Linking Roads in Forested Watersheds to Stream Stability and Stream Health:
Tools for Assessing Road Impacts and Restoration Options

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Road networks, specifically those located in rural, forested, upland watersheds were examined to discover relationships between road geometry characteristics (i.e., their proximity to streams, and orientation with respect to streams) and the impact on channel geomorphology. We developed a new set of connectivity metrics for rural road networks within forested watersheds and tested their efficacy to 1) predict geomorphic condition (stream stability) of downstream channels and 2) discriminate among channels in various stages of geomorphic adjustment. Two metrics (i.e., the proximity and orientation of roads to streams and the density of road crossings) provide important explanatory power in discriminating the condition of streams in this setting, when compared to the more traditional road density metrics (i.e., road network density and number of stream crossings) especially at a large catchment scale.

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http://www.nsrcforest.org

Project Summary

Roads in rural, upland forested 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 transport or channel morphology. In this research, 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, we related road connectivity metrics to channel condition (stability) using a unique set of 102 forested, upland streams with minimal development other than predominantly gravel road networks. Logistic regression showed 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 (i.e., stream bed material, bed form and channel slope) combined with road connectivity metrics successfully distinguished channel condition for nearly 67% of the channels evaluated and for 90% of channels within ± one class of stream condition. This research contributes to efforts in evaluating the cumulative downstream effects of roads on stream channels and aquatic resources within the forested landscape of the Northern Forest region.

Background and Justification

- By channeling overland runoff and intercepted subsurface flows into the stream network, road delivered waters are prevented from recharging the local water table, and instead manifest as higher energy flows downstream. Hydrological connectivity of roads and streams is generally understood to increase the drainage density of a region, a characteristic used to qualitatively gauge the subsequent hydrologic pressures potentially manifested at the mouth of a catchment. This is of particular concern during peak flow events, in which increased flows and corresponding sediment loads can severely impact the geomorphic condition and natural stream channel dynamics, causing further instability and floods.

- Although the literature reflects an awareness of the proximity of roads to streams as stressors, no one as yet has methodically and quantitatively examined the effects of road proximity and orientation on the geomorphic health of streams.

- We believe this study to be one of the first in which a robust, statistically independent dataset of forested stream reaches (N=102) was identified and used to examine the relationships between road network geometry and stream channel morphology, nearly exclusive of other anthropogenic influences except roads.

Methods

- New road metrics were designed to quantify both proximity to and orientation (i.e., parallel, perpendicular) with respect to streams. These metrics were tested in upland, mostly forested settings, against channel reaches classified by VTANR field experts according to peer-reviewed stream geomorphic assessment protocols. The effects of roads on channel geomorphology were examined over four geographic scales, defined to differentiate the riparian corridor (zone) from the total subwatershed drainage area (catchment), while also limiting the scope to the local study reach or extending it to include the total upstream network.

- As a first step, ordinal logistic regression was used to identify road metrics with relative significance impact on the variation of the four fluvial adjustment process response variables (AGG, DEG, WID, PLAN) and the overall stream geomorphic (RGA) score at each geographic scale of observation.

- A discriminant function analysis was used to examine combinations of all candidate connectivity metrics to determine their effectiveness in discriminating among overall geomorphic stream condition classified into one of four ordinal categories (*Poor, Fair, Good, Reference*).

Results – Selection of Study Reaches

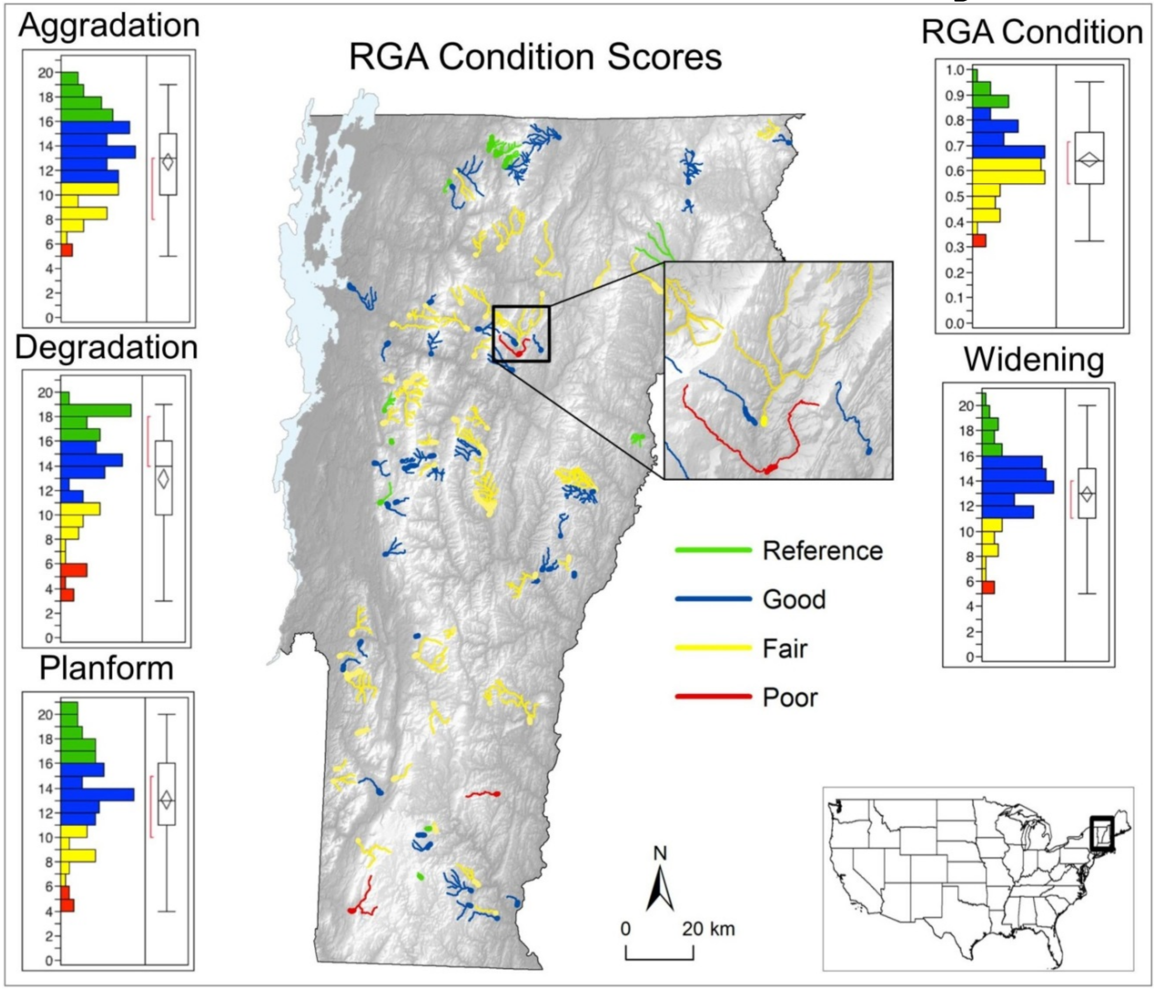

Figure 1. The 102 selected study reaches filtered from the 2300+ reaches field-assessed as of March 2010 offer the unique opportunity to evaluate the impacts of road networks on downstream channel geomorphology nearly exclusive of other anthropogenic influences. Distribution of the reach-scale rapid geomorphic assessment (RGA) and fluvial adjustment process scores are color coded. The 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 inter-quartile range (whiskers).

Results – Regions/Scales at which metrics were analyzed

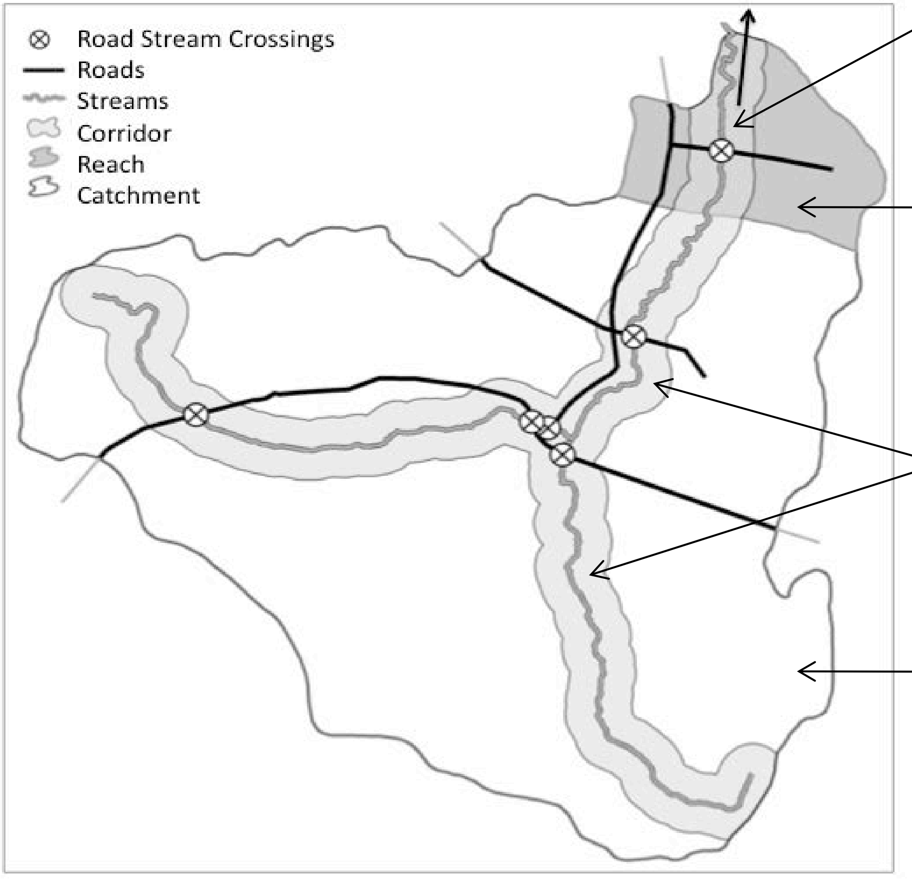

Figure 2. Schematic showing the four regions/scales at which the connectivity metrics were analyzed.

- *Reach Corridor* (*ReachCorr*) includes the land area directly adjacent to 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 Corridor* (*CatchCorr*) includes all upstream land area within the stream network corridor draining to the study reach.
- *Catchment* (*Catch*) includes all upstream land area draining to the study reach.

Results – Road Connectivity Metrics

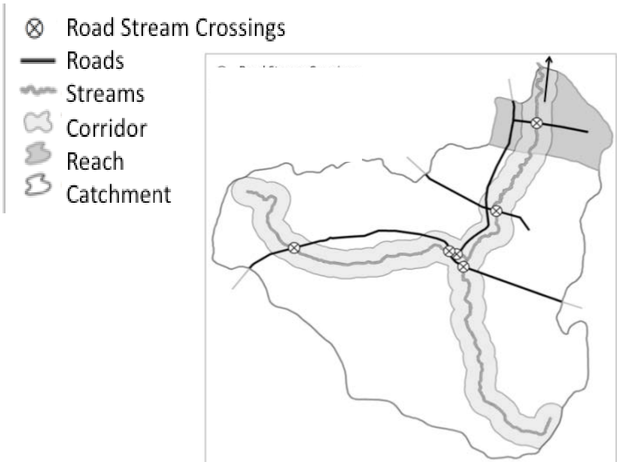

Figure 3. a) Schematic illustrating the network of roads and their stream crossing. Three somewhat traditional road metrics are defined as follows:

- *Roads Present* = binary variable used only to indicate the presence or absence of roads within the *Reach Corridor*.
- *Road Density* = the total length of roads present, divided by the area of a given region.
- Road crossing density (*RoadXStream*) = the number of road-stream crossings, normalized by the area of the region.

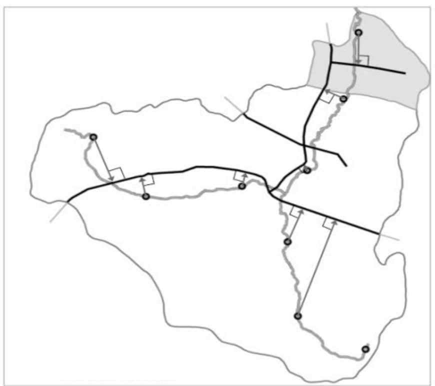

Figure 3. b) Schematic showing points along the stream segmented at 50 m intervals (circles), and vectors identifying distances to the nearest road. This enabled the development of two new *Proximity* metrics:

- *Proximity Sum* = the sum of the stream-to-nearest-road distances within each of the four regions (*ReachCorr, ReachDD, CatchCorr, Catch*) normalized by the stream length, where distances between stream and roads were defined normal to the road.
- *RoadXStream, Length* = the number of road crossings normalized by the length of the study reach or catchment corridor, depending upon the region/scale of the analysis.

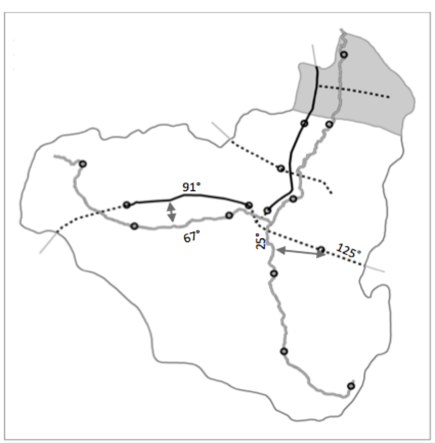

Figure 3. c) Six additional *Orientation* metrics were developed. The same 50 m stream segmentation of Figure 3 b) is retained; however, all roads are segmented at 50 m intervals as well. Each road segment is paired with its nearest stream segment and the bearing or orientation is calculated. The distances and orientation of each paired (road, stream) segment is then categorized into one of two categories as follows:

Perpendicular: $45° < |\theta_{stream} - \theta_{road}| < 135°$

Parallel: $|\theta_{stream} - \theta_{road}| < 45°$ *or*
$|\theta_{stream} - \theta_{road}| > 135°$

Results – Logistic Regression

	Riparian Corridor		Catchment Area	
Region	*ReachCorr*	*CatchCorr*	*ReachDD*	*Catch*
Density Metrics				
Roads Present (*yes, no*)	.05			
Road Density, km/km²			.002	
Road X Stream by drainage area, #/km²	.005	.02	.0003	
Proximity Metrics				
Road X Stream*, #/m	.02	.006	.02	.006
Sum of distances, stream to nearest roads*, m/m	.002		.01	
Orientation Metrics				
PARALLEL ROADS TO NEAREST STREAM				
Sum of distances*, m/m		.03		.02
Mean of distances, m	.02			
Roads, % Parallel		.0004		
PERPENDICULAR ROADS TO NEAREST STREAM				
Roads, % Perpendicular			.03	

** Normalized by stream length*

Figure 4. Results of logistic regression, used to test significance of road connectivity metrics at each of the four regional areas/scales. Table entries show p-values for all metrics showing significance ($\alpha = 0.05$) in predicting overall geomorphic condition (RGA).

- Among the traditional road density measures, the number of stream crossings per unit drainage area (*RoadXStream*) was the best predictor of overall channel geomorphic condition (*RGA*).

- The two new proximity metrics proved as effective as the density measures in predicting geomorphic condition within the reach and corridor geographic regions, but offered additional predictive power at the catchment scale.

- The value of the orientation metrics as predictors of channel condition varied by metric and region/scale; however, again showing additional predictive power at the largest catchment scale.

Results – Logistic Regression (cont.)

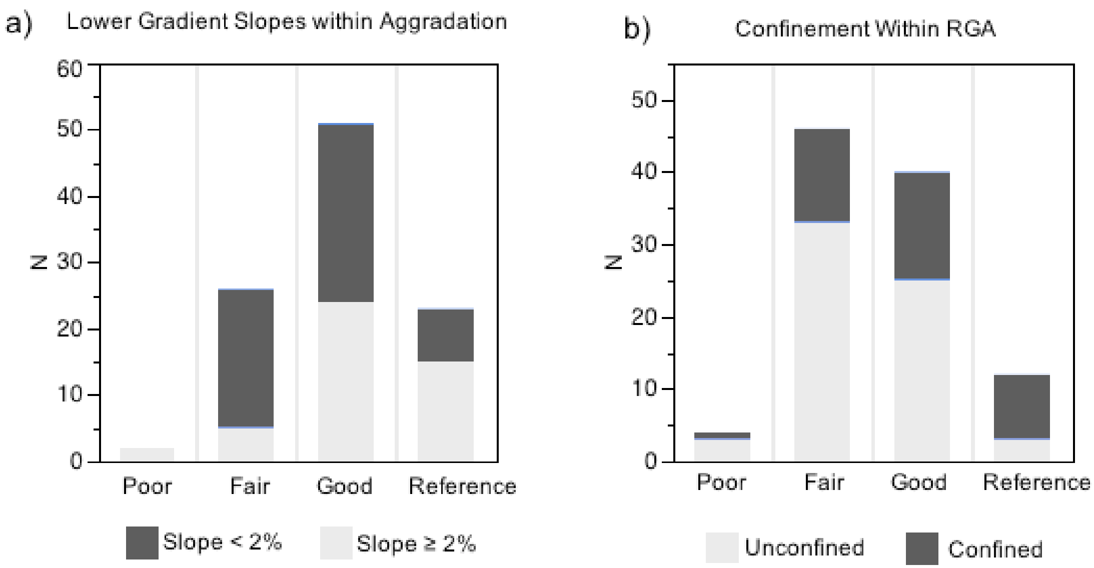

Figure 5. Relationship between a) Aggradation scores and slope and b). RGA scores and confinement.

• Logistic regression analyses of the *Inherent* stream channel metrics indicated that as one might expect, *bedform*, *bed material*, *confinement, and reach slope* were all significant factors (α = 0.05) in differentiating the overall geomorphic condition of the study reaches.

NOTE: Reaches in *Reference* and *Poor* geomorphic condition were typically characterized by confined channels, whereas Fair and Good reaches were dominated by unconfined channels.

Discriminant Analysis

	N = 99	**Predictions**			
		Poor	*Fair*	*Good*	*Reference*
Actual	*Poor*	**3**	1	0	0
	Fair	10	**24**	7	5
	Good	6	11	**18**	3
	Reference	0	1	1	**9**

Figure 6. DA contingency table with counts for *RGA* classification using combined *Inherent* and *Proximity* metrics as inputs at the *Reach Direct Drainage* scale (shown here as an example).

• Discriminant Analysis returns a classification matrix (known as a contingency table shown left) reflecting how well the chosen input predictor metrics (all 15 combinations) collectively differentiate among the stream *RGA* response categories (*Poor, Fair, Good, Reference*). We illustrate the DA's ability to correctly predict the channel RGA class with the contingency table (Figure 6, left) generated using the *Inherent* stream metrics and the two new *Proximity* metrics (computed for only one particular regions/scale- *ReachDD*). Rows represent the actual class membership of the 102 study reaches, while columns represent their classification as determined by the DA. Ideally, one would like every element on the diagonal would be populated with positive integers, with all remaining off-diagonal values at zero.

Results –
1) using one metric category at a time.

• In the reach corridor, the *Inherent* channel metrics outperformed all road metrics, successfully predicting channel condition exactly in 44.1% of the study reaches or within one class in 77.5%.

• The new road Proximity and Orientation metrics outperformed the traditional Density metrics at all spatial scales, although not as well as the inherent stream characteristics.

• Note: The new road Proximity and Orientation metrics were best in predicting overall channel condition at the catchment (*Catch*) scale, where inherent channel metrics could not be meaningfully quantified.

Results – Discriminant Analysis
2) using multiple metric categories

• At the reach scale, the best-performing metric pairs consistently involved the *Inherent* stream channel variables. When paired with either the new road *Proximity* or *Orientation* metrics, accuracies (+/- 1 class) in predicting overall channel condition ranged from 87%–94% at the reach scale and from 76%–86% at the catchment scale, demonstrating that after accounting for *Inherent* channel conditions, the road *Proximity* and *Orientation* metrics provide additional power when discriminating among stream channel conditions.

•At the reach scale, the *Inherent-Proximity-Orientation* combination out-performed all other three-way combinations, achieving a classification success rate (+/- 1 class) of approximately 90%.

•At the catchment scale, the *Density-Proximity-Orientation* combination exhibited the highest accuracies (83%–92%).

• 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 they 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 at the catchment scale any pair-wise combination that included the *Proximity* metrics exhibited the highest classification success rates. In comparison, adding *Slope (%),* the only *Inherent* metric available at this scale, did not significantly improve classification success over the use of individual road metrics alone

Summary

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 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. The results provide new ways of thinking 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).

Our analyses showed that after accounting for inherent characteristics (slope, valley confinement, dominant bed material, and bedform) 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).

The significance of the road *Orientation* metrics 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 opportunity 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. At all scales that we examined, measures of road *Proximity* to streams 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 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

Implications and applications in the Northern Forest region

Urban growth is projected to subsume 2-48% (by state) of the forestlands in the Northeastern U.S. by 2050 (Nowak and Walton, 2005; Deacon et al., 2005). A recent report by the National Research Council (NRC, 2008) emphasized the need for research to address the impacts of increasing development on freshwater quality and quantity, riparian and aquatic habitats, flood management and stream stability. The research conducted here identifies factors contributing to geomorphic condition of stream channels in the Northern Forest region and clearly identifies the role of road networks in degrading channel condition. We focused on identifying controls on channel geomorphic condition for reaches draining watersheds that were at least 75% forested, in order to isolate the effects of transportation infrastructure on stream geomorphic condition. Our results show that human impacts in forested watersheds, in the form of road network development to access the rural landscape, private landholdings, and timber products, have significant effects on the geomorphic condition of stream channels in the region.

Future directions

- Our results at the catchment scale highlight the importance and necessity of monitoring inherent channel characteristics along with measures of development and land use change in order to understand the geomorphic condition of the stream reaches in the forested watersheds we studied. River monitoring programs, such as the program established by the Vermont Agency of Natural Resources and used as the primary data set for this analysis, provide a means for assessing long-term stream channel condition and change. Throughout the Northern Forest region, similar monitoring programs across the neighboring states would allow regional assessments of channel condition.

- This GIS analysis and model development undertaken in this study leveraged field studies of runoff and sediment production from roads to assess the on-site and cumulative downstream effects of whole road networks on river channel condition. Future studies that build on past NSRC and other regional research and long-term monitoring projects aimed at documenting conditions of forested streams can provide the basis for understanding the evolving condition of waterways and aquatic resources in the Northern Forest region.

List of products

Four abstracts accepted and presented, one M.S. Thesis, and one manuscript in review (now accepted pending revisions):

- Pechenick, A., D.M. Rizzo, L. Morrissey, K. Garvey, K. Underwood, B. Wemple, Hydrological connectivity of road and stream networks: Implications for channel morphology", EOS Transactions, *American Geophysical Union*, Fall Meeting, San Francisco, CA, December 2012.
- Wemple, B, K. Garvey, L. Morrissey, A. Pechenick, D.M. Rizzo, and D. Ross, Hydrological connectivity of road and stream networks and implications for material transfer and channel morphology, Geophysical Research Abstracts, Vol. 14, *European Geosciences Union*, Vienna, Austria, April, 2012.
- Wemple,B., K.M.Garvey, L.A.Morrissey, A.Pechenick, D.M.Rizzo and D.Ross, "Assessing the Effects of Unpaved Road Networks on Downstream Water Quality in a Forested, Upland landscape: A Multi-scale Approach", EOS Transactions, *American Geophysical Union*, Fall Meeting, San Francisco, CA, December 2012.
- Pechenick, A.M., *A multi-scale approach to assess the hydrological connectivity of road and stream networks.* University of Vermont, M.S. Thesis, Spring 2013.
- Pechenick,A. (presenter), D.M.Rizzo, L.A.Morrissey, K.M.Garvey, K.Underwood and B.C.Wemple, "A Multi-Scale Approach to Assess the Hydrological Connectivity of Road and Stream Networks", NEARC Northeast Arc Users Group Conference, Amherst, MA, May 14, 2013.
- Same as NEARC, also presented (now archived on web) to NEURISA (New England Chapter of the Urban & Regional Information Systems Association): NEURISA Lightning Talks Dartmouth College, NH - April 16th, 2013
- Pechenick, A.M., Rizzo, D.M., Morrissey, L.A., Garvey, K., Underwood, K., and Wemple, B.C. "A multi-scale approach to assess the connectivity of road and stream networks". *Earth Surface Processes and Landforms*. Accepted with revisions, 2013.

Outreach and Dissemination of Results

Meetings and presentations with state agency staff and interested constituencies in Vermont

- February 22, 2010 – Consultation with Vermont Agency of Natural Resources River Management Program staff M. Kline and G. Alexander. State Office Complex, Waterbury, Vermont.
- January 23, 2012 – Progress meeting and feedback session with Vermont Agency of Natural Resources River Management Program staff. University of Vermont.
- July 3, 2012 – Consultation with Vermont Agency of Natural Resources Department of Environmental Conservation staff N. Kamman and S. Pomeroy. University of Vermont.
- May 31, 2013 – Public seminar "Assessing the Effects of Unpaved Roads on Lake Champlain Water Quality." Staff from Vermont Agency of Transportation in attendance. University of Vermont Transportation Research Center.
- January 14, 2014 – Seminar and meeting with staff of Ecosystem Restoration Program, Vermont Department of Environmental Conservation, and Better Backroads Program, Vermont Agency of Transportation. National Life Building, Montpelier, Vermont.

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- Wemple BC, Jones JA and Grant GE. (1996) Channel network extension by logging roads in two basins, Western Cascades, Oregon. *Water Resources Bulletin* 32: 1195-1207.