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Master's Project: Assessing Unpaved Road Runoff in the Mad River Watershed of Central Vermont

Catherine Webster
University of Vermont

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Assessing Unpaved Road Runoff in the Mad River Watershed of Central Vermont

A Master's Project Paper written by:

Catherine Webster

Dept. of Natural Resources
Rubenstein School of Environment and Natural Resources (RSENr)
University of Vermont

Advisory Committee:

Beverly Wemple, Ph.D., Dept. of Geography
Leslie Morrissey, Ph.D., RSENr
Donna Rizzo, Ph.D., P.E., School of Engineering
Donald Ross, Ph.D., Dept. of Plant and Soil Science

Abstract

Over half of the local town roads in Vermont are unpaved (VBB, 2009). In the Mad River Watershed of central Vermont, 58% of the roads are unpaved. These compacted surfaces, despite their lack of tar, provide hundreds of miles of impermeable surfaces that extend the stream network, and transport runoff and pollutants to our water bodies. In this project, 12 sites within the Mad River watershed were monitored with the goal of evaluating the amount of runoff that is generated on the road surface itself as compared to flow that enters roadside ditches via groundwater seeps and overland flow from adjacent land. Each site was monitored for stage using an ISCO 6712 Automated Water Sampling Unit with an attached pressure transducer, and rating curves were developed from manual volume measurements in order to connect stage values with runoff volumes. Each site was mapped to determine the contributing road surface drainage area, and these values were compared to the slope of linear regressions developed for storm precipitation and runoff totals. Modeled road surface hydrographs were developed for 11 of the 12 sites, using the rational method, and were compared to hydrographs developed using measured runoff. One-quarter of the sites appear to have regular runoff contributions that originate outside of the bounds of the mapped drainage area. Five of the eleven sites also displayed seasonal variations where runoff originated outside of the mapped road surface area during times of greater land saturation. These results indicate that roads can sometimes contribute far more than just the runoff that is generated on their surface alone, and that the quantity and occurrence of these external contributions may increase with an increase in the drainage source area that can be seen in seasons when the ground is saturated.

1.0 Introduction

The study of road ecology has developed over the past few decades with the understanding that roads have a variety of widespread, deleterious effects on the watersheds in which they reside. The effects of roads on hydrology, geomorphic processes, water quality, and wildlife habitat have been studied and documented across the globe (Gucinski, Furniss, et al., 2001; Jones, Swanson, et al., 2000; Chomitz & Gray, 1996; Hutchinson, 1973). It has been estimated that 15-20% of the United States has been ecologically impacted by roads (Forman & Alexander, 1998). Seven main impacts of roads on aquatic and terrestrial ecosystems have been noted in the road ecology literature: road construction related mortality, mortality due to vehicle collisions, modification to animal behavior, alteration of the physical environment, alteration of the chemical environment, spread of exotic species, and increases in human use of natural areas (Trombulak & Frissell, 2000; Hourdequin, 2000). One of the most dramatic of these road impacts is their effect on the physical and chemical environment through resultant runoff and sedimentation.

Runoff is generated after rain strikes a road's impervious surface, or snow melts and water quickly flows to the nearest channel. The quantity of runoff transported by roads to water bodies is affected by factors such as cutslopes created during road construction, the existence of roadside ditches that extend the natural stream channel network, and adjacent land use. Roads and roadside ditches add to the total contributing channel lengths within drainage networks through their connectivity to surface waters at stream-road crossings and through channels created where roads are proximal to streams (Forman & Alexander, 1998; Croke et al., 2005; Bracken & Croke, 2007; Wemple, 1994). Cutslopes bring subsurface flow into the road runoff equation. Their creation during the construction of roads can lead to conversions of groundwater into fast-moving surface water when the geologic conditions are such that groundwater does not drain to levels beneath the road (Wemple & Jones, 2003). In fact, cutslopes have been found to increase runoff at a rate dependent upon the contributing area above them (Macdonald, et al., 2001).

The size of the contributing drainage area has been shown to have temporal variations due to seasonal changes in the water table, antecedent soil moisture, depth of soil, and resultant infiltration rates amongst other factors (Dunne & Black, 1970a; Dunne & Black, 1970b, Betson & Marius, 1969). In 1967, Hewlett and Hibbert raised the variable source area concept as an alternative to the prevailing assumption that surface runoff was the primary culprit in the flooding of streams in forested, humid areas. This concept, which prevailed for decades after its initial delivery, is that the area over which runoff occurs changes seasonally, and over the course of individual storms. The basis of this claim is that the ground must be saturated for runoff/overland flow to develop in forested humid catchments, and that the area of saturated ground changes over time, leading to the expansion of the channel network during times of high saturation (high antecedent moisture), and the depletion of this network during drier times (low antecedent moisture). Hewlett and Hibbert reasoned that if precipitation (or "new water")

immediately affected direct runoff¹, then the direct runoff should approach net rainfall – which in their studies, it did not.

In essence, the importance of the variable source area (VSA) concept is that it explains why the same amount of rainfall may produce different amounts of runoff and resultant stream flow depending on the antecedent wetness of the catchment area. For example, a prolonged late spring rain, falling on saturated soils, may produce more runoff, and have a greater immediate effect on the river stage than would a mid-summer rain falling on dry soils. The resulting spatial effect of the expansion of the runoff drainage area due to ground saturation, also leads to a greater potential for surface erosion, and the transport of sediment and other pollutants (e.g. nitrogen and phosphorus) depending on the land use and land cover of the expanded contributing area.

Land-use has also been found to affect the presence and quantity of Hortonian overland flow, though studies have primarily involved models and/or rainfall simulations (Butzen, 2014; Corbett, 1997). Significant variations in the existence and extent of runoff have been found in simulations comparing urbanized and forested watersheds (Corbett, 1997), degraded land and agricultural land (Zokaib & Naser, 2011), and even between deciduous and coniferous forest floors (Butzen, 2014). On the island of St John in the US Virgin Islands, Macdonald, Sampson, and Anderson (2001) compared vegetated hillslope plots to unpaved road plots and found that the vegetated hillslopes only produce runoff during large storm events whereas unpaved roads regularly produced runoff when rainfall exceeded 6mm.

This study focused on the measurement of runoff on twelve road segments throughout the Mad River Watershed of central Vermont. Through the mapping of the road sites and analysis of measured runoff data, road drainage areas and their hydrologic behavior during storm events were characterized and hydrograph variations between sites were discussed drawing from the VSA concept and the presence or absence of cutbank seeps.

¹ Hewlett and Hibbert (1967) defined “direct runoff” as a combination of overland flow, channel interception, and “interflow” (subsurface flow), with the specific exclusion of base flow.

2.0 Methods

2.1 Study Area and road system

The Mad River watershed, a subwatershed of the Winooski River and Lake Champlain basins is located in central Vermont (Figure 1) on the east-central portion of the Lake Champlain basin. It covers approximately 145 square miles (370 km²) of the Winooski River Basin's 1,060 square miles (2750 km²), or approximately fourteen percent. The Mad River subbasin falls mostly under the political boundaries of Washington County with a small portion of the southern tip within Addison County. The watershed includes a wide variety of land use types (agricultural, urban and forested) and topographic settings.

Data collection was focused on unpaved roads passing through various topography types. Based on the E911 dataset available from the Vermont Center for Geographic Information (www.vcgi.org), there are approximately 290 miles of roads running through the watershed. Table 1 displays the distribution of roads across the watershed by length and class. It is evident that a large portion of the road network (approximately 33%) is made up of Class 3 town roads, with 10% being Class 4, and 26% being private.

Class 1-4 roads are all undivided town highways. Class 3 roads are defined in Vermont Statute (19 V.S.A. §302) as “traveled town highways other than class 1 or 2 highways”. Minimum standards for class 3 highways require that the highway is “negotiable under normal conditions all seasons of the year by a pleasure car.” Class 4 roads are defined in Vermont Statute as “town highways that are not class 1, 2, or 3 town highways or unidentified corridors”. Town selectboards are given the authority to determine how these roads are further defined. Vermont Agency of Transportation documents state that class 4 roads do not receive state aid for maintenance. This project focused primarily on Class 3 and Class 4 roads with some sites from classes 9 and 91 representing private roads and driveways.

In selecting the 12 sites, both cross-slope and upslope road segments were chosen, as well as segments with varying adjacent land uses (agricultural and forested), and grades (steep and flat), for the purpose of broadly representing unpaved roads in the Mad River valley. Within these landscape-level categories, six additional criteria were used to pinpoint sites that were more conducive to the set up of equipment and continuous monitoring and sample collections. These six criteria included:

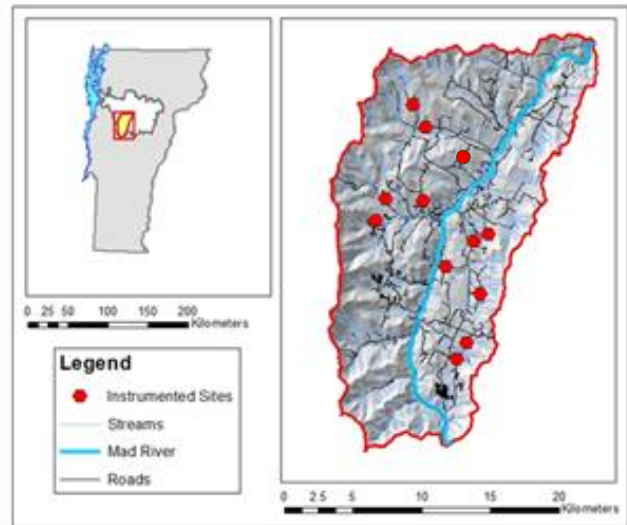


Figure 1. Map illustrating the 12 instrumented culvert locations within the Mad River Watershed (right) and its location within the larger Winooski River Watershed in Vermont, USA.

- 1) 18-inch culverts for the purpose of attaching previously designed weirs
- 2) Culverts transporting road runoff only (no stream crossings)
- 3) Smooth ditch-line approaches for more accurate stage measurements
- 4) Outlets with ≥ 12 inches of clearance for volume measurements needed to create rating curves
- 5) Relatively secure sites
- 6) Minimal evidence of seepage

Although sites with minimal evidence of seepage were sought after for the purposes of the original larger study of which this project was one part, such sites were extremely difficult to find, as most were

Class	Description of Road Class	Road Length (miles)	Percent of Total
2	Town	40.8	14%
3	Town	95.8	33%
4	Town	28.0	10%
6	National Forest	1.0	0%
7	Trail	2.0	1%
8/9/91	Private Road	75.7	26%
30/35	VT State Highway	34.8	12%
70	Unconfirmed Legal Trail	6.0	2%
96	Discontinued Road	2.4	1%
Total Miles		286.3	100%

Table 1. Roads of the Mad River Watershed by class and length.

observed to have either some level of baseflow, or actual seepage, and/or overland flow during or subsequent to storm events.

2.2 Field Measurements and Mapping

The 12 sites studied here were mapped and measured in order to create both schematics and ArcGIS maps (Appendix 1). These maps were used for site characterizations and the calculation of the area of the road surface and adjacent ditches that contributed to the total measured runoff. Measurements for schematics were taken in the field based on a visual determination of expected flow direction to the instrumented culvert inlet. For example, in some cases a road length measurement was from the instrumented culvert inlet upslope to the next inlet, which sent flow across the road. In other cases, a length measurement would extend to the next upslope culvert outlet, and then would continue with the contributing ditch length that extended upslope across the road. In yet other cases, length measurements reached the top of a slope before flow was directed in a different direction. Where roads were crowned, only half of the road width measurement was used to estimate contributing road area.

ArcGIS maps were created using a National Agriculture Imagery Program (NAIP) 2011 imagery dataset, overlain with road and culvert layers downloaded from the Vermont Center for Geographic Information (VCGI) website. Where the VCGI culvert layers placed the local culvert points on the outlet side of the measured culvert, new culvert points were created in order to create an accurate representation of the instrumented inlet site. These maps were used in the assessment of land cover and land use surrounding the instrumented inlets. The 12 mapped and monitored sites are described in Appendix 1.

Between July 2011 and June 2012, the selected road segments were monitored to develop continuous records of runoff in response to measured storm events. Using an ISCO 6712 Automated Water Sampling Unit, and an attached pressure transducer, stage data were measured at culvert inlets of these 12 sites every 5 to 10 minutes. In order to aid in resolution of water level entering the culvert inlet, aluminum weirs (Figure 2), were attached to each of the 12 inlets. Each weir was marked with lines indicating centimeters of water flowing over the weir. During the summer and fall of 2011, hand measurements of flow rates and stage were taken to develop rating curves for the purpose of deriving calculated discharge measurements for all ISCO recorded stages. Two rating curves were developed, one for stages of ≤ 10 cm and one for stages of > 10 cm (Figure 3). At 5 selected sites, a HOBO rain gauge was installed to monitor precipitation. The precipitation data from these 5 sites were used for all

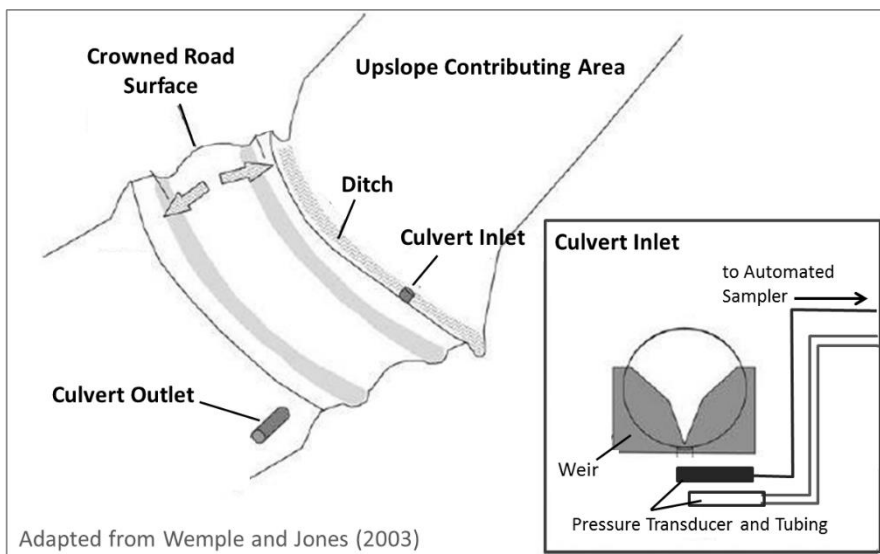


Figure 2. Schematic illustrating an example of an instrumented road site and the corresponding weir placement on a culvert inlet.

12 sites, choosing the closest HOBO installation as being representative of rainfall at sites where no HOBO was installed. Rainfall was also collected in standard plastic rain collectors at each site to compare to HOBO data to check HOBO accuracy.

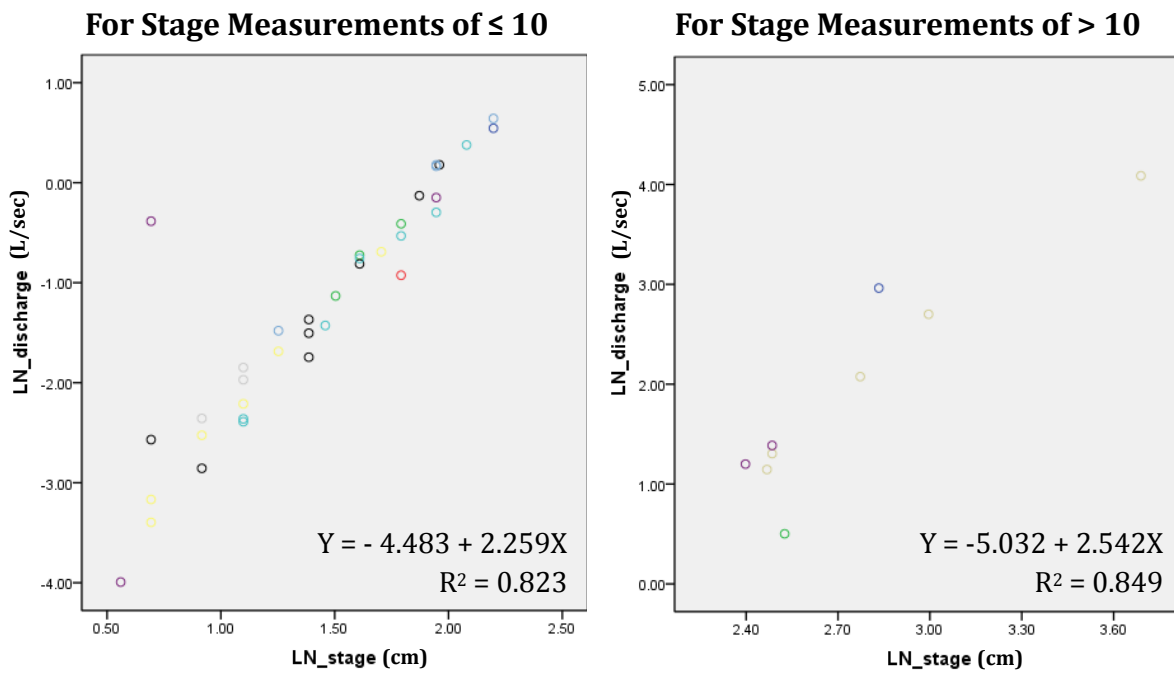


Figure 3. Rating curves correlating stage (cm) and discharge (L/sec) for stage measurements of ≤ 10 cm and > 10 cm.

2.3 Data Analysis

Two approaches were used for analyzing the data collected in this study. First, for each site, time series data of precipitation and culvert runoff were plotted for visual inspection. In order to visually evaluate the relative contribution of mapped road surface runoff, a modeled road surface hydrograph was calculated using the rational method (Dunne and Leopold, 1978) by estimating road discharge rate (Q_r) in $m^3/15$ minutes as

$$Q_r = c i A_{rs} \quad (1)$$

where A_{rs} is the contributing road surface area mapped in the field (in m^2) (Appendix 1), i is the rainfall rate in meters per 15 minutes, and c is a runoff coefficient, taken to be 1.0 here in order to simulate the maximum overland flow generated from the contributing road surface. Visual inspection of the road discharge plots was used to demonstrate patterns of runoff in response to storms and qualitatively assess the relative importance of the road surface in contributing to measured runoff. Deviations of modeled runoff from measured values were used as evidence of a contributing source beyond the road surface. Storm data for each site were also used in a regression analysis of storm event totals to relate runoff volume to precipitation depth, using a model of the form

$$Y = \beta_0 + \beta_1 X \quad (2)$$

where Y is the total volume of runoff (in m³) and X is the storm precipitation (in m) for individual storm events used in the analysis. $\beta_0 + \beta_1$ are regression coefficients, with β_1 having implied units of m² when X and Y are plotted in the units given above.

To isolate storm events for this analysis, HOBO precipitation data were summed starting at the first measured rainfall, and ending where ten hours had passed without measured rainfall (see Table 2 for precipitation totals by storm). This ten-hour threshold of no rain as the basis for identifying discrete storm events was selected based on visual inspection of rainfall records. Runoff data were summed from the moment rainfall began until the hydrograph had returned to pre-storm, baseflow levels, before baseflow was subtracted. In cases where one hydrograph had not yet reached its pre-

Storm Start Date	Rain Depth (cm)	Storm Duration (d:hh:mm)		Storm Start Date	Rain Depth (cm)	Storm Duration (d:hh:mm)
7/8/11	0.03	0:00:15		10/19/11	0.56 - 0.91	0:20:15 - 1:12:30
7/17/11	1.52	0:12:15		10/22/11	0.2 - 0.30	0:09:15 - 0:10:00
7/25/11	1.14	0:05:45		10/24/11	0.74 - 1.91	0:16:00 - 0:23:15
7/29/11	0.69	0:03:00		10/30/11	0.36 - 0.51	0:00:45 - 0:01:15
8/6/11	0.30 - 0.38	0:21:15 - 0:19:00		4/22/12	3.89	1:13:30
8/8/11	0.56 - 0.89	0:00:45 - 0:02:00		4/26/12	0.74	0:11:30
8/9/11	3.56 - 4.2	0:08:15 - 0:08:30		4/30/12	1.09	0:10:00
8/14/11	6.50 - 7.47	1:14:30 - 1:18:30		5/3/12	0.36	0:04:15
8/21/11	1.68 - 2.26	0:08:15 - 0:08:15		5/8/12	3.07	0:22:00
8/25/11	1.09 - 1.32	0:16:00 - 0:17:15		5/10/12	0.53	0:22:30
9/5/11	4.75	1:02:30		5/15/12	2.31	0:16:45
9/7/11	1.63	0:22:15		5/16/12	0.56	0:05:00
9/13/11	0.33 - 0.41	0:02:00 - 0:01:45		6/2/12	0.74	0:21:00
9/15/11	1.12 - 1.40	0:07:00 - 0:07:30		6/12/12	0.91 - 1.17	1:01:30 - 0:17:00
9/20/11	0.1 - 0.13	0:06:00 - 0:06:30		6/24/12	0.84 - 1.32	0:19:45 - 0:16:30
9/23/11	1.8 - 1.9	0:07:45 - 0:20:15		6/26/12	1.83 - 4.11	2:02:15 - 1:21:00
9/29/11	3 - 3.81	0:21:00 - 0:21:15		7/4/12	0.23 - 0.41	0:00:45 - 0:03:45
10/13/11	0.66 - 0.88	0:04:15 - 0:04:45		7/15/12	0.36 - 0.97	0:00:15 - 0:16:45
10/14/11	3.78 - 4.62	1:10:30 - 1:10:45		7/17/12	2.67 - 3.61	0:17:15 - 0:13:15
10/16/11	0.41 - 0.43	0:02:45 - 0:07:30		7/23/12	6.2	0:22:30
10/17/11	0.56 - 0.97	0:10:45 - 0:11:00				

Table 2. Dates, rainfall depths, and durations for storm events monitored during the study period. Rain depth and duration ranges are displayed where more than one rain gage was used for different monitored sites during the same time frame.

storm baseflow level before additional rainfall commenced, storms were combined into a single “event” for analysis. Linear regressions were then fit to the plotted data, with rainfall depth expressed in units of meters and runoff volume expressed in units of cubic meters. Modeled regressions were used to characterize road site response and to evaluate how mapped road contributing areas compared to regression-based estimates of the rainfall-runoff relationship, since the slope of the linear regression model could be interpreted as an estimate of contributing area in square meters.

3.0 Results and Discussion

3.1 Site Characteristics

The road sites studied here covered a range of gradient, contributing area, and adjacent land cover conditions. Road gradients ranged from 0.5% for a road segment contributing runoff on Senor Road to 16% for a road segment contributing runoff on Cider Hill Road. Three sites (North Fayston, Senor and Common) had gradients of less than 5%; four sites (Barton, 3-Way, Bragg Hill, and Sharpshooter) had gradients between 5 and 10%, and five sites (Cider Hill, Randell, Ski Valley, Mansfield, and Rolston) had gradients equal to or exceeding 10%. Field-mapped contributing road surface areas ranged from 125 m² at Common Road to over 2000 m² on Ski Valley Road. Collectively, the 12 sites fell equally into a group of six with contributing areas ≤ 500 m² and a group of six with contributing areas > 1000 m². Visual evidence during storm events also showed variable contribution of cutbank seeps and overland flow to runoff, as described in Appendix 1. Three of the sites (Common, Senor, 3-Way) were situated in settings with agriculture as the adjacent land use. The remaining sites were located in forested settings, the dominant land cover in upland settings in Vermont (Table 3), or forested settings surrounding cleared and developed areas.

Site Name	Width (m)	Road Grade (%)	Contributing Drainage Area (m ²)	Adjacent Land Use
Common	7.7	1.5	124.78	Agriculture
Cider Hill	3.8 - 4.3	10 - 16	149.78	Forest
North Fayston	8	2.5	180.90	Forest
Bragg Hill	8.3	9	389.85	Forest
Sharpshooter	8.3	9	485.14	Forest
Rolston	5.9	12	503.90	Forest
Randell	7.8	15	1,005.28	Forest
Senor	7.3	0.5 - 2.5	1,174.05	Agriculture
Barton	6.3 - 7.1	8 - 11	1,325.38	Forest
Mansfield	7.5 - 8	12	1,549.65	Forest
3way	7.8 - 7.9	8	1,862.33	Agriculture
Ski Valley	5.9	5 - 12.5	2,087.85	Forest/Cleared

Table 3. Road widths, percent grades, contributing drainage areas, and adjacent land use types at each of the 12 monitored sites. Road percent grade ranges are presented for sites with more than one contributing road segment.

3.2 Runoff Observations

Total precipitation from analyzed storms ranged from 0.10 cm to 7.47 cm while the total calculated runoff volumes measured on roads ranged from 0.00 to 972.75 cubic meters. The 12 sites regularly demonstrated classic headwater hydrograph curves, rising quickly following rainfall, while

falling at various rates.

The evaluated sites displayed diverse responses to individual storm events ranging from 0.74 to 6.38 centimeters (Figure 4, 5; Note that Randell was removed from these figures as data was not available for the storm dates used here). Figures 4 and 5 represent a sampling of the storms measured in 2011 and 2012 and display the results of a comparison of measured versus simulated runoff. While it is difficult to draw conclusions from this limited sampling, some possible trends can be seen upon a visual examination of the plots in Figures 4 and 5.

Five of the 11 sites for which modeled and measured runoff were compared (Senor, Ski Valley, Common, Rolston, and Barton) displayed modeled runoff responses that were consistently greater than the measured runoff during summer months, but lower than measured runoff during fall months. Four of these five sites (all but Rolston) were observed to have seepage or overland flow inputs coming from adjacent land. Since there were known flow inputs from adjacent lands, it seems reasonable to conclude that the antecedent moisture of the adjacent land may have resulted in these seasonal variations. During the summer, when there was low antecedent moisture, more rainfall was absorbed by the adjacent land, and therefore, less seeped into their neighboring roadside ditches. In the fall, when antecedent moisture was greater, the land was able to reach a saturation level, above which water was available to flow to the roadside ditches. Cider Hill, Mansfield, Sharpshooter, Bragg Hill, and North Fayston all displayed similar measured and modeled runoff curves. Of these five sites, four (Cider Hill, Mansfield, Sharpshooter, and North Fayston) were not observed to have any seepage points, although Cider Hill and Sharpshooter had a regular low volume baseflow. At the Bragg Hill site, minor seepage was possible through a drainage pipe, which was directed to the ditch from the upland residential property. Although some seepage was observed, the inputs at these five sites appeared to be relatively minor compared to those at the sites with seasonal variations cited above.



Figure 4: Graphs illustrating total measured runoff (L/sec) in green lines and simulated road surface runoff (L/sec) in red lines using the rational method for selected storms and sites monitored during Summer 2011.

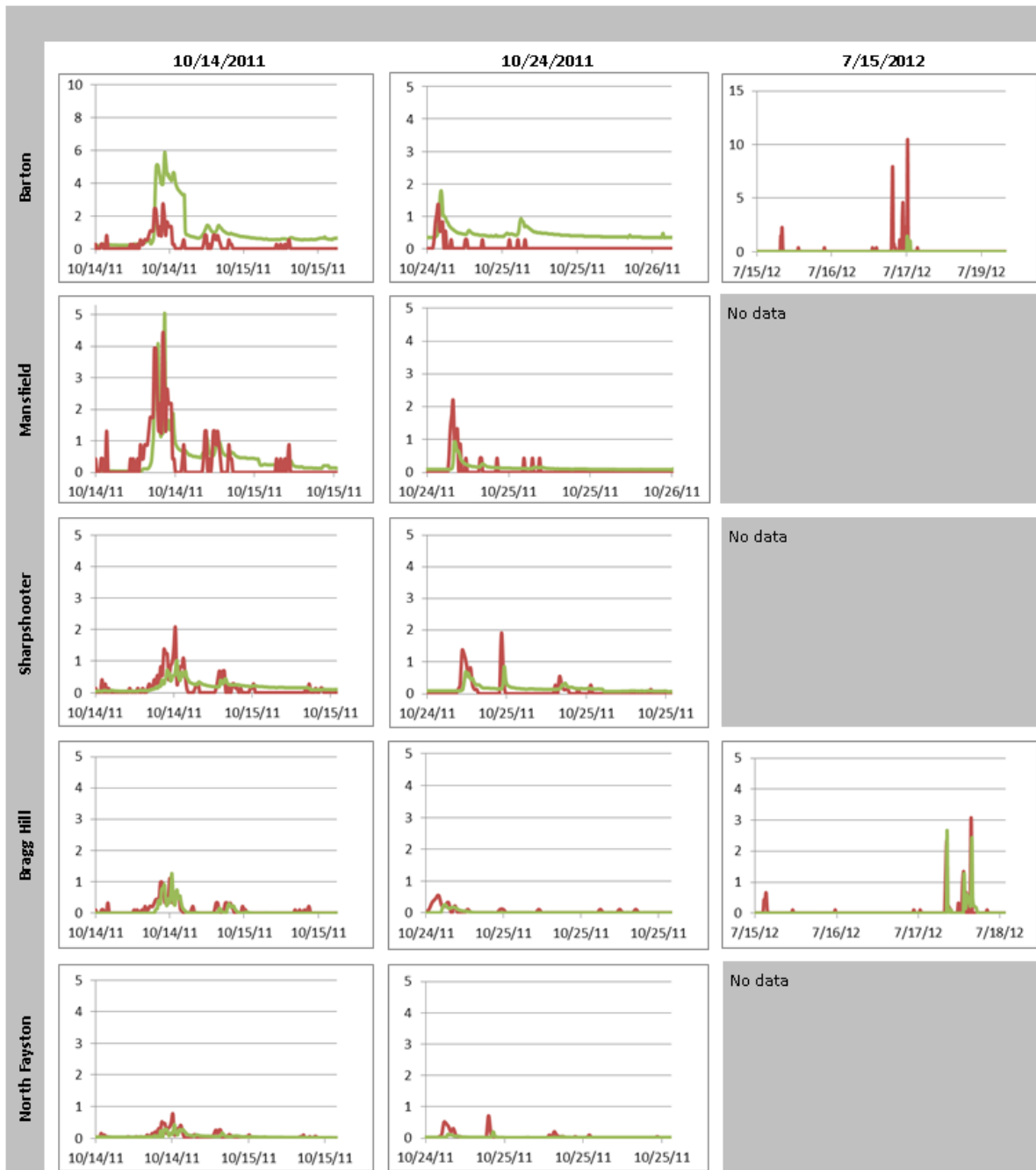


Figure 5: Graphs illustrating total measured runoff (L/sec) in green lines and simulated road surface runoff in red lines using the rational method for selected storms and sites monitored during Fall 2011 and Summer 2012.

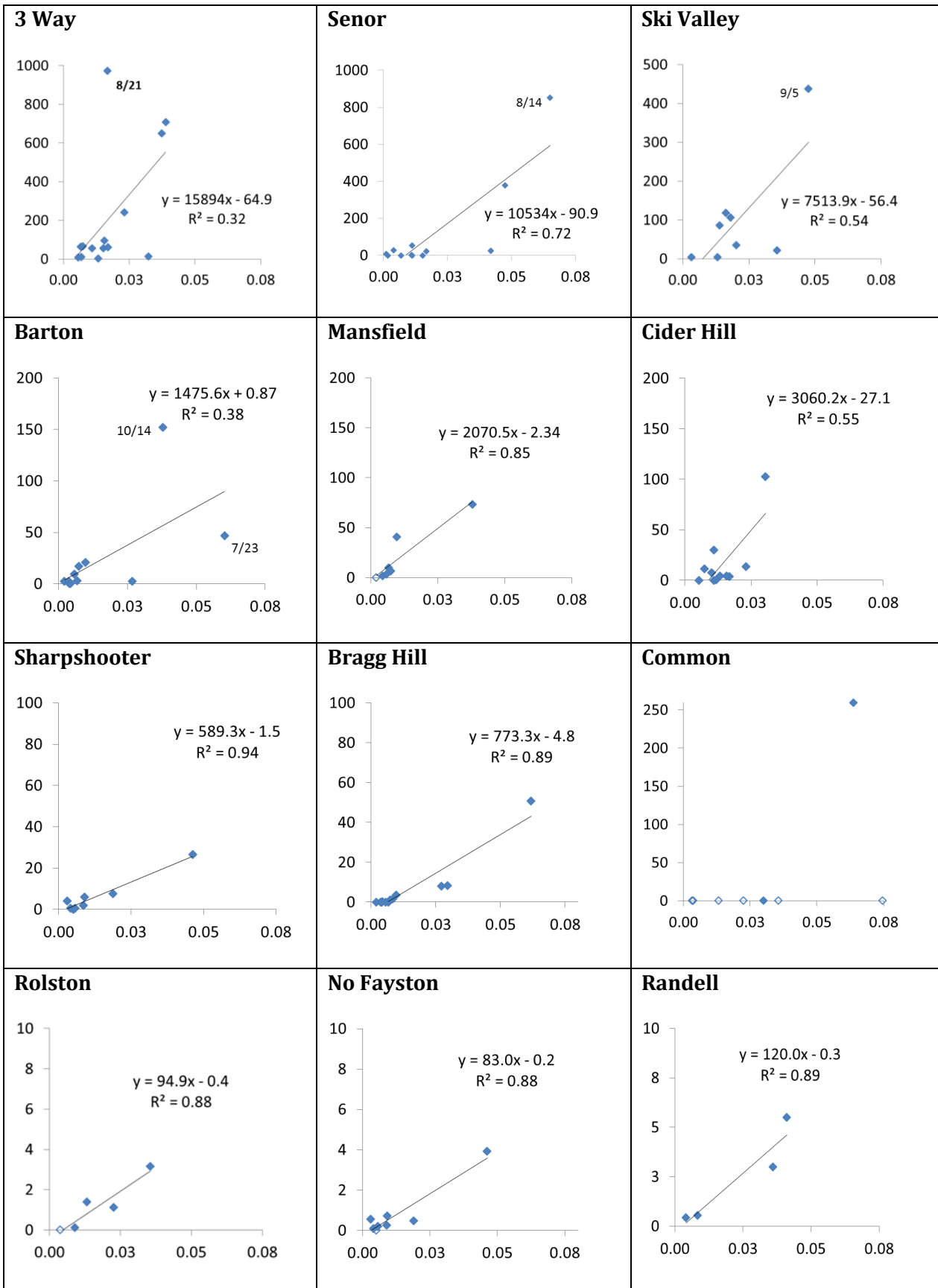


Figure 6 (previous page). Storm precipitation totals (x-axis in meters) versus storm runoff totals (y-axis in cubic meters) for each of the 12 monitored sites. Outliers were removed where measured stage values during storm events exceeded the bounds of the rating curve measurements. Non runoff-producing storms were not included in regressions, though they are represented in these graphs with empty diamonds. Month/day of some events are labeled.

Linear regression models for storm events monitored at the road sites show generally strong relationships between storm precipitation and runoff. Regression R^2 values exceeded 0.7 for all but 4 of the 11 sites for which regressions could be developed (Figure 6). Of these 4 sites (3 Way Intersection, Ski Valley, Barton, and Cider Hill), 3 regularly produced enough sediment to cover the pressure transducer, potentially skewing the stage data collected by the automated sampler.

Collectively, observations from the monitored sites show that road surface contributing area is often, but not always a good predictor of the rainfall-runoff relationship on roads examined for this study (Figure 7). Seven of the eleven sites studied exhibited rainfall-runoff relationships that were predicted rather closely by the mapped surface area of the road draining to the measured culvert, indicating that the impervious surfaces of the road are the primary source of runoff measured. Four of the sites (3-Way Intersection, Ski Valley, Senor, and Cider Hill) had runoff volumes that far exceeded contributions from the road surface alone, indicating the importance of seepage from the cutbank or drainage from the adjacent hillslope to measured runoff on road sites. Three of these four sites had adjacent land uses that were agricultural or predominantly cleared (3-Way Intersection, Senor, and Ski Valley). In addition to the unique land uses adjacent to these sites, each were observed to have obvious seepage inputs. It is not clear why Cider Hill's linear regression slope, at 3,060.2 is greater than one order of magnitude more than the mapped drainage area of 149.78 square meters, as no seepage points were directly observed at this site, however it is possible that groundwater inputs drew from a greater drainage area as a low-level baseflow was regularly observed at this site. One site, Common Road, yielded little runoff throughout the study period, except during tropical Storm Irene, and during the storm that occurred on 9/5/2011, when a veritable stream broke through from the ditch on the road located on the upper side of a hayfield, connecting an entirely new drainage area to the original mapped road surface drainage area (Appendix 1).

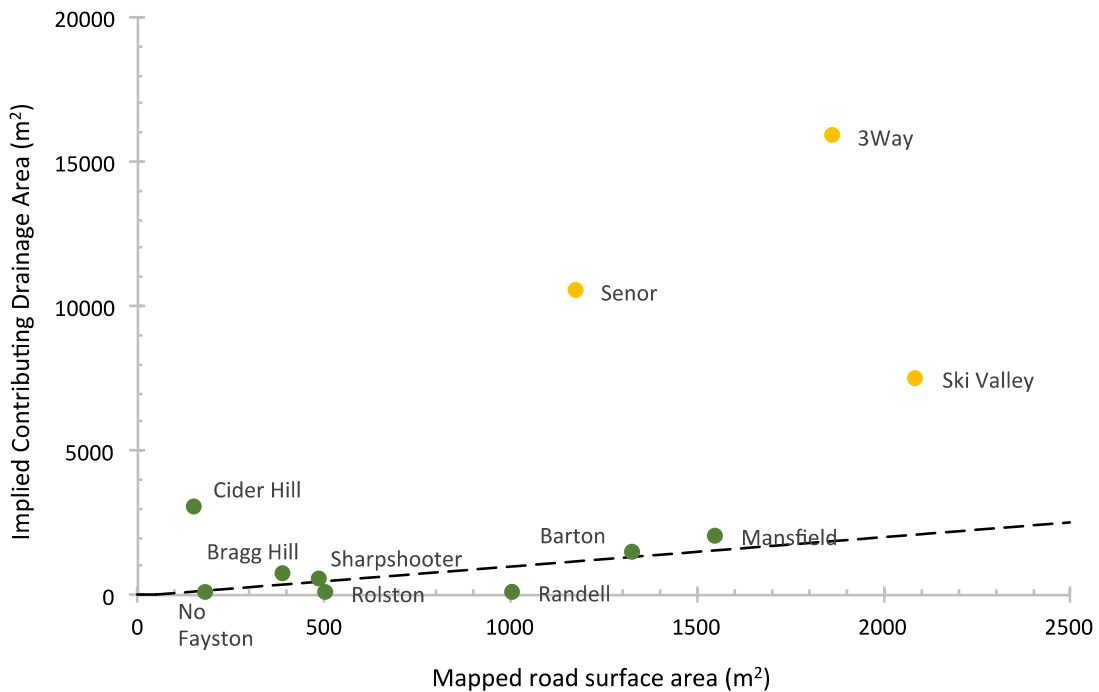


Figure 7: Plot of mapped road surface area (m²) versus “implied contributing drainage area” derived from the linear regression slopes of Figure 6. Units of the y-axis are inferred to be in m² based on units used in the linear regression described with Equation (2). Yellow points have agricultural adjacent land cover or have significant cleared portions of adjacent land; green points have forested adjacent land cover (see Table 3). Common Road is not displayed. Dotted line is 1:1.

4.0 Conclusions

This study examined runoff behavior on a set of 12 road segments in the Mad River watershed between June 2011 and June 2012. Road segments studied ranged from 124 to 2,088 m² and generated runoff ranging from 0 to 973 m³ in response to storm events of 0.1 to 7.47 cm over the two field seasons. All 12 sites generally displayed classic headwater hydrograph responses where curves rise quickly and dissipate relatively quickly. Site data were analyzed through mapping, and through comparing simulated and measured hydrographs, linear regression analysis, and regression slopes to mapped road areas in order to evaluate the amount of runoff that was generated on the road surfaces themselves as compared to runoff produced from adjacent land through groundwater seeps and overland flow.

The results shown here indicate that roads are an important source of runoff in the otherwise highly permeable forested and agricultural landscape in upland, rural settings of Vermont. Observations from a quarter of the sites measured here show that runoff routed through the road ditch network is collected from contributing areas that far exceed the impervious surface of the road itself, and adjacent

land use appears to be an important variable in the resultant runoff quantities collected in roadside ditches. This runoff extends the stream network, erodes slopes and discharges sediment and pollutants to downstream receiving waters. Seasonal differences in contributing drainage area were observed at almost half of the sites (5 out of 11 where modeled and measured runoff were compared) where notable increases in runoff were found in the fall as compared to the summer.

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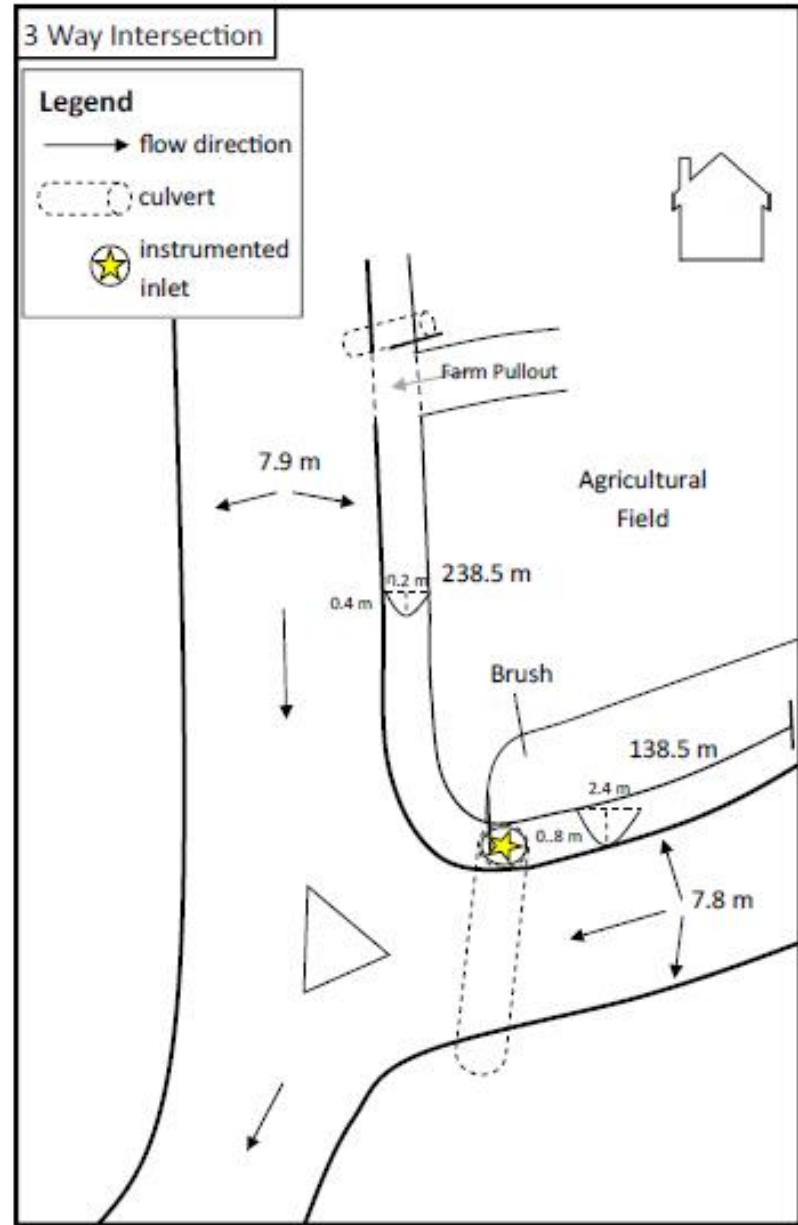
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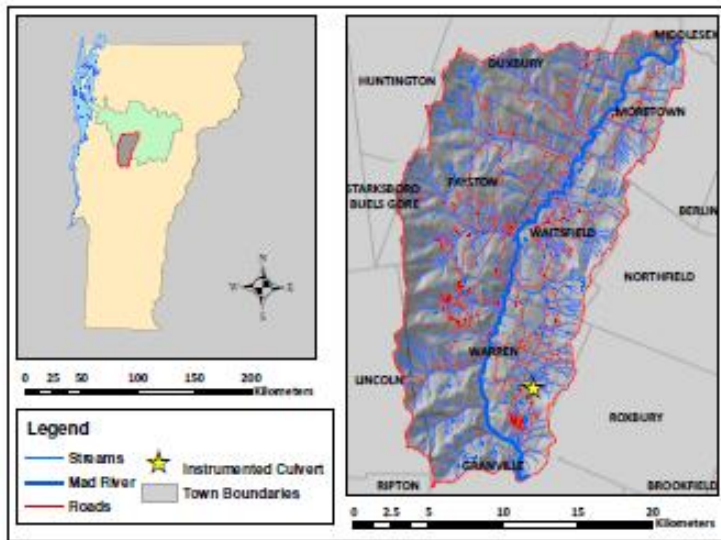
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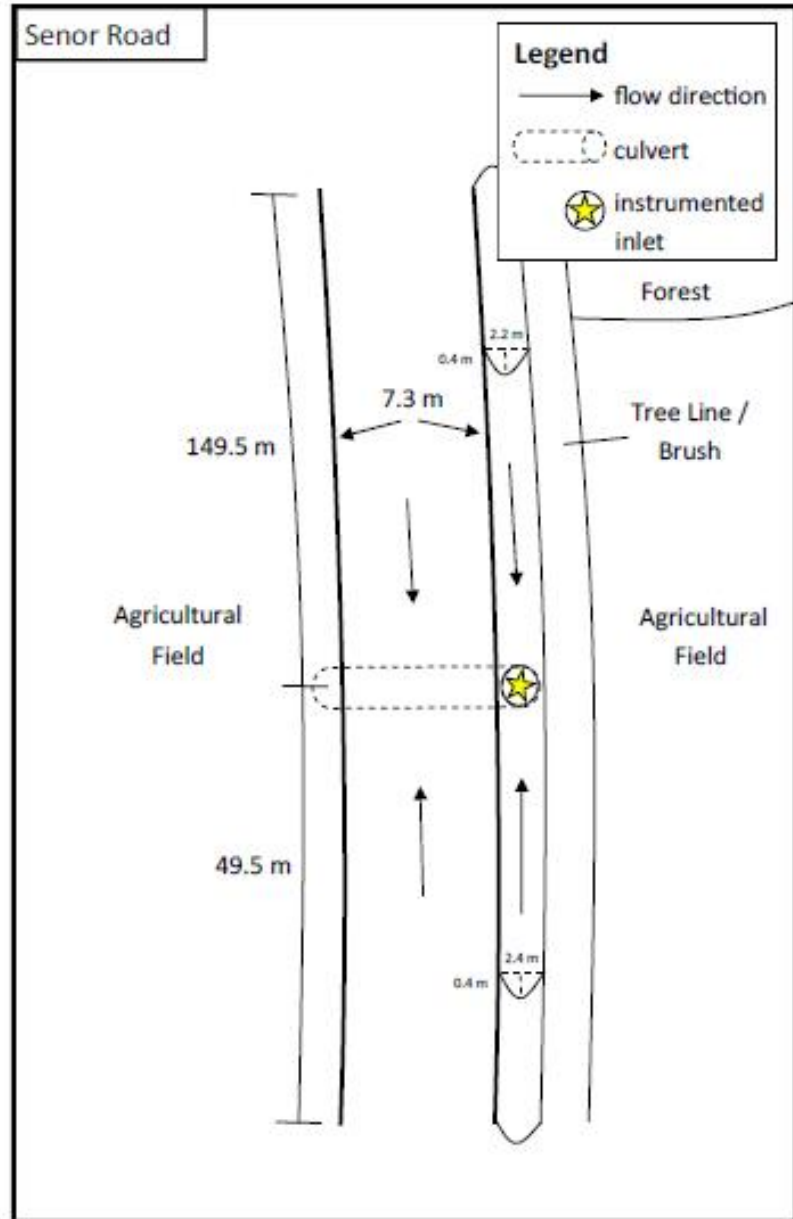
This project was made possible by the efforts of numerous individuals and organizations. Funding was provided by the Vermont NSF EPSCoR program and the Lake Champlain Basin Program. My project committee members Beverley Wemple, Leslie Morrissey, Don Ross, and Donna Rizzo all provided key guidance over the course of this 5-year endeavor. Rebecca Zeyzus and Henry Schmid each worked one field season assisting in the setting up of equipment and collection of field data. Alejandro del Peral and Gordon Clark also supported field work efforts by assisting in some equipment installation. Scott Hamshaw provided assistance with data analysis using Matlab, speeding up our precipitation data analysis. The towns of Waitsfield, Fayston, and Warren, VT all graciously allowed us to install equipment at these 12 culverts, and the Better Backroads Team provided information on road classes and assisted with site selection. Caitrin Noel and Kate Sudhoff of the Friends of the Mad River provided their knowledge and data associated with their own work in the Mad River Valley. In addition Kate assisted with rating curve measurements in the Mad River Valley in the fall of 2011. Finally, I would like to include a second acknowledgement of my primary advisor Beverley Wemple, who not only accepted me as a graduate student in 2010, but also stuck with me throughout these past 5 years and supported my work with her knowledge, experience, and strength.

Appendix 1: Site Descriptions and Maps

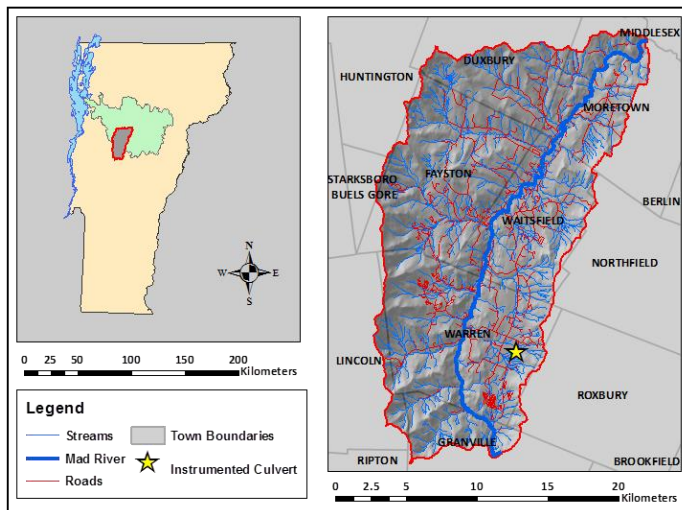


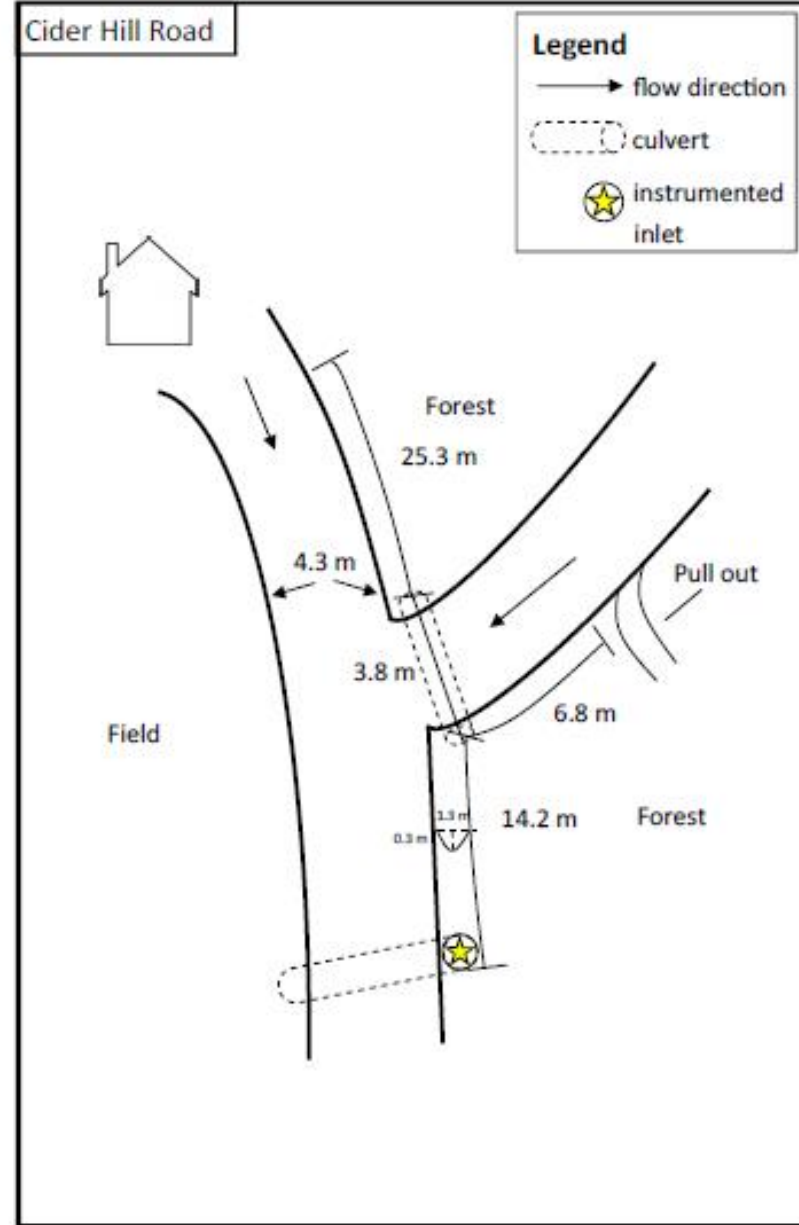
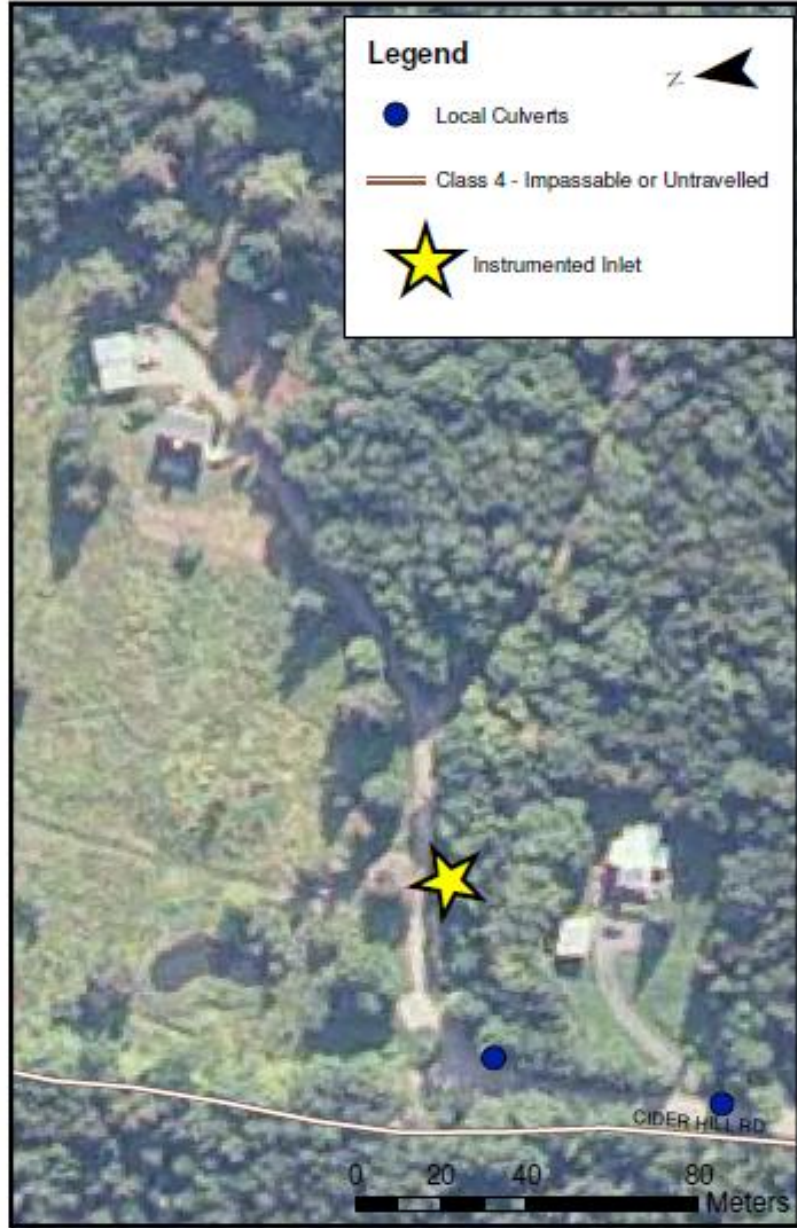
The monitoring station at the **3-Way** intersection of Prickly Mountain, Fuller Hill, and Senor Road is located in the Freeman Brook subbasin in the town of Warren, Vermont. These three roads are all Class 3, gravel roads, maintained by the town of Warren. The instrumented inlet sits just below an agricultural field, approximately 14 acres in size, with a residential home at the far upper side of the field. The drainage area for this site extends from an elevation of 1398 feet at the inlet, to 1478 feet at the uphill culvert to cross Prickly Mountain Road (elevations derived from a 30 m DEM). Prickly Mountain Road, the inlets primary channel for runoff, averages 7.9 meters wide and is crowned, resulting in approximately 3.95 m of road width draining to the inboard ditch. Fuller Hill Road averages 7.8 meters in width, and is also crowned, resulting in 3.9 m of road width draining to the inboard ditch. The monitored culvert drains runoff along a 238.5 m segment of Prickly Mountain Road and a 138.5 segment of Fuller Hill Road; the former having a roadside ditch averaging 0.2 m in width and the latter roadside ditch averaging 2.4 m in width. Together the road surface and ditch drainage area total 1862.3 m². A farm pullout from the field to Prickly Mountain Road may contribute runoff from the field during intense storm events, and seepage was observed directly from the field near the inlet point during several storm events in the summer and fall of 2011. The road grade is 8% along Prickly Mountain Road leading to rapid transmission of runoff and minor incising of the ditch, and 1% along Fuller Hill Road. At the culvert outlet, runoff is discharged into a wide bare ditch which eventually discharges to a stream which discharges to Freeman Brook. Automated monitoring on this site took place from July 7, 2011 to August 2, 2011, August 18, 2011 to September 9, 2011, and from April 22, 2012 to July 26, 2012.



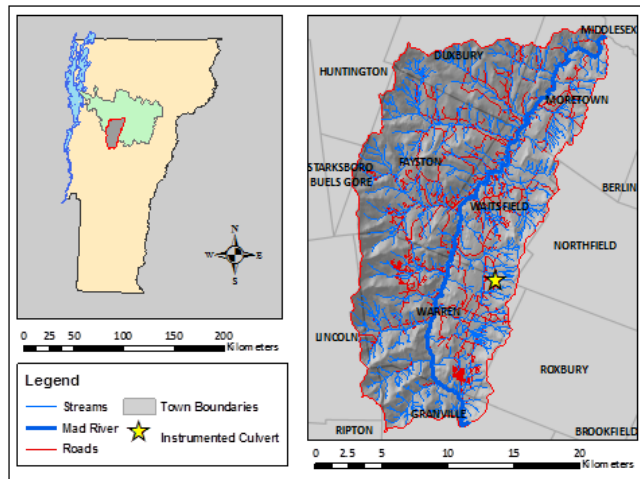


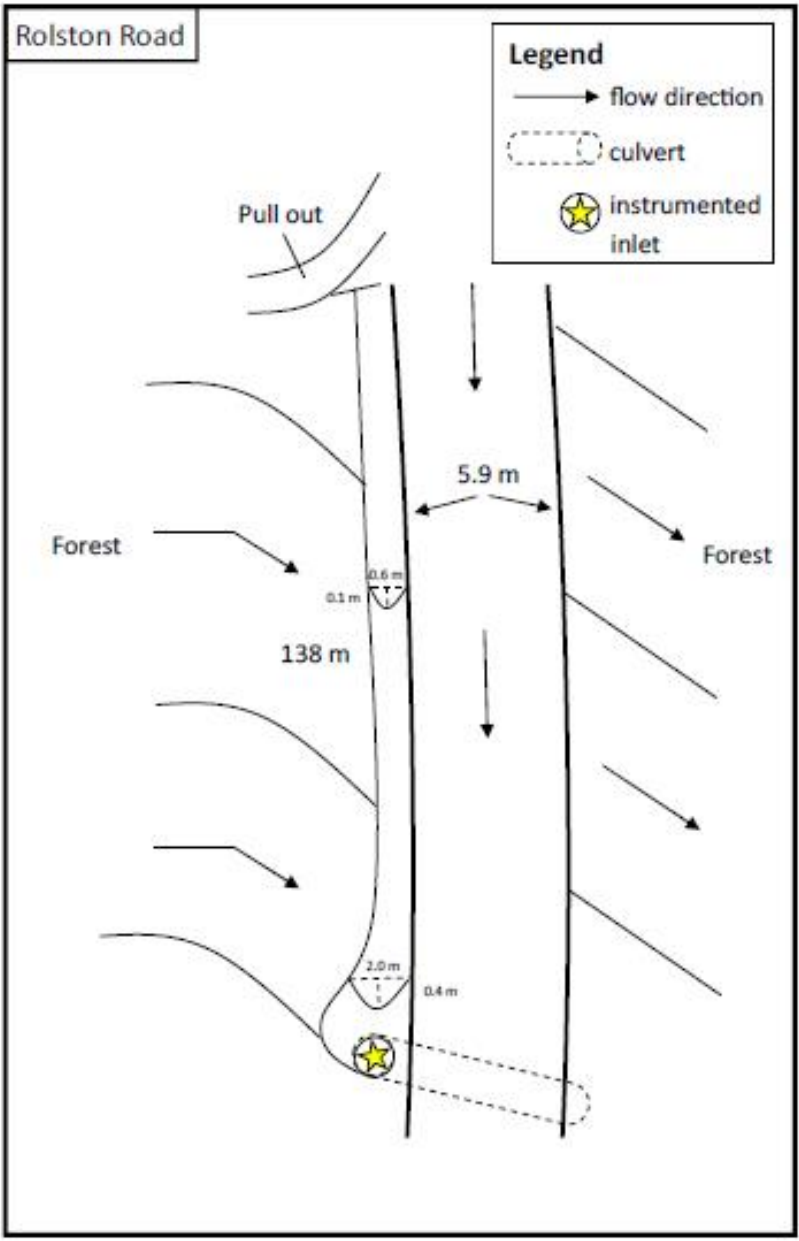
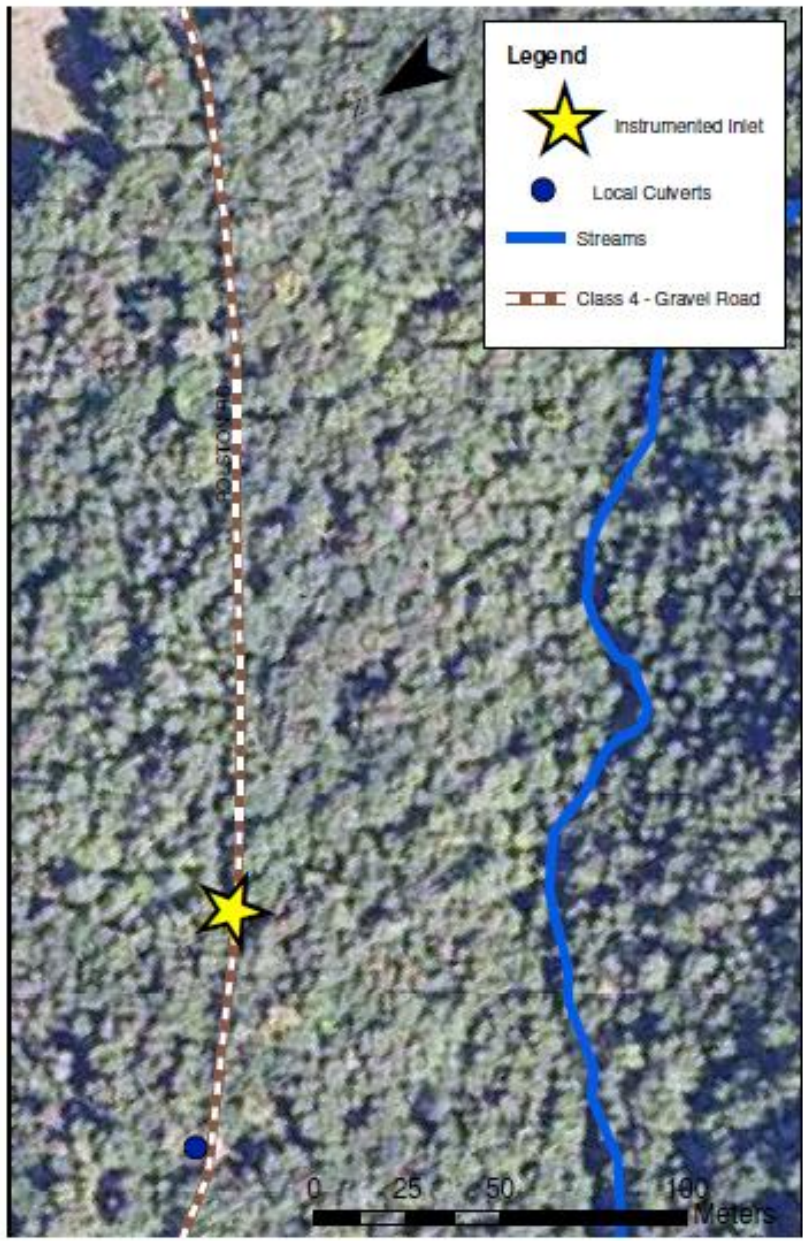
The monitoring station on **Senor Road** is located in the Freeman Brook drainage in the town of Warren, Vermont. The monitored segment of Senor Road is a relatively flat, Class 3, gravel road, the majority of which transects two agricultural fields with a 50 m segment passing through a forested patch of land on the inlet side, and with a 10 m forested buffer on either side of the agricultural segment. The instrumented inlet is at a low point, at an elevation of 1472 feet, where it receives runoff from both the north and south sides which rise with gentle slopes to 1478 feet in the northern direction and to 1472 to the south (an undetectable elevation difference in the 30 m DEM). The road averages 7.3 meters in width and is slightly crowned, resulting in 3.65 meters of the road width draining to the inboard ditch. The monitored culvert drains runoff along a 149.5 m segment to the north and a 49.5 m segment to the south. The adjacent roadside ditch for the north and south segments average 2.2 meters and 2.4 meters in width, respectively. The total contributing road surface and ditch drainage area is 1174.05 m². At least five seepage points were observed, one originating from overland flow, in the fall of 2011 during a minor storm event under wet conditions indicating an additional unmeasured contributing drainage area directly adjacent to the road. Little to no seepage was observed during drier summer condition of 2011. The road grade is 2.5% in the northern direction and 0.5% in the southern direction. At the culvert outlet, runoff is discharged into another agricultural field along a tree-lined ditch, and appears in the Vermont Hydrography Dataset Streams layer to eventually discharge to Freeman Brook. Automated monitoring on this site took place between July 7, 2011 and September 24, 2011.





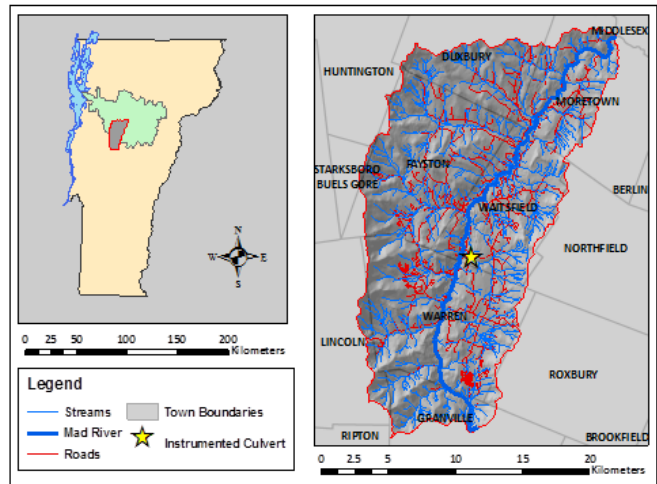
The monitoring station on **Cider Hill Road** is located in the Folsom Brook drainage in the town of Warren, Vermont. The road is a private, Class 4, gravel road which transverses a forested area to the south and a field to the north. Just east of the instrumented inlet, the road splits with a driveway leading to a residential building used as a second home to the northeast and an extension of the private road to the southeast. The elevation rises from 1592 ft. at the inlet to 1624 at the highest drainage point in the northeast direction and 1617 ft. at the highest drainage point in the southeast direction. The upper northeast and southeast roads are both slightly crowned and average 4.3 m and 3.8 meters in width, respectively, resulting in 2.15 m and 1.9 m of road width draining to the instrumented inlet, with respective drainage lengths of 43.3 m and 6.8 meters. The northeast road also has a grassy roadside ditch averaging 1 meter in width above the side road, and 1.3 meters below the side road, leading to a total ditch and road surface drainage area of roughly 149.8 m². A source of seepage was not observed at this site, but a minor amount of groundwater did lead to a moist inlet area even during dry seasons. The road grade is 10% on the northern road and 16% on the eastern, resulting in significant rills on both. At the culvert outlet, runoff is discharged into a field from which it flows to a pond. Automated monitoring on this site took place from August 18, 2011 to October 7, 2011 and from April 23, 2012 to June 28, 2012.

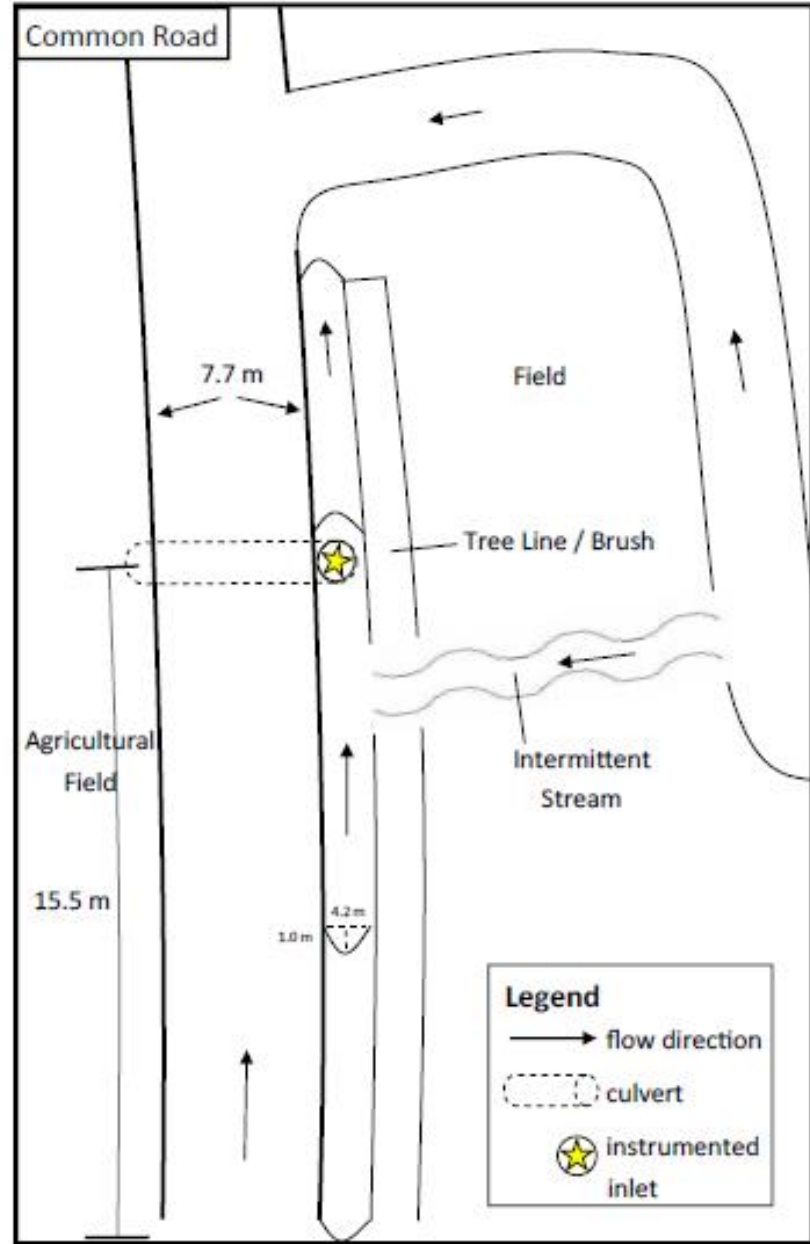




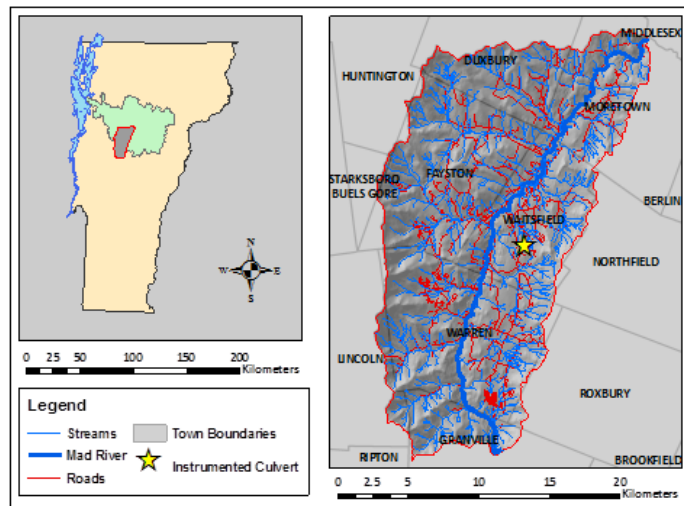
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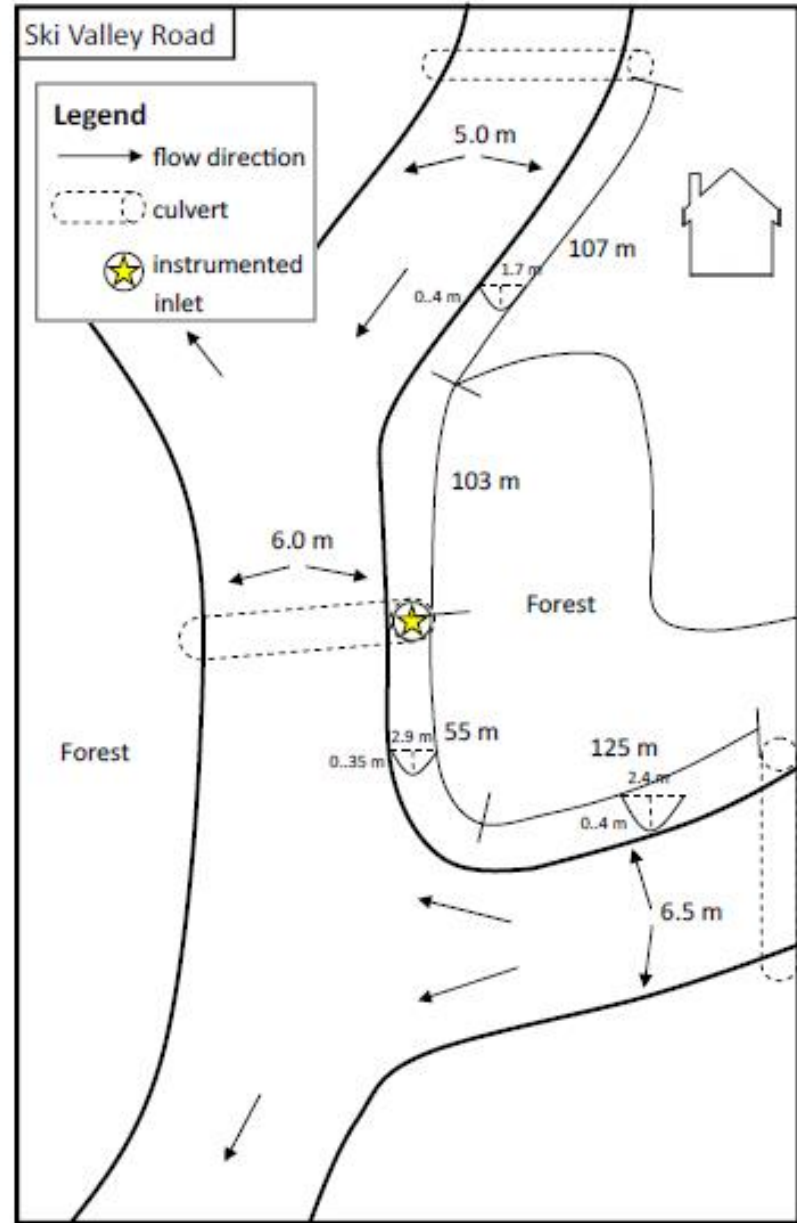
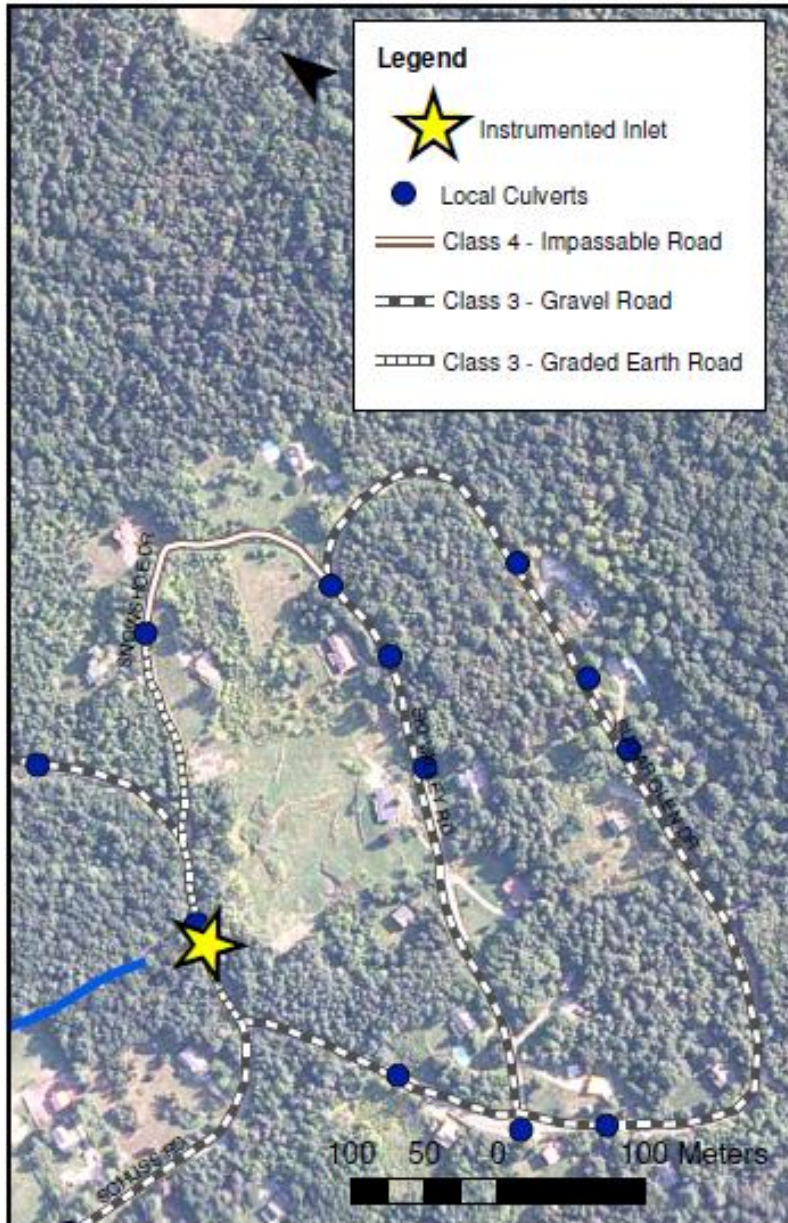
Rolston Road is a steep, Class 4, gravel road. This monitoring station is located in the Folsom Brook watershed in the town of Waitsfield, Vermont. Rolston Road is a cutslope road which is located on the side of a steep hill with a densely forested area to the north and a very steep forested area to the south. The road segment draining to this site rises from an elevation of 981 feet to 1029 feet, 138 meters upslope where drainage to the monitored inlet begins. The road averages 5.9 meters in width and is crowned resulting in roughly 2.95 meters of road width draining to the inboard ditch with a weighted average width of roughly 0.7 meters. The resulting total drainage area including ditch and road surface area is 503.9 m². For much of the 138 meter road segment the upper road bank is largely bare or moss-covered, leaving much of it very susceptible to erosion. The road grade is 12% along the monitored segment, resulting in rapid transmission of runoff from the road surface and ditch to the inlet and sedimentation was so prevalent at this site that are equipment was regularly clogged and/or buried between site visits in the summer of 2011. At the culvert outlet, runoff is discharged onto a steep forested bank where runoff may, during intense storm events, flow directly to Folsom Brook, approximately 90 meters below. No seepage was observed over the one-month period of automated and manual monitoring that took place between August 1, 2011 and September 1, 2011.



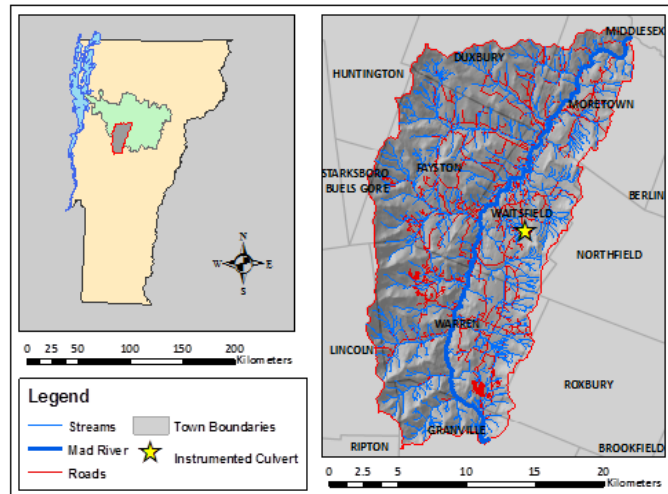


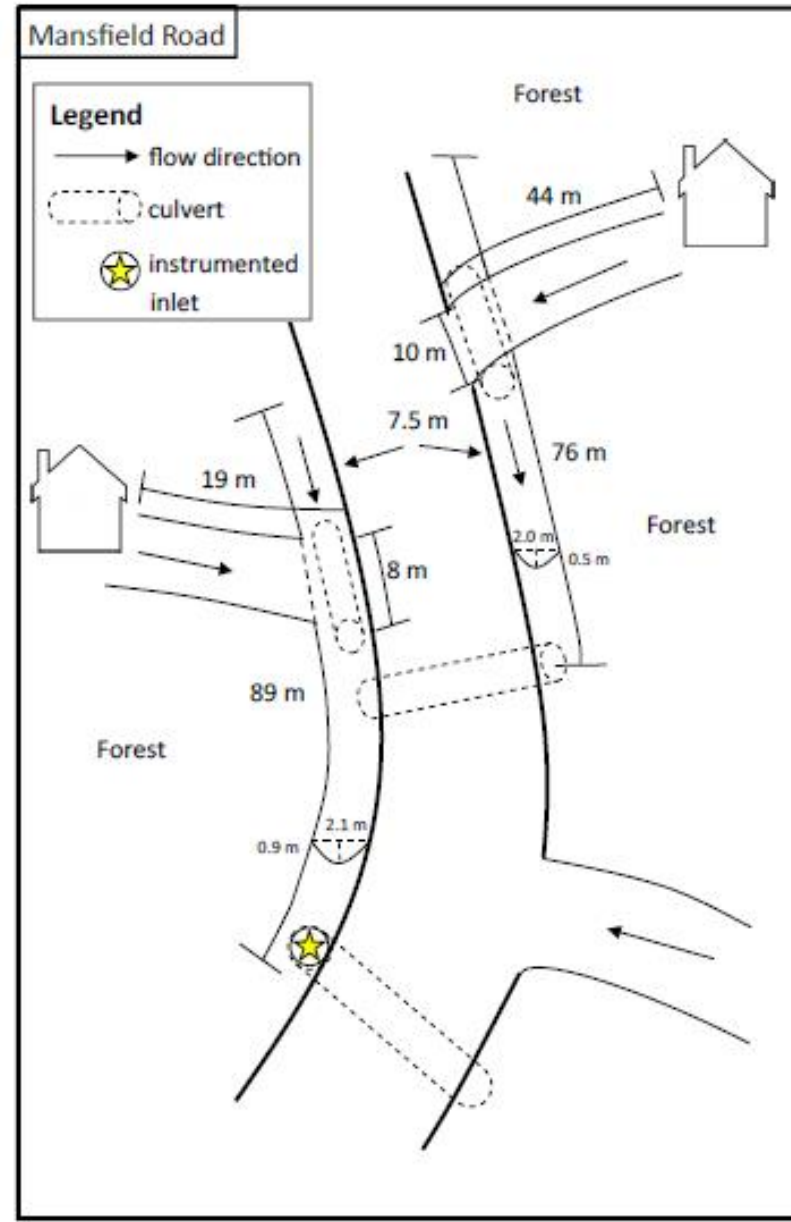
Common Road is a relatively flat, Class 3, gravel road. The monitoring station is located in the High Bridge Brook drainage in the town of Waitsfield, Vermont. This segment of road, mimics Senor Road in that it transects two fields with an approximately 10 meter tree-line roadside buffer. The inlet rests at 1227 feet and rises to 1244 feet at the height of the southeastern end of the road segment. The road averages 7.7 meters in width, and is crowned, resulting in roughly 3.85 meters of road width draining to the inboard ditch. The monitored culvert drains runoff along a 15.5 m stretch of road, and the adjacent roadside ditch averages 4.2 m in width, giving an estimated road surface and ditch drainage area of roughly 124.8 m². The wide vegetated ditch, short contributing road segment, and low road grade of 1.5% leads to little to no observed or measured runoff during medium to low intensity storms. High intensity storm events, however, create an entirely different, larger, unmeasured drainage area, as an intermittent stream develops from Scrag Mountain Road to the ditch (a 12% grade) which leads to the instrumented inlet. At the culvert outlet, runoff is discharged into a field with no visible connection to a stream. Automated monitoring on this site took place from August 1, 2011 to September 15, 2011 and from September 24, 2011 to September 30, 2011.





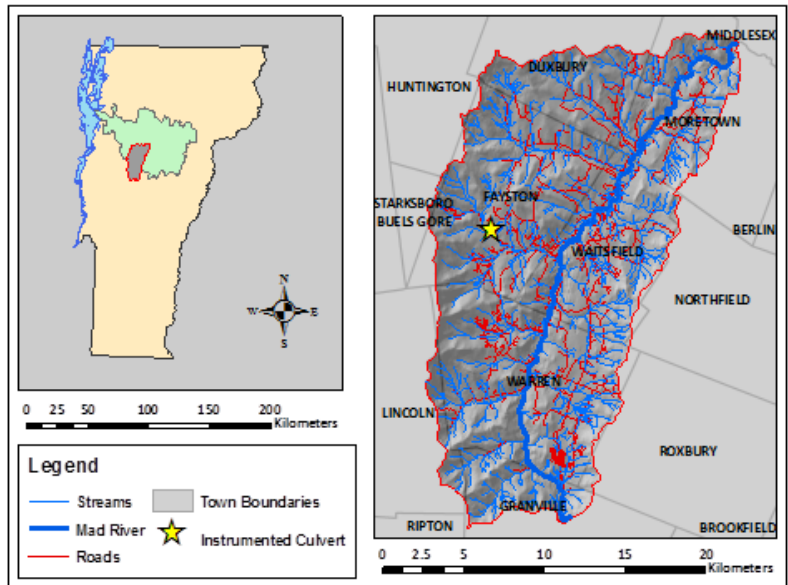
Ski Valley Road is comprised of two varieties of Class 3 roads: gravel and graded earth. The monitoring station is located in the High Bridge Brook drainage in Waitsfield, Vermont. The graded earth portion of the road passes through a densely forested area to the northwest (outlet side) and approximately 40 m of dense forest to the southeastern, upland side of the inlet. Roughly 158 m of the graded earth road that extends to either side of the inlet is relatively flat, before rising to the east for another 107 meters. At the southwest end of the flat extend of the graded earth road, the road shifts to the south and rises more steeply for another 125 meters. The elevation ranges from 1335 feet at the inlet to 1373 to the east and up to 1392 to the south. The road is crowned, and has a weighted average of 5.88 m, resulting in roughly 2.94 m of road width draining to the inboard ditch. The ditch itself has an overall weighted average of roughly 2.4 meters in width, resulting in an estimated total road surface and ditch drainage area of 2087.9 m². During storms of medium to high intensity, overland flow was observed coming through the forested area during the summer and fall of 2011. This may originate from the residential properties and roads above the inlet, on the eastern side of the 40 meter densely forested area above the inlet, but this was not visually confirmed. This overland flow indicates that there is, during medium to high intensity storm events, and larger, unmeasured drainage area beyond the road and ditch surfaces. The road grade is 5% across the 158 m flatter portion, and 10% and 12.5% at the northern and southeastern extents of the road drainage extent, respectively. The ditch surface ranges from bare gravel, to slight grassy vegetation. At the culvert outlet, runoff is discharged into a forested area where it becomes its own tributary which, after meeting with several other unnamed channels, it reaches High Bridge Brook. Automated monitoring on this site took place from August 1, 2011 to September 30, 2011.

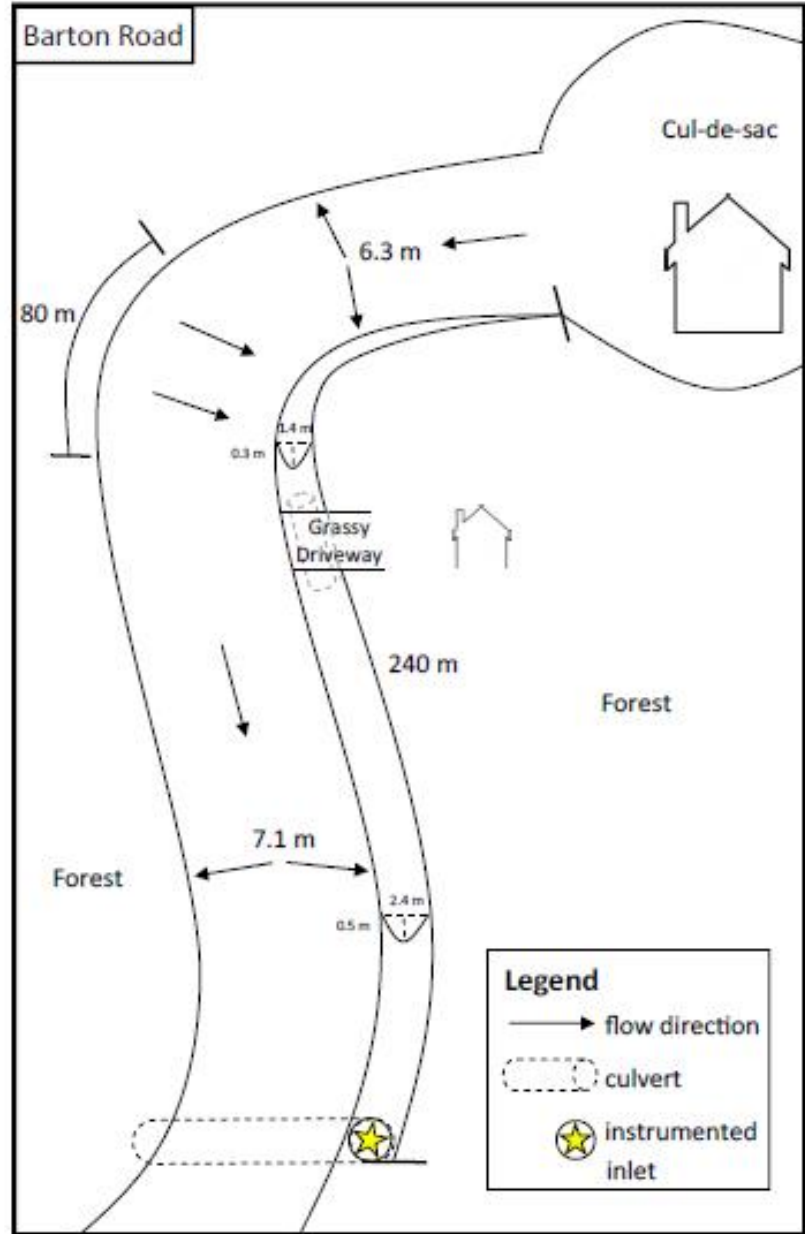




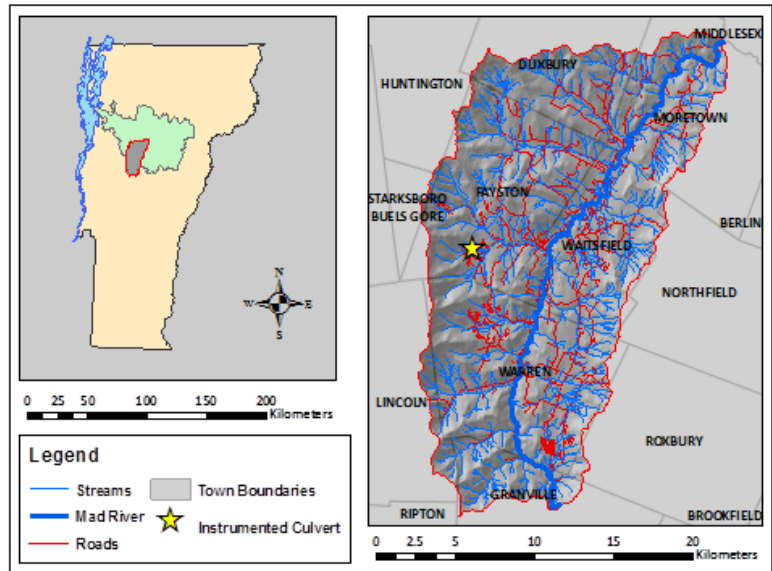
Mansfield Road is a Class 3, unpaved road located in the Mill Brook drainage in Fayston, Vermont. The road rises steeply (12% grade), through a forested area with a series of small (< 0.2 acre) clearings accommodating residential building sites, from an elevation of 1149 feet at the instrumented inlet to an elevation of 1200 feet north of a driveway to the east. The monitored inlet receives runoff directly from the western side of the road for an 89 meter length, and from the eastern side of the road for a 76 meter length due to a culvert which crosses under the road at 36 meters above the inlet. The ditch averages 2.1 meters wide on the western side and 2.0 meters wide on the eastern side. Two driveways, one on the eastern side and one on the western side, also contribute to the runoff drainage area, leading to a total ditch and road surface drainage area of roughly 1549.65 m². Automated monitoring took place between October 18, 2011 and November 11, 2011.

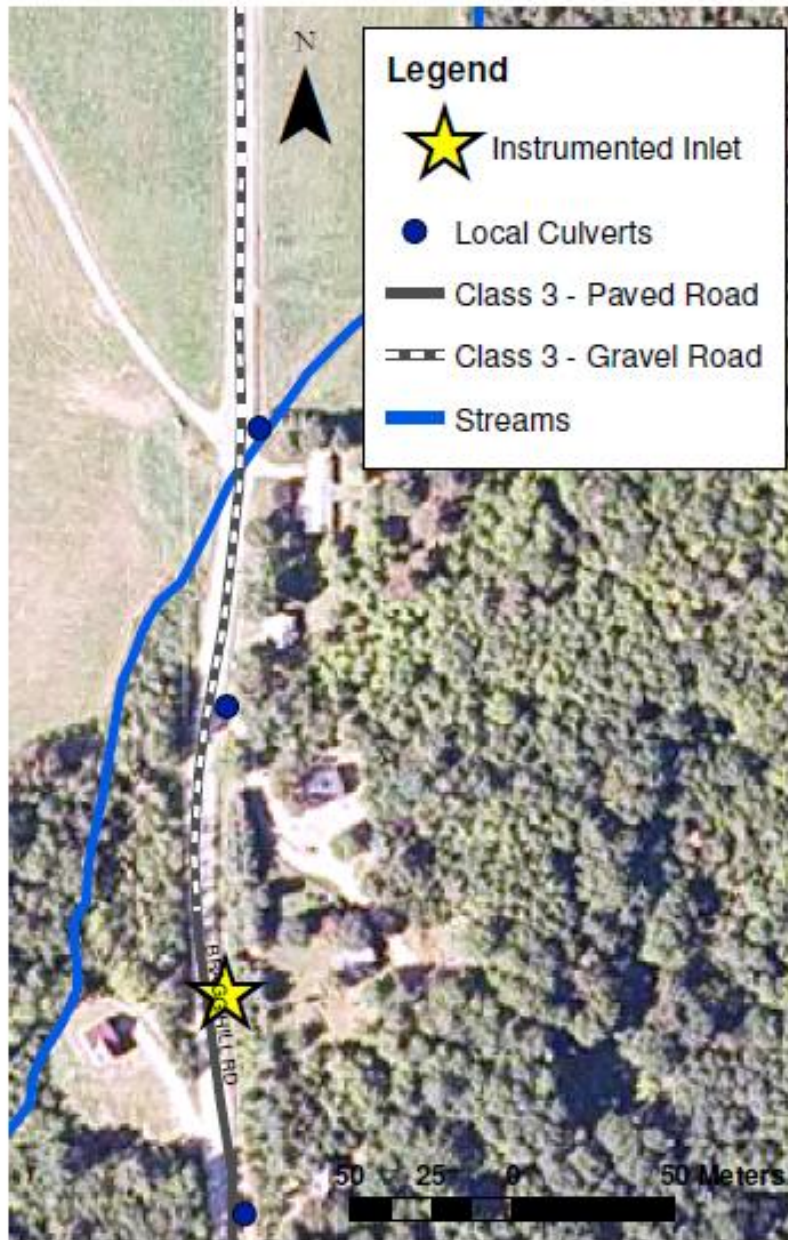
During this time, no seepage was observed, although researchers were not often on site during significant storm events. At the culvert outlet, runoff discharges onto a forested bank which slopes directly to a tributary of Mill Brook.



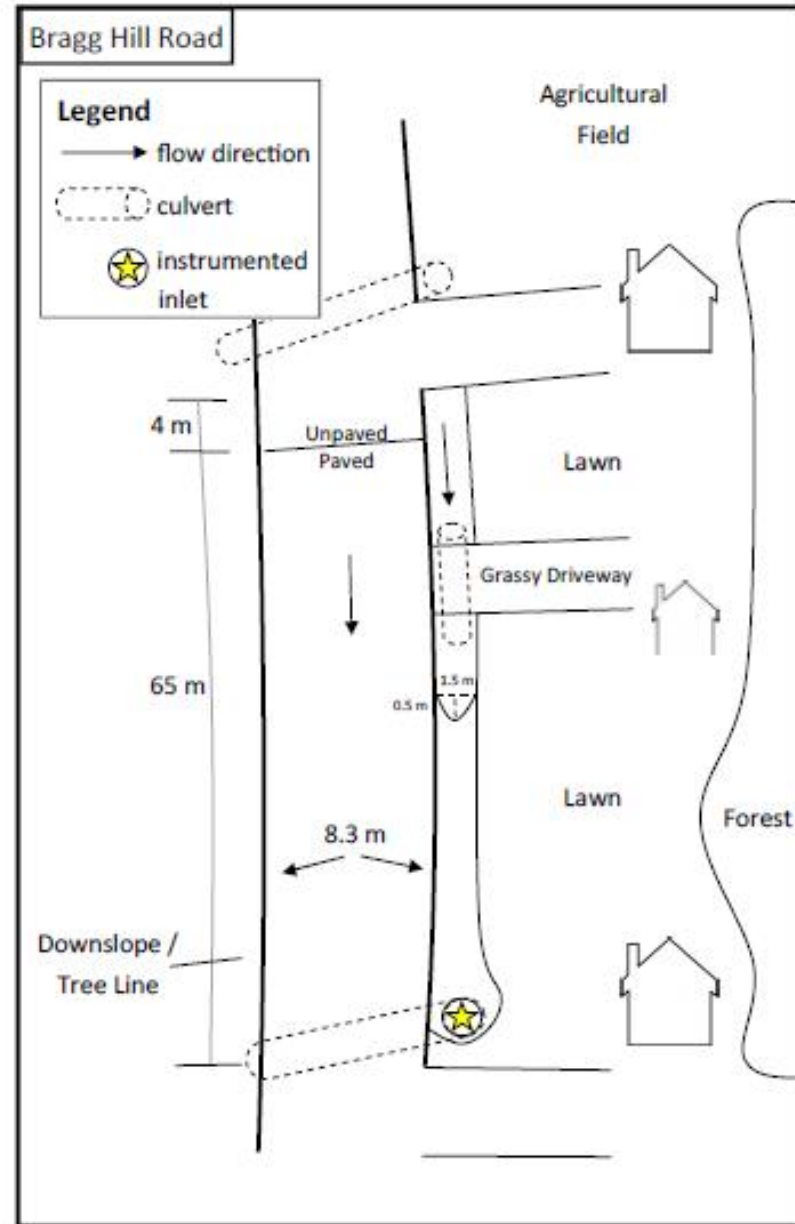


The monitoring station on **Barton Road** is located on a Class 3, unpaved road, located in the Mill brook drainage in the town of Fayston, Vermont. The road traverses a densely forested area, with a series of small (< 3.2 acre) clearings where residential buildings reside, and climbs from 1465 feet at the instrumented inlet to 1541 feet at the highest extent of the road surface drainage area, to just below a cul-de-sac driveway. The road averages 7.1 meters in width over the course of the lower 77.4 meters, and 6.3 meters in width for the upper 163 meters. The road primarily slightly crowned, with the exception of an 80 meter stretch around a corner over which the entire road surface drains to the inboard ditch. The ditch averages 2.4 meters in width over the lower 77.4 meters and 1.4 meters in width in the upper 80 meters, with no ditch along the corner or upper reaches of the road just below the cul-de-sac. This results in a total ditch and road surface drainage area of roughly 1325.4 m². One seepage point was observed during a light intensity storm under saturated conditions in December, indicating that there is a larger, unmeasured drainage area that contributes to the measured runoff at least intermittently. The road grade is 8-11% along the monitored segment, most likely leading to moderately rapid transmission of runoff from the road surface to the inlet. At the culvert outlet, runoff is discharged into a 40 meter wide forested area with no visible connection to a stream though Chase Brook is approximately 140 meters downhill of the culvert, and theoretically may be accessible by runoff during very large storm events. Automated monitoring on this site took place from October 7, 2011 to November 9, 2011 and between July 3, 2012 and July 26, 2012.

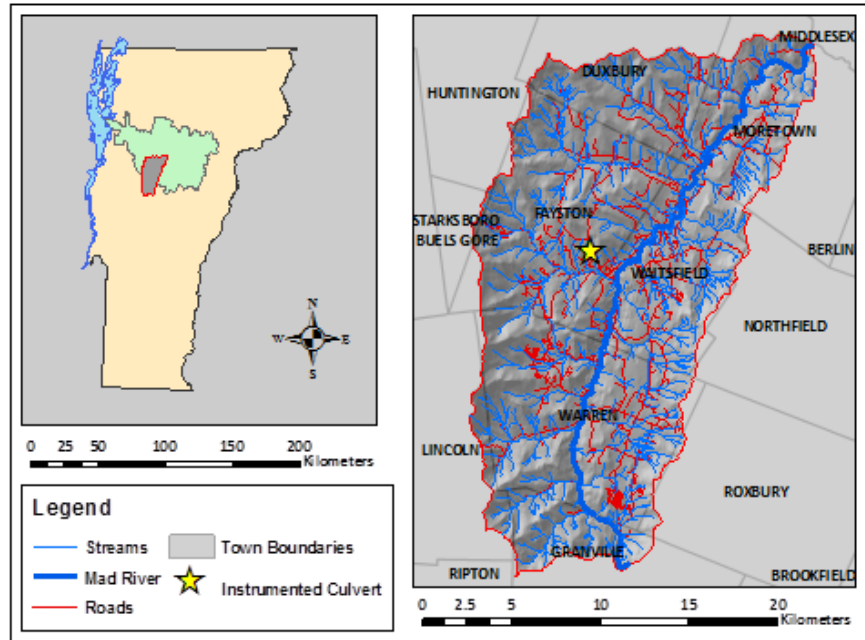


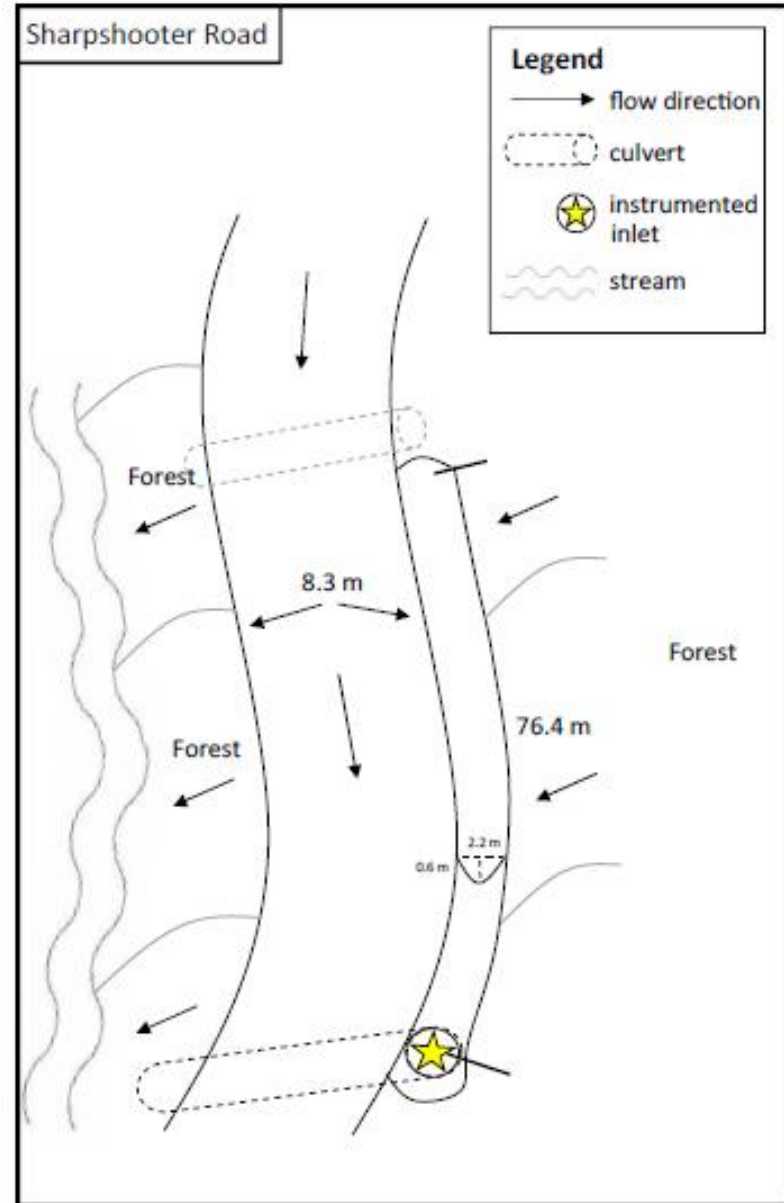
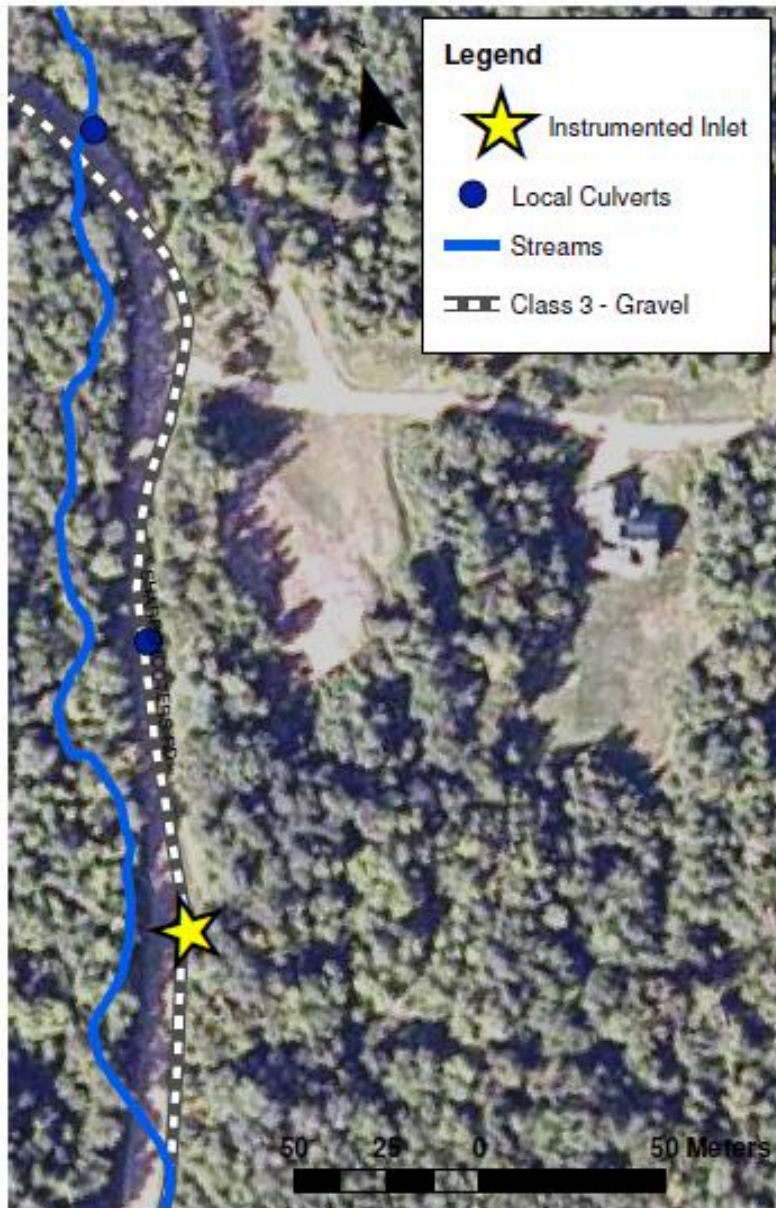


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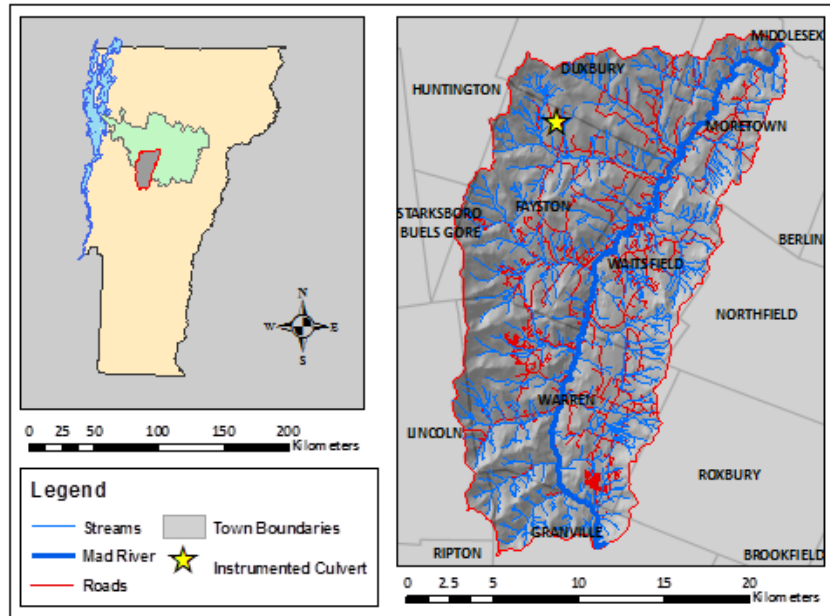
Bragg Hill Road is the one primarily paved road segment that was monitored in the fall of 2011. The monitoring station is located in the Mill Brook drainage in the town of Fayston, Vermont. The monitored road segment traverses two densely forested areas with a series of small (< 0.4 acre) clearings where residential buildings reside. The short road segment climbs from 1437 feet to 1476 feet with the paved segment extending 65 meters north before become unpaved for an additional 4 meters of the extent of the road drainage length. The road averages 8.3 meters in width, and is crowned, resulting in roughly 4.15 m of road width draining to the inboard ditch, which averages 1.5 meters in width, resulting in a total road surface and ditch drainage area of approximately 389.9 m². Under saturated conditions an average storm can lead to seepage through a buried drainage pipe located under the yard of a house on the eastern side of the road, which discharges to the monitored ditch. The road grade is 9% along the monitored segment. Automated monitoring on this site took place from October 1, 2011 to November 11, 2011.

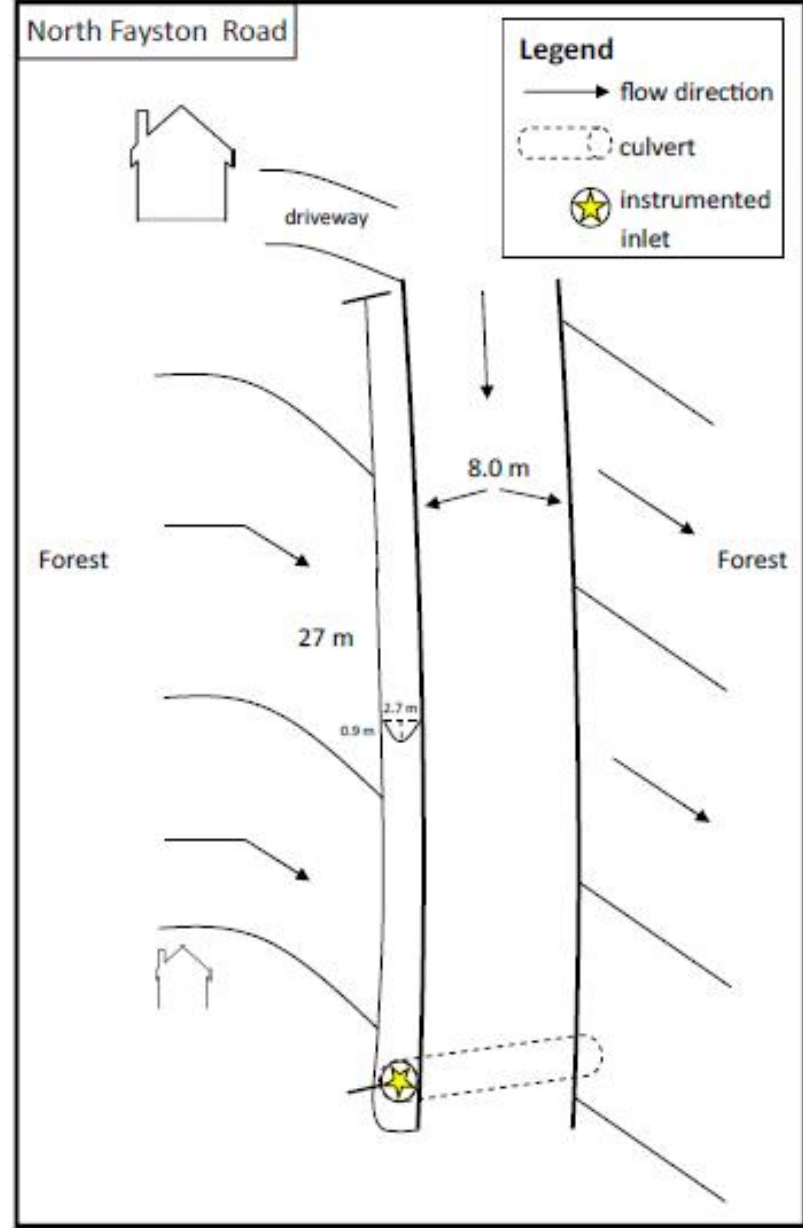




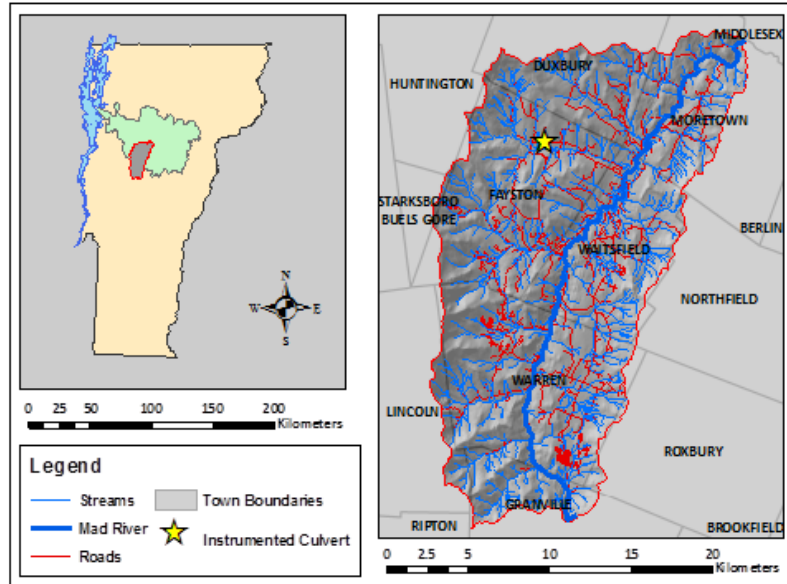
Sharpshooter Road is a Class 3, gravel road located in the Shepard Brook drainage in the town of Fayston, Vermont. The monitored segment of the road traverses a densely forested area with a few small (< 2.7 acres) clearings accommodating what appear to be residential buildings. The site climbs relatively steeply (road grade of 9%) from 1417 feet at the instrumented inlet to 1441 feet at the upper extent of the road drainage segment, 76.4 meters upslope. The road averages 8.3 meters in width, and is crowned, resulting in roughly 4.15 meters of the road width draining to the inboard ditch. The roadside ditch averages 2.2 meters in width, resulting in a total road and ditch surface drainage area of 485.1 m². The ditch is primarily bare gravel, with some slight vegetation along some segments. No seepage points were directly observed along the ditch, but a low level baseflow was frequently present during site visits throughout the fall of 2011, indicating an additional, unmeasured source of drainage beyond the road and ditch surface. At the culvert outlet, runoff is discharged onto a short (~15 meter) bank before reaching a tributary of Shepard Brook. Automated monitoring on this site took place from October 1, 2011 to November 11, 2011.

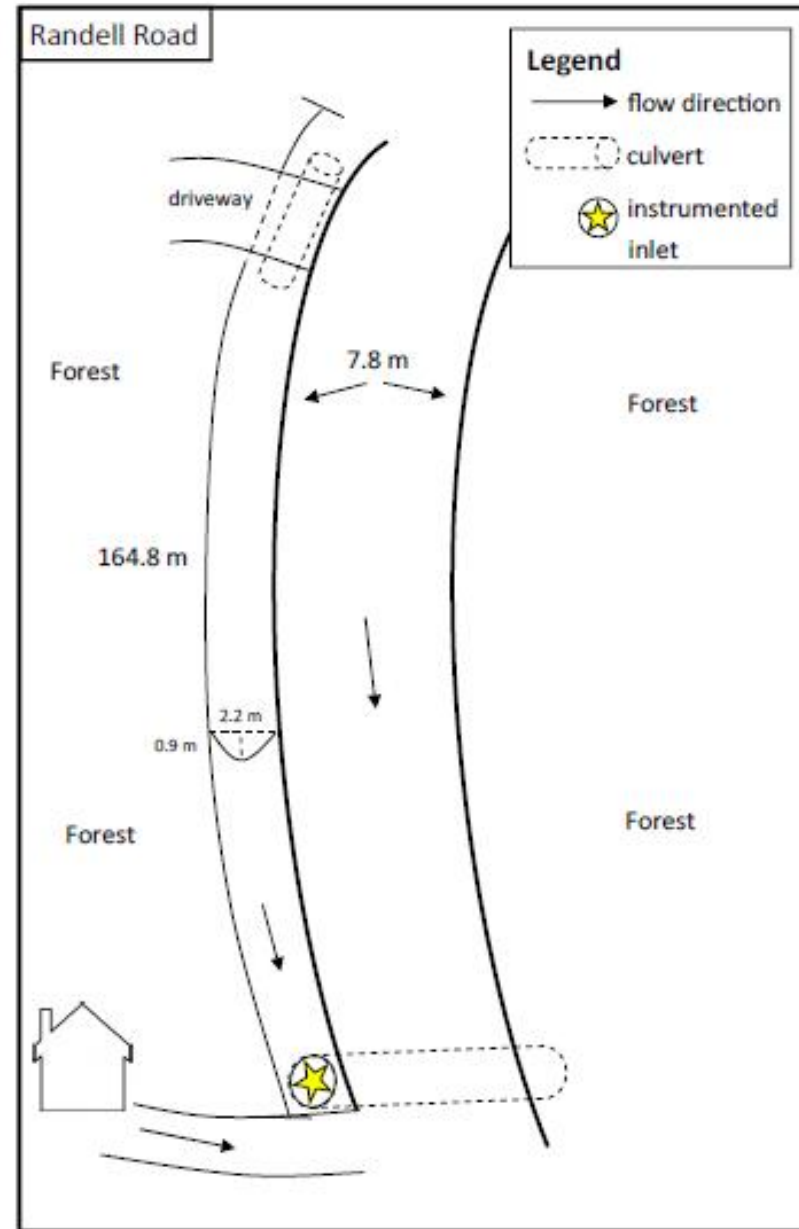
No seepage points were directly observed along the ditch, but a low level baseflow was frequently present during site visits throughout the fall of 2011, indicating an additional, unmeasured source of drainage beyond the road and ditch surface. At the culvert outlet, runoff is discharged onto a short (~15 meter) bank before reaching a tributary of Shepard Brook. Automated monitoring on this site took place from October 1, 2011 to November 11, 2011.





North Fayston Road is a Class 2 gravel road located in the Shepard Brook drainage in the town of Fayston, VT. The monitored road segment traverses a densely forested area, before reaching a public spring and small clearing for residential building just outside and to the east of the road surface drainage area. The road segment is quite flat (road grade of 2.5%) and stretches just 27 meters without a measurable elevation change (using a 30 m DEM). The road averages 8.0 m in width, and is slightly crowned, resulting in roughly 4 meters of road width draining to the inboard ditch. The ditch is slightly vegetated, and averages 2.7 meters in width, leading to a total road and ditch drainage surface area of approximately 180.9 m². No seepage sources and little to no baseflow was observed at this site during the fall of 2011 and spring of 2012. At the culvert outlet, runoff is discharged down a bank into a forested area, with no visible connection to a stream. Automated monitoring on this site took place from October 1, 2011 to November 11, 2011.





The monitoring station on **Randell Road** is located in the Shepard Brook drainage in the town of Fayston, Vermont. Randall Road traverses a densely forested area, with a series of small (< 2.2 ha, 5.5 acres) clearings accommodating residential home sites, climbing from an elevation of 325 m (1066 ft) at its intersection with North Fayston Road to an elevation of 426 m (1397 feet) at its intersection with Center Fayston Road. The road is on average 7.8 meters wide and crowned, resulting in roughly 3.9 meters of the road width draining to the inboard ditch. The monitored culvert drains runoff along a 164.8 meter segment of the road. The adjacent roadside ditch is 2.2 meters wide. A driveway approximately 30 meters long and 5 meters wide drains to the road and contributes runoff to the monitoring station during storms, giving an estimated road surface, driveway, and ditch drainage area of 1155 m². An excavated road cut is not present along the monitored segment, but during intense storm events in June and July 2012, intermittent seepage was observed along the ditch, adding an additional unmapped source from the area directly proximal to the road. Little to no seepage was observed during low precipitation intensity storms in September 2012. The road grade is 15% along the monitored segment, resulting in rapid transmission of runoff from the road surface to the ditch and culvert and visible erosion of the ditch. At the culvert outlet, runoff is discharged into a forested area with no visible connection to a stream. Automated monitoring on this site took place between June 13 and July 26, 2012, with storms sampled on 6/27, 7/4, 7/17 and 7/23-24/2012.

