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A multi-scale statistical approach to assess the effects of connectivity of road and stream networks on geomorphic channel condition

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ABSTRACT: Roads in rural, upland landscapes are important sources of runoff and sediment to waterways. The downstream effects of these sources should be related to the connectivity of roads to receiving waters. Recent studies have explored this idea, but only simple metrics have been used to characterize connectivity and few studies have quantified the downstream effects of road–stream connectivity on sediment or solute budgets and channel morphology. In this study, we evaluated traditional and newly developed connectivity metrics that utilized features of landscape position and delivery pathway to characterize road–stream connectivity in upland settings. Using data on stream geomorphic conditions developed by the Vermont Agency of Natural Resources (Montpelier, VT), we related road connectivity metrics to channel condition on a set of 101 forested, upland streams with minimal development other than predominantly gravel road networks. Logistic regression indicated that measures of road density, proximity and orientation successfully distinguished among categories of stream geomorphic condition at multiple geographic scales. Discriminant function analysis using a set of inherent channel characteristics combined with road connectivity metrics derived at the reach corridor scale successfully distinguished channel condition for over 70% of the channels evaluated. This research contributes to efforts to evaluate the cumulative downstream effects of roads on stream channels and aquatic resources and provides a new means of watershed assessment to derive metrics that can be used to predict channel condition. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: connectivity; road impacts; multiple scales; forested roads; fluvial geomorphology

Introduction

Roads are a conspicuous element of the landscape with increasingly recognized effects on a wide range of ecosystem processes (Formann and Alexander, 1998; Gucinski *et al.*, 2001; Bracken and Croke, 2007). 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 settings of humid, temperate landscapes where soil infiltration capacity typically exceeds precipitation rates, roads represent relatively impervious surfaces that generate overland flow and efficiently route it to receiving waters (Luce and Cundy, 1994; Ziegler and Giambelluca, 1997; Croke and Mockler, 2001; Arnáez *et al.*, 2004; Lane *et al.*, 2006; Jordán-López *et al.*, 2009; Buchanan *et al.*, 2012). When roads are constructed on steep slopes with shallow soils in mountainous terrain, subsurface flow can be intercepted along road cuts and ditches and redistributed as concentrated surface runoff (Megahan and Clayton, 1983; Wemple and Jones, 2003). Roads on steep slopes also pose a risk of shallow landslide initiation, producing sediment that can be delivered to downslope receiving waters (Montgomery, 1994; Borga *et al.*, 2005). Roads constructed alongside rivers can function to constrain lateral mobility of river channels and effectively disconnect rivers from their floodplains (Blanton and Marcus, 2009). Under some conditions, roads in valley floor settings have been shown to function as sediment traps, thereby disconnecting hill slope sediment sources from rivers (Wemple *et al.*, 2001; Poeppl *et al.*, 2012). Through these various mechanisms, roads generate water and sediment at levels significantly greater than the undisturbed or lightly disturbed terrain they occupy, effectively extend the natural channel network providing a direct conduit for water and pollutants to enter receiving waters (Jones *et al.*, 2000; Bracken and Croke, 2007) and modify river–floodplain dynamics.

The connectivity of the road drainage to the stream network determines the efficiency with which road-generated runoff and water quality contaminants reach receiving waters (Bracken and Croke, 2007). Previous studies provide empirical evidence that connectivity between road and stream networks is related to the topographic setting of individual road segments (Montgomery, 1994; Wemple *et al.*, 2001) and to the nature of the delivery pathway at road drainage outlets (Wemple *et al.*, 1996; Croke and Mockler, 2001; Hairsine *et al.*, 2002; Lane *et al.*, 2006). Various studies have quantified direct road–stream connectivity through field surveys of drainage outlets on rural road networks (Wemple *et al.*, 1996; Croke and Mockler, 2001; Buchanan *et al.*, 2012), although little effort to date has been given to developing metrics that characterize road network density, proximity, and orientation or the extent to which these geometric properties effectively predict downstream water quality or channel morphological condition. In this study, we developed and assessed a new set of connectivity metrics applicable to rural road networks and tested the efficacy of these metrics in predicting the geomorphic condition of downstream channels at multiple spatial scales. Our goal was to discriminate among channels in various stages of geomorphic adjustment in response to the road network within their watersheds.

Study Area and Vermont Geomorphic Assessments

River reaches evaluated in this study were broadly distributed across the state of Vermont (24 923 km^2) located in the northeastern United States (Figure 1). Vermont is characterized by mountainous, previously-glaciated terrain and a humid continental climate. Elevations range from a maximum of 1340 m above sea level (a.s.l.) (4395 ft) in the Northern Green Mountains to a minimum of 29 m a.s.l. (95 ft) at Lake Champlain, the sixth-largest freshwater body in the United States by volume. Average annual precipitation ranges from more than 178 cm (70 in.) in the mountains to 76 cm (30 in.) in the lowlands. Surface waters of Vermont drain east to the Connecticut River, north and west to the St Lawrence River (mostly via Lake Champlain), and southwest to the Hudson River. Land cover is predominantly rural, consisting of 73% forest, 13% agriculture, and 6% developed (Homer *et al.*, 2004).

Selection of study reaches

Study reaches were selected to address the effects of roads on streams, independent of other anthropogenic influences. To that end, a geographic information system (GIS)-based selection process was employed that leveraged stream geomorphic assessment data developed by the Vermont Agency of Natural Resources (VTANR) (Kline *et al.*, 2007; Kline and Cahoon, 2010). To isolate reaches where human impacts on channel condition could be attributed primarily to road and driveway networks in forested areas, the study was restricted to river and stream reaches with at least 75% forest cover and without channel margin development. Reaches with impoundments (e.g. dams and other diversions related to flow control),

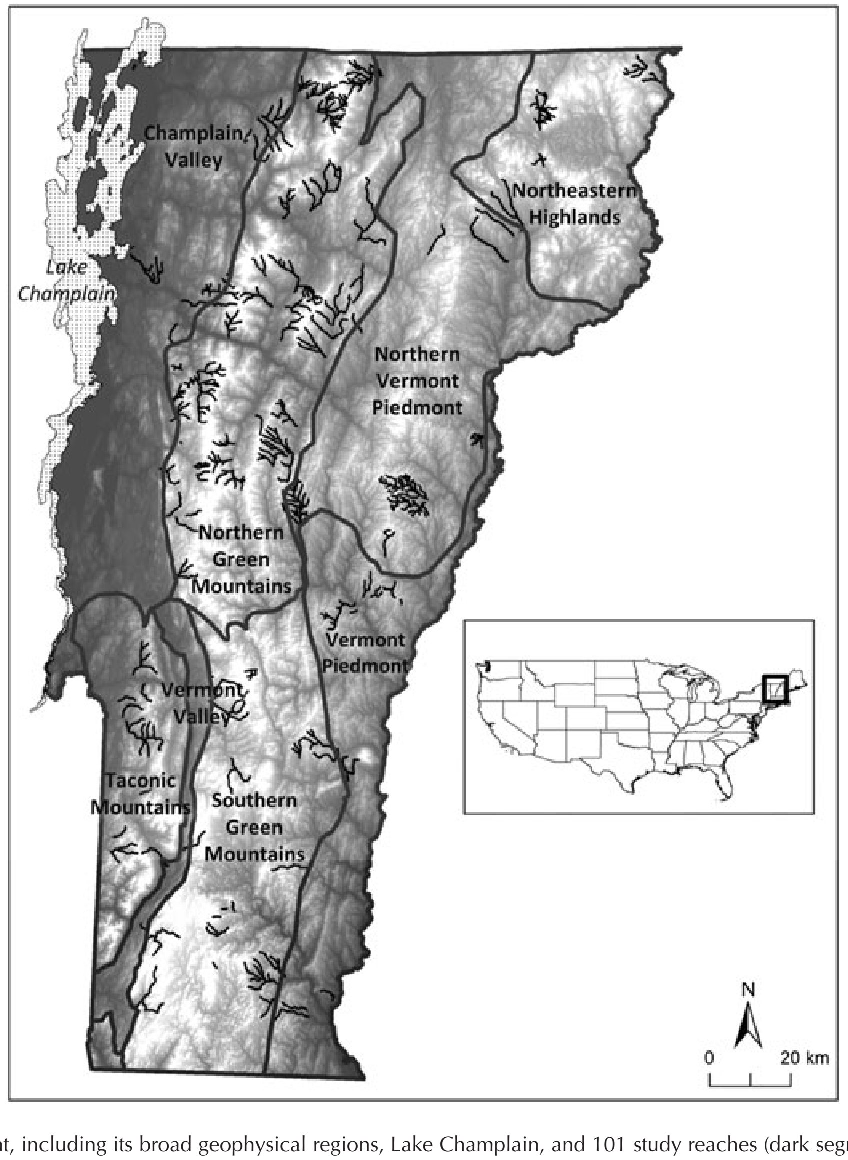

Figure 1. State of Vermont, including its broad geophysical regions, Lake Champlain, and 101 study reaches (dark segments).

railroads, a history of dredging, or more than 10% development (residential, commercial, industrial, etc.) over their length were also excluded, resulting in 101 study reaches.

Geomorphic assessment

The VTANR River Management Program (RMP) has developed stream geomorphic assessment data for more than 2850 km (1800 miles) of river over the past decade (Kline *et al.*, 2007; Kline and Cahoon, 2010). VTANR stream assessment protocols are peer-reviewed (Somerville and Pruitt, 2004; Besaw *et al.*, 2009) and assimilate components of several fluvial geomorphic classification systems and measurement techniques, including those of Montgomery and Buffington (1997), Rosgen (1994), Schumm (1977), Schumm *et al.* (1984), Simon and Hupp (1986), and Simon (1989). Fluvial geomorphic assessments are conducted by trained practitioners following a quality assurance plan and are used to support river management goals of reducing flood hazards, and improving water quality and aquatic habitats (Kline and Cahoon, 2010).

The VTANR protocols are designed to evaluate and quantify an individual stream segment's degree of departure from an expected reference condition and its likelihood for future adjustment. Stream networks are delineated into segments of relatively uniform slope, valley confinement (VC) and sinuosity for further evaluation based on available remote-sensing resources (hydrography, topography, geology) and limited field observations. Segment lengths are generally a minimum of 20 channel widths. A reference stream type is assigned, which is a hybrid of the Rosgen (1994) and Montgomery and Buffington (1997) classification systems. The stream type describes the VC, slope, dominant bed material, and dominant bedform that would be expected in the reference condition, given the geologic and topographic setting. Field-based assessment is then carried out to verify (or revise) the provisional reference stream type and to characterize the existing condition of the channel and degree of departure from reference condition.

A rapid geomorphic assessment (RGA) score is calculated for each segment to quantify the degree of departure from reference condition. The overall RGA index is a combination of individual scores for four primary channel adjustment processes: vertical adjustments including (1) degradation (DEG) and (2) aggradation (AGG), and lateral adjustments including (3) widening (WID) and (4) planform (PLAN) (e.g. meander migration, braiding, and/or avulsions). Each adjustment score is generated from a combination of quantitative metrics (e.g. width/depth ratio, incision ratio) and qualitative observations (e.g. headcuts, tributary rejuvenation, frequency and height of depositional bars, embeddedness, flood chutes), and integrates to a limited degree the human and natural stressors that may have led to the channel adjustment process(es). Each adjustment score is rated as 'Poor' (1–5), 'Fair' (6–10), 'Good' (11–15) or 'Reference' (16–0). The overall RGA score is then computed as the sum of the four adjustment scores and normalized to a value between zero and one. The normalized RGA score is then itself classified into non-equal categories of 'Poor' (0.00–0.34), 'Fair' (0.35–0.64), 'Good' (0.65–0.84) or 'Reference' (0.85–1.0). The temporal scale of each adjustment process is also described as either active (recent) or historic, with 'historic' defined in the protocols as occurring within the last 200 years (Kline *et al.*, 2007). A poor adjustment score is designed to reflect only an active adjustment process that is occurring as the net result of historic and/or recent stressors impacting the channel/floodplain/upstream catchment. To rank in the 'Poor' quadrant of the overall adjustment score for Aggradation, Widening, or Planform Adjustment, the process must be actively (or very recently) occurring. For degradation, however, the reach can be ranked in the Poor quadrant solely as a result of historic incision – as well as active incision, or a combination of both. The protocols do not as yet include reliable means for discerning between post-glacial incision (occurring over the last 12 000 years) and incision during colonial times (occurring over the last 200 years). As such, there is the potential for incision classified as 'historic' to include some degree of adjustment that occurred during post-glacial periods (e.g. incision as a result of isostatic rebound or base-level changes caused by draining of pro-glacial lakes as described in Brackenridge *et al.* [1988]). Examples of reaches classified overall as 'Reference' and 'Poor' are provided in Figure 2.

To address the continuum of reference stream types present in the Vermont landscape, the protocols contain three separate categories of RGA forms defined for different valley settings including ranges of VC (defined as the ratio of valley width to bankfull channel width). These include: (a) confined channels ($VC < 4$ and valley gradients $> 2\%$; typically, cascade, step-pool channels), (b) unconfined channels ($VC \geq 4$; typically, riffle-pool or dune-ripple channels), and (c) plane-bed channels ($VC \geq 3$ and ≤ 5) often found in transfer zones (Kline *et al.*, 2007). The scoring parameters and metric ranges are somewhat different for each set of forms. In this manner, the interpretation of the dominant process of adjustment is stratified by stream type and accounts for the landscape context (Schumm, 1985; Montgomery and MacDonald, 2002).

Methods

We used a statistical approach to relate measures of inherent stream and landscape condition, geomorphic stressors, and

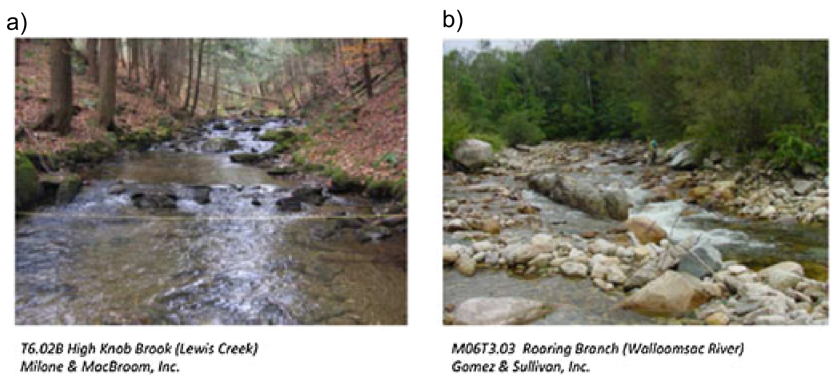

Figure 2. Sample reaches classified according to the VTANR stream assessment protocols with an RGA rating of (a) Reference (confined, gravel-dominated, step-pool channel undergoing minimal adjustment) and (b) Poor (unconfined, cobble-dominated, braided channel undergoing active aggradation, widening, and planform adjustment in response to historic degradation). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

road network metrics to channel condition, with the latter being captured in the Vermont stream geomorphic assessments. The stream network used to generate these metrics, which included the delineated main stem and principal tributaries of the study reaches, was provided by the RMP or derived from the 1:5000 Vermont Hydrography Data (VHD) available through the Vermont Center for Geographic Information (VCGI, http://vcgi.vermont.gov). To characterize the road network, we employed both traditional metrics that capture elements of network *density* (after Flanagan *et al.*, 1998, Jones *et al.*, 2000), as well as newly developed metrics based on road *proximity* and *orientation* to streams. The road network data layer was created by merging two comprehensive statewide layers, maintained for emergency management purposes by the state E911 Board and made available through the VCGI. The roads data layer includes interstate highways, state, town and private roads and driveways, with over 80% of the road length within the state and within the catchments and corridors we analyzed falling into only four groups – class 2 and 3 town roads, driveways and private roads (Table I). Only class 2 town highways and some driveways tend to be paved; the remainder are unpaved gravel or native surface roads.

Scales of investigation

Road network metrics were calculated for each of our 101 study reaches within four geographic scales or regions of influence. In so doing, we were able to distinguish the area directly proximal to the channel (i.e. the riparian zone or 'corridor') and the upslope catchment area that drains to the channel (i.e. reach direct drainage and catchment), as well as the river system at two scales: the targeted study reach, and the reach with its upstream channel network (Figure 3). The corridor was defined by the RMP as three channel (bankfull) widths buffered on either side of the centerline (Kline *et al.*, 2007). The four geographic scales were defined as follows:

- *Reach Corridor* (*ReachCorr*) includes the land area directly adjacent to the study reach.
- *Total Network Corridor* (*NetworkCorr*) includes the reach corridor plus the land area directly adjacent to the total stream network draining into the study reach.
- *Reach Direct Drainage* (*ReachDD*) is the land area that drains directly to the study reach, excluding land areas that drain to upstream reaches.
- *Catchment* (*Catch*) includes all direct and upstream land area draining to the study reach.

Inherent stream or landscape metrics and independent stressors

To test the hypothesis that stream geomorphic condition for the selected channel reaches could be predicted based on channel characteristics, landscape features, or stressors independent of the road network, we developed a set of what we term *inherent* metrics for each reach included in the study. These inherent metrics included a measure of channel gradient (*slope*) for the assessed reach, an indicator of VC, the *dominant streambed material*, an indicator of *parent material* that distinguishes between cohesive and non-cohesive materials, the *physiographic province* in which the reach is located, the dominant *landuse/landcover*, and an indicator variable for whether the reach has been exposed to an extreme *flood* in the decade prior to the conduct of the geomorphic assessment (Table II). Variable values for slope, confinement, dominant streambed material, and parent material were extracted from the database for the stream geomorphic assessments. The remaining variables were derived through GIS overlays of the channel corridor and catchment with data layers available through VCGI or in a recent report and associated data layer on historical flooding in Vermont (Cahoon and Copans, 2013).

Road metrics

To test the role of roads as a predictor of stream geomorphic condition, after accounting for inherent channel and landscape

Table I. Road length by class as mapped in spatial data layers available through Vermont Center for Geographic Information (VCGI) (vcgi.vermont.gov)

Road class [a]	Class description	Within state		Within catchment for assessed reaches		Within corridor for assessed reaches	
		(km)	(%)	(km)	(%)	(km)	(%)
0	Driveways	11903	28	1123	27	114	27
1	Class 1 town highway, undivided	233	1	2	0	0	0
2	Class 2 town highway, undivided	4123	10	438	11	32	8
3	Class 3 town highway, undivided	14266	34	1405	34	163	39
4	Class 4 town highway, undivided	2076	5	349	8	24	6
5	State forest highway	212	1	19	0	0	0
6	National forest highway	168	0	34	1	0	0
7	Legal trail	245	1	45	1	6	1
8–9	Private road	4125	10	377	9	37	9
30–49	State highway	2823	7	266	6	24	6
40–49	US highway	984	2	21	1	2	0
50–59	Interstate highway	1142	3	62	2	13	3
83–99	Other [b]	93	0	6	0	0	0
	Total	42393		4147		416	

Note: Columns show length and percentages by class for state of Vermont and within catchments and stream corridors (see text for definitions) for assessed reaches used in this study.
[a]Road class code given in spatial data layers available through VCGI data portal. Code ranges summarized for subclasses equaling < 10% of network. Classification of town highways is based on distinctions in jurisdiction and maintenance levels, as mandated by state statute and described in http://vtransoperations.vermont.gov/sites/aot_operations/files/documents/AOT-OPS_OrangeBook.pdf
[b]Includes segments coded as *new*, *unknown*, and *proposed*.

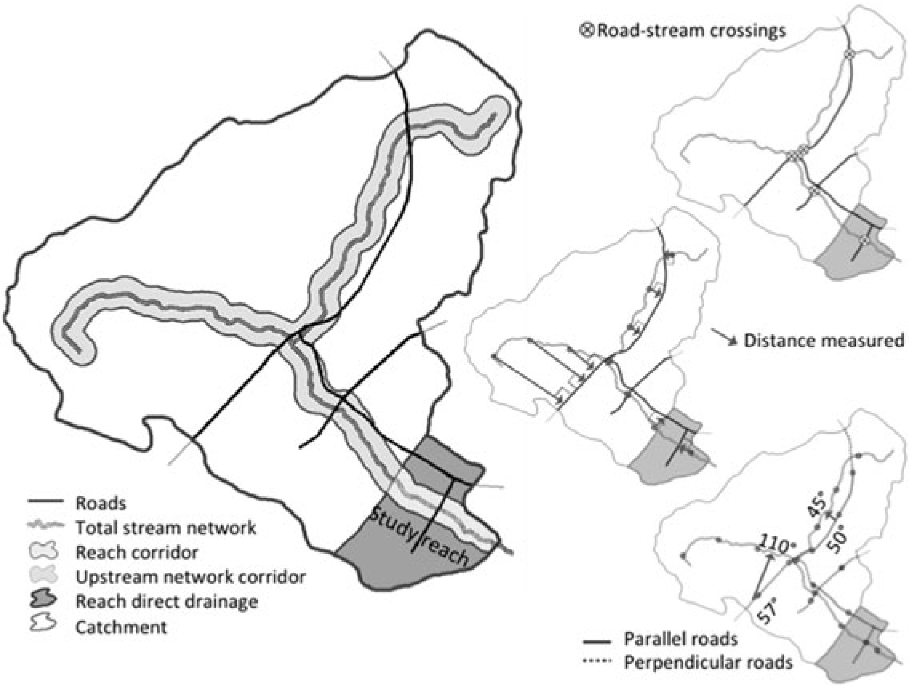

Figure 3. Conceptual diagram for a stream and road network delineates the extents of the four geographic regions evaluated in this study (*Reach Corridor, Total (reach plus upstream) Network Corridor, Reach Direct Drainage, Catchment*). Inset diagrams at right illustrate road and stream features on which density, proximity and orientation metrics were based, including points along road and stream network segmented at 50 m intervals (circles) and vectors identifying distances between road segments and stream segments.

Table II. Inherent stream and landscape metrics used as independent variables to test for differences in stream geomorphic condition for 101 study reaches using logistic regression analysis

Variable	Metric	Type	*p*-Value
Slope	Average channel slope along reach length	Continuous	*0.0004*
Confinement	Indicator for valley width (yes if more than four times channel width)	Binary	*0.0056*
Dominant bed material	Sand, gravel, cobble, boulder, bedrock	Nominal	0.1355
Parent material	Cohesive versus non-cohesive	Binary	*0.0118*
Floods	At least one event between 1992 and 2002, inclusive	Binary	0.9563
Physiographic province	Valley, north-eastern highlands, piedmont, mountains	Nominal	0.8232
Landuse/landcover in reach corridor	Dominant class is forest (versus agricultural or urban)	Binary	*0.0116*

Note: *p*-values for statistically significant predictors of geomorphic condition are in italic typeface.

characteristics, along with hypothesized stressors, we developed a set of metrics using GIS data for the road and stream networks. Three existing road metrics were selected to quantify road network density. *Roads Present* is a binary variable used only to indicate the presence or absence of roads at a given geographic scale, while *Road Density* was defined as the total length of roads present, divided by the area of that region. Road crossing density (*RoadXStream_km*^{2}) is the number of road-stream crossings, normalized by the area of the region. Each of these metrics was calculated for each of the four geographic scales described earlier.

In addition, new metrics were developed based on the *Proximity* of roads to adjacent streams and their *Orientation* (parallel versus perpendicular) with respect to streams, each derived at each of the four geographic scales. These metrics were defined to clarify the connectivity of the road and stream networks and to capture elements of the mechanisms by which roads alter the routing of water and sediment. For example, roads proximal to the channel might effectively transport road water and sediment to receiving waters (e.g. Buchanan *et al.*, 2012), and roads distant from the riparian corridor and above the threshold for channel initiation might effectively extend the channel network through shallow land sliding and initiation of new channelized flow paths (e.g. Montgomery, 1994). Similarly, roads oriented parallel to streams, especially in mid-slope positions, might effectively intercept subsurface flow (e.g. Wemple and Jones, 2003) thereby modifying undisturbed flow paths, while roads oriented perpendicular to the stream network might effectively increase drainage density (Wemple *et al.*, 1996; e.g. Croke and Mockler, 2001).

Two *Proximity* metrics were defined to characterize the distance from a stream to its nearest road(s) (Figure 3). A point layer was created at 50 m intervals along the centerline of the stream. The first metric (*Proximity Sum*) was calculated as the sum of the stream-to-nearest-road distances normalized by the stream length, where the distances between stream points and roads were defined normal to the road. The second metric (*RoadXStream_m*) was defined as the number of road crossings normalized by the total length of the study reach or total network corridor, depending upon the geographic scale of the analysis. This additional approach for normalizing the tally of road–stream crossings was introduced in order to more directly consider the impact of crossings upon the reach, irrespective of the land area draining to that reach.

Six *Orientation* metrics were also developed to assess the effects of roads oriented parallel or perpendicular to the 101 study sites. The 50 m stream segmentation developed for the *Proximity* metrics was retained. In addition, all roads within the region were segmented at 50 m intervals. We then paired each road segment to its nearest stream segment and calculated the bearing or orientation of each segment (both stream and road) (Figure 3). The distances between these segments were recorded, and the orientations of each pair of segments (road, stream) were compared. If the difference between orientations was between 45° and 135°, the road segment was considered perpendicular to the stream segment. Conversely, if the difference between paired orientations was less than 45° or greater than 135° degrees, the road segment was considered parallel to the stream. The resulting *Orientation* metrics computed from these measures for each study reach and geographic scale are:

- *Sum Parallel* – sum of the paired road-to-stream distances, normalized by stream length. Includes only those road segments *parallel* to their nearest stream segment.
- *Mean Parallel* – arithmetic mean of the paired road-to-stream distances.
- *Percent Parallel* – percentage of roads within the geographic scale *parallel* to the stream.
- *Sum Perpendicular* – sum of the paired road-to-stream distances, normalized by stream length. Includes only those road segments *perpendicular* to their nearest stream segment.
- *Mean Perpendicular* – arithmetic mean of the paired road-to-stream distances.
- *Percent Perpendicular* – percentage of roads within the geographic scale *perpendicular* to the stream.

Statistical analyses

As a first step, ordinal logistic regression was used to identify factors associated with RGA as recorded by the VTANR assessments for the reaches we selected. We first used logistic regression to test whether inherent characteristics or hypothesized stressors (collectively termed *Inherent* here) could explain RGA scores of study reaches. We then used logistic regression to identify road metrics with relative significance and impact on the variation of the four fluvial adjustment categorical response variables (AGG, DEG, WID, PLAN) and the overall geomorphic (RGA) score at each geographic scale of observation. Unlike multivariate analysis techniques, logistic regression is robust to assumptions of normality, can be used with continuous and categorical data, and can accommodate more than two categorical outcomes (Chao-Ying *et al.*, 2002).

Next, we used discriminant analysis (DA) to examine combinations of all candidate metrics to determine their effectiveness in discriminating among RGA stream classes ('Poor-Fair', 'Good', 'Reference'). DA is designed to (1) test the significance of a set of discriminant functions (computationally identical to multivariate analysis of variance [MANOVA], but with the groups as dependent variables), and (2) classify a new observation using the values of its predictor variables (Poulsen and French, 2008). Canonical scores calculated during the analysis were used to identify meaningful metrics, and gauge their relative worth in discriminating between known classes. The value of N varies by analysis. For example, only 46 study sites have reach corridors containing both parallel AND perpendicular roads (Table III). Only four of the 101 study reaches were assessed as being in poor condition; as a result, the two RGA categories Poor and Fair were lumped into one class (Poor-Fair).

Table III. Contingency table showing counts from discriminant analysis for *RGA* classification using combined *Inherent* and *Orientation* metrics as inputs at the *Reach Corridor* scale ($N = 46$)

	Predictions		
Actual	Poor-fair	Good	Reference
Poor-fair	*17*	8	2
Good	3	*12*	0
Reference	0	0	*4*

Note: By definition, this particular analysis includes only those 46 study sites whose reach corridors include the presence of both parallel AND perpendicular roads.

Ideally, DA would involve every possible combination of metrics, in our case a total of $2^{15} - 1$, or 32 767 combinations. For practical purposes, we confined our investigation to all metric combinations by category (*Inherent*, *Density*, *Proximity*, *Orientation*). For example, a DA that uses both the *Proximity* and *Orientation* metrics as predictor variables would include the two *Proximity* metrics and all six *Orientation* metrics identified by logistic regression as statistically significant. This yields 14 category combinations, including each individual metric group (*Inherent*, *Density*, *Proximity*, or *Orientation*), and all possible pair-wise and three-way combinations. DA returns a classification matrix (contingency table) reflecting how well the chosen input predictor metrics collectively differentiate among the stream RGA response categories (Poor-Fair, Good, Reference). We illustrate the ability of DA to predict the correct RGA class with the contingency table (Table III) generated using the *Inherent* and *Orientation* metrics (as computed for the *ReachCorr* scale). Rows represent the actual class membership of the study reaches, while columns represent their classification as determined by the DA. Ideally, every element on the diagonal would be populated with positive integers, with all off-diagonal values at zero. In this example, overall classification accuracy (33/46) was 71.7%.

All statistical analyses were conducted using JMP Pro 11.0.0 (SAS Institute Inc., Cary, NC, 2013). Geospatial analyses were performed using ArcGIS 10 (ESRI, Redlands, CA, 2010), with additional data preparation handled by MATLAB R2013a (The Mathworks, Natick, MA, 2013).

Results

The selection process utilized in this study to identify assessed reaches offered the unique opportunity to evaluate the impacts of road networks on downstream channel geomorphology nearly exclusive of other anthropogenic influences and resulted in a total of 101 independent reaches (Figure 4, Table IV) from the 2300+ reaches field-assessed as of March 2010. In general, most study reaches were located in upland watersheds (drainage areas ≤ 130 km^2), along the spine of the Green Mountains and the Taconic Range that trend from north to south in the western half of the state and along the Vermont Piedmont, running north – south in the eastern half of the state.

Based on their overall RGA score, 12% of the study reaches were in Reference condition, 39% in Good, and 49% in Poor or Fair condition (Figure 4). Of the four adjustment processes, Degradation scores were the most broadly distributed across all geomorphic categories, with the largest representation of both Poor ($n = 10$) and Reference ($n = 33$) reaches. For the remaining adjustment processes, most reaches were categorized as being in Good geomorphic condition.

Among the reaches included in our study, key variables emerged as inherent controls or stressors on stream geomorphic

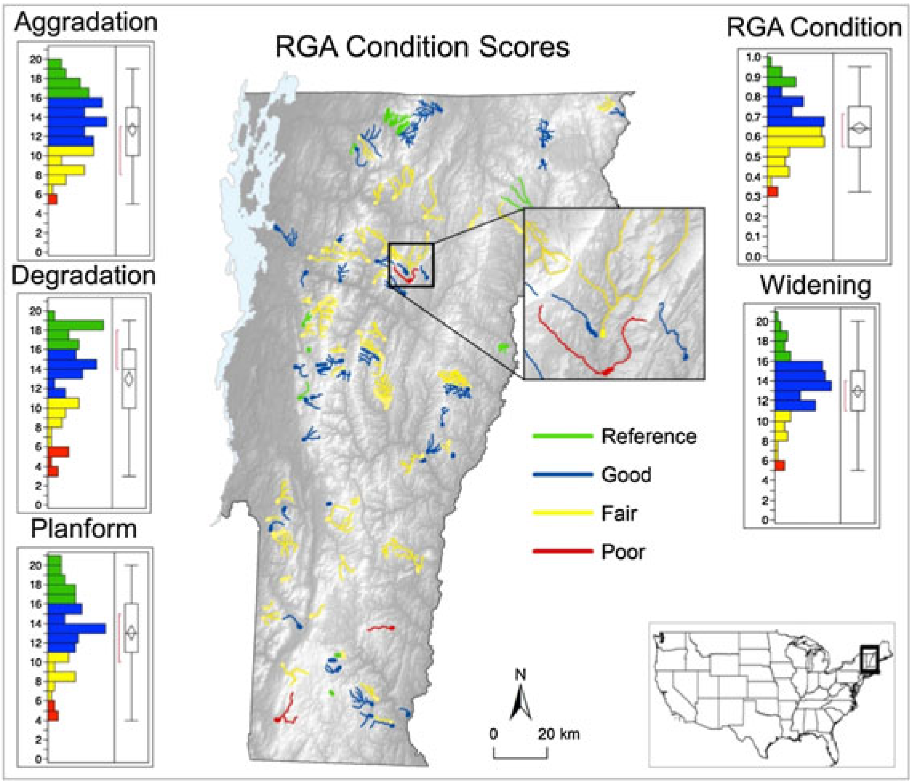

Figure 4. Distribution of reach-scale rapid geomorphic assessment (RGA) and fluvial adjustment process scores across the 101 study reaches. The encoding of the reaches matches that of the histograms. The outlier box plots represent the median (horizontal line within the box), the mean (95% confidence diamond), the first and third quartiles (upper and lower box boundaries), and 1.5 times the interquartile range (whiskers). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Table IV. Site characterization for the 101 study reaches and their drainage areas at the subwatershed (*Direct Drainage*) and stream network (*Catchment*) scales

Characteristics	Reach direct drainage		Catchment
Drainage area (km^2)	0.01 to 28.7 (2.33 ± 4.34)		0.4 to 128.6 (30.6 ± 26.5)
Channel length (m)	84 to 7943 (1292 ± 1443)		707 to 63215 (16537 ± 13249)
Road area (%) (percent of drainage area impervious due to roads)	0 to 26.8 (6.1 ± 4.7)		0 to 12.0 (3.5 ± 1.8)
Channel slope (%) (Catch slope = Main stem)	0.01 to 30.3 (2.9 ± 3.7)		0.6 to 30.3 (5.0 ± 3.7)
Channel elevation (m a.s.l.)			
Downstream reach point	141 (251 ± 103)		141 (251 ± 103)
Upstream reach point	994 (279 ± 128)		1079 (634 ± 197)
Average landuse/landcover (%):			
Forest	79.8 ± 18.2		89.0 ± 6.7
Agriculture	9.4 ± 11.5		5.3 ± 4.5
Developed	2.0 ± 5.6		0.5 ± 0.7
Confinement status (% of study sites)	Unconfined	63 %	NA
	Confined	37 %	
Parent material (% of study sites)	Cohesive	33 %	NA
	Non-cohesive	67 %	
Dominant landuse/landcover in the reach corridor (% of study sites)	Forest	86 %	NA
	Agriculture	12 %	
	Developed	2 %	
Dominant bed material (% of study sites)	Sand	7 %	NA
	Gravel	52 %	
	Cobble	38 %	
	Boulder	1 %	
	Bedrock	2 %	

Note: NA, not available.

condition. Logistic regression analyses indicated that *reach slope*, *confinement*, and *parent material* were all significant factors in differentiating the overall geomorphic condition of the study reaches (Table II). In general, low gradient (<2%) reaches were more commonly rated as fair, whereas high gradient (≥2%) reaches were more commonly rated as Reference (Figure 5a). Similarly, unconfined streams were more commonly rated as Fair or Good, whereas confined streams were more commonly rated as Reference (Figure 5b). In addition to these inherent characteristics of assessed reaches, landuse/landcover in the corridor of the assessed reach was also a significant predictor of reach geomorphic condition. There

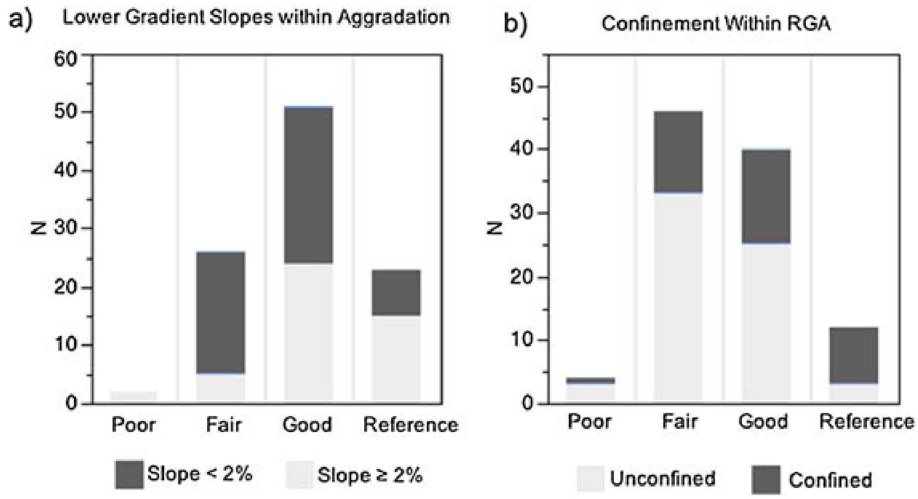

Figure 5. Relationship between (a) Aggradation scores and slope and (b) RGA scores and confinement.

was no statistical evidence that the geomorphic condition of reaches included in this study differed by dominant bed material, region (or physiographic province) of the state, or exposure to extreme floods in the decade prior to conduct of the assessment (Table II).

Road densities (in km/km^2) associated with the assessed reaches ranged from a maximum of 18.8 within the reach corridor (*ReachCorr*) scale to a minimum of 4.5 within the total catchment (*Catch*). The number of road–stream crossings ranged from zero to seven for the study reaches and zero to 61 for the total (reach plus upstream) river networks. Within each geographic scale, there were regions without roads: *ReachCorr* ($n = 27$), *ReachDD* ($n = 3$), *NetworkCorr* ($n = 7$), and *Catch* ($n = 2$). The mean impervious surface area was 6.1% ± 4.7% at the reach direct drainage scale, and 3.5% ± 1.8% at the catchment scale, both well below the typically identified threshold (10–12%) for aquatic impacts (Klein, 1979; Booth and Jackson, 1997; Horner *et al.*, 1999; MacRae and DeAndrea, 1999; Fitzgerald, 2007).

Among the road density metrics, the number of stream crossings per unit drainage area (*RoadXStream_km*^{2}) was the best predictor of overall reach geomorphic condition (*RGA*) for both reach scales (i.e. reach corridor and reach direct drainage) (Table V) while *Road Density*, i.e. the length of the road network per unit area, and the presence of roads (*Roads Present*) were significant ($\alpha = 0.05$) predictors at the reach direct drainage and reach corridor scales, respectively. These density measures were also reasonable predictors of channel adjustment (aggradation and/or degradation) at both reach scales and within the network corridor. None of the existing density metrics were able to predict channel condition at the catchment scale. As illustrated in Figure 6a, a reduction in the number of road–stream crossings in the direct drainage to the assessed reach was associated with improved geomorphic condition of the reach.

The new *Proximity* metrics proved as effective as the existing road density metric in predicting geomorphic condition within the two reach geographic scales (i.e. reach corridor and reach direct drainage), and offered additional predictive power at both catchment scales (catchment and network corridor). The sum of distances from stream to nearest roads (*Proximity Sum*) was the best proximity predictor of geomorphic condition

Table V. Results of logistic regression, used to test significance of road metrics at each study scale

	Riparian corridor		Drainage area	
	ReachCorr	*NetworkCorr*	*ReachDD*	*Catch*
Existing Metrics (*Density*)				
Roads Present, yes/no	*0.0391*, D 0.03	D 0.04		
Road Density (km/km^2)	D 0.02	D 0.04	*0.009*, A 0.004	
RoadXStream_km^2 Count normalized by drainage area	*0.05*, A 0.002, D 0.003		*0.01*, A 0.001, D 0.005	
New Proximity Metrics Vantage point: *Stream to nearest roads*				
RoadXStream_m Count normalized by stream length	*0.03*		*0.03*	
Proximity Sum (m/m)	*0.007*, A 0.0008, D 0.006	A 0.003	*0.04*, A 0.004	*0.05*
New Orientation Metrics, *Parallel Vantage point*: *All roads to nearest stream*				
Sum Parallel (m/m)[a]	D 0.05		D 0.0007	*0.001*
Mean Parallel (m)	*0.02*, A 0.05, D 0.04			
Percent Parallel		*0.0005*, D 0.007		
New Orientation Metrics, *Perpendicular Vantage point*: *All roads to nearest stream*				
Sum Perpendicular (m/m)[a]			D 0.002	*0.03*
Mean Perpendicular (m)		D 0.0044		D 0.0162
Percent Perpendicular	A 0.002		*0.004*, A 0.04, D 0.04	

Note: Table entries are p-values ($\alpha = 0.05$) for predicting overall geomorphic condition (RGA) (shown in italic typeface), Aggradation (A), and Degradation (D) adjustment processes.
[a]Normalized by stream length.

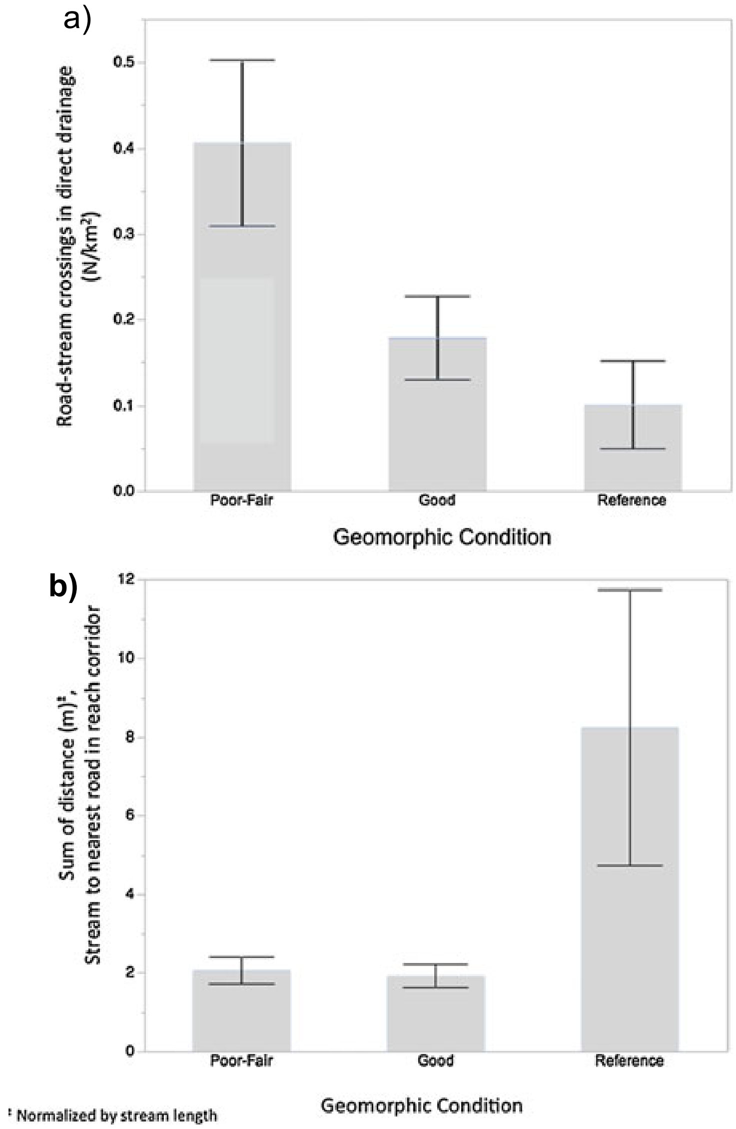

Figure 6. Examples of relationship between selected road metrics and stream geomorphic condition: (a) density metric, (b) proximity metric. Box plots reflect class mean and standard error.

when calculated at the reach corridor scale. Larger distances between roads and streams were associated with increasingly better geomorphic condition of reaches in our data set (Figure 6b).

The value of the new orientation metrics as predictors of channel condition varied by geographic scale. The sum of road-to-stream distance metrics (*Sum Parallel*) and (*Sum Perpendicular*) were both significant predictors of overall channel condition at the catchment scale, and of degradation at one or both reach scales, thus highlighting the importance of orientation and reinforcing the importance of proximity as a measure of road impact on channel condition. Although the new parallel and perpendicular road metrics differentiated classes of aggradation and/or degradation at various scales, two of the parallel road metrics (*Mean Parallel* and *Percent Parallel*) were the most effective predictors of overall reach geomorphic condition at the two corridor scales, with *Percent Perpendicular* serving in a similar manner at the reach direct drainage scale.

Results of the DA allow comparison of the relative value of categories of metrics (Inherent, Density, Proximity and Orientation) in predicting geomorphic condition. Tests for each category of metrics individually (Table VI), showed that all four categories of metrics correctly predicted geomorphic condition for between roughly 40 to 50% of the reaches, with the exception of Density at the Catchment scale, which provided little predictive power. This was to be expected, as the size of the catchment is large when compared with the road network, whereas Proximity and Orientation metrics focus the impact of roads more directly on the stream reach. At the Catchment and total network corridor scales, slope (%) is the only available Inherent metric, rendering a DA on Inherent metrics alone statistically infeasible.

For analyses combining two or more metric categories, we were able to include the Inherent category at the two largest scales. Results for two categories of metrics in combination (Table VII) were very similar to the individual results, with the exception of both reach scales, where Orientation coupled with Inherent or Proximity appeared to improve prediction. For example, at the Reach Corridor scale, combining Inherent with Orientation metrics (Table VII) improved prediction by at least 20 percentage points over either alone (Table VI). Similarly, combining Orientation with Proximity improved prediction by at least 13 percentage points over either alone. The best predictive model included a combination of Inherent and Orientation metrics, with 71% of the 46 reaches whose corridor regions include both perpendicular and parallel roads correctly classified.

Although it may appear unusual that combining density metrics with the new proximity and/or orientation metrics does not improve prediction results, comparing these results with those derived from analyzing only one metric set at a time is not viable, due to the difference in *N* values (study sites).

Table VI. Results of discriminant function analyses, using one set of metrics at a time, computed for all four geographic regions

Metric set	Inherent	Density	Proximity	Orientation
Geographic region				
ReachCorr				
% Correctly classified	47.9	50.5	48.6	52.2
–2 Log Likelihood	264.2	198.7	147.6	95.65
N	94	91	70	46
ReachDD				
% Correctly classified	47.9	47.9	45.2	52.9
–2 Log Likelihood	264.2	230.1	202.2	175.6
N	94	94	93	85
NetworkCorr				
% Correctly classified	NA[a]	48.9	38.9	42.5
–2 Log Likelihood		215.8	199	189.8
N		92	90	87
Catch				
% Correctly classified	NA[a]	29.8	44.7	44.7
–2 Log Likelihood		24807	210	201.5
N		94	94	94

Note: Table values include (a) the number of study reaches (*N*) included in the analysis, (b) –2 Log Likelihood, a measure of fitness (which the algorithm seeks to minimize), and (c) prediction success rate.
[a]Slope is only available inherent metric at this scale; single input not appropriate for discriminant analysis.

Table VIII summarizes the results of the DA involving all combinations of three metric categories. The highest predictive power (69.6% correctly classified for 46 reaches) was for a model that included Inherent, Proximity and Orientation metrics at the reach corridor scale. This same combination of metrics applied at the reach direct drainage scale correctly classified 60% of the 85 reaches. Predictive power at other scales using three metric category combinations did not exceed 50%.

When interpreting the potential value of these metrics, we note that their respective costs, both in terms of resources and availability, differ greatly. The Inherent metrics are the most costly and difficult to acquire because accurate classifications for the smaller reaches in remote forested settings require extensive field observations, whereas the Density, Proximity and Orientation metrics may be derived using readily available GIS data layers and software. In this context, we note that for the two reach geographic regions, combining Orientation metrics with either Proximity or Inherent metrics exhibited similarly promising classification success rates (Table VII). This proviso does not apply at the catchment scales, whose only available Inherent metric, *Slope* (%), is also GIS-derived.

Discussion

To our knowledge, this study is the first to examine the relationships between road network geometry and river channel morphology, using an extensive data set that incorporates field-based stream geomorphic assessments and road metrics with study reaches nearly exclusive of other anthropogenic influences except roads. The study channel reaches span a range of upland channel types, including step-pool, riffle-pool and plane bed morphologies, over varying channel slopes, all of which are experiencing some level of impact due to development of a road network. The availability of a consistent method of channel assessment, combined with a comprehensive spatial dataset of the transportation networks (including local roads and driveways), permitted the quantitative analyses conducted in this study. These results demonstrate the value of road metrics to discriminate channel condition, providing new ways to think about measures of road–stream network connectivity that go beyond simple measures of drainage density extension and direct discharges to receiving waters (i.e. road–stream crossings).

At all scales that we examined, measures of road *Proximity* to stream proved valuable in discriminating channel condition. These findings reinforce the importance of physical road–stream connections and suggest that transportation system design and/or watershed restoration efforts might effectively accomplish water quality and channel stability objectives when minimizing roads in close proximity to waterways. Such measures have been the basis of successful watershed restoration programs to mitigate the impacts of roads (Madej, 2001; Madej *et al.*, 2006; Patterson and Cooper, 2007). The significance of the road *Orientation* metrics (particularly the sum of distances

Table VII. Results of discriminant function analyses, using combinations of two metric groups, computed for all four geographic regions

Metric sets	Inherent Density	Inherent Proximity	Inherent Orientation	Density Proximity	Density Orientation	Proximity Orientation
Geographic region						
ReachCorr						
% Correctly classified	60.4	57.1	71.7	27.1	21.7	65.2
–2 Log Likelihood	244.6	170.8	171.6	81000	108.1	84.51
N	91	70	46	70	46	46
ReachDD						
% Correctly classified	55.3	51.6	60.0	36.6	25.9	56.5
–2 Log Likelihood	291.4	196.6	169	94500	100000	170.1
N	94	93	87	93	85	85
NetworkCorr						
% Correctly classified	48.9	42.2	41.4	30	44.8	49.4
–2 Log Likelihood	210	197	189.6	296.7	75000	179.3
N	99	90	87	90	87	87
Catch						
% Correctly classified	29.8	48.9	44.7	33.0	37.2	46.8
–2 Log Likelihood	25751	208	201.3	100000	93000	190.6
N	94	94	94	94	94	94

Note: Column headers identify the metric combination. Table values include (a) the number of study reaches included in the analysis (*N*), (b) –2 Log Likelihood, a measure of fitness (which the algorithm seeks to minimize), and (c) prediction success rates.

Table VIII. Results of discriminant function analyses, using combinations of three metric groups, computed for all four geographic regions

Metric sets	Inherent Density Proximity	Inherent Density Orientation	Inherent Proximity Orientation	Density Proximity Orientation
Geographic region				
ReachCorr				
% Correctly classified	27.1	32.6	69.6	32.6
–2 Log Likelihood	81000	49500	172.9	51000
N	70	46	46	46
ReachDD				
% Correctly classified	36.6	27.1	60.0	30.6
–2 Log Likelihood	93000	99000	160.9	91500
N	93	85	85	85
NetworkCorr				
% Correctly classified	28.9	44.8	49.4	42.5
–2 Log Likelihood	100000	75000	177.9	81000
N	90	87	87	87
Catch				
% Correctly classified	33.0	36.2	47.9	39.4
–2 Log Likelihood	10000	94500	190.4	91500
N	94	94	94	94

Note: Column headings indicate the metric combinations. Table values include (a) the number of study reaches (*N*) included in the analysis, (b) –2 Log Likelihood, a measure of fitness (which the algorithm seeks to minimize), and (c) prediction success rate.

to parallel roads) is consistent with at least two mechanisms whereby roads alter hydrogeomorphic processes. Within the channel corridor, parallel roads collecting and concentrating runoff in ditches have ample opportunities to discharge water and sediment, not only at stream crossings but also at cross-drain culverts, with a high likelihood of physical connections to the stream network through short overland flow paths or gullies. Within the catchment draining to assessed reaches, roads parallel to streams would be situated along hillslope contours, with ample opportunity to intercept subsurface flow and modify the partitioning of subsurface and overland flow. A recently completed field study conducted in Vermont provides clear evidence that unpaved roads located in rural settings effectively generate surface runoff and contribute significant volumes of fine sediment to Vermont streams (Wemple, 2013).

Our results highlight the importance of inherent channel characteristics when discriminating channel condition. Because these characteristics are attributed to the reach during the geomorphic assessment, efforts to derive these inherent channel controls at a cumulative or upstream scale were not feasible. Our new measures (i.e. road density, proximity to channels, and orientation with respect to channels) provide a means of discriminating channel condition at this catchment scale (albeit with a loss of statistical power when compared to using reach-scale measurements). Nevertheless, after accounting for inherent channel and landscape conditions and geomorphic stressors such as flooding and landcover change, our results provide substantial evidence that roads have a cumulative downstream effect on stream geomophic condition.

VTANR's RGA results indicate that higher-gradient, confined reaches in our dataset were generally transport-dominated and often resistant to change due to bedrock controls even though they may receive excessive sediment and runoff from nearby road networks. As a result, these confined, high gradient reaches typically route excess water and sediment to downstream reaches (lower-gradient unconfined settings) where transport capacity is reduced and sediments are deposited, driving lateral adjustments. In addition, as bedrock transitions to sediments in downstream reaches, boundary conditions become less resistant to erosion, enabling increased scour and leading to vertical or lateral channel adjustments.

Conclusions

The metrics we derived and tested reveal that roads in upland, mostly forested settings have measurable impacts on the morphology of rivers in our study area. Our analyses showed that after accounting for inherent characteristics (slope, VC, parent material, and landuse/landcover) of the assessed reaches, measures of road network geometry provide important explanatory power in discriminating the condition of rivers and streams in this setting, especially at the largest catchment scale. Simple and more traditional measures of road network *Density* were effective predictors of channel condition when applied to the reach or channel network corridor and to the direct drainage of the assessed reach, but failed to predict channel condition when calculated for the upstream catchment area, where they are more typically applied in watershed assessments (Flanagan *et al.*, 1998). These findings add new insights on the role of road connectivity on channel morphology and provide a new means of watershed assessment to evaluate where the road network may impact river reaches.

The road metrics proposed in this study serve as direct measures of the effects of transportation networks on river channel morphology. Although process-based studies provide important insights into the mechanisms whereby roads influence hydrologic and geomorphic processes, these studies are often limited in the number of observations afforded by the cost and time associated with such field studies. The work described here represents a new and different means of assessing channel condition through indirect measures of road-channel network geometry and connectivity. Results of this work may help inform watershed managers and restoration efforts for upland watersheds by providing a set of road encroachment metrics related to degraded channel conditions.

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