Transportation Research Center Research Reports

6-30-2014

Impacts of Transportation Infrastructure on Stormwater and Surfaces Waters in Chittenden County, Vermont, USA

William Bowden
University of Vermont, Breck.Bowden@uvm.edu

Joseph Bartlett
University of Vermont

Recommended Citation

Bowden, William and Bartlett, Joseph, "Impacts of Transportation Infrastructure on Stormwater and Surfaces Waters in Chittenden County, Vermont, USA" (2014). *Transportation Research Center Research Reports*. 179.
https://scholarworks.uvm.edu/trc/179

A Report from the University of Vermont Transportation Research Center

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TRC Report 14-013 | Bartlett, Bowden | June 2014

DISCLAIMER

Impacts of Transportation Infrastructure on Stormwater and Surfaces Waters in Chittenden County, Vermont, USA

Part 5c of Signature Project 1

By

Joseph Bartlett and William B. Bowden
Rubenstein School of Environment and Natural Resources
University of Vermont
Burlington, Vermont

This project was supported by funding from the US DOT through the UTC program at the University of Vermont Transportation Research Center (TRC).

30 June 2014

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Abstract

Transportation infrastructure is a major source of stormwater runoff that can alter hydrology and contribute significant loading of nutrients, sediment, and other pollutants to surface waters. These increased loads can contribute to impairment of streams in developed areas and ultimately to Lake Champlain. In this study we selected six watersheds that represent a range of road types (gravel and paved) and road densities (rural, suburban, and urban) present in Chittenden County, one of the most developed areas in Vermont. The location and density of road networks were characterized and quantified for each watershed using GIS analysis. Monitoring stations in each watershed were constructed and instrumented to measure discharge and water quality parameters continuously from spring through early winter. Storm event composite samples and monthly water chemistry grab samples were collected and analyzed for total nutrients, chloride, and total suspended sediments. Results from this study show that road type and road density are closely linked with the level of impairment in each watershed. Total phosphorus and total nitrogen from storm event composite samples and monthly grab samples significantly increased along a gradient of increasing road network density. Chloride concentrations increased several orders of magnitude along this same gradient. With the exception of Alder brook where total suspended sediment (TSS) concentrations tended to be high, there were no significant differences in TSS concentrations between rural and developed watersheds. The event TSS concentrations in the rural streams were slightly higher than we expected and the event and base TSS concentrations in the developed streams were somewhat lower than we expected, suggesting that the unpaved roads in the rural watersheds might contribute to stormwater runoff loads and that sediment control, at least, in the developed watersheds might be fairly effective. The overall results from this study show that local roads are significant source of impairment for streams in the Chittenden County area. Most of these roads are municipal roads that are not under to management of the Vermont Agency of Transportation. Thus, local actions will be necessary to control runoff from these roads.

Introduction

Project Justification

Numerous studies have been conducted that clearly describe the impact of urbanization at broad (catchment) to fine (parking lot) scales (as reviewed in Paul and Meyer 2001). These studies have quantified and described myriad physical, biological, and chemical impacts to streams collectively known as the urban stream syndrome (Meyer et al. 2005). Typically characterizations of impacts from development are based on the percentage of the watershed covered in impervious surfaces (%TIA), the most common variable used to estimate the level of development and associated impacts. Population metrics are also used to describe development level and potential stream impacts.

The effects of dense urbanization on watersheds are well studied. Less research has been done for watersheds that are characterized by lower levels of urbanization (Wang et al. 2003). In studies of densely urbanized area it is not uncommon to consider 30-40% TIA to be a moderate level of development (Chadwick et al. 2006). By contrast, the level of development in smaller, less populous states like Vermont is lower; on the order of 10-20% TIA found in the most developed watersheds in Vermont.

However, despite the lower level of overall development in Vermont's urbanized areas (measured as TIA), roads still constitute an important fraction of the developed area and may be an important source of impairment to local streams. The specific impacts of roads are not often isolated in studies of urban and suburban development in moderately developed areas. Road network information is easily and publicly available and the close association with overall watershed development indicates that road networks may be a valuable tool to quickly estimate potential surface water impacts within a watershed. Specifically, we reason that:

- Road surfaces are major sources of runoff and stormwater pollutants.
- Roads are frequently one of the largest sources of watershed imperviousness, especially in the low to moderate levels of development most commonly found in New England.
- Roads are frequently associated with drainage infrastructure that provide direct or expedited pathways for runoff to enter streams.
- Road networks are simple to map and can be consistently applied to a wide range of watershed development levels.

Local Context

In the Lake Champlain Basin and Chittenden County, sediment, nutrients, and road salt are the pollutants that most often are cause for management concern. Because the stormwater generated from impervious surfaces itself alters the hydrology and geomorphology of streams and rivers, the State of Vermont's new stormwater control approach focuses first on controlling the discharge of water in developed watersheds (VT ANR 2005). The water as well as the sediments, nutrients, and other pollutants in stormwater alter habitat quality and the species composition of streams and rivers (e.g., Waters 1995, Jackson et al 2001, Stupenuck et al. 2002, Par and Mason 2003, Sullivan et al. 2006) but equally, the increased pollutant load moving downstream frequently leads to impaired receiving waters, as it the case for Lake Champlain (VTDEC and NYDEC 2003). To make good decisions about transportation futures, managers need information about the magnitude of these problems and how different road types and densities affect stream networks and receiving waters.

Project Goal, Objective and Hypotheses

This project was a part of the University of Vermont Transportation Research Center Signature Project #1. The primary goal of this component of the overall project was to evaluate the effects of the transportation network on water quality and freshwater ecosystem integrity. The specific objective (5c) of this project within the Signature 1 framework was to evaluate the effects of road type and road density on water quality, stream stability, and the pollutant load exported to Lake Champlain. We hypothesized that:

- Metrics generated from relatively simple spatial analysis of road networks and streams can be used to predict water quality impacts and stream conditions at a watershed scale.
- Water quality indicators will decrease along a gradient of increasing road density.
- Unpaved roads will generate proportionately more sediment loading than paved roads.

Methods

Study Area

Chittenden County is located in northwestern Vermont and is closely connected to two of the most important aquatic resources within the state: Lake Champlain and the Winooski River. Stormwater runoff and water quality impacts on receiving waterbodies are a primary concern for residents and municipalities within the county. Chittenden County contains the highest density of development in Vermont. Despite the fact that these “urban” areas are less developed than other larger developed and commercial centers in the United States, segments of several of the streams the Chittenden County area have been listed by the state of Vermont as “impaired” by stormwater runoff. The state has developed total maximum daily load (TMDL) plans for some of these streams and is actively working to reduce the stressors that are causing the reported impairments.

The watersheds selected for this study spanned the range of the road network density and road type found within Chittenden County. Watershed areas range from 13 to 53 km^2 and stream order is 3rd or 4th. General watershed characteristics and land use summary are shown in Table 1 in order of increasing development and road network density (NOAA, 2006). A map of the study watersheds and monitoring station locations is shown in Figure 1.

Table 1. Watershed and landuse characteristics for the study area. In this and subsequent tables the watersheds are organized from least to most developed.

Watershed	Size (km^2)	Order	Towns	Forest	Agriculture	Developed	Water/ Wetland
Snipe	13.1	4	Richmond, Jericho, Bolton	95.4%	1.8%	0.1%	1.6%
Mill	29.8	3	Jericho, Bolton	88.0%	7.4%	2.1%	1.2%
Allen	16.8	3	Williston	43.7%	41.1%	7.3%	4.6%
Alder	25.5	4	Essex, Westford	44.2%	40.9%	10.4%	2.9%
Muddy	53.3	4	Williston, Shelburne, S. Burlington, St. George	38.4%	40.7%	10.7%	7.2%
Potash	18.2	3	S. Burlington, Burlington	16.9%	25.8%	54.3%	1.7%

- The two rural watersheds (Mill Brook and Snipe Island Brook) are primarily forested and contain low densities of gravel and dirt roads. Both watersheds contain low densities of single-family homes and minimal agriculture. Both watersheds are steeper and the main stream channels are located in narrower valleys typically shared with roads.
- Alder and Allen Brook drain primarily suburban watersheds with moderate forest and agricultural cover. The lower portion of Alder Brook closely follows the circumferential highway (I-289). Both watersheds drain areas of suburban residential development typical to Chittenden County.
- Muddy Brook has the most variable land use in this study. The upper watershed (southern) drains rural and suburban areas, the lower watershed (northern) drains dense commercial areas and has a high concentration of major roads (Rt. 2 and I-89) immediately upstream of the monitoring station.
- Potash Brook is one of the most developed watersheds in Vermont and represents the highest degree of residential and commercial development in this study. The entirety of I-189 and significant stretches of I-89, Rt. 2, Rt. 7, and Rt. 116 area located within the watershed.

Figure 1. Location of the monitoring stations and the portions of each watershed included in this study. Potash Brook drains directly to Lake Champlain; the remaining five watersheds drain to the Winooski River.

Monitoring Station Location, Construction, and Instrumentation

Locations for continuous monitoring stations were identified based on channel stability, substrate, protection from flooding, access, and security. Several potential sites were identified on each stream and landowners were identified using property maps. Landowner permission was secured for all sites.

Continuous monitoring stations were constructed in each watershed. Stations included ISCO 6712 auto-samplers with ISCO 720 pressure transducers and YSI 6600 OMSv2 sondes with temperature, specific conductance, and optical dissolved Oxygen. Weather stations were installed near the monitoring stations and were instrumented with HOBO micro-stations, photosynthetically active radiation sensors (PAR), and tipping rain buckets (0.2mm increment). ISCO auto-samplers were installed above the flood-prone elevation and were tethered and locked to trees. Pressure transducer and suction lines were housed in flexible plastic conduit and were staked to the bank with rebar and mounted to a PVC carrier staked to the stream bottom with 4’ rebar. YSI sondes were bolted in to heavy PVC holders that were staked to the stream bottom in the thalweg with 4’ rebar. Equipment was installed as early as flow levels allowed and remained in place until the onset of anchor ice in late December. Monitoring stations in all watersheds were operated from June-December 2008, April-December 2009, and April-December 2010.

Continuous Monitoring and Maintenance

Stream temperature, specific conductance, temperature, dissolved oxygen saturation, and stage height were measured continuously at a 5 minute interval. YSI sondes required weekly maintenance for DO calibration and battery changes. The sonde was wrapped in a wet towel and following temperature stabilization the DO saturation was calibrated using the current barometric pressure from a handheld digital barometer, following the manufacturers listed calibration methods. Conductivity sensors were calibrated in the lab using 3 standards (1, 100, 1000 us/cm) at the beginning of each field season and checked for drift at the end of each season.

Discharge Rating Curves

Stage/Discharge rating curves were established for each stream using approximately 10-15 manual area-velocity discharge measurements taken at a range from baseflow to highest wadeable flow levels. Discrete discharge measurements were collected with a Sontek Flowtracker 2D ADV. Rating data were plotted in Microsoft Excel and fitted with single or two-part power curves following standard USGS stream rating methods (Turnipseed and Sauer 2010).

Storm Event Sampling

ISCO auto-samplers were programmed to collected stage triggered, time paced, single composite samples into a 9L plastic jug. Stage triggers were programmed before each storm event and a triggering threshold was selected based on current flow conditions and predicted storm forecast. Samplers collected 36, 200ml samples into the composite jug. We fully acknowledge that volume-weighted sampling would be preferable for the purposes of this study. However, in most cases we did not have good information about the discharge characteristics of these streams prior to study. In addition, it has been our experience that it is logistically difficult to maintain good flow-weighted sampling, simultaneously, in several different streams. Thus, there is a high risk that samples and data will be lost at one or more sites during any given storm. Given that our primary objective was a comparative study of differently developed watersheds and not a quantitative study of area-specific loading from the study watersheds, we concluded that this tradeoff was acceptable. It is likely that by compositing samples taken over regular time intervals during storms, we have underestimated the true loads. Thus, the actual differences among our study watersheds may be larger than we have reported. Time pacing for the 200ml samples was programmed based on predicted storm intensity. We found that a 30 minute sampling interval was ideal for most storms and successfully captured the rising limb, peak, and most of the falling limb without over sampling any particular period of the storm. A total 15 to 25 storm events were successfully sampled each year.

Monthly Grab Sampling

Monthly water quality grab samples were collected for December 2008 through January 2011. These samples were collected using a clean 9 liter jug and were collected at low flows to characterize baseflow and season water quality conditions.

Water Sample Processing and Analysis

Composite storm event and baseflow grab samples were split into sample bottles for each analyte and were stored at the Rubenstein Lab until analysis. 150ml plastic bottles were filled and frozen for Total Phosphorus. 50ml conical tubes were filled, acidified with HNO_3, and refrigerated for Total Nitrogen. Chloride samples were collected in 10ml scintillation vials and refrigerated. TSS samples were collected from the 9 liter jugs immediately following vigorous shaking. Water was filtered through pre-combusted 47mm Type 934-AH GF filter paper using a hand vacuum pump and Nalgene 500ml vacuum filter apparatus. Filtered sample volumes ranged from 30ml to 5,000ml depending on sediment load in samples. Filter papers were dried for at least 24 hours in pre combusted and weighed aluminum tins. Dried samples were allowed to cool in a dessicator and then reweighed. Samples were then combusted in a 550^0C muffle furnace for 4 hours and re-weighed.

Frozen total phosphorus (TP) samples were thawed in the refrigerator and were analyzed on the Lachat auto-analyzer using the Quick Chem Method 10-115-01-4-F, determination of total phosphorus by flow injection analysis colorimetry (acid persulfate digestion method). Total nitrogen (TN) samples were analyzed using Lachat Quick Chem method 10-107-04-4-A, determination of nitrate+nitrite in manual persulfate digests. Chloride samples were diluted so that all samples would range from 0-10 mg/l Cl. Dilutions were 1:3 for rural streams and up to 1:50 for urban streams. Dilutions were determined based on specific conductance readings at the time of sample collection. Chloride samples were analyzed by the University of Vermont Plant and Soil Testing Laboratory on an ion chromatograph.

All TP and TN samples were run twice and a 10% replicate and standard were used. Any samples with greater than 10% difference were re-run automatically by the Lachat auto-analyzer. Replicates that were greater than 10% different from the original sample were re-run. Chloride samples included a 10% replicate.

Benthic Macroinvertebrate Sampling

Benthic macroinvertebrates (BMIs) were sampled at all sites during the late fall index period (September-early October 2010) following the Vermont Department of Conservations (VTDEC) Biomonitoring protocols (VTDEC 2004). We partnered with the VTDEC Biomonitoring sampling to share in sampling effort and analysis costs. VTDEC collected annual samples at Potash Brook, Muddy Brook, and Alder Brook, and BMIs were picked and identified at the VTDEC lab. We collected and processed samples from Allen Brook, Mill Brook, and Snipe Island Brook and picked samples were analyzed by Rapid Watershed Associates (Schenectady, NY). BMI community composition was characterized through several metrics to describe diversity, pollution tolerance, and similarity to reference communities.

Rapid Habitat Assessment

Rapid Habitat assessments (RHA) were completed at all sites following the VTDEC guidelines (VTDEC 2009). Each stream was assessed over an approximate 100m reach centered on the monitoring station. All categories were scored from 0 (worst) to 20 (reference) for each RHA category.

GIS Analysis

Watersheds for each study stream were delineated using the ArcHydro tool in ESRI ArcMap 9. All data layers were clipped to watershed boundaries. Road networks were characterized based on road surface type from the VTRANS TRANS_RDS database. Class 4 roads were manually classified based on ground observations and aerial imagery. Road networks were also characterized based on proximity to streams. Road crossings within each watershed were counted and road lengths were measured within 100m buffers from the stream centerline. We selected a 100m buffer to best capture the portion of roads that directly impact neighboring streams as described by Schiff and Benoit (2007).

We conducted a simple analysis of total impervious area and road impervious area in the study watersheds. Total percent impervious area (%TIA) was estimated for each watershed using the method describe by Fitzgerald (2007). Road impervious area was estimated for each watershed by manually measuring width for at least 50 manually selected road segments for each of the four AOT classes within each watershed (highway; paved and ditched; gravel and ditched; gravel/dirt no ditch). A mean width was determined for each surface type by watershed and was multiplied by total length of each road class to estimate total road area within each watershed. This calculation method indicated that road area represented over 90% of the total imperviousness within the Snipe Island Brook watershed. Due to the small size and low level of development we manually measured all non-road imperviousness (less than 100 driveways and rooftops) within the watershed and adjusted the %TIA from 0.5% to 0.76% accordingly.

Data Analysis

Continuous data (5-minute) from ISCO and YSI sensors were converted to Microsoft Excel-readable formats and was compiled into annual master datasets. All data were manually checked for errors. YSI files were trimmed by 1 to 2 readings on the start and end to remove data points influenced by sonde temperature changes due to downloading and calibration. Daily mean values were calculated for all continuous variables. Daily mean streamflow data were used to calculate flow duration curves and additional metrics for baseflow contribution and the flood-peak index (Hauer and Lamberti, 2006).Additional metrics were calculated for stream temperature data (maximum daily mean, maximum 7-day mean, and mean of the daily maxima for first 3 weeks of July) as described in Wang et al. (2003).

All water quality data were summarized to generate mean concentrations for storm event and baseflow grab samples. Mean values were tested for significant differences between sites for baseflow and storm event samples, and for differences between baseflow and storm event concentrations within each watershed using ANOVA (α=0.05). A multivariate analysis with Spearman's ρ correlation was selected to test the strength of road network variables as predictors for physical, biological, and chemical responses (α=0.05 and 0.1).

Results

GIS Results

Road networks within each watershed were characterized by length within each major AOT category (highway; paved and ditched; gravel and ditched; gravel/dirt no ditch) (Table 2). The Potash Brook watershed contains the several major roads and highways (I-89, I-189, US 2, US 7, and VT 116) a high density of residential roads, and a very low density of unpaved roads. Muddy, Allen, and Alder Brooks all drain portions of highway and major roads, large networks of residential roads, and small to moderate densities of unpaved roads. Mill and Snipe Ireland Brooks drain predominantly gravel and dirt roads with only a small stretch of paved roads in the upper Mill watershed.

Table 2. Length of road (km) by type in each study watershed.

Watershed	Highway	Paved	Gravel w/ ditch	Gravel/Dirt	Paved Total	Unpaved Total

Snipe Island	0.0	0.0	4.7	3.0	0.0	7.7
Mill	0.0	1.4	29.2	2.9	1.4	32.1
Allen	4.3	46.9	16.0	0.4	51.2	16.3
Alder	8.7	30.9	5.3	0.0	39.6	5.3
Muddy	10.2	81.5	25.6	1.0	91.7	26.6
Potash	21.8	91.8	0.9	0.0	113.6	0.9

Road network metrics and watershed impervious cover were calculated to quantify potential road and development impacts to streams as shown in Table 3. The number of intersections between road centerlines and the VHD stream centerline layer were identified to calculate the density of stream/road crossings in each watershed. The road density within 100m of the stream centerline indicates a higher proportion of roads in the rural watersheds closely follow streams. This is due to topographic constraints in the steeper watersheds that frequently restrict road construction to stream and river valleys. Total impervious area percentages characterize the overall development level for each watershed and show the elevated percentage of watershed imperviousness represented by roads in moderately developed watersheds with higher densities of major roads (Allen and Alder) and in low development rural watersheds (Snipe).

Table 3. Characteristics of the road network in each study watershed.

Watershed	(Stream/Road Crossings) /km^2	Road Density (km/km^2)	Road Density within 100m stream buffer (km/km^2)	%TIA	%TIA from roads
Snipe Island	0.53	0.63	0.34	0.8	86.2
Mill	0.74	0.99	0.49	1.6	33.1
Alder	0.78	2.20	0.55	4.5	51.8
Allen	1.31	2.56	0.60	4.1	59.6
Muddy	1.33	2.22	0.57	6.0	30.3
Potash	3.41	5.41	1.62	22.0	22.2

Stream Flow

Discharge estimates were collected across a wide range of wadeable flows for all six monitoring stations. We developed one-part or two-part rating curves to best fit discharge (y) to stage height (x) shown in Table 4. Changes in channel dimensions typically located near bankfull at five of the monitoring stations (Allen, Mill, Muddy, Potash, and Snipe) required the use of a lower and upper rating curve to best fit flows above and below bankfull (Figure 2).

Table 4. Discharge rating curve equations.

Watershed	Low Curve	R^2	High Curve	R^2	Transition Stage (m)

Snipe	$y=79.53x^{6.13}$	0.98	$y=10.28x^{4.17}$	0.96	0.35
Mill	$y=7.32x^{2.09}$	0.99	$y=17.22x^{2.93}$	0.96	0.36
Alder	$y=32.46x^{3.00}$	0.99	n/a		n/a
Allen	$y=59.79x^{4.14}$	0.96	$y=10.2x^{2.79}$	0.97	0.28
Muddy	$y=16.08x^{3.50}$	0.98	$y=9.0x^{2.93}$	0.99	0.36
Potash	$y=0.341x^{0.232}$	0.98	$y=0.399x^{0.495}$	0.99	0.30

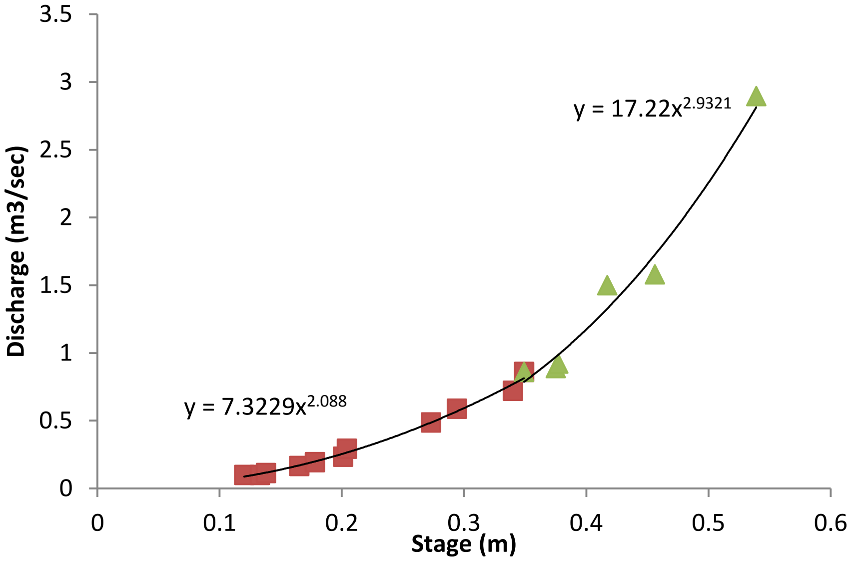

Figure 2. Two-part rating curve for Mill Brook

Discharge above the extent of the rating curve measurements is estimated and there is increasing potential for error in the estimates at the highest flows. We calculated the total proportion of time each station was above the extent of our rating curves and these values ranged from 0.14% (Potash) to 2.4% (Snipe) with a mean of 1.4%.

Flow duration curves based on area normalized hourly mean flows ($m^3/sec/km^2$) were calculated for each site to characterize changes in peak and base flows based on watershed imperviousness (Figure 3). We observed a large decrease in baseflow discharge in the three most developed watersheds as described in Booth and Jackson (1997) and CWP (2003). However, we did not observe increases in peak flow volumes in the developed watersheds. This discrepancy is likely due to runoff attenuation in stormwater retention structures throughout the developed watersheds. The undeveloped watersheds are also steeper, increasing peak discharge. Allen Brook was observed to have consistently lower mean discharge (Q50) and baseflow (Q90) than the other study watersheds. This is likely due to the well-drained sandy soils prevalent in much of the study watershed. The baseflow contribution metric (Q90/Q50) and the flood peak index both show a shift towards reduced baseflow and increased flood peaks relative to mean flows in the watersheds with higher road density and development (Table 5).

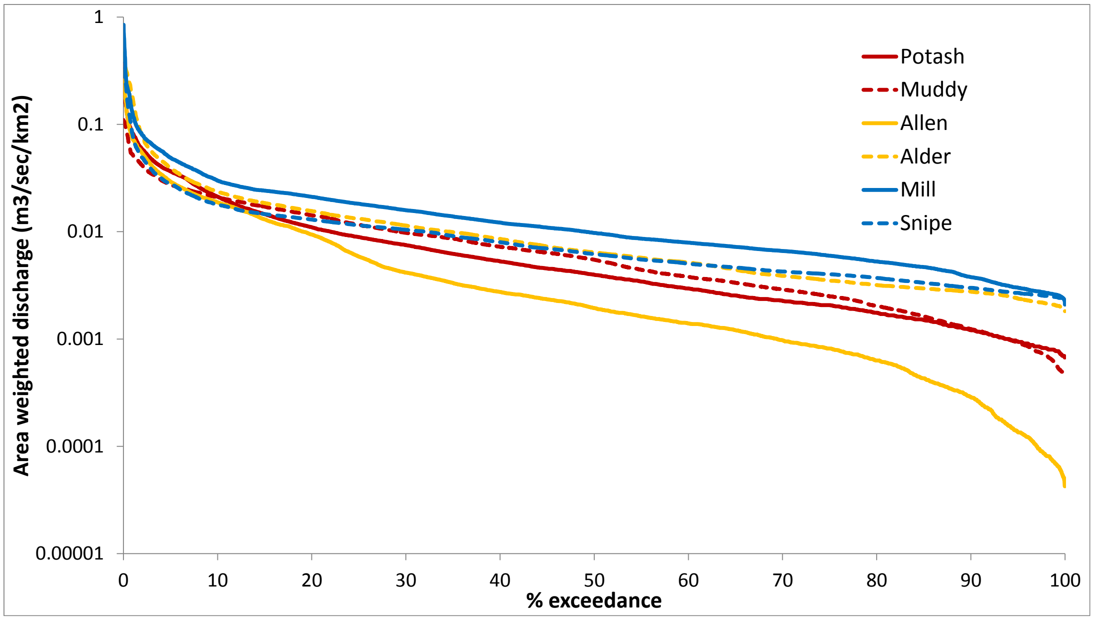

Figure 3. Flow duration curves based three-year hourly flow data.

Table 5. Flow duration analysis summary.

Watershed	Q10	Q50 Median	Q90 Baseflow	Q90/Q50 Baseflow Contribution	Q10/Q50 Flood Peak Index
Snipe	0.018	0.006	0.0030	0.484	5.97
Mill	0.030	0.010	0.0038	0.392	7.90
Alder	0.024	0.006	0.0028	0.438	8.43
Allen	0.019	0.002	0.0003	0.145	65.52
Muddy	0.021	0.006	0.0012	0.225	16.94
Potash	0.021	0.004	0.0012	0.300	17.67

Continuous Water Quality Results

The YSI multi-parameter sondes collected readings of water temperature, dissolved oxygen, and specific conductivity at a 5 minute interval. We collected approximately 140,000 sets of these readings at each monitoring station over the duration of the project. These continuous data allow for observation of interactions between numerous parameters over a discrete rainfall event, and the characterization of water quality data over longer periods of time. Figure 4 shows 10 days of continuous data from Potash Brook. Regular daily fluctuations in temperature and dissolved oxygen are observed until a moderate storm on 9/23/09. The storm event causes a small spike in water temperature as runoff is produced on hot surfaces (i.e. pavement and rooftops). Conductivity is very high Potash Brook throughout the summer as a result of high salt loading in groundwater which will be discussed later in this section. Conductivity levels are highest at low discharges when the groundwater contribution is greatest. The conductivity drops during the storm event as rainwater and surface runoff increase discharge.

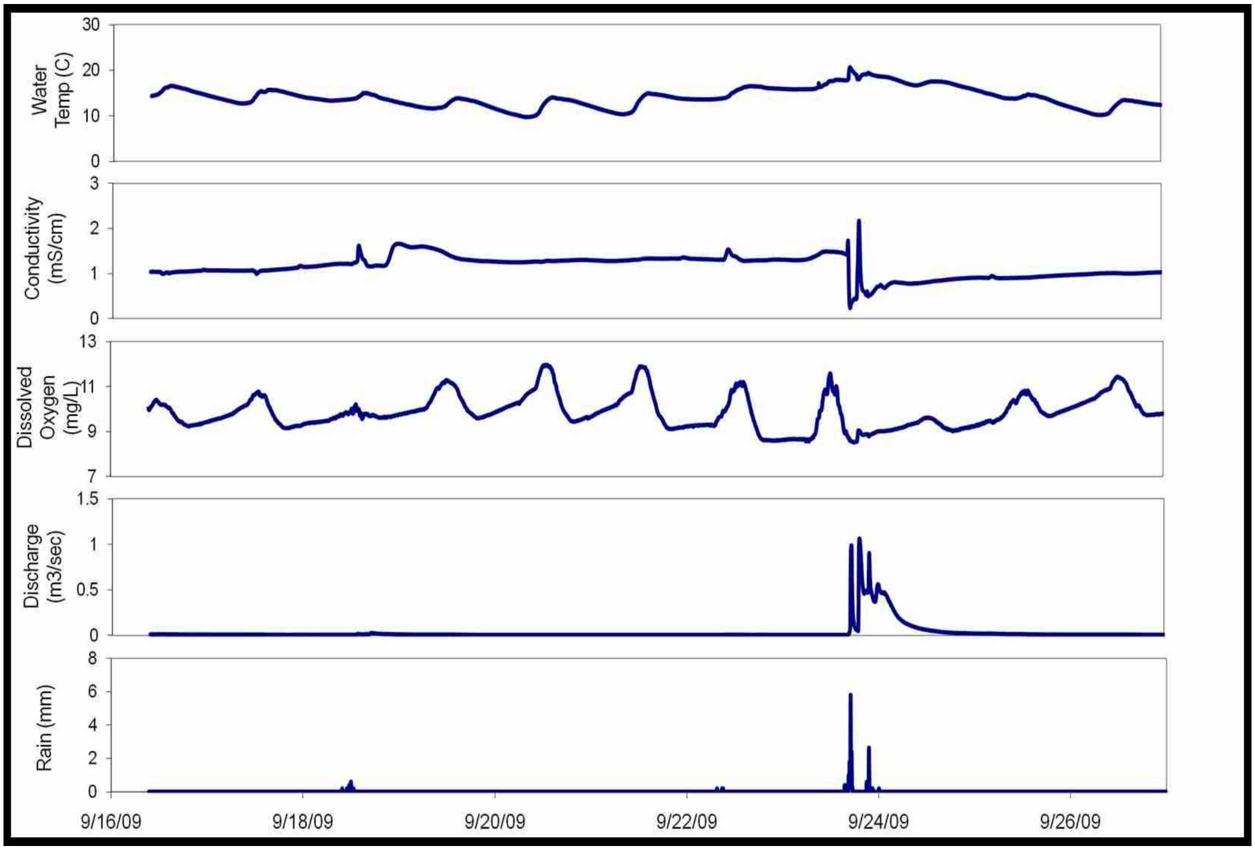

Figure 4. Typical water quality parameter values from continuous monitoring sondes with a moderate storm late on 9/23/09

Water temperature and dissolved oxygen concentration data were analyzed for minimum and maximum values for discrete readings, daily means, and seven day means as described in Wang et al. (2003). We observed increased maximum temperatures, decreased dissolved oxygen concentration, and large increases in the daily ranges for both of these parameters (Table 6).

Table 6. Water temperature and dissolved oxygen concentration summary data.

Watershed	Max Temp °C	7-day Max Temp °C	Max Daily Range Temp °C	Min DO (mg/L)	7-day Min DO (mg/L)	Max Daily Range DO (mg/L)
Snipe	22.0	20.0	6.7	8.4	8.8	1.8
Mill	25.2	21.9	7.3	7.9	8.5	1.9
Alder	27.5	23.0	7.7	5.9	7.6	5.8
Allen	28.9	25.3	8.5	5.4	7.0	3.8
Muddy	31.1	26.5	7.1	6.7	7.7	5.2
Potash	27.4	23.8	6.2	6.2	8.0	6.0

High temperatures and low dissolved oxygen concentrations are major stressors for aquatic life in developed watersheds. We observed increased maximum temperatures in the more developed streams; however this is strongly influenced by shading of the channel within the reach immediately upstream of the monitoring station. Dissolved oxygen concentrations are closely linked with temperature and biological activity within the stream. The more developed watersheds had lower minimum oxygen concentrations and much higher daily variation in concentration. The minimum concentrations we observed in these streams are at or near the requirements for sensitive fish and macroinvertebrate species (Meador et al. 2008).

Baseflow and Storm Event Water Quality Results

Baseflow grab samples were collected 2-4 times at each station in 2008 and then once a month at all stations from January 2009 through January 2011, for a total of 28-29 samples per watershed. Time-paced composite storm event samples were collected for 26 – 35 storms at each station. Baseflow concentrations of TP were lower than storm event concentrations at all sites and significant at Alder and Potash (Figure 5). Storm event concentrations were significantly higher at Alder and significantly lower at Mill compared to the remaining watersheds. Baseflow TP concentrations were significantly higher at Muddy and lower at Snipe, with an additional grouping of Muddy and Allen significantly higher than Mill and Snipe.

Concentrations of total nitrogen in baseflow and storm event samples were generally similar for each site; Snipe had significantly higher storm event concentrations (Figure 6). Tukey-Kramer comparison of means for both baseflow and storm event samples had three significant groups: Potash was highest; Alder, Allen, and Muddy were moderate; and Mill and Snipe had the lowest concentrations.

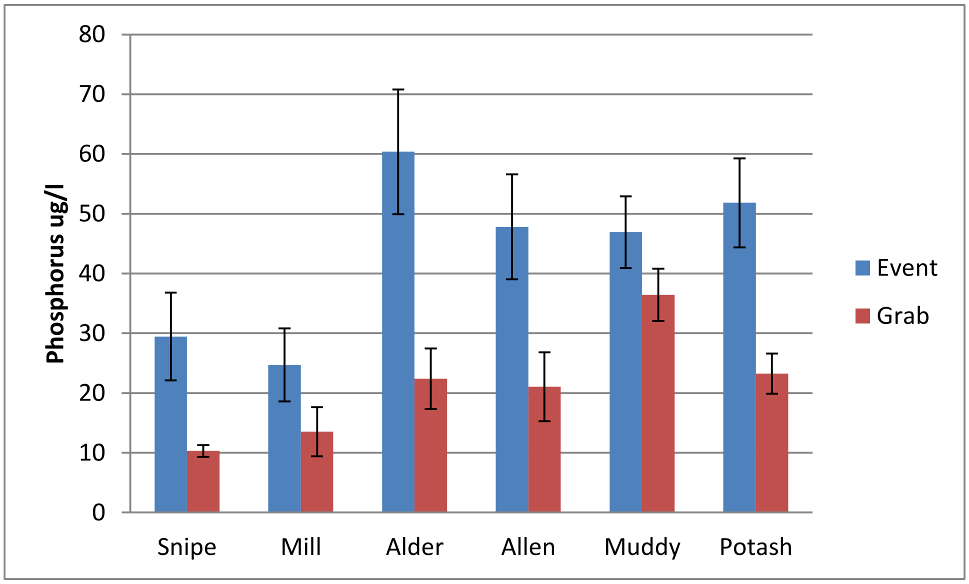

Figure 5. Mean total phosphorus concentrations for storm event and baseflow grab samples (error bars represent +/1 1 SE)

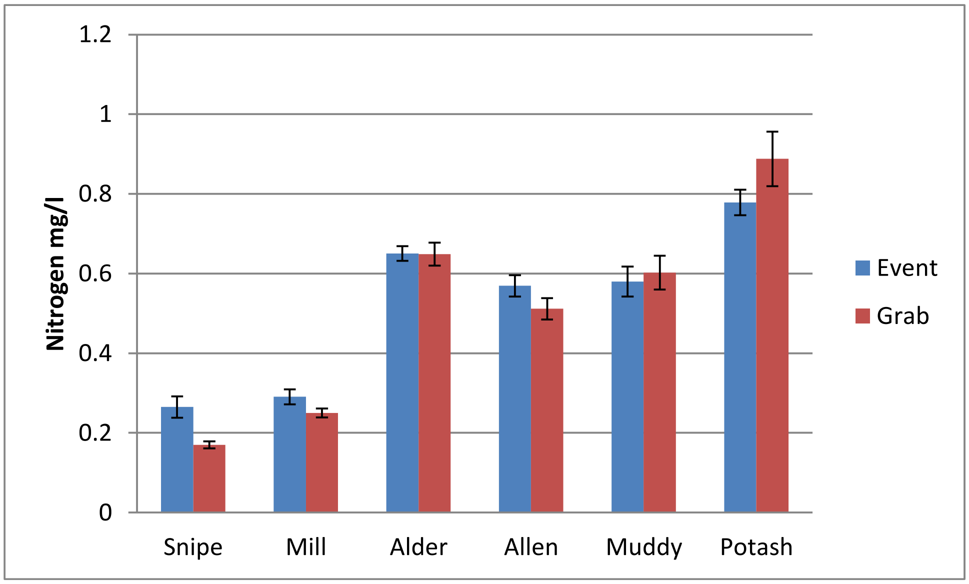

Figure 6. Mean total nitrogen concentrations for storm event and baseflow grab samples (error bars represent +/- 1 SE)

Chloride concentrations were significantly higher in the watersheds with paved roads and higher development (Figure 7). Potash had significantly higher concentrations for baseflow and storm event samples. Muddy had significantly higher storm event concentrations than Alder and Allen, and Mill and Snipe had the lowest concentrations by over an order of magnitude. Baseflow concentrations produced the following Tukey-Kramer groupings in decreasing order: Potash, Muddy and Alder, Alder and Allen, and Mill and Snipe. Chloride concentrations were significantly higher in baseflow samples at Potash compared to storm event samples. The high concentrations of chloride in the watersheds with large networks of paved roads are directly linked to the extensive use of road salt during icing months. The highest chloride concentration (795 mg/L) in Potash Brook was observed in February; however levels remained very high throughout the summer suggesting that groundwater contributions are a major source of chloride. Similar seasonal patterns were also observed in the remaining watersheds with paved roads. Concentrations in Mill and Snipe were consistent throughout the year indicating minimal contributions from road maintenance.

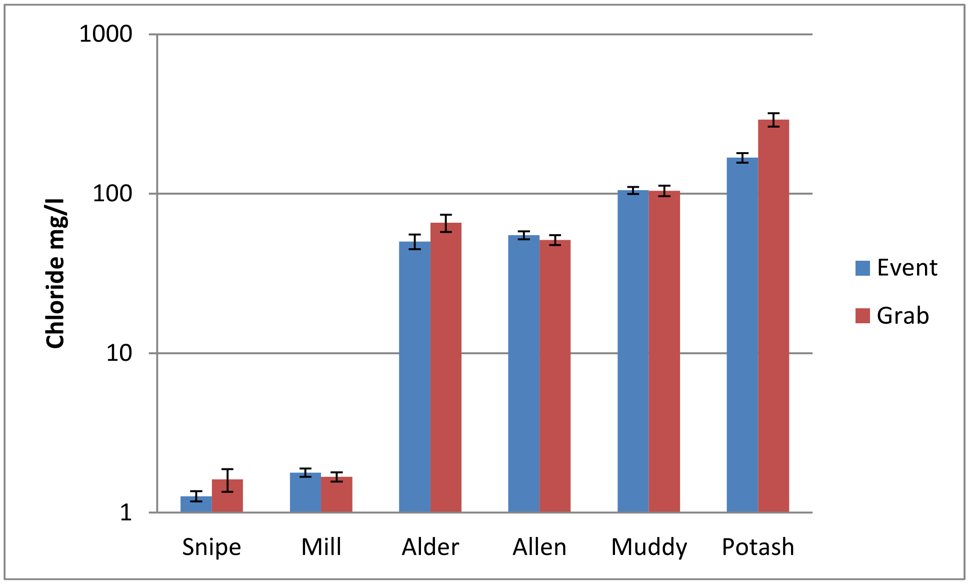

Figure 7. Mean Chloride concentrations for storm event and baseflow grab samples (error bars represent +/- 1 SE) *Note logarithmic scale on y-axis

Total suspended sediment concentrations were significantly higher during storm events for all watersheds (Figure 8). In contrast to the nutrient and chloride results, Alder Brook has significantly higher storm event sediment concentrations and Alder and Muddy have significantly higher baseflow concentrations to the other watersheds. The two rural watersheds with primarily dirt/gravel roads have statistically similar sediment concentrations to watersheds with much higher densities of roads and development.

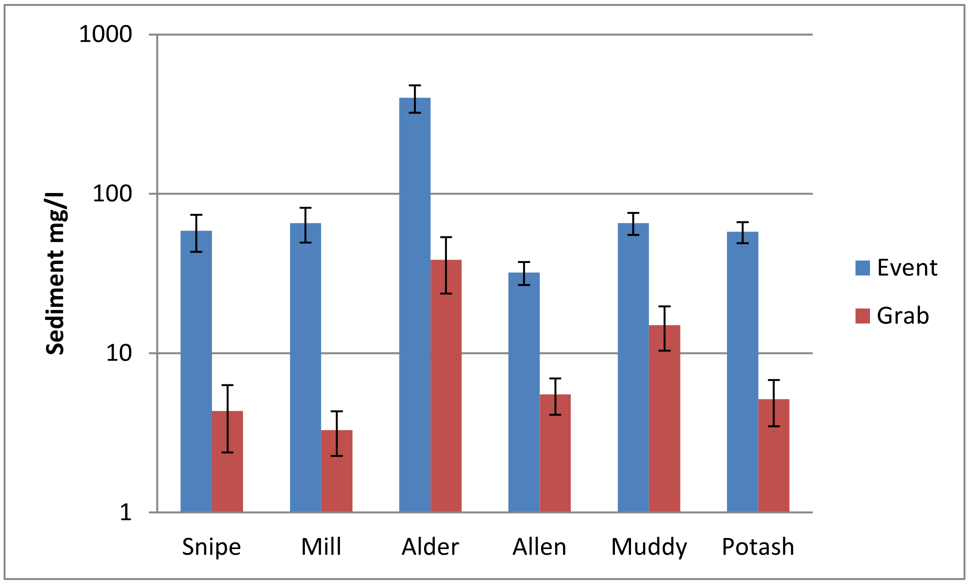

Figure 8. Mean total suspended sediment concentrations for storm event and baseflow grab samples (error bars represent +/- 1 SE) *Note logarithmic scale on y-axis

Macroinvertebrate Results

The total number of unique macroinvertebrate species (richness) and the number of unique species from pollution sensitive Ephemeroptera, Plecoptera, and Trichoptera (EPT) families both decreased in the watersheds with higher road density and development (Table 7). The Index of Biotic Integrity (BI) summarizes the overall pollution tolerance of the BMI community and also followed the same pattern with scores increasing (more pollution tolerant) with increasing road density and development. PMA-O1 is a comparison of the sampled BMI community to the reference community for a given stream type and was least similar in the most developed watersheds and most similar for Mill Brook.

Table 7. Benthic macroinvertebrate community results.

Watershed	Species Richness	EPT Richness	BI	PMA-O1
Snipe	46	27.5	3.14	73.1
Mill	47.5	29	2.80	89.2
Alder	40	19	3.88	64.5
Allen	42.5	19	4.02	73.2
Muddy	41	16	4.52	63.7
Potash	39	13	5.45	56.1

RHA Results

The rapid habitat assessment results show a decrease in RHA rating and condition in the developed watersheds (Table 8). The RHA was conducted on the reach immediately upstream and downstream of the monitoring station, weighting the importance of the local condition. Sediment deposition was a common impact in the developed streams with decreased riffle and pool variability and increased embeddedness. Bank stability impacts were important at several sites and are frequently a response to increased peak flows.

Table 8. Rapid habitat assessment results

Watershed	RHA Rating	RHA Condition	Impacts
Snipe	72.5	Good	Substrate, Buffer
Mill	89.0	Reference	Deposition, Bank Stability
Alder	68.5	Good	Pools, Deposition, Bank Stability
Allen	72.5	Good	Pools, Channel Alteration, Buffer
Muddy	53.5	Fair	Substrate, Channel Alteration, Buffer
Potash	60.5	Fair	Substrate, Pools, Bank Stability

Road Network/Water Quality Parameter Relationships

We tested the strength of several road network metrics for predicting water quality, BMI characteristics, habitat quality, and the relationship with watershed imperviousness. Spearman's ρ correlation results that are significant at $\alpha=0.10$ are shown in gray, significant correlations are shown in black: * denotes $p=0.05$, ** denotes $p=0.01$, and *** denotes $p<0.001$ (Tables 9-11). Total watershed imperviousness (%TIA) is a strong predictor of water quality, BMI, and habitat quality. This supports findings from numerous studies on urbanization and watershed impacts (multiple citations). Stream crossing density was the most powerful road network predictor of water quality, BMI, and stream habitat quality. Correlations with road/stream crossings were significant for 7-day maximum temperature, maximum dissolved oxygen range, event and baseflow concentrations of TN and Cl, baseflow TP concentration, and BMI biotic integrity, EPT richness (negative). As expected, the road network metrics and watershed imperviousness are all correlated, however the lower level of significance between imperviousness and road density within a 100m stream buffer highlights the potential for underestimating impacts of development in steeper watersheds where a large percentage of the imperviousness may be very close to the receiving waterbody.

Table 9. Road network metric correlation with water quality results

Predictor	Max Temp 7d	Min DO	Max DO Range	Event Concentrations TP	Event Concentrations TN	Event Concentrations Cl	Baseflow Concentrations TP	Baseflow Concentrations TN	Baseflow Concentrations Cl
Stream Crossings	0.83 *		0.83 *		0.83 *	1.00 ***	0.89 *	0.83 *	0.95 **
Road Density	0.77		0.77		0.77	0.94 **		0.77	0.83 *
100m Road Density	0.77		0.77		0.77	0.94 **		0.77	0.83 *
%TIA			0.94 **		0.94 **	0.94 **	0.94 **	0.94 **	1.00 ***
%Road TIA		-0.8 *	0.83 *	0.8	0.83 *	0.83 *		0.83 *	0.77

Table 10. Road network metric correlation with BMI and habitat results

Predictor	Species Richness	EPT Richness	PMA-O1	BI	RHA
Stream Crossings	-0.77	-0.93 **		0.94 **	-0.75
Road Density		-0.84 *		0.89 *	
100m Road Density		-0.84 *		0.89 *	
%TIA	-0.89 *	-0.93 **	-0.83 *	0.89 *	-0.84 *
%Road TIA	-0.77	-0.75		0.77	

Table 11. Road network and watershed imperviousness correlation

Predictor	Stream Crossings	Road Density	Road Density 100m
Stream Crossings	--		
Road Density	0.94 **	--	
100m Road Density	0.94 **	1.00 ***	--
%TIA	0.94 **	0.83 *	0.83 *
%Road TIA	0.83 *	0.95 **	0.95 **

Selected regression plots from the road network metric analysis are shown in Figures 9-11. These regressions show the significant positive correlations of stream/road crossing density with TN and Cl storm event and baseflow concentrations and the significant negative correlation with EPT richness.

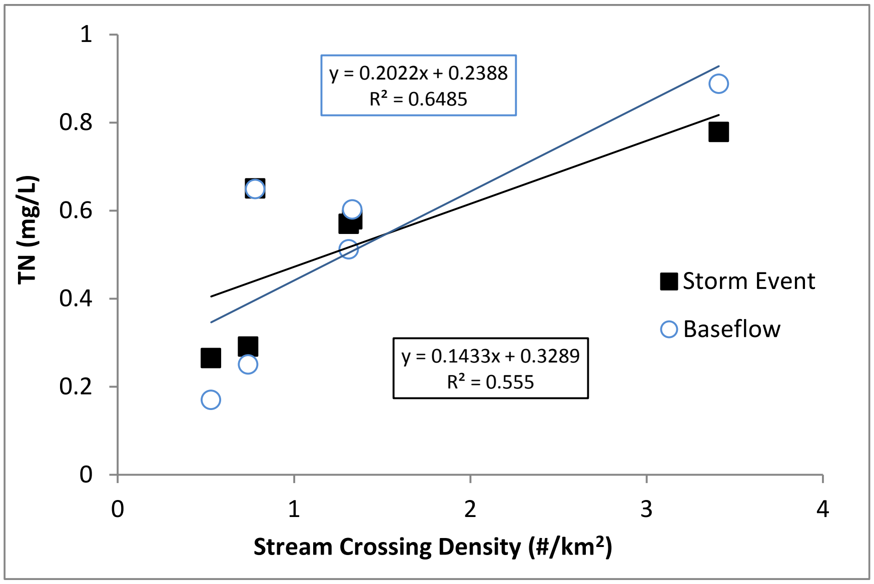

Figure 9. Regression of stream crossing density and TN concentrations

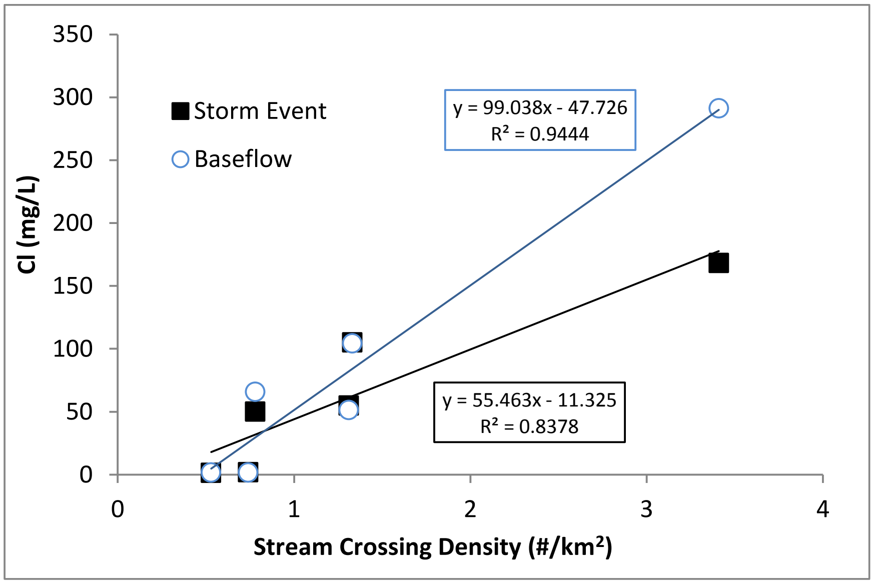

Figure 10. Regression of stream crossing density and Cl concentrations

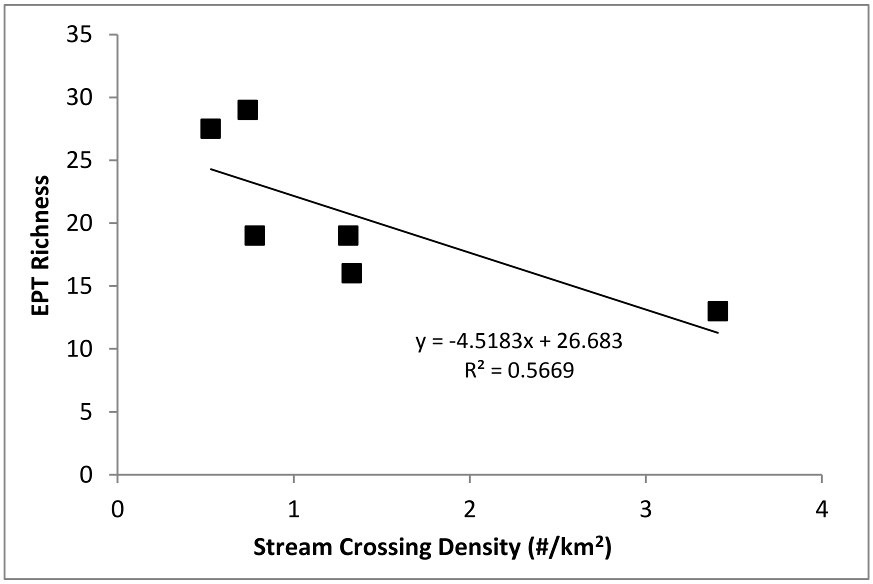

Figure 11. Regression of stream crossing density and EPT Richness

Discussion

Over the years, stormwater has become a politically charged issue in Vermont and throughout the country. Although stormwater is generated on all surfaces every time it rains or snows, the transportation network (roads, parking lots, and railways) represents a large percentage of the impervious surfaces across that landscape that can increase the peak flow and contribute significant quantities of pollution to surface waters (Eyles and Meriano 2010, Kang and Marston 2006). While important progress has been made to treat and reduce pollution from point sources, less progress has been made to address nonpoint sources of pollution, and for many streams, rivers, lakes and estuaries, this source of pollution is now responsible for the majority of the load (US EPA 2002, 2006). We calculated a series of road density metrics that can be used to easily and consistently quantify potential water quality impacts in a watershed. All of the road density metrics correlated with a range of observed impacts; however the density of stream/road crossings was the most successful predictor for impacts. This is in part due to the inherent proximity of road surfaces and drainage infrastructure located at or near every crossing. Drainage infrastructure such as culverts and ditches directly channels stormwater runoff to streams and has greater impact than other impervious surfaces in the watershed (Booth and Jackson 1997, Schiff and Benoit 2007, Wheeler et al. 2005). Undersized structures and associated channel alterations near these crossings can cause major physical impacts such as sediment transport interruption, bank erosion, buffer degradation, and deposition (Lane and Sheridan 2002, Wheeler et al. 2005).

Concentrations of phosphorus and nitrogen increased along the gradient of development and road network density. These findings were consistent with numerous studies in urbanized watersheds (Cunningham et al. 2009, Noll and Magee 2009, Paul and Meyer 2001, and Wheeler et al. 2005). We also found large increases in chloride concentrations in baseflow and storm event samples. These findings are supported by studies in Vermont and other cold-weather regions where deicing chemicals are applied throughout the winter (Cunningham et al. 2009, Denner et al. 2009, and Kelly et al. 2008).

Total suspended sediment concentrations were not correlated with development or road network density. The presence of unpaved roads in the rural watersheds increased suspended sediment concentrations to levels that were statistically similar to the most developed watersheds (Schoonover et al. 2007). Major transport of sediment from unpaved roads has been described in several studies; however these watersheds primarily contained logging roads (Jordan and Martinez-Zavala 2008, Lane and Sheridan 2002, Sheridan and Noske 2007).

We did not observe significant changes in the hydrologic regime in our watersheds, however decreased baseflow likely increases temperature and dissolved Oxygen impacts that were significantly correlated with road network metrics (Herb et al. 2008, Richter et al. 1996, and Wang et al. 2003). Riparian buffer degradation also contributes to the increased water temperature and daily ranges we observed (Angermeier et al. 2004, Schiff and Benoit 2007, Walsh et al. 2005).

The levels of imperviousness and road network density in our six study watersheds are lower than levels previous studies have classified as “moderate”, however these watersheds are representative of the full range of developed areas of Vermont (Chadwick et al. 2006). The relatively low level of total imperviousness likely increases the proportional impact of roads within each watershed. Despite the relatively low level of development in our study watersheds, our results showed significant physical, chemical, and biological impacts associated with increasing watershed imperviousness and road network density metrics. Most of our findings closely follow the results of numerous studies that link watershed imperviousness to a suite of physical, chemical, and biological impacts known as the “urban stream syndrome” (Cunningham et al. 2009, Denner et al. 2009, Noll and Magee 2009, Paul and Meyer 2001, and Wheeler et al. 2005). These results suggest that additional safeguards are necessary to reduce the impacts of roads and associated development on streams in the Chittenden County area of Vermont.

Acknowledgements

Drs. Mary Watzin and Donald Ross provided important advice and support for this project. We thank Colin Penn, Patrick Tobin, Dan Freedman, Bianca Rodriguez, and Kelsey McAuliffe for essential assistance with field and laboratory work during this project. Susan Fuller and Leman Bronson provided additional laboratory assistance. We thank Steve Fiske and the Vermont Department of Environmental Conservation BASS lab for collaboration on the benthic macroinvertebrate data. We express special thanks to the members of the Bowden Watershed Research Team for their input and support. This project was supported by funding from the University of Vermont Transportation Research Center (TRC). The summaries and conclusions expressed in this report are those of the authors and do not represent the opinions of the TRC. We express our thanks to the staff of the TRC for their support and patience as we completed this report.

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