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Quantifying Gully Erosion and Potential for Sediment and Phosphorus Pollution Reductions Achieved by Erosion Remediation Projects on Vermont's Roads

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16. Abstract

Erosion at road drainage outfalls and culvert outlets contributes to water quality impairment by discharging stormwater, sediment, sediment-bound nutrients, and other water quality contaminants to receiving waters. In Vermont, past work has quantified the importance of road surface and roadside (i.e. ditch) erosion to water quality impairment and provided insights into the effectiveness of best management practices in addressing this impact. This study documented rates of gully erosion at road drainage outfalls and culvert outlets in northern Vermont, quantified phosphorus content of eroded soils, assessed efficacy of erosion mitigation practices, and provided a first-order estimate of the magnitude of gully erosion relative to base loads for phosphorus contributions to receiving waters. We used terrestrial LiDAR scanning to conduct ground surveys at 13 intensively monitored sites and multi-date airborne LiDAR data to conduct GIS-based assessments at culverts in 35 northern Vermont towns. Soil sampling at the 13 intensively monitored sites was used to quantify soil bulk density and phosphorus concentration. The efficacy of erosion mitigation projects was assessed through the installation and monitoring of experimental "treatments" at a set of the intensively monitored sites and through the retrospective assessment of a larger set of sites where erosion mitigation projects had been installed in the past. We found that the rate of gully erosion varies widely across sites studied and relates to both site conditions and weather variability (as measured by precipitation magnitude). Erosion mitigation practices were highly effective in reducing gully erosion at the experimentally installed sites and appear to remain largely intact, functioning to provide water quality benefits at the retrospectively assessed sites. A first order "upscaling" of the study observations suggests that gully erosion is a modest contributor to loads of phosphorus in receiving waters of the Lake Champlain basin. Where the incidence of gullies is high and rates of gully erosion large, erosion mitigation can provide valuable water quality benefits and contribute to the resilience of valuable transportation infrastructure in the face of climate change. We lay out some recommendations for using research results for crediting erosion remediation under the Lake Champlain TMDL for phosphorus and comment on the broader implications of this research for other communities, workforce development, and research-stakeholder partnerships.

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ABSTRACT

Erosion at road drainage outfalls and culvert outlets contributes to water quality impairment by discharging stormwater, sediment, sediment-bound nutrients, and other water quality contaminants to receiving waters. In Vermont, past work has quantified the importance of road surface and roadside (i.e. ditch) erosion to water quality impairment and provided insights into the effectiveness of best management practices in addressing this impact. This study documented rates of gully erosion at road drainage outfalls and culvert outlets in northern Vermont, quantified phosphorus content of eroded soils, assessed efficacy of erosion mitigation practices, and provided a first-order estimate of the magnitude of gully erosion relative to base loads for phosphorus contributions to receiving waters. We used terrestrial LiDAR scanning to conduct ground surveys at 13 intensively monitored sites and multi-date airborne LiDAR data to conduct GIS-based assessments at culverts in 35 northern Vermont towns. Soil sampling at the 13 intensively monitored sites was used to quantify soil bulk density and phosphorus concentration. The efficacy of erosion mitigation projects was assessed through the installation and monitoring of experimental "treatments" at a set of the intensively monitored sites and through the retrospective assessment of a larger set of sites where erosion mitigation projects had been installed in the past. We found that the rate of gully erosion varies widely across sites studied and relates to both site conditions and weather variability (as measured by precipitation magnitude). Erosion mitigation practices were highly effective in reducing gully erosion at the experimentally installed sites and appear to remain largely intact, functioning to provide water quality benefits at the retrospectively assessed sites. A first order "upscaling" of the study observations suggests that gully erosion is a modest contributor to loads of phosphorus in receiving waters of the Lake Champlain basin. Where the incidence of gullies is high and rates of gully erosion large, erosion mitigation can provide valuable water quality benefits and contribute to the resilience of valuable transportation infrastructure in the face of climate change. We lay out some recommendations for using research results for crediting erosion remediation under the Lake Champlain TMDL for phosphorus and comment on the broader implications of this research for other communities, workforce development, and research-stakeholder partnerships.

1. Project Overview

1.1. Motivation

Transportation networks have been recognized as contributors to water quality impairment by discharging stormwater, sediment, and nutrients to receiving waters. These contributions can occur through chronic inputs of water and pollutants washed from the road surface during storm events or through episodic and often catastrophic road failure by mass wasting during extreme storms. Research studies in forested areas of the eastern U.S. (Swift, 1984; Egan *et al.*, 1996) and elsewhere (Ziegler and Giambelluca, 1997; Wemple *et al.*, 2001; Borga *et al.*, 2005; Lane *et al.*, 2006) have documented rates of erosion and mass wasting from low volume roads and impacts on water quality. A recent study on roads in an agricultural watershed in central New York documented a high level of road-stream connectivity and identified roads as an important vector for pollutant delivery to waterways (Buchanan *et al.*, 2012). New research is also documenting the role of urban roads in water pollution (Pearson *et al.*, 2018).

Within Vermont, inventories are emerging to document the extent and form of road-drainage impairments to water quality (VBB, 2008; Bartlett *et al.*, 2009; Wemple *et al.*, 2017). Watershed planning efforts in the state call for attention to this issue (VCCAP, 2009; VTANR, 2010), and the recently-released Phosphorus Total Maximum Daily Load for Vermont Segments of Lake Champlain calls for reductions in phosphorus contributions from the transportation sector (USEPA, 2016). Our previous research has documented the importance of unpaved roads on water quality impairment and quantified the effectiveness of best management practices in reducing sediment and phosphorus contributions (Wemple, 2016). This project aims to expand this work by focusing on erosion at culvert outlets and road drainage outfalls, and measures to mitigate this source of slope instability and pollutant transfer. In particular, we focus on gully features that erode at road drainage outfalls, to provide information on rates of gully erosion and the potential for phosphorus load reductions possible through remediation of gully erosion. An overarching goal of the project is to provide insights that can be used in the development of a phosphorus crediting protocol for gullies on Vermont's roadways under the Lake Champlain Phosphorus TMDL (hereafter "TMDL").

1.2. Background: Gully erosion and the development of road-stream linkages via gullies

Road and stream connectivity can be increased via gully erosion (Croke and Mockler, 2001), making them a potential pathway for transfer of pollutants such as sediment, nutrients, and salt to receiving waterways (Montgomery, 1994; Wemple *et al.*, 1996; Croke and Mockler, 2001; Katz *et al.*, 2014; Galia *et al.*, 2017; Wemple *et al.*, 2017). Gullies are morphological features formed through fluvial erosion by concentrated runoff (Conforti *et al.*, 2011; Arabameri *et al.*, 2018). They typically form at steep headcuts, can extend hundreds of meters in a single storm, and can be difficult and costly to remediate (Kirkby and Bracken, 2009). Observations of gullies over time indicate that their volumes increase through widening and deepening (Hayas *et al.*, 2019).

Gully erosion has been studied in diverse environments, including in South Africa, Ethiopia, Australia, Brazil, the U.S., and countries of eastern and western Europe (Daba *et al.*, 2003; Martineli Costa and de Almeida Prado Bacellar, 2007; Perroy *et al.*, 2010; Seutloali *et al.*, 2016; Galia *et al.*, 2017). Poesen (2003) compiled several studies and concluded that rates of soil loss due to gully erosion varied widely by setting, comprising as little as 10% of total soil loss in study sites in Europe to more than 70% in arid settings of California, USA, Australia, Spain, China and South Africa. Mass soil loss rates due to gully erosion ranging from 20-60% were common in study sites of humid settings in the eastern U.S. (see Table 1 of Poesen *et al., 2003*). The prevalence of gully erosion and its contribution to downslope sediment transfer, especially to receiving waters, raises the importance of understanding this form of sediment and associated nutrient transport for mitigating soil loss and downstream water quality degradation.

Prior studies of gully erosion have employed a range of approaches in documenting their occurrence, rates of change, and controls (Castillo and Gómez, 2016). Rates of gully erosion can be quantified through a variety of field methodologies, including erosion pins, silt fences, and topographic surveys that range in accuracy (Ritter *et al.*, 2002; Castillo *et al.*, 2012). The use of terrestrial lidar scanning (TLS) is emerging as means of obtaining very high resolution (cm-scale) surface topography data (Perroy *et al.*, 2010; Eitel *et al.*, 2016; Goodwin *et al.*, 2016), allowing for gully volume estimation and detection of rates of change through repeat surveys (e.g. Perroy *et al.*, 2010).

To stabilize slopes at road drainage outfalls and address the downstream effects of roads on water quality, various design interventions are recommended for road placement, construction and drainage (Lynch et al., 1985; Aust and Blinn, 2004). These practices vary by jurisdiction but generally include guidelines for locating roads, sizing and installing stream crossings, spacing of culverts to minimize discharge of runoff from impervious road surface, stabilizing road cuts and fill slopes through reseeding applications, and use of vegetated buffer strips and energy dissipating devices to control discharges to receiving waters. Studies have documented the application and efficacy of these interventions in reducing runoff and sediment production associated with forest roads (Kochenderfer et al., 1997; Schuler and Briggs, 2000; Turton et al., 2009; Anderson and Lockaby, 2011; Wear et al., 2013; Nasiri et al., 2017). More recent studies in Vermont provide insights into the effectiveness of erosion control practices on unpaved roads, suggesting that they produce measurable benefits in addressing water quality impacts from the transportation network (Wemple, 2013; Wemple, 2015). Within Vermont, more information is needed to assess whether stabilization measures used to address road drainage outfalls are effective in mitigating erosion and the transfer of sediment and sediment-bound phosphorus to receiving waters.

1.3. Study objectives

This study examined the occurrence of gully formation and change at road outfalls in northern Vermont to address three objectives:

1. quantify rates of sediment and phosphorus (P) production associated with erosion at concentrated road drainage points on unpaved and paved roads;
2. assess the effectiveness of intervention measures in reducing sediment and P mobility from roads, and
3. develop a framework for providing credits for erosion mitigation measures that can be implemented under the Lake Champlain TMDL.

The following sections of this report describe our approach, findings and recommendations for integrating this research into sediment and phosphorus management within the transportation sector of the state.

2. Approach

To address study objectives, we used repeated surveys with terrestrial lidar scanning at a set of 13 intensively monitored road drainage outfalls in Chittenden, Lamoille and Washington counties, combined with inspection and analysis of a larger set of road drainage outfalls in northern Vermont using airborne lidar data to quantify gully size and change over time. We evaluated the effectiveness of erosion mitigation using both experimental installations at a limited number of study sites and retrospective assessment of past erosion control projects to provide insights into the efficacy of erosion control measures used on Vermont's transportation network.

2.1. Intensive gully monitoring using field-based surveys and terrestrial lidar scanning

2.1.1 Site selection and survey frequency

In consultation with members of our Technical Advisory Committee, we inspected over 30 sites in northwestern Vermont and selected 13 sites for intensive monitoring at road drainage outfalls (Table 1, Figure 1). Each site designated as a "treatment" for installation of an erosion mitigation project was paired with an untreated "control" site, located nearby and situated on a similar slope inclination with similar soil type. Two treatment sites on I-89 in Colchester were paired with a single nearby control site.

Site surveys began in the September 2019 on eight sites. Five more sites were added to the study in late fall 2019 and first surveyed in spring 2020. Surveys were conducted at least once each season (summer, fall, and spring following snowmelt) over the two-year study until May 2021 to assess gully change and quantify erosion rates. Each site was surveyed at least four times, with the highest frequency of surveying at sites 10 and 11 where we conducted 8 surveys over the two-year study period. Repeated surveys at all sites prior to installation of erosion mitigation treatments were used to quantify gully change in time. Surveys following installation of treatments provided a means of assessing stability of the erosion mitigation measures relative to the untreated control. Monitoring on one planned treatment site at Vale Drive in Essex was terminated by request of town officials, but provided a measure of change over time for the four completed surveys at the site.

2.1.2 Estimation of gully size and change using terrestrial lidar scanning

Following site selection, each site was visually inspected and multiple scan positions established, using 4-foot rebar stakes marked with reflective tape and survey caps to establish monumented tie points. Cylindrical reflectors were mounted on each tie point and raised to a height of 8 feet from the ground for surveying. To ensure coverage of the region of active erosion, an area of interest for each gully was set at three times the gully width and 3 scan positions down the length of the gully. Surveys of the gully length were terminated when fencing or private property restrictions prevented access or when the gully feature entered a receiving stream. Tie point locations were set to ensure visibility from all scan positions along the elevation profile occupied by the gully.

Topographic data were acquired using a RIEGL VZ-1000 terrestrial lidar scanner at each scan position (Figure 2). A rugged field laptop with RiScan software was used for visual inspection of the resulting 3-dimensional point cloud in the field after each scan to ensure full coverage of the gully. Survey scans were processed using RIEGL software package RiScan Pro. This involved registering the raw 3D point clouds from the individual scans to a single scan. The 3D point cloud was edited to remove vegetation and anthropogenic features like culverts to create a 3D point cloud of the bare earth. The bare earth point cloud was then exported to Applied Imagery Quick Terrain Modeler where a DEM of the gully was generated. In Civil 3D 2020 Metric, a surface was created from the resulting DEM of the first survey of each site, using surrounding terrain to create a synthetic surface elevation of the pre-gullied land surface as a baseline. This baseline DEM and the lidar-scanned DEM were then compared in Quick Terrain Modeler to calculate the volume of each gully. The baseline DEM was used as the reference model to calculate feature volume for every survey over the monitoring time period. To quantify rates of gully erosion, we computed the difference in gully volume between survey dates.

2.1.3 Gully Soil Characterization

To characterize phosphorus content of gullied soils, samples were collected in summer and fall 2019 from the walls of gullies at 30-centimeter depth intervals using a 2-inch diameter AMS soil core sampler (Figure 3). Samples were transported to the Agricultural and Environmental Testing Lab (AETL) at the University of Vermont for analysis. The bulk core sample (fine soil and pebbles) were oven dried at 105°C overnight and weighed to determine dry bulk density. Samples were subsequently sieved through a #10 (2mm) mesh to remove coarse grains and ground with mortar and pestle before passing through a #35 (0.5 mm) sieve. Approximately 0.5 g of this ground fraction was weighed to 0.001 g and digested using a microwave-assisted nitric acid digest (EPA method 3051). Digests were analyzed for total phosphorus (TP) by ICP-OES (Avio 300, Perkin Elmer Corp., Norwalk, CT, USA). Site #1 on I-89 North in Colchester was added to the study in late Spring 2020, following the shut down of laboratory facilities at the University of Vermont during the Covid-19 pandemic, and not included in soil samples collected.

Soil texture for each gully site was characterized using Natural Resource Conservation Service (NRCS) soils data accessed through the Vermont geodata portal (https://geodata.vermont.gov/). Attributes including percent sand, silt and clay and the NRCS soil erodibility (Kw) factor were used in statistical analysis of the dataset.

2.1.4 Study restrictions imposed by Covid-19 pandemic

Some aspects of planned study elements were impacted by the university and statewide restrictions imposed by the Covid-19 pandemic in spring 2020. Initial study plans called for a round of field surveys immediately after snowmelt in Spring 2020, followed by installation of erosion mitigation treatments at selected study sites, in order to measure change following summer and fall rainstorms and after spring snowmelt. Pandemic-imposed stay-at-home orders resulted in a delay of post-snowmelt surveys until early May 2020. The first erosion mitigation project was installed at the Milo White, Jericho (#16) site in mid-June, followed by installations at other sites in early or late fall (Table 1). Although all sites were surveyed in a final round in Spring 2021, this survey served as a post-treatment baseline at Elm St., Winooski (site 11), making it impossible within the timeframe of this study to assess post-treatment change. For most treatment-control site pairs, change following treatment is only measured for the late fall 2020 to spring 2021 period, during which snowmelt was the primary driver of erosional change.

Table 1: Intensively monitored road outfall sites.

Site Name, Town (ID)	**Site type** [1]	**Survey Begin Date**	**Treatment installation date**	**Number of Surveys**
I-89 North, Colchester (2)	Control	10/25/2019		5
I-89 North, Colchester (1)	Treatment	5/14/ 2020	10/27/20	4
I-89 South, Colchester (3)	Treatment	10/21/ 2019	10/30/20	5
Young St., Essex (10)	Control	10/4/2019		8
Elm St., Winooski (11)	Treatment	10/3/2019	11/23/20	8
Corduroy Rd., Essex (13)	Control	10/10/2019		5
Vale Dr., Essex (15)	Treatment[2]	9/27/2019		4
I-89 South, Middlesex (28)	Control	5/12/2020		5
Milo White Rd, Jericho (16)	Treatment	5/12/2020	6/12/20	5
Maple Run Ln., Stowe (31)	Control	10/2/2019		5
Maple Run Ln., Stowe (30)	Treatment	10/2/2019	9/25/20	6
Clay Hill Rd., Johnson (33)	Control	5/8/2020		4
Clay Hill Rd., Johnson (32)	Treatment	5/8/2020	9/30/20	4

[1] Per project design, sites were designated as reference or "control" sites or as "treatment" sites where erosion mitigation projects would be installed. For treatment sites, approximate dates of installation of erosion mitigation work are given, based on email notifications by contacts on the project Technical Advisory Committee.

2 Vale Dr. in Essex was selected as a treatment site at the inception of the study. Logistical issues within the town prevented the installation of erosion control at this site and necessitated termination of monitoring in September 2020.

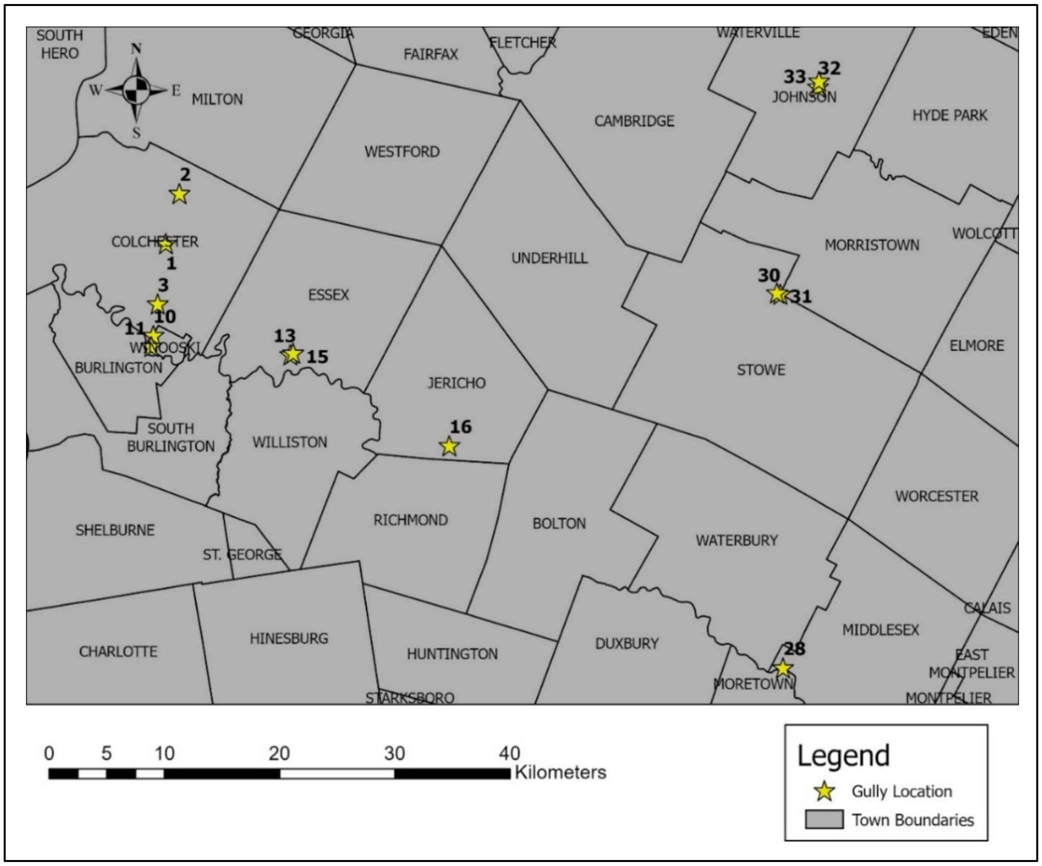

Figure 1: Location of intensively monitored gully sites in northwestern Vermont. See Table 1 for site names associated with site numbers.

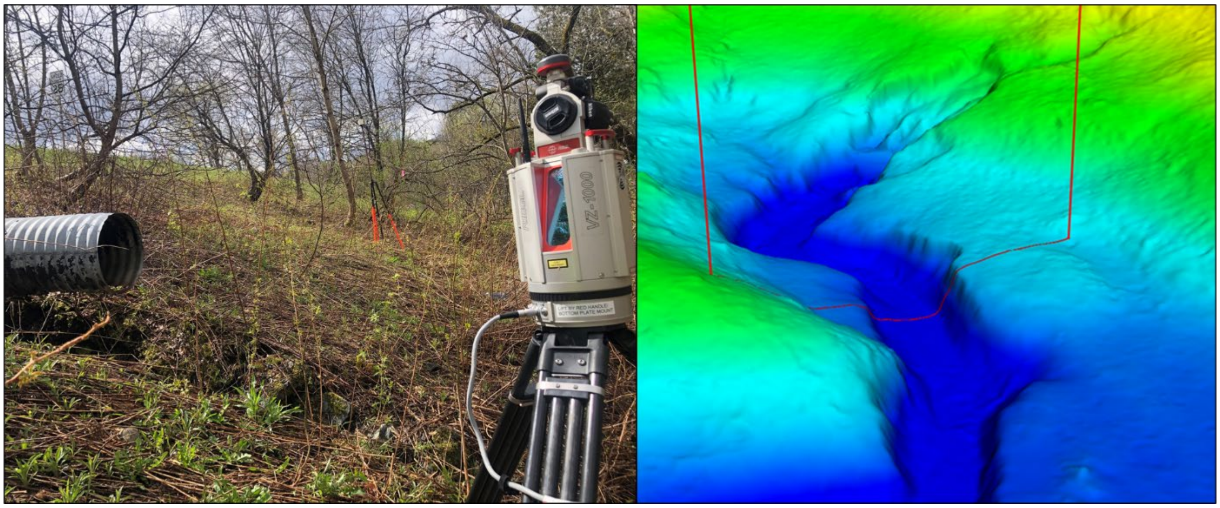

Figure 2: Terrestrial lidar scanning employed in this study. Left panel shows the terrestrial lidar scanner with a culvert, a small gully, and flagged tie points in the background. Right panel shows resulting DEM used to estimate volume and change in time.

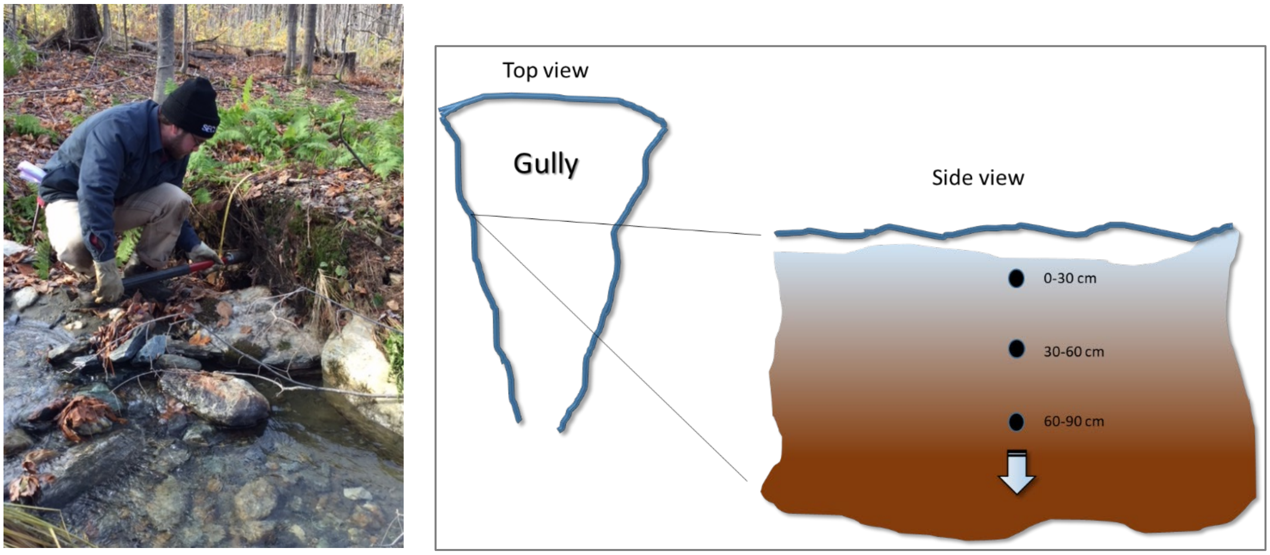

Figure 3: Soil sampling. Left panel displays technician collecting a soil sample with AMS soil coring device. Right panel displays sample collection approach, with samples collected along the gully wall, at 30 cm depths.

2.2. Extensive gully monitoring using GIS and statewide airborne lidar data

2.2.1 Datasets and Study Area Selection

To expand the dataset of gully features and quantify gully volume change, we used airborne lidar data from the Vermont's Quality Level 3 (QL3) collects between 2005-2012 and the Quality Level 2 (QL2) collects between 2013-2017, focusing on northern Vermont from Brandon (48.8234°N) to the Canadian border (Figure 4). Time periods of comparison for areas with multi-date collects ranged from 5 years (2012 to 2017) to 11 years (2005 to 2016) over the regions we assessed. We identified road drainage outfall locations using the VTrans Small Culvert Inventory available on the Vermont geodata portal (https://geodata.vermont.gov/) and the VTCulverts dataset compiled by the Vermont Agency of Transportation and made available at https://vtculverts.org/. To select representative towns for assessment, we conducted a GIS-based analysis using ArcGIS Pro v. 2.6 (ESRI, ©2020) of road grade and slope steepness. Slope steepness was estimated by reclassifying the 0.7 m resolution slope (expressed as a percent value) raster obtained from the Vermont geodata portal to a 10-meter resolution and extracting the slope value to each culvert point dataset. Road grade was estimated by extracting the minimum and maximum elevation from the statewide QL2 digital elevation model for 50-meter road segments within the entire road network for the study region, then dividing the difference in elevation by segment length. This percent grade was joined to each culvert point. We used these analyses to calculate the mean and median statewide road grade and outfall slope steepness values. Using these statewide summary statistics, we selected 35 towns with outfall steepness and road grade values similar to the study region distribution, and with multi-date airborne lidar data coverage, for inspection of road drainage outfalls.

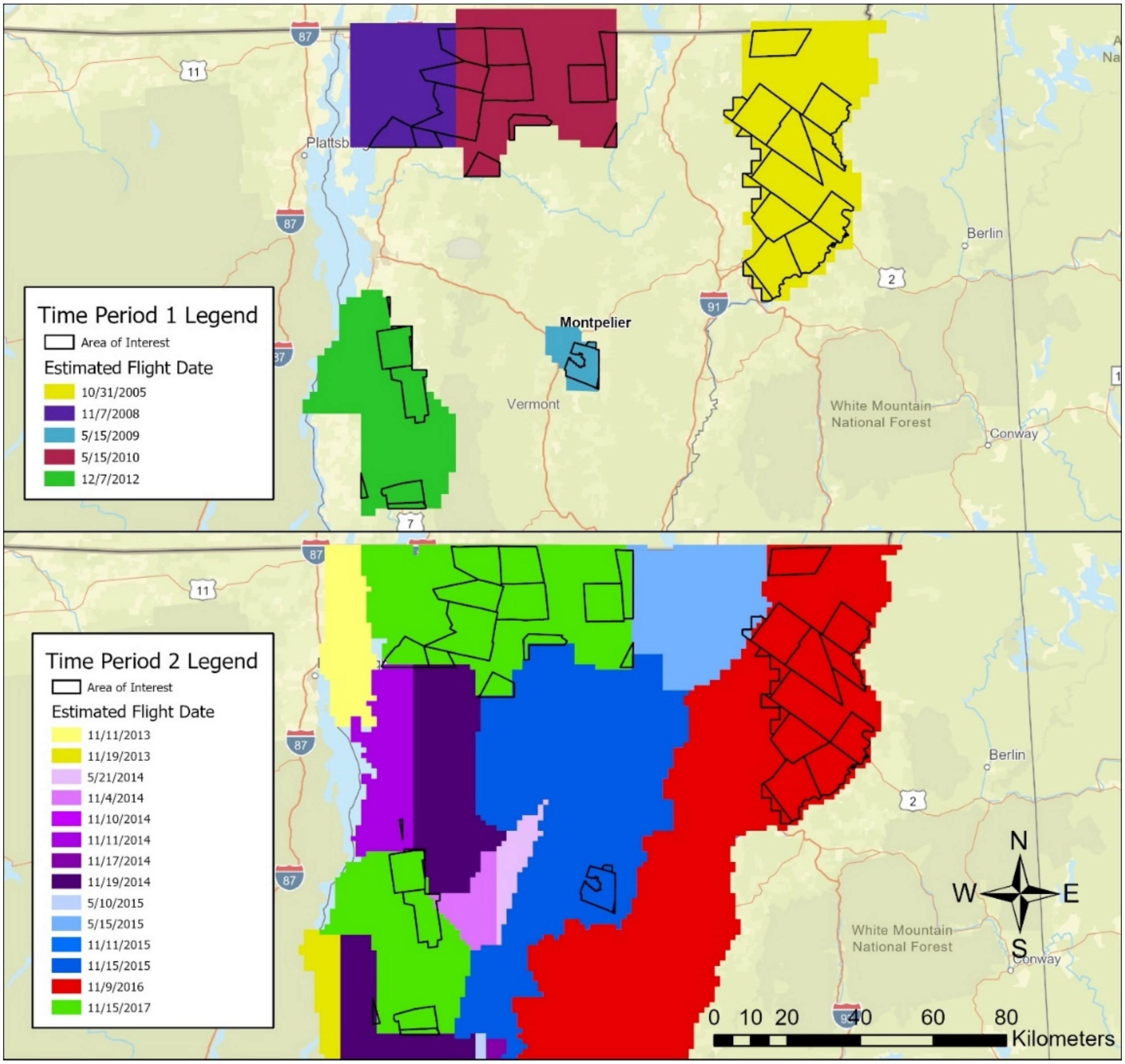

Figure 4: Extents of airborne lidar used for this study and towns (area of interest) selected for representative distribution of slopes and road gradients to assess road drainage outfalls.

2.2.2 Outfall inspections and DEM differencing

Within each of the 35 selected study towns, for the extents covered by multi-date lidar, we conducted "heads up" inspections in a GIS environment of all culverts in the Small Culvert Inventory and VTCulverts datasets. This was done by zooming to each culvert point and visually inspecting for evidence of erosion near the culvert point location. Evidence of gully erosion was determined by a depression in the land, downslope of the culvert (Figure 5). If evidence of gully erosion was found, we coded a binary data field "gully" with the value 1. The "gully" field for all inspected culverts with no evidence of gullying was coded 0. For a randomly selected set of gullies across the study region, we digitized the perimeter of the gullies to estimate change over time.

To estimate volume change between the two time periods for each DEM grid cell *i*, a DEM of Difference (DoD) was generated to assess change in elevation between two lidar surveys as

$$\mathrm{DoD}i = \mathrm{DEM}i_{\mathrm{T1}} - \mathrm{DEM}i_{\mathrm{T2}} \qquad (1)$$

where $\mathrm{DEM}i_{\mathrm{T1}}$ is the elevation value for grid cell *i* in the first time period using lidar data from the QL3 collects, and $\mathrm{DEM}i_{\mathrm{T2}}$ is the elevation value for grid cell *i* in second time period using lidar data from the QL2 collects. Positive values of DoD grid cells indicate a lowering of the surface from T1 to T2 (erosion) and negative values indicate elevation of the surface (deposition), for consistency in sign with our volume change estimates from the terrestrial lidar surveys.

The resulting DoD was resampled to the resolution of $\mathrm{DEM}_{\mathrm{T1}}$ which was the larger resolution of the inputs. We then calculated the uncertainty and bias of the DoD to correct potential sources of error. The bias was estimated by digitizing a set of 25 to 30 reference polygons per QL3 collect in areas where we did not expect change to have occurred. We located these reference polygons in steep and flat areas including agricultural fields, parking lot surfaces, roadways, and urban settings to be representative of the collection area. We used zonal statistics to calculate the mean (and standard deviation) of the DoD for these reference polygons and designated the grand mean of these values as the bias (Ɛ). Using the raster calculator, we then created a bias corrected DEM of Difference as follows

$$\mathrm{DoD}i_{\mathrm{corr}} = \mathrm{DoD}i + 1.645\ \mathcal{E} \qquad (2)$$

where 1.645 Ɛ approximates a 90% confidence interval correction and the error term Ɛ may be positive or negative, resulting in a net raising or lowering of the corrected DoD surface to remove elevation bias associated with the two time periods compared.

With the bias corrected DoD, we calculated net volume change (Vchg) for each identified gully feature as

$$Vchg_{G_k} = \sum_{i=1}^{N} (\mathrm{DoD}i_{corr} * Ni) * A \qquad (3)$$

where N is the count of grid cells with elevation difference *i* within the digitized extent of each gully (G_k), DoD*i* represents unique values of the vertical dimension of change, and A is the pixel resolution. To normalize volume change by the time interval between lidar acquisition dates, we used the lidar metadata to determine when a lidar collect was flown (Table 2). We then calculated the time interval in days between $\mathrm{DEM}_{\mathrm{T2}}$ and $\mathrm{DEM}_{\mathrm{T1}}$ and divided that interval by 365.25 for years between lidar collects. We normalized the volume change for each gully ($\mathrm{Vchg}_{\mathrm{Gk}}$ from eq. 3) by time between collects in years and expressed this as the volume change per year.

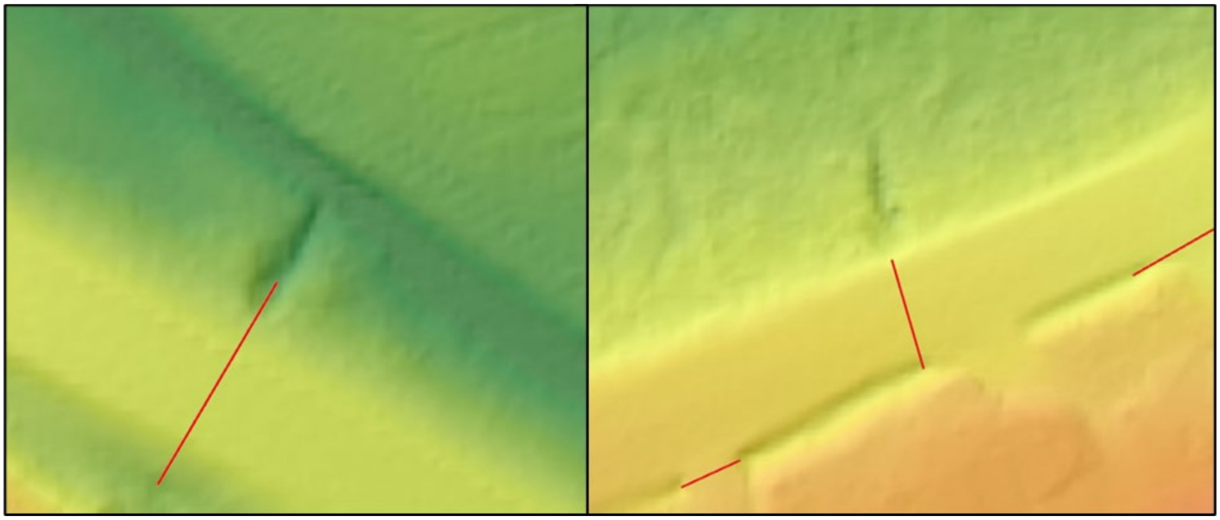

Figure 5: Examples of evidence of gully erosion on the QL2 digital elevation model. Red lines are culvert pipes from the Vermont Small Culvert Inventory and VTCulverts datasets.

Table 2: Quality level, acquisition dates and pixel resolution for airborne lidar data used for this study. All lidar data accessed from the Vermont geodata portal at https://geodata.vermont.gov/.

Quality level	**Collect Name**	**Estimated acquisition date**	**Pixel resolution (m)**
QL3	2005	October 31st, 2005	1.0
QL3	2008	November 13th, 2008	1.6
QL3	2009	May 15th, 2009	1.0
QL3	2010	May 15th, 2010	1.6
QL3	2012	December 6th, 2012	1.6
QL2	Rutland, Northeast	November 13th, 2013	0.7
QL2	Rutland, Middle East	May 15th, 2014	0.7
QL2	Rutland, Middle West	November 4th, 2014	0.7
QL2	Eastern VT, Lot 5	November 10th, 2014	0.7
QL2	Eastern VT, Lot 6	May 15th, 2015	0.7
QL2	Eastern VT, Lot 7	November 15th, 2015	0.7
QL2	Windham County	November 10th, 2015	0.7
QL2	Middle CT River	November 10th, 2016	0.7
QL2	Western VT	November 15th, 2017	0.7

2.3. Analysis of factors influencing gully size and change

2.3.1 Terrestrial Lidar Surveys

We developed a set of likely explanatory variables to explain gully size and change using publicly available GIS and precipitation data and data derivatives developed from these products (Table 3). Using the aerial imagery we measured road length and road surface area to each surveyed gully site using heads up digitizing in a GIS environment with a 0.7-meter resolution digital elevation model to indicate slope breaks. The contributing upslope area draining to a site was determined by using 0.5-meter contours (derived from 0.7 meter digital elevation model) and visually delineating the drainage area. In urbanized areas with subsurface stormwater infrastructure, we used municipal stormwater collection system GIS data inventories to define areas draining to a site. We then used each of the inlets draining to a site as a pour point to visually delineate the drainage area using 0.5-meter contours. Slope steepness at the culvert outfall was estimated by reclassifying the 0.7-meter percentage slope raster to a 10 meter resolution and using the Extract Values to Point geoprocessing tool to estimate the slope percentage at each gully location monitored. For data visualization and statistical analysis, we used SPSS v. 27 and R v. 4. Statistically significant relationships were assessed at an alpha level of 0.05.

To assess spatial variation in gully volumes collected from the terrestrial lidar surveys, we used gully volume from the May 2020 surveys, when all sites were surveyed within a two-week period. With this dataset, we examined the relationship of gully volume to road length, road surface area, contributing upslope area draining to the site, and slope steepness at the culvert outfall. We also used Natural Resources Conservation Service (NRCS) soils data to extract the soil erodibility factor and soil texture (quantified as a percent range of sand) for soil units at the culvert outfall and assessed these variables statistically against gully volume.

To assess the temporal variations in volume change, daily rainfall accumulation data for the period from September 2019 to May 2021 was acquired from the Burlington International Airport and Morrisville Airport. We summed the total rainfall to determine the accumulated rainfall between survey dates. We assessed temporal variation in gully erosion rates by examining the relationship between gully volume change and accumulated rainfall between survey dates.

Table 3: Description of explanatory variables analyzed for gully data acquired from terrestrial lidar surveys. VCGI is the Vermont Center for Geographic Information. NRCS is the Natural Resources Conservation Service. VCGI and NRCS data are available on the Vermont geodata portal at https://geodata.vermont.gov/ . UVM Derived refers to variables developed within our research group at the University of Vermont.

Variable	**Description (Units)**	**Data Source**
Slope Steepness	Slope steepness at road outlet (%)	VCGI, Slope
Road Segment Length	Length of road draining to culvert with gully (meters)	UVM Derived
Surface Area	Surface area of road draining to culvert with gully (meter^2)	UVM Derived
Contributing Area	Drainage area of upslope topography draining to culvert (meter^2)	UVM Derived
Soil Erodibility Factor	Susceptibility of a soil to erode by runoff and precipitation (Kw)	NRCS
Soil Texture	Estimated percent range of sand based on NRCS soil type (%)	UVM & NRCS

2.3.2 Airborne Lidar

Similar to the analysis constructed for the terrestrial lidar surveys, we developed a set of likely explanatory variables using publicly available GIS data, but for this larger dataset we relied more heavily on GIS algorithms to derive variables (Table 4). We used the GIS algorithm described above to extract slope steepness at culvert outfalls and used the 0.7-meter resolution statewide lidar elevation to extract elevation at culvert outfalls. We developed a Python script to estimate road length and road gradient draining to each culvert, using the culvert datasets to split the Vermont Road Centerlines data, conducting an iterative search within each segment for a high point that exceeds the elevation of the segment culvert endpoints (and, if found, re-splitting the segment at the highpoint), and assigning the resulting segments to the lower elevation culvert on the segment. The Python script then computes road length and average slope for the segment(s) draining to each culvert. We used the Vermont Impervious Surfaces Land Cover 2016 dataset produced by the UVM Spatial Analysis Lab and VCGI for the Lake Champlain basin. Percent impervious was derived by generating a 100-meter buffer around each culvert and summarizing the area of impervious surface within each buffer. Soil erodibility factor (Kw), parent material group, and hydrologic soil group for each culvert outfall were derived from the NRCS TOP20 Soils data. The parent material group was also recoded into three generalized groups: more erodible (glacial fluvial outwash, alluvial, and glaciolacustrine), less erodible (glacial till and dense till), and other (water, organic deposits, and miscellaneous units). The hydrologic soil group was also recoded into four more generalized groups: high drainage (A and B), low drainage (C and D), mixed (A/D, B/D, and C/D) and unknown (often used to indicate modern fill, urbanized at the time of the soil survey, quarries, water, etc.). Proximity to river was derived from the Vermont Agency of Natural Resources River Corridors GIS dataset by buffering the river centerline by 200-meters and coding all culverts within this buffer with a proximity flag. Culverts within the 2011 Tropical Storm Irene impact zone were derived by an overlay with the map extents of the region impacted by this 2011 storm documented in Castle *et al.,* (2013)

Table 4: Description of explanatory variables analyzed for gully data acquired from airborne lidar datasets. Data sources are as in Table 3.

Variable	Description (Units)	Data Source(s)
Slope Steepness	Slope steepness at road outlet (%)	VCGI, Slope
Culvert Elevation	Elevation of culvert (meters)	VCGI, Digital Elevation Model
Road Segment Length	Length of road draining to culvert (meters)	UVM Derived
Average Road Gradient	Average slope of road segments draining to culvert (%)	UVM Derived
Percent Impervious	Percent impervious from 100-m buffer around culvert (%)	VCGI, Vermont Impervious Surfaces Land Cover 2016
Soil Erodibility Factor	Susceptibility of a soil to erode by runoff and precipitation (Kw)	NRCS
Parent Material Group	Coded value for more and less erodible parent material (see narrative)	NRCS
Hydrologic Soil Group	Coded value of high and poor drainage based on the hydrologic soil group (see narrative)	NRCS
River Proximity (< 200m)	Binary variable (yes/no) - within 200 meters of a river corridor	Vermont Agency of Natural Resources

Irene Impact Zone	Binary variable (yes/no) - culvert located within impact zone of 2011 Tropical Storm Irene	Lake Champlain Basin Program (Castle et al., 2013)

Using the airborne lidar gully dataset, we examined bivariate relationships between gully occurrence (n=933) and volume change (n=303) with slope steepness, road segment length, road gradient, culvert elevation, soil erodibility, parent material, hydrologic soil group, river proximity, and Irene impact zone. We also used regression tree analysis (Klimberg and McCullough, 2016) in JMP Pro v. 15.0 to examine more complex and non-linear relationships between gully volume change and the set of derived predictor variables.

2.4. Evaluating effectiveness of erosion mitigation measures

Our approach for assessing the effectiveness of intervention measures on gully erosion involved both experimental installation of erosion control “treatments” and retrospective assessments of past erosion control projects. Erosion control treatments were installed at six of the intensively surveyed sites between July and November 2020 by municipal road crews and state contractors. Treatments ranged in design from engineered specifications at the I-89 sites in Colchester and the Elm Street site in Winooski to large stones installed by municipal road crews at sites in Johnson, Stowe and Jericho (Appendix 1). Lidar surveys of varying numbers (due to varied dates of treatment installations) provide a means of quantifying gully stabilization for the period studied.

To supplement the work at our intensively monitored sites, we conducted a retrospective assessment in summer 2020 of erosion control projects funded through the Better Backroads and Grants in Aid programs and sites documented in Detailed Damage Inspection Reports (DDIRs) maintained by VTRANS. Using a mobile GIS-application, we located and inspected 217 erosion control practices installed at 149 project sites (Figure 6). At each site, we reviewed project notes provided by the Better Roads Program, the Grants in Aid Program and VTRANS (for the DDIR sites) for the erosion control project designs or storm damage details. For each erosion control practice at a site, we assigned a qualitative assessment of “intact” if the practice appeared to be functioning as designed to mitigate erosion at the site. We made a qualitative assessment of “failed” if erosion controls (large stones, revetments, erosion mats or fabric) had been washed out by water or showed evidence of significant erosion that we deemed as undermining the intended design goal of erosion control. We used a qualitative assessment of “compromised” if the erosion control measure appeared to continue functioning to address erosion at the site, but would need continued maintenance to remain effective. Common occurrences of “compromised” were assigned to rip rap, stone work or armored installations where sediment was accumulating (as designed). In these instances, we used this “compromised” rating to indicate that the design life of the erosion control measure would eventually be exceeded without maintenance. This might be the case if a turnout or plunge pool appeared to be filling with sediment, since we deemed this to be an indicator of the practice approaching its design life and conditions that might result in the future in downstream sourcing of deposited sediment. In other cases, a “compromised” rating, such as at an inlet headwall, was used to indicate debris deposition that limits water drainage.

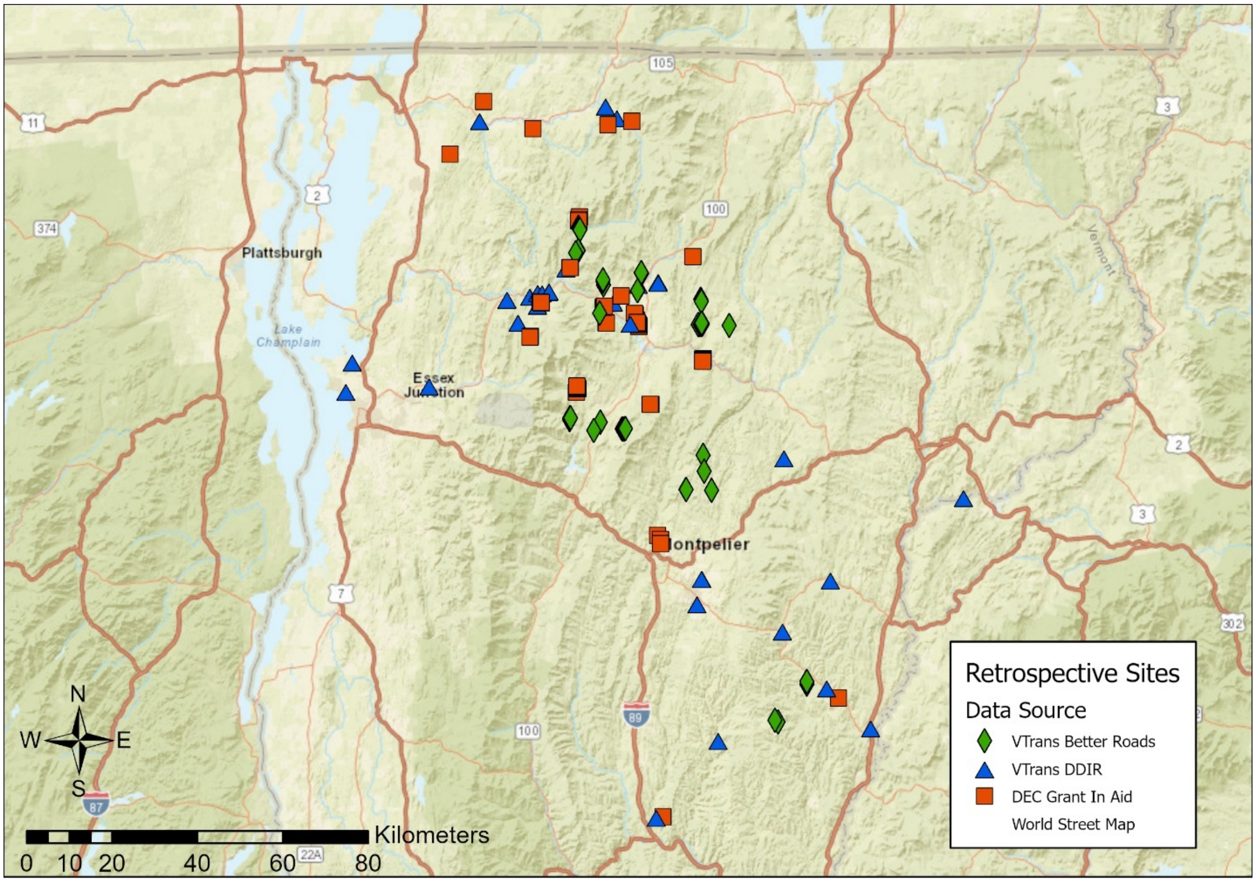

Figure 6: Locations of erosion control project sites inspected for the retrospective assessments conducted for this study.

3. Findings

3.1. Intensive Field Surveys

Gullies studied through our intensive field surveys were located on Interstate highways and on paved and unpaved municipal roads (Appendix 1). Sites located on I-89 drained the road surface and adjacent road margins through a combination of open- and closed-system drainage. Additional sites were paved municipal roads draining closed systems in Winooski, Colchester and Essex, and rural, unpaved class 3 roads draining open systems in Johnson, Stowe and Jericho. Two sites on Maple Run Lane in Stowe were located on a municipal class 4 road. Surveyed gullies ranged in size from under 2 m^3 to over 200 m^3.

Properties of the soils sampled from gully walls varied both within and across sites (Figure 7, Appendix 2). In general, soil bulk density tended to increase with depth but P concentration showed no clear pattern with depth. The range in depth-sampled bulk density was greatest at I-89 Colchester (site 3), varying between 750 kg/m^3 in the 60-90 cm depth to 1,650 kg/m^3 in the 180-210 cm depth. Depth-averaged bulk density across all sites ranged from 950 to 1,458 kg/m^3 and averaged 1,239 kg/m^3. Soil phosphorus (P) concentrations ranged from 450 mg per kg (mg/kg) of soil at the 30-60 cm depth at Young St, Colchester (site 10) to just over 1,200 mg/kg in the 0-30 cm depth at I-89 Colchester (site 3). Depth-averaged P concentrations across all sites ranged from 486 mg/kg to 1,207 mg/kg with an average of 694 mg/kg (Appendix 2).

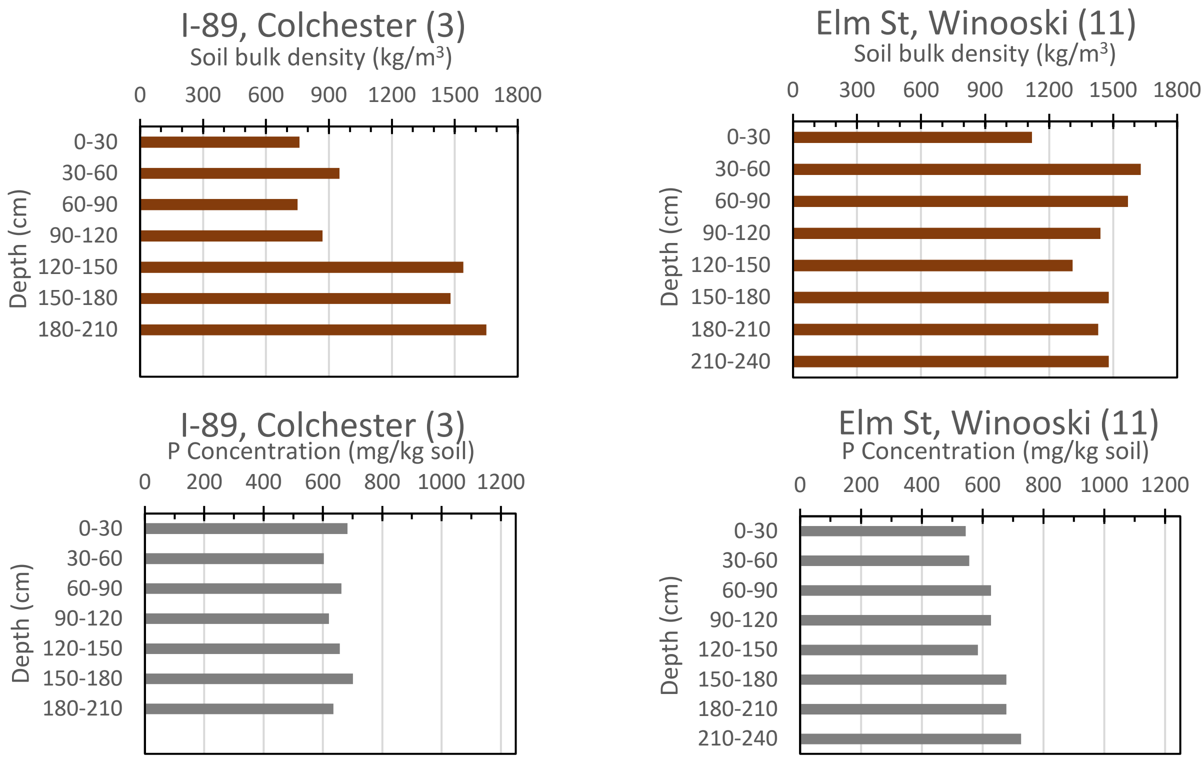

Figure 7: Soil bulk density (top panel) and soil phosphorus concentrations (bottom panel) for two sampled sites. Full dataset presented in Appendix 2.

Results from the intensive terrestrial lidar surveys show that gully volumes are related to characteristics of the sites they drain. Road length, road area, and upslope contributing area explain between 45% and nearly 70% of the variability in gully volume mapped in May 2020 (Figure 8a,b,c). These findings point to the importance of concentrated runoff in scouring gullies at road drainage outfalls. In general, larger gullies were associated with steeper slopes at culvert outfalls, but the relationship is not statistically significant (Figure 8d). The I-89 Site 28 in Middlesex is located on a very steep slope, but had the smallest gully volume among the study sites. This site drains a road segment of only 91 meters, the third shortest segment among the study sites. The I-89 northbound site 2 was located on a low gradient slope, but drains a road segment of 323 meters and the largest upslope contributing area of all sites.

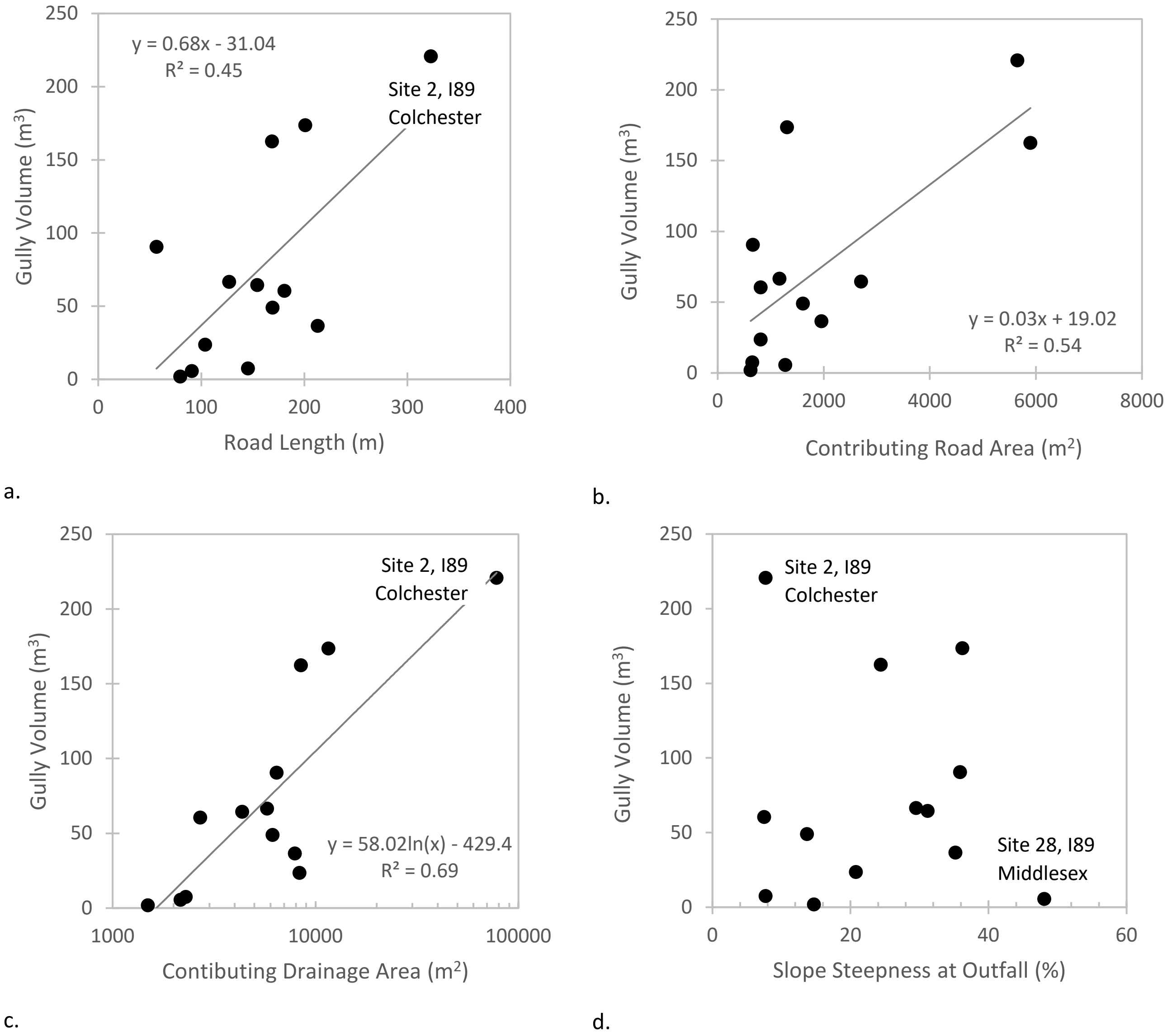

Figure 8: Gully volume for May 2020 surveys vs. contributing road length (a), contributing road surface area (b), upslope contributing area (c), and slope steepness at culvert outfall (d). See Appendix 1 for additional details on sites.

Soil properties appear to exert a lesser influence on gully volume compared to road length and area. Soil erodibility index, taken from NRCS soils data for each site, is statistically related to gully volume, though the form of the relationship is counter intuitive, with higher values of the index (more erodible soils) associated with smaller gully volumes (Figure 9a). Mean soil bulk density (Figure 9b) measured from field samples and soil texture (Figure 9c) taken from NRCS soils descriptions also appear less important than contributing water volumes (as indicated by road length, road area, and contributing area) in explaining gully volume.

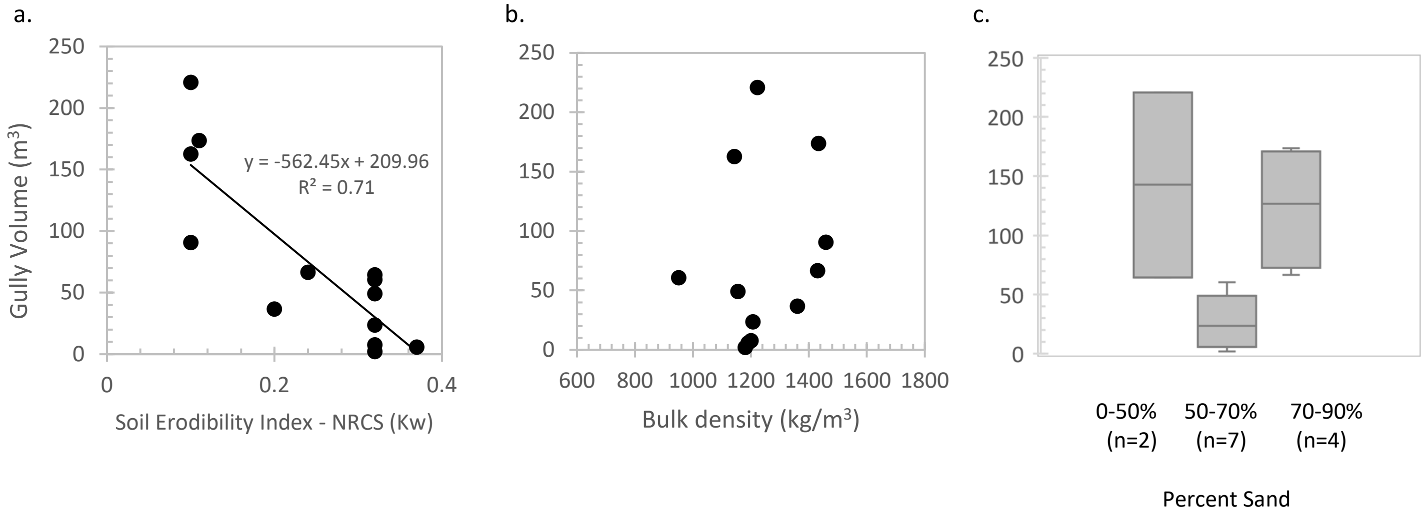

Figure 9: May 2020 gully volume at study sites vs. soil erodibility index (a), mean site soil bulk density (b), and percent sand (c). Sample size values (n) on panel c are the number of gullies represented in each group.

Repeated surveys of gully sites indicate where dynamic changes are occurring. Across time periods spanning accumulated rainfall totals ranging from 10 to nearly 60 cm, net change of gully volume was generally positive indicating erosion occurred and eroded soils were evacuated from the gully. Instances of negative net gully volume change were also observed, indicating of deposition of soils (possibly from upslope areas) within the gully. The magnitude of change was roughly related to accumulated rainfall totals during the survey intervals (Figure 10). Volume changes of 16 m^3 or more occurred at Site 3 and Site 31 for survey intervals with some of the highest accumulated precipitation totals.

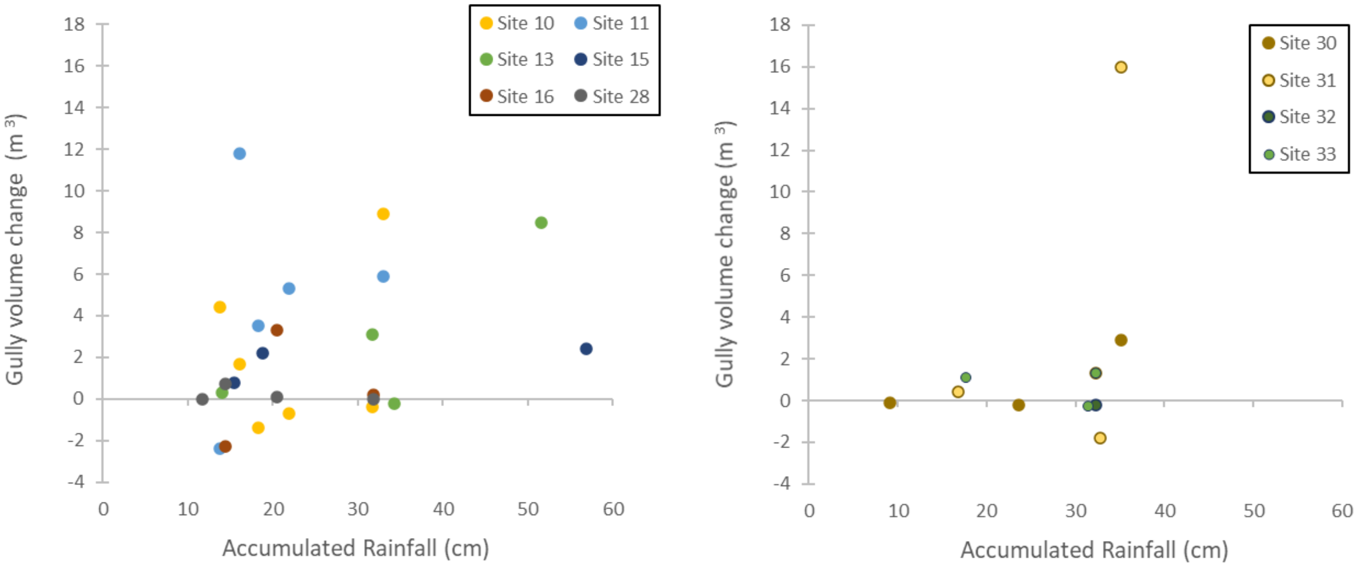

Figure 10: Plots of gully volume change vs accumulated rainfall total. Each point represents a survey interval, spanning one or more months (see Appendix 3). Left panel includes sites in Chittenden County and nearby I-89 (#28) site in Middlesex, plotted against rainfall from the Burlington International Airport. Right panel includes sites in Lamoille and Washington counties, plotted against rainfall from the Morrisville Airport.

3.2. Extensive Airborne LiDAR and GIS Analysis

Inspections of the multi-date airborne LiDAR imagery indicate that gully erosion is a common occurrence at culvert outfalls. Among the 9,823 culverts inspected, we identified 933 with evidence of gully erosion, for a frequency of roughly one in every ten culvert outfalls showing evidence of gullying (Figure 11). Gully occurrence was statistically related to slope steepness, elevation, and soil erodibility (Table 5), but mean values of the continuous variables assessed at gullied and ungullied sites vary by only small amounts, suggesting that these statistically significant results are driven primarily by the large sample size in the dataset (see also Appendix 4). Gully occurrence was not statistically related to road segment length, road gradient, parent material, soil hydrologic group or river proximity, but was statistically greater, by a small margin, for culverts situated within the extents of the region impacted by Tropical Storm Irene in 2011.

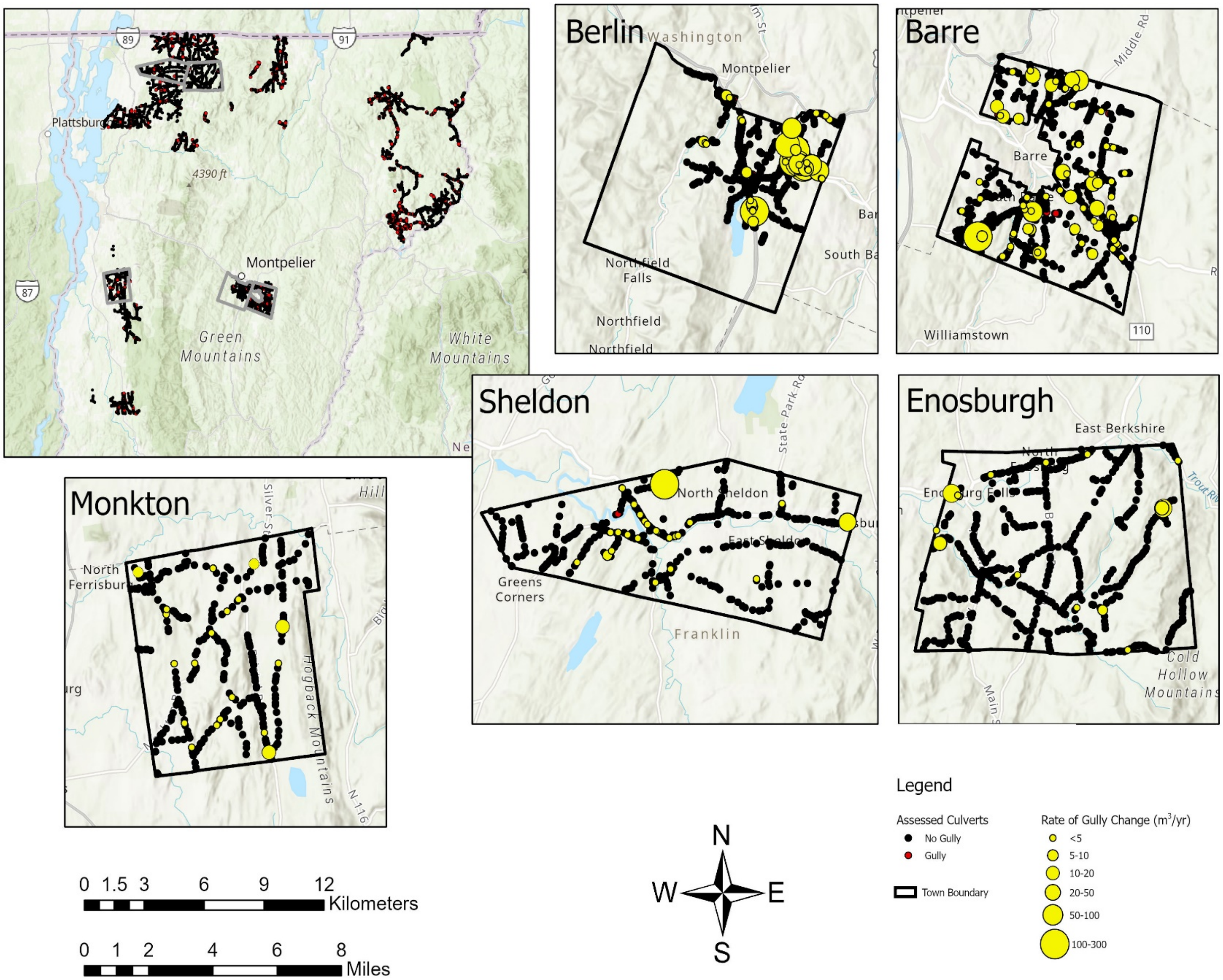

Figure 11: Locations of culvert inspections conducted in GIS to assess gully occurrence (upper left panel) and detailed maps for selected towns. See also report section 4 for detailed town-level analysis of the gully change variable.

Table 5: Results of analysis of the binary response variable ***gully occurrence*** versus explanatory variables examined. To assess relationships, binary logistic regression was used for continuous explanatory variables and contingency (cross-tabs) analysis was used for categorical explanatory variables.

Explanatory variable	**Variable type**	**Related to gully occurrence**	**p-value**
Slope Steepness	Continuous	Yes	<0.0005
Road Segment Length	Continuous	No	0.79
Average Road Gradient	Continuous	No	0.07
Culvert Elevation	Continuous	Yes	<0.0005
Soil Erodibility Factor (Kw)	Continuous	Yes	0.027
Parent Material Group	Categorical	No	0.447
Hydrologic Soil Group	Categorical	No	0.609
River Proximity (< 200m)	Categorical	No	0.307
Irene Impact Zone	Categorical	Yes	0.039

Estimates of gully change in time derived from the analysis of 303 features identified on the multi-date lidar range from -24 m^3/yr to 269 m^3/yr (Figure 11, Figure 12). Although the dataset includes some cases of very high change over the compared time periods, 76% of features examined (230 of 303) eroded less than 10m^3/year. None of the explanatory variables examined were strong predictors of gully change in time for the entire dataset (Appendix 4), but a regression tree analysis revealed complex controls on gully change (Figure 13). For example, gullies located on slopes greater than or equal to 23% experienced considerably higher mean rates of change than those on lower gradient slopes. On these steeper slopes that fell within the region impacted by Tropical Storm Irene in 2011, rates of gully change were higher than in areas outside of Irene's impact zone. On lower gradient slopes (< 23%), a small number (n = 13) were located in areas where the percent impervious area was high (≥) and resulted in a larger mean gully size than in locations where impervious area surrounding the gully was smaller than 39%. Soil erodibility was also identified by the regression tree as a factor in discriminating gully size, though the most meaningfully distinctive group here was for the small number (n=5) of relatively large gullies on developed lands.

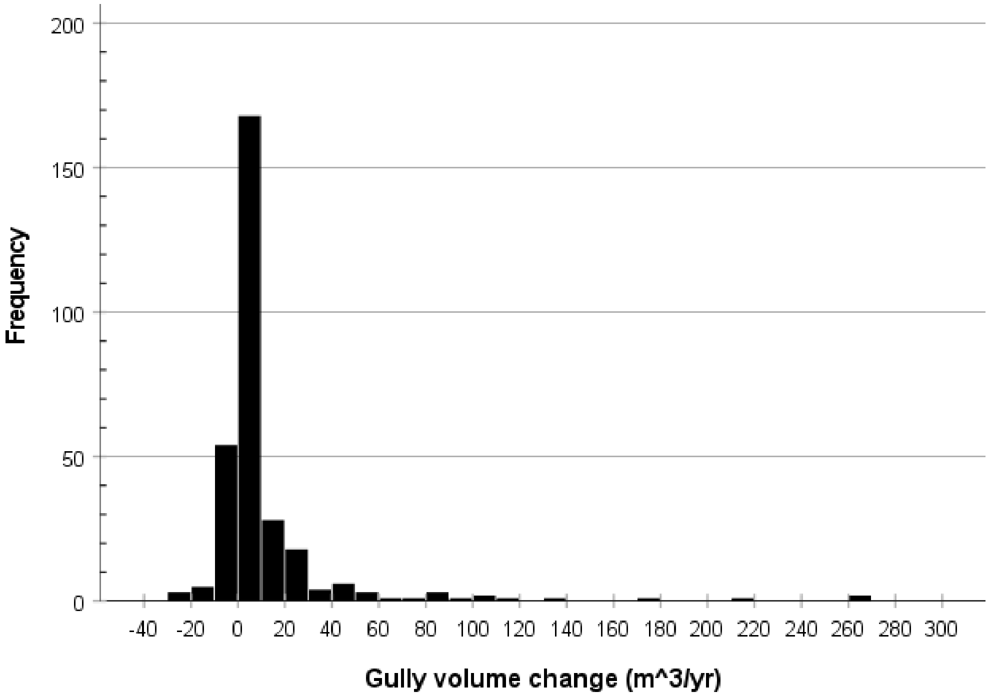

Figure 12: Histogram of rates of gully volume change derived from comparison of 303 features on multi-date lidar datasets.

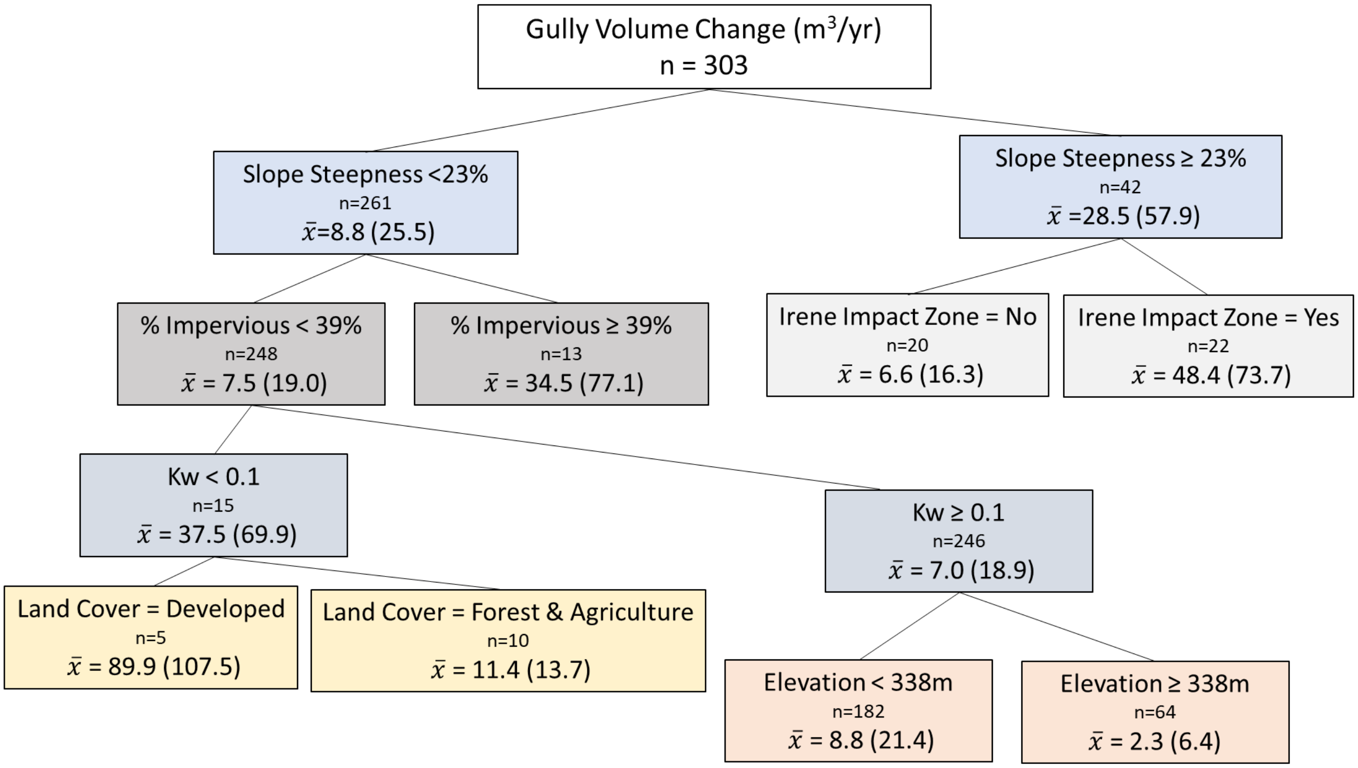

Figure 13: Regression tree analysis of gully volume change in time using 303 features identified on multi-date lidar datasets. Number of gullies (n), mean ($\bar{x}$), and standard deviation (in parenthesis) given for each group discriminated in the tree.

3.3. Efficacy of Erosion Mitigation Practices

Experimental manipulations at our intensively studied sites provide some insights into the efficacy of erosion mitigation practices (Figure 14). At I-89 in Colchester, the sites selected for erosion mitigation had lower rates of change than the control site prior to the installation of erosion mitigation, but all three sites showed considerable instability and gully volume change during the pre-treatment interval. Following installation of stabilizing rock at Sites 1 and 3 in late October 2020, change by May 11, 2021 at site 1 was only 40% of the change that occurred at the untreated control site 2, and change at site 3 was only 20% of the change that occurred at the untreated control. At Clay Hill Road in Johnson, the control site eroded 1.3 m^3 during the pre-treatment period while the treatment site aggraded 0.2 m^3. Following installation of stabilizing rock at the treatment site on September 30, 2020, the control site aggraded by 0.3 m^3 but change at the treatment site was not detected by our surveys. The outcome at Maple Run Lane in Stowe differed from these other site pairs. Here, change at the control site was roughly 5 times the rate of change at the treatment site during the nearly year-long pre-treatment period from early November 2019 to late September 2020. The rate of change at the control site was much lower for the period between November 2020 and May 2021 at only 1.3 m^3, but at the site treated with stabilizing rock, change over the same November 2020 to May 2021 period equaled nearly 4 m^3, indicating that slope stabilization measures were not effective in mitigating erosion. Repeated surveys at Elm and Young Streets, our most intensively monitored sites, showed that the Elm Street site (selected as the treatment site for the study) eroded roughly twice the volume of the control site at Young Street during the period from early October 2019 to November 23, 2020. Following the installation of the treatment at Elm Street, volume change (which occurred in the form of aggradation) in the period from

May 11 to July 7, 2020 at the treated Elm Street site was roughly half that measured at the untreated control site at Young St.

Collectively, these observations are limited, and more information could be gleaned by follow-up surveys in future years, but they do indicate that erosion mitigation measures can significantly reduce gully volume change. Based on results of this study, with the limited window of time for post-treatment monitoring, the rate of effectiveness spanned a range from 50% (at Elm St.) to 60% and 80% (at I89 Site 1 and 3, respectively) to 100% (at Clay Hill Road in Johnson). At the one site pair where this was not true (Maple Run Lane in Stowe), the treatment extended only 3.5 meters of the more than 27 meter surveyed gully length, with the majority of the change occurring along that untreated length.

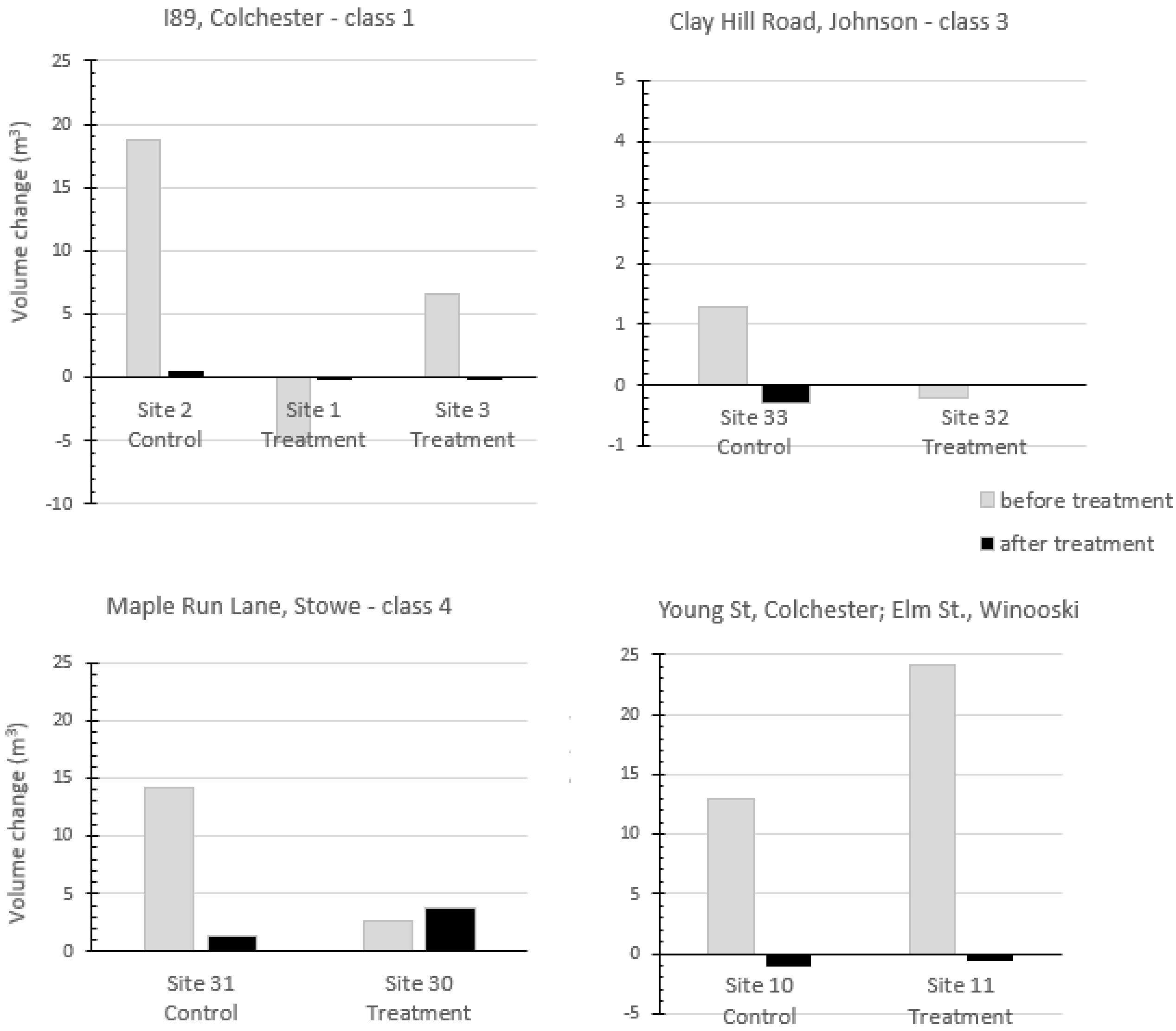

Figure 14: Comparison of paired control and treatment sites surveyed using terrestrial lidar scanning. Bars measure total volume change in the pre-treatment period (gray bars) and post-treatment period (black bars) at paired sites. Pre- and post-treatment periods vary. See Table 1 for survey begin date and treatment installation date.

Results of our retrospective assessments of erosion control projects provide additional insights into the efficacy of erosion control measures (Figure 15). Among the 217 outlet structure or slope stabilization measures, 71% were assessed as intact and functioning to provide water quality benefits as designed. Only 20 of the 217 practices were assessed as failed, with evidence of washouts or slope failure. Installations of armored turnouts and rock aprons or plunge pools were the most common practices assessed as compromised. In these cases, accumulation of sediment is the design intent, mitigating discharges into downstream receiving waters, and the "compromised" assessment score can be interpreted as a measure of the need for ongoing maintenance of these practices.

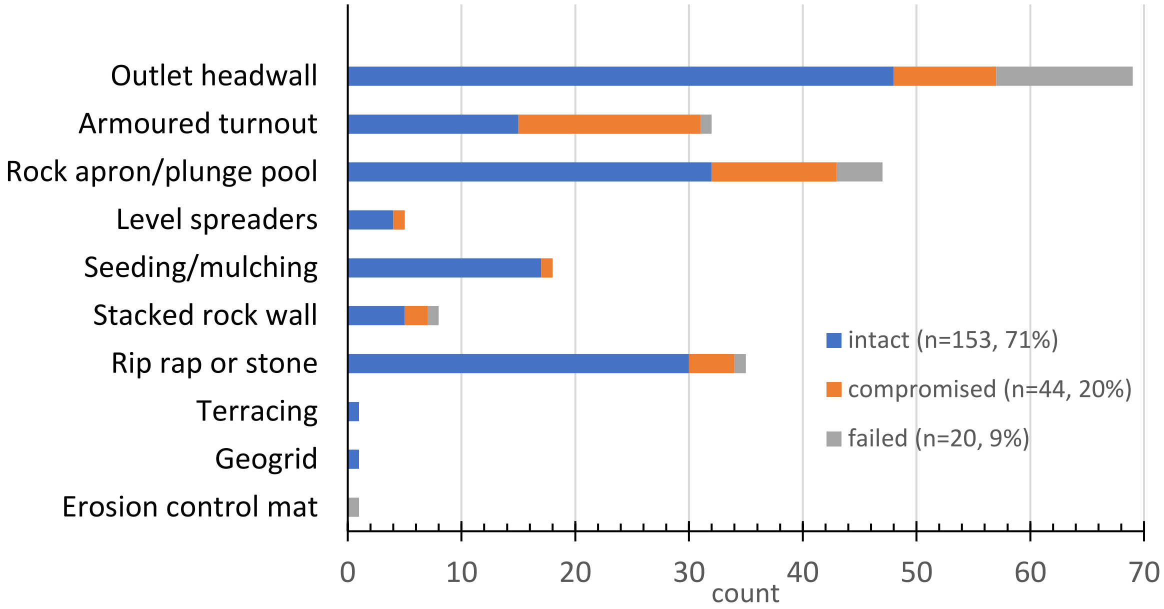

Figure 15: Results of retrospective assessments of erosion control projects conducted in summer 2020 in collaboration with Lamoille County Planning Commission. Appendix 5 provides additional details on the retrospective assessment dataset.

4. Evaluating phosphorus loads associated with gullies at road drainage outfalls

The results of this study provide a means for estimating the contribution of gully erosion to the production of sediment and sediment-bound phosphorus (P) at the town and watershed level, which may inform P reduction strategies and crediting under the Lake Champlain TMDL. To this end, we provide two examples for "scaling up" the results of the airborne lidar data analysis to the town and catchment level to evaluate the importance of this source of phosphorus production, relative to modeled loads. Our approach and estimates are provided below.

4.1. Approach

From the set of 35 towns for which we used airborne lidar datasets to identify a larger set of gullies at culvert outlets and estimate change from multi-date lidar imagery, we selected five towns[1] to provide an estimate of phosphorus production from gully erosion (Figure 11). For each town, we extracted the set of assessed culverts with gully change estimates (expressed as a volume in m^3/yr), multiplied each observation of gully erosional change[2] by the mean bulk density estimated in this study (1,239 kg/m^3) for an estimate of eroded soil mass from gullies per year, and multiplied this quantity by the mean soil phosphorus concentration estimated in this study (694 mg P/kg soil). We then summed this estimate of P production per year for gullies in each town (converting this sum from mg to kg) for a net estimate of phosphorus production, expressed in kg/year. We repeated this for two HUC12 watersheds, the Missisquoi River from Trout River to Black Creek and Lewis Creek, where we had relatively complete assessments of culvert outlets and estimates of change over time (Figure 16).

We referenced this estimate against an estimate of phosphorus loads for each town using the Vermont Clean Water Roadmap tool, available at https://anrweb.vt.gov/DEC/CWR/CWR-tool. This tool allows a user to display and interactively identify a HUC12 subwatershed and generate a screen display of total phosphorus (TP) load, expressed in kg/year. For the town-level analysis, we separately conducted GIS overlays of the town boundaries with the HUC12 watershed boundaries available on the Vermont geodata portal to determine the fraction of town area in each HUC12 catchment. Using these area proportions, we weighted estimates of HUC12 TP load and summed these area-weighted estimates for a town-level estimate of TP load (Table 6).

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[1] The five towns selected here were those for which we had estimates of change over time from multi-date lidar coverage for at least 15 gullies and in towns for which change estimates were conducted on at least two-thirds of all identified gullies.

[2] Some of the assessed culvert in the dataset show aggradation, rather than erosion, over the time period assessed. The calculations presented here only include those gullies with a net erosional change.

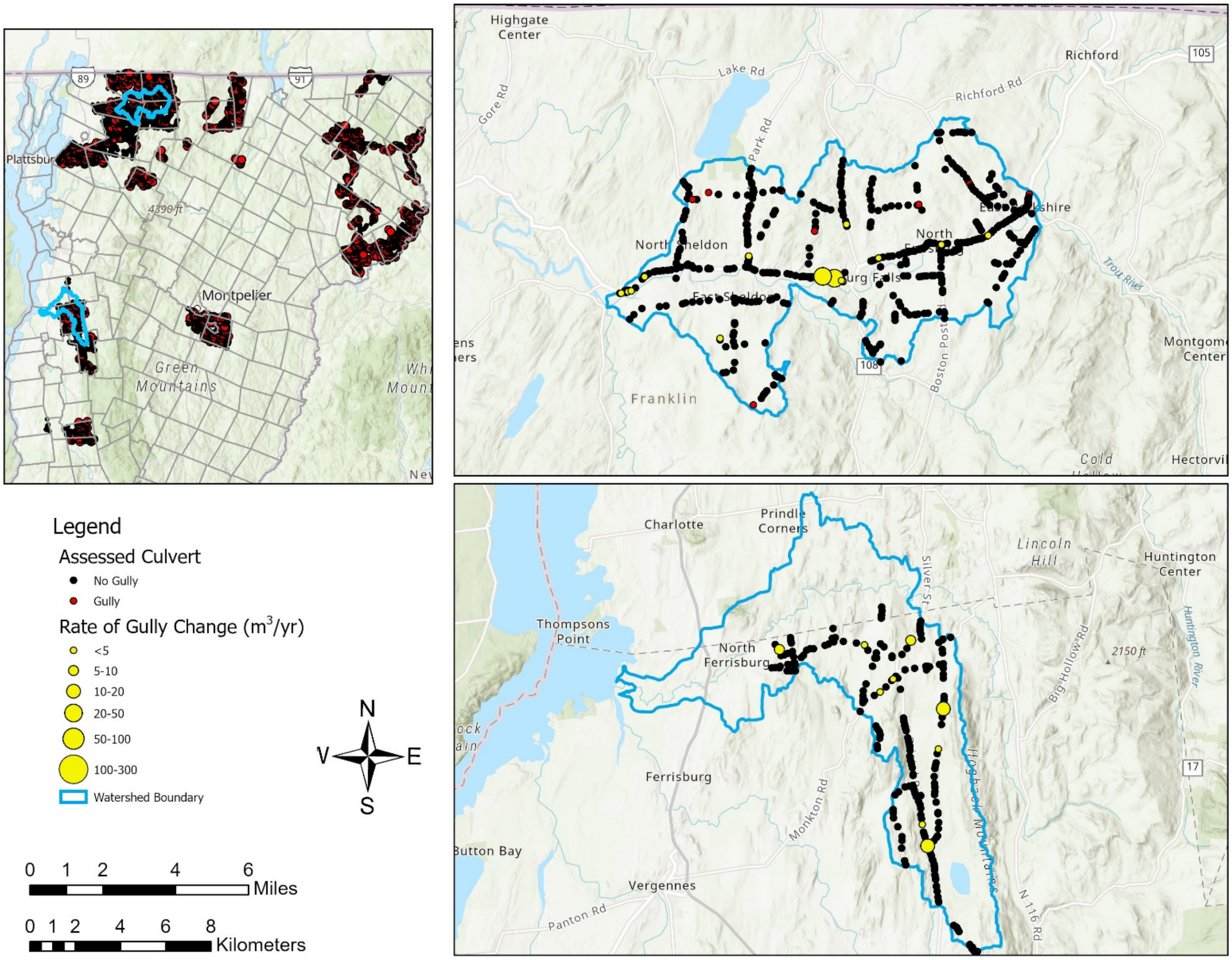

Figure 16: Locations of culvert inspections conducted in GIS to assess gully occurrence (upper left panel, same dataset presented in Figure 11) and detailed maps for two HUC12 watershed where culvert assessments covered much of the watershed.

We note in presenting this analysis that the Clean Water Roadmap tool uses downscaled estimates of TP load from the watershed model used to produce them, introducing some additional uncertainty in these estimates (*Phillip Jones, Vermont Department of Environmental Conservation, personal communication, July 8, 2021*). While the values presented here are clearly a simplification, they provide a first-order estimate of the importance of gully erosion at road drainage outfalls for phosphorus production at the town and subwatershed scale, for a few selected examples.

Table 6: Example of HUC12 subwatersheds covering the town of Barre, with total phosphorus (TP) loads extracted from the Clean Water Roadmap tool. Estimates were weighted for the percentage of town area in each HUC12 subwatershed and summed to generate an estimate of TP load by town.

HUC12 ID from VT subwatershed boundaries_HUC12	HUC12 NAME	Area (m^2)	% Area	TP load from CWR (kg/yr)	HUC12 ID from CWR tool	Weighted TP load (kg/yr)
020100030204	Stevens Branch-Jail Branch to mouth	20,968,910	0.3	5213	41504030103	1478
020100030103	Jail Branch	30,067,528	0.4	4145	41504030102	1649
020100030103	Stevens Branch-headwaters to Jail Branch	23,828,021	0.3	4049	41504030101	1293
	total:	79,596,348				**4419**

4.2. Findings and Interpretations

Using calculations described above for five selected towns, our estimates show that gully erosion at road drainage outfalls comprises a variable share of phosphorus load in the Lake Champlain basin, ranging from quite modest fractions to a more significant fraction, particularly where the frequency of gully erosion on the transportation network is high and gully change in time is on the larger end of estimates we generated (Table 7). For example, 16 of 19 assessed culverts in Monkton exhibited erosional change over the multi-date lidar datasets compared, with a median rate of change of 2.5 m^3/year. The sum of change estimates from these gullies, converted to an estimate of phosphorus production, totals 53 kg/year. This represents less than 1% of the estimated P load from the subwatersheds draining the town of Monkton. In Berlin, 33 of 42 assessed culverts exhibited erosional change over the multi-date lidar datasets compared, with a median change almost three times that in Monkton and a third of the gullies eroding at more than 10 m^3/year. The sum of change estimates from these gullies, converted to an estimate of phosphorus production, totals 1,210 kg/year, or nearly one-third of the CWR model-estimated phosphorus load for subwatersheds draining the town of Berlin. At the subwatershed scale, for the two cases we generated, gully production of phosphorus represents a small share of the HUC12 modeled load (Table 8).

These estimates are admittedly coarse and miss inclusion of gullies for which we did not have change estimates (Table 7, Table 8) and where our assessments did not cover the full town extents (Figure 11) or HUC12 extents (Figure 16). They also rely on a simplified estimate of town-level or HUC12-scale phosphorus loading, using the CWR tool. Nevertheless, they provide a first order assessment, using the annual gully volumetric change generated by this study, of the relative magnitude of P production associated with erosion at road drainage outfalls and the potential for P reduction with erosion mitigation. Beyond the benefits of mitigating phosphorus pollution, controlling erosion at road drainage outfalls minimizes the transfer to receiving waters of fine sediment, which is a pollutant of concern in many freshwater systems, and secures the integrity of community investments in valuable transportation infrastructure, making our roadways more resilience to the impacts of extreme storm events and reducing on-going costs of storm damage (Garton, 2015; Wemple, 2016).

Table 7: Case 1 - summaries for five selected towns used to generate estimates of phosphorus production from gullies and compare to phosphorus load extracted from the Vermont Clean Water Roadmap tool.

	Barre	**Berlin**	**Enosburgh**	**Monkton**	**Sheldon**
Road length (km)	180.8	101.1	154.6	118.1	116.9
Culverts - Small culvert inventory (no.)	258	626	132	0	212
Culverts - VT culverts (no.)	503	248	459	304	227
Culverts - total (no.)	761	874	591	304	439
Culvert frequency (no./km)	4.2	8.6	3.8	2.6	3.8
Gullies at culvert outlets (no.)	102	48	15	19	33
Percent assessed outlets with gullies	13.4%	5.5%	2.5%	6.3%	7.5%
Gullies with multi-date lidar coverage for change assessment	69	42	15	19	25
No. of culverts with net erosional change/yr	56	33	14	16	14
Max. gully change (m^3/yr)	213.2	268.5	42.8	14.7	100.9
Median gully change (m^3/yr)	3.4	6.8	4.2	2.5	3.4
No. of eroding gullies with change > 10 m^3/yr	14	11	5	2	2
Percentage eroding gullies with change > 10 m^3/yr	25%	33%	36%	13%	14%
Sum - phosphorus production from gullies (kg/yr)	666	1210	110	53	137
HUC 12 phosphorus load (kg/yr)	4419	3802	6174	9188	5640
Gully erosion as percent of HUC12 phosphorus load	15.1%	31.8%	1.8%	0.6%	2.4%

Table 8: Case 2 - summaries for two selected HUC12 subwatersheds used to generate estimates of phosphorus production from gullies and compare to phosphorus load extracted from the Vermont Clean Water Roadmap tool.

	Lewis Creek	**Missisquoi Trout River to Black Creek**
Road length (km)	152.4	146.1
Culverts - Small culvert inventory (no.)	38	276
Culverts - VT culverts (no.)	661	251
Culverts - total (no.)	699	527
Culvert frequency (no./km)	4.6	3.6
Culverts assessed	226	525
Gullies at culvert outlets (no.)	9	27
Percent assessed outlets with gullies	4.0%	5.1%
Gullies with multi-date lidar coverage for change assessment	9	14
No. culverts with net erosional change/yr	8	9
Max. gully change (m^3/yr)	14.7	29.8
Median gully change (m^3/yr)	5.2	1.5
No. eroding gullies with change > 10 m^3/yr	2	2
Percentage eroding gullies with change > 10 m^3/yr	25%	22%
Sum - phosphorus production from gullies (kg/yr)	40	54
HUC 12 phosphorus load (kg/yr)	6648	10028
Gully erosion as percent of HUC12 phosphorus load	0.6%	0.5%

5. Discussion and Recommendations

5.1. Summary

Results of this study show that gully erosion at road drainage outfalls is a common occurrence, with a frequency of roughly 1 in 10 culvert outlets exhibiting evidence of gullying among the sites we studied. High-resolution lidar products are a readily available data source for identifying gullies and useful supplements to the on-going road erosion inventories being conducted at the municipal level. Rates of gully change assessed from multi-date lidar range widely, with some of the largest features exceeding 10 m^3/year, but 76% of the features we assessed exhibited erosion rates of less than 10 m^3/year for comparisons spanning 5 to 11 years.

The greatest rates of change occurred on slopes over 23% in the region impacted by the 2011 Tropical Storm Irene. Gullies were largest, on average, on lower gradient slopes when they occurred on "developed" landcover and when a large share of their contributing area was comprised of impervious surfaces.

High-frequency and very high spatial resolution surveys of gullies in northwestern Vermont showed that gully volume is related to contributing road length, road surface area, and upslope area, with slope steepness at the outfall as a secondary control. Change in gully volume over time is positively related to accumulated rainfall, and rates of gully erosion during late spring, summer and fall exceed erosion following snowmelt.

While limited in temporal scope and number, experimental erosion mitigation treatments indicate that the practice of stabilizing road drainage outfalls with reinforcing rock reduces rates of erosion compared to untreated controls. In some cases (Milo White Road, Jericho and Maple Run Lane, Stowe), erosion mitigation treatments did not extend the full length of the gully due to right-of-way restrictions, and surveys following treatment show evidence of erosional change in these untreated zones. This observation demonstrates a challenge in mitigating gully erosion when the extents of the eroding feature extend beyond the jurisdictional right-of-way that can be managed by public entities.

The larger dataset of retrospectively assessed slope stabilization and erosion mitigation treatments supported by the Better Roads, Grants in Aid, and Vermont Agency of Transportation funds for state highways (inventoried in the Direct Damage Inspection Reports) showed that investments in these projects are highly effective in addressing erosion and slope stability, with only 9% of the sites assessed having failed to perform as designed. These assessments also show that maintenance is required to sustain the function of these installations, especially at turn outs and plunge pools that are designed to trap eroding sediment, which compromises their design function over time. Continued implementation of these types of retrospective assessments, combined with on-going road erosion inventory work at the municipal level, could be an effective adaptive management (*sensu* Williams, 2011) approach at the state level to assess where investments pay off over time.

5.2. Study limitations

The results of this study provide a database of occurrence frequency and change rates, but certain limitations likely obscure underlying controls. Gully erosion is an episodic process that should be expected to vary considerably in space and time. For the field-based (using terrestrial lidar scanning) work, the limited size of the dataset makes it difficult to disentangle other controls on gully formation and enlargement, such as pipe condition, on-going road and roadside maintenance practices, and the role of impervious cover in the catchment draining to the outfall or culvert outlet. Similarly, the short period of post-treatment monitoring (made shorter by restrictions of the Covid-19 pandemic) and choices of road crews to treat smaller gullies at most of the paired treatment-control sites limit the inferences we can draw here about erosion mitigation effectiveness. An important lesson from the implementation phase of this project, though, is that treating the largest, most-active gullies will be costly and in some cases pose significant access challenges for construction crews. For the dataset derived from airborne lidar, we relied extensively on GIS-derived explanatory variables to explain gully occurrence and rates of change. In some cases, the quality of primary datasets might have limited the derivation of robust explanatory variables. For example, our GIS algorithm to estimate road segment length draining to outfalls relies on culvert datasets to split the road network and identify contributing road lengths. In some cases, the estimates of segment length appear longer than might be expected and are probably due to missing drainage structures in the culvert dataset. In addition, the quality of statewide soils data to capture site-level soil characteristics controlling erosion and slope stability might obscure these controls.

5.3. Recommendations for phosphorus crediting with gully stabilization

Achieving pollution reductions is mandated by federal Clean Water implementation plans (a.k.a. Total Maximum Daily Loads or TMDLs) for impaired waters. The Chesapeake Bay program in the mid-Atlantic U.S. provides an example of protocols for crediting pollution mitigation measures, including those associated with channel or gully erosion (see, for example CBP Protocol 1 for projects without engineering support and CBP Protocol 5 for projects with engineering support). Implementation of these types of approaches in Vermont could draw upon soil bulk density and soil phosphorus concentration measurements collected for this study to replace literature values with locally-measured values. We note, though, that our intensively monitored sites did not include gullies that have formed on agriculturally amended soils, which have been shown in Vermont to have elevated phosphorus concentrations (Perillo et al., 2018). Site-specific P concentrations could be obtained for project sites through soil sampling and laboratory analysis. The BANCS method recommended in the Chesapeake Bay protocols requires the user to indicate the eroded feature's age, which can be difficult to assess. An alternate approach for implementation of phosphorus crediting in Vermont could be to use rates of gully change estimated from lidar differencing conducted for this study. Lidar topographic data are now widely available in Vermont, such that this approach could be implemented by GIS professionals at state agencies and regional planning commissions, or mean values from this study could be used.

Limited funding for implementation of Clean Water projects will undoubtedly constrain the number and extent of gully mitigation projects. Results of this study suggest that targeting gullies on steeper slopes (> 23%) and at higher elevations outside the low gradient terrain of the Champlain valley might be most effective in reducing this source of pollutant delivery to receiving waters. Further targeting mitigation measures on sites that drain longer road segments and discharge to steep slopes may narrow the range of suitable candidates at the local level.

A few additional recommendations are offered based on this study:

- Gully erosion (and in some cases deposition of road surface and ditch sediments into gullies) at road drainage outfalls is correlated with rainfall totals. As the magnitude and intensity of storm events increases in Vermont, attention to gully erosion on the transportation network will be an important element of reducing the transfer of sediment and phosphorus to receiving streams and rivers. Common erosion mitigation practices on municipal roads, funded through the Better Roads and Grants in Aid programs, are highly effective in stabilizing slopes and mitigating erosion. Funding of these programs should be continued.
- Periodic assessments of water quality improvement projects provide an on-going record of the efficacy of clean water investments and an opportunity for adaptive management. We recommend that the Vermont's Regional Planning Commissions or Clean Water Service Providers adopt a retrospective assessment approach like the one used here and in a previous UVM study (Garton, 2015) to track the efficacy and longevity of these investments.
- Through this study, the Vermont Agency of Transportation has invested funds in the development of intensive monitoring of gully erosion and the installation of erosion mitigation projects on roads ranging

from the interstate highway system to class 4 municipal roads. We recommend that the state continues surveying these sites (both erosion mitigation installations and their paired untreated controls) in order to build a longer-term record of changes in response to storm events and the efficacy of the treatments installed. Pre- and post-event surveys at these sites, set up to capture conditions before and after forecasted extreme storm events, could be a particularly useful investment into documenting change and would help identify gully erosion sensitivity to variations in rainfall rates or intensity, to supplement the longer-term (multi-month) estimates provided in this study on gully change associated with total accumulated rainfall.

5.4. Transferability and broader impacts

Although this study was conducted in northwestern Vermont, the approach developed here could inform studies elsewhere. The emergence of new surveying technologies and data products that leverage LiDAR technology represents an important opportunity to generate high resolution estimates of land surface change that is relevant to infrastructure stability and water quality.

This project also provided important workforce development benefits through the training of a group of university students. Nine undergraduate students and one graduate student at the University of Vermont were supported by the project and gained important field and data analysis skills. The opportunity to gain these skills while engaged in policy and management-relevant research is an important dimension of their professional development.

This research project benefitted from on-going engagement with a group of stakeholders who served as technical advisors in the development of the methods and interpretation of the results. The participation and on-going engagement of transportation agency professionals, environmental conservation specialists, environmental consultants, and regional planning commission specialists provided multiple perspectives on research needs and applications for this study. This type of collaborative research-stakeholder partnership is an important model for conducting societally relevant research.

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