommodate the change. The next step would be to engage a professional to develop an estimate of potential costs for moving the road. This information will provide a general cost for such a project, allowing for the development of a benefit-cost analysis to determine if the cost of maintaining the road in its current location is more than the cost to move the road.

Most communities will need to use multiple funding sources to balance the cost to the community with the overall cost of the project, typically through federal programs such as the FEMA Hazard Mitigation Grant Program, or Community Development Block Grant Disaster Relief funding. Each of these programs is tied to a federally declared disaster. It is essential that communities maintain good records that document previous damage and repair work to support benefit-cost analysis work and preparation of funding applications. Documentation must include photos and an accurate accounting of time and materials needed to repair damages.

Communities that have identified a road that can be moved should engage in planning to be prepared if a funding opportunity arises. To start, the identified road segment should be highlighted in the Municipal Hazard Mitigation Plan – identify the location of the segment to be moved, describe past damages and summarize the potential approaches to moving the road. Following the hazard mitigation planning process, the next step would be to have an engineer conduct a scoping study that will identify the preferred alternative.

Site Examples

Two site examples identified in the TRPT from the Whetstone Brook Watershed follow that will protect local transportation assets and improve the transportation network resilience. The site examples include:

- Inundation and erosion along Williams Street in Brattleboro; and
- Erosion along Vermont Route 9 near the Marlboro-Brattleboro Town line.

Inundation and erosion along Williams Street in Brattleboro

During Tropical Storm Irene flood waters, sediment, and large wood filled Whetstone Brook. With much of its floodplain developed with buildings, roads, bridges, and other infrastructure, the flooding led to damages. Flooding took place along Williams Street (Figure 5) where buildings and the road embankment encroach on the channel and where a floodplain was filled in the past to run mills. Both inundation of the road and buildings, and erosion of the edge of the road embankment, sidewalks, and river channel took place.

Figure 5: Flooding along Williams Street during Tropical Storm Irene in Brattleboro, Vermont. (Source: Town of Brattleboro, 2011)

The Williams Street bend is shown to be high risk in the TRPT (Figure 6) – the road is very vulnerable (10 of 10 for erosion and 3 of 5 for inundation), yet not too critical since it can be easily bypassed. Stream power is moderate (145 Watts per square meter), a long portion of the road segment is in the river corridor (1,451 feet), the corridor is filled with infrastructure, and the river cannot access its floodplain. This combination of conditions can lead to excessive damages in future floods.

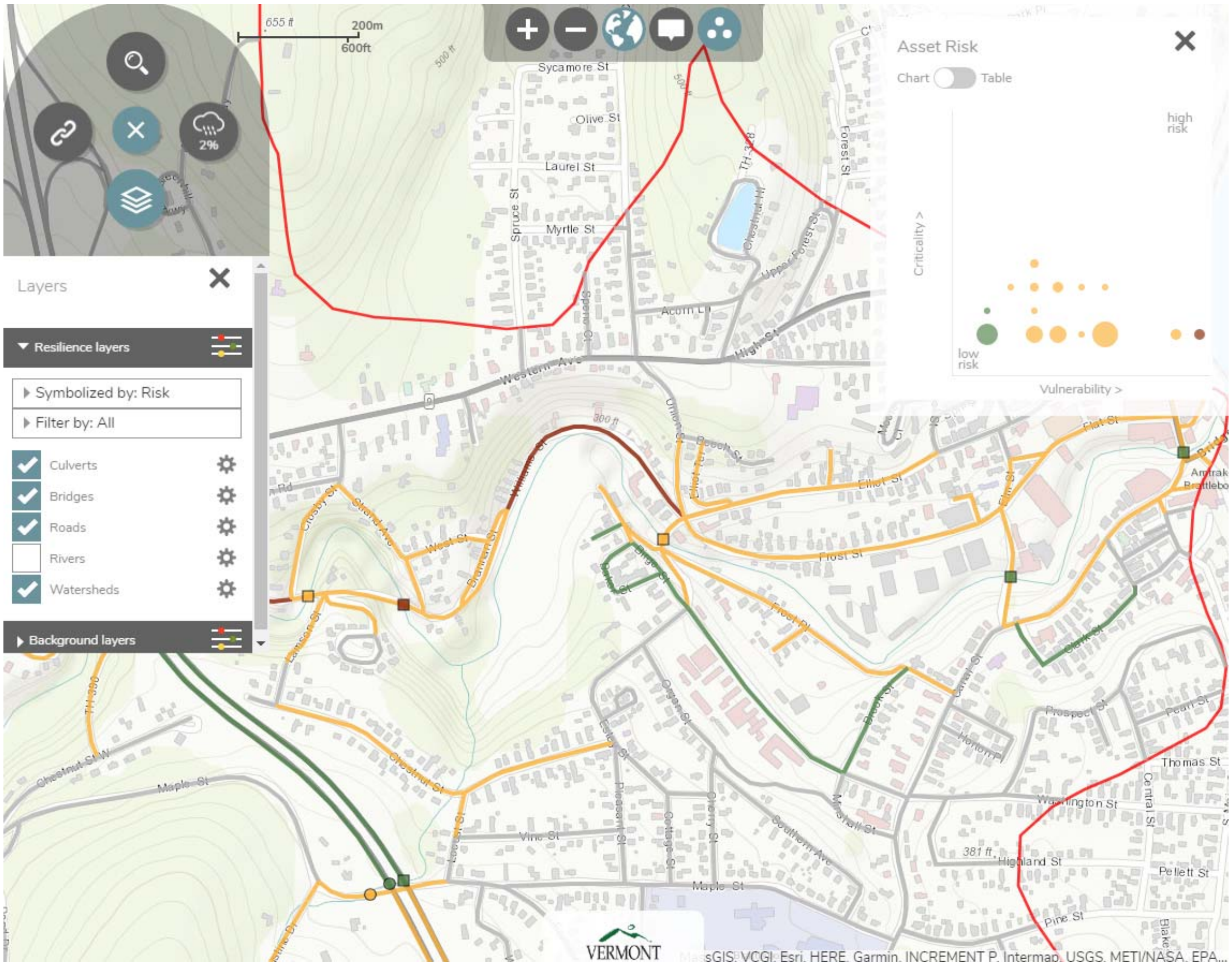

Figure 6: Screen shot of the TRPT that shows high risk along Williams Street in Brattleboro. (Source: Vermont Transportation Resilience Planning Tool, exported 5/29/2018)

The high level of encroachment and lack of floodplain access along Whetstone Brook illustrates the need for floodplain restoration to safely slow, spread, and store flood waters and debris even in this urban setting. Due to these conditions and an opportunity to restore a floodplain parcel at a former mill site that had been filled in the past, the Vermont River Conservancy has embarked on a project to restore the floodplain on the insde of the bend along Williams Street (Figure 7). The project will include removal of past fill, plantings, a stormwater treatment element and creation of a rustic trail (Figure 8).

Figure 7: Proposed floodplain restoration site near Williams Street in Brattleboro. (Source: MMI, 2016)

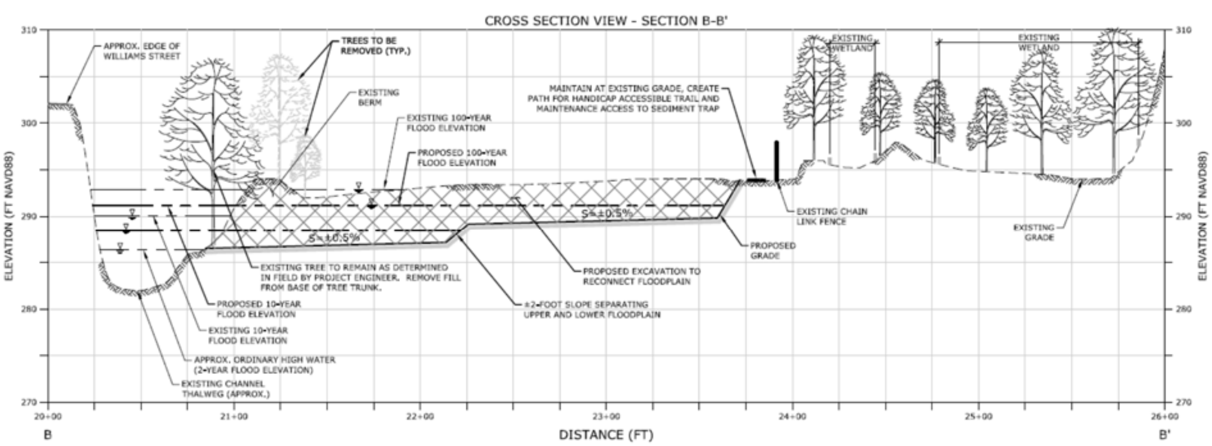

Figure 8: Design cross section of the proposed floodplain restoration site near Williams Street in Brattleboro. (Source: MMI, 2018)

Additional mitigation recommendations in the TRPT include conserving the river corridor to prevent future development in this hazardous setting and to revegetate the floodplain to slow the flood flow on the future floodplain – all actions that will be taking place in this location in the future. A similar project is being completed by the Brattleboro Housing Partnership at the Melrose Terrace property to move residents to a safer location and reduce flood risks in the area by restoring functioning floodplain.

A High-Risk Site along Vermont Route 9 near the Marlboro-Brattleboro Town line

Vermont Route 9 runs up the Whetstone Brook river corridor and is often very close to the channel. In fact, in many locations that edge of the road embankment and the river bank are one and the same (Figure 9). During Tropical Storm Irene several sections of Vermont Route 9 were eroded due to the overlap in the corridor, moderate stream power, erodible bank and bed material, and lack of floodplain. Some of the most confined and hazardous settings in the state exist along the Vermont Route 9 corridor (See Figure 9).

Figure 9: A pinch-point in the channel where the Vermont Route 9 embankment was eroded during Tropical Storm Irene. (Source: MMI, 2011)

The TRPT shows high risk sections of Vermont Route 9 in this location mostly due to high erosion potential (10 out of 10 vulnerability score) (Figure 10). The vulnerability is due to a long length (i.e., 1,580 feet) of the road in the floodplain, moderate stream power (284 Watts per square meter), and past road failure in the area.

The recommended mitigation strategies are largely impactful to the river and costly given the high-risk setting and proximity of the road embankment to the river channel. The recommendations include restoring flood benches and floodplains as possible and armoring the edge of the road likely with placed riprap wall to try and maintain as much channel width as possible. Vegetative practices alone will not work in this highly erosive setting and thus are proposed as a companion such as joint plantings in riprap to filter runoff and restore riparian habitat.

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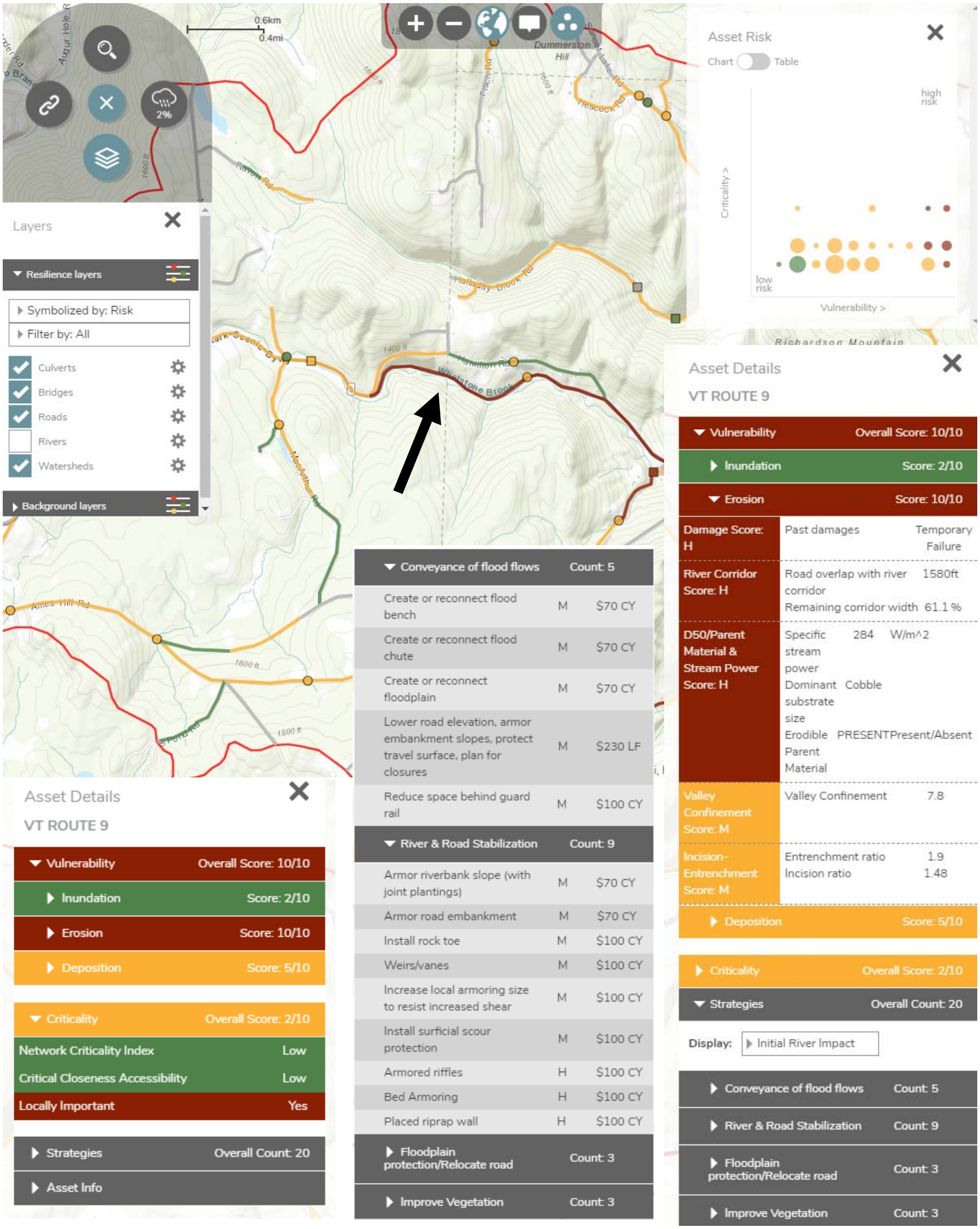

Figure 10: Clips of data details from the TRPT for the high-risk site along Vermont Route 9 near the Brattleboro-Marlboro town line, exported 5/29/2018).

The Upper White River Watershed Resiliency Case Study

March 23, 2018

Introduction

The Transportation Flood Resilience Planning Tool (TRPT) (Schiff et al., 2018) is a web-based application that identifies bridges, culverts and road embankments within a watershed that are vulnerable to damage from floods; estimates risk based on the vulnerability and criticality of roadway segments; and identifies potential mitigation measures based on the factors driving the vulnerability. The TRPT was developed by the Vermont Agency of Transportation (VTrans) with consultant assistance and with significant input from regional, local and state agency partners.

The Upper White River Watershed is one of three pilot watersheds used to develop and validate the TRPT. This case study provides an overview of the Upper White River Watershed, summarizes the vulnerability, criticality and risk concepts in the TRPT, demonstrates how the TRPT can be used to rank needs, and presents three site specific examples that demonstrate how the TRPT can be used to inform decisions to improve the resilience of the transportation system to flooding.

Watershed Overview

The Upper White River watershed (Figure 1) is part of the greater White River Basin. The White River is unique in that it is one of Vermont's last free-flowing rivers (the longest undammed tributary to the Connecticut River). The Upper White River Watershed covers a land area of 173,203 acres in thirteen communities: Barnard, Bethel, Bridgewater, Chittenden, Goshen, Granville, Hancock, Killington, Mendon, Pittsfield, Rochester, Royalton and Stockbridge. The vast majority (over 90%) of the area is forested or in agriculture, with only roughly 2% developed. The most concentrated development is located within the villages and hamlets of Granville, Hancock, Rochester, Pittsfield, Stockbridge and Barnard.

The communities in the Upper White River Watershed have a combined population of 6,661[1]. The Town of Stockbridge is the only one located completely within the watershed. There are 355 established businesses located in the watershed that employ roughly 3,300 people. The largest employers, GW Plastics in Bethel and Killington Mountain Ski Resort, are located outside of the Upper White River Watershed. A majority of residents commute to employment centers outside of the watershed, which means access to transportation routes (Table 1) is vital from an economic standpoint.

[1] US American Community Survey, 2012-2016

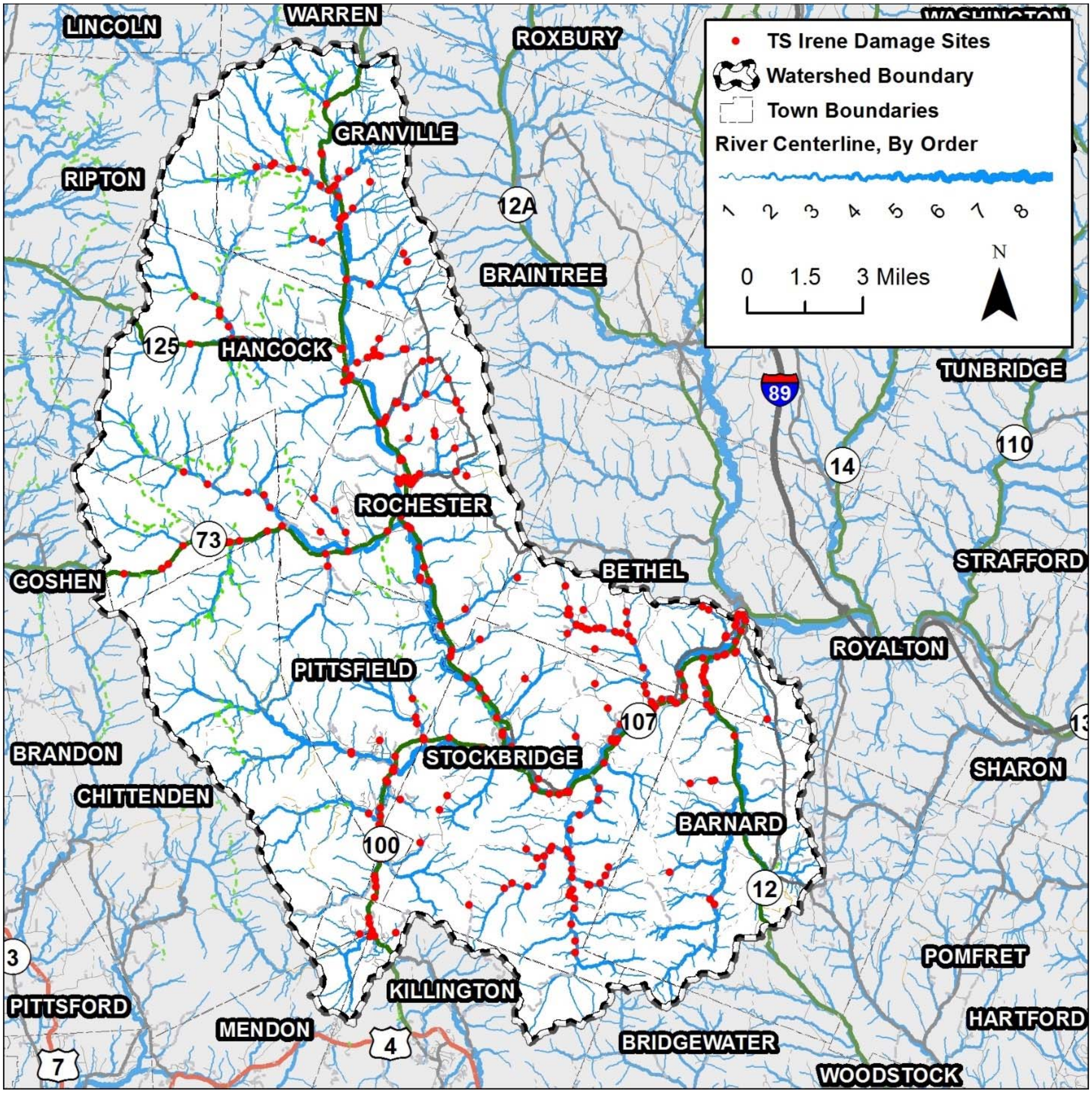

Figure 1: Upper White River Watershed

Significant Transportation Routes - Upper White River Watershed				
Road ID	**Owner**	**Classification**	**AADT**	**Importance**
VT 100	State	Minor Arterial	1,200-2,000	Primary north/south route in study area
VT 107	State	Minor Arterial	3,300-4,000	Important east/west connector from I-89 to Rutland County
VT 125	State	Major Collector	1,200-1,500	East/west connector over gaps in Green Mountains
VT 73	State	Major Collector	700-1,200	East/west connector over gaps in Green Mountains
VT 12	State	Major Collector	1,000-1,200	Important north/south connector from I-89 in Bethel to Woodstock
Local Roads	Town	Town Highways		Provides alternate routes for north of Brandon Mountain Rd.

Table 1 - Significant transportation routes in the Upper White River Watershed

The Upper White River and its tributaries have a combined length of 663 miles within the 271 square mile watershed. Coupled with over 360 miles of roads, there are inevitably areas where waterways and roadways will conflict during flood-related events. This was no more apparent than on August 28, 2011, when the State of Vermont found itself in the path of Tropical Storm Irene. The storm caused power outages statewide for approximately 50,000 households and widespread flooding that resulted in six deaths. Record amounts of rain fell in a short period of time resulting in widespread flood and erosion damages. Rainfall totals were between 4 and 7 inches with some locally higher amounts up to 10 inches concentrated during a 6 to 8-hour period.

The Otter Creek reached an historic crest (nearly 4 feet over the previous record in 1938) and the Mad, Winooski and White Rivers were very close to records established in 1927. Those mainstem rivers were fed by many smaller tributaries that caused damaging flash flooding throughout the central and southern parts of the state. More than 1,500 Vermont families were displaced and transportation and public infrastructure was severely damaged. Of Vermont's 251 municipalities, 223 were impacted by Irene causing household damage, infrastructure damage or both. Forty-five (45) municipalities were considered severely impacted, seven of them (Bethel, Granville, Hancock, Killington, Mendon, Pittsfield, Rochester and Stockbridge) are located in the Upper White River Watershed.

Hundreds of state and local roads were closed for extended periods of time completely isolating numerous towns and limiting access to many others. This resulted in state and National Guard missions to deliver emergency supplies by ground and air. The flooding also caused the first-ever evacuation of the State Emergency Operations Center due to access challenges and the impact to the buildings and support mechanism in the state office complex in Waterbury.

Some of the most severe damage from Irene took place in and around the communities of Pittsfield, Bethel, Rochester, Stockbridge and Killington (Figure 2). Several towns found themselves completely isolated geographically and technologically. Electrical services to the towns had been broken. Telephone and cellular communications were predominantly down. Highways leading out of Rochester and Stockbridge were all so severely damaged that no one that could get in or out by vehicle.

Figure 2 - Significant damage during Tropical Storm Irene, Town of Stockbridge. Photo Source: David Brown, Road Foreman

The need for increased flood resiliency throughout Vermont's communities and along the transportation system was obvious after Irene. Since 2000, Vermont has had twenty-four (24) federally declared disasters related to severe storms and flooding. While most severe flooding events in Vermont do not produce damages that are as widespread as during Tropical Storm Irene, the local damages are severe, disrupting, and costly.

Watershed Partners

The Upper White River Watershed includes several important partners who work together to implement flood mitigation and watershed protection strategies. The Upper White River has the most towns and stakeholders of the three pilot study watersheds, and thus coordinated efforts are required to increase flood resiliency of infrastructure and private property. This work must be done across municipal jurisdictions and in a coordinated way.

Vermont Agency of Transportation (VTrans)

VTrans manages and maintains State highways, bridges, and culverts in the Upper White River Watershed, including Routes 100, 107, 125, 73 and 12. There are 62 miles of state roads, 41 bridges, approximately 50 large culverts (short structures that have widths between 6 and 20 feet), and approximately 360 small culverts (ultrashort structure that have widths less than 6 feet) owned and operated by the State in the Upper White River watershed. VTrans supports the backbone of the transportation network, on which the extensive local road network (254 miles) is built. In addition to managing the state system, VTrans provides funding and technical assistance to municipalities to support bridge, culvert and roadway improvements, and works closely with regional planning commissions on planning, outreach and project prioritization. See A Handbook for Local Officials (a.k.a. the "Orange Book" for more information http://vtrans.vermont.gov/sites/aot/files/operations/TheOrangeBook.pdf) (VTrans, 2009).

Agency of Natural Resources (ANR)

All of the departments and divisions within ANR work collaboratively on a range of watershed assessment, restoration and protection projects. The Department of Environmental Conservation (DEC) is responsible for the development of the White River Tactical Basin Plan (VTANR, 2018). DEC also helped establish river corridor easements and zoning across the watershed. There are 45 acres of easements in place to give the rivers of the Upper White room to move in their floodplains.

Two Rivers-Ottauquechee Regional Commission (TRORC)

TRORC is an association of thirty municipalities in east-central Vermont, governed by a Board of Directors appointed by each member town. The Commission provides technical assistance to municipalities, coordinates the Region's planning and policy with state and federal levels of government and collaborates with the Region's non-profits and businesses, including watershed related programs such as:

- Disaster recovery assistance to municipalities
- Emergency Management
- GIS Services
- Land Use Planning
- Transportation Planning

Municipalities

Municipalities within the Upper White River Watershed have an important role in watershed protection and in improving the resilience of the transportation system to floods. Through municipal land use planning and regulation, they can determine where development can and cannot occur, or how it can be planned to minimize flood vulnerability in the watershed. Additionally, towns are responsible for the maintenance of significant road networks, drainage ditches and bridges and culverts at stream crossings.

White River Partnership (WRP)

The White River Partnership is a member-based, non-profit organization that works to improve the long-term health of the White River. Since 1996 the WRP has worked to address these concerns by uniting citizens, schools, businesses, towns, local and regional organizations, and state and federal agencies to implement on-the-ground programs designed to evaluate the health of the watershed, to protect and restore the watershed, and to raise awareness about watershed issues, including sustainable agriculture, forestry, and recreational uses. The WRP has coordinated numerous watershed resiliency, and protection projects working independently and in collaboration with partners including:

- Water quality monitoring
- River corridor planning and protection
- Aquatic organism passage
- Class IV roads evaluation and erosion control program
- Riparian buffer plantings

The WRP was directly responsible for the development of the Upper & Middle White River Watershed Corridor Plan in 2015 with the Agency of Natural Resources. This plan identifies a broad list of potential restoration, conservation and flood resiliency projects using stream geomorphic assessment data collected for the Plan.

US Department of Agriculture Forest Service (USFS)

A portion of land in the Upper White River Watershed is part of the Green Mountain National Forest. These lands are managed by the USFS who undertake projects to maintain the health of the forest and its wildlife. The USFS is involved in the establishment and maintenance of riparian buffers on GMNF land. The USFS completed a river restoration project on the West Branch north of VT Route 73 in 2015. The project addressed a reach that had been impacted by gravel dredging following the Irene flood, with the goal of restoring channel function and habitat, and improving flood resiliency in the watershed.

White River Natural Resource Conservation District (NRCD)

The NRCD is a local organization that promotes and supports soil and water conservation. The mission of the district is to "help provide conservation assistance to the people living in the area through education programs and partnerships with federal, state, and local entities." NRCDs are do tree plantings along river banks and floodplains, and other conservation efforts related to flood resiliency.

Transportation Flood Resiliency Mapping and Prioritization

The Vermont Transportation Flood Resilience Planning Tool (TRPT) developed here has identified risk levels within the Upper White River Watershed for roads, bridges and culverts due the consequences of failures associated with erosion, inundation and deposition. A vulnerability (V) scoring system was created and linked to different levels of transportation failures (Table 2 and Figure 3). Low levels of vulnerability may lead to small-scale damages, while high levels of vulnerability may indicate that asset failure is likely due to severe erosion or deposition. The vulnerability methods were vetted with towns, field-verified, and found to be accurate predictors of potential damages.

Vulnerability Score	Vulnerability Rank	Likely Failure Mode	Transportation Influence	Distance (miles)	Vulnerability Type
0	Low	None	Road far from river such that vulnerability is unlikely.	N/A	N/A
1, 2	Low	Partial Closure	Single lane closure, reduced capacity with some allowable travel, <24 hours	<0.25	Temporary inundation, minor erosion or deposition
3, 4	Low	Full Closure	Multi-lane closure, detour required, 24 hours to several days	0.25 – 1	Large-scale inundation, localized erosion, localized deposition
5, 6, 7	Medium	Temporary Operational Failure	Partial destruction of facility. Several days to a 1 week for recovery.	0.25 – 1	Severe inundation, erosion, deposition
8, 9, 10	Medium, High	Complete Failure	Complete destruction of facility. 1 week to months for recovery.	Varies	Severe erosion or deposition

Table 2 – Vulnerability Screen Scoring

A criticality (C) score was assembled to represent the consequence of a transportation link failure, the importance of a link to access critical facilities such as a hospital, and how important the road is for local detour use. Simulations were performed to identify the links in the transportation network where failure due to flooding would cause the longest delays or the most number of trip reductions. The probability of failure in the model was derived from the vulnerability score. A high criticality score (i.e., >5) indicates that failure of the link could lead to many failed trips or long delays, access to critical facilities could be reduced, and a local detour route may be cut off.

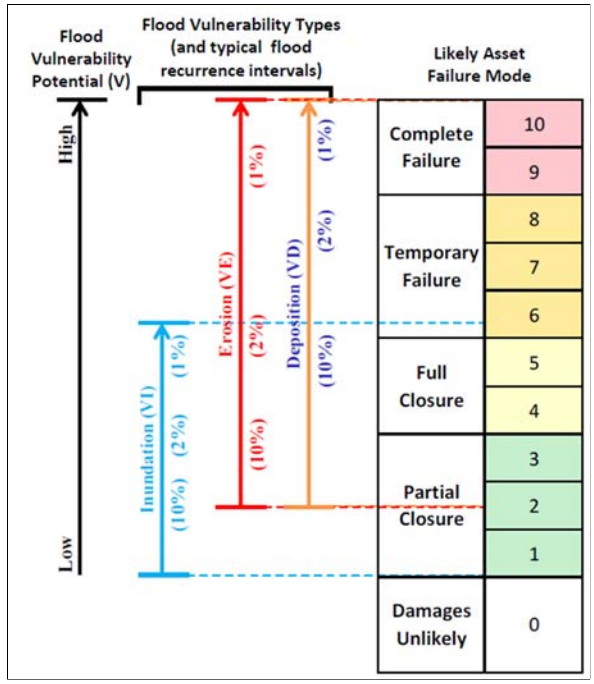

Figure 3 - Flood Vulnerability Screen by Vulnerability Type

The vulnerability and criticality scores were averaged to develop a risk (R) score that can be used to help prioritize actions. High risk locations (i.e., R > 5) may be vulnerable to damages and important for efficient travel, and thus are locations should be addressed sooner and where greater investment may be warranted. Low risk locations (i.e., R < 2) means that V and C are low and the resiliency will not be the primary driver of the need for improvements.

The TRPT identifies mitigation recommendations based on the characteristics that contribute to vulnerability and criticality for each location in the pilot watersheds. A list of initial recommendations is provided to begin an alternatives analysis to reduce vulnerability. Mitigation options include vegetative practices in low risk locations and hard armor stabilization practices in high risk locations. Floodplain reconnection and river corridor conservation are also considered to reduce long-term vulnerability to transportation infrastructure.

The Vermont Transportation Flood Resilience Planning Tool (TRPT) has been created to display results and improve transportation planning. The web-based application is available for use by anyone connected to the internet. Maps show the vulnerability, criticality, and risk results. Variable scores for each road segment or structure may also be viewed to understand what is driving the level of risk. The list of possible mitigation strategies is also provided.

Roads

Roads - 50 Year Storm Configuration							
Rank	**Asset Risk**	**Town**	**Road Name**	**Jurisdiction**	**V**	**C**	**Location**
1	8	Killington	Route 100	State	9	7	Route 100 from Nob Hill Rd. (north end) to Stage Rd (south end)
2	8	Pittsfield	Route 100	State	9	7	Route 100 from Johnson Brook Ln (north end) to Fellows Rd. (south end)

3	7	Rochester	Route 100	State	7	7	Route 100 from Woodlawn Dr (north end) to Route 73 (South end)
4	7	Bethel	Route 107	State	7	7	Route 107 from North Rd (north end) to Cleveland Brook Rd (South End)
5	6.5	Pittsfield	Route 100	State	7	6	Route 100 from Leigh Kelly Dr. (north end) to Pittsfield/Killington Town Line (south end)
6	6	Stockbridge	Route 107	State	10	2	Town Line (north end) to Arnold Mtn Rd. (south end)
7	6	Bethel	Peavine Blvd	Town	10	2	Peavine Park (north end) to Sand Hill Rd. (South End)
8	6	Stockbridge	River Rd.	Town	10	2	Town Line (north end) to Lilliesville Rd. (south end)
9	6	Bethel	Route 107	State	10	2	South of Route 12 (north end) to Town Line (south end)
10	6	Stockbridge	Route 107	State	10	2	Arnold Mt. Rd (north end) to Sweet Ln. (south end)

Table 3: Upper White River watershed high-risk roads

The primary threat to roads in the Upper White River watershed is erosion due to the proximity of roads to steep and erosive river channels. The following roads in the Upper White River Watershed ranked highest in terms of overall risk (Table 3).

Bridges

The primary threat to bridges in the Upper White River watershed is either erosion or deposition. Bridges on steep channels and bends in the river can be prone to scour where banks and the structure foundation can be eroded. In lower power settings where the slope of the channel tends to be flatter, sediment and large wood can drop out of the flow during and after floods leading to bridge clogging. In extreme deposition cases the pre-flood channel can fill with sediment and the river will carve a new path during the flood. This depositional setting can be extremely damaging to nearby infrastructure and has led to many of the complete road and bridge failures observed in the State in the past. The following bridges in the Upper White River Watershed ranked highest in terms of overall risk (Table 4).

							50-year Storm Configuration
Rank	**Asset Risk**	**Town**	**Jurisdiction**	**BR#**	**V**	**C**	**Location**
1	8.5	Rochester	State	00019	10	7	Junction of Route 73 and 100
2	6	Pittsfield	State	00124	10	2	Route 100, just north of River View Trail over Tweed River.
3	6	Hancock	State	00024	10	2	Route 125, just east of Taylor Brook Rd. (over Taylor Brook)
4	6	Hancock	State	00023	10	2	Route 125, just west of Fassett Hill Rd.
5	5.5	Stockbridge	Town		10	1	Davis Hill Rd

6	5.5	Stockbridge	Town		10	1	Fletcher Brook Rd. over Fletcher Brook.
7	5.5	Stockbridge	Town	00005	10	1	Stony Brook Rd.
8	5.5	Bethel	Town	00048	10	1	Old Route 12 (southern bridge over Locust Creek)
9	5.5	Stockbridge	Town	00033	10	1	Fletcher Brook Rd. over Stony Brook
10	5.5	Pittsfield	Town	00011	10	1	Tweed River dr.

Table 4 - Upper White River watershed high-risk bridges

Culverts

The primary threat to culverts in the Upper White River watershed is either erosion or deposition, such as it is for bridges. Culverts on steep channels with large fills across a floodplain are prone to scour due to strong contractions in flood flows. Many culvert failures (i.e., washouts) take place due to erosion of the road embankment that they pass through since culverts traditionally were undersized relative to the river channel. New standards requiring larger culverts are allowing more culverts to pass flow, sediment, large wood, and ice during floods. Many culverts are prone to accumulating sediment and large wood due to their small size relative to the channel width and floodplain width. Many culverts clog during floods when trees, limbs, and sediment block the inlet opening. The following culverts in the Upper White River Watershed ranked highest in terms of overall risk (Table 5).

					Culverts - 50-year Storm Configuration
Rank	**Asset Risk**	**Town**	**V**	**C**	**Location**
1	6.5	Pittsfield	6	7	Route 100, South of Johnson Brook Ln.
2	6	Stockbridge	10	2	South of Notown
3	6	Stockbridge	10	2	Route 107, south of Guernsey Hollow Rd.
4	6	Rochester	5	7	Bethel Mountain Rd. East of South Hollow Ln.
5	6	Rochester	5	7	Bethel Mountain Rd. over Nason Brook.
6	5.5	Stockbridge	10	1	Davis Hill Rd.
7	5.5	Bethel	10	1	Bryant Rd, west of junction with Campbell Rd.
8	5.5	Rochester	10	1	River Brook Dr.
9	5	Killington	3	7	Route 100, North of Doubleday Hill Rd.
10	5	Royalton	6	4	Rousseau Rd.

Table 5 - Upper White River watershed high risk culverts

Reducing Flood Risk

Reducing Risk through Mitigation

A list of possible mitigation strategies is provided in the TRPT to begin the alternatives analysis of solutions to improve resiliency. The strategies are grouped in the following categories, with examples.

- **Fortify infrastructure or river channel**

- **Bank stabilization** – For high risk locations where river-road conflicts cannot be avoided, innovative rip rap solutions such as stacked toe walls may be necessary to protect infrastructure.
- **Riparian buffer plantings** – Planting native tree and shrub species to restore riparian habitat, provide floodplain roughness and cover along banks, and stabilize bank erosion. This method is particularly useful in lower risk streams.
- **Improve channel roughness** – By adding woody debris and vegetation in the channel and on the floodplain, stream flow energy can be reduced due to increased roughness and friction.

- **Address resiliency**
  - **Bridge & Culvert Replacement** – Improperly sized bridges and culverts are often unable to handle the effects of a flood, which can result in water running over or around them, or undermining them due to bed erosion, and ultimately may be washed out. By upgrading undersized structures, the potential for damage can be reduced.
- **Restoration**
  - **Stream bed restoration** – Installing weirs can stabilize the streambed by adding "plunge pools" which can dissipate energy in the stream channel. A stabilized stream bed can improve floodplain access.
  - **Wetland restoration** – By repairing wetlands lost to "ditch and drain" practices, floodwater and sediment storage is improved.
  - **The creation of new floodplain** - Improved flood access provides more space for flood storage and sediment deposition.
- **Relocate or remove**
  - **Road relocation** – Relocating vulnerable infrastructure reduces the potential for conflicts between man-made development and the river's natural need to adapt and move.
  - **Bridge & Culvert Removal** – Removing abandoned bridges and culverts can improve channel stability and overall water quality.
- **Change land use**
  - **Easements (Conservation and ANR River Corridor)** – By preserving large tracts of land and restricting future encroachments, rivers are provided with room to reach equilibrium.

Reducing Risk through Mitigation Policy and Planning

In addition to active mitigation projects, improved policy and planning initiatives are essential parts of promoting flood resiliency. State agencies, regional organizations and municipalities are all expected to take an active role in improving the statewide response to severe flooding events and planning for future flood protection.

As an incentive to encourage good mitigation policy and planning, the state has created the Emergency Relief and Assistance Fund (ERAF) that provides State funding to match Federal Public Assistance after federally-declared disasters. Eligible public costs are reimbursed by federal taxpayers at 75%. For disasters after October 23, 2014, the State of Vermont will contribute an additional 7.5% toward the costs. For communities that take specific mitigation planning and policy related steps to reduce flood damage the State will contribute 12.5% or 17.5% of the total cost. This additional match can result in a significant reduction in municipal contribution in the event of a federally-declared disaster (Table 6).

	7.5% ERAF Rate	12.5% ERAF Rate	17.5% ERAF Rate
Federal Share	$750,000	$750,000	$750,000
State Share	$75,000	$125,000	$175,000
Municipal Share	**$175,000**	**$125,000**	**$75,000**
Total Damages	$1,000,000	$1,000,000	$1,000,000

Table 6 - ERAF rates and Municipal Cost Share based on $1,000,000 in damages from a federally declared disaster

Communities have several tools at their disposal such as adoption and adherence to Road and Bridge Standards that improve flood resilience, the adoption of River Corridor protections in their zoning bylaws, maintaining an up-to-date Local Hazard Mitigation Plan, and participation in the National Flood Insurance Program. Table 7 shows the various tools towns have adopted and the corresponding ERAF rate.

	12.5% ERAF Rate (must adopt all four)				*17.5% ERAF Rate*
Town	NFIP Standards	Road & Bridge Standards	Local Emergency Operations Plan	Local Hazard Mitigation Plan	River Corridor Protection
Barnard	Yes	Yes	Yes	Yes	Yes
Bethel	Yes	Yes	Yes	Yes	No
Bridgewater	Yes	Yes	Yes	Yes	No
Chittenden	Yes	Yes	Yes	Yes	No
Goshen	Yes	Yes	Yes	Yes	No
Granville	Yes	Yes	Yes	Yes	Yes
Hancock	Yes	Yes	Yes	Yes	No
Killington	No	Yes	Yes	Yes	No
Mendon	Yes	Yes	Yes	Yes	No
Pittsfield	Yes	Yes	Yes	Yes	No
Rochester	Yes	Yes	Yes	Yes	No
Royalton	Yes	Yes	Yes	Yes	No
Stockbridge	Yes	Yes	Yes	Yes	No

Table 7 - Status of Mitigation policy and planning in Upper White River watershed communities, 2017

Vermont Town Road & Bridge Standards (VTRB)

Act 110 of the 2009-2010 Legislative session required that the Vermont Agency of Transportation work with municipal representatives to "revise the Agency's current recommended town road and bridge standards to include a suite of practical and cost-effective Best Management Practices (BMPs) for the construction, maintenance, and repair of all existing and future town highways in order to address pollution caused by transportation-related stormwater runoff." VTRB Standards are minimum standards that represent best minimum practices to address transportation safety, design, construction and maintenance. Additionally, by design, these standards are intended to help minimize roadway runoff, protect water quality and address future bridge and culvert flood resilience. Adoption of the VTRB and an annual letter of certification signed by the Town, ensures that FEMA will provide funding to upgrade existing sub-standard roads, bridges or culverts that are damaged in a federally declared disaster.[2]

River Corridor Protections

Many of the locations damaged during Tropical Storm Irene were well outside of mapped Flood Hazard Areas based on inundation alone. Many streams experienced erosion and deposition damage due to confined flow with high velocity. The Legislature created the ability for communities to limit development within the River Corridor Area. The River Corridor includes both the river/stream channel and the adjacent land area needed for the river to establish and maintain "equilibrium" conditions. Some communities have adopted River Corridor protections that prohibit, or limit new development in this highly dynamic and vulnerable location on the landscape.

Hazard Mitigation Plans

To ensure that communities are actively planning for future flood events (and other significant hazards), communities maintain Local Hazard Mitigation Plans (LHMP). The LHMP is a broad-based plan for each town that assesses hazards (including flooding) and proposes mitigation measures to lessen their vulnerability to those with the most impact. Communities that have FEMA approved LHMP are eligible to apply to the Vermont Division of Emergency Management and Homeland Security for HMGP mitigation grants administered by FEMA. LHMPs expire every five years and RPCs are available to help towns re-adopt these plans. Additionally, mitigation plans are eligible for points under the National Flood Insurance Program's Community Rating System (CRS). The TRPT could help municipalities identify bridges, culverts and road embankments for funding through the HMGP program.

National Flood Insurance Standards

Uncontrolled development within flood hazard areas can exacerbate the impacts of flooding; cause significant damages to property and infrastructure, and potentially put lives at risk. While many locations that experience significant damage during flood hazard events are outside of the mapped FEMA floodplain, a community's commitment to protecting life, property and the natural environment from flooding is demonstrated through participation in the NFIP. Communities that adopt and enforce FEMA's NFIP standards can control the types and design of development that occur within the floodplains.

Water Quality Planning and Project Identification

Municipal Roads Stormwater General Permit

In 2016 the Vermont Legislature passed a law specifically focused on reducing the environmental impacts of stormwater runoff. A primary component of this law is the Municipal Roads Stormwater General Permit (MRGP), which is administered by the Vermont Department of Environmental Conservation. As a requirement of the MRGP Municipalities must develop a Road Stormwater

[2] The standards within the VTRB that address water quality are being superseded by standards within the Municipal Roads General Permit required by Act 64, the Vermont Clean Water Act. Municipalities must apply for the MRGP by July 31, 2018. More information on the MRGP is provided below. Adoption and compliance with the VTRB, which will continue to provide flood resilience standards, will still be required to ensure FEMA funding can be used to upgrade sub-standard roads, bridges and culverts damaged by a flood.

Management Plan (Road SWMP). The Road SWMPs include two components; a comprehensive Road Erosion Inventory (REI) of "hydrologically-connected" road segments and associated Implementation Plan. The purpose of the Implementation Plan is to bring non-complying road segments up to MRGP Standards as soon as possible, but no later than 12/31/2036.

Compliance with the MRGP presents communities with an opportunity to improve flood resiliency as well as water quality. Many of the roads that are identified as having erosion issues during the inventory process are likely to be subject to damage during a severe flooding event. While inventorying roads, municipalities can do an overall assessment of needs that will help prioritize flood resiliency improvements.

Hydrologically Connected Roads

The criteria that defines a road as "hydrologically connected" are:

- Municipal roads within 100' of a water resource
- Municipal road that crosses and drains into a water source
- Municipal road located within the mapped River Corridor area
- Catch basin outfalls within 500' of a water resource and those segments associated with those outfalls.

The MRGP will require replacement or stabilization retrofits for eroding road drainage culverts, intermittent stream culverts, and driveway culverts located within municipal right-of-ways. Upsizing culverts, improving culvert headwalls/headers, stabilizing drainage ditches and culvert outlets and mitigating catch basin outfall erosion will be among the tasks required to meet MRGP standards. Communities can utilize a prioritized list of necessary repairs which can be integrated into municipal planning and budgeting. The prioritization of infrastructure investments should be part of a locally adopted Municipal Plan. For communities with an adopted Capital Budget and Program, a prioritized plan for road improvements can be incorporated and budgeted for.

Investments in transportation infrastructure will improve water quality, and reduce the potential for severe damage and loss during a severe flooding event. In turn, improved flood resiliency will reduce future costs for repair, and limit the potential for loss of life and property throughout the watershed.

Buyouts and Infrastructure Protection

One way to reduce the risk of damage to transportation infrastructure is to identify properties that are prone to damage that may have a direct impact on roads, bridges and culverts (Figure 4). During extreme flooding events, flood-prone structures can suffer catastrophic failure. A house that is located too close to a river, for example, can be swept into the floodwaters, traveling downstream until it meets a bridge or culvert. The effect of a large mass plugging a bridge inlet can result in bridge or road failure.

Figure 4 - Example of a floodprone property that puts infrastructure at risk. East Orange Branch of the Waits River in West Topsham. Source: Google Maps.

The Federal Emergency Management Agency (FEMA) maintains a program through which flood-prone properties can, in the event of a federally declared disaster, be purchased for the purposes of removing the structure and permanently conserving the property. FEMA pays 75% of the value of the flood-prone property, and the remaining 25% is handled by the landowner or possibly through other federal and state funding such HUD CDBG-DR and VHCB. It should be noted that the FEMA buyout program only covers properties that are in the mapped floodplain.

To prepare for future buyouts, communities should inventory previously flood-prone properties and prioritize them based on their public benefit as it relates to transportation infrastructure. Priority should be given to:

- Buildings that could cause damage to transportation infrastructure during catastrophic failure
- Are located on a road segment that only serves the flood-prone structures

Communities may also want to consider developing a contingency fund for the purpose of providing the necessary level of match to complete a buyout. Because flood-prone properties outside of the mapped floodplain are not covered under FEMA's buyout program, communities or the state may want to consider allocating enough funding to conduct their own buyouts. While bearing the full cost of a buyout might not be preferred, it is important to weigh the cost benefit of the buyout vs. the cost of repeatedly repairing or reconstructing infrastructure that fails due to the flood-prone property. Also a local or state program can eliminate much of the paperwork required by the federal government and prioritize sites outside of the mapped floodplain that may impact infrastructure. An average FEMA buyout from TSI Irene cost $10,000 in administrative costs (TRORC TSI State Buyout Manager). The TRPT could help municipalities identify buyouts that would improve bridges, culverts and road embankments flood resiliency.

Removing Vulnerable Infrastructure

Many communities have damage-prone road segments that regularly require repair due to inundation, erosion, or deposition. To address these problem areas, communities should consider discontinuing or moving a road segment where feasible. If a damage-prone road serves a limited number of floodprone homes and has very low traffic volume, it may be financially sound to buy out the floodprone homes and discontinue the road. Communities should also consider if there is adequate access through alternative safe routes to properties. This may also provide reasonable justification to discontinue the road.

In some instances, it is possible to move a road segment away from a river or stream. Moving roads is expensive (Table 8), and thus careful planning and analysis is necessary.

Gilman Rd. Relocation, Royalton	
Administration & Engineering	$103,464
Stream Bank Stabilization	$408,059
Moving Road	$226,609
Total	$738,132

Table 8 - Costs for moving an 850ft (1/6mile) segment of Gilman Rd. 40ft in Royalton. Does not include procurement of adjacent property.

Communities may want to proactively identify road segments that have the potential to be moved. Look for areas where the adjacent topography would allow for moving a road segment with minimal ground work to minimize costs. In areas where the landscape makes it feasible to move a road, communities should identify ownership of adjacent properties and determine what reasonable compensation would be for the land necessary to accommodate the change. The next step would be to engage a professional to develop an estimate of potential costs for moving the road. This information will provide a general cost for such a project, allowing for the development of a benefit-cost analysis to determine if the cost of maintaining the road in its current location is more than the cost to move the road.

Most communities will need to use multiple funding sources to balance the cost to the community with the overall cost of the project, typically through federal programs such as the FEMA Hazard Mitigation Grant Program, or Community Development Block Grant Disaster Relief funding. Each of these programs is tied to a federally declared disaster. If federal funding is made available due to a federally declared disaster, it may become much more feasible to move a road segment. It is essential that communities maintain good records that document previous damage and repair work. Documentation must include photos and an accurate accounting of time and materials needed to repair damages.

Communities that have identified a road that can be moved should engage in advance planning to be prepared if a funding opportunity arises. To start, the identified road segment should be highlighted in the Municipal Hazard Mitigation Plan. This would include identifying the location of the segment to be moved, an overview of past damages and a summary of potential approaches to moving the road, with an eye toward reducing or eliminating long-term risk. Following the hazard mitigation planning process, the next step would be to have an engineer conduct a scoping study that will clearly identify the preferred alternative to leaving the road in place. With an identified alternative in place, a municipality will be well positioned to tap into available funding more quickly.

It is important to recognize that even with federal disaster assistance funding, a project as significant as moving a road will be expensive. Creating a reserve fund specifically for providing necessary match, or for purchasing the property needed to improve mitigation is recommended.

Site Examples

Three site examples identified in the TRPT from the Upper White River Watershed follow that will protect local transportation assets and improve the transportation network resilience. The site examples include:

- Mitigation options at a high-risk site along Vermont Route 100 where erosion damages have taken place due to flooding on the Tweed River in Pittsfield and Killington;
- Mitigation options at a moderate risk site on Vermont Route 100 due to inundation and deposition on the Tweed River in Stockbridge; and
- Previous bankfull width culvert replacements completed by the White River Partnership and others.

High-Risk Site along Vermont Route 100 along the Tweed River in Pittsfield and Killington

The Tweed River valley in Killington and Pittsfield is mostly narrow due to the mountainous setting and additional confinement by the road embankment. In many cases, the small natural floodplains in the narrow valley have been disconnected from the river channel as the river has cut down (i.e., incised) due to erosion. The Tweed River along Vermont Route 100 is very erosive as it has a lot of (stream) power to move sediment and is overly confined.

During Tropical Storm Irene, the erosive nature of the Tweed led to loss of several sections of the Vermont Route 100 road embankment. High velocity flows that could not spread into a floodplain gouged holes in the road embankment to make new floodplain (Figure 5). Small culverts and bridges were washed out.

Figure 5: Failure of the Vermont Route 100 road embankment due to erosion during Tropical Storm Irene in Pittsfield. (Source: Mansfield Heliflight, 2011)

The Vermont Transportation Flood Resiliency Planning Tool (TRPT) shows high and moderate risk sections of Vermont Route 100 along the Tweed River (Figure 6).   The vulnerability due to erosion is high (10 out of 10). Stream power is moderate (123 Watts per square meter) and a long portion of the road segment is in the river corridor (1,464 feet). More than 10% of the floodplain is filled by the road embankment that is leading to high vulnerability. Road sections near Stage Road and Hadley Lane are the most constricted (V = 9 out of 10), lead to severe transportation consequences if damaged (C = 7 out of 10), and thus have the highest risk in the area (R = 8 out of 10).

This Due to the high power and erosive setting along Vermont Route 100 identified in the TRPT web application, the mitigation strategies that can protect the road, bridges and culverts require rigid stabilization using large rock. Although vegetative practices are preferred to naturalize the river, the high flood velocity in the area will erode roots and soils so rock is needed to protect the road. Practices such as armoring all or part of the riverbanks while maintaining the channel bankfull width; armoring the bed with weirs, stone riffles, or full bed armoring; or installing local scour protection at bridges and culverts are needed to protect the transportation network (See the “Strategies” drop down menu in the TRPT web application). A truly resilient design approach will address the root problem in the area – reducing confinement and reconnecting floodplain. This last practice is the top recommendation to improve conveyance of flood flows and reduce the process of erosion.

Emergency bank armoring took place along several sections of Vermont Route 100 following Tropical Storm Irene as short-term, temporary repairs to get the road open. The armoring allowed for rebuilding of the road embankment and provided temporary stabilization. Unfortunately, this approach also narrowed the river channel below the bankfull channel width that led to a higher potential for erosion. Many river channel stabilization practices inadvertently increase future risk, yet do not rectify the primary problem such as incision (Figure 7).

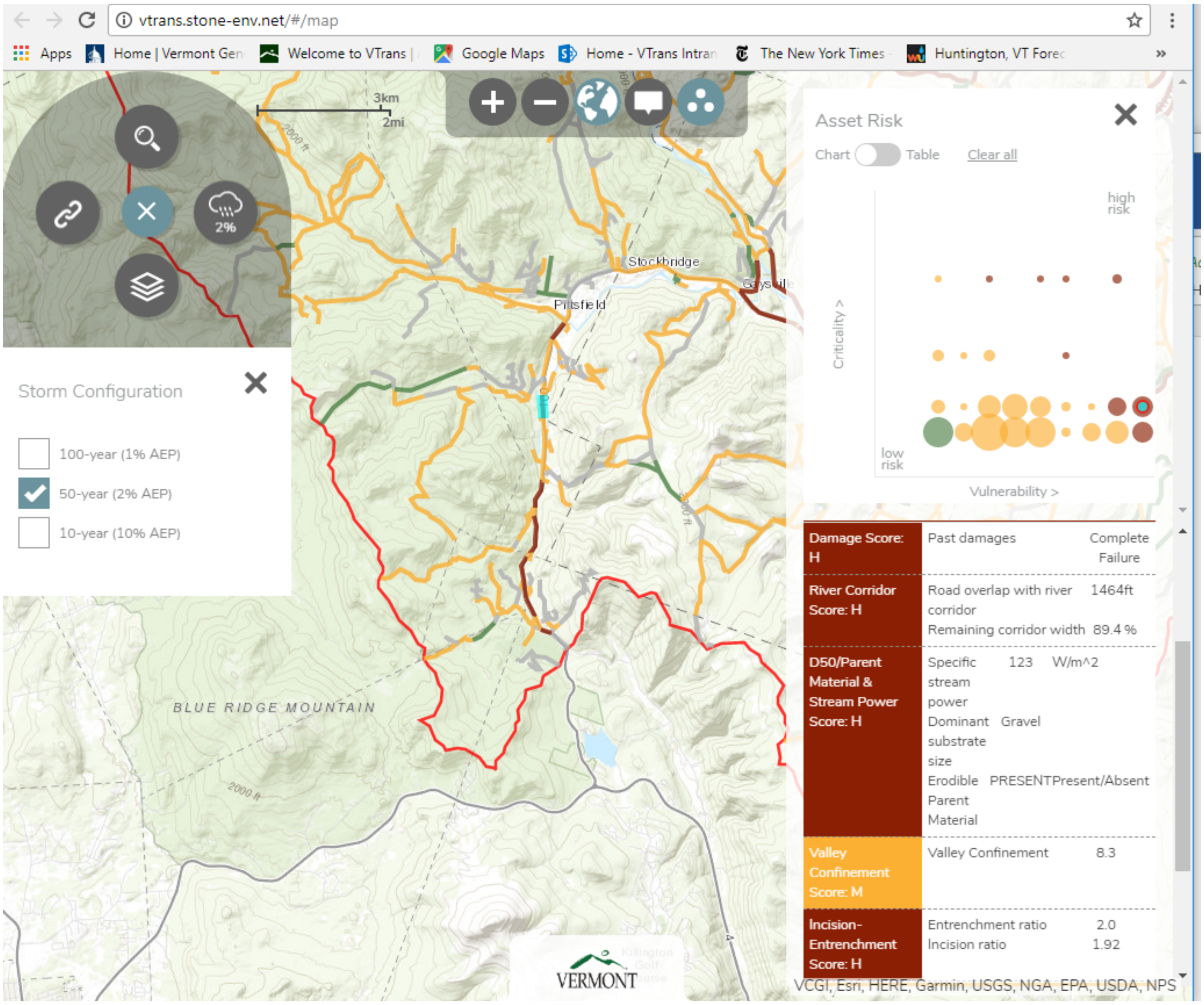

Figure 6: Screen shot of the TRPT that shows high risk along Vermont Route 100 road embankment due to erosion in Pittsfield. See inset for project area south of Pittsfield. (Source: Vermont Transportation Resilience Planning Tool, exported 2/14/2018)

Figure 7: Incision and floodplain disconnection due to confinement on Tweed River following Tropical Storm Irene in Killington, Vermont. (Source: MMI, 2012)

With the understanding of the driving processes behind the vulnerability a mitigation project was designed to both protect the road and reduce erosion. Bed armoring was installed to elevate the channel to pre-flood levels and reconnect floodplain (Figure 8). The over-steepened bank armoring that spilled into the river channel was pulled back to restore the bankfull channel width. The bank armoring was re-installed at a shallower slope and the lower portion was covered with grubbings and then seeded to restore riparian vegetation. Proper sediment and erosion controls were used during installation of this aggressive alternative to minimize construction impacts. The practice has been installed for nearly four years and is stable. The reconnected floodplain has been accessed several times.

Figure 8: Elevated channel via bed armoring right after construction. Note the reconnected floodplain and the gentler side slope of the road embankment. (Source: Fitzgerald Environmental, 2013)

Moderate Risk Site on Vermont Route 100 along the White River in Stockbridge

The White River valley in Stockbridge has some areas where the channel is connected to its floodplain and the road is near the elevation of the river channel. This setting leads to an area that is prone to inundation and deposition during high flows.

During Tropical Storm Irene, the depositional nature of the White River and connection to floodplain led to temporary inundation and minor damages along a portion of Vermont Route 100. Flood waters overtopped the road embankment, overtopped the bridge, and damaged pavement. Travel was reduced to a single lane while repairs were made (Figure 9).

Figure 9: Road repairs following inundation and deposition damages during Tropical Storm Irene. (Source: VTrans, 2011)

The TRPT shows moderate risk sections of Vermont Route 100 in this location (Figure 10). The vulnerability to the road embankment is moderate due to deposition (4 out of 10) and inundation (3 out of 10). The vulnerability is due to a long length (i.e., 1,326 feet) of the road in the floodplain, the road surface being located 2.9 feet below the 100-year flood level, 20% of the river corridor being filled, low stream power, and the road being located near a confluence location. Confluence areas are known to have dynamic channels in deposition-prone locations. The bridge on Vermont Route 100 is vulnerable to inundation. Although the bridge is nearly double the bankfull channel width (structure width / bankfull channel width = 194%), the bridge has had temporary failure in the past due to clogging with sediment and debris. The road and bridge have moderate criticality (C = 2) and risk (R=3) as they are locally important, but are easy to bypass if flood damage takes place and are not near critical facilities.

The recommended mitigation strategies that can protect the road, bridges and culverts in this location include restoring floodplains to allow more storage and less impacts on infrastructure. Perhaps the road could be elevated, but that should be done with caution as this approach would cut off floodplain and increase downstream risk where vulnerability is higher. Floodplain restoration near and upstream of this site would also allow for more dispersed sediment, large wood and ice storage to reduce clogging at the bridge during floods. The floodplain restoration could take place further upstream along the White River and its tributaries.

Vegetative practices are recommended to naturalize the river corridor and to provide hydraulic roughness to slow floodwaters, and capture and store sediment. This will reduce the likelihood of channel avulsion and improve water quality. (See the “Strategies” drop down menu in the TRPT web application). A truly resilient design approach will enhance floodplain connection near the study site and further upstream.

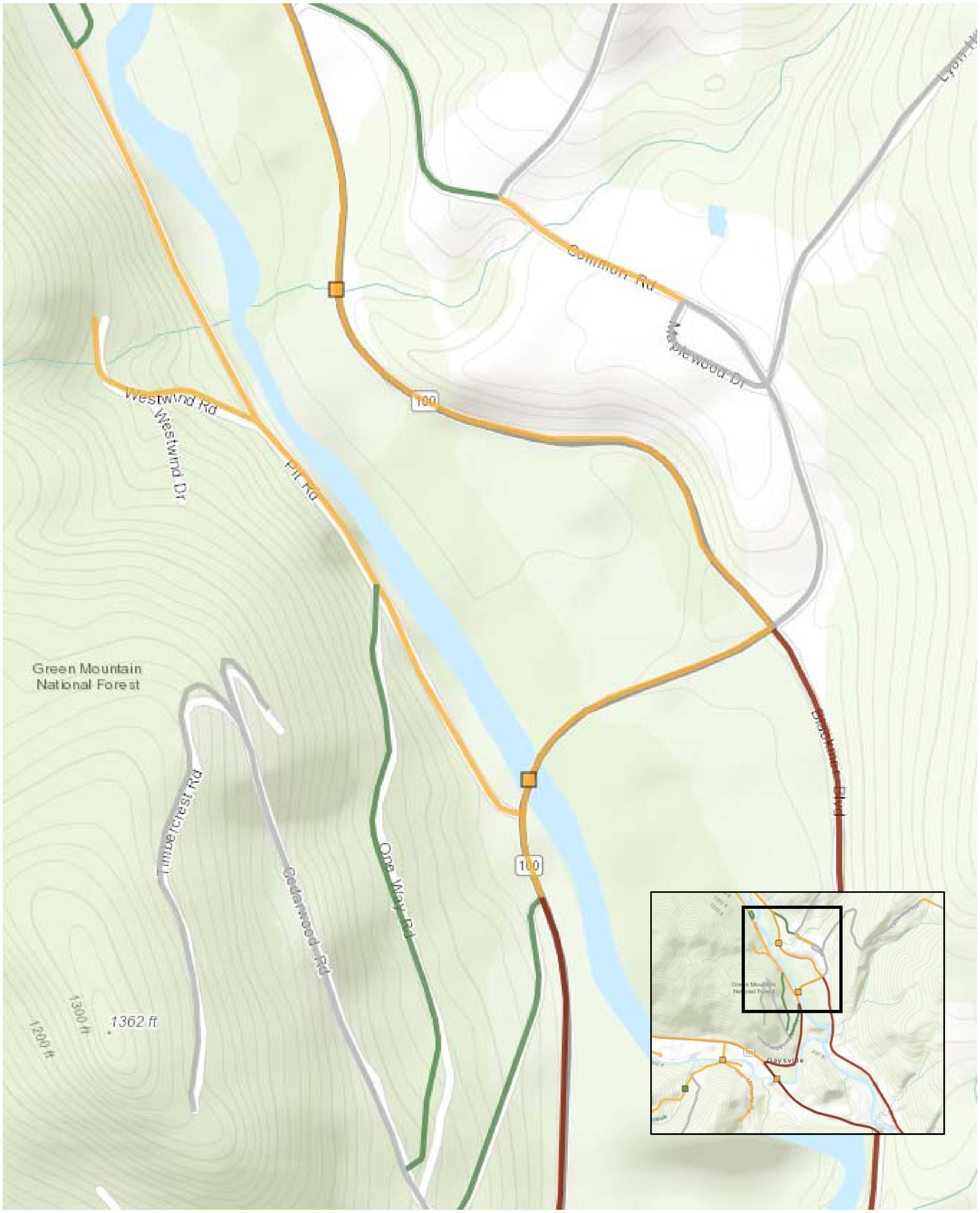

Figure 10a: Results of the Vermont Transportation Resilience Planning Tool that show moderate risk along Vermont Route 100 due to inundation and deposition in Stockbridge. See inset for project area. (Source: Vermont Transportation Resilience Planning Tool, exported 3/13/2018).

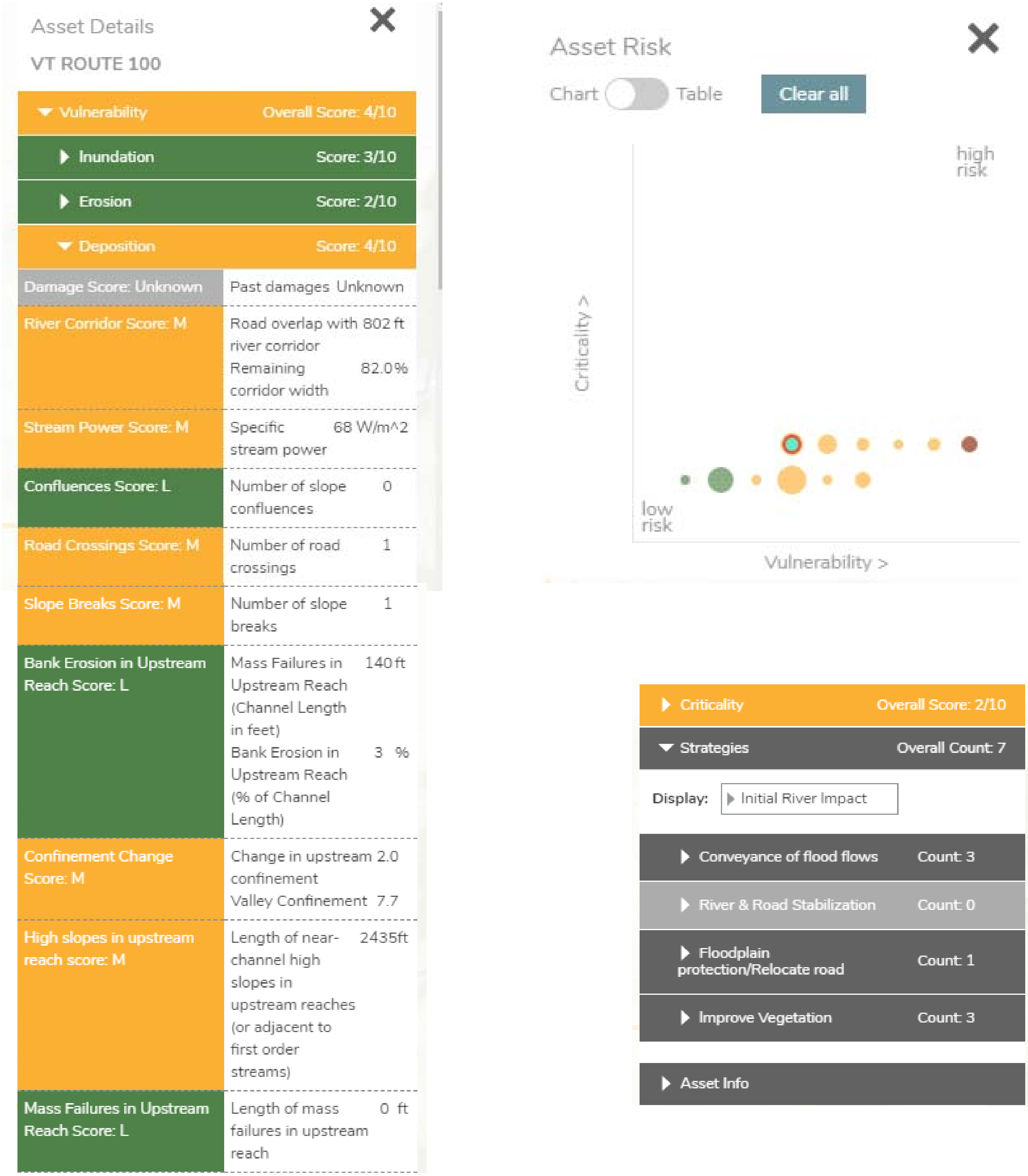

Figure 10b: Clips of data details from the TRPT, exported 3/23/2018).

Culvert Replacements in Rochester

(Adapted from the White River Partnership (WRP) website http://whiteriverpartnership.org/fish-passage/.)

In Rochester, Tropical Storm Irene blew out numerous under-sized culverts and bridges. From 2011 – 2014 the WRP worked with the town and multiple partners, including the US Fish & Wildlife Service, US Forest Service, and Trout Unlimited, to put in six (6) properly sized crossing structures in three impacted stream systems: Oak Lodge Road and Fiske Road on Howe Brook (Figure 11); North Hollow Road and Marsh Brook Road on Marsh Brook; and Moose Run and Woodlawn Cemetery on Nason Brook.

Almost all of Rochester's high-elevation streams overflowed their banks during Tropical Storm Irene. As a result, every culvert and bridge failed in three stream systems that flow into the main stem of the White River, causing massive damage to the town road system, private residences, and a cemetery located along the stream corridors. These damages were a primary focus for USFWS technical experts, who designed replacement structures for 6 culverts that failed during the flood. With funds from the USFWS, USFS, Orvis/Trout Unlimited, and private foundations, the WRP worked with the town of Rochester, FEMA, and the state of Vermont to replace the 6 flood-damaged culverts with stream crossing structures designed to accommodate a 100-year flood event as well as the passage of debris, ice, and aquatic organisms. These projects would not have completed without additional funding from federal and private sources outside of the typical FEMA, VTrans, and town funding streams as well as the coordination by the WRP.

The TRPT shows that each of these culverts has a percent bankfull channel width of larger than 100%. In other words, the culverts fit the channel that they are located in and are able to pass flood flows, along with sediment, large wood and ice.

The WRP replacement structures still show some vulnerability in the TRPT as the records for past damages remain connected to the structures. A decision was made to retain past damage records that will increase vulnerability even if improvements were made to a structure or road segment. This is a conservative planning approach since the sites may remain vulnerable to erosion or deposition, even with recent improvements, due to the geomorphic setting. Field verification will illustrate if vulnerability has been addressed for the life cycle of the new structure or other mitigation practice.

Figure 11: Fiske Road culvert on Howe Brook before (left) and after (right) replacement in 2014. Source: White River Partnership.

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The North Branch of the Deerfield River Watershed Case Study
August 27, 2018

Introduction

The Transportation Flood Resilience Planning Tool (TRPT) (Schiff et al., 2018) is a web-based application that identifies bridges, culverts and road embankments within a watershed that are vulnerable to damage from floods; estimates risk based on the vulnerability and criticality of roadway segments; and identifies potential mitigation measures based on the factors driving the vulnerability. The TRPT was developed by the Vermont Agency of Transportation (VTrans) with consultant assistance and with significant input from regional, local and state agency partners.

The North Branch of the Deerfield River is one of three pilot watersheds used to develop and validate the TRPT. This case study provides an overview of the North Branch of the Deerfield River Watershed; summarizes the vulnerability, criticality and risk concepts in the TRPT; demonstrates how the TRPT can be used to rank needs; and presents two examples that demonstrate how the TRPT can be used to inform decisions to improve the resilience of the transportation system to flooding and erosion.

Watershed Overview

The headwaters of the North Branch Deerfield River watershed are located on the eastern slopes of the Green Mountains (Figure 1). The watershed that feeds the North Branch covers a land area of 35,840 acres in five communities – Dover, Marlboro, Somerset, Stratton, Wardsboro and Wilmington. The majority (over 90%) of the area is forested or in agriculture, with only 1% developed. The most concentrated development is located within the Village of Wilmington.

Dover and Wilmington are characterized by mountainous terrain with steep slopes. Much of the development within Dover is concentrated in the floodplains around the river and its tributaries. The prevailing pattern of development is influenced heavily by the presence of the Mount Snow ski resort. The communities in the North Branch Deerfield River Watershed have a combined population of 5,551[1]. There are 329 established businesses located in the watershed municipalities that employ roughly 4,800 people. The largest employers are Mount Snow, Hermitage Club and Southeast Vermont Transit. The majority of residents commute to employment centers outside of the watershed (specifically to Brattleboro, the greater region's largest employment center) that means access to transportation routes (Table 1) is vital.

Mount Snow and the Hermitage Club attract tourists to the area year-round offering skiing, golfing, boating and other seasonal sports. The most direct route to these recreational amenities is via Route 9, particularly if guests are coming from the south. Should Route 9 experience flood damage within the North Branch watershed, it would impact the region from an economic standpoint. Travel from the north is possible via Route 100 but the route is not direct and would not be as desirable during the winter months.

[1] US American Community Survey, 2012-2016

Significant Transportation Routes - North Branch Watershed				
Road ID	**Owner**	**Classification**	**AADT**	**Importance**
VT 100	State	Minor Arterial	1,300-5,300	Primary north/south route in study area
VT 9	State	Principal Arterial	4,900-9,900	Important east/west connector from I-91 to Bennington
Local Roads	Town	Local		

Table 1 –Transportation routes in the North Branch of the Deerfield River Watershed

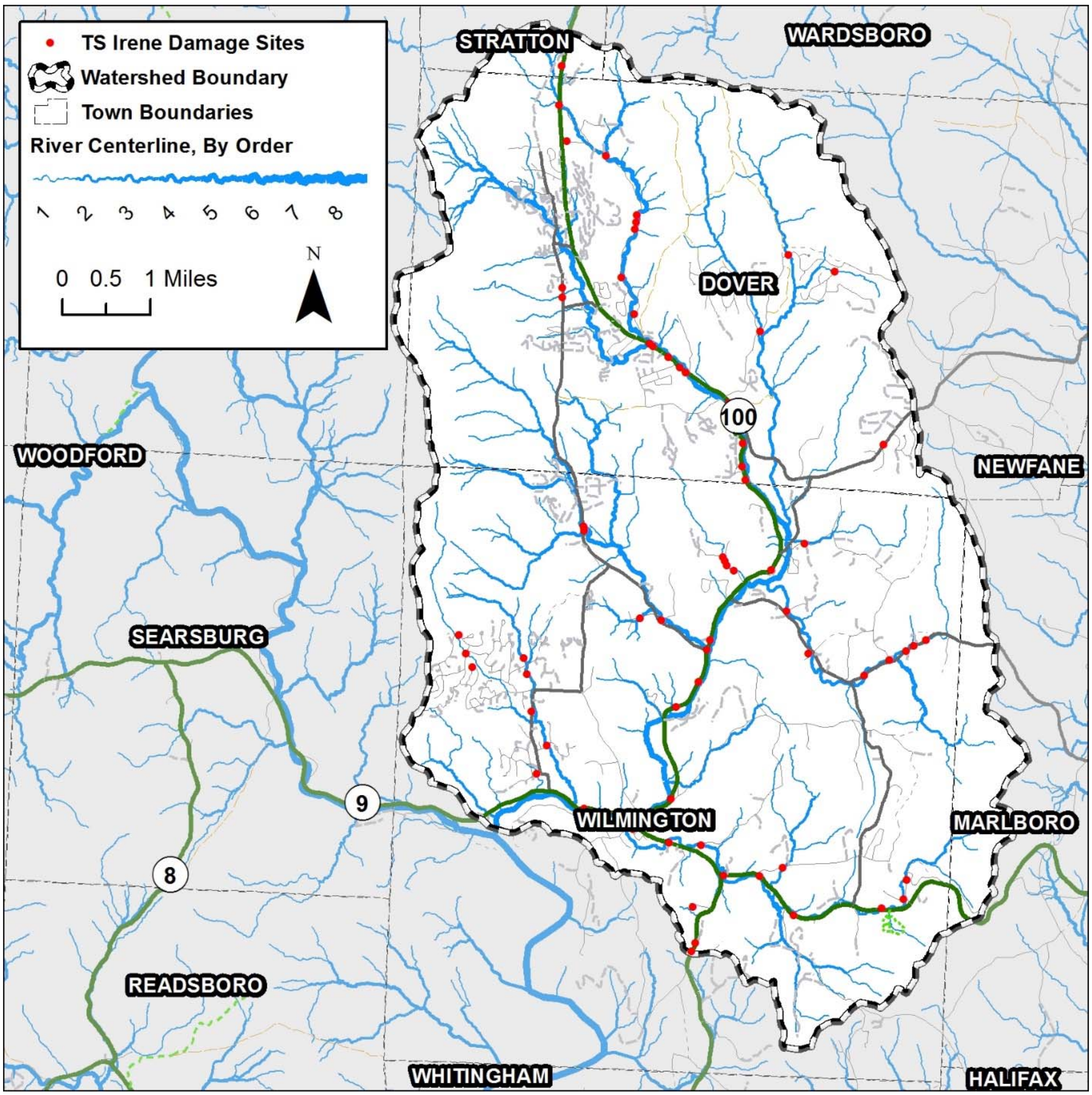

Figure 1 - North Branch of the Deerfield River Watershed

The North Branch Deerfield River and its tributaries cover over 149 miles within the 56 square mile watershed. Coupled with over 175 miles of roads, there are inevitably areas where waterways and roadways will conflict during flood-related events. This was no more apparent than on August 28, 2011, when the State of Vermont found itself in the path of Tropical Storm Irene. The storm caused power outages statewide for approximately 50,000 households and widespread flooding that resulted in six deaths. Record amounts of rain fell in a short period of time resulting in widespread flood and erosion damages. Rainfall totals were between 4 and 7 inches with some locally higher amounts up to 10 inches concentrated during a 6 to 8-hour period.

The Otter Creek reached an historic crest (nearly 4 feet over the previous record in 1938) and the Mad, Winooski and White Rivers were very close to records established in 1927. Those mainstem rivers were fed by many smaller tributaries that caused damaging flash flooding throughout the central and southern parts of the state. More than 1,500 Vermont families were displaced and transportation and public infrastructure was severely damaged in many towns. Of Vermont's 251 municipalities, 223 were impacted by Irene causing household damage, infrastructure damage or both. Forty-five (45) municipalities were considered severely impacted, three of them (Dover, Marlboro and Wilmington) have lands within the North Branch Watershed.

Hundreds of state and local roads were closed for extended periods of time completely isolating numerous towns and limiting access to many others. This resulted in state and National Guard missions to deliver emergency supplies by ground and air. The flooding also caused the first-ever evacuation of the State Emergency Operations Center due to access challenges and the impact to the buildings and support mechanism in the state office complex in Waterbury.

Some of the most severe damage from Irene took place in Wilmington (Figure 2). Several towns found themselves completely isolated geographically and technologically. Electrical services to the towns had been broken. Telephone and cellular communications were predominantly down. In Southern Vermont, damage from erosion and flooding devastated much of the area, hitting the North Branch and Whetstone Brook particularly hard, disrupting travel and destroying important community assets.

Figure 2 – Flooding along VT Route 9 in Wilmington. Photo Source: Town of Wilmington

The need for increased flood resiliency throughout Vermont's communities and along the transportation system was obvious after Irene. Since 2000, Vermont has twenty-four (24) federally declared disasters related to severe storms and flooding. While most severe flooding events in Vermont do not produce damages that are as widespread as during Tropical Storm Irene, the local damages are severe, disrupting, and costly.

Watershed Partners

The North Branch Deerfield River Watershed contains several important partners who work together to implement flood mitigation and watershed protection strategies. Watershed protection requires effort from multiple partners to increase flood resiliency of infrastructure and private property. This work must be done across municipal jurisdictions and in a coordinated way.

Vermont Agency of Transportation (VTrans)

VTrans manages and maintains State highways, bridges and culverts primarily along Route 9. There are 20 miles of state roads, 11 bridges, approximately 23 large culverts (short structures that have widths between 6 and 20 feet), and approximately 300 small culverts (ultrashort structure that have widths less than 6 feet) owned and operated by the State in the North Branch Deerfield River watershed. VTrans supports the backbone of the transportation network, on which the extensive local road network (99 miles) is built. In addition to managing the state system, VTrans provides funding and technical assistance to municipalities to support bridge, culvert and roadway improvements, and works closely with regional planning commissions on planning, outreach and project prioritization. See A Handbook for Local Officials (a.k.a. the "Orange Book" for more information http://vtrans.vermont.gov/sites/aot/files/operations/TheOrangeBook.pdf) (VTrans, 2009).

Agency of Natural Resources (ANR)

All the departments and divisions within ANR work collaboratively on a range of watershed assessment, restoration and protection projects. The Department of Environmental Conservation (DEC) is responsible for the development of the Deerfield River Tactical Basin Plan (VTANR, 2014). DEC also helped establish river corridor easements and zoning across the watershed.

Windham Regional Commission

WRC is an association of twenty-seven municipalities in southeastern Vermont, governed by a Board of Directors appointed by each member town. The Commission provides technical assistance to municipalities, coordinates the Region's planning and policy with state and federal levels of government and collaborates with the region's non-profits and businesses, including watershed related programs such as:

- Disaster recovery assistance to municipalities
- Emergency Management
- GIS Services
- Land Use Planning
- Transportation Planning

Municipalities

Municipalities within the North Branch Deerfield River watershed have an important role in resource protection and in improving the resilience of the transportation system. Through municipal land use planning and regulation, towns can determine where development can and cannot occur, or how it can be planned to minimize flood vulnerability. Additionally, towns are responsible for the maintenance of significant road networks, drainage ditches and stream crossings.

Windham County Natural Resource Conservation District (NRCD)

The NRCD is a local-led and operated organization that promotes and supports soil and water conservation. The mission of the district is to 'help provide conservation assistance to the people living in the area through education programs and partnerships with federal, state and local entities involved in natural resource management." NRCDs are often involved in tree plantings along river banks and floodplains, and other land conservation efforts related to flood resiliency.

Deerfield River Watershed Association (DRWA)

DRWA is a volunteer, non-profit that serves to preserve and protect the Deerfield River watershed. Their mission is primarily focused around natural habitat and ecosystems management, but they also lead education and outreach to communities related to rivers and the watershed.

Transportation Flood Resiliency Mapping and Prioritization

The Vermont Transportation Flood Resilience Planning Tool (TRPT) developed through the *Methods and Tools for Transportation Resilience Planning Project* has identified risk levels within the North Branch Deerfield River for roads, bridges and culverts due the consequences of failures associated with erosion, inundation and deposition. A vulnerability (V) scoring system was created and linked to different levels of transportation failures (Table 2 and Figure 3). Low levels of vulnerability may lead to small-scale damages due to inundation or minor erosion/deposition, while high levels of vulnerability may indicate that asset failure is likely due to severe erosion or deposition. The vulnerability methods were vetted with towns, field-verified, and found to be accurate predictors of potential damage locations.

Vulnerability Score	**Vulnerability Rank**	**Likely Failure Mode**	**Transportation Influence**	**Distance** (miles)	**Vulnerability Type**
0	Low	None	Road far from river such that vulnerability is unlikely.	N/A	N/A
1, 2	Low	Partial Closure	Single lane closure, reduced capacity with some allowable travel, <24 hours	<0.25	Temporary inundation, minor erosion or deposition
3, 4	Low	Full Closure	Multi-lane closure, detour required, 24 hours to several days	0.25 – 1	Large-scale inundation, localized erosion, localized deposition
5, 6, 7	Medium	Temporary Operational Failure	Partial destruction of facility. Several days to a 1 week for recovery.	0.25 – 1	Severe inundation, erosion, deposition
8, 9, 10	Medium, High	Complete Failure	Complete destruction of facility. 1 week to months for recovery.	Varies	Severe erosion or deposition

Table 2 - Vulnerability Screen Scoring

A criticality (C) score was assembled to represent the consequence of a transportation link failure, the importance of a link to access critical facilities such as a hospital, and how important the road is for local detour use. Simulations were performed to identify the links in the transportation network where failure due to flooding would cause the longest delays or the greatest number of trip reductions. The probability of failure in the model was derived from the vulnerability score. A high criticality score (i.e.,

>5) indicates that failure of the link could lead to many failed trips or long delays, access to critical facilities could be reduced and a local detour route may be cut off.

The vulnerability and criticality scores were averaged to develop a risk (R) score that can be used to help prioritize actions. High risk locations (i.e., R > 5) may be vulnerable to damages and important for efficient travel, and thus are locations should be addressed sooner and where greater investment may be warranted. Low risk locations (i.e., R < 2) means that V and C are low and the resiliency will not be the primary driver of the need for improvements.

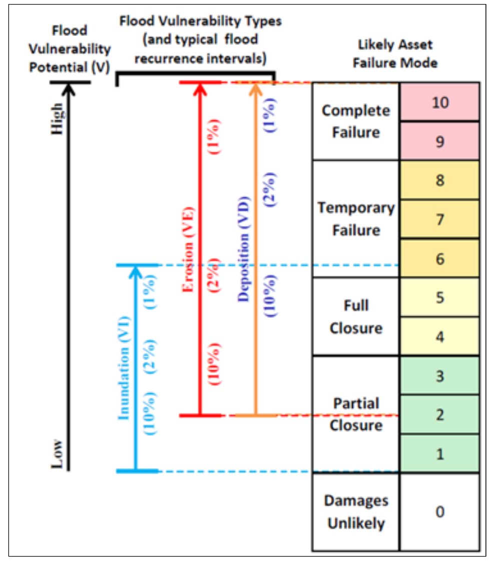

Figure 3 - Flood Vulnerability Screen by Vulnerability Type

The TRPT identifies mitigation recommendations based on the characteristics that contribute to vulnerability and criticality for each location in the pilot watersheds. A list of initial recommendations is provided to begin an alternatives analysis to reduce vulnerability. Mitigation options include vegetative practices in low risk locations and hard armor stabilization practices in high risk locations. Floodplain reconnection and river corridor conservation are also considered to reduce long-term vulnerability to transportation infrastructure.

The Vermont Transportation Flood Resilience Planning Tool (TRPT) has been created to display results and improve transportation planning. The web-based application is available for use by anyone connected to the internet. Maps show the vulnerability, criticality, and risk results. Variable scores for each road segment or structure may also be viewed to understand what is driving the level of risk. The list of possible mitigation strategies is also provided.

Roads

The primary threat to roads in the North Branch watershed is erosion due to close proximity of roads to steep and erosive river channels. The following roads in the watershed ranked highest in terms of overall risk.

							Roads - 50 Year Storm Configuration
Rank	**Asset Risk**	**Town**	**Road Name**	**Jurisdiction**	**V**	**C**	**Location**
1	7	Wilmington	Route 9	State	7	7	Route 9 from Haystack Rd. (west end) to Ray Hill Rd. (east end)
2	6.5	Wilmington	Route 9	State	4	9	Route 9 from Windswept Dr. (west end) to Country Club Rd. (east end)
3	6.5	Wilmington	W. Main St.	Town	4	9	W. Main St. from Ray Hill Rd. (west end) to N. Main St. (east end)
4	6	Wilmington	Route 9	State	10	2	Route 9 from Shearer Hill Rd (west end) to Charles Forrest Rd. (east end)
5	6	West Dover	Route 100	State	10	2	Route 100 from Burchard Rd. (north end) to town line (south end)

6	6	West Dover	Route 100	State	5	7	Route 100 from Valley View Rd. (north end) to Parsonage Rd. (south end)
7	5.5	Wilmington	Route 9	State	9	2	Route 9 from Charles Forest Rd. (west end) to Ruth Way (east end)
8	5.5	Wilmington	Route 9	State	9	2	Route 9 from Sparrow Ln. (west end) to Molley Stark State Park access (east end)
9	5.5	Wilmington	Route 9	State	4	7	Route 9 from Oxbow Loop (west end) to 1000ft west of Haystack Rd.

Table 2: High-risk roads in the North Branch Deerfield River watershed

Bridges

The primary threat to bridges in the North Branch Deerfield River watershed is either erosion or deposition. Bridges on steep channels and bends in the river can be prone to scour where banks and the structure foundation can be eroded. In lower power settings where the slope of the channel tends to be flatter, sediment and large wood can drop out of the flow during and after floods leading to bridge clogging. In extreme deposition cases the pre-flood channel can fill with sediment and the river will carve a new path during the flood. This depositional setting can be extremely damaging to nearby infrastructure and has led to many of the complete road and bridge failures observed in the State in the past. The following bridges in the North Branch Deerfield River Watershed ranked highest in terms of risk (Table 4).

							50-year Storm Configuration
Rank	**Asset Risk**	**Town**	**Jurisdiction**	**BR#**	**V**	**C**	**Location**
1	5.5	Wilmington	State	00031	2	9	W. Main St. over N. Branch of Deerfield River
2	5	Wilmington	Town	00055	8	2	Whites Rd. over Beaver Brook
3	4.5	Wilmington	Town		8	1	Haynes Rd. over Hall Brook
4	4.5	Wilmington	Town	00056	8	1	Look Rd. over Cold Brook
5	4	Wilmington	State	00034	6	2	Route 9 over Beaver Brook
6	4	Wilmington	State	00030	1	7	Route 9 over Binney Brook
7	4	Wilmington	Town		6	2	Higley Hill Rd. over Hall Brook
8	4	Wilmington	Town		6	2	Higley Hill Rd. over Hall Brook
9	4	W. Dover	State	00058	6	2	Route 100 over North Branch Deerfield River
10	3.5	Wilmington	Town		5	2	Lake Raponda Rd. over Beaver Brook

Table 3 - High-risk bridges in the North Branch Deerfield River watershed

Culverts

The primary threat to culverts in the North Branch Deerfield River watershed is either erosion or deposition. Culverts on steep channels with large fills across a floodplain are prone to scour due to strong contractions in flood flows. Many culvert failures (i.e., washouts) take place due to undersized structures relative to the stream channel and erosion of the road embankment. New standards requiring larger culverts are allowing more culverts to pass flow, sediment, large wood, and ice during floods. Many culverts are prone to accumulating sediment and large wood due to their small size relative to the channel width and floodplain width. Many culverts clog during floods when trees, limbs, and sediment block the inlet opening. The following culverts in the North Branch Deerfield River watershed ranked highest in terms of overall risk (Table 5).

Culverts - 50-year Storm Configuration					
Rank	**Asset Risk**	**Town**	**V**	**C**	**Location**
1	6	Wilmington	5	7	Route 9
2	4.5	Wilmington	2	7	Route 9
3	4.5	Wilmington	2	7	Route 9
4	4.5	Wilmington	2	7	Route 9
5	4.5	Wilmington	8	1	Old Ark Rd.
6	4.5	Wilmington	8	1	Old Ark Rd.
7	4.5	Wilmington	8	1	Old Ark Rd.
8	4.5	Wilmington	5	4	Cross Town Rd.
9	4.5	Wilmington	8	1	Old Ark Rd.
10	4.5	Wilmington	2	7	Cold Brook Rd.

Table 4 - High risk culverts in the North Branch Deerfield River watershed

Reducing Flood Risk

Reducing Risk through Mitigation

A list of possible mitigation strategies is provided in the TRPT to begin the alternatives analysis of solutions to improve resiliency. The strategies are grouped in the following categories, and an example is provided.

- **Fortify infrastructure or river channel**
  - **Bank stabilization** – For high risk locations where river-road conflicts cannot be avoided, innovative rip rap solutions such as stacked toe walls may be necessary to protect infrastructure.
  - **Riparian buffer plantings** – Planting native tree and shrub species to restore riparian habitat, provide floodplain roughness and cover along banks, and stabilize bank erosion. This method is particularly useful in lower risk streams.
  - **Improve channel roughness** – By adding woody debris and vegetation in the channel and on the floodplain, stream flow energy can be reduced due to increased roughness and friction.
- **Address resiliency**
  - **Bridge & Culvert Replacement** – Improperly sized bridges and culverts are often unable to handle the effects of a flood, which can result in water running over or around them, or undermining them due to bed erosion, and ultimately may be washed out. By upgrading undersized structures, the potential for damage can be reduced.

- **Restoration**
    - **Stream bed restoration** – Installing weirs can stabilize the streambed by adding “plunge pools” which can dissipate energy in the stream channel. A stabilized stream bed can improve floodplain access.
    - **Wetland restoration** – By repairing wetlands lost to “ditch and drain” practices, floodwater and sediment storage is improved.
    - **The creation of new floodplain** - Improved flood access provides more space for flood storage and sediment deposition.
- **Relocate or remove**
    - **Road relocation** – Relocating vulnerable infrastructure reduces the potential for conflicts between man-made development and the river’s natural need to adapt and move.
    - **Bridge & Culvert Removal** – Removing abandoned bridges and culverts can improve channel stability and overall water quality.
- **Change land use**
    - **Easements (Conservation and ANR River Corridor)** – By preserving large tracts of land and restricting future encroachments, rivers are provided with room to reach equilibrium.

Reducing Risk through Mitigation Policy and Planning

In addition to active mitigation projects, improved policy and planning initiatives are essential parts of promoting flood resiliency. State agencies, regional organizations and municipalities are all expected to take an active role in improving the statewide response to severe flooding events and planning for future flood protection.

As an incentive to encourage good mitigation policy and planning, the state has created the Emergency Relief and Assistance Fund (ERAF) that provides State funding to match Federal Public Assistance after federally-declared disasters. Eligible public costs are reimbursed by federal taxpayers at 75%. For disasters after October 23, 2014, the State of Vermont will contribute an additional 7.5% toward the costs. For communities that take specific mitigation planning and policy related steps to reduce flood damage the State will contribute 12.5% or 17.5% of the total cost. This additional match can result in a significant reduction in municipal contribution in the event of a federally-declared disaster (Table 6).

	7.5% ERAF Rate	12.5% ERAF Rate	17.5% ERAF Rate
Federal Share	$750,000	$750,000	$750,000
State Share	$75,000	$125,000	$175,000
Municipal Share	**$175,000**	**$125,000**	**$75,000**
Total Damages	$1,000,000	$1,000,000	$1,000,000

Table 5 - ERAF rates and Municipal Cost Share based on $1,000,000 in damages from a federally declared disaster

Communities have several tools at their disposal that improve flood resilience such as adoption and adherence to Road and Bridge Standards, the adoption of River Corridor protections in their zoning bylaws, maintaining an up-to-date Local Hazard Mitigation Plan, and participation in the National Flood Insurance Program (Table 7).

	12.5% ERAF Rate (must adopt all four)				17.5% ERAF Rate
Town	NFIP Standards	Road & Bridge Standards	Local Emergency Operations Plan	Local Hazard Mitigation Plan	River Corridor Protection
Dover	Yes	Yes	Yes	Yes	No
Marlboro	Yes	Yes	Yes	Yes	No
Somerset	No	Yes	No	No	No
Stratton	Yes	Yes	Yes	No	No
Wardsboro	Yes	Yes	Yes	Yes	No
Wilmington	Yes	Yes	Yes	Yes	No

Table 6 - Status of Mitigation policy and planning in North Branch watershed communities, 2017

Vermont Town Road & Bridge Standards (VTRB)

Act 110 of the 2009-2010 Legislative session required that the Vermont Agency of Transportation work with municipal representatives to "revise the Agency's current recommended town road and bridge standards to include a suite of practical and cost-effective Best Management Practices (BMPs) for the construction, maintenance and repair of all existing and future town highways in order to address pollution caused by transportation-related stormwater runoff." VTRB Standards are minimum standards that represent best minimum practices to address transportation safety, design, construction and maintenance. Additionally, by design, these standards are intended to help minimize roadway runoff, protect water quality and address future bridge and culvert flood resilience. Adoption of the VTRB and an annual letter of certification signed by the Town, ensures that FEMA will provide funding to upgrade existing sub-standard roads, bridges or culverts that are damaged in a federally declared disaster.[2]

River Corridor Protections

Many of the locations damaged during Tropical Storm Irene were well outside of mapped Flood Hazard Areas. Many streams experienced erosion and deposition damage due to confined flow with high velocity. The Vermont Legislature created the ability for communities to limit development within the River Corridor Area. The River Corridor includes both the river/stream channel and the adjacent land area needed for the river to establish and maintain "equilibrium" conditions – the most stable channel setting over the long term. Some communities have adopted River Corridor protections that prohibit or limit new development along rivers in vulnerable locations on the landscape.

Hazard Mitigation Plans

To ensure that communities are actively planning for future flood events (and other hazards), communities maintain Local Hazard Mitigation Plans (LHMP). The LHMP is a broad-based plan for each

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[2] The standards within the VTRB that address water quality are being superseded by standards within the Municipal Roads General Permit required by Act 64, the Vermont Clean Water Act. Municipalities must apply for the MRGP by July 31, 2018. More information on the MRGP is provided below. Adoption and compliance with the VTRB, which will continue to provide flood resilience standards, will still be required to ensure FEMA funding can be used to upgrade sub-standard roads, bridges and culverts damaged by a flood.

town that assesses hazards (including flooding) and proposes mitigation measures to lessen their vulnerability to those with the most impact. Communities that have FEMA approved LHMP are eligible to apply to the Vermont Division of Emergency Management and Homeland Security for HMGP mitigation grants administered by FEMA. LHMPs expire every five years and RPCs are available to help towns re-adopt these plans. Additionally, mitigation plans are eligible for points under the National Flood Insurance Program's Community Rating System (CRS). The TRPT could help municipalities identify bridges, culverts and road embankments for funding through the HMG program and other sources.

National Flood Insurance Standards

Development within flood hazard areas can exacerbate the impacts of flooding, cause damages to property and infrastructure and put lives at risk. While many locations that experience damage during flood hazard events are outside of the mapped FEMA floodplain, a community's commitment to protecting life, property and the natural environment from flooding is demonstrated through participation in the NFIP. Communities that adopt and enforce FEMA's NFIP standards can limit the types and design of development that occur within the floodplains.

Water Quality Planning and Project Identification

Municipal Roads Stormwater General Permit

In 2016 the Vermont Legislature passed a law specifically focused on reducing the environmental impacts of stormwater runoff. A primary component of this law is the Municipal Roads Stormwater General Permit (MRGP) that is administered by the Vermont Department of Environmental Conservation. As a requirement of the MRGP Municipalities must develop a Road Stormwater Management Plan (Road SWMP). The Road SWMPs include two components; a comprehensive Road Erosion Inventory (REI) of "hydrologically-connected" road segments and associated Implementation Plan. The purpose of the Implementation Plan is to bring non-complying road segments up to MRGP Standards as soon as possible, but no later than 2037.

Hydrologically Connected Roads

The criteria that defines a road as "hydrologically connected" are:

- Municipal roads within 100' of a water resource
- Municipal road that crosses and drains into a water source
- Municipal road located within the mapped River Corridor area
- Catch basin outfalls within 500' of a water resource and those segments associated with those outfalls.

The MRGP will require replacement or stabilization retrofits for eroding road drainage culverts, intermittent stream culverts, and driveway culverts located within municipal rights-of-way. Upsizing culverts, improving culvert headwalls/headers, stabilizing drainage ditches and culvert outlets and mitigating catch basin outfall erosion will be among the tasks required to meet MRGP standards. Communities can utilize a prioritized list of necessary repairs that can be integrated into municipal planning and budgeting. The prioritization of infrastructure investments should be part of a locally adopted Municipal Plan. For communities with an adopted Capital Budget and Program, a prioritized plan for road improvements can be incorporated and budgeted for.

Investments in transportation infrastructure will improve water quality, and reduce the potential for severe damage and loss during a flood. In turn, improved flood resiliency will reduce future costs for repair, and limit the potential for loss of life and property throughout the watershed.

Buyouts and Infrastructure Protection

Figure 4 - Example of a floodprone property that puts infrastructure at risk. East Orange Branch of the Waits River in West Topsham. Source: Google Maps.

One way to reduce the risk of damage to transportation infrastructure is to identify properties that are prone to damage that may have a direct impact on roads, bridges and culverts (Figure 4). During extreme flooding events, floodprone structures can suffer catastrophic failure. A house that is located too close to a river, for example, can be swept into the floodwaters, traveling downstream until it meets a bridge or culvert. The effect of a large mass plugging a bridge inlet can result in bridge or road failure.

The Federal Emergency Management Agency (FEMA) maintains a program through which floodprone properties can, in the event of a federally declared disaster, be purchased for the purposes of removing the structure and permanently conserving the property. FEMA pays 75% of the value of the floodprone property, and the remaining 25% is handled by the landowner or possibly through other federal and state funding sources (e.g., HUD CDBG-DR and VHCB). The FEMA buyout program only covers properties that are in the mapped floodplain.

To prepare for future buyouts, communities should inventory floodprone properties, especially those that have been damaged in the past, and prioritize them based on their public benefit as it relates to transportation infrastructure. Priority should be given to:

- Buildings that could cause damage to transportation infrastructure during catastrophic failure; and
- Buildings that are located on a road segment that only serves floodprone structures.

Communities may also want to consider developing a contingency fund to provide the necessary level of match to complete a buyout. Because floodprone properties outside of the mapped floodplain are not covered under FEMA's buyout program, communities or the state may want to consider allocating enough funding to conduct their own buyouts. While bearing the full cost of a buyout might not be preferred, it is important to weigh the cost of the buyout versus the benefit of avoiding repeatedly repairing or reconstructing infrastructure that fails. A local or state buyout program has the advantage of prioritizing sites outside of the mapped floodplain that are prone to regular erosi9on damages. Also, a state or local buyout program can eliminate much of the paperwork required by the federal government and. An average FEMA buyout from TSI Irene cost $10,000 in administrative costs (personal communication, TRORC TSI State Buyout Manager). The TRPT could help municipalities identify buyouts that would improve bridges, culverts and road embankments flood resiliency.

Removing Vulnerable Infrastructure

Many communities have damage-prone road segments that regularly require repair due to inundation, erosion or deposition. To address these problem areas, communities should consider discontinuing or moving a road segment where feasible. If a damage-prone road serves a limited number of floodprone homes and has very low traffic volume, it may be financially sensible to buy out the floodprone homes and discontinue the road. Communities should also consider if there is adequate access through alternative safe routes to properties. This may also provide reasonable justification to discontinue the road.

In some instances, it is possible to move a road segment away from a river or stream. Moving roads is expensive (Table 8), and thus careful planning and analysis is necessary.

Gilman Rd. Relocation, Royalton	
Administration & Engineering	$103,464
Stream Bank Stabilization	$408,059
Moving Road	$226,609
Total	$738,132

Table 8 - Costs for moving 850 feet (1/6 mile) segment of Gilman Rd. just 40 feet in Royalton. Costs do not include procurement of adjacent property.

Communities may want to proactively identify road segments that have the potential to be moved. Look for areas where the adjacent topography would allow for moving a road segment with limited ground work to minimize costs. In areas where the landscape makes it feasible to move a road, communities should identify ownership of adjacent properties and determine what reasonable compensation would be for the land necessary to accommodate the change. The next step would be to engage a professional to develop an estimate of potential costs for moving the road. This information will provide a general cost for such a project, allowing for the development of a benefit-cost analysis to determine if the cost of maintaining the road in its current location is more than the cost to move the road.

Most communities will need to use multiple funding sources to balance the cost to the community with the overall cost of the project, typically through federal programs such as the FEMA Hazard Mitigation Grant Program or Community Development Block Grant Disaster Relief funding. Each of these programs is tied to a federally-declared disaster. It is essential that communities maintain good records that document previous damage and repair work. Documentation must include photos and an accurate accounting of time and materials needed to repair damages.

Communities that have identified a road that can be moved should engage in planning to be prepared if a funding opportunity arises. To start, the identified road segment should be highlighted in the Municipal Hazard Mitigation Plan. This would include identifying the location of the segment to be moved, an overview of past damages and a summary of potential approaches to moving the road, with an eye toward reducing or eliminating long-term risk. Following the hazard mitigation planning process, the next step would be to have an engineer conduct a scoping study that will clearly identify the preferred alternative to leaving the road in place. With an identified alternative in place, a municipality will be well positioned to tap into available funding more quickly.

It is important to recognize that even with federal disaster assistance funding, a project as significant as moving a road will be expensive. Creating a reserve fund specifically for providing necessary match, or for purchasing the property needed to improve mitigation is recommended.

Site Examples

Two site examples identified in the TRPT from the North Branch Deerfield River Watershed follow that will protect local transportation assets and improve the transportation network resilience. The site examples include:

- Mitigation options at a high-risk erosion site along Vermont Route 9 in Wilmington; and
- Inundation and erosion along Vermont Route 100 near the confluence of the North Branch Deerfield River and Cold Brook.

Mitigation Options at a High-Risk Erosion Site along Vermont Route 9 in Wilmington

The edge of the Vermont Route 9 road embankment and the bank of the North Branch Deerfield River are often the same in Wilmington. The road fills the floodplain and confines the river. The result is a road segment that is prone to flood and erosion damages.

During Tropical Storm Irene, flooding took place on Vermont Route 9 in Wilmington (Figure 5) that ultimately caused the road embankment to erode (Figure 6).

Figure 5: Flooding of Vermont Route 9 in Wilmington during Tropical Storm Irene. (Source:

The Vermont Transportation Flood Resiliency Planning Tool (TRPT) shows high risk sections of Vermont Route 9 along the North Branch Deerfield River (Figure 7). The vulnerability due to erosion is high (7 out of 10). Over a mile of the road segment lies in the river corridor. Stream power is 111 Watts per square meter where erosion damages are most common with erodible material. More than 20% of the floodplain is filled by the road embankment that is leading to high vulnerability. Vermont Route 9 is a major east-west route that would lead to severe transportation consequences if damaged (C = 7 out of 10), and thus have the highest risk in the area (R = 7 out of 10).

Figure 6: Erosion along Vermont Route 9 following emergency repairs after Tropical Storm Irene. (Source: R. Schiff, 2012).

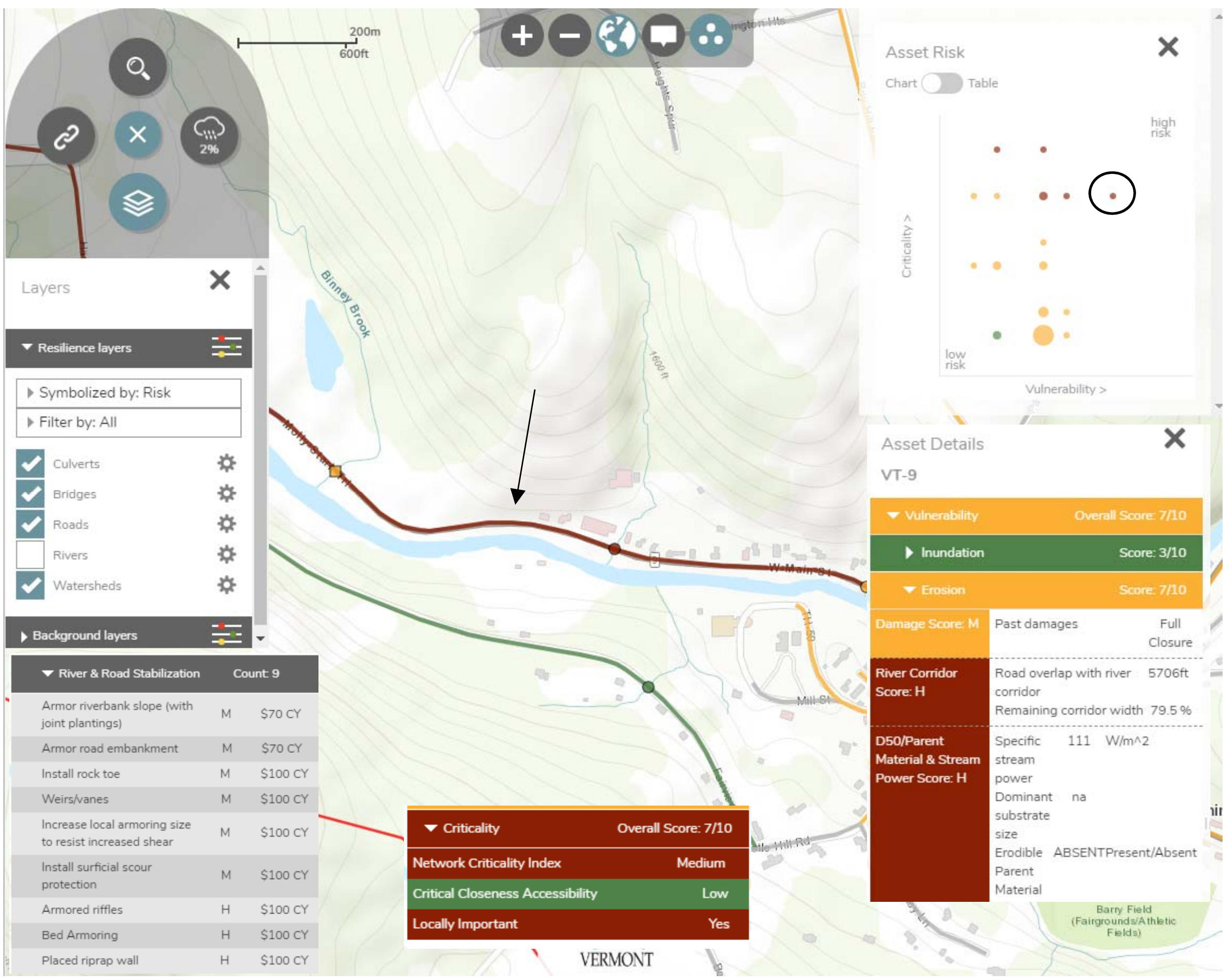

Figure 7: TRPT results for Vermont Route 9 in Wilmington.

Due to the erosive setting along Vermont Route 9 identified in the TRPT, the mitigation strategies that can protect the road, bridges and culverts require rigid stabilization using large rock. Although vegetative practices are preferred to naturalize the river, the high flood velocity in the area will erode roots and soils so rock is needed to protect the road. Practices such as armoring the riverbanks while maintaining the channel bankfull width and installing local scour protection at bridges and culverts are needed to protect the transportation network (See the “Strategies” drop down menu in the TRPT web application). A truly resilient design approach will address the root problem in the area – reducing confinement and reconnecting floodplain. This last practice is the top recommendation to improve conveyance of flood flows and reduce the process of erosion.

Emergency bank armoring took place along several sections of Vermont Route 9 following Tropical Storm Irene as short-term, temporary repairs to get the road open. The armoring allowed for rebuilding of the road embankment and provided temporary stabilization. Unfortunately, this approach also narrowed the river channel below the bankfull channel width that led to a higher potential for erosion. Permanent recovery work took place in this area to pull back the stone in the river channel and apply larger stone on the riverbank.

Inundation and Erosion Along Vermont Route 100 near the Confluence of the North Branch Deerfield River and Cold Brook

Vermont Route 100 near the intersection of Coldbrook Road in Wilmington fills the floodplain and is prone to both inundation and erosion damages. The road sits low near the rivers and can get flooded, and the fill confines the river channel leaving the embankments susceptible to erosion. During Tropical Storm Irene, flooding took place on Vermont Route 100 that scoured the road and shoulder (Figure 8).

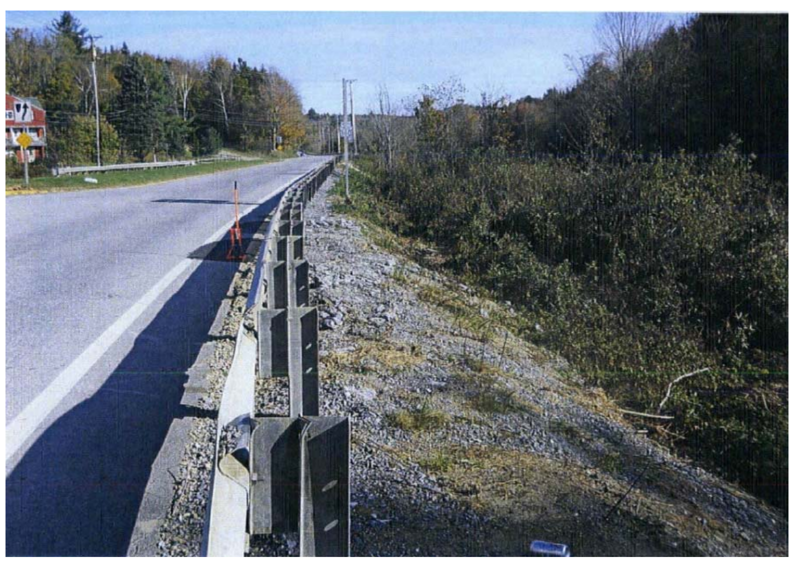

Figure 8: Erosion along Vermont Route 9 following emergency repairs after Tropical Storm Irene. (Source: VTrans, 2011).

The Vermont Transportation Flood Resiliency Planning Tool (TRPT) shows high risk sections of Vermont Route 100 in this area (Figure 9). The vulnerability due to erosion is high (9 out of 10), while the vulnerability due to inundation is 4 out of 10, with 5 being the maximum given the lower level of damages typical of inundation). Just under a mile of the road segment lies in the river corridor. Stream power is 146 Watts per square meter where erosion damages are most common with erodible material. More than 5,000 feet of road lie in the 100-year floodplain, and the road elevation is

6 feet below the base flood level. Vermont Route 100 has moderate criticality in this area, with it serving as an important local detour (C = 2 out of 10). Risk level is high (R = 5.5 out of 10).

Due to the erosive setting along Vermont Route 100 identified in the TRPT, the mitigation strategies that can protect the road, bridges and culverts require rigid stabilization using large rock. Also, the edge of

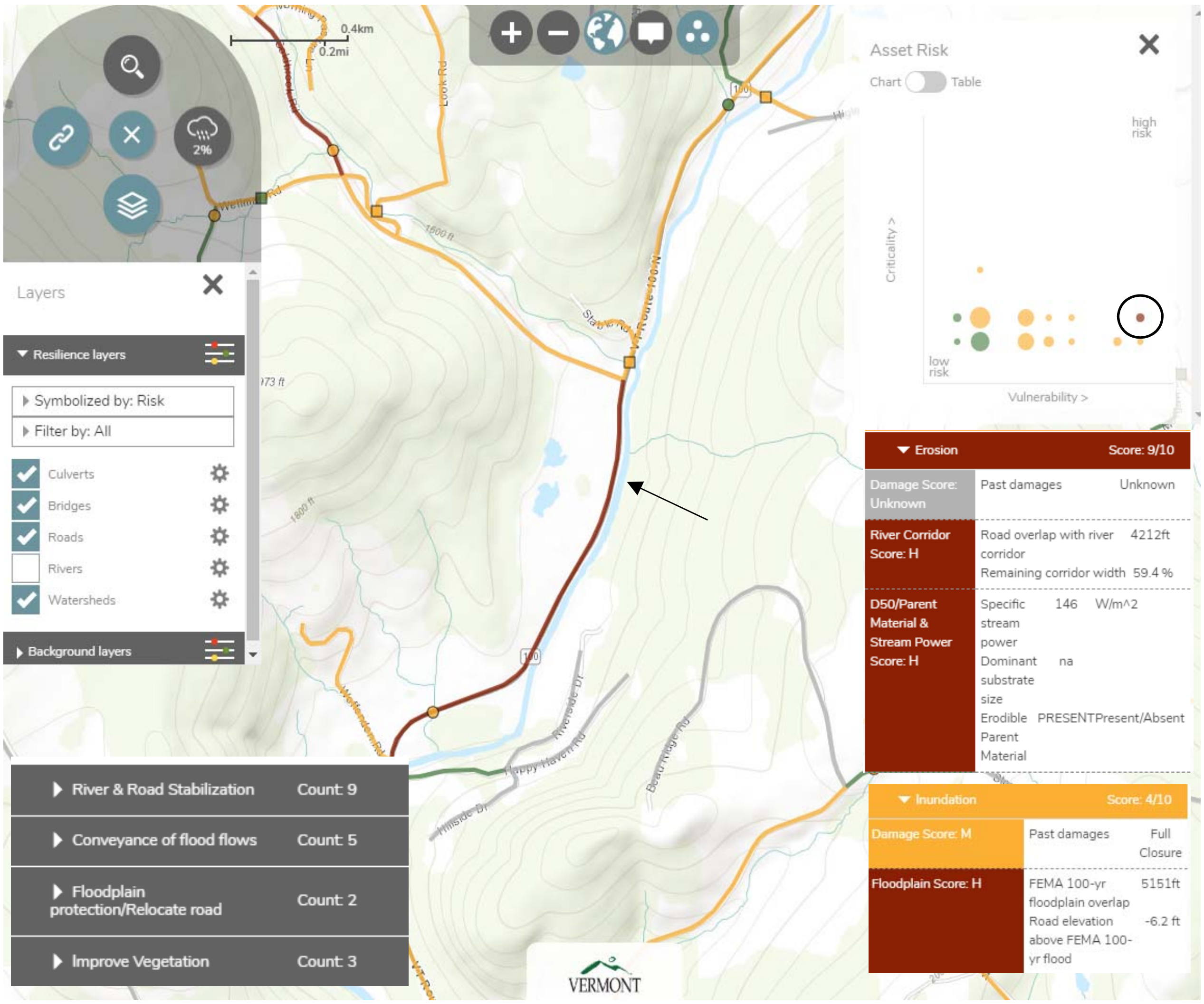

Figure 9: TRPT results for Vermont Route 100 in Wilmington.

the road embankment needs to be protected when inundation takes place. Although vegetative practices are preferred, the confined setting will require rock to protect the road. Practices such as armoring the riverbanks while maintaining the channel bankfull width and installing local scour protection at bridges and culverts are needed to protect the transportation network (See the "Strategies" drop down menu in the TRPT web application). A truly resilient design approach will address the root problem in the area – reducing confinement and reconnecting floodplain. A good consideration for this confluence location is to design and build the roads to allow for overtopping to spread out the flood waters, but also to fortify surfaces so they can withstand flood waters.

Emergency road and shoulder repair took place along Vermont Route 100 following Tropical Storm Irene to get the road open (Figure 10). More work may be needed in this location to fortify the road embankment and surface.

Figure 10: Road and shoulder repair following Tropical Storm Irene. (Source: VTrans, 2011).

References

Schiff, R., E. Fitzgerald, E. Boardman, L. Gibson, N. Marshall, L. Padilla, and J. Segale, 2018. The Vermont Transportation Resilience Screening Tool (Trpt) (Https://Roadfloodresilience.Vermont.Gov). Prepared by Milone & MacBroom, Fitzgerald Environmental Associates, DuBois & King, Smart Mobility, and Stone Environmental for and in collaboration with the Vermont Agency of Transportation, Montpelier, VT.

VTANR, 2014. Tactical Basin Plan Deerfield River and Southern Connecticut River Tributaries of Vermont (Basin 12/13). Vermont Agency of Natural Resources, Department of Environmental Conservation, Watershed Management Division, Montpelier, VT.

VTrans, 2009. Local Transportation Facilities Guidebook for Municipally Managed Projects. Vermont Agency of Transportation, Montpelier, VT.

APPENDIX M

TRPT APPLICATION

Web Hosting Environment

Stone Environmental migrated the Transportation Resilience Planning Tool (TRPT) to State of Vermont servers, which may be accessed at https://roadfloodresilience.vermont.gov.

The application delivered to the state was comprised of four main parts:

- Front-End Web Application code
- Data (contained in a File Geodatabase)
- ArcGIS Map Document
- ArcGIS Server Map Service

Front-End Web Application code, including HTML, CSS, JavaScript, and image files, was delivered to the state in a single zip file. For each watershed included in the application, the front-end stores thumbnail images based on the FIRST_Name field of the watersheds layer. For example, for the "Whetstone Brook" watershed, there is an image file called "Whetstone Brook.png." If the FIRST_Name field for the watershed changes, the thumbnail will not display on the splash screen (unless its name in the images folder also changes).

The file geodatabase (GDB) data and ArcGIS Map Document (MXD) were delivered together in another zip file. The file geodatabase was a convenient container used for the data transfer; however, the originating development database at Stone and the intended destination database at VTrans are ArcSDE-type databases. VTrans should import the file geodatabase data into ArcSDE for use with data processing tools to be developed in Phase 2 of the project. The MXD references the spatial data in the geodatabase and provides the basis for the symbology, layer order, and color scheme of the web app display. The four color groups of the "Roads" layer determine the color scheme of much of the application (chart/table, asset details, roads). Changing the colors of that layer in the map document will automatically update those colors in the application without any changes to the front-end. It is important to note that the layer order in the MXD should not be changed. Changing the order will require changes to be made to the front-end JavaScript code to reference any updated layer IDs. Changes to JavaScript code should be avoided to minimize the risk of introducing bugs.

The TRPT ArcGIS Server Map Service is based on the MXD in the GDB zip file. The map service uses relative paths to reference the spatial data that is organized in the MXD. The data sources of these layers will need to be updated to reference the ArcSDE database location at VTrans. This map service is referenced by the front-end application within three JavaScript files (below). If any part of the map service REST URL changes (currently: https://maps.vtrans.vermont.gov/arcgis/rest/services/PPID/resilienceplanning/MapServer), the front-end will need to be updated with that change (i.e., domain name, folder name, service name, etc.). Performing a global search for "arcgis/rest" will help find all references to map service links.

- scripts/controllers/MapPageController.js: This file holds all the references for the application layers using the map service URLs, both for the TRPT map service as well as reference layers developed outside of this project (E911 Buildings, Mileposts, etc.).

- scripts/directives/seMap.js: This file is fairly large and contains three map services. One for the out-of-the-box print task hosted on the state's server (line 901), one for the Geocoder hosted at

ArcGIS.com (line 945), and one to populate the watershed list (splash screen, watershed filter) from the TRPT map service (line 1498).

- scripts/services/map_service.js: There is only one reference to the TRPT map service (line 462). This block of code gets the asset details from the TRPT map service for roads (layer ID 6 on line 464) and bridges/culverts (layer ID 5 on line 466).

The State of Vermont-hosted version of the TRPT application is located at: https://roadfloodresilience.vermont.gov. This replaces the Stone development version previously available at: vtrans.stone-env.net.

A data input tool has been developed to enable the state, RPC, and other future TRPT data developers to be able to properly prepare data for the TRPT.

Data File Downloads

File Name	Content	Notes
roads_VtransApp_2022Oct.shp	Road GIS shapefile	Link to FAID
structures_VTransApp_2022Oct.shp	Structures GIS shapefile	Link to Struc_ID
1. Vulnerability_Roads_2022Oct.csv	See README.TXT below	See README.TXT below
2. Vulnerability_Structures_2022Oct.csv	See README.TXT below	See README.TXT below
3. Criticality_Roads_2022Oct.csv	See README.TXT below	See README.TXT below
4. Criticality_Structures_2022Oct.csv	See README.TXT below	See README.TXT below
5. Strategies_Roads_2022Oct.csv	See README.TXT below	See README.TXT below
6. Strategies_Structures_2022Oct.csv	See README.TXT below	See README.TXT below

The following text file is downloaded with the TRPT data package.

5/9/2018
This README.TXT describes the contents of the zip file downloaded from https://roadfloodresilience.vermont.gov. The zip file contains six csv files which describe the detailed asset data represented in the Asset Details section of the application. The Asset Details are displayed after clicking on a road, structure, or bridge.

1. Vulnerability_Roads_2022Oct.csv – Vulnerability data for each road segment by FAID. Data fields include the following:

   a. FAID – The unique identifier for the road segment
   b. Variable Type – Total, Inundation, Erosion, Deposition – Corresponding to the sections under the Vulnerability panel
   c. Variable – The variable\parameter measured
   d. flood – The flood event: 10-, 50-, or 100-year flood
   e. Valuefmt – The value for that variable for that specific FAID and flood
   f. units – the units associated with the value
   g. decplace – The decimal places displayed for the value

2. Vulnerability_Structures_2022Oct.csv – Vulnerability data for each bridge and culvert by Struc_ID. Data fields include:

    a. Struc_ID – The unique identifier for the structure
    b. Variable Type – Total, Inundation, Erosion, Deposition – Corresponding to the sections under the Vulnerability panel
    c. Variable – The variable\parameter measured
    d. flood – The flood event: 10-, 50-, or 100-year flood
    e. Valuefmt – The value for that variable for that specific FAID and flood
    f. units – the units associated with the value
    g. decplace – The decimal places displayed for the value

3. Criticality_Roads_2022Oct.csv – Criticality data for each road segment. Data fields include:

    a. FAID – The unique identifier for the road segment
    b. LI_Score – Locally Important – Yes or No
    c. NCI_Score – Network Criticality Index – Low, Medium, High, NA
    d. CCA_Score – Critical Closeness Accessibility – Low, Medium, High, NA
    e. Criticality – Overall Criticality score with values from 1 to 9

4. Criticality_Structures_2022Oct.csv – Criticality data for each structure. Data fields include:

    a. Struc_ID – The unique identifier for the bridge or culvert
    b. LI_Score – Locally Important – Yes or No
    c. NCI_Score – Network Criticality Index – Low, Medium, High, NA
    d. CCA_Score – Critical Closeness Accessibility – Low, Medium, High, NA
    e. Criticality – Overall Criticality score with values from 1 to 9

5. Strategies_Roads_2022Oct.csv – The strategies identified for each road segment. Data fields include:

    a. FAID – The unique identifier for the road segment
    b. Project – A description of the project
    c. VariableType – Deposition, Erosion, Inundation – Identifies which of these the project addresses.
    d. Group F – Conveyance of flood flows, FP: Floodplain protection/Relocate road, S: River and Road Stabilization, V: Improve Vegetation. These correspond to the individual panels underneath the Strategies panel.
    e. Application Scale – P, RR, RS
    f. Cost_unit – The cost and units of the project
    g. Short or Long – Whether the project will have short- or long-term impacts
    h. River Impact – L: Low, M: Medium, H: High
    i. Network Impact – L: Low, M: Medium, H: High

6. Strategies_Structures_2022Oct.csv – The strategies identified for each bridge or culvert. Data fields include:

    a. Struc_ID – The unique identifier for the bridge or culvert
    b. Project – A description of the project
    c. VariableType – Deposition, Erosion, Inundation – Identifies which of these the project addresses.
    d. Group – F: Conveyance of flood flows, FP: Floodplain protection/Relocate road, S: River and Road Stabilization, V: Improve Vegetation. These correspond to the individual panels underneath the Strategies panel.
    e. Application Scale – P, RR, RS
    f. Cost_unit – The cost and units of the project
    g. Short or Long – Whether the project will have short- or long-term impacts
    h. River Impact – L: Low, M: Medium, H: High
    i. Network Impact – L: Low, M: Medium, H: High