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Identifying the spatial pattern and importance of hydro-geomorphic drainage impairments on unpaved roads in the northeastern USA

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ABSTRACT

Roads have been widely studied as sources of runoff and sediment and identified as pollutant production sources to receiving waters. Despite the wealth of research on logging roads in forested, upland settings, little work has been conducted to examine the role of extensive networks of rural, low-volume, unpaved roads on water quality degradation at the catchment scale. We studied a network of municipal unpaved roads in the northeastern US to identify the type and spatial extent of “hydro-geomorphic impairments” to water quality. We mapped erosional and depositional features on roads to develop an estimate of pollutant production. We also mapped the type and location of design interventions or best management practices (BMPs) used to improve road drainage and mitigate water quality impairment. We used statistical analyses to identify key controls on the frequency and magnitude of erosional features on the road network, and GIS to scale up from the survey results to the catchment scale to identify the likely importance of unpaved roads as a pollutant source in this setting. An average of 21 hydro-geomorphic impairments were mapped per kilometer of road, averaging 0.3 m^3 in volume. Road gradient and slope position were key controls on the occurrence of these features. The presence of BMPs effectively reduced erosion frequency. Scaled up to the watershed and using a conservative estimate of road-stream connectivity, our results for the Winooski River watershed in the northeastern US suggest that roughly 16% and 6% of the average annual sediment and phosphorus flux, respectively, of the Winooski River may be derived from unpaved roads. Our study identifies an under-appreciated source of water quality degradation in rural watersheds, provides insights into identifying “hot spots” of pollutant production associated with these networks, and points to effectiveness of design interventions in mitigating these adverse impacts on water quality.

Keywords: erosion and sedimentation, watershed processes, low-volume roads, BMP, water quality

Introduction

Transportation networks are a critical element of our society's infrastructure, linking communities and commerce, but with environmental effects that negatively impact a range of ecosystem processes (Formann and Alexander, 1998; Gucinski *et al.*, 2001; Sidle and Ziegler, 2012). The linear nature of roads and their tendency to cross topographic gradients influence watershed hydrologic processes on a scale far greater than one might expect from the small fraction of the land area they occupy (Luce and Wemple, 2001). In rural, mountainous settings, roads generate water and sediment at levels significantly greater than the undisturbed or lightly disturbed terrain they occupy by effectively extending the natural channel network and providing a direct conduit for water and pollutants to enter receiving waters (Jones *et al.*, 2000; Bracken and Croke, 2007; Buchanan *et al.*, 2013a), thus contributing to degradation of water quality.

Previous studies have documented hydrologic and geomorphic impacts of unpaved roads in forested, mountainous settings, where native soil infiltration capacity typically exceeds precipitation rates, and compacted road surfaces generate Hortonian overland flow that efficiently routes to receiving waters (Luce and Cundy, 1994; Ziegler and Giambelluca, 1997; Ziegler *et al.*, 2000; Croke and Mockler, 2001; Arnáez *et al.*, 2004; Zemke, 2016). When constructed on steep slopes, subsurface flow can be intercepted along deep road cuts and ditches and redistributed as concentrated surface runoff (Megahan and Clayton, 1983; Wemple and Jones, 2003; Negishi *et al.*, 2008). These changes imposed by road construction tend to persist over time, leading to long-term changes in hillslope and catchment hydrology (Jones and Grant, 1996; Ziegler *et al.*, 2007). Roads on steep slopes also pose a risk of gully initiation (Wemple *et al.*, 1996; Croke and Mockler, 2001; Takken *et al.*, 2008; Svoray and Markovitch, 2009) and shallow landslides (Montgomery, 1994; Borga *et al.*, 2005). These changes in hydrogeomorphic processes can elevate sediment production and delivery to streams, thereby degrading water quality, as documented in studies in diverse geographic settings (Reid and Dunne, 1984; Bilby *et al.*, 1989; Megahan *et al.*, 1992; Luce and Black, 1999; Lane and Sheridan, 2002; Ramos-Scharrón and MacDonald, 2007; Sheridan and Noske, 2007; Thomaz *et al.*, 2014; van Meerveld *et al.*, 2014; Yousefi *et al.*, 2016; Zemke, 2016).

The concept of connectivity, and the role of roads as distinctive landscape features influencing connectivity between hillslopes and channels, has emerged as an important theoretical basis for understanding the transfer of water, sediment and nutrients through drainage basins (Bracken and Croke, 2007; Bracken *et al.*, 2013). Though variously defined in the literature, *connectivity* includes the spatial dimensions (lateral, vertical, longitudinal) and temporal dynamics that mediate material transfers through catchments (Tetzlaff *et al.*, 2007; Covino, 2017). Variations in connectivity among landscape and channel elements in different settings may help explain variability in the response of natural systems to human disturbance (Brierley *et al.*, 2006). Hydrologic connectivity as it relates to roads has received considerable attention in recent years through field and remote-sensing or GIS-based studies to inventory extent of road-channel connection in catchments (Croke *et al.*, 2005; Lane *et al.*, 2006; Sosa-Pérez and MacDonald, 2016; Thomaz and Peretto, 2016), empirical approaches to link roads to stream channel condition or sedimentation (Cover *et al.*, 2008; Pechenick *et al.*, 2014; Al-Chokhachy *et al.*, 2016), and model development for simulating effects of connected road networks on runoff, erosion and sedimentation (Anderson and MacDonald, 1998; Brooks *et al.*, 2006; Cuo *et al.*, 2006; Akay *et al.*, 2008). Addressing road to stream connectivity has also emerged as an important consideration in ecological restoration schemes (Madej *et al.*, 2006; Al-Chokhachy *et al.*, 2016). Collectively, these studies point to the importance of recognizing both the site-scale impacts of unpaved roads on runoff and pollutant production and the integrated catchment-scale effects of roads on enhancing hillslope to channel connectivity and providing pathways for downstream delivery of pollutants that degrade water quality.

To mitigate both site-scale and downstream effects of roads various design interventions are recommended for road placement, construction and drainage (Lynch *et al.*, 1985; Aust and

Blinn, 2004). These "best management practices" (BMPs) vary by jurisdiction but generally include guidelines for locating roads, sizing and installing stream crossings and drainage structures including bridges, culverts and water bars, 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).

Despite this wealth of information on hydro-geomorphic impacts of forest roads and mitigation measures, few studies have focused on the extensive *network* of low-volume (*sensu* Deller *et al*., 1988; Keller and Sherar, 2003) unpaved roads that extend throughout rural landscapes, and, in particular, the degree to which road-stream connectivity may impair water quality at the catchment scale. These road networks interact with catchment processes in a fashion similar to those constructed for timber harvesting in that their compacted surfaces limit infiltration, their ditch and drainage infrastructure channel runoff and discharge it to receiving waters; and when constructed on steep slopes, they tend to destabilize soil and transport it downslope and downstream. This study extends these lessons from forest road studies and identifies the type and magnitude of what we term "hydro-geomorphic impairments" evident on an unpaved municipal road network, typical of road systems in rural, mountainous settings of northeastern North America and elsewhere. We defined hydro-geomorphic impairments as features evident within the road right of way that exhibited characteristics of an evacuated erosional scar or an accumulated sediment deposit, thus indicating runoff and erosion impacts associated with the transportation infrastructure that potentially impact water quality (Figure 1). The road right of way includes the native- or gravel-surfaced driving lanes and the adjacent excavated cutslope and compacted fillslope required to provide a level driving surface of adequate width on steep slopes (see Wemple et al., 2001 for illustration). We aimed to (1) identify the type and extent of these drainage impairments using a landscape-level survey, (2) assess factors that explain the occurrence of these impairments, (3) evaluate the effectiveness of BMPs in mitigating against these impairments, and (4) provide an first-order estimate of the relative importance of these drainage impairments on water quality degradation at the watershed scale.

Study Area

Our work was situated within the Winooski River watershed, a 2753 km^2 basin draining to Lake Champlain (Figure 2). The Winooski River is the largest tributary watershed to Lake Champlain and includes almost 10% of land area in Vermont. Lake Champlain is a designated impaired water under the U.S. Clean Water Act, with phosphorus (P) designated as the pollutant of concern (USEPA, 2015). Thus, identification of pollutant sources and opportunities for pollutant reduction are a key concern throughout the basin (LCSC, 2003).

The Winooski River has seven major tributaries including the Little River, North Branch, and Kingsbury Branch (or Headwaters) north of the main stem, and Huntington River, Mad River, Dog River, and Stevens Branch south of the main stem. Land cover in the watershed includes about 72% forested land, 12% agriculture, 9% developed land (including rural roads and built structures), and 5% water area. The majority of the land is privately owned, with approximately 31,000 hectares (11%) managed by the state and 5,000 hectares (2%) managed by the federal government. There are 4162 km of road in the Winooski watershed of which 2509 km or approximately 60% are unpaved (Figure 3). Most of this road network is managed by small municipalities responsible for regular maintenance and repairs.

The watershed is characterized by a humid temperate climate, with annual rainfall ranging from 600 to nearly 1200mm/year at the mouth of the Winooski to 1049-2122mm/year at the highest elevations along the spine of the Green mountains (PRISM Climate Group, 2004). Soils in the watershed range from fine sandy loams derived from glacial till deposits in the uplands to silty clays derived from glacial lacustrine deposits in the lowlands of the Champlain valley. Total phosphorus concentration of surface soils (0-15 cm depth), naturally sourced through soil weathering products and decomposition of soil organic matter, were shown to vary by soil texture and soil series, ranging from roughly 300 to more than 900 mg/kg (Ishee *et al.*, 2015). Elevated soil P concentrations exceeding 1100 mg/kg have been measured along eroding streambanks adjacent to agricultural fields in the Champlain valley (Young *et al.*, 2012). Estimates of annual loads for the Winooski River at the USGS gage 04290500, where concentration was measured, average 128,047 MT/yr for total suspended solids and 169,000 kg/yr for total phosphorus (Medalie, 2014).

Methodology

GIS Analysis

We conducted an initial spatial analysis of road distribution within the Winooski watershed in order to develop a sampling strategy for field study. All spatial data were downloaded from the Vermont Center for Geographic Information (VCGI) data portal (http://vcgi.vermont.gov/)[3] between June 1 and July 1, 2011 and compiled into a geographic information system (GIS) using ArcGIS v. 10.0. The Vermont Agency of Transportation road layer (TransRoad_RDS, hereafter *roads*), which included attributes for road class and pavement/surface type, was used for all road network analyses. The Vermont Bridges and Structures data layer (TransStructures_TRANSTRUC, hereafter *culverts*) identified the location and size of all road culverts. Locations of the stream network were taken from the 1:5000 orthographically corrected Vermont Hydrography layer (WaterHydro_VHD, hereafter *streams*). The 10m Digital Elevation Model (ElevationDEM_VTHYDRODEM, hereafter *DEM*) was used to represent topography.

The *DEM* was processed to derive topographic products for analysis. The ArcGIS ***SLOPE***[4] algorithm was used to derive a grid of slope angles for each grid cell of the *DEM*. The

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[3] All data layer names given in parentheses refer to names posted on the VCGI dataware site, accessed July 1, 2015.
[4] All ArcGIS algorithms referred to in ITALICIZED CAPS are documented within the ArcGIS v. 10.0 (ESRI Press, Redlands, CA) software help.

resulting *slope* grid was overlain with the *roads* layer to calculate slope steepness across which roads traversed. Road grade was calculated in ArcGIS by extracting maximum and minimum elevation data (Z-values) for 50-meter road segments along the entire road network using the *DEM*, then dividing the difference in elevation by road length. The result was a percent grade attribute field for the road layer segments. Because statewide municipal road management guidelines (VBB 2009) call for different management practices on roads with grades greater than or equal to 5%, a binary field to represent steep (>=5 %) roads and low gradient (< 5 %) roads was also created, with values assigned as 1 and 0 respectively.

Hillslope position (ridge, midslope or valley floor) was delineated through a series of DEM-based raster calculations. The ArcGIS ***FLOW ACCUMULATION*** algorithm was used to derive a grid delineating the upslope contributing area to each grid cell (*flow_accum*). This grid was then used in conjunction with the *slope* grid to derive a topographic index (TI) (Quinn *et al.*, 1995) as follows:

$$\mathrm{TI} = \ln\left[(\mathit{flow\_accum}) / (\mathit{slope})\right] \qquad (1)$$

where ln is the natural log transform, taken on the ratio of the flow accumulation value to the slope value for each grid cell. Low topographic index values represent areas with low contributing area and high slope steepness, positions typical of ridge settings. High values of the topographic index represent areas with high contributing and low slopes, which are typical of valley floor settings. The raster was reclassified based on a geometric distribution of values binned into one of three categories (0-0.1, > 0.1-0.3, and > 0.3-MAX) based upon visual inspection of the relationship between the index value and the location of ridges, mid-slope, and valley floor positions, respectively, evident on the shaded relief map of the Winooski watershed. These binned TI values were subsequently converted to polygon format and recoded as a categorical variable to represent ridges, mid-slopes and valley floors. The *roads* layer was overlain with the hillslope position polygons to identify the topographic setting for discrete segments along the entire transportation network within the Winooski watershed. Based on the topographic slope position delineations, 69% of the road length in the Winooski basin fell in valley floors, 29% on areas defined as mid-slope, and about 2% in the ridgeline with slight variations across each of the sub-watersheds. Roughly 54% of roads in the basin were classified as steep roads (greater than or equal to 5%) and about 46% are low gradient.

Field Inventory

To develop the methodology for inventory of drainage impairments and application of BMPs, we conducted preliminary pilot studies over a two-week period from May 23 to June 6, 2011. During this period, we drove and observed unpaved roads, noting physical evidence of sediment erosion and deposition along the road right-of-way and photo documenting these features (Figure 1). Past project histories from the Vermont Better Backroads program, a state-assistance program that funds municipal road drainage improvement projects (VBB, 2009), were also reviewed; and pilot surveys of these sites were conducted to gain familiarity with the types of BMPs employed to mitigate erosion on roads.

The inventory was implemented by selecting unpaved road segments of about 2 kilometers in length, using a stratified sampling design, proportional to their distribution in the sub-watersheds by hillslope position (valley floor, mid-slope, upper-slope/ridge), and road grade (Figure 2b). Along sampled road segments, the location and size of hydro-geomorphic impairments were surveyed by walking the length of road with a handheld GPS unit to mark the location of features (Figure 2c). Erosional features were coded as locations showing evidence of fluvial (rills or gullies) or colluvial (slumps, slides) transport of sediment. Depositional features were recorded at all culvert inlets with evidence of sediment obscuring at least 10 cm (4 inches) of the inlet. The presence of BMPs, including stone lined ditches, rock aprons, stone check dams, log/brush check dams, turnouts, waterbars, riprap conveyance channels, silt fences, erosion control fabric, and retention/ponding areas, were also recorded. Volume parameters (length, average width and average depth of the erosional scar) were measured and recorded for all erosional features and blockage depths of culverts were measured for all depositional features. Location data were recorded for all features using a handheld Trimble® GeoXT GPS unit. Point locations and associated attributes for each surveyed segment were uploaded into the GIS master database, with each surveyed road segment representing an observational unit.

Two observers, working either in tandem or separately, recorded all surveyed segments. Five of the segments were surveyed independently by each observer, with results compared to evaluate observer bias. All but five of the surveyed segments were completed between June 30 and August 25, 2011, before Tropical Storm Irene passed over Vermont on August 28, 2011.

Determining mass of sediment and phosphorus eroded from roads

To convert inventoried sediment volumes of eroded features to mass of sediment and phosphorus, soil samples were collected along roadsides at two hillslope positions (midslope and valley floor) in four different sub-watersheds for a total of eight (8) sites (Figure 2b). At each of the 8 sites, 3 samples were collected to determine bulk density using a 9.8-cm hammer-driven corer in the upper horizon of surficial material at the road margin along a gradient from the unpaved driving surface to the native soil of the roadside ditch. Samples were oven dried for 24 hours at 105˚ F and dry weight was determined to 0.1 of a gram. Following oven drying, the subset of three samples from each site where composited, ground and passed through a 2-mm sieve. Approximately 0.5g of the <2mm fraction was weighed to 0.001g and digested using a microwave-assisted nitric acid procedure (EPA Method SW846-3051). Digests were analyzed for total phosphorus by ICP-OES (Optima 3000DV, Perkin Elmer Corp, Norwalk, CT, USA).

Mass of sediment eroded from each surveyed segment ($\text{Mass}_{\text{road sed}}$) was estimated as the product of the measured volume (i.e. feature length, width and depth, as described above) of the erosional feature (V_r) and the mean bulk density (ρ) of the 24 soil samples collected, normalized by the length of the road surveyed (L_r), as follows:

$$\text{Mass}_{\text{road sed}} = (V_r \times \rho) / L_r \quad . \qquad (2)$$

Mass of phosphorus ($\text{Mass}_{\text{road P}}$) in the eroded sediment for each road segment was estimated as the product of the eroded sediment mass ($\text{Mass}_{\text{road sed}}$) and the average P concentration (c_p) of the eight composited site samples collected, as follows:

$$\text{Mass}_{\text{road P}} = \text{Mass}_{\text{road sed}} \times c_p \quad . \qquad (3)$$

Sediment and phosphorus mass were expressed for each surveyed segment as a mass per unit road length to normalize for varying lengths of surveyed road segments and to provide a basis for scaling surveyed road results to the full unpaved road network.

Because only material eroded on roads that are hydrologically connected to streams (Wemple *et al.*, 1996; Croke and Mockler, 2001) will impair water quality, we estimated connectivity of the road and stream network using GIS analysis and a set of rules or assumptions based upon field observations. Using ArcGIS, we estimated the mean length of roads draining to culverts, commonly expressed as culvert spacing, as the quotient of road length and culvert number (Figure 4). We identified stream crossing culverts by conducting an ***INTERSECT*** analysis of the *roads* and *streams* layers, and used these intersection points to attribute culverts as such in the *culverts* layer, with all remaining culverts coded as cross drains. Based upon field observations, we made the simplifying assumption that road segments on both sides of a topographic depression occupied by a stream drained to a stream crossing. This allows the road network length directly connected to stream crossings to be derived as the product of two times the average culvert spacing and the number of stream crossing culverts. For the remaining culverts, we estimated the number of cross drains within 50 m of a stream using the ***NEAR*** function, and assumed, based upon field observations, that runoff discharged at these stream-proximal points would reach receiving waters.

Statistical Analysis

Field survey data for each segment were organized as three response variables and a set of explanatory variables (Table 1). Response variables represented the frequency (for erosion and deposition) and volume (for erosion only) of surveyed features on roads, normalized by the surveyed road length. The explanatory variables were derived from both field measurements and GIS analysis and organized into categories – road design variables, culvert condition variables, road grade variables, and a set of topographic or gradient variables.

Analysis of variance (ANOVA) was used to compare data across the sub-watersheds of the Winooski. Linear regression was used to analyze the relationship between response variables and explanatory variables. For these parametric tests, standard diagnostics were used to ensure data met normality assumptions prior to future statistical testing. Where needed, square root transformations were used to achieve normally-distributed datasets and equality of variance across groups. A principal components analysis (PCA) was used to reduce the dimensionality of the explanatory variables and explore the coincident roles of various landscape and design factors on sediment mobility on roads.

Results

The 52 surveyed segments, totaling 98.4 km and 2.2% of the entire road network in the Winooski watershed and representing nearly 4% of unpaved road network (Table 2), constituted a representative sample for each sub-watershed. The hillslope position and gradient of surveyed roads was similar to the distribution of unpaved roads in the watershed, in that approximately 30% of the surveyed roads were in the valley and about 70% were in mid-slope positions and about half the surveyed road segments had grades greater than or equal to 5% (Figure 5). Surveyed segments ranged in length from 0.4-4.5 km, with an average length of 1.9 km. The proportion of road length surveyed in each sub-watershed varied slightly, ranging from 2.8-5.2% of the unpaved road network.

A total of 1,940 hydro-geomorphic impairments were recorded on the 52 road segments surveyed. The majority of features (1866, 96%) surveyed was erosional, and occurred between 4 and 87 times per kilometer of road surveyed, with an average of frequency of 21 features per km of surveyed road (Figure 6). These erosional features occurred on the road surface, in ditches, on cutslopes, or on fillslopes with a significantly higher proportion on the road surface (78%). Most of the erosional features in the road right of way were very small in volume, averaging 0.318 ± 0.64 m^3. Many of the individual fillslope erosion features were small in volume as well, averaging 0.24 ± 0.62 m^3. Although there were fewer erosional features recorded in ditches, the average volume was higher (1.66 m^3) than the other erosional features. Depositional features, or culverts that were impaired or plugged by sediment, occurred on average 1.2 times for every two kilometers of road surveyed. Most (46%) of these impaired culverts had more than half of their diameter blocked with sediment and debris, while more than a third (35%) had between 25-50% of their inlet blocked.

There were 609 best management practices recorded on the 52 road segments surveyed (Table 3). Of these, the most frequently recorded management practice was turnouts (70%), which were recorded in 424 independent locations. The second most frequently applied management practice was stone-lined ditches (11%).

The frequency of erosional features and the length-normalized erosion volume on surveyed roads were related to the average grade of the road segment. As road grade increased, both erosion frequency and volume of material eroded increased exponentially (Figure 7). Road grade alone explained 37% of the variability in both erosional frequency and eroded volume of sediment per unit length of surveyed road.

Among the suite of independent variables measured in the field and developed in GIS, we found that road grade, measures of hillslope position, slope steepness and the implementation of best management practices were key controls on the tendency for erosion to occur on roads. Results of a principal components analysis (PCA) indicated that nearly 70% of the variability in erosional frequency measured on the 52 surveyed road segments could be explained by four new variables (the components) that represent combinations of the original independent variables (Table 4). The first component, which explains 32% of the variability in erosion frequency along inventoried roads, is most strongly related to measures of road grade and, to a lesser extent, to measures of slope steepness on which the road is situated and to the percentage of the road in compliance with recommended practices for stone-lined ditching. The second component, explaining an additional 15% of the variability in erosion frequency, is most strongly related to slope position and slope angle on which roads are constructed, and to some extent to the presence of BMPs. The sign of the weighting scores associated with the second component provides additional insight in the role of slope position on erosion frequency. Though somewhat counterintuitive, the negative score associated with maximum and mean slope suggests that some element of variability in erosion frequency is inversely related to slope steepness. A possible mechanism may be that as upslope-contributing area increases along a slope profile and slope steepness decreases, soil moisture rises, increasing the risk of drainage impacts on roads. The positive sign of the slope position variable also supports this notion, where higher rates of erosion would be associated with higher values of slope position. Here, slope position was coded as a categorical variable (1=ridge, 2=midslopes, 3= valley floors). Along the hillslope profile from ridge to valley floor, cumulative flow contributions increase and must be accommodated by roads traversing these settings. Although both the first and second components include elements of BMP implementation or non-compliance with BMPs, the third and fourth components, together explaining about 21% of the variability in erosion frequency, most clearly reflect the role of best management practices, including overall BMP frequency, culvert frequency, turnout frequency, the percent of roads with stone-lined ditch, on erosion frequency along surveyed road segments. The negative weighting, of all variables (except culvert frequency) associated with the 3rd and 4th components, indicate that with lower BMP application, higher rates of erosion frequency occur on roads, a finding that is intuitively meaningful and suggests BMPs provide important mitigation against erosion on roads, but that their effect in this study is masked by other more influential variables. The positive score for culvert frequency here suggests the converse – that higher culvert frequency is associated with higher erosion frequency, but the relation here is probably not causal. It is likely that mid-slope roads with frequent stream crossings and drainage conditions that motivated the placement of more frequent culverts correspond with places along the road network that see high rates of erosion associated with abundant runoff.

Survey results compiled at the sub-watershed scale reveal important spatial patterns in erosion on unpaved roads and serve as the basis for scaling up results from the survey to the Winooski watershed. Erosional frequency varied across sub-watersheds of the Winooski, with highest mean erosion frequency and the greatest variability in erosion frequency recorded in the Stevens Branch (Figure 8a). Analysis of variance on the square root transformation of erosion frequency (performed to meet ANOVA assumptions) indicated no significant differences in this variable across sub-watersheds ($F = 1.02$, $p = 0.432$). The mean volume of material eroded per length of road was highest on those road segments surveyed in the Little River and Mad River sub-watersheds and lowest on segments surveyed in the North Branch (Figure 8b). ANOVA on the square root transformation of this variable indicated significant differences in the mean normalized volume of material eroded across sub-watersheds ($F = 4.097$, $p = 0.002$). Tukey's HSD post-hoc test revealed that the Little River and Mad River sub-watersheds had significantly higher mean normalized volume of material eroded, when compared to the other sub-watersheds surveyed ($p < 0.05$). These between-watershed differences in erosion volume were correlated to median slope steepness of each watershed, with higher mean erosion volumes recorded on sampled roads occurring in the steeper watersheds of the Winooski (Figure 9).

Results for soil samples collected on the roadside margin and in ditches provide additional information needed to estimate the mass of sediment and phosphorus associated with eroded road materials. Bulk density across the eight measured sites varied little, averaging 1731 kg/m^3 (Figure 10a). Concentration of total phosphorus ranged from 255 mg/kg at Country Club Road in the North Branch watershed to 531 mg/kg on Turner Hill Road in the Mad River watershed, and averaged 396 mg/kg across all sites (Figure 10b). These values fall within the range of background soil P concentrations measured regionally (Young *et al.*, 2012; Ishee *et al.*, 2015) and globally (Yang *et al.*, 2013), and below the global average of 630 mg/kg for surficial materials (Hartmann et al. 2012). There was no clear pattern in TP concentration across the Winooski watershed from headwaters to the mouth. At three of the four sites, TP concentrations were higher on mid-slope sites than on valley floor sites, but this pattern was reversed in the Huntington River watershed.

Although our field-based estimates of sediment and phosphorus production from unpaved roads cannot with certainty be pro-rated annually, reports from town road crews indicate that at least annual re-grading of the unpaved road network occurs in most towns. Typical practices involve one annual grading for most gravel roads following the snowmelt season. This grading activity would create a "clean" road surface, on which new erosional features might emerge in subsequent storms. Assuming at least an annual cycle of road grading, the features we inventoried during the summer 2011 would represent those that were eroded since the last road grading occurred. Our survey results should therefore approximate, or perhaps even underestimate (if late summer and fall storms generate additional erosion not captured in our survey or multiple grading passes cleaned and reset the road surface for erosion), annual sediment and P sourcing from unpaved roads.

Scaling up of the inventory results to the full road network indicates a mass of eroded sediment in excess of 40,000 metric tons and total phosphorus in excess of 15,000 kg from all unpaved roads in the watershed for the period captured by our field inventory (Table 5). Summed across the subwatersheds of the Winooski and normalized by road length, these rates of pollutant production on roads equate to 16,080.4 kg/km of sediment and 6.1 kg/km of phosphorus. Our estimates indicate that sediment production rates on unpaved roads in the Winooski watershed equate to approximately 31% the annual load of suspended sediment and

11% of the annual load of total phosphorus in the Winooski watershed (Table 6). Only a fraction of these road-derived pollutants likely contributed directly to receiving waters, however. Based on our GIS analysis, we estimate that across the Winooski River watershed, 38% of the unpaved road network discharges to stream crossing culverts and 15% of the road network discharges to cross drains within 50 m of a stream. Using these levels of road-stream connectivity, a more conservative estimate of unpaved road contributions would be roughly 16% of the average annual sediment load and roughly 6% of the average annual phosphorus load discharged to receiving waters (Table 6).

The results of this study provide an opportunity to identify “hot spots” of pollutant production from roads. For example, normalizing the unpaved road network distribution and the relative share of sediment mass from unpaved roads to the fraction that each subwatershed contributes to the entire Winooski watershed illustrates that the Mainstem, Headwaters, and North Branch together comprise 50% of the unpaved road network in the Winooski watershed but only about 20% of the estimated sediment mass eroded from unpaved roads. In contrast, the steep Little and Mad River subwatersheds together comprise 25% of the unpaved road network in the Winooski watershed but generate about 53% of the estimated sediment mass from unpaved roads (Figure 11). This suggests significant opportunities to facilitate reductions in water quality degradation as well as improvements in resilience of infrastructure to erosion during storm events through the targeting of limited funds for system upgrades and BMP interventions in the steepest portions of the landscape.

Discussion

The results reported here reinforce findings from previous studies conducted in diverse geographic settings. Road segment length between drainage structures, gradient of the road segment, slope gradient on which the road is constructed, drainage area above the road which may contribute to subsurface flow interception, and slope position along an elevation profile have been shown to be key controls on road surface erosion and gully incision below road drainage features (Wemple *et al.*, 1996; Luce and Black, 1999; Croke and Mockler, 2001; Takken *et al.*, 2008; Cao *et al.*, 2014; Sosa-Pérez and MacDonald, 2016; Yousefi *et al.*, 2016). As such, these variables could be used to predict the type of hydro-geomorphic impairment to downstream water quality attributable to roads and documented in this study. Similarly, as seen in this study, the application of design interventions used to slow the flow of water, increase surface roughness in ditches, and dissipate concentrated runoff below drainage structures have proven effective in minimizing erosion on unpaved roads (Turton *et al.*, 2009; Meals *et al.*, 2010; Wear *et al.*, 2013; Nasiri *et al.*, 2017).

Though much of the work to date on hydrologic and geomorphic impacts of unpaved roads has been conducted on forest (logging) roads, notable exceptions include the work of Ramos-Scharrón and MacDonald (2005), documenting elevated landscape scale erosion rates on rural roads on St. John, Virgin Islands, and the recent works of Svoray and Markovitch (2009) and Buchanan et al. (2013b) documenting road impacts on pollutant production and transfer in agricultural landscapes. These types of studies, applied to the extensive network of municipally- or provincially- (i.e. counties in the US) managed unpaved roads in rural settings, such as those documented in this study, have the potential to improve insights into a ubiquitous watershed impact and source of water quality degradation. This information may help managers and policy makers in sectors beyond forestry target resources for improving water quality and protecting valuable infrastructure.

Assessing the catchment scale implications of road surface erosion requires scaling site-level observations to extensive road networks within catchments, as attempted in this study. Common approaches for this type of scaling exercise include intensive measurements at selectively sampled sites that are then used to extrapolate measures of erosion to the road network within catchments (Lu *et al.*, 2007; Sheridan and Noske, 2007; Svoray and Markovitch, 2009). Alternate approaches involve the use of process-based models to simulate plot scale road erosion and routing through the catchment (Brooks *et al.*, 2006; Surfleet *et al.*, 2011). Capturing the highly localized and scale-dependent effects of roads on sediment production, as identified by Thomaz et al. (2014), and catchment-scale integration of roads with channel networks, as demonstrated by Bracken and Croke (2007), will be critical to appropriate upscaling.

Because of the dynamic and interacting processes driving sediment production from unpaved roads, it is still incredibly difficult to reliably predict the dominant controls and physical processes involved at any specific location (Luce, 2002). However, catchment scale approaches provide a means to aggregate processes and study compounding effects at a broader scale. This may be of significant importance to planners and decision makes at a regional level when evaluating methods to reduce water quality impairments within a watershed. The results presented through the approach used in this study suggest that using BMPs in "hot spot" areas may provide tangible, meaningful reductions in water quality impairments.

Despite uncertainties in the time scale represented by the pollutant production estimates captured in our inventory, this study provides at least a first-order estimate of the relative importance of unpaved roads in contributing to sediment and phosphorus discharged from the Winooski River to Lake Champlain. Phosphorus concentrations associated with road-derived sediments from this mostly forested landscape are relatively low, resulting in rather modest contributions of unpaved roads to catchment-wide P fluxes, as demonstrated in the one other catchment-scale study we have seen that addressed P production from unpaved roads in forested catchments (Sheridan and Noske, 2007). In settings where dense networks of roads traverse agricultural lands, especially where those lands receive exogenous nutrient applications, the efficient routing of nutrients through connected roads and ditches to receiving waters may be an important and underappreciated pathway of nutrient transfer (Buchanan *et al.*, 2013a). In these settings, P transported through road networks may be more biologically available in soluble form than the primarily particulate-bound P associated with eroded forest soils. Including the hydrologically-connected pollutant transfer pathways associated with roads will be important in addressing the water quality problems that plague freshwater and coastal marine systems.

Summary

Unpaved road segments in the Winooski River watershed, systematically selected based on road grade and slope position, were used to document both the form and magnitude of hydro-geomorphic impairments as well as the application of best management practices. The analysis presented herein also provides a suitable framework for providing first-order estimates of water-quality impacts from unpaved roads to receiving waters. More than 1900 features were inventoried on 98 km of road, largely representing features indicative of fluvial and colluvial erosion of road surface, road-side and ditch materials. The frequency of erosional features was related to the steepness, or grade, of the road and to the absence of best management practices recommended for unpaved roads located in these rural settings. Extrapolation of survey results to the unpaved road network at the catchment scale yielded estimates of sediment eroded from unpaved roads in excess of 40,000 metric tons and total phosphorus in excess of 15,000 kg. Assuming these estimates represent an annual production of sediment on the unpaved road network, these masses equate to approximately 31% of the annual suspended sediment load and 11% of the annual phosphorus load for this study area. Estimates of connectivity indicate that roughly 53% of the road network is hydrologically integrated with streams, providing a direct conduit for pollutant transfer to receiving waters, and resulting in the delivery of slightly more than half of the pollutant load generated on roads to streams.

Our survey results also provide a suitable method for identifying key areas where reductions in erosion from unpaved roads should yield meaningful water quality improvements and confirm that the suite of recommended best management practices on unpaved roads are effective in reducing pollutant production at the catchment scale.

The results of this study facilitate a greater understanding of how hydro-geomorphic connectivity operates at the catchment scale and also serves to provide a framework for estimating the degree of impairment that these types of roads may have on regional surface-water quality in rural forested landscapes, thereby increasing the capacity of decision and policy makes in helping to mitigate adverse environmental impacts while simultaneously augmenting the resiliency of local transportation infrastructure.

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Table 1: Variables measured or computed for each surveyed road segment, taken from field or GIS-derived measures (see table footnotes and text)

Variable	Description
Response variables	
Erosional frequency[F]	Number of erosional features per surveyed road length
Depositional frequency[F]	Number of depositional features per surveyed road length
Volume eroded [F]	Sum of volume of all erosional features per surveyed road length
Explanatory variables	
Road design	
BMP frequency[F]	Number of BMPs per surveyed road length
Turnout frequency[F]†	Number of turnouts per surveyed road length
Culvert frequency[F]†	Number of culverts per surveyed road length
Percent of road with SL ditch[F]	Measured length of stone-lined ditch divided by surveyed road length
Percent non-compliance[F]	For all roads with grade ≥5% grade, length of road without stone-lined ditch divided by surveyed road length
Culvert condition	
Inlet blockage[F]	Categorical variable: 1 = inlet blockage < 25%, 2 = inlet blockage 25-50%,3 = inlet blockage ≥ 50%
Topographic/gradient conditions	
Road grade[G]	Multiple variables including mean, maximum, standard deviation and mode of grade for 50 meter segments along surveyed length
Dominant grade[G]	Categorical variable coded as 0 = road grade < 5%, 1 = road grade ≥ 5% and taken as mode for 50 meter segments along surveyed length
Percent steep[G]	Percentage of surveyed road length with road grade ≥ 5%
Slope steepness[G]	Average of DEM-derived slope value measured along segments of surveyed road length (measures slope inclination on which road is constructed)
Dominant slope position[G]	Hillslope position (ridge, midslope, valley floor) for longest fraction of surveyed road length

Notes:

[F] Variable measured in the field survey

[G] Variable derived from GIS data for surveyed road segments

† The placement of frequent turnouts and culverts to relieve water from the road are considered best management practices, but calculated separately as variables here to assess their importance in mitigating erosion on roads.

Table 2: Summary road lengths for tributary watersheds of Winooski River and lengths surveyed for this study.

	Road Length (km)	Unpaved Road Length (km)	Length Surveyed (km)	Percent (%) Unpaved Road Length Surveyed
Mainstem	1230.1	462.5	13.0	2.8
Huntington	152.3	119.4	4.4	3.7
Mad River	453.7	344.4	11.8	3.4
Dog River	344.0	236.7	8.1	3.4
Stevens Branch	644.9	330.2	10.3	3.1
Headwaters	783.5	613.5	31.8	5.2
North Branch	197.0	137.9	6.7	4.9
Little River	356.3	265.1	12.3	4.6
Winooski watershed	4161.8	2509.7	98.4	3.9

Table 3: Best management practices recorded on 52 surveyed road segments

BMP	Count
Turnout	424
Stone lined ditch	64
Rip rap conveyance channel / rock apron	33
Vegetated ditch	28
Erosion control fabric	21
Check dams	13
Water bar	10
Other[1]	16
Total	609

[1] Category "other" included bank stabilization (6), mesh netting in ditch (3), vegetated grass bank (1), logs directing flow of water (1), plastic conveyance at culvert endwall (1), hay bale (1), flow directed to retention area (1), and other rock stabilization (2)

Table 4: Component weighting scores (cell values) for principal components analysis of 52 surveyed road segments, using independent variables measured in field or derived using GIS. Numbers in bold draw attention to component weighting scores that are highly correlated (> ± 0.5) to independent variables.

Component number:	1	2	3	4
% of Variance in Erosional Frequency Explained	32.295	15.312	12.032	9.330
BMP frequency	0.381	**0.611**	**-0.568**	0.031
Culvert frequency	0.316	0.264	**0.708**	-0.089
Percent road with stone-lined ditch	0.228	-0.077	0.180	**-0.788**
Turnout frequency	0.358	**0.597**	**-0.614**	0.096
Percent road not in compliance[a]	**0.577**	0.208	-0.227	0.396
Blockage < 25%[b]	**0.539**	0.252	0.361	0.415
Blockage 25-50%[b]	0.377	0.269	0.496	0.463
Blockage > 50%[b]	0.022	0.211	0.443	0.205
Mean Grade	**0.947**	0.082	-0.026	-0.168
Max Grade	**0.856**	-0.112	0.027	-0.153
Standard deviation of Grade	**0.774**	-0.205	0.037	-0.310
Dominant Grade[c]	**0.817**	0.090	-0.055	-0.179
Percent Grade	**0.851**	0.169	-0.008	-0.118
Mean Slope	0.450	**-0.641**	-0.081	0.214
Max Slope	0.423	**-0.748**	-0.231	0.230
Dominant Slope[d]	**0.514**	-0.397	0.228	0.142
Dominant Slope Position[e]	-0.182	**0.589**	0.263	-0.226

Notes:

[a] defined as proportion of road with slopes ≥ 5% without stone-lined ditch.

[b] Blockage depth= count of culverts with a percentage (< 25%, between 25-50%, > 25%) of inlet diameter blocked by sediment.

[c] binary variable representing grades ≥ 5% or grades < 5% according to avg. grade measurements.

[d] binary variable representing steep slopes or not steep slopes

[e] hill slope position category for the majority of road length (ridge, mid-slope, valley).

Table 5: Estimates of eroded sediment and phosphorus from unpaved roads for sub-watersheds and the main stem of the Winooski.

Sub-watershed	**Unpaved road length** (km)	**Mean Vol. Sediment per km** (m3/km)	**Estimated Mass of Sediment Eroded** (metric tons)	**Estimated Mass of Phosphorus Eroded** (kg)
Mainstem	462.5	5.55	4443	1693
Huntington	119.4	6.45	1333	508
Mad River	344.4	19.52	11637	4435
Dog River	236.7	6.54	2680	1021
Stevens Branch	330.2	10.21	5836	2224
Headwaters	613.5	4.06	4312	1643
North Branch	137.9	1.51	360	137
Little River	265.1	21.26	9756	3718
Winooski watershed	2509.7		40357	15380

Table 6: Comparison of watershed estimates of suspended sediment and phosphorus with estimates for unpaved roads

	Suspended Sediment (MT/year)	Total phosphorus (kg/yr)
Winooski River watershed †	130,390	134,400
Winooski River unpaved roads ‡		
- maximum estimate (all unpaved roads)	40,357	15,380
- conservative estimate (assuming 53% of road network network connected via stream crossings and cross drains) [a]	21,389	8,151
Percentage of Winooski river load attributable to roads		
- maximum estimate	31%	11%
- conservative estimate	16%	6%

† Estimates taken from (Medalie, 2014) using flow normalized derived values.
‡ Estimates taken from this study, see Table 5
[a] See text for methodology used to estimate road-stream connectivity

Figure captions

Figure 1: Examples of erosional and depositional features on roadways that impair water quality, including (a) fluvial erosion of road surface, (b) plugged culvert, and (c) slump on roadside margin. Also shown are examples of best management practices used to address water-quality impairment from roads, including (d) a stone-lined ditch designed to reduce erosion of roadside ditch and cutslope and (e) turnouts used to divert eroded sediment into roadside forest and away from receiving waterways.

Figure 2: Study area and sampling design: (a) Winooski River watershed (dark gray) within the Lake Champlain basin in northeastern North America, (b) location of inventoried road segments (n=52) and soil sampling sites (n=8), and (c) example of surveyed road segment in Little River subwatershed, displaying discrete features inventoried.

Figure 3: Distribution of the 2509 km of unpaved road length in the seven sub-watersheds and main stem of the Winooski River.

Figure 1: Conceptual diagram of road and stream networks, culverts, and connectivity of roads to streams.

Figure 2: Distribution of road length by slope position (left panel) and grade (right panel) for Winooski River watershed (top panels) and surveyed road segments (bottom panels).

Figure 3: Frequency of (left) n=1866 erosional features and (right) n=74 depositional features mapped on 52 surveyed road segments. X-axis on plots is number of features per kilometer of surveyed road.

Figure 4: Scatter plots of (left) erosional feature frequency and (right) length normalized erosion volume vs. mean road grade for road segments surveyed.

Figure 5: Mean values of length-normalized (a) erosional feature frequency and (b) erosion volume on surveyed road segments across the 7 sub-watersheds and the main stem of the Winooski River. Error bars are two standard errors of the mean.

Figure 6: Mean length-normalized erosion volume (from Figure 8b) vs. median watershed slope for seven tributaries and main stem of Winooski watershed.

Figure 7: Bulk density (a) and total phosphorus concentration (b) estimates for road surface and road side soils collected at eight locations across the Winooski watershed (see Figure 1 for site locations). First bar in watershed pair is valley floor site; second bar is midslope site. Bars are organized from downstream (on left) to upstream (on right) on the Winooski. Error bars on (a) are standard deviation of three measured samples. Samples were composited by site for analysis of total phosphorus on a single sample.

Figure 8: Summary of the distribution of the unpaved road network (left bar) and estimated mass of sediment eroded from unpaved roads (right bar) in the sub-watersheds and the main stem of the Winooski.

Figure 1

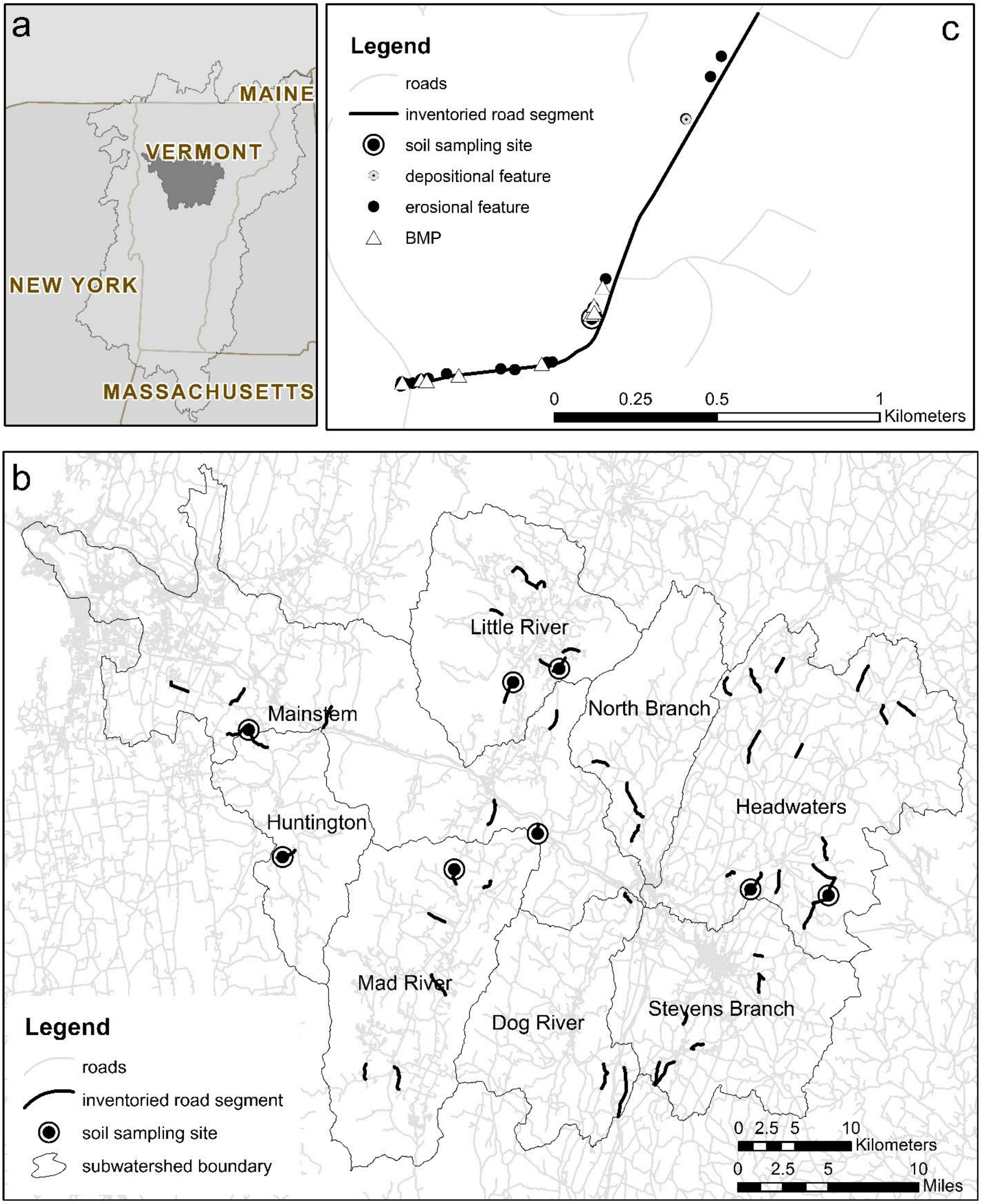

a
MAINE
VERMONT
NEW YORK
MASSACHUSETTS
c
Legend
roads
inventoried road segment
soil sampling site
depositional feature
erosional feature
BMP
0
0.25
0.5
1
Kilometers
b
Little River
Mainstem
North Branch
Headwaters
Huntington
Mad River
Dog River
Stevens Branch
Legend
roads
inventoried road segment
soil sampling site
subwatershed boundary
0 2.5 5 10
Kilometers
0 2.5 5 10
Miles

Figure 2

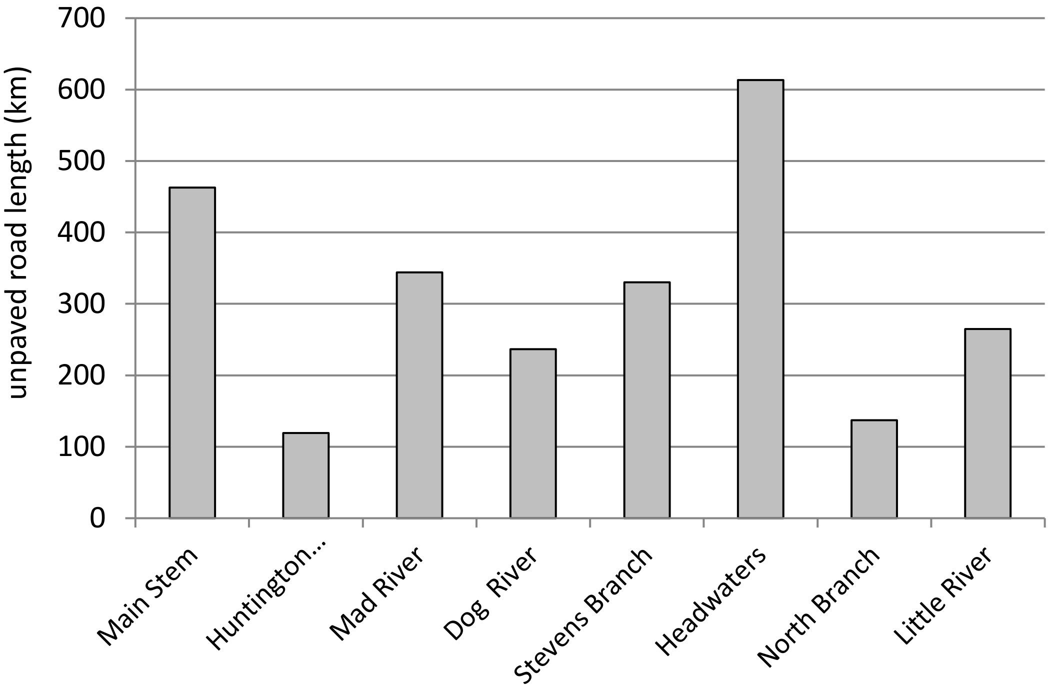

unpaved road length (km)
700
600
500
400
300
200
100
0
Main Stem
Huntington...
Mad River
Dog River
Stevens Branch
Headwaters
North Branch
Little River

Figure 3

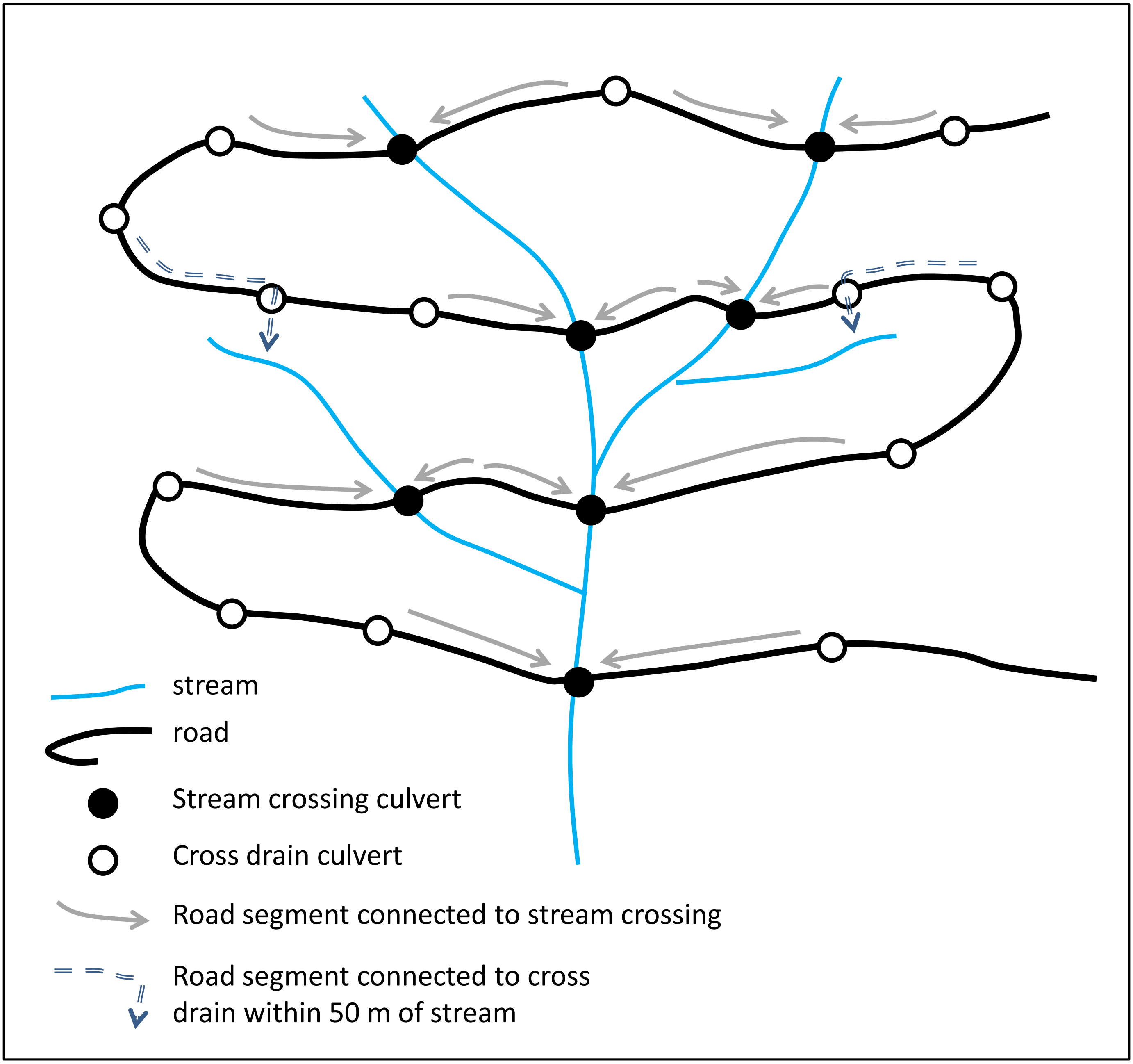

stream
road
Stream crossing culvert
Cross drain culvert
Road segment connected to stream crossing
Road segment connected to cross drain within 50 m of stream

Figure 4

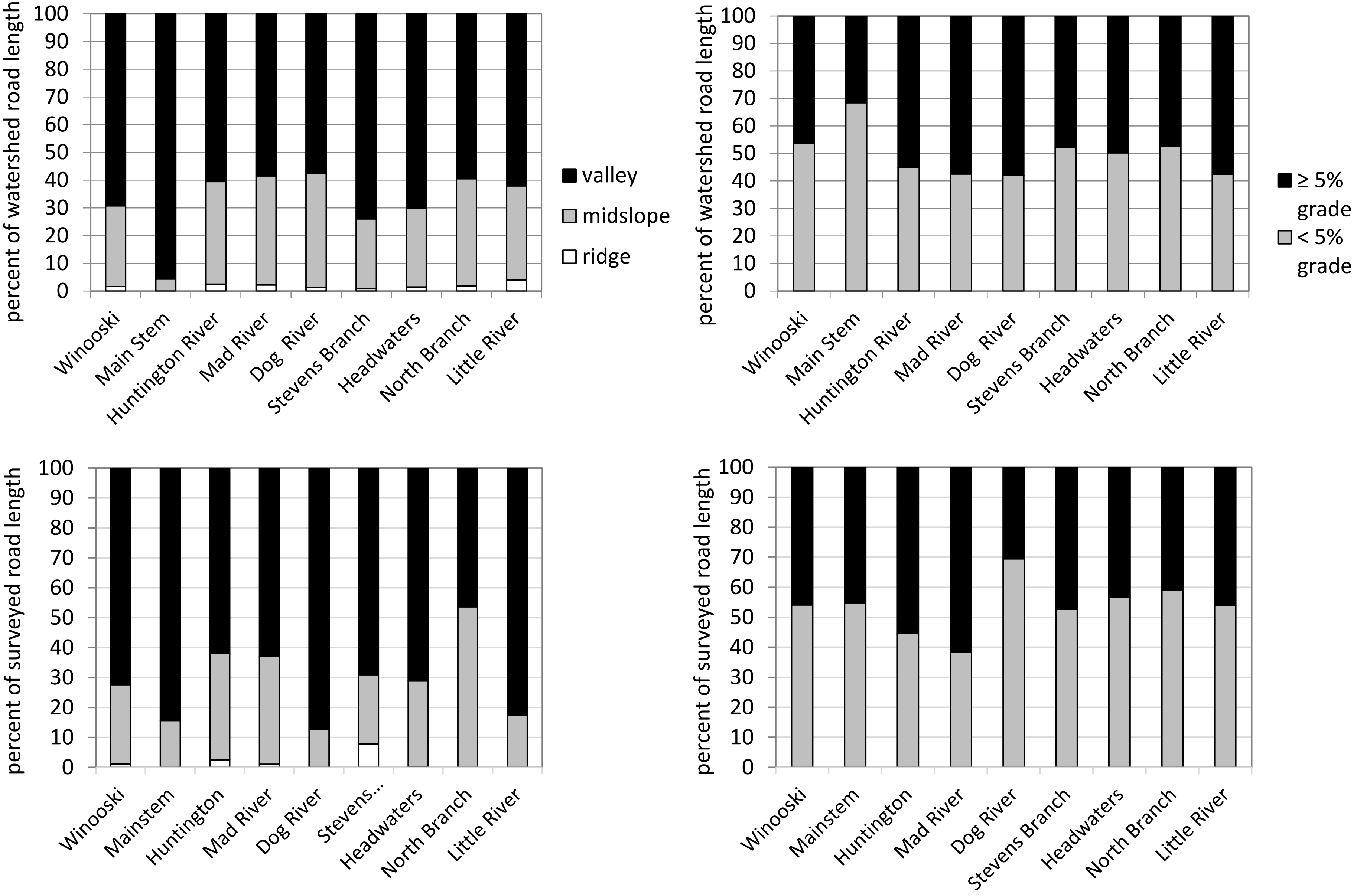
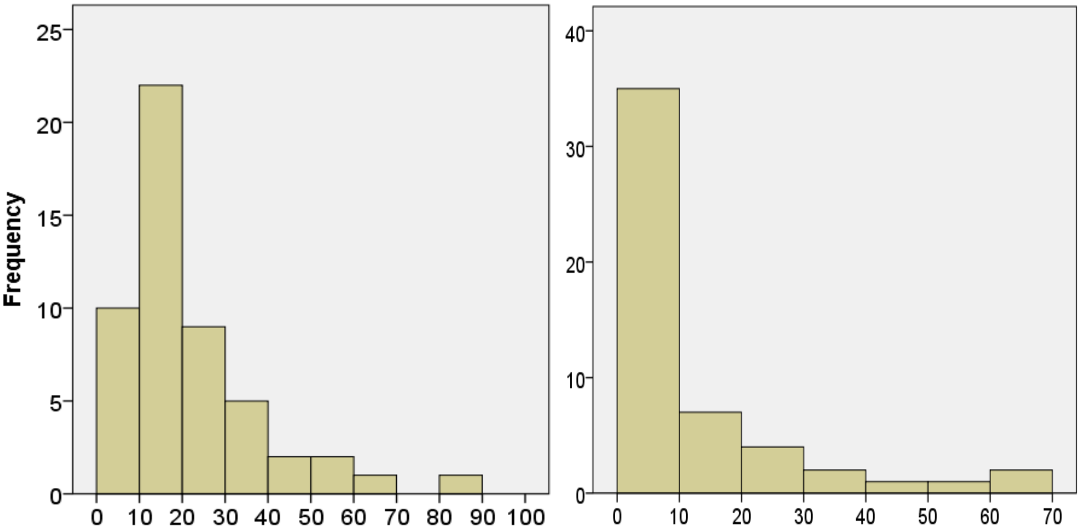

percent of watershed road length
100
90
80
70
60
50
40
30
20
10
0
Winooski
Main Stem
Huntington River
Mad River
Dog River
Stevens Branch
Headwaters
North Branch
Little River
■ valley
▨ midslope
☐ ridge
percent of watershed road length
■ ≥ 5% grade
▨ < 5% grade
percent of surveyed road length
Winooski
Mainstem
Huntington
Mad River
Dog River
Stevens…
Headwaters
North Branch
Little River
percent of surveyed road length
Winooski
Mainstem
Huntington
Mad River
Dog River
Stevens Branch
Headwaters
North Branch
Little River

Figure 5



Frequency
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100
40
30
20
10
0
0
10
20
30
40
50
60
70

Figure 6

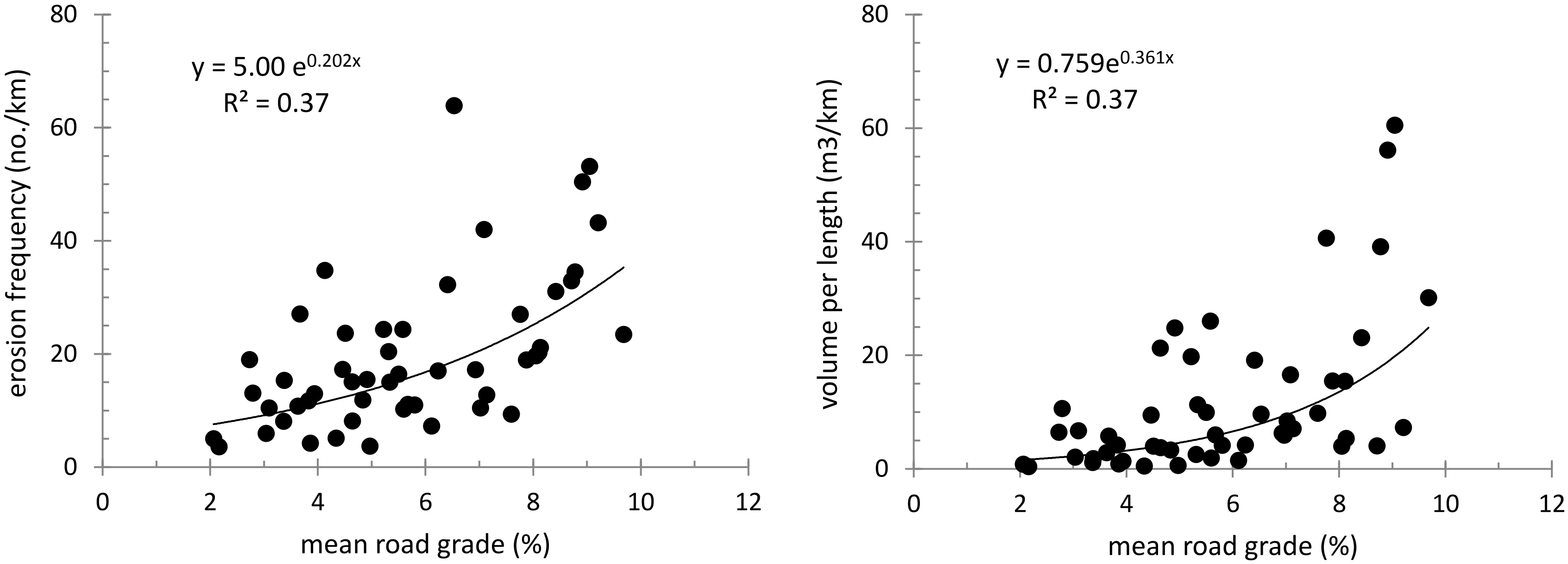

80
60
40
20
0
erosion frequency (no./km)
y = 5.00 e^0.202x
R² = 0.37
0
2
4
6
8
10
12
mean road grade (%)
80
60
40
20
0
volume per length (m3/km)
y = 0.759e^0.361x
R² = 0.37
0
2
4
6
8
10
12
mean road grade (%)

Figure 7

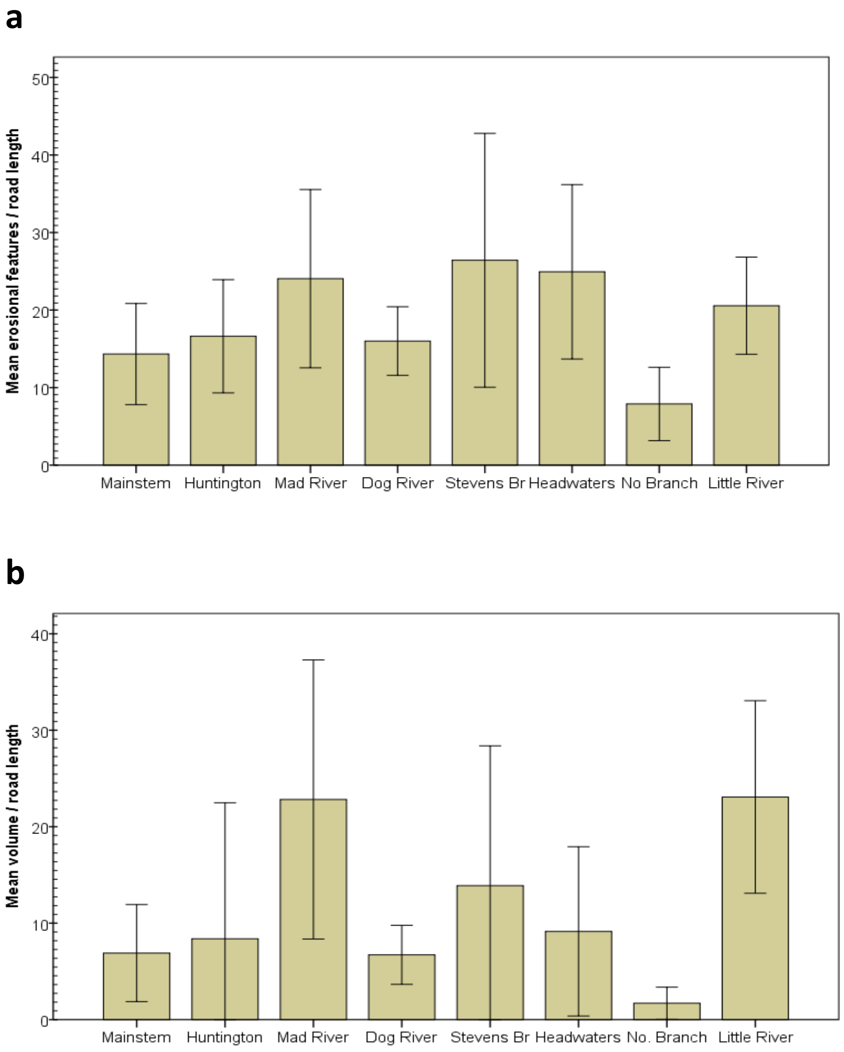
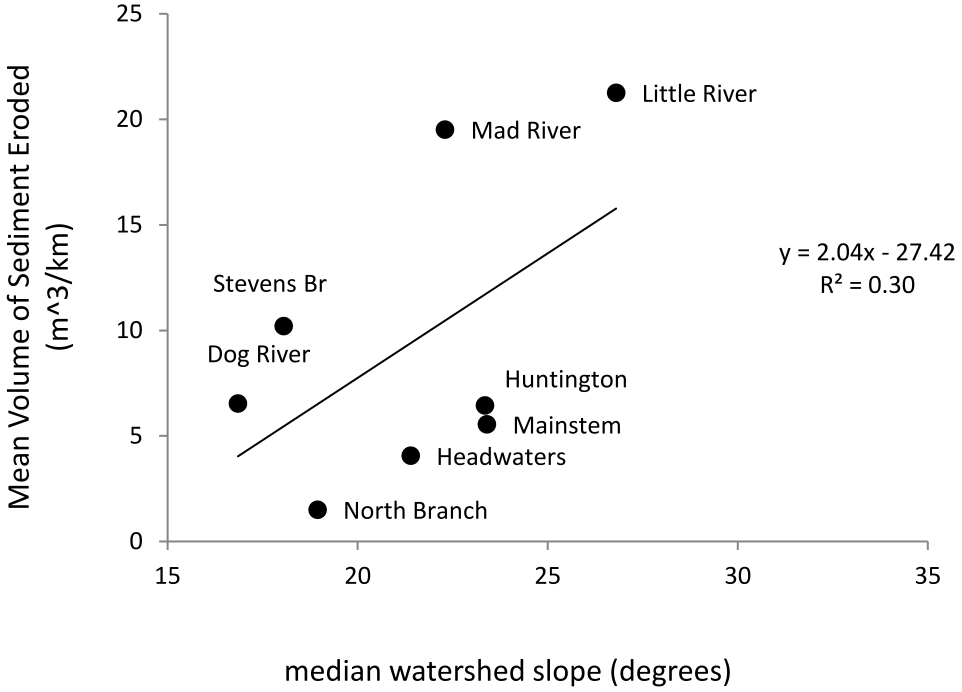

a
Mean erosional features / road length
0
10
20
30
40
50
Mainstem
Huntington
Mad River
Dog River
Stevens Br
Headwaters
No Branch
Little River
b
Mean volume / road length
0
10
20
30
40
Mainstem
Huntington
Mad River
Dog River
Stevens Br
Headwaters
No. Branch
Little River

Figure 8



25
20
15
10
5
0
15
20
25
30
35
Mean Volume of Sediment Eroded (m^3/km)
median watershed slope (degrees)
Little River
Mad River
Stevens Br
Dog River
Huntington
Mainstem
Headwaters
North Branch
y = 2.04x - 27.42
R² = 0.30

Figure 9

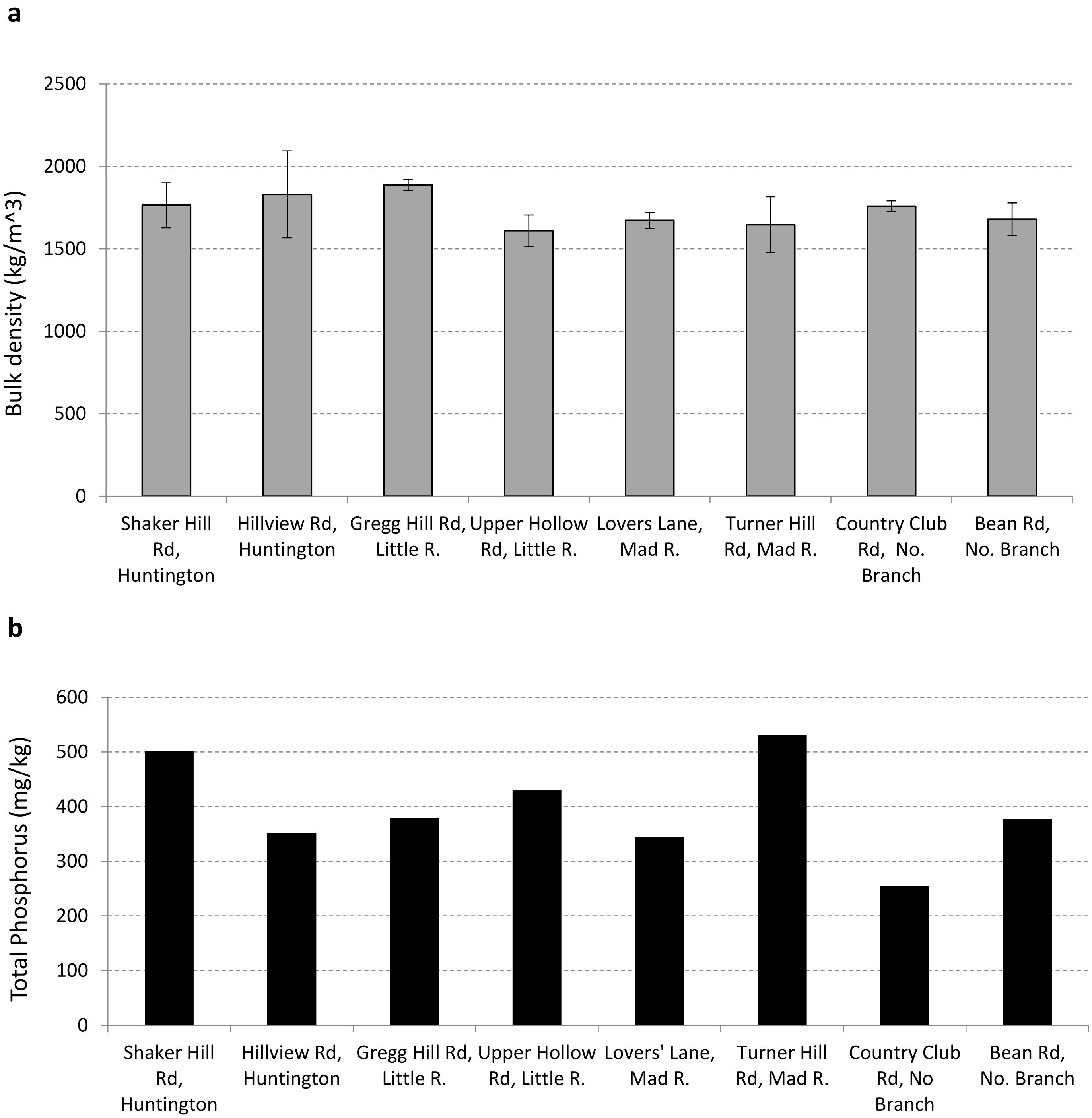

a
Bulk density (kg/m^3)
0
500
1000
1500
2000
2500
Shaker Hill Rd, Huntington
Hillview Rd, Huntington
Gregg Hill Rd, Little R.
Upper Hollow Rd, Little R.
Lovers Lane, Mad R.
Turner Hill Rd, Mad R.
Country Club Rd, No. Branch
Bean Rd, No. Branch
b
Total Phosphorus (mg/kg)
0
100
200
300
400
500
600
Shaker Hill Rd, Huntington
Hillview Rd, Huntington
Gregg Hill Rd, Little R.
Upper Hollow Rd, Little R.
Lovers' Lane, Mad R.
Turner Hill Rd, Mad R.
Country Club Rd, No Branch
Bean Rd, No. Branch

Figure 10

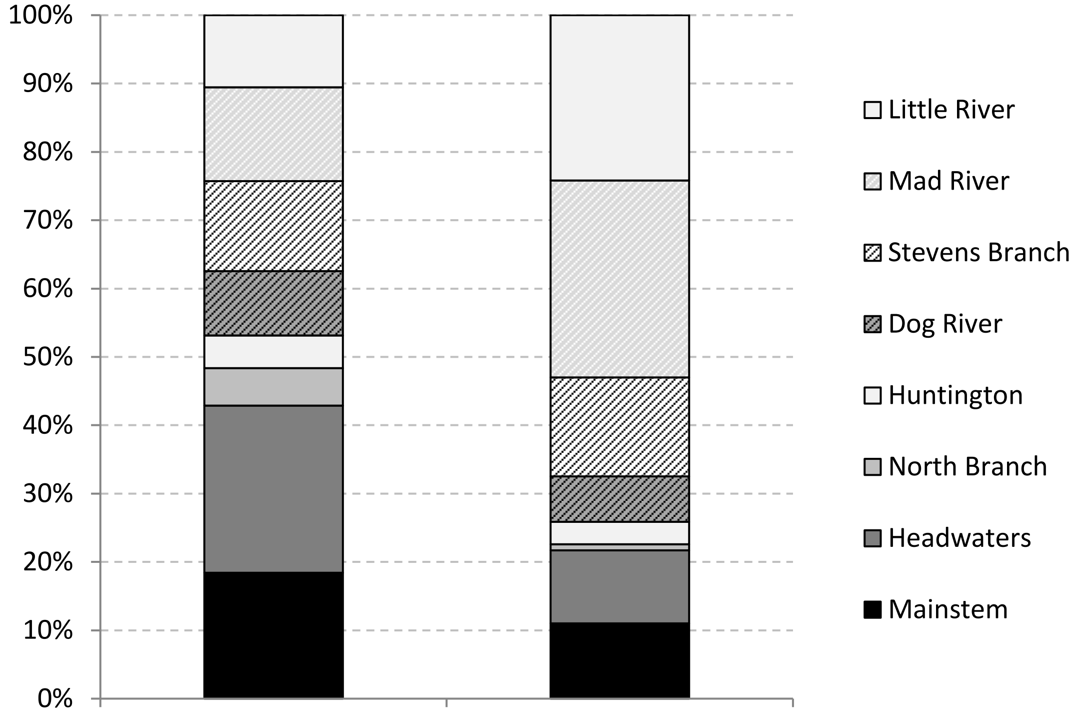

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Little River
Mad River
Stevens Branch
Dog River
Huntington
North Branch
Headwaters
Mainstem

Figure 11