Memorandum

TO: Joe Segale, VTrans

FROM: Roy Schiff, Jessica Louisos, and Lauren Weston, Milone & MacBroom
Evan Fitzgerald and Evelyn Boardman, Fitzgerald Environmental

DATE: April 12, 2018

RE: Adding Resiliency to the Vermont Project Selection and Prioritization Process

INTRODUCTION

A new vulnerability screen has been developed for Vermont to describe the threats of inundation, erosion, and deposition to roads, bridges and culverts. The screening variables and approach developed during the *VTrans Methods and Tools for Transportation Resiliency Planning in Vermont* project were applied in three pilot watersheds: Whetstone Brook, Upper White River, and North Branch Deerfield River. The Vermont Transportation Flood Resilience Screening Tool (TRPT) (Schiff et al., 2018) is a web application that displays the project results to evaluate risk at roads, bridges, and culverts.

An analysis was performed to identify the pilot study variables that are readily calculated for the entire State of Vermont and that describe the vulnerability in the more detailed analysis. The goal of this task is to identify statewide vulnerability variables that can readily be incorporated into the ongoing *VTrans Vermont Project Selection and Prioritization Process* project to include a flood resiliency component.

METHODS

Statistical analysis was performed to identify the variables that separate past flood damage sites from those sites that have not been damaged. Most of the damage records originated from Tropical Storm Irene in 2011. Spearman rank correlation analyses tested the relationship between inundation, erosion, and deposition vulnerability scores with component scoring variables (Table 1). Classification trees highlighted the variables that described road and structure damages (Figure 1). The trees were fit with recursive partitioning using *rpart* package (R Core Team, 2013; Therneau et al., 2017). The results of the classification informed the selection of the variables and score ranges to be used in the state prioritization.

Due to the relative rarity of damaged road segments and structures in the dataset compared to undamaged road segments, a loss matrix was incorporated into the model to weight the importance of separating damaged and undamaged infrastructure. Additionally, due to the stochasticity in where damages were observed versus where conditions make it most likely for damages to be observed given the right circumstances, the loss matrix was weighted such that false-positives predicting damages were penalized much less than false-negatives. Different weighting schemes were tested in the loss matrix to achieve a relatively simple model that converged on a set of variables that best described damages.

Table 1: Spearman correlation for road vulnerability scores and selected variables. Variables selected for statewide prioritization are italicized.

Spearman Correlation for Road Vulnerability Scores

	Road-River Relief	SGA Valley Slope	100-Yr Flood Depth above Road	*Road-Floodplain Overlap*	Log-Transformed Confinement	*Stream Power*	*Road- River Corridor Overlap*	Corridor Remaining
Inundation	-0.69	-0.02	-0.66	0.51	-0.13	-0.03	0.33	0.03
Erosion	-0.22	0.2	-0.3	0.21	-0.27	0.59	0.38	-0.23
Deposition	-0.42	-0.2	-0.45	0.4	-0.24	-0.06	0.45	-0.59
p-value								
Inundation	> 0.001	0.49	> 0.001	> 0.001	> 0.001	0.27	> 0.001	0.28
Erosion	> 0.001	> 0.001	> 0.001	> 0.001	> 0.001	> 0.001	> 0.001	> 0.001
Deposition	> 0.001	> 0.001	> 0.001	> 0.001	> 0.001	0.03	> 0.001	> 0.001
Sample Size (number of road segments)								
Inundation	167	873	141	1502	1502	1502	1502	1501
Erosion	167	873	141	1502	1502	1502	1502	1501
Deposition	167	873	141	1502	1502	1502	1502	1501

Loss Matrix Weights

		Predicted		
		C	F	ND
Observed	C	0	5	10
	F	5	0	10
	ND	1	1	0

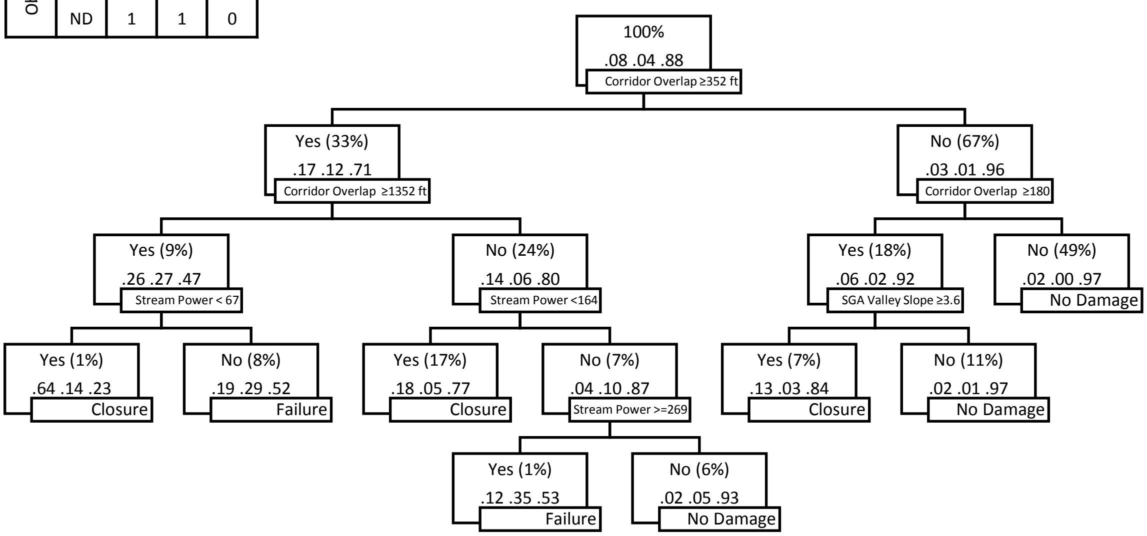

Figure 1: Sample Classification Tree from the Prioritization Methods development. The proportion of the overall road embankment dataset for the pilot subwatersheds categorized into each branch is represented as a percentage in parentheses. The proportion of each branch that had (in order) a closure, failure, or no damage recorded is represented as a proportion. In this example, the loss matrix is weighted such that the classification tree predicting no damage when a closure or failure was observed on a road segment is highly penalized (10), while predicting a closure or failure when no damage was recorded on a segment is not highly penalized (1).

RESULTS

The following variables have been selected for the state prioritization (Table 1).

- Documented Past Damages
- Length of road segment ROW in River Corridor (feet)
- Length of road segment ROW in 100-Year Floodplain (feet)
- Specific Stream Power (W/m^2)
- Valley Slope
- Structure Width vs. Bankfull Channel Width (%)
- Bridge (and large culvert) scour criticality (FHWA Item 113)

Definitions, application use, and data development information for each variable are provided with this document to assist with understanding and updating this statewide resiliency screening (See appendices). A screening method has been created using the selected variables that both indicate when damages have taken place in the past and align with the more detailed vulnerability analysis indicating where future damages are most likely (see Figures 2 to 5). In a comparison of the road and structure prioritizations with the detailed vulnerability analysis for the pilot watersheds, we found the detailed screening highlighted similar road segments and structures as vulnerable (Figure 4), with mean vulnerability patterns increasing with higher prioritization (Figure 5).

Table 1: State-Scale Prioritization Variables and Screen Method

	VARIABLE SCORING (H, M, L)		
ROADS	**INUNDATION**	**EROSION**	**DEPOSITION**
Documented Past Damages	Present / Absent (no M)	Present / Absent (no M)	Present / Absent (no M)
Length of ROW in River Corridor (feet)		>1,320', 660'-1,320', <660'	>1,320', 660'-1,320', <660'
Length of ROW in 100-Year Floodplain (feet)	>200, 50-200, <50		
Specific Stream Power (W/m²)		100-300 W/m², >300, <100	<100, 100-300 W/m², >300
Valley Slope	>1.5, 0.5-1.5, <0.5		

	VARIABLE SCORING (H, M, L)		
BRIDGES AND CULVERTS	**INUNDATION**	**EROSION**	**DEPOSITION**
Documented Past Damages	Present / Absent (no M)	Present / Absent (no M)	Present / Absent (no M)
Length of ROW in River Corridor (feet)		>1,320', 660'-1,320', <660'	>1,320', 660'-1,320', <660'
Length of ROW in 100-Year Floodplain (feet)	>200, 50-200, <50		
Specific Stream Power (W/m²)		100-300 W/m², >300, <100	<100, 100-300 W/m², >300
Structure Width vs. Bankfull Channel Width (%) (HGR-based)	<50, 50-100, >100	<50, 50-100, >100	<50, 50-100, >100
Scour Criticality		1-4, 5-7 & U, 8-9 & U	1-4, 5-7 & U, 8-9 & U

For roads and structures vulnerable to damages, the type of flood vulnerability (i.e., inundation, erosion, or deposition) will affect the magnitude and severity of any damages that occur. 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. Thus, the erosion and deposition scores range from 1 (low vulnerability) to 10 (high vulnerability). Damage sites are automatically ranked as high as their probability of being vulnerable to damages has been realized. If past damages have not occurred, the screening is determined using the other factors. Scoring tables show all possible combinations of variables (Figure 2) and an example of how to apply the scoring criteria logic is provided here (Figure 3).

For structure prioritization where a scour criticality score is available, it is included as an override to the erosion and deposition scores. If the scour criticality is 1, 2, 3, or 4 (i.e., high scour criticality) and the vulnerability score is less than 10, the score is increased to 10 to indicate high vulnerability potential. If the scour criticality is 5, 6, 7, T, or U (i.e., moderate scour criticality) and the score is less than 5, the score is increased to 5 to indicate moderate vulnerability potential.

After applying the criteria for each flood vulnerability type, the maximum score is used for the prioritization. Finally, the scores are grouped into low (1 to 4), moderate (5 to 8), and high (9 to 10) prioritization categories for map display.

ROADS - INUNDATION

Length of ROW in FP	Damage N	Damage Y	Valley Slope
null	1	5	L
null	2	5	M
null	3	5	H
L	1	5	L
L	2	5	M
L	3	5	H
M	3	5	L
M	3	5	M
M	4	5	H
H	4	5	N/A

ROADS - EROSION/DEPOSITION

Length of ROW in Corridor	Damage N	Damage Y	Stream Power
L	1	10	L
L	2	10	M
L	3	10	H
M	4	10	L
M	5	10	M
M	6	10	H
H	7	10	L
H	8	10	M
H	9	10	H

BRIDGES AND CULVERTS - INUNDATION

Length of ROW in FP	Damage N	Damage Y	Structure Width vs. Bankfull Width
null	1	5	L
null	2	5	M
null	3	5	H
L	1	5	L
L	2	5	M
L	3	5	H
M	3	5	L
M	3	5	M
M	4	5	H
H	4	5	N/A

BRIDGES AND CULVERTS - EROSION/DEPOSITION

Length of ROW in Corridor	Damages; Scour Criticality N; N,8,9	N; 5,6,7,T,U	N; N,8,9	N; N,8,9	N; 5,6,7,T,U	Y; 1,2,3,4	Structure Width vs. Bankfull Width
L	1	5	1	1	5	10	L
L	1	5	2	2	5	10	M
L	2	5	3	3	5	10	H
M	3	5	4	4	5	10	L
M	4	5	5	5	5	10	M
M	5	5	6	6	5	10	H
H	6	6	7	7	7	10	L
H	7	7	8	8	8	10	M
H	8	8	9	9	9	10	H
Stream Power	L	L	M	H	M / H	N/A	

Figure 2: Prioritization Scoring Criteria for Roads (Top) and Structures (Bottom) by Flood Vulnerability Type.

BRIDGES AND CULVERTS - EROSION/DEPOSITION

		Damages; Scour Criticality							
		N; N,8,9	N; 5,6,7,T,U	N; N,8,9	N; N,8,9	N; 5,6,7,T,U	Y: 1,2,3,4		
Length of ROW in Corridor	L	1	5	1	1	5	10	L	Structure Width vs. Bankfull Width
	L	1	5	2	2	5	10	M	
	L	2	5	3	3	5	10	H	
	M	3	5	4	4	5	10	L	
	M	4	5	5	5	5	10	M	
	M	5	5	6	6	5	10	H	
	H	6	6	7	7	7	10	L	
	H	7	7	8	8	8	10	M	
	H	8	8	9	9	9	10	H	
	Stream Power	L	L	M	H	M / H	N/A		

Example #1 (Black Circles):

1) No Damage Record, No Scour Criticality Rating
2) Length of ROW in Corridor: Moderate Vulnerability
3) Structure Width to Bankfull Width: High Vulnerability
4) Stream Power: Low Vulnerability
5) Erosion Score: Moderate (5)

Example #2 (Gray Circles):

1) Damage Record
2) Erosion Score: High (10)

Figure 3: Prioritization Scoring Example for Structure Erosion Vulnerability.

DISCUSSION

This resiliency screen is one component of the updated project prioritization method being developed by VTrans. The other prioritization criteria in addition to flood resilience are mobility/connectivity, safety, economic access, community, environment, asset condition, and health access.

This statewide vulnerability screen is modified from a more detailed screen developed in three pilot watersheds. The detailed screening began with a desktop analysis and included a field verification step to refine the vulnerability ratings. While the field-based refinements were limited (5% of roads or fewer), they were needed for a few critical road segments such as I-91 in Brattleboro which was given an artificially high score. Because the statewide screen involves less detailed data inputs than the pilot study, a field-verification component may be needed on a case-by-case basis to verify results of the statewide prioritization. Visit the Vermont Transportation Resilience Planning Tool (TRPT) (Schiff et al., 2018) web application for more detailed information in watersheds where the full resiliency analysis has been performed.

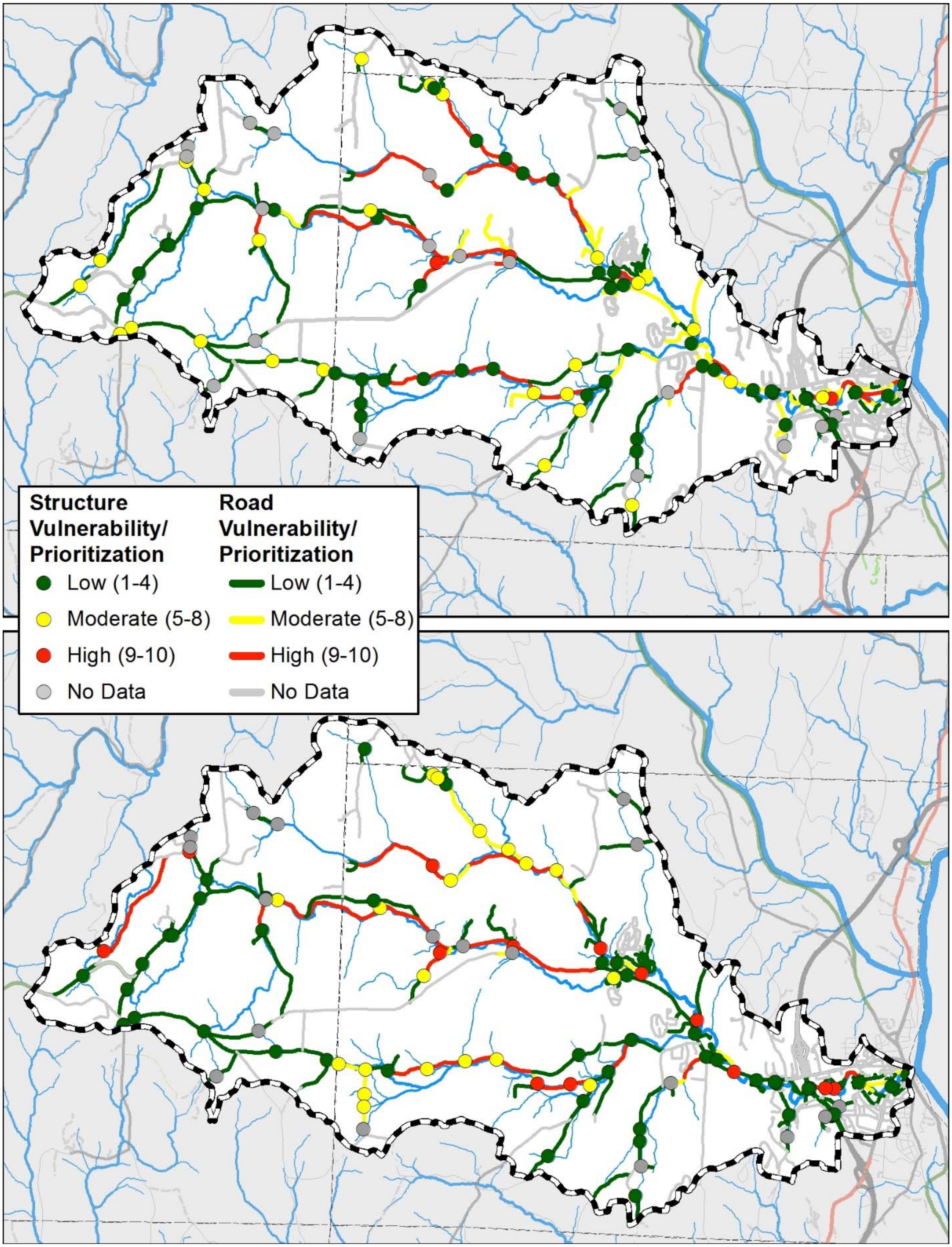

Figure 4: Detailed Vulnerability Screen (Top) and Coarser State Prioritization (Bottom) for Erosion in the Whetstone Brook Pilot Watershed

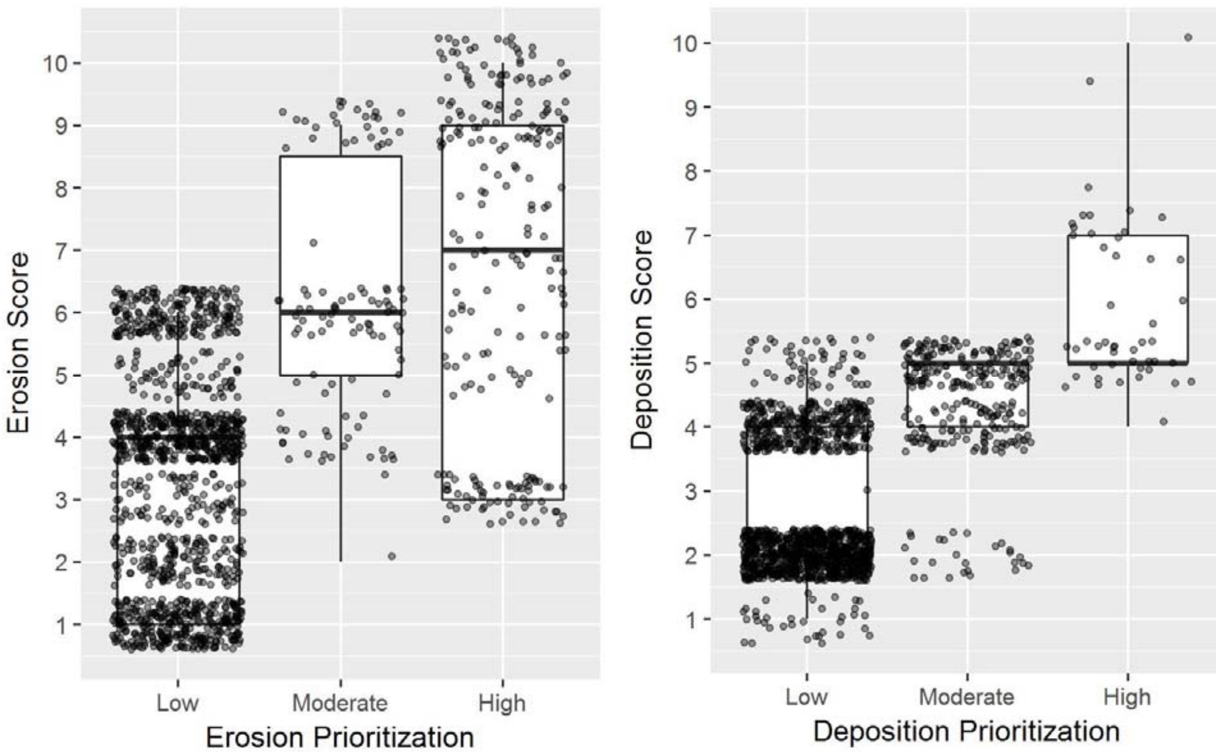

Figure 5: Comparison of pilot subwatershed detailed vulnerability scores (y-axis) and state prioritization categorical scores (x-axis) for erosion (left) and deposition (right) for road embankments.

APPENDIX A: DOCUMENTED PAST DAMAGES

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

Low Vulnerability	High Vulnerability
No Damage Record	Damage Record

Definition: Documented damages described in VTrans Detailed Damage Inspection Reports (DDIR) from Tropical Storm Irene. Damage records included a GIS shapefile and documentation about the repair and approximate costs, as well as site photographs in many cases. Further damage records, such as FEMA PA Projects or data provided by Regional Planning Commissions and municipalities could be included in this prioritization for assessing roads maintained by Towns. See pilot watershed scoring for more detail on including other sources of damage data.

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). Currently the statewide screen assigns the highest score possible if a damage record is present, regardless of the damage severity. This analysis could be refined in the future with more effort to code and classify statewide damage records.

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 (ex. 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 intersect between the road and river networks. Then the intersected points were spatially joined with all available structure datasets.

GIS Methods:
Data:

Files	Type	Unique ID Field
VTrans Detailed Damage Inspection Reports	Point	REPORT_NUM
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 DDIR points with stream and road IDs.
    a. Open the "Spatial Join" tool.
    b. 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" dropdown. 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.
    c. 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 DDIR 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 DDIR 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.
    d. 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 DDIR 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")
        - [SF_Mode]: 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").
        - [RF_Mode]: 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").

b. Go through each damage record, filling in the newly added fields for each record.
   - Examine proximity to perennial streams and the damage descriptions in the reports to limit the inclusion of damages from stormwater runoff from impervious surfaces (e.g. riling 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 culvert data layers can be used for additional information to verify the identity and location of structure damages.
   - 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 result 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, if chose 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.
   - 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.

APPENDIX B: LENGTH OF ROAD SEGMENT ROW IN RIVER CORRIDOR (FEET)

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) right-of-way (ROW) located in the approximate Vermont River Corridor (VTANR, 2015). A standard 3-rod (49.5 feet) right-of-way (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 B-1).

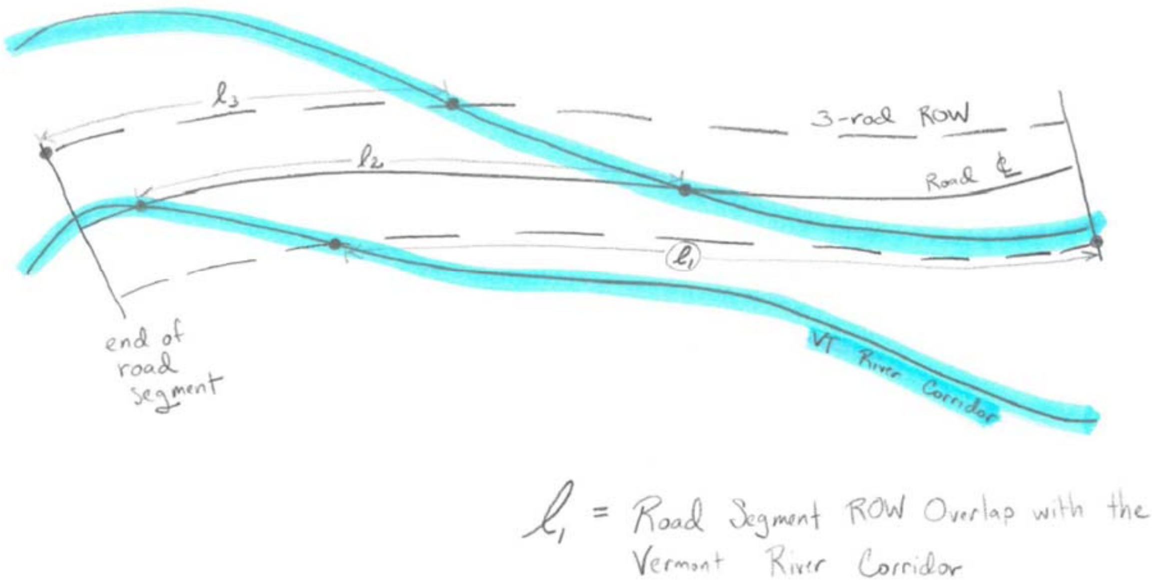

Figure B-1: Sketch of Length of Road Segment ROW in River Corridor

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 in Appendix C 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 "Statewide River Corridors" 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 in "Statewide River Corridors"
   a. Open "Clip" tool. Input "ROW Roads" file. Under "Clip Features" specify the "Statewide River Corridors" 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. for: between 660 and 1320 = "MODERATE" and >1320 = "HIGH".

APPENDIX C: LENGTH OF ROAD SEGMENT ROW IN FLOODPLAIN (FEET)

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) right-of-way (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/non-official 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. The statewide level analysis for this variable has been performed (Figure C-1).

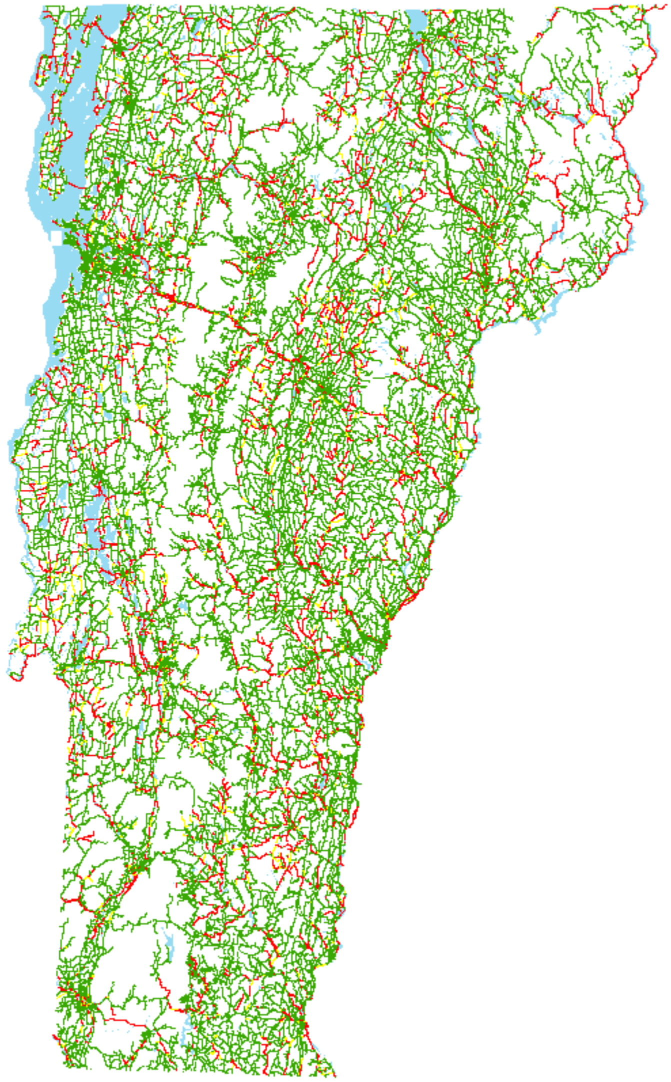

Figure C-1: Example of State-Level Output for Road Segment ROW in Floodplain

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 ft) in each direction. The ROW lines and the floodplains were clipped and had their lengths measured to determine the overlap (Figure C-2). The maximum total overlapping length of the ROW lines was used as the overlap between the road segment ROW and the floodplain (Figure C-3). The complete GIS process for finding the maximum length of the right of way associated with each segmented VTrans Road in the 100-yr floodplain can be found in Appendix B.

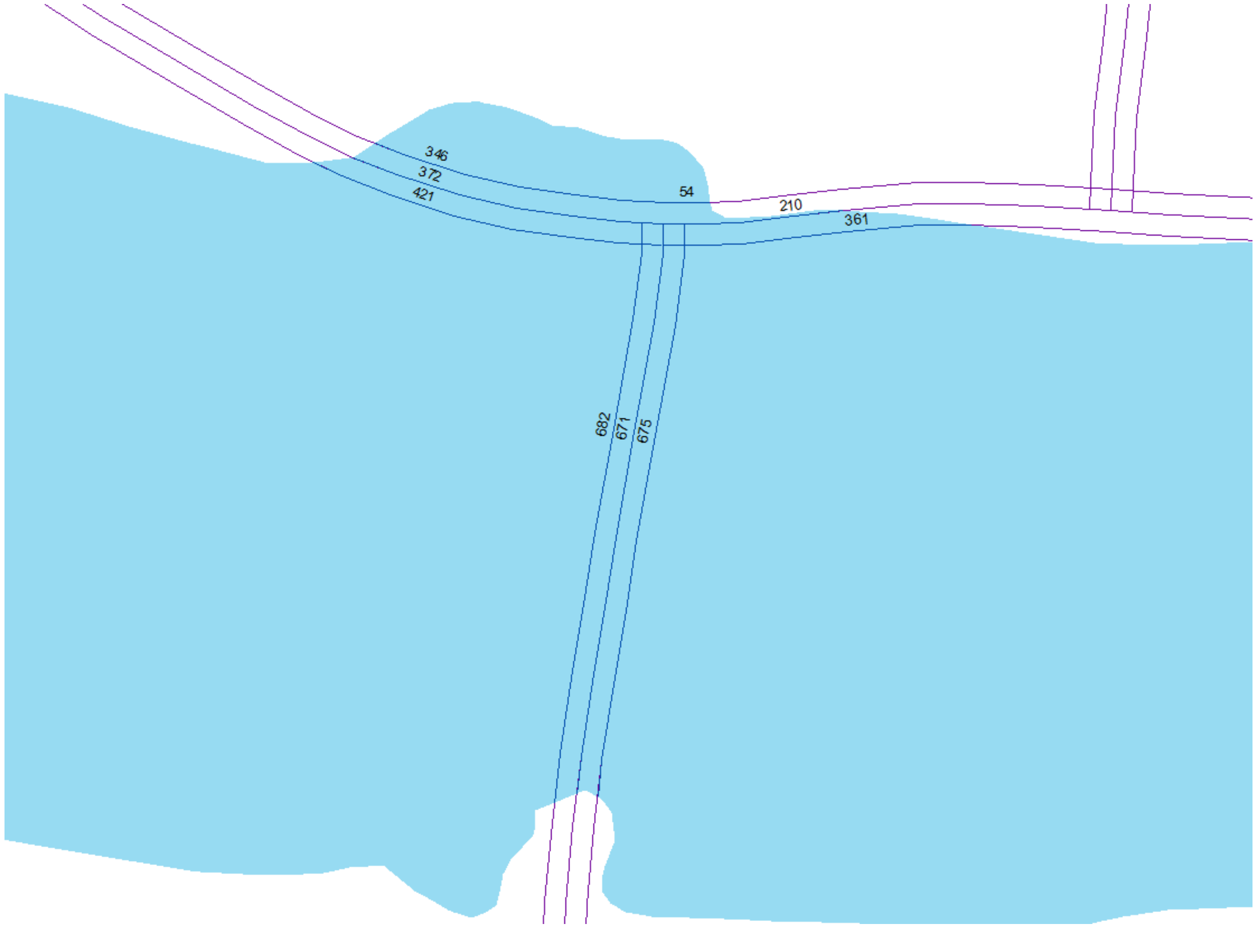

Figure C-2: Example of Lengths of Road Segment ROW in Floodplain

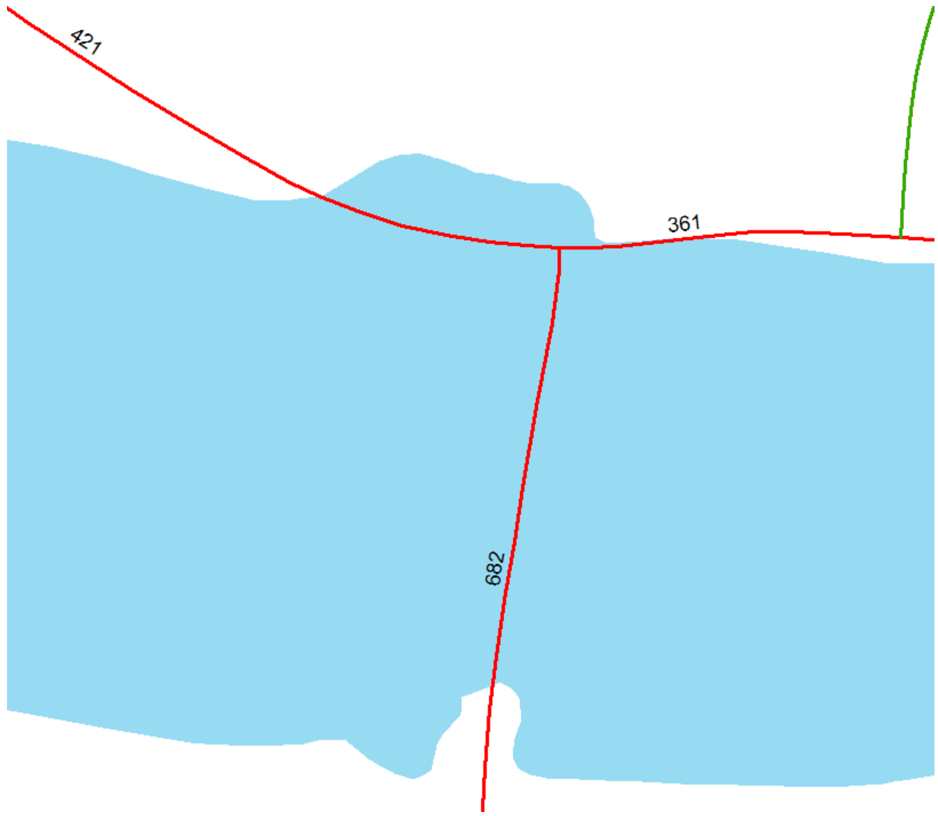

Figure C-3: Example of Maximum Length of Road Segment ROW in Floodplain

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 combined “Statewide Floodplains” 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 in “Statewide Floodplains”
   a. Open “Clip” tool. Input “ROW Roads” file. Under “Clip Features” specify the “Statewide Floodplains” 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 ft; in "Field Calculator" for the new text field, specify "LOW".
   d. Repeat step 3c. for: between 50 and 200 = "MODERATE" and >200 = "HIGH".

APPENDIX D: SPECIFIC STREAM POWER (W/m^2)

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

Erosion Screening

Low Vulnerability	Moderate Vulnerability	High Vulnerability
<100 W/m^2	>300 W/m^2	100 – 300 W/m^2

Deposition Screening

Low Vulnerability	Moderate Vulnerability	High Vulnerability
>300 W/m^2	300 – 100 W/m^2	<100 W/m^2

Definition: Stream power per unit area of channel bed (Knighton, 1999) in watts per square meter was calculated 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. The formula for bankfull width is provided in the **Structure Width vs. Bankfull Channel Width** section.

Application: As outlined in the tables above, channels with stream power greater than 100 watts per square meter are presumed to be more vulnerable to erosion and channels with stream power less than 300 watts per square meter are presumed to be more vulnerable to deposition. Segments with stream power between 100 and 300 watts per square meter are vulnerable to erosion and deposition but are more likely to experience erosion damages.

Data Development: River segments were associated with any road segments within the statewide valley walls, within a 50-foot buffer of the valley walls, or within a 50-foot buffer of blue-line streams with drainage areas less than 2 mi^2 that have no mapped valley walls. The stream power values were joined from past project work with the Vermont Land Trust (Schiff et al., 2015).

GIS Methods:

Data:

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

1. Associate river segments with road segments and select road segments to score.
    a. Open the “Dissolve” tool. Dissolve the valley walls layer.
    b. If provided with separate files containing VLT catchments, use the “Merge” tool to combine them into a single shapefile. If the MMIGRID fields do not pull into the same field, use the field calculator to migrate them into one column. If MMIGRID is missing, the “Spatial Join – Largest Overlap” tool (available here: https://www.arcgis.com/home/item.html?id=e9cccd343bf84916bda1910c31e5eab2) can be used to join the ID field from the stream segments layer.
    c. Open the “Intersect” tool. Intersect the dissolved valley walls and merged catchments layer.
        - Optional: If available, use the “Eliminate” tool to merge polygons created from small tributary catchments entering larger rivers into the valley polygon for the larger segment the shape was intended to encapsulate. In the pilot subwatersheds, values ranging from 100,000 ft^2 to 300,00ft^2 were used as thresholds for merging. This tool was not available for the statewide scoring process.
    d. Open the “Buffer” tool. Add the split valley walls layer and apply a 100-foot buffer, dissolving by the MMIGRID. Select the VLT segments that are completely within the buffered valley walls layer, then switch the selection and create a layer from the selected stream segments. Apply a 100-foot buffer to this layer and dissolve by MMIGRID.
        - Optional: If possible, specify a “FLAT” end type for the rivers buffer to avoid relating road segments to small downstream river segments. This option was not available for the statewide scoring.
    e. Open the “Intersect” tool. Add the roads layer and buffered valley walls layer, joining all attributes and keeping the output type the same as the input type. Repeat this process with the roads layer and buffered stream segments layer (Figure D-1).
    f. Open the “Merge” tool. Merge the two intersect layers created in step 1e.
    g. Open the “Dissolve” tool. Dissolve the merged layer created in step 1f by MMIGRID and FAID to narrow the table to each unique road-stream pairing. Export a copy of this table for scoring. The vulnerability of each road segment to the stream segments it is associated with is assessed separately and the scores are dissolved to choose the maximum vulnerability after scoring.

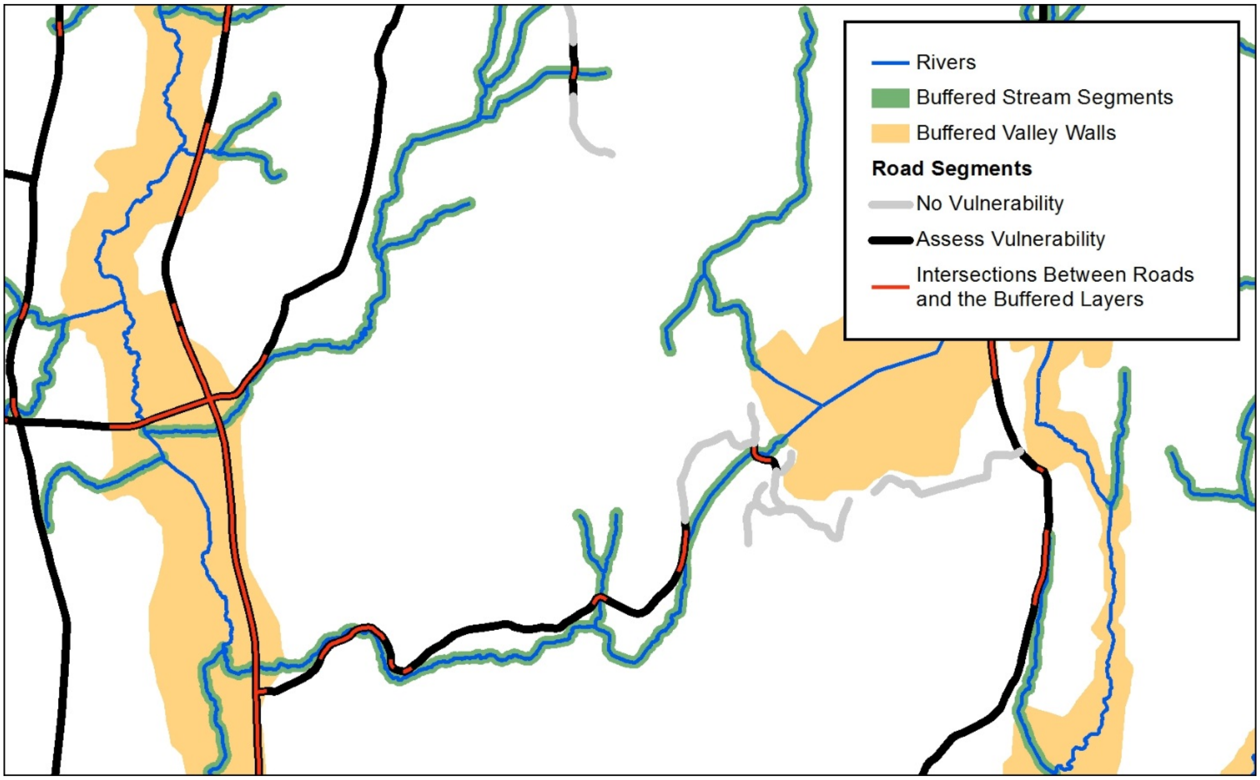

Figure D-1: Example of road association with river segments by valley wall and stream buffers.

2. The MMIGRID associated with the stream segments is carried over to the buffered river and valley wall layers, then to the roads layer in step 1. Use the MMIGRID associated with the road segments to join the stream power ("w_W_m2") to the road-stream intersect attribute table if it was not carried through to the table in step 1.

APPENDIX E: STRUCTURE WIDTH VS. BANKFULL CHANNEL WIDTH (%) (HGR-BASED)

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 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 data was 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:

Data:

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 (identical to step 1 in Appendix A).
   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, FAI, 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 DDIR 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. We recommend reducing 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 6 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. Filter the crossings by AOT class, keeping only crossings on roads maintained by the state. Add in any crossing catalogued in the VT Long Structures dataset to keep state-maintained bridges.
        - Select by Attributes VBSCRIPT:
          "AOTCLASS" = 30 OR "AOTCLASS" = 31 OR "AOTCLASS" = 32 OR "AOTCLASS" = 33 OR "AOTCLASS" = 34 OR "AOTCLASS" = 35 OR "AOTCLASS" = 40 OR "AOTCLASS" = 41 OR "AOTCLASS" = 42 OR "AOTCLASS" = 43 OR "AOTCLASS" = 44 OR "AOTCLASS" = 45 OR "AOTCLASS" = 47 OR "AOTCLASS" = 51 OR "AOTCLASS" = 52 OR "AOTCLASS" = 53 OR "AOTCLASS" = 54 OR "AOTCLASS" = 55 OR "AOTCLASS" = 56 OR "AOTCLASS" = 57 OR "AOTCLASS" = 59 OR "AOTCLASS" = 1 OR "AOTCLASS" = 11 OR "AOTCLASS" = 12 OR "AOTCLASS" = 13 OR "AOTCLASS" = 14 OR "AOTCLASS" = 15 OR "VTLNG_DIST" > 0
    b. Select features from those selected in step 4a to 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)
    c. 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.
        - We filtered out widths that were negative, zero, or less than 1 foot.
        - We filtered out widths that of 999, 9999, and greater than 9999.

- We also filtered out crossings where the road had an AOT class of 4, 7, and 8 the distance to a VTRANS Long structure was greater than 10 meters, finding that these crossings tended to be pulled in erroneously due to a nearby state highway or were dams.
- We filtered out widths where the structure width was less than or equal to the stream order, finding that joins where this was the case were usually from a small drainage culvert joining to the crossings layer.

d. Compile the structure width data after filtering by choosing the nearest joined structure for each crossing.

e. The bankfull width field, "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 multiplying by 100 to get structure width vs. bankfull channel with as a percentage.

- Note: Stream power can also be carried through from the initial intersect, as an alternative to using the MMIGRID to join stream power back to the data in the scoring process.

APPENDIX F: VALLEY SLOPE (%)

River Process	Road	Bridge	Culvert
Inundation	√		
Erosion			
Deposition			

Low Vulnerability	Moderate Vulnerability	High Vulnerability
>1.5	0.5 – 1.5%	<0.5%

Definition: In the pilot watershed screening, valley slope was assigned only to reaches where Phase 1 SGA assessments had been conducted (VTANR, 2009). This variable was included to provide surrogate information for incision and entrenchment ratio due to its larger extent. For the statewide screening, we used slope calculated for each river segment included in the VLT Screen Results data as a surrogate for valley slope.

Application: As outlined in the tables above, areas with slope lower than 0.5% are likely more vulnerable to inundation. Areas with higher slope are less prone to inundation.

Data Development: River segments were associated with any road segments within the statewide valley walls, within a 50-foot buffer of the valley walls, or within a 50-foot buffer of blue-line streams with drainage areas less than 2 mi^2 that have no mapped valley walls. The slope values were joined from past project work with the Vermont Land Trust (Schiff et al., 2015).

GIS Methods:

Data:

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

1. Perform Appendix D, Step 1.
2. The MMIGRID associated with the stream segments is carried over to the buffered river and valley wall layers, then to the roads layer in Appendix D, Step 1. Use the MMIGRID associated with the road segments to join the slope (“Slope_Edit”) to the road-stream intersect attribute table if it was not carried through to the table in the previous step.

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