Environ Monit Assess (2015) 187: 510
DOI 10.1007/s10661-015-4730-0

Landscape level estimate of lands and waters impacted by road runoff in the Adirondack Park of New York State

Sean A. Regalado · Daniel L. Kelting

Received: 8 January 2015 / Accepted: 7 July 2015 / Published online: 20 July 2015

Abstract Road runoff is understood to be a significant stressor in terrestrial and aquatic ecosystems, yet the effects of this stressor are poorly understood at large spatial scales. We developed an efficient method for estimating the spatial impact of road runoff on lands and waters over large geographic areas and then applied our methodology to the 2.4 million ha Adirondack Park in New York State. We used TauDEM hydrologic modeling and a series of ESRI GIS processes to delineate surface flow downslope of paved roads, illustrating the potential movement of pollutants originating from paved roads through the USGS 10 m DEM topography. We then estimated the land and surface water areas, number of water bodies, and total stream length potentially impacted by road runoff from paved roads. We found that as much as 11 % of land area, 77 % of surface water area, 1/3 of the water bodies, and 52 % of stream length in the Adirondack Park may be impacted by road runoff. The high degree of hydrologic association between paved roads and the lands and waters of this region strongly suggests that the environmental impacts of road runoff should be evaluated along with other regional stressors currently being studied. Being able to estimate the spatial impact of road runoff is important for designing monitoring programs that can explicitly monitor this stressor while also providing opportunities to understand the interaction of multiple environmental stressors.

Keywords Road runoff · Road salt · GIS · TauDEM · Multiple environmental stressors · Adirondack Park

Introduction

The 2.4 million ha Adirondack State Park in northern New York State, USA, encompasses the world's largest intact temperate forest which contains a globally unique landscape of wetlands, northern hardwood and boreal forests, alpine tundra, and vast fresh water resources (Jenkins and Keal 2004). This large rural landscape is exposed to multiple environmental stressors operating at varying spatial scales and often in interacting ways that are poorly understood (Allan 2004; Palmer and Yan 2013). Historically, the principal environmental stressors studied in the region have been acid deposition and climate change (Ito et al. 2002; Stager et al. 2009). In recent years, road runoff has been identified as a significant threat to aquatic and terrestrial ecosystems in the region, comparable to acid deposition (Kaushal et al. 2005; Kelting and Laxson 2010). Over 8000 km of paved roads traverse the Adirondack Park; therefore, the potential land and surface water area receiving road runoff pollutants may be significant and likely also occurs on protected state lands which represent 45 % of the area.

S. A. Regalado · D. L. Kelting (✉)
Adirondack Watershed Institute, Paul Smith's College,
Routes 86 & 30, PO Box 265, Paul Smiths, NY 12970, USA
e-mail: dkelting@paulsmiths.edu

S. A. Regalado
e-mail: sregalado@s.paulsmiths.edu

The main categories of pollutants found in road runoff are road de-icing salts, heavy metals, herbicides, and polycyclic aromatic hydrocarbons (Trombulak and Frissell 2000; Fay and Shi 2012; Tang et al. 2013). Road runoff pollutants have been shown to induce tree mortality (Fan et al. 2014), shift the composition of floral and faunal communities (Kaspari et al. 2010; Ke et al. 2013; Neher et al. 2013; Snell-Rood et al. 2014), promote establishment of terrestrial and aquatic invasive species (Johnston and Johnston 2004; Crooks et al. 2011), and elevate Na concentrations in roadside soils, displacing base cations (Ca, Mg, K) essential to ecosystem function (Norrström and Bergstedt 2001). Flux of displaced cations and Cl into streams has been reported downslope of salted roads (Daley et al. 2009; Price and Szymanski 2013; Corsi et al. 2015), and Na and Cl concentrations in lakes correlate positively with paved road density (Kelting et al. 2012). Road runoff pollutants in lakes and rivers can increase fish and amphibian mortality (Yousef et al. 1983; Karraker et al. 2008) and may induce top-down (Sloman et al. 2003) and bottom-up trophic cascades (Hodkinson and Jackson 2005). Road runoff pollutants can affect ecosystem function similarly to other regional stressors (Norrström and Bergstedt 2001) and can often interact synergistically, enhancing their effects on terrestrial and aquatic communities (Holmstrup et al. 2010). Pollutants commonly found in road runoff have been shown to exacerbate the effects of warming temperatures (Qiang et al. 2012), drought (de Silva et al. 2012), acid deposition (Rosfjord et al. 2007), eutrophication (Ferreira et al. 2008), and disease (Kiesecker 2002).

Although the impacts of road runoff on terrestrial and aquatic ecosystems are well known, no studies have been published that model the spatial extent of road runoff over large geographic areas. Accurate knowledge of the spatial extent of road runoff is essential to understanding and managing the interacting impacts of road runoff and other regional stressors on aquatic and terrestrial ecosystems (Soranno et al. 2014). Our objectives were to develop an efficient method of estimating the spatial extent of road runoff impacts on lands and waters over large geographic extents and to quantify the land area and surface water areas, number of water bodies, and total length of streams potentially impacted by road runoff from state and federal, county, and local roads within the Adirondack Park.

Methods

Study area

The Adirondack Park (Park) is located in New York State, USA (Fig. 1). The Park is 2.4 million ha in size and is roughly divided equally between private and public lands that are dominated by natural forest cover. The Park contains over 8000 km of paved roads, broken out into 1965 km of state and federal roads, 1803 km of county roads, and 4421 km of local roads (Table 1). The Park also contains about 103,000 ha of surface water (lakes and ponds) and over 13,000 km of streams.

Estimating spatial extent of road runoff

Spatial data for depth to bedrock and groundwater flow was lacking for the Adirondack region, so we used surface topography to delineate the potential flow of runoff downslope of paved roads. We used ArcGIS - ArcMap 10.2 (Esri, Redlands, CA) with a hydrologic terrain analysis toolset TauDEM 5.1.1 (TauDEM Toolbox 5.1.1, www.hydrology.usu.edu/taudem) to develop a series of parameters: a hydrologically relevant surface based on the D-infinity flow direction algorithm (Tarboton 1997), indicator grids of rasterized road networks, effective precipitation weights, and decay multipliers (Fig. 2). TauDEM 5.1.1's "D-Infinity concentration limited accumulation" tool used these parameters to delineate flow downslope of the rasterized road networks. We then used a series of ArcGIS processes to quantify the total land area represented by the downslope accumulations, as well as to identify the hydrologically connected water bodies, and to quantify the length of rivers and streams downstream of road runoff. We used Adirondack Park Agency (APA) land use classification shapefiles to determine the estimated lands and waters impacted by road runoff in the Park's forest preserves. Our methods are briefly described here, a more detailed description is provided in the Appendix.

Producing a hydrologically relevant surface

We obtained 202 USGS 10 m New York State 7.5-min Digital Elevation Models (DEMs) from the Cornell University Geospatial Information Repository (cugir.mannlib.cornell.edu). These DEMs were mosaicked; then, sinks were removed by raising their elevation to the lowest pour point using the TauDEM

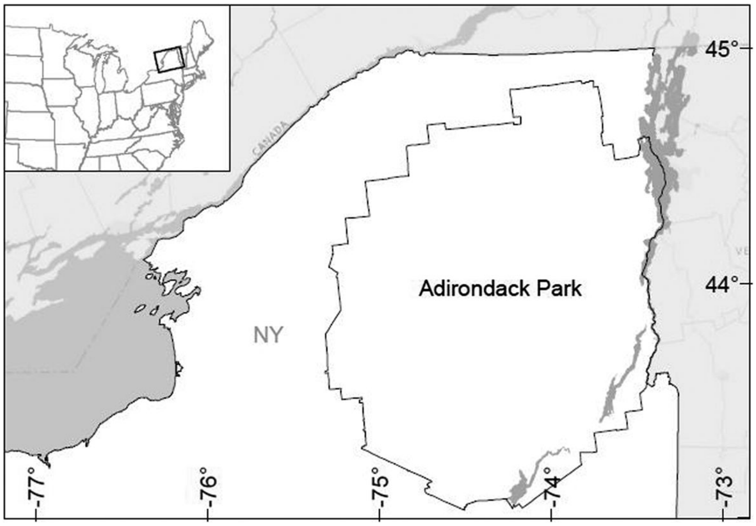


Fig. 1 Location of Adirondack Park in New York State, USA

5.1.1 Pit Remove tool (TauDEM Toolbox 5.1.1, www.hydrology.usu.edu/taudem). Pits often occur due to deficiencies in DEM production (Jenson and Domingue 1988). A D-infinity flow direction grid was derived from the pit removed DEM using the TauDEM D-infinity flow direction algorithm (Tarboton 1997).

Producing road disturbance grids

Road disturbance grids indicate the spatial location of road runoff inputs in the flow delineation process. Road polyline shapefiles were created by extracting road polylines from NYSDOT Local Highway Inventory datasets by three separate road categories: state and federal (SF), county (C), and local (L) roads (apa.ny.gov/gis). The ESRI "buffer" tool was used to create 100 m road spray influence shapefiles for each category, including a combined dataset of all paved roads (SFCL). The buffer added 100 m to each side of the road. These eight shapefiles (SF, C, L, and SFCL and 100 m SF, 100 m C, 100 m L, and 100 m SFCL) were converted into 10 m cell size raster datasets using the ESRI "polyline to new raster" tool and the "polygon to new raster" tool. Field experiments have shown vehicular spray, and wind can transport pollutants hundreds of meters from the road (e.g., Zechmeister et al. 2005; Bernhardt-Roemermann et al. 2006), so the 100 m buffer was selected as a conservative estimate of road spray.

Table 1 Total road length by category, total area of surface water, and total length of streams in the Adirondack Park, New York

Landscape parameter	Total park
State and federal roads (km)	1965
County roads (km)	1803
Local roads (km)	4421
Surface water (ha)	102,792
Stream length (km)	13,153

Producing input weights

An effective runoff grid and a first-order decay multiplier grid were required model parameters. Effective runoff grids represent the precipitation over an area. For simple contributing area delineations such as this, the weighting field was a constant raster set to 1 (Tarboton et al. 2009). The decay multiplier grid value was an exponential decay factor. The decay factor for road runoff was set to a constant raster of 1; this value was arbitrary for we were only interested in the spatial extent of runoff, not any quantitative accumulation values.

Delineating overland flow grids

TauDEM's "D-Infinity concentration limited accumulation" tool was used to delineate substance accumulation downhill of the eight disturbance indicator grids, SF, C, L, and SFCL and the 100 m buffered SF, C, L, and SFCL.

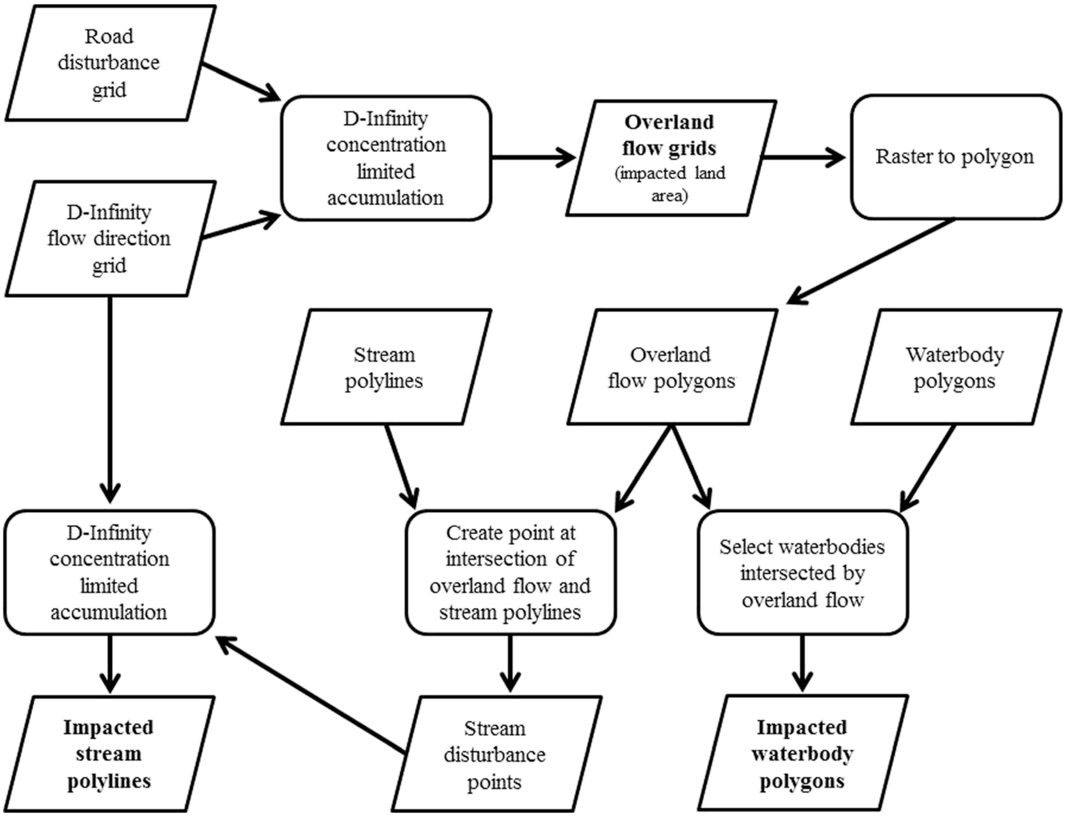


Fig. 2 Flow chart of TauDEM hydrologic modeling and ArcGIS processes used to delineate surface flow downslope of paved roads and to estimate the land area, surface water area, and total stream length impacted by road runoff from paved roads

Quantifying impacted land area

Cells with a value greater than zero represented overland flow. The >0 cells were extracted using the ArcGIS "extract by attribute" tool. To exclude overland flow cells that traversed open water areas, extracted cells were multiplied by a park wide open water raster dataset (cell values: open water=NoData, land=1) using the ArcGIS "times" tool.

Identifying simultaneous impacts of multiple road categories

Lands impacted by multiple road sources were found by multiplying the overland flow rasters by category using the ArcGIS "times" tool (SF×C, SF×L, SF×C×L, et cetera). Lands not impacted by the multiple roads in question resulted in a NoData output value.

Identifying impacted lakes and ponds

The original eight overland flow grid outputs (those without open water cells removed) were converted to polygons using the ArcGIS "raster to polygon" tool. ArcGIS's "select by location" tool was used to select lakes and ponds from the NYS area hydrography shapefile that intersected with the overland flow polygons. Intersected lakes and ponds were extracted according to the road category they intersected with. These intersected lakes and ponds were hydrologically connected to road runoff based upon the DEM-derived flow direction.

Calculating downstream length of impacted streams

The converted polygons of the eight overland flow categories were intersected with linear hydrography polylines from a NYS hydrography dataset of rivers and streams (gis.ny.gov) using the ArcGIS "intersect" tool. Point shapefiles were created and then converted to raster datasets using the ArcGIS “point to raster” tool and were treated as disturbance indicator grid parameters for the TauDEM “concentration limited accumulation” tool. The eight subsequent flow grids were then converted to polylines. The eight polylines shape files (SF, C, L, and SFCL and 100 m SF, C, L, and SFCL impacted streams) represented impacted stream channels.

Quantifying impacted lands and waters in APA forest preserve lands

The ArcGIS “zonal statistics as table” tool was used to categorize total impacted terrestrial area for each of the 15 APA land use types in the Adirondack Park Land Use and Development Plan dataset (apa.ny.gov/gis).

Results

A total of 156,561 ha of land area was estimated to be impacted by road runoff, which constituted 6.5 % of the land area of the Park (Table 2). Of this total, runoff from state and federal roads was estimated to impact 36,991 ha of land area, while runoff from county and local roads was estimated to impact 44,182 and 96,550 ha of land area, respectively. The total land area estimated to be impacted by road runoff increased to 254,224 ha when including the 100 m buffer on all roads, which constituted 11 % of the land area of the Park. The relative contribution to impacted land area from state and federal, county, and local roads was the same with and without the 100 m buffer and was proportionate to the length of each road type in the Park (e.g., local roads represented 54 % of total road length and 61 % of the impacted land area). An example of the relationship between the three road types and land area impacted by road runoff is provided for a 5000-ha area in the vicinity of the Village of Saranac Lake within the Park (Fig. 3). In this example, runoff from state and federal roads impacted 6 % of the land area (Fig. 3a), runoff from county roads impacted 5 % of the land area (Fig. 3b), runoff from local roads impacted 11 % of the land area (Fig. 3c), and all three road types together impacted 18 % of the land area (Fig. 3d). The close association between the road network and impacted land and surface waters is also clearly seen.

We found a total of 1787 ha of land to be impacted by state, federal, county, and local roads simultaneously (Table 3). This value increased to 4042 ha when including the 100 m buffer. State, federal, and county roads simultaneously impacted 3255 ha without the buffer and 6980 ha with the buffer. State, federal, and local roads simultaneously impacted 8378 ha without the buffer and 19,009 ha with the buffer. County and local roads simultaneously impacted 11,228 ha without the buffer and 20,837 ha with the buffer.

A total of 77,860 ha of surface waters was estimated to be impacted by road runoff, which constituted 76 % of the surface water area of the Park (Table 2, Fig. 4d). Note that two large lakes, Great Sacandaga Reservoir and Lake George, constitute 26 % of this total. Including all lakes, runoff from state and federal roads was

Table 2 Land and surface water area, number of lakes, and stream length impacted by surface runoff from paved roads with and without a 100 m buffer in the Adirondack Park, New York

Landscape parameter	Road category			Total[a]
	State and federal	County	Local	
Land area (ha)	36,991	44,182	96,550	156,561
Land area (ha) (100 m)	63,018	71,291	164,823	254,224
Surface water area (ha)	62,656	62,218	72,982	77,860
Surface water area (ha) (100 m)	62,852	62,656	73,777	78,792
Number of lakes	326	299	644	820
Number of lakes (100 m)	351	328	711	884
Stream length (km)	2795	2859	4915	5934
Stream length (km) (100 m)	3238	2976	5230	6830

[a] Total is not the sum of the land and water impact of each road category as it includes land and water values with overlap

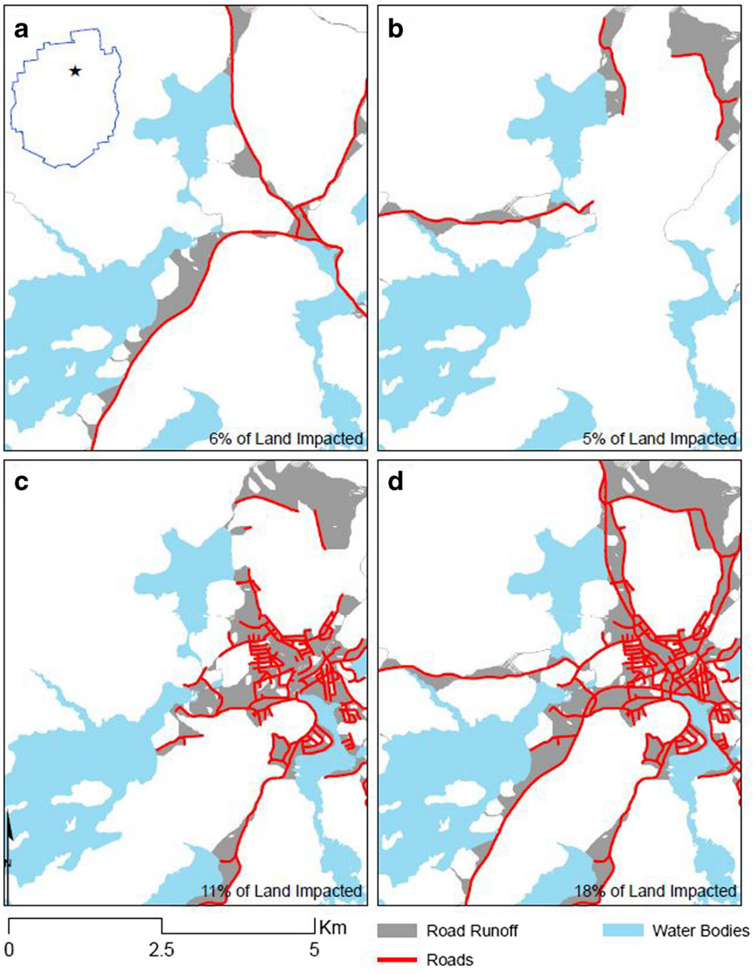


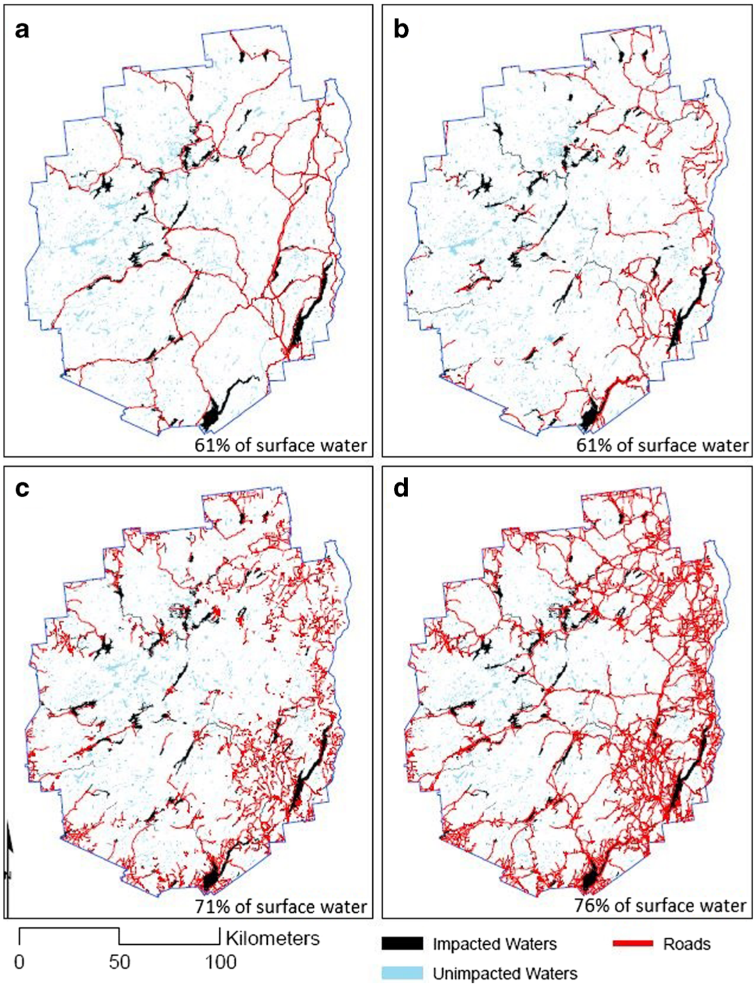
Fig. 3 Estimated land area impacted by road runoff from state and federal (**a**), county (**b**), local (**c**), and the total paved road networks (**d**) in a 5000-ha area centrally located within the Adirondack Park, New York. Location is indicated by the star symbol on map inserted into Fig. 3a

estimated to impact 62,656 ha (61 %, Fig. 4a) of surface water area, while runoff from county and local roads was estimated to impact 62,218 ha (61 %, Fig. 4b) and 72,982 ha (71 %, Fig. 4c) of surface water area, respectively. The total surface water area estimated to be impacted by road runoff increased slightly to

Table 3 Land and surface water area, number of lakes, and stream length impacted by surface runoff from multiple road categories with and without a 100 m buffer in the Adirondack Park, New York

Landscape parameter	Multiple road categories			
	State, federal, and county	State, federal, and local	County and local	State, federal, county, and local
Land area (ha)	3255	8378	11,228	1787
Land area (ha) (100 m)	6980	19,009	20,837	4042
Surface water area (ha)	61,503	63,217	63,268	59,893
Surface water area (ha) (100 m)	62,279	63,601	64,915	60,633
Number of lakes	207	287	269	184
Number of lakes (100 m)	216	312	291	194
Stream length (km)	1005	1295	2056	922
Stream length (km) (100 m)	1305	1731	2442	1222

Fig. 4 Estimated surface waters impacted by road runoff from state and federal (**a**), county (**b**), local (**c**), and the total paved road networks (**d**) within the Adirondack Park, New York



78,792 ha when including the 100 m buffer on all roads, which constituted 77 % of the surface water area of the Park. There were a total of 820 waters impacted by road runoff, with 326 waters impacted by state and federal roads, 299 waters impacted by county roads, and 644 waters impacted by local roads (Table 2). The relative contribution to impacted surface water area from state and federal, county, and local roads was the same with and without the 100 m buffer.

We found a total of 59,893 ha of surface water area to be impacted by the four road types (state, federal, county, and local roads) simultaneously, with this value increasing slightly when including the 100 m buffer (Table 3). The other multiple road categories had similar areas of surface waters impacted. The four road types impacted 184 lakes and 922 km of stream length simultaneously, with these values increasing to 194 lakes and 1222 km of stream length when including the 100 m buffer. The number of lakes and stream length impacted by the other multiple road categories was more variable compared to surface water area; for example, county and local roads simultaneously impacted over twice the stream length (2056 km) compared to the four road types together (922 km).

A total of 5934 km of stream length was estimated to be impacted by road runoff, which constituted 45 % of stream length in the Park (Table 2, Fig. 5d). Of this total, runoff from state and federal roads was estimated to impact 2795 km (21 %, Fig. 5a) of stream length, while runoff from county and local roads was estimated to impact 2859 km (22 %, Fig. 5b) and 4915 km (37 %, Fig. 5c) of stream length, respectively. The total stream length estimated to be impacted by road runoff increased to 6830 km (a 15 % increase) when including the

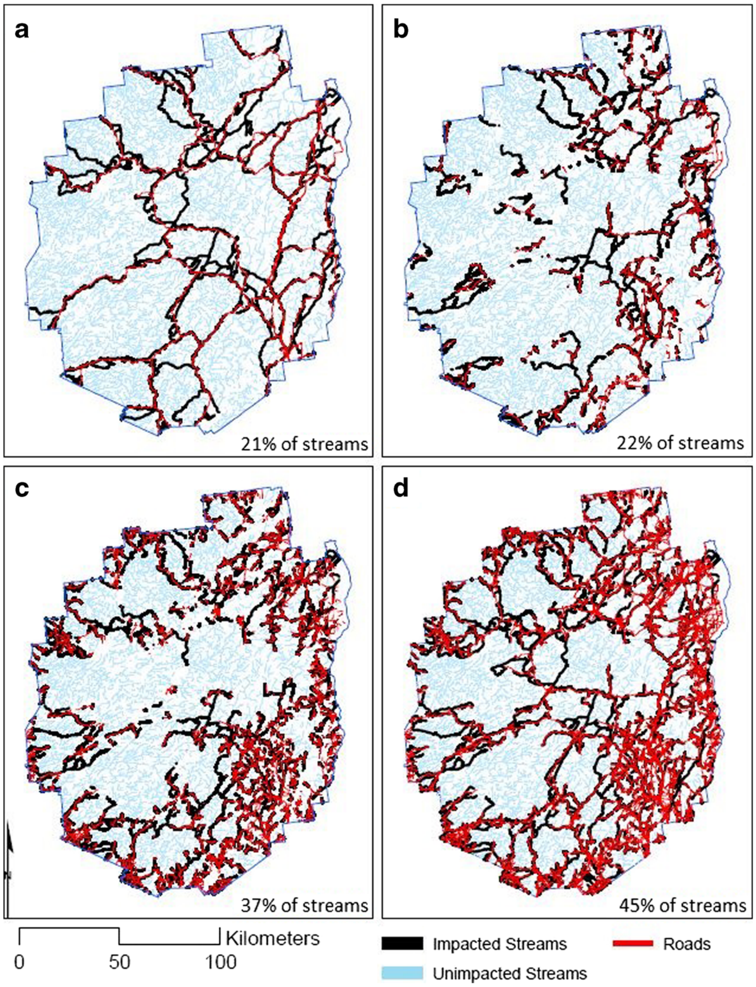


Fig. 5 Estimated streams impacted by road runoff from state and federal (**a**), county (**b**), local (**c**), and the total paved road networks (**d**) within the Adirondack Park, New York

100 m buffer on all roads, which constituted 52 % of stream length the Park.

Of the total 156,561 ha of land area estimated to be impacted by road runoff, 20,474 ha (13 %) was in the forest preserve, including the 100 m buffer which increased the impacted land area to 34,889 ha (Table 4). Of the total 78,153 ha of surface water area estimated to be impacted by road runoff, 67,496 ha (86 %) was in the forest preserve. Of the total 820 lakes estimated to be impacted by road runoff, 334 (40 %) were in the forest preserve. Of the total 5934 km of stream length estimated to be impacted by road runoff, 1152 km (19 %) was in the forest preserve. Within the forest preserve, 12 % of the impacted land area and 26 % of the impacted surface water area were located in lands classified as Wilderness, which are the most protected lands in the Park.

Discussion

Impacted lands and waters

Our results show a high degree of connectivity between paved road networks and lands and waters within the Park. Due to this high connectivity and the basic hydrologic connectivity between water and its watershed (Hynes 1975; Vannote et al. 1980), road runoff pollutants may flow through substantial land and surface water area in the Park. This area may be significantly greater than what we estimated with our 100 m buffer, as field experiments have shown vehicular spray and wind can transport pollutants hundreds of meters from the road (Zechmeister et al. 2005; Bernhardt-Roemermann et al. 2006); thus, our estimates are likely conservative. The results further show that local roads impact substantially more land area than state and federal roads;

Table 4 Land and surface water area, number of lakes, and stream length impacted by surface runoff from paved roads with and without a 100 m buffer located in state-owned forest preserve lands within the Adirondack Park, New York

Landscape parameter	Road category			Total[a]
	State and federal	County	Local	
Land area (ha)	7118	4490	10,470	20,474
Land area (ha) (100 m)	12,360	7196	18,274	34,889
Surface water area (ha)	58,177	57,163	63,530	67,496
Surface water area (ha) (100 m)	58,306	58,426	64,002	68,216
Number of lakes	157	126	254	334
Number of lakes (100 m)	165	135	272	353
Stream length (km)	454	474	860	1099
Stream length (km) (100 m)	477	447	927	1152

[a] Total is not the sum of the land and water impact of each road category as it includes land and water values with overlap

however, the impact of state and federal roads may be more intense. For example, road salt loading is largest for state and federal roads in the Park (Kelting and Laxson 2010) and the loading of heavy metals and PAH pollutants has been shown to increase with road use intensity, giving evidence to a disproportionate impact of high-use roads (Klimaszewska et al. 2007). The impacts of road runoff may be compounded in areas hydrologically connected to multiple road categories, which represents a challenge to monitoring and management as the road categories are managed in different ways. While state and federal roads are all salted, county, town, and local roads in the Park receive a variety of winter road management treatments from salting to just plowing (Kelting et al. 2012). Modeling flow downslope of high-use roads will identify high-risk land areas for effective monitoring regimes.

A substantial area of land downslope of roads may be at risk from decreasing soil fertility and increasing toxins. Road salt (NaCl) is widely used on roads throughout the region for snow and ice control, for example the New York State Department of Transportation applies 28 t of road salt per kilometer of state and federal road annually (NYSDOT 2006). Increased Na concentrations in road runoff have similar base cation depleting effects as acid deposition (Norrström and Bergstedt 2001) and may become a more relevant stressor as public policy has greatly reduced levels of acid deposition in the northeast (Waller et al. 2012). Given that 67,496 ha of land may be impacted by runoff from 1965 km of state and federal roads, we can assume that this land area is at risk of base cation depletion and may also be experiencing the toxic effects of other associated road pollutants such as heavy metals and PAHs. Road salt discharge compounded by the northeasterly gradient of acid deposition in the Park (Ito et al. 2002) can also have implications for soil fertility (Gałuszka et al. 2011), tree physiology (Fan et al. 2014), and forest community dynamics (McEathron et al. 2013).

Aquatic ecosystems and groundwater resources hydrologically connected to paved roads may also be at risk from the toxic effects of road runoff pollutants. Regional salinization of lakes in the Park has already been documented by Kelting et al. (2012), who found state and federal road densities explained 86 % of the variation in both Na and Cl concentrations in lakes. Similar relationships between road density and salt concentration in surface waters were reported for studies in New Hampshire (Daley et al. 2009) and Rhode Island (Nimiroski and Waldron 2002). Now, through this new work, we have estimated that 76 % of surface water area and at least 45 % of stream length (dependent on buffer width) in the Park may be receiving road runoff pollutants such as salt. Salt is one of the most widely studied road runoff pollutants, and the effects of salinization on freshwater ecosystems are well documented; for example, studies have reported reduced aeration and water circulation at depth (Fay and Shi 2012), decreased spotted salamander (*Ambystoma maculatum*) and wood frog (*Rana sylvatica*) survival (Karraker et al. 2008), shifts in community structure (Collins and Russel 2009), reduced copepod density and changes in algal resources (Meter et al. 2011), and decreased productivity at all trophic levels in model freshwater communities (Dalinsky et al. 2014). A significant amount of road salt also enters groundwater where it can accumulate over years and exceed thresholds for potable water and aquatic organisms (Perera et al. 2012).

Given the large regional extent of road runoff and the potential for negative ecological effects at a large scale, the effects of this stressor should be more deliberately evaluated, particularly with its potential to interact with other regional stressors. Road salt, and other runoff pollutants, may confound the recovery of acidified lakes, complicating the assessment of lake management and policies on air pollution (Rosfjord et al. 2007). Jensen et al. (2014) found the biological recovery of an acidified lake receiving road salt discharge lagged behind the biological recovery of a similarly acidified lake not receiving road salt discharge. Thus, the application of road salt may create a mosaic of varying levels of lake recovery from acid deposition in the Park. Additionally, climate change may exacerbate the effects of road runoff pollutants on aquatic ecosystems (Schiedek et al. 2007). Warming spring temperatures break the diapause of aquatic invertebrates (Goddeeris et al. 2001) which corresponds temporally with high stream salt loads in snow melt (Oberts 1994). Also considering that the variability and intensity of spring storms are projected to increase in the northeastern USA (Hayhoe et al. 2007), the likelihood of physiologically active aquatic invertebrates being exposed to road salt discharge and other pollutants must increase (Silver et al. 2009). Our method for identifying areas receiving road runoff is vital to understanding the extent to which these multiple stressors of water quality interact across a large geographic area.

We can conceptualize road runoff from the road network as a geographically extensive stressor with spatially explicit inputs, and from this perspective, the ecological implications of road runoff are largely unknown. Acid deposition and climate change in the northeast are characterized at the regional scale by a smooth distribution of continuous stress inputs over an extensive geographic area, or in other words, the stress inputs of acid deposition and climate change do not vary much from hectare to hectare and thus are monitored at coarse scales (Ito et al. 2002; Hayhoe et al. 2007). Conversely, eutrophication is characterized at the watershed scale by discontinuous, but spatially explicit stress inputs (Agha et al. 2012) and therefore monitored at finer scales. Road runoff shares characteristics of each of the abovementioned stressors. Total runoff from a road network spans the entire region similar to that of acid deposition and climate change, but the stress inputs occur in spatially explicit distributions similar to eutrophication, creating a mosaic of environmental stress defined by topography and road position which is never the same from hectare to hectare.

Application of methods

Our methods create a spatially defined sampling unit that provides the framework for regional monitoring of road runoff as well as provides an estimate of aquatic and terrestrial ecosystems that may benefit from reductions in road salt applications (McDonald 2002; Kilgour et al. 2014). As mentioned above, road runoff pollutants often share similar environmental impacts as other regional stressors and often act synergistically, enhancing their effects on ecosystem function (Palmer and Yan 2013). A solid understanding of the spatial extent of road runoff stress allows researchers to focus regional monitoring efforts as well as develop study designs for experiments investigating the interactions of our significant regional stressors (Fancy et al. 2009).

Our results show that roads are hydrologically connected to a substantial area of land and water in the Park's forest preserve, which includes four categories of land use: wilderness, primitive, canoe, and wild forest. The wilderness category is the most protected land and is managed to protect or restore its natural conditions (apa.ny.gov). Yet, we find that roads connect to over 5000 ha of land and nearly 70 % of surface water in the wilderness category. Road runoff may put at risk substantial forest preserve lands given the multitude of well-studied ecological impacts of runoff pollutants. Our methods may direct management to use alternatives to road salt in these sensitive areas (Jackson and Jobbagy 2005).

There is no New York State-wide monitoring program that chooses monitoring sites based on a single, spatially sound framework. The selection of monitoring sites in the state is predominately based on voluntary cooperation of lake associations (New York DEC 2009). New York State primarily utilizes the Citizen Statewide Lake Assessment Program (CSLAP; www.dec.ny.gov) to produce data for US Environmental Protection Agency Clean Water Act reports. CSLAP monitors sites on the basis of voluntary cooperation of lake associations, although the in-lake sampling protocols used adhere to the literature (Kishbaugh 1988). The New York State Department of Conservation's Rotating Integrated Basin Studies and Lake Classification and Inventory programs monitor specific water bodies, but in a rotation of the State's 17 major basins and the methodologies of choosing sampling sites are based on random and targeted selections, but are not based upon a regional framework and may produce sampling bias

(New York DEC 2009; Larsen et al. 2007). Few lakes are monitored by CSLAP in the Park, though two other programs monitor the Park's water quality: the Adirondack Lake Assessment Program (www.adkwatershed.org), which monitors lakes based on voluntary cooperation similar to CSLAP, and the Adirondack Long Term Monitoring Program (www.adirondacklakessurvey.org), which monitors only minimally impacted water bodies. Given that road runoff is hydrologically connected to the majority of surface water area in the Park and that road salt represents a major external pollutant load in our region (Kelting and Laxson 2010), our methods may provide a model for a useful study design that can answer real questions regarding statewide water quality.

Efficacy of methods

Subresolution variability is an inherent issue with DEM-based hydrologic modeling (Woods 2006), but for identifying impacted lakes and streams in this study area, the 10 m USGS DEMs are of sufficient resolution to meet this channel-based objective in this topographically variable study area (McMaster 2002). The total impacted area values are more subject to resolution biases. Coarser resolutions produce higher accumulation area values (Yang and Chu 2013), possibly overestimating the area impacted by overland flow. Zhang and Montgomery (1994) analyzed the effects of DEM resolution on geomorphic and hydrologic process in a moderate to steep gradient landscape. They found that 10 m resolution DEMs such as those used in this study should be sufficient to model surface flow processes, while DEMs greater than 30 m resolution produce erroneous estimates of hill slope and runoff processes.

This study quantifies total land area downslope of roads impacted by road runoff, but does not differentiate between surface and subsurface flows within this land area. Surface flow is a combination of direct runoff of salt-laden melt waters through road drainage networks (Labadia and Buttle 1996) and Hortonian flow (de Lima and Singh 2002). Hortonian flow is an important process during spring snow melt when soils are saturated and when frozen soils prevent infiltration of melt waters during thaws (Laudon et al. 2004). Surface flow removes about 50 % of road salt annually, and the remainder accumulates and moves through soils and groundwater as subsurface flow (Meriano et al. 2009), though a greater percentage of road salt may enter subsurface flow in the Adirondacks, as the region is dominated by coarse texture sandy soils with high infiltration rates (Sullivan et al. 2006; Kelting et al. 2012). Groundwater salt concentration increases every year with road salting as only a portion of salt entering in subsurface flow will flush annually (Perera et al. 2012), resulting in higher salt concentrations in streams during summer when biological activity is highest and perhaps most vulnerable to negative effects of salt (Jackson and Jobbagy 2005; Corsi et al. 2015). Given the importance of subsurface flow to road runoff impacts, landscape level modeling estimates would be enhanced by partitioning surface and subsurface flow paths when the additional soil and geologic data necessary to make these estimates exists.

Conclusions

The high degree of hydrologic association between paved roads and the lands and waters of the Park strongly suggests that the environmental impacts of road runoff should be evaluated along with other regional stressors currently being studied. Being able to estimate the spatial extent of road runoff is important for designing monitoring programs that can explicitly monitor this stressor while also providing opportunities to understand the interaction of multiple environmental stressors. Our methods provide an efficient way to estimate the spatial extent of road runoff for large geographic areas.

Acknowledgments Support for this research was provided with a grant from the Northeastern States Research Cooperative (nsrcforest.org).

Appendix

Methods

Below are detailed instructions that accompany each subsection in "Methods".

Producing a hydrologically relevant surface

The DEMs were mosaicked into a single raster dataset using the ArcGIS data management tool "workspace to new raster dataset." Missing cells within the mosaicked dataset were identified using the “Is Null” tool. Identified missing cells were then replaced with interpolated elevation values using a conditional statement in ArcGIS. A low pass filter was used to remove DEM artifacts and noise from the appended DEM (Gesch and Wilson 2001).

Producing road disturbance grids

The eight shapefiles (SF, C, L, and SFCL and 100 m SF, 100 m C, 100 mL, and 100 m SFCL) were converted into 10 m cell size raster datasets using the ArcGIS “polyline to new raster” tool and the “polygon to new raster” tool. The new rasters were reclassified so that roads were set to a value of 1 and non-road cells were set to a value of 0. Reclassification was necessary to create a disturbance grid input parameter for the accumulation tool. The final indicator grids were then converted to TIFF as the accumulation tool requires this file format. The disturbance grid indicates the zone of the area of substance supply (runoff) with 1 representing the zone and 0 representing the rest of the domain.

Producing input weights

The effective runoff and decay multiplier grids were created by reclassifying of one of the disturbance area grids to a constant value of 1.

Delineating overland flow grids

TauDEM’s “D-Infinity concentration limited accumulation” functionality applies to a situation where an unlimited supply of a substance is loaded at a constant concentration over the cells of a value of 1 in the disturbance grid. For this paper, road runoff was the substance, and roads were the cells with a value of 1 in the disturbance grid. All inputs were clipped to a standard size to fit the needs of the tool parameters. The outputs were eight overland flow grids representing downhill flow originating from SF, C, L, and SFCL roads. These eight outputs were clipped by the extent of the Adirondack Park boundary polygon (apa.ny.gov/gis) to retain park only overland flow.

Quantifying impacted land area

Multiplying the overland flow dataset by open water cells represented by NoData excluded the original values from the output, and multiplying by 1 retained the original values in the output. The park wide open water raster data was created by clipping a NYS hydrography shapefile of lakes and ponds (gis.ny.gov) to the Adirondack Park boundary shapefile used above and then converting the clipped shapefile into a raster dataset using the ArcGIS “polygon to new raster” tool. The new raster dataset was then reclassified so that open water was represented by NoData and land area represented by a value of 1. The cell counts in the eight no-open-water overland flow grids were found and then multiplied by the cell area (100 m^2) to find the total terrestrial area impacted by road runoff. Values were reported in hectares.

Identifying impacted lakes and ponds

Total surface area (hectares) of these impacted water bodies was calculated using the calculate geometry function.

Calculating downstream length of impacted streams

Point shapefiles were created at their intersections by setting the output type in the “intersect” tool to point. The raster dataset was then reclassified so that cells represent intersection as a value of 1 and non-intersection cells as a value of 0. Input effective runoff and decay grids as well as the original D-Infinity flow direction grid were reused. The eight output flow grids were thinned using the ArcGIS “thin” tool, and flow cells over lakes and ponds were removed. Thinning accumulation rasters efficiently identifies stream channels over large geographic areas (Betz et al. 2010). This approach is aimed at sidestepping the process of using flow accumulation thresholds to identify stream channels across the entire park. We found the intersection of overland flow from roads and linear stream data was sufficient for identifying the presence of a stream. Total lengths (kilometers) of these impacted stream channels were calculated using the calculate geometry function.

Quantifying impacted land and waters in APA forest preserve lands

Forest preserve land is represented by 4 of the 15 land use types, wilderness, primitive, canoe, and wild forest. These four land use types were merged, and impacted surface waters and streams for each of the six disturbance categories within the preserve were calculated by ESRI's Select by Location and calculate geometry functions.

Betz, R., Hitt, N. P., Dymond, R. L., & Heatwole, C. D. (2010). A method for quantifying stream network topology over large geographic extents. *Journal of Spatial Hydrology, 10,* 15-29.

Gesch, D., & Wilson, R. (2001). Development of a seamless multisource topographic/bathymetric elevation model of Tampa Bay. *Marine Technology Society Journal, 35(4),* 58-64.

References

Agha, R., Cires, S., Wörmer, L., Domínguez, J. A., & Quesada, A. (2012). Multi-scale strategies for the monitoring of freshwater cyanobacteria: reducing the sources of uncertainty. *Water Research, 46*, 3043–3053.

Allan, J. (2004). Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution and Systematics, 35*, 257–284.

Bernhardt-Roemermann, M., Kirchner, M., Kudernatsch, T., Jakobi, G., & Fischer, A. (2006). Changed vegetation composition in coniferous forests near to motorways in Southern Germany: the effects of traffic-born pollution. *Environmental Pollution, 143*, 572–581.

Betz, R., Hitt, N. P., Dymond, R. L., & Heatwole, C. D. (2010). A method for quantifying stream network topology over large geographic extents. *Journal of Spatial Hydrology, 10*, 15–29.

Collins, S. J., & Russell, R. W. (2009). Toxicity of road salt to Nova Scotia amphibians. *Environmental Pollution, 157*, 320–324.

Corsi, S. R., De Cicco, L. A., Lutz, M. A., & Hirsch, R. M. (2015). River chloride trends in snow-affected urban watersheds: increasing concentrations outpace urban growth rate and are common among all seasons. *Science of the Total Environment, 508*, 488–497.

Crooks, J. A., Chang, A. L., & Ruiz, G. M. (2011). Aquatic pollution increases the relative success of invasive species. *Biological Invasions, 13*, 165–176.

Daley, M. L., Potter, J. D., & McDowell, W. H. (2009). Salinization of urbanizing New Hampshire streams and groundwater: effects of road salt and hydrologic variability. *Journal of the North American Benthological Society, 28*, 929–940.

Dalinsky, S. A., Lolya, L. M., Maguder, J. L., Pierce, J. L. B., Kelting, D. L., Laxson, C. L., & Patrick, D. A. (2014). Comparing the effects of aquatic stressors on model temperate freshwater aquatic communities. *Water, Air, & Soil Pollution, 225*. doi: 10.1007/s11270-014-2007-9.

de Lima, J. L. M. P., & Singh, V. P. (2002). The influence of the pattern of moving rainstorms on overland flow. *Advances in Water Resources, 25*, 817–828.

de Silva, N. D. G., Cholewa, E., & Ryser, P. (2012). Effects of combined drought and heavy metal stresses on xylem structure and hydraulic conductivity in red maple (*Acer rubrum* L.). *Journal of Experimental Botany, 63*, 5957–5966.

Fan, Y., Weisberg, P. J., & Nowak, R. S. (2014). Spatio-temporal analysis of remotely-sensed forest mortality associated with road de-icing salts. *Science of the Total Environment, 472*, 929–938.

Fancy, S. G., Gross, J. E., & Carter, S. L. (2009). Monitoring the condition of natural resources in US national parks. *Environmental Monitoring and Assessment, 151*, 161–174.

Fay, L., & Shi, X. (2012). Environmental impacts of chemicals for snow and ice control: state of the knowledge. *Water, Air, & Soil Pollution, 223*, 2751–2770.

Ferreira, A. L., Loureiro, S., & Soares, A. M. (2008). Toxicity prediction of binary combinations of cadmium, carbendazim and low dissolved oxygen on *Daphnia magna. Aquatic Toxicology, 89*, 28–39.

Gałuszka, A., Migaszewski, Z. M., Podlaski, R., Dołęgowska, S., & Michalik, A. (2011). The influence of chloride deicers on mineral nutrition and the health status of roadside trees in the city of Kielce, Poland. *Environmental Monitoring and Assessment, 176*, 451–464.

Gesch, D., & Wilson, R. (2001). Development of a seamless multisource topographic/bathymetric elevation model of Tampa Bay. *Marine Technology Society Journal, 35*(4), 58–64.

Goddeeris, B. R., Vermeulen, A. C., De Geest, E., Jacobs, H., Baert, B., & Ollevier, F. (2001). Diapause induction in the third and fourth instar of Chironomus riparius (Diptera) from Belgian lowland brooks. *Archiv für Hydrobiologie, 150*, 307–327.

Hayhoe, K., Wake, C. P., Huntington, T. G., Luo, L., Schwartz, M. D., & Sheffield, J. (2007). Past and future changes in climate and hydrological indicators in the US Northeast. *Climate Dynamics, 28*, 381–407.

Hodkinson, I. D., & Jackson, J. K. (2005). Terrestrial and aquatic invertebrates as bioindicators for environmental monitoring, with particular reference to mountain ecosystems. *Environmental Management, 35*, 649–666.

Holmstrup, M., Bindesbøl, A. M., Oostingh, G. J., Duschl, A., Scheil, V., & Köhler, H. R. (2010). Interactions between effects of environmental chemicals and natural stressors: a review. *Science of the Total Environment, 408*, 3746–3762.

Hynes, H. B. N. (1975). The stream and its valley. *Verhandlungen der Internationalischen Vereinigung für Theoretische und Angewandte Limnologie, 19*, 1–15.

Ito, M., Mitchell, M. J., & Driscoll, C. T. (2002). Spatial patterns of precipitation quantity and chemistry and air temperature in the Adirondack region of New York. *Atmospheric Environment, 36*, 1051–1062.

Jackson, R. B., & Jobbagy, E. G. (2005). From icy roads to salty streams. *Proceedings of the National Academy of Sciences, 102*, 14487–14488.

Jenkins, J., & Keal, A. (2004). *The Adirondack Atlas*. Syracuse: Syracuse University Press.

Jensen, T. C., Meland, S., Schartau, A. K., & Walseng, B. (2014). Does road salting confound the recovery of the microcrustacean community in an acidified lake? *Science of the Total Environment, 478*, 36–47.

Jenson, S. K., & Domingue, J. O. (1988). Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric Engineering and Remote Sensing, 54*, 1593–1600.

Johnston, F. M., & Johnston, S. W. (2004). Impacts of road disturbance on soil properties and on exotic plant occurrence in subalpine areas of the Australian Alps. *Arctic, Antarctic, and Alpine Research, 36*, 201–207.

Karraker, N. E., Gibbs, J. P., & Vonesh, J. R. (2008). Impacts of road deicing salt on the demography of vernal pool-breeding amphibians. *Ecological Applications, 18*, 724–734.

Kaspari, M., Chang, C., & Weaver, J. (2010). Salted roads and sodium limitation in a northern forest ant community. *Ecological Entomology, 35*, 543–548.

Kaushal, S. S., Groffman, P. M., Likens, G. E., Belt, K. T., Stack, W. P., Kelly, V. R., & Fisher, G. T. (2005). Increased salinization of fresh water in the northeastern United States. *Proceedings of the National Academy of Sciences of the United States of America, 102*, 13517–13520.

Ke, C., Li, Z., Liang, Y., Tao, W., & Du, M. (2013). Impacts of chloride de-icing salt on bulk soils, fungi, and bacterial populations surrounding the plant rhizosphere. *Applied Soil Ecology, 72*, 69–78.

Kelting, D. L., & Laxson, C. L. (2010). Review of effects and costs of road de-icing with recommendations for winter road management in the Adirondack Park. Adirondack Watershed Institute, Paul Smith's College, Paul Smiths, NY, Adirondack Watershed Institute Report# AWI2010-01.

Kelting, D. L., Laxson, C. L., & Yerger, E. C. (2012). Regional analysis of the effect of paved roads on sodium and chloride in lakes. *Water Research, 46*, 2749–2758.

Kiesecker, J. M. (2002). Synergism between trematode infection and pesticide exposure: a link to amphibian limb deformities in nature? *Proceedings of the National Academy of Sciences, 99*, 9900–9904.

Kilgour, B. W., Gharabaghi, B., & Perera, N. (2014). Ecological benefit of the road salt code of practice. *Water Quality Research Journal of Canada, 49*, 43–52.

Kishbaugh, S. A. (1988). The New York citizens' statewide lake assessment program. *Lake and Reservoir Management, 4*, 137–145.

Klimaszewska, K. K., Polkowska, Ż. Ż., & Namieśnik, J. J. (2007). Influence of mobile sources on pollution of runoff waters from roads with high traffic intensity. *Polish Journal of Environmental Studies, 16*, 889–897.

Labadia, C. F., & Buttle, J. M. (1996). Road salt accumulation in highway snow banks and transport through the unsaturated zone of the Oak Ridges Moraine, Southern Ontario. *Hydrological Processes, 10*, 1575–1589.

Larsen, D. P., Olsen, A. R., Lanigan, S. H., Moyer, C., Jones, K. K., & Kincaid, T. M. (2007). Sound survey designs can facilitate integrating stream monitoring data across multiple programs. *Journal of the American Water Resources Association, 43*, 384–397.

Laudon, H., Seibert, J., Köhler, S., & Bishop, K. (2004). Hydrological flow paths during snowmelt: congruence between hydrometric measurements and oxygen 18 in meltwater, soil water, and runoff. *Water Resources Research, 40*, doi:10.1029/2003WR002455.

McDonald, T. L. (2002). Review of environmental monitoring methods: survey designs. *Environmental Monitoring and Assessment, 85*, 277–292.

McEathron, K. M., Mitchell, M. J., & Zhang, L. (2013). Acid-base characteristics of the Grass Pond watershed in the Adirondack Mountains of New York State, USA: interactions among soil, vegetation and surface waters. *Hydrology and Earth System Sciences, 17*, 2557.

McMaster, K.J. (2002). Effects of digital elevation model resolution on derived stream network positions. *Water Resources Research, 38*, doi: 10.1029/2000WR000150.

Meriano, M., Eyles, N., & Howard, K. W. (2009). Hydrogeological impacts of road salt from Canada's busiest highway on a Lake Ontario watershed (Frenchman's Bay) and lagoon, City of Pickering. *Journal of Contaminant Hydrology, 107*, 66–81.

Meter, R., Swan, C., Leips, J., & Snodgrass, J. (2011). Road salt stress induces novel food web structure and interactions. *Wetlands, 31*, 843–851.

Neher, D. A., Asmussen, D., & Lovell, S. (2013). Roads in northern hardwood forests affect adjacent plant communities and soil chemistry in proportion to the maintained roadside area. *Science of the Total Environment*. doi:10.1016/j.scitotenv.2013.01.062.

New York DEC. (2009). New York State section 305(b) and 303(d) consolidated assessment and listing strategy. New York State Department of Environmental Conservation.

New York State Department of Transportation. (2006). Highway maintenance guidelines: snow and ice control.

Nimiroski, M.T., & Waldron, M.C. (2002). Sources of sodium and chloride in the Scituate Reservoir Drainage Basin, Rhode Island. U.S. Geological Survey Report WRIR 02-4149.

Norrström, A. C., & Bergstedt, E. E. (2001). The impact of road de-icing salts (NaCl) on colloid dispersion and base cation pools in roadside soils. *Water, Air, & Soil Pollution, 127*, 281–299.

Oberts, G. L. (1994). Influence of snowmelt dynamics on stormwater runoff quality. *Watershed Protection Techniques, 1*(2), 16–22.

Palmer, M. E., & Yan, N. D. (2013). Decadal-scale regional changes in Canadian freshwater zooplankton: the likely consequence of complex interactions among multiple anthropogenic stressors. *Freshwater Biology, 58*, 1366–1378.

Perera, N., Gharabaghi, B., & Howard, K. (2012). Groundwater chloride response in the Highland Creek watershed due to road salt application: a re-assessment after 20 years. *Journal of Hydrology, 479*, 159–168.

Price, J. R., & Szymanski, D. W. (2013). The effects of road salt on stream water chemistry in two small forested watersheds, Catoctin Mountain, Maryland, USA. *Aquatic Geochemistry*. doi:10.1007/s10498-013-9193-8.

Qiang, J., Ren, H., Xu, P., He, J., & Li, R. (2012). Synergistic effects of water temperature and salinity on the growth and liver antioxidant enzyme activities of juvenile GIFT Oreochromis niloticus. *Yingyong Shengtai Xuebao, 23*, 255–263.

Rosfjord, C. H., Webster, K. E., Kahl, J. S., Norton, S. A., Fernandez, I. J., & Herlihy, A. T. (2007). Anthropogenically driven changes in chloride complicate interpretation of base cation trends in lakes recovering from acidic deposition. *Environmental Science & Technology, 41*, 7688–7693.

Schiedek, D., Sundelin, B., Readman, J. W., & Macdonald, R. W. (2007). Interactions between climate change and contaminants. *Marine Pollution Bulletin, 54*, 1845–1856.

Silver, P., Rupprecht, S. M., & Stauffer, M. F. (2009). Temperature-dependent effects of road deicing salt on chironomid larvae. *Wetlands, 29*, 942–951.

Sloman, K. A., Scott, G. R., Diao, Z., Rouleau, C., Wood, C. M., & McDonald, D. (2003). Cadmium affects the social behavior of rainbow trout, Oncorhynchus mykiss. *Aquatic Toxicology, 65*(2), 171–185. doi:10.1016/S0166-445X(03)00122-X.

Snell-Rood, E. C., Espeset, A., Boser, C. J., White, W. A., & Smykalski, R. (2014). Anthropogenic changes in sodium affect neural and muscle development in butterflies. *Proceedings of the National Academy of Sciences*. doi:10.5061/dryad.v2t58.

Soranno, P. A., Cheruvelil, K. S., Bissell, E. G., Bremigan, M. T., Downing, J. A., Fergus, C. E., & Webster, K. E. (2014). Cross-scale interactions: quantifying multi-scaled cause-effect relationships in macrosystems. *Frontiers in Ecology and the Environment, 12*, 65–73.

Stager, J., McNulty, S., Beier, C., & Chiarenzelli, J. (2009). Historical patterns and effects of changes in Adirondack climates since the early 20th century. *Adirondack Journal of Environmental Studies, 15*, 14–24.

Sullivan, T. J., Fernandez, I. J., Herlihy, A. T., Driscoll, C. T., McDonnell, T. C., Nowicki, N. A., Snyder, K. U., & Sutherland, J. W. (2006). Acid-base characteristics of soils in the Adirondack Mountains, New York. *Soil Science Society of America Journal, 70*, 141–152.

Tang, J. M., Aryal, R., Deletic, A., Gernjak, W., Glenn, E., McCarthy, D., & Escher, B. I. (2013). Toxicity characterization of urban stormwater with bioanalytical tools. *Water Research, 47*, 5594–5606.

Tarboton, D. G. (1997). A new method for the determination of flow directions and contributing areas in grid digital elevation models. *Water Resources Research, 33*, 309–319.

Tarboton, D. G., Schreuders, K. A. T., Watson, D. W., & Baker, M. E. (2009). Generalized terrain-based flow analysis of digital elevation models. In *Proceedings of the 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Cairns, Australia* (pp. 2000-2006).

Trombulak, S. C., & Frissell, C. A. (2000). Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology, 14*, 18–30.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences, 37*, 130–137.

Waller, K., Driscoll, C., Lynch, J., Newcomb, D., & Roy, K. (2012). Long-term recovery of lakes in the Adirondack region of New York to decreases in acidic deposition. *Atmospheric Environment, 46*, 56–64.

Woods, R. (2006). Hydrologic concepts of variability and scale. In M. G. Anderson (Ed.), *Encyclopedia of hydrological sciences, part 1. Theory, organization and scale*. New York: Wiley.

Yang, J., & Chu, X. (2013). Effects of DEM resolution on surface depression properties and hydrologic connectivity. *Journal of Hydrologic Engineering, 18*, 1157–1169.

Yousef, Y. A., Wanielista, M. P., Harper, H. H., & Skene, E. T. (1983). Impact of bridging on floodplains. *Transportation Research Record, 948*, 26–30.

Zechmeister, H. G., Hohenwallner, D. D., Riss, A. A., & Hanus-Illnar, A. A. (2005). Estimation of element deposition derived from road traffic sources by using mosses. *Environmental Pollution, 138*, 238–249.

Zhang, W., & Montgomery, D. R. (1994). Digital elevation model grid size, landscape representation, and hydrologic simulations. *Water Resources Research, 30*, 1019–1028.