JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 47, No. 2 AMERICAN WATER RESOURCES ASSOCIATION April 2011

UNDERSTANDING THE FACTORS THAT INFLUENCE HEADWATER STREAM FLOWS IN RESPONSE TO STORM EVENTS[1]

Les W. Stanfield and Don A. Jackson[2]

ABSTRACT: Headwater drainage features (first- to second-order streams) are the capillaries of the landscape that, among other things, moderate the timing and volumes of water available to the riparian and aquatic ecosystems. How these features respond to summer rainfall is poorly understood. We studied how geology and an index of land use/land cover influenced peak flows following rainfall events in 110 headwater stream sites that were studied over a four-month period during a drought year. Highest peak flows were observed in the most urbanized catchments and in poorly drained soils, but specific responses were variable depending on both geology and land disturbance. Redundancy analysis indicated that both surficial geology and land disturbance were important factors influencing peak flows under drought conditions. We conclude that responses of these headwater streams to individual storms during drought conditions are unpredictable from data collected using our methods, but increased peak flows were associated with increased urban and agricultural development, but mitigated by surficial geology. These findings demonstrate the challenges to accurately predict flow conditions in headwater streams during periods of extreme weather that concurrently have the greatest potential effect on biota. The combination of these challenges and importance of such events indicates the need to develop new approaches to study and manage these resources.

(KEY TERMS: stream response; headwater streams; landscape influences; flashiness; land use; crest-stage gauge; redundancy analysis; Manning's equation; monitoring.)

Stanfield, Les W. and Don A. Jackson, 2011. Understanding the Factors That Influence Headwater Stream Flows in Response to Storm Events. *Journal of the American Water Resources Association* (JAWRA) 47(2):315-336. DOI: 10.1111/j.1752-1688.2010.00518.x

INTRODUCTION

Conserving biodiversity in the throes of unprecedented planetary change is one of the greatest challenges that humanity faces. Success requires that land- and water-use decisions be made in the context of both natural and human-induced cumulative changes to ecosystems. Water is a key driver of ecological systems (Karr and Chu, 1999) and there are many cases of remediated point-source problems that impact ecosystem health (e.g., Hunt, 1976; Hughes and Gammon, 1987; Rosgen, 1996). Canada applies some of the strictest legal protection of fish and fish habitat in the world (e.g., *The Fisheries Act*; Canada, 1985), and has been vigorously applying the no-net-loss-of-habitat policy (DFO, 1986) for over 20 years. Within Ontario, Canada, recent planning

---

[1] Paper No. JAWRA-09-0122-P of the *Journal of the American Water Resources Association* (JAWRA). Received August 18, 2009; accepted November 23, 2010. © 2011 American Water Resources Association. **Discussions are open until six months from print publication**.

[2] Respectively, Senior Fisheries Specialist, Southern Science and Information Section, Ontario Ministry of Natural Resources, RR4, Picton, Ontario, Canada K0K 2T0; and Professor, Department of Ecology and Evolutionary Biology, University of Toronto, Toronto, Ontario, Canada M5S 3B2 (E-Mail/Stanfield: les.stanfield@ontario.ca).

and policy directions, such as the Oak Ridge Moraine Act (ORMCA, 2001) and the Green Belt Act (GBA, 2005), have further recognized the importance of protecting valley lands and key groundwater recharge zones. Despite this type of progressive legislative framework, several recent studies have documented significant declines in fish populations from mainstem sections of rivers in northeastern North America (e.g., Morse *et al.*, 2003; Stanfield and Kilgour, 2006; Stanfield *et al.*, 2006; COSEWIC, 2007) that call into question the likelihood that these legislative initiatives will be sufficient to reverse the negative trends. In these studies, the relationship between measures of the biotic community and land use/land cover was found to have a threshold response. That is, the relationship was linearly correlated for lower levels of development; however, above a moderate level of development in a catchment, the slope of the relationship becomes flat. Although it is clear that the biological assemblages are degraded in landscapes above the threshold, there remains much uncertainty of the mechanism and importance of various processes driving the relationship for sites that are below the threshold. To date, there has been a limited incorporation of development targets into planning, based on these studies. Better understanding of the relationship below the threshold is necessary to enable planners and resource managers to better protect ecosystems in the face of continued human growth and resource use.

The studies described above generally do not examine headwater drainage features, where the strongest association between terrestrial and aquatic environments exists (Schlosser, 1991). We propose that this scale (<1 km^2) is a missing key connection for demonstrating the linkage between small-scale alterations in land use, the level at which most individuals interact with the land (e.g., a building lot, farm, or subdivision). These alterations affect stream conditions that accumulate in downstream reaches; however, changes in stream conditions can be observed and somewhat isolated in the headwater areas.

Existing landscape models, like those carried out studying fish, are generally developed at larger spatial scales of 10 to 1,000 km^2 due to the prevalence of sampling being conducted on "fishable reaches" (see Wang *et al.*, 2006). Models based on large spatial-scale input variables do not provide results that enable investigators to fully understand the interconnectedness of landscape changes and biological differences (Winsor *et al.*, 2006). Having study sites further downstream in the system, that is, greater than second-order streams in the drainage system, offers a greater opportunity for the homogenization effect, which can mask upstream disturbance impacts (Ward, 1984). As an example, if land use in a specific area causes loss of base flow in a catchment, the probability of detecting this impact would diminish with increasing distance downstream, because contributions from other sources would potentially offset these losses and mask the overall impact (see Ward, 1984, for details, and Richardson and Danehy, 2007, for an example). Incremental losses of permanently flowing headwater streams (i.e., cumulative impacts) could slowly reduce biological diversity and production in the entire system, as refuge populations are lost. Over time, these changes could reduce the overall resiliency and complexity of the aquatic ecosystem. Therefore, it is unlikely that we can disentangle the landscape factors that influence stream condition, based solely on information measured in the lower portions of large catchments, in ways that allow us to understand causal mechanisms or aid in resource planning within headwater areas.

There is qualitative support that such a scenario exists in the tributaries to Lake Ontario where flow rates in the lower reaches of these tributaries are routinely gauged. In rural areas, base flows have been shown to have generally increased from pre-reforestation periods (Buttle, 1994). Today, although streams in the greater Toronto area have become flashier, for the most part streams to the east of this area are not seen as having seriously degraded flow conditions (TRCA, 2007). These conditions have been thought to be the result of the stronger regulatory framework that has been in place to protect mainstem portions of these watersheds since the 1950s (Bradford, 2008). However, in recent years, concerns have emerged that incremental changes in some of these watersheds might be associated with alterations that are occurring in the headwater drainage features.

Headwater drainage features are small source-water features including: swales, springs, small streams (typically first and second Strahler stream order), rivulets, and intermittent features. These features are easy to bury, move, ditch, or otherwise modify. However, alterations to headwater drainage-feature conditions and critical habitats/processes that they influence may go undetected if routine sampling is only conducted in lower reaches of systems, for example, at discharge gauging stations. Further, many easily accessible flow prediction tools that are available for routine plan review purposes are generally conducted using mean conditions collected over many years (Prudic, 1989; Dinicola, 1990; Gerber and Howard, 2002; Moore and Wondzell, 2005; Li *et al.*, 2008). Because changes in conditions within specific headwater drainage features are known to vary seasonally and in concert with weather patterns (see Richardson and Danehy, 2007, for a recent synthesis) sampling at greater than a daily time step might miss the timing and magnitude of true differences in the conditions of these features. This masking of effects could be due to a mismatch of scales of where and when measurements are made and where and when the effects are located. That is, monitoring needs to be performed at the scales required to answer the questions being investigated so that cause and effect relationships may be detected. Further, this scaling effect also extends to inventories of landscape conditions generated using GIS so that the data are of sufficient resolution to support the analysis. Reconciling these scaling effects is recognized as a challenge both by scientists and legislators (Alexander *et al.*, 2007).

The present study was undertaken to develop a better understanding of the catchment features that influence the magnitude of stream responses (peak flows) following rainfall events (short time scale) in small headwater catchments (0.2-1 km^2). We define catchment features as those relevant factors that are found within the drainage basin of each site and can be measured readily using geographic information systems. This understanding is an essential component to the broader question of understanding how land-use decisions in upstream areas cumulatively influence flows throughout the drainage network. The intention is to demonstrate how studies in small-size catchments (0.2-1 km^2) might offer insights to larger-scale issues of conservation and to identify the factors to be considered to better manage flows as lands are developed.

We hypothesize that as land is converted from natural cover to agriculture or urban lands, a key process that is being interrupted is the temporal patterns of, and the magnitude of flows, in response to rain events in small headwater streams. The specific questions that we seek to answer through this work are as follows:

1. What are the landscape factors that correlate with flows in headwater streams following storm events that occur during a growing season?
2. How much of the variance in stream response is associated with land use/land cover in the watershed in comparison to rainfall?
3. Can relatively low-cost field techniques provide meaningful measures of these relationships?

We expect that, in general, sites with more extensive and intensive land cover within their catchments will have more rapid and extreme peak flows in response to rainfall events (stream response). The magnitude of the stream response will differ depending on the magnitude of the rain event, the porosity of the geology in a catchment, and the water content in the surface soils.

METHODS

Study Area

This study was conducted in small streams that drain into Lake Ontario, an area dominated by the Oak Ridge Moraine (Figures 1 and 2). In this study, only streams are studied as these systems have clearly defined banks that enable the demarcation of high-flow events. The glacial history of this area created a gradient in materials from the coarsest (i.e., sands and gravels) and most hummocky in the north to the finest (silts and clays) in the south (Figure 2). In this area, the depth to bedrock is generally deep but is highly variable with a typical depth of up to 225 m in the Oak Ridge Moraine area, declining to near zero close to Lake Ontario (Kassenaar and Wexler, 2006), although the minimum depth to bedrock for any of our sites would have been approximately 5 m for the furthest downstream site on the Ganaraska River.

Throughout the 1800s and until about 1920, nearly all lands in this area were cleared of forest cover, and used for row-crop agriculture (Puric-Mladenovic, 2003). Over the last 100 years, much of the northern lands have been returned to forest cover or low-intensity agriculture (hay and pasture), whereas the land use in the remainder of the area has remained row-crop agricultural or become urbanized (Figure 3). Urban areas are predominantly near Lake Ontario and in the western part of the study area. Tile-drained areas are found in the central and eastern parts of the study area, associated mainly with the glaciolacustrine deposits (Figure 3).

One hundred and ten sampling sites were identified within the four watersheds (Duffins, Ganaraska, Harmony, and Oshawa). Each site was located at the first stream road-crossing that provided a minimum 300 m of mapped upstream length and that also had defined banks. Data collection involved three distinct components: measuring the stream response associated with each storm event, measuring the mean rainfall in each catchment, and attributing landscape characteristics within each catchment.

Measuring Stream Response

Maximum stream discharges (peak flows) were measured for each storm event that occurred between July 3 and October 31, 2007. Storm events were defined as being of sufficient intensity to generate at least 5 mm of rain and generally were of sufficient spatial extent as to cover all of the study area. Stream response for each rainfall event was computed

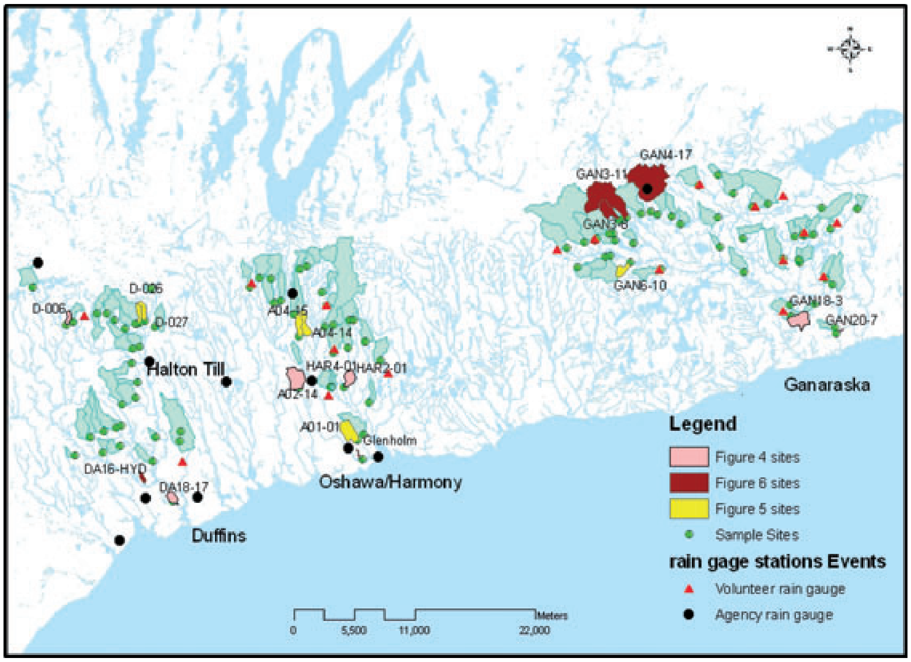

FIGURE 1. The Study Area Showing 110 Study Sites/Catchments and 29 Rain-Gauge Site Locations, Distributed Across the Four Major Streams.

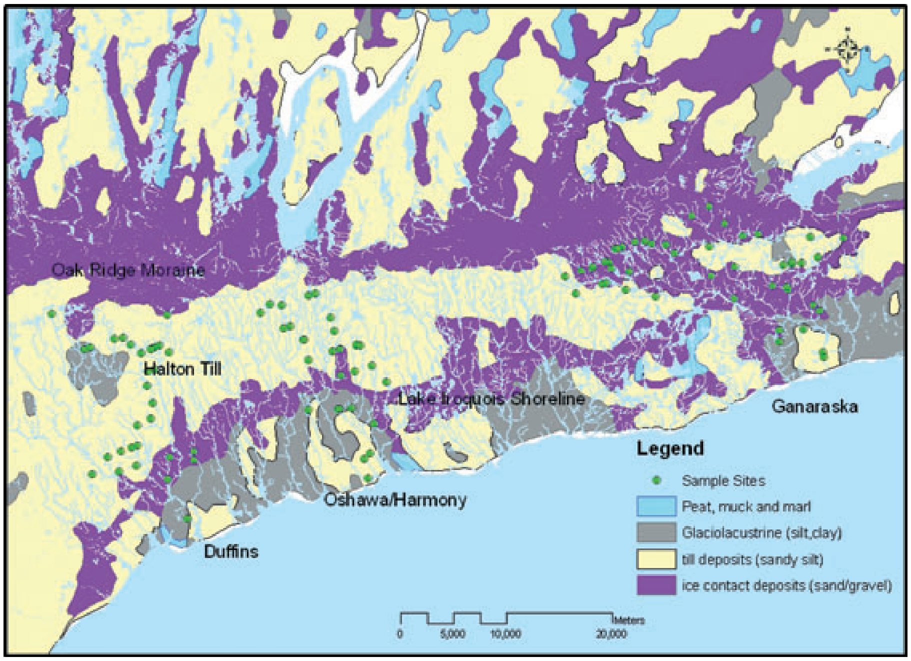

FIGURE 2. Quaternary Geology and Location of the 110 Sample Site Locations. Note the north-south gradient between well-drained soils on the moraine to poorly drained near the lake and the importance of the band of well-drained soil (beach front) of the Lake Iroquois shoreline. Most sites are wholly included in one class of soils.

by multiplying the maximum wetted area of the channel for the depth of the peak flow by the estimated velocity for each event.

The maximum wetted area of the channel from each storm event was calculated based on the stage response and a detailed cross-sectional depth profile of the channel that was extended to a bank height that was at, or above, the bankfull stage. A crest-stage gauge (CSG) was used to determine the wetted area of the channel for each site event (Weight and

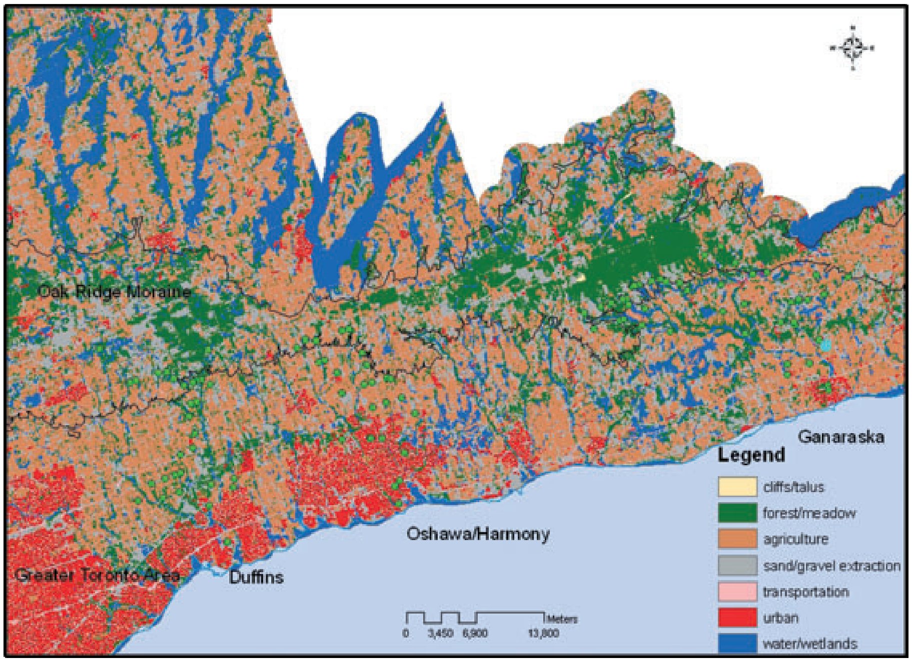

FIGURE 3. Land Use/Land Cover for the Study Area Based on OMNR (2007) SOLRIS Data. Note that agricultural land use dominates this area and that urban lands are common close to Lake Ontario and forest cover on the moraine.

Sonderegger, 2001). The version of the CSG used in this study consisted of a clear PVC pipe and the inside was coated with talc powder that dissolved as the water levels rose (see Stanfield, 2009, for details). Each CSG was placed at the optimal location within a site that provided a constriction in the channel, uniform elevations of both banks, fine substrate material, and where necessary protection from high flows and debris. These were generally at cross-overs, or where the thalweg is in the middle of the channel and the mid-point of each site.

Manning's equation (Manning, 1891) was used to generate velocity estimates associated with each event, following modified procedures as described by Cowan (1956), Chow (1959), Henderson (1966), and Sturm (2001). For this study, the parameters for this equation were measured in the field through a length of stream that was, in general, approximately 20 m long. Following Sturm (2001), stream slope was measured through the site and based on McCuen's (1989) suggestion that bed elevation should exceed 150 mm of drop across a site; eight sites were *post hoc* removed from the dataset for analysis purposes. Details of the approaches used to quantify each attribute are provided in the Appendix.

Only the discharge that occurred within the "vertical" boundaries of the bankfull channel was measured for each event. In essence, the depth of flow that was above the bankfull level was added to the bankfull width of the channel to the area of flow. This in effect assumes that "0" discharge is accumulating from the area within the flood plain. Although it is known that velocities decrease within the flood plain (Leopold *et al.*, 1995), this assumption ensures that the estimates of discharge for the above bank measures are an underestimate of the true discharge.

Attempts were made to validate the measures of velocity by visiting a number of sites as soon as possible after storms and measuring discharge using traditional approaches (Hauer and Lamberti, 1996) and through the CSG methods described above. Both an electromagnetic and a flo-through velocity meter were used for this task in addition to using the volume by time approach. Further, eight pressure transducers were employed at other sites where CSGs were used in tandem to compare the reliability of both approaches for measuring the stage height. Comparison of peak flows to downstream gauge station measures of peak flow were explored but did not provide a reliable comparison due to both the paucity of suitable gauge stations and smoothing effects.

Attributing Catchment Characteristics

ARC-Hydro (v1.1 for ArcGIS 9.0) (Maidment, 2002) was applied to a 10-m resolution flow-rectified DEM to determine the catchment polygons for each site (OMNR, 2006). The water layer, although continually upgraded, is based on aerial photo interpretation from 1986 photos, generated at a 1:50,000 scale.

The GIS analysis did not identify two urban streams, and their associated catchments and one stream had been diverted and could not be accurately delineated using ARC-Hydro. These three catchment polygons were manually added within ArcGIS using the DEM and the road layer as guidelines. Valley slope was measured as a function of slope (rise/run) over a 200-m length of river centered at the site. Land cover was attributed from the SOLRIS data layer with 25 m resolution based on 2002 LANDSAT images and included the area coverage of water and wetlands (OMNR, 2007). Landscape-disturbance indices (LDI) were weighted and used to generate a single measure of the land cover within each site's catchment following Morrison *et al.* (2006). Local ecologists and planners collaborated to rank each land-use/land-cover category from the greatest to the least change in condition from a reference state and then a coefficient from between 0 and 1 was assigned to each category *i* (Table 1). The ratings of imperviousness from Shaver and Maxted (1995) and Shuster *et al.* (2005) were used as guidelines for this exercise

$$\mathrm{LDI} = \sum_i (\%''\text{land use/land cover}''_i \times \text{LDI coefficient}_i). \quad (1)$$

Additionally, a tile-drained field layer was developed for this study using records and procedures developed by OMAFRA (2008) and it was used as a separate predictor of stream response.

Surficial geology for each catchment was measured using a 1:250,000 Quaternary surficial geology layer with a horizontal accuracy of ±200 m (Ontario Geological Survey, 1997). A weighted measure of the porosity of the surficial geology was obtained using Piggott *et al.* (2002) base-flow index (BFI). In this approach, base-flow coefficients were determined by comparing the base flow at Ontario gauge stations (as determined using the hydrograph separation procedure) to the proportion of upstream area in each geologic type. Proportion estimates of base flow were calculated for each gauge station and then a nonlinear optimization algorithm was used to determine the overall rating for each geologic unit (Piggott *et al.*, 2002). Catchments were classified as being either well (≥0.68), moderately (0.345), or poorly (0.145) drained.

Estimating Rainfall for Each Site by Event

A network of 17 volunteer rain watchers was set up to complement the 11 agency weather stations, as a means of documenting the rainfall from storm events, in each site's catchment (Figure 1). Volunteer rain-gauge data were recorded on a daily basis, whereas agency stations used tipping buckets that recorded rainfall every 15 min. Our intention was to use the agency data to validate the intensity of rainfall throughout the study area; however, due to the nature of the rainfall during this sampling season, this was not possible.

TABLE 1. Land-Use/Land-Cover Categories and LDI Coefficients and Base-Flow Index (BFI) Ratings for Quaternary Geology Classes for This Study Area.

Land-Use/Land-Cover Category	LDI Coefficient[1]	Quaternary Geology	BFI Rating[2]
Wetland and open water	0.000	Glaciofluvial ice-contact deposit	0.704 (w)
Forest (five categories)	0.010	Glaciofluvial outwash deposit of gravel	0.73 (w)
Open tallgrass prairie	0.020	Undifferentiated till deposit	0.681(w)
Plantations – tree cultivated	0.030	Glaciolacustrine basin deposit of silt and clay	0.149 (p)
Hedge rows	0.040	Glaciolacustrine beach and near-shore deposits	0.68 (w)
Open shorelines	0.050	Halton till (Ontario/Erie lobe unit)	0.345 (m)
Idle lands, alvar, cultural thicket/meadow/woodland	0.100	Abandoned flood plain fluvial deposit	0.73 (w)
Unimproved hay/pasture	0.150		
Manicured open space	0.160		
Open sand, dunes, orchards, vineyards	0.200		
Mixed agriculture	0.250		
Urban pervious	0.300		
Monoculture agriculture	0.350		
Sand and gravel extraction	0.450		
Rural/estate residential	0.500		
Urban impervious (subdivisions/institution)	0.750		
Transportation, industrial, commercial, rail	0.900		

Note: Source for BFI: Piggott *et al.* (2002).

[1] Ratings represent the median value for each category, acknowledging local use of best management practices or poor land management would result in greater of lower LDI ratings.

[2] Letters in parentheses refer to classifications based on drainage potential, whereby w = well, m = moderately, and p = poorly drained.

Spline analysis was carried out on the daily rainfall data using routines within ArcGIS (v. 9.2) in order to estimate spatial coverage of rainfall. Details regarding the spline estimation are found in Stanfield (2009). Additionally, the total amount of rainfall in each catchment for the two preceding days of the day of maximum rainfall between event sampling was also calculated. This measure was intended to capture a measure of soil moisture levels and the two-day period was chosen based on both field observations that indicated that, in general, no evidence of rainfall was observable in soils during the sampling period and that this time period captured most of the variance in this measure.

Data Analysis

Unit discharge [mm/day = (mm^3/s) × s/day/catchment area (mm^2)] and rainfall data were plotted for each site to determine how these relationships related across sites relative to their LDI and geology categories. Due to the multivariate nature of the dataset, redundancy analysis was used to investigate the influential factors that correlated with peak discharge. For this study, data were grouped into sets of events that were complete (i.e., no missing values) and these data were evaluated to determine the correlations and amount of variation explained by the environmental predictor variables in the response variable, discharge. Results from two of the groups were analyzed: one that provided at least six rainfall events per site (the "many-events" group) and another that provided the greatest contrast in site conditions and a minimum of four events of data (the "few-events" group). For brevity, we present only the results from the four-event analysis here as this group had the greatest contrast in catchment conditions. The many-events group showed similar patterns and, most importantly, a consistent pattern among the events (Stanfield, 2009).

Variables were transformed [log(x + 1)] for all area, length, and height measures and a square-root (x + 1) transformation for each proportional variable (LDI, slope), all standardized to z-scores, and bivariate relationships were examined for linearity. The redundancy analysis was conducted using the R software and the rdaTest application (Legendre and Durand, 2008).

Partial RDA is typically used to examine multivariate hypotheses of habitat (Stendera and Johnson, 2006) or biological data (Legendre and Anderson, 1999); however, these approaches are equally appropriate for the analysis of flow event data (Legendre and Legendre, 1998). This procedure partitions the variation of the response variable among the different sets of explanatory variables. This procedure is a direct extension of multiple regression to datasets where there are multiple response variables (discharges in this instance). Flow responses to each event are comparable to a species abundance or habitat attribute. This procedure partitions the variation of the response variables matrix (discharge for each flow event) among the sets of explanatory variables and calculates the proportions that are independent and shared between variable groupings. Three groupings of variables were used based on the original hypothesis of the study; rainfall (antecedent and the event), geology (BFI and slope); and a land-use/land-cover group. A Venn diagram is used to illustrate the fraction of variation explained by each variable alone (a, b, and c), or that is shared between two groupings (d, e, and f) and that is shared between all three groupings (g). To test for the significance of groupings, a bootstrapping approach is used with no transformations because, with this dataset, 0 discharges are important observations. The test was carried out using the VarCan1 software of Peres-Neto *et al.* (2006a) with 1,000 resamplings used. This approach corrects for the bias in R^2 estimation due to the number of variables included (Peres-Neto *et al.*, 2006b). Sites having zero discharge for all observations in the subset of events were removed given the lack of differences in response.

Because our measure of discharge for each event included all flow (base flow and peak flow) for a specific event, we were concerned that inclusion of the base flow might mask the magnitude of stream responses for each event. That is, increases or decreases in base flow over time could potentially result in stream responses that over- or underestimated the change in peak flow associated with specific rainfall events. As an alternative measure of stream response, the lowest measured discharge at each site during the study (base flow) was subtracted from each event discharge as a means of calculating a standardized discharge ("response above base flow") for each event. The base-flow discharge was determined from either the lowest CSG reading recorded where streams maintained flow or zero for those streams that were intermittent. The RDA analysis was repeated using the standardized discharge data and results compared with the peak-flow analysis.

RESULTS

Description of the Data

Sampling generated a total of 807 CSG readings and a measurable response was observed on most

TABLE 2. Summary of the Mean and Standard Deviation (in parentheses) Rainfall and Stage Response Characteristics for Each Event.

Event	No. Sites Sampled	Rain Dates	Rainfall (mm)	Rainfall Two Days Previously (mm)	Discharge (mm)
1	73	July 5, 6	4.5 (4.1)	0.2 (1.0)	4.1 (8.8)
2	10	July 8-10, 13, 14	9.8 (3.5)	0 (0)	5.2 (9.6)
3	74	July 14, 15	12.4 (9.7)	3.0 (4.1)	2.6 (5.8)
4	93	July 19, 20	25.4 (13.3)	5.8 (3.0)	7.4 (18.3)
5	26	August 1, 2, 3, 7	6.5 (8.7)	4.3 (9.6)	5.7 (14.8)
6	13	August 12, 16	2.7 (1.4)	0 (0)	12.9 (30.0)
7	99	August 23, 24	16.7 (7.6)	2.4 (5.6)	7.6 (26.4)
8	105	August 25, 26	8.8 (7.9)	21.1 (11.8)	5.5 (24.5)
9	11	September 5	2.8 (0.4)	0.1 (0.3)	31.7 (68.7)
10	89	September 9-12, 14, 15	7.8 (2.6)	0.8 (2.1)	0.1 (0.4)
11	104	September 24-29; October 6	25.7 (16.4)	0.3 (1.3)	9.2 (29.4)
12	102	October 23	16.9 (9.3)	1.3 (2.3)	5.6 (23.3)

TABLE 3. Median, Maximum, Minimum, and Coefficient of Variation (CV) Statistics for Attributes Used to Estimate Manning's n for All the Study Sites.

Variable	Median	Maximum	Minimum	CV
D_{50}	0.1	100.00	0.05	2.27
D_{85}	15.1	200.00	0.05	1.35
Site slope	1.4	8.00	0.05	0.94
Sinuosity class (0-1)	0.4	1.00	0.00	0.58
Width/depth	4.7	18.00	1.28	0.56
Undercut banks	0.02	2.24	0.00	2.70
Sum wood m^3	0.01	18.30	0.00	4.69
Proportion of channel with grass	0.01	0.88	0.00	1.23
Bankfull width	2.4	6.77	0.48	0.50
n_0 – substrate type	0.02	0.055	0.015	2.08
n_1 – degree of irregularity	0.02	0.020	0.000	0.24
n_2 – sinuosity	0.004	0.015	0.000	0.54
n_3 – channel obstructions	<0.001	0.085	0.000	0.83
n_4 – vegetation	<0.001	0.142	0.000	3.07
Final Manning's n	0.05	0.168	0.024	1.60

TABLE 4. Mean and Standard Deviation Statistics for Each Input Variable by Group.

Variable	Event No.	Few-Events Group
Discharge event	7	9.3 ± 6.6
	8	6.7 ± 6.3
	11	11.2 ± 7.4
	12	5.1 ± 4.6
Rainfall event	7	16.2 ± 1.7
	8	9.0 ± 1.8
	11	23.5 ± 3.4
	12	12.0 ± 0.9
Rain two days previous	7	1.9 ± 1.1
	8	20.7 ± 2.5
	11	0.4 ± 0.3
	12	0.9 ± 0.6
Area (ha)		199 ± 47
LDI		0.23 ± 0.04
Slope (%)		0.018 ± 0.002
Well-drained deposits (ha)		90.3 ± 194.7
Moderate-drained deposits (ha)		92.5 ± 145.2
Poorly drained deposits (ha)		12.5 ± 35.2
Wetland and water (ha)		7.8 ± 17.3
Number of sites (n)		79

(78%) visits, although only 59% of sites had a response on every visit (Table 2). Sixty-four (8%) of CSG observations were above the bankfull level of flow. Four sites did not have a measurable response observed during the study. These sites all had small catchments (<80 ha) but varied both geographically and with respect to surficial geology.

At most sampling sites, bankfull width was small, with a median width of 2.4 m (Table 3). Substrate composition and sinuosity were quite variable, contrasting along continuums of cobble to clay and from linear to highly sinuous channels, respectively. The amount of wood and grass at a site also varied considerably, with many sites having zero values and a few sites being dominated by one or the other of these characteristics. Site slope varied from 0.5 to 8.0%. Final measures of channel roughness varied from 0.024 to 0.168, similar to the ratings described by Chow (1959) for open natural stream channels.

Catchment areas were generally <130 ha, but there was considerable variation in their size (7 to 1,345 ha) and in other catchment characteristics (Table 4). Land use/land cover varied from nearly pristine to almost fully urbanized, although most site catchments had relatively low amounts of disturbance (LDI < 0.2). Tile drainage was only found in 24 of the catchments, but where present, could occupy substantial proportions of the catchment (e.g., 30% in one catchment area).

One of the driest summers in 50 years occurred during 2007, such that our study area was considered to be in drought conditions sufficient to result in local water-use restrictions (Klaassen *et al.*, 2008). What rainfall did occur was spatially and temporally heterogeneous and resulted in a disparate sampling schedule for the CSGs that covered only 12 rainfall events (Table 2). Only Events 7, 8, 11, and 12 met the criteria for inclusion in the RDA analysis. Events 7 and 11 were accompanied by intense thunderstorms and intermittent recurring drizzle that resulted in a disparate distribution of rainfall and only a moderate correlation in rainfalls between sites of $r^2_{\text{adj}} = 0.30$ (Table 5). Events 8 and 12 consisted of all day drizzles that varied considerably in intensity across the area, but this variability was not captured by the distribution of agency stations and, as a result, this dataset was poorly correlated ($r^2_{\text{adj}} = 0.16$). Further, where rainfall was documented at both the agency and volunteer rain-gauge sites, there was good agreement in depth recorded; however, on many occasions, one station would record rainfall, whereas the other location did not, and there was no consistent trend in these observations. The poor correlation between agency and volunteer rainfall data precluded our attempt to include a measure of intensity or duration in the assessment of rainfall.

No discharge measurements were obtained during periods of peak flows and problems with obtaining reliable velocity measures from the flow-through meters reduced the number of observations available for discharge comparisons to 27. In general, discharge estimates using Manning's equation were underestimated (slope of 0.39) and poorly correlated ($r^2 = 0.48$) with these lower levels of discharge. Data from only two of the pressure transducers were available for comparisons, and these confirmed a strong positive correlation between results from both approaches to measure the stage height with average $r^2 = 0.73$ and slope of 0.81. These findings suggest that CSGs are likely providing a reliable measure of stage response, but there remains considerable uncertainty in the reliability of the measures of velocity used to generate each discharge event.

Patterns of Event Discharges and Rainfall in the Data

In general, event discharges or peak flows at specific sites increased with increasing rainfall, but the magnitude of the response decreased along a gradient from poorly drained to well-drained soils (Figures 4 to 6). Response patterns at individual sites to rainfall did not demonstrate a linear response in most situations and responses were generally greater at sites with higher LDI, but there was a great deal of variability in the responses. Sites like Har1_03 and Har1_04 from the low-porosity soil group and with high LDI values often but not always had very high peak flows even at low rainfall (Figure 4a). Site A01_01 in the moderate-porosity soil group had consistently high discharges regardless of the rainfall (Figure 5a). Sites such as Har2_01 and A04_14 (Figures 4c and 5c) had no consistent pattern in responses. Several sites such as Gan18_3, A04_15, and Gan6_10 (Figures 4f, 5b, and 5d) had no response to rainfall. Sites Gan18_7 and D-027 showed a low slope but linear response (Figures 4e and 5f) to rainfall, whereas other sites showed a weak but possible threshold response (Figure 5e). Within the poorly and moderately drained geology types, sites with higher LDI tended to have much higher responses and responded at lower amounts of rainfall than sites with low LDI, although there was only one site from the moderately well-drained soils group (Site A01_01) that had very high LDI (Figure 5a). Sites A04_14 and A04_15 (Figure 5a) are adjacent catchments; but they showed quite different response patterns and do not appear to be correlated with LDI or geology. Sites in the well-drained soil grouping had minimal response to rain, regardless of the LDI ratings (Figure 6). Often in the dataset, low rainfall events were associated with higher discharges than were observed at higher rainfall events.

Example bivariate plots (Figure 7) and correlations (Table 5) indicated that the comparisons of event discharges at each site were the most strongly correlated input variables. Sites tended to respond in consistent ways for each rain event (Figure 7a), but in general rain-event data were poorly correlated with each discharge event, including the matching-event discharges, where the highest correlation was only 0.12 and, in two instances, the correlation was negative ($r = -0.07$ and -0.13). Correlations of discharge with the antecedent rainfall were also variable and inconsistent, with the strongest correlation occurring for Event 12 ($r = 0.13$). Rainfall Events 7 and 8 were only two days apart, therefore rainfall before Event 8 was excluded from further analysis. Rainfall was generally correlated with broader geographic position, although the strength of the correlation varied between events (Figure 7c). There was a consistent moderately positive correlation ($r = 0.31$ to 0.43) between LDI and discharge (Figure 7d). Geographic coordinates were correlated with geology, LDI, slope, and rainfall, but were, in general, not correlated with discharges (Table 5). Because geographic location was strongly correlated with other metrics included in the analysis, location was deemed redundant and excluded from further analysis.

Redundancy Analysis

The redundancy analysis of the discharges against the landscape properties and rainfall data explained 27% of the total variation in the discharges on Axis 1 and contrasted a gradient of sites having higher to

TABLE 5. Pearson Correlation Matrix for Variables From the Few-Events Group of Sites for Which Complete Records Were Available for Rain Events 7, 8, 11, and 12 ($n = 78$ sites).

	EAST	NORTH	DIS7	DIS8	DIS11	DIS12	RN7	RN8	RN11	RN12	RB7	RB8	RB11	RB12	LDI	SLOPE	AREA	BFI	WELL	MOD	POOR	TILE	WATER
EAST	1.00																						
NORTH	0.73	1.00																					
DIS7	−0.02	−0.11	1.00																				
DIS8	−0.08	−0.25	0.85	1.00																			
DIS11	0.07	−0.01	0.79	0.78	1.00																		
DIS12	−0.08	−0.20	0.72	0.84	0.76	1.00																	
RN7	0.07	0.33	0.05	−0.20	−0.06	−0.17	1.00																
RN8	−0.04	−0.27	0.06	0.12	−0.02	0.04	−0.06	1.00															
RN11	0.37	0.74	−0.15	−0.26	−0.13	−0.23	0.30	−0.38	1.00														
RN12	−0.43	−0.20	−0.07	−0.04	−0.10	−0.07	0.25	0.16	0.04	1.00													
RB7	0.28	0.27	−0.06	−0.12	0.05	−0.20	0.10	−0.42	0.07	−0.37	1.00												
RB8	0.33	0.47	0.04	−0.19	−0.05	−0.17	0.85	−0.19	0.36	0.04	0.32	1.00											
RB11	−0.38	−0.30	−0.04	0.02	−0.02	0.02	−0.05	0.15	−0.32	0.04	−0.11	−0.36	1.00										
RB12	0.57	0.29	0.04	0.08	0.16	0.13	−0.09	0.26	0.03	−0.37	−0.08	0.03	−0.17	1.00									
LDI	−0.06	−0.51	0.32	0.43	0.31	0.39	−0.39	0.16	−0.60	−0.16	−0.16	−0.40	0.13	0.18	1.00								
SLOPE	−0.14	0.16	0.08	−0.19	−0.03	−0.15	0.34	−0.18	0.20	0.19	0.03	0.30	−0.11	−0.19	−0.29	1.00							
AREA	0.10	0.26	−0.18	−0.08	−0.14	−0.19	0.04	−0.27	0.26	−0.06	0.16	0.12	0.12	−0.08	−0.33	−0.22	1.00						
BFI	0.66	0.55	−0.11	−0.16	−0.06	−0.03	0.04	−0.27	0.27	−0.36	0.35	0.24	−0.22	0.20	−0.21	−0.04	0.03	1.00					
WELL	0.74	0.46	0.15	0.15	0.19	0.16	−0.01	−0.15	0.21	−0.38	0.26	0.18	−0.27	0.31	−0.07	−0.16	0.16	0.76	1.00				
MOD	−0.75	−0.38	−0.23	−0.23	−0.24	−0.19	0.15	0.04	0.00	0.45	−0.33	−0.05	0.24	−0.40	−0.17	0.17	0.09	−0.64	−0.82	1.00			
POOR	0.11	−0.20	0.37	0.48	0.35	0.37	−0.28	0.32	−0.31	−0.10	−0.14	−0.25	0.06	0.24	0.39	−0.26	0.01	−0.27	0.22	−0.39	1.00		
TILE	0.04	−0.01	−0.26	−0.13	−0.07	−0.11	0.03	0.10	−0.05	0.13	−0.14	−0.02	−0.14	0.25	0.05	−0.11	0.08	−0.20	−0.17	0.17	0.03	1.00	
WATER	−0.05	0.18	−0.09	−0.09	−0.09	−0.10	0.17	−0.17	0.30	−0.06	0.22	0.18	0.00	−0.15	−0.54	−0.10	0.45	0.01	0.01	0.14	−0.16	−0.14	1.00

Note: RN, event rain; RB, antecedent rain.

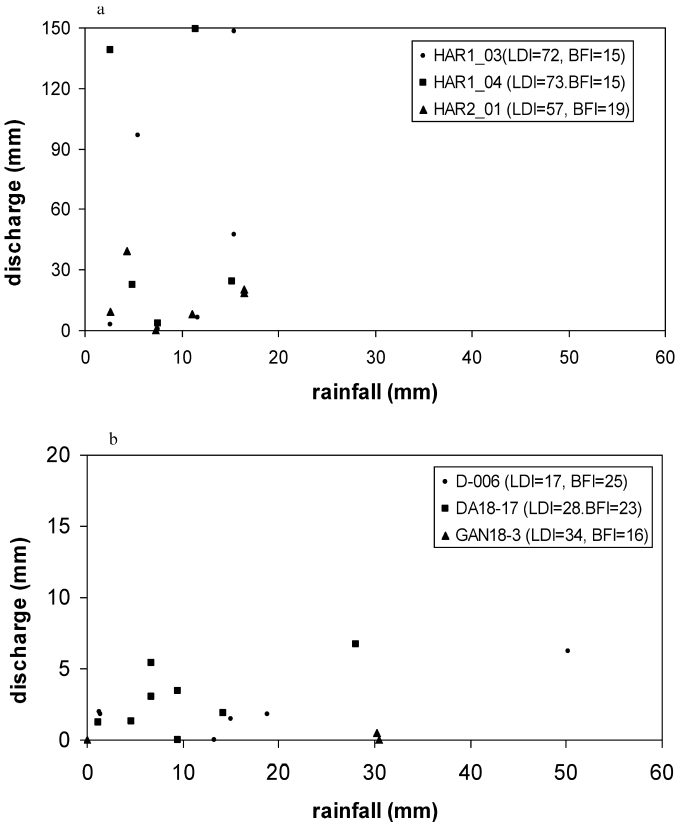

FIGURE 4. Comparison of Stream Responses to Rainfall Between Three Sites Each (e.g., HAR1_03) With the Highest and Lowest Land Disturbance Index (LDI) Ratings for Those Sites With the Poorest Drainage Capabilities [i.e., low base-flow index (BFI values)]. *Y*-axis scales are different to facilitate examination of between-event responses at individual catchments. Note the much higher discharges in sites with high LDI even at low rainfall.

lower discharge, from left to right along the axis (Table 6, Figure 8). Sites on the left tended to have higher LDI and either poorly or well-drained surficial geology conditions (Figure 8). Sites on the right side had lower discharges and more area drained by moderate-porosity soils and higher slope. These sites also tended to have more water/wetlands and increased tile drainage. In general, rainfall was poorly correlated with site discharge and none of the prior rainfall events explained more than 10% of the variance in discharge. An exception was the rainfall for the late-season sampling Event 11, which was more strongly correlated with site discharges ($r = 0.15$) than any of the other rainfall data. Axis 2 explained only 2% of the variance in the dataset and is not considered further here. Of the landscape variables, poorly and moderately drained surficial geology types and the LDI were the most influential variables in the RDA for this group. This analysis was repeated with the standardized discharge data leading to very similar results, with Axis 1 explaining only 22.7% of the variation in the data.

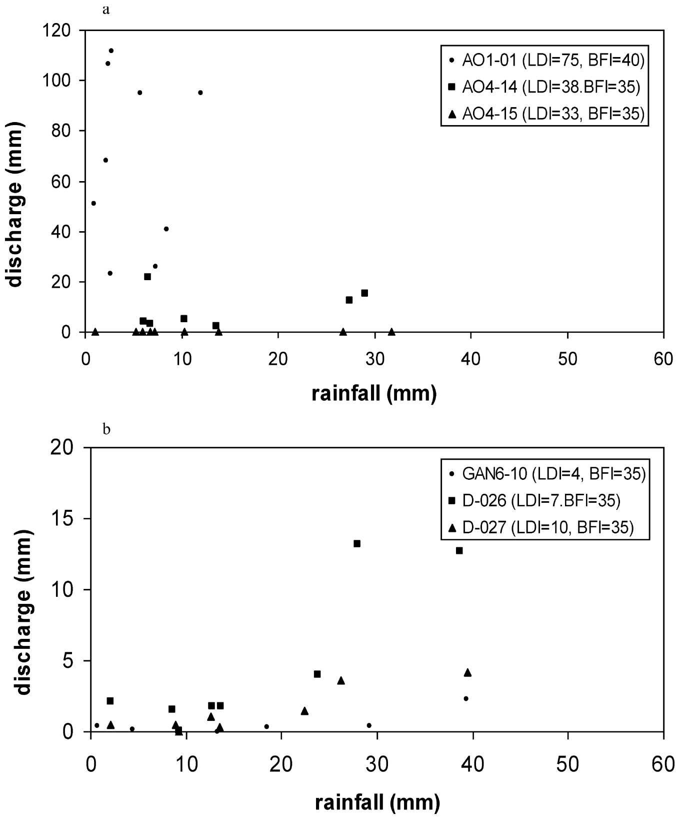

FIGURE 5. Comparison of Stream Responses to Rainfall Between Three Sites Each (e.g., A01_01) With the Highest and Lowest Land Disturbance Index (LDI) Ratings for Those Sites With Moderate Drainage Capabilities [i.e., moderate base-flow index (BFI values)]. *Y*-axis scales are different to facilitate examination of between-event responses at individual catchments. Note the extreme responses of Site A01_01 that was the only fully urbanized site in this category of drainage and the inconsistent responses with the other sites.

The pRDA determined that both LDI and geology explained similar and significant amounts of the variation ($R^2 = 0.11$) in peak flow, after the shared variation had been removed (Table 7, Figure 9). Collectively, the rainfall data explained the least amount of variation ($R^2 = 0.05$) of all the variable groupings. It can be inferred from the occurrence of negative variance components for a, d, and e that either there are elements within the groups that are having opposite effects on the correlations of peak flow or that there are strong direct effects on rainfall and landscape conditions on rainfall that are nonorthogonal in nature. This result confirms the inconsistencies observed in the other analysis of rainfall and peak-flow discharge (see above). The negative values for the variation explained that is shared between both rainfall and geology-slope and between geology-slope and LDI, suggest that the two groupings together explain more of the variation (additive effects) than keeping them apart (Legendre and Legendre, 1998).

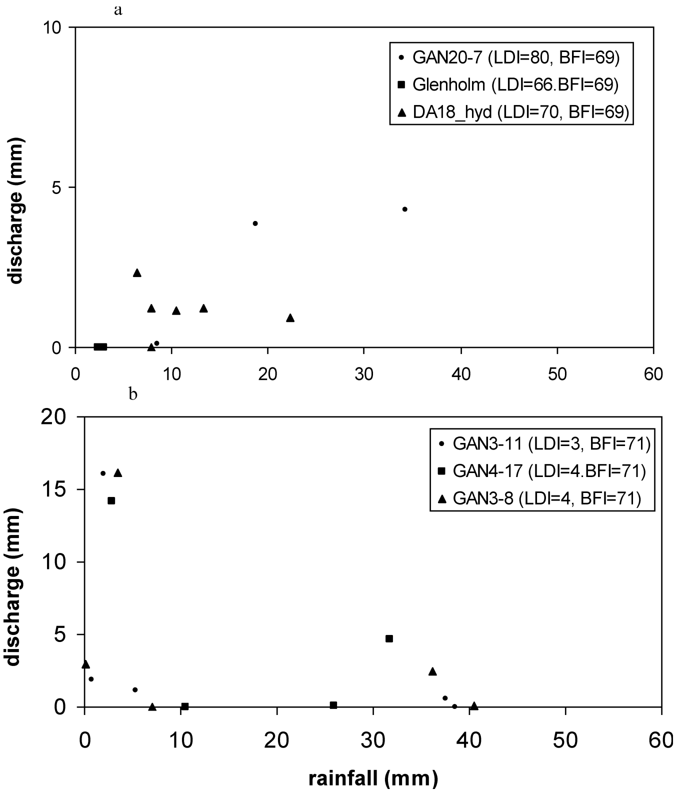

FIGURE 6. Comparison of Stream Responses to Rainfall Between Three Sites Each (e.g., Gan20-7) With the Highest and Lowest Land Disturbance Index (LDI) Ratings for Those Sites With the Highest Drainage Capabilities [i.e., high base-flow index (BFI values)]. *Y*-axis scales are different to facilitate examination of between-event responses at individual catchments. Note the minimal response in flows even with very high development in the catchment.

Overall, the amount of adjusted shared variation between the variables was generally low or negative (see *d* and *e* in Figure 9). A large amount of residual variation in the data remained unexplained (R^2 = 0.65). A second pRDA that included the amount of tile drainage and water coverage in a more comprehensive land-use/land-cover grouping did not improve the model substantially as most (80%) of the variation explained by this group (R^2 = 0.011) was shared with LDI.

DISCUSSION

To the best of our knowledge, this study represents the first attempt of a broad-scale comparative study of the factors that influence peak flows in headwater streams. Although not planned in the design, the study was carried out during a drought year in Southern Ontario, and these conditions helped emphasize the inherent heterogeneity in rainfall and stream response within headwater systems. As well, it shows the limitations in predicting how a particular catchment will respond to a given storm event during drought conditions. There are four major findings of this study. (1) Headwater streams responded to even small rainfalls with increased flows that are governed more by the geology and land use/land cover, than by the actual amount of rainfall. In fact, for some of the events, there was a negative correlation between the amount of rainfall and discharge. Sites in the most urbanized catchments tended to have the greatest discharges, but the response was highly influenced by the type of underlying geology. Geology and land use/land cover had a larger effect on the stream response than did the amount of rainfall. (2) The magnitude of stream responses in headwater streams was highly variable and, partly for this reason, the statistics explained only a small amount of the variation in the peak discharges. Some error or unexplained variance can be attributed to imprecision with methods used; however, it is also clear that both the flow conditions and the factors that influence the flow conditions are inherently variable. (3) Explained variance in the models was reduced by the low number of highly urbanized sites in the dataset, the confounding effects of surficial geology and land use/land cover, and the coarse methods used in this spatially extensive study. These factors combined to reduce the ability to determine the importance of the individual predictor variable influences on peak flows. (4) Finally, there are enormous challenges to working in highly variable systems and we have demonstrated that innovative approaches and volunteers can help expand the type and accuracy of collected data in ways that can help better understand these systems. But there remain considerable methodological challenges in conducting studies such as this one. In the following paragraphs, we expand on these findings and offer suggestions to guide future studies of headwater systems, in ways that we hope will assist in better management of these critically important features.

Significant Predictors of Peak Discharge

We show that land use/land cover and geology were both independently and equally significant predictors of peak flow after a rainfall, at least in headwater streams. This finding confirms what has been proposed theoretically (Hynes, 1970; Dunne and Leopold, 1978; Ward, 1984; Allan *et al.*, 1997) and helps elucidate the role of these two factors in influencing peak flows. Both geology and land use/land cover have been shown in many cases to be

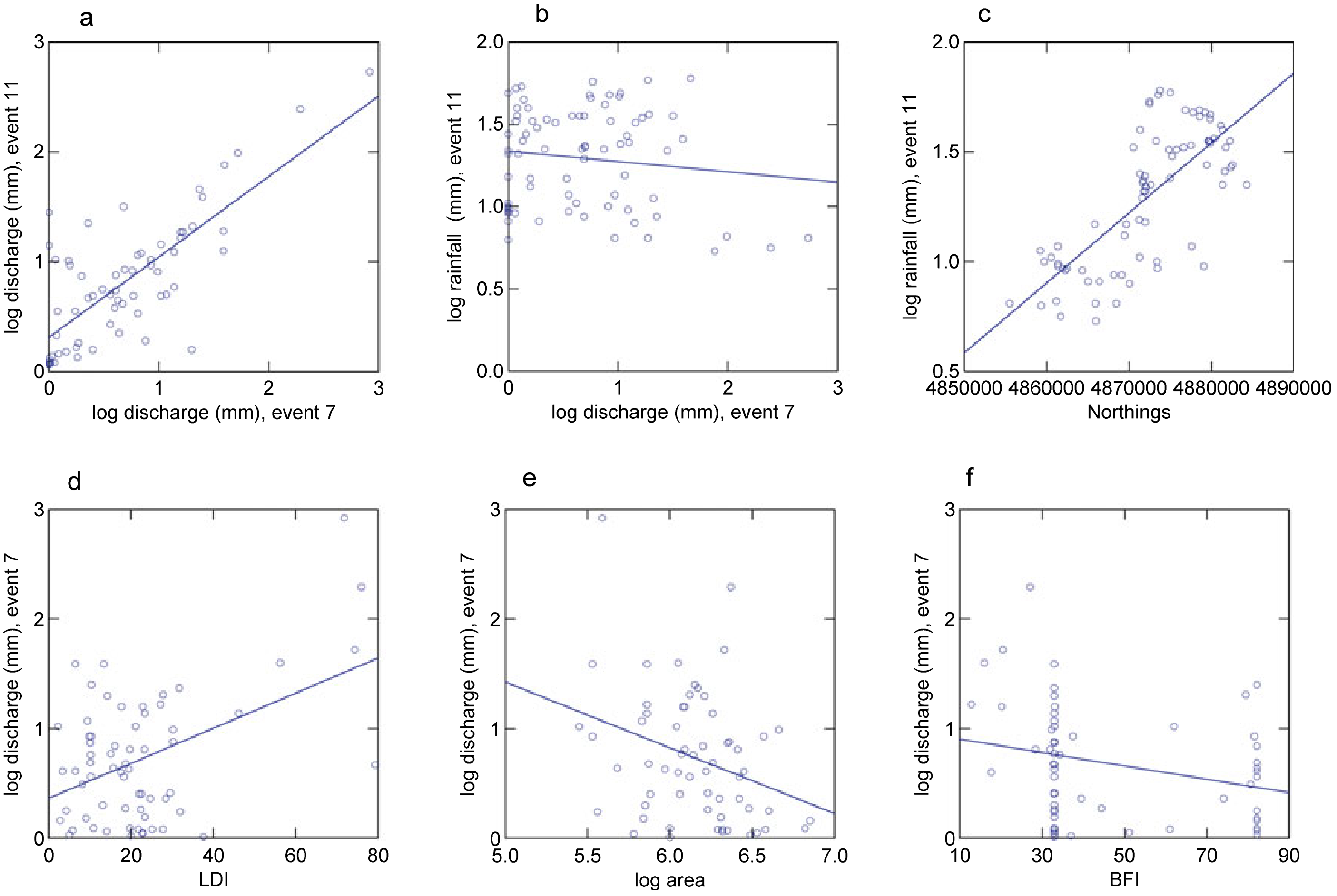

FIGURE 7. Example Bivariate Scatterplots of Selected Variables Used in the RDA Analysis. Note the consistency in discharge between events (a), the poor correlation and high variability in discharge and rainfall for even the largest rainfall event (b), the strong north-south gradient in rainfall (c), an apparent step function in discharge and LDI (d), poor correlation with area (e), and geology (f) for Event 7.

independent predictors of flows (e.g., for geology, see Gerber and Howard, 2002; for base flows, see Moore and Wondzell, 2005; for land use/land cover, see Dunne and Leopold, 1978; Cook and Dickinson, 1986; and see Dinicola, 1990, for peak flows). Many simulation models consider the combined influence of forest cover and geology (Ng and Marsalek, 1989; Beckers and Frind, 2001; Li *et al.*, 2008), but our study supports the inclusion of land use/land cover as a major modifying factor for headwater systems and provides direction for how the two factors interact, in different geologic settings.

In this study, the highest discharges were observed in areas with poorly drained soils and highest amounts of urbanization (high LDI). Results from the few sites that we were able to sample under such conditions suggest that the flows in urban areas can be extreme, at even very low rainfall levels. High discharges in urban areas have been observed in many other studies (Leopold, 1968, and a summary by Paul and Meyer, 2001). In this study area, urbanization tends to concentrate along lake shores, which is also where the poorly drained soils are located, so the effects of the two cannot be fully uncoupled.

That stream responses in the well-drained soils tended to be low regardless of both rainfall and land use/land cover was expected as these hummocky, well-drained areas are considered to be mainly recharge zones (Gerber and Howard, 2002). However, the event discharges from catchments located on the Halton till, where much of the intensive agriculture is located, were more variable than was hypothesized. Results from this geographic area played a large role in influencing patterns observed in this study and, as such, we offer several explanations for this finding.

Headwaters Are Variable. That considerable amounts of residual variation in the RDA remained unexplained following model development is common for ecological studies (Moller and Jennions, 2002). However, our observation of orthogonal relationships among the various explanatory variables ensured that our modeling results would explain even less of the variation in event discharges. These findings

TABLE 6. Results of Redundancy Analysis of the Few-Events Group Discharge Data (Y) and the Environmental Variables.

	Canonical Axis			
	Axis 1	**Axis 2**	**Axis 3**	**Axis 4**
Eigenvalues with respect to total variance of: 4.00	1.09	0.07	0.04	0.01
Percent of total variance in Y (eigenvalues) explained by each axis. Note: $R^2_{\text{adj}} = 0.15$	27.30	1.91	0.94	0.24
Correlations of environmental variables with site scores				
rn7	0.09	0.08	−0.03	0.02
rn8	0.03	−0.02	0.05	−0.01
rn11	0.15	0.01	−0.01	0.02
rn12	0.05	0.02	<0.01	0.01
rb7	0.06	0.02	−0.04	−0.03
rb11	0.05	−0.03	0.01	−0.01
rb12	−0.09	−0.04	−0.03	−0.01
LDI	−0.23	0.01	0.01	<−0.01
Slope	0.12	0.08	−0.02	<0.01
Well-drained soils	−0.23	0.01	−0.03	<0.01
Moderately drained soils	0.22	−0.02	0.01	0.02
Poorly drained soils	−0.34	−0.02	0.03	−0.02
Tile-drained lands	0.10	−0.07	−0.03	<0.01
Water	0.08	−0.02	0.01	0.01

Note: This dataset represents the set of sites with data from Events 7, 8, 11, and 12.

TABLE 7. Results of a Partial RDA on the Few-Events Group Matrix (sites with complete records from Events 7, 8, 11, and 12), Where Letters Represent the Permuted Fractions of Variation Explained by the Sum of the Eigenvalues for Each Landscape Group After Controlling for Other Variables (see Figure 9).

Landscape Groups	**Partitions of Covariable Included**	R^2	**Adj** R^2	**Probability**
Rainfall	$a + d + f + g$	0.111	0.014	0.326
Geology/slope	$b + d + e + g$	0.133	0.082	**0.024**
LDI	$c + e + f + g$	0.149	0.137	**0.002**
All variables	$a + b + c + d + e + f + g$	0.347	0.214	**0.004**
Partitioning				
Rainfall alone	a	0.053	−0.027	0.725
Geology and slope alone	b	0.149	0.118	**0.010**
LDI alone	c	0.105	0.111	**0.005**
Shared between geology/rain	d	−0.004	−0.014	
Shared between geology/LDI	e	−0.018	−0.029	
Shared between rain/LDI	f	0.056	0.048	
Shared between all three groups	g	0.006	0.007	
Residual variation		0.653	0.786	

Notes: Probability statistic is calculated using a bootstrapping approach following Peres-Neto *et al.* (2006b). Significant results are in bold.

support the warning by Gomi *et al.* (2002) that "the relationship between hydrologic response and landscape attributes contains inherently large uncertainties, which result in poor representation of physical processes and therefore low resolution models."

It is unlikely that the poor relationship observed between rainfall and discharge results from a unique condition of this topography or climate, as these relationships have been developed in a wide variety of climatic and geologic regimes (Dunne, 1978; Mosley, 1979; Post and Jakeman, 1996; Montgomery *et al.*, 1997; Beckers and Frind, 2001; Ebel *et al.*, 2007;

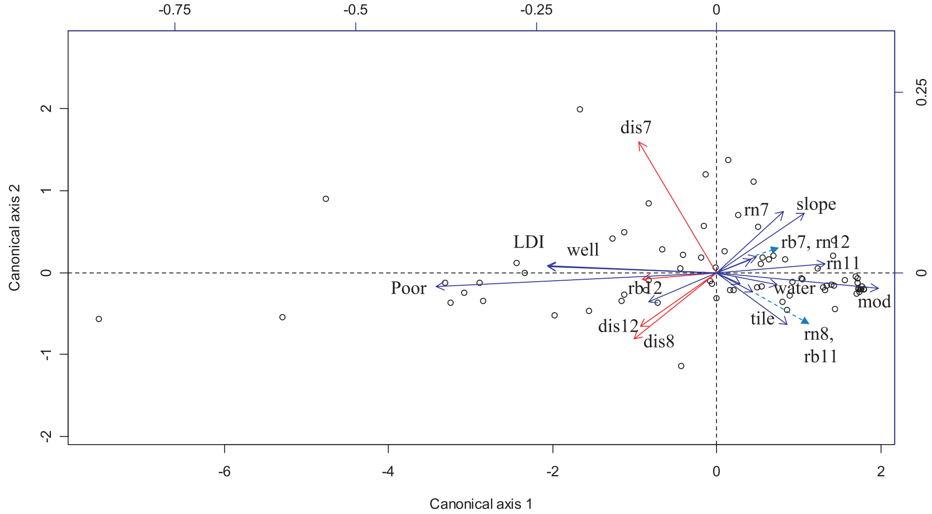

FIGURE 8. RDA Ordination Biplot of the Few-Events Group (n = 79; sites with complete records from Events 7, 8, 11, and 12) Discharge and Environmental Data. Note: rn indicates event rain, rb indicates antecedent rain, red arrows indicate discharges, and blue arrows indicate environmental variables. Arrow length is indicative of the proportion of variance correlated with each variable. The dashed lines represent extensions of vectors to facilitate plotting of labels and have no statistical meaning.

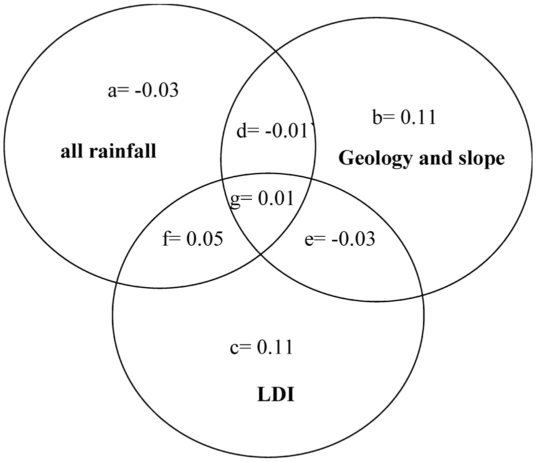

FIGURE 9. Covariance Plot of the Partitioned Adjusted Variance From the RDA for the Few-Events Group Matrix: (a) Represents All Rainfall, (b) Represents Geology and Slope, and (c) Represents LDI.

Li *et al.*, 2008). Rather, it is more likely that the difference between these findings and other published findings is related to either differences in the input variables used to develop the models, errors in our estimates of stream velocities and/or landscape variables, or because small headwater streams behave differently than is observed in downstream areas. The relevance of each of these factors in influencing the results of this study are discussed below.

Other Environmental Factors Likely Contribute to Variability in Flow Responses. By sampling in only one season, the dry soil conditions that prevailed during most of this study likely contributed to the poor correlations between discharges and the various input variables than might have been expected if mean conditions over a longer time period were considered. Drier soil conditions would affect both the overland and shallow-subsurface runoff during a storm event and the effects would likely differ, depending on geology and vegetative cover. Teasing out this effect from our datasets was challenging due to the heterogeneity of rainfall that was observed during this study period and our inability to include the intensity or duration of rainfall events in the analysis. We observed that many of the sites on the Halton till, where agricultural land use dominates, demonstrated their highest discharges during Event 11 (see Figures 4 to 6 where rainfall exceeded 30 mm). This, the most extensive and largest event, was sufficient to saturate at least the shallow soils and occurred at the end of the growing season. This suggests that at least in these moderately well-drained soils that both soil moisture and stage of vegetative growth might be important confounding factors on peak flows.

The influence of vegetative cover on discharges has been demonstrated in several studies (Finch, 1998; Moore and Wondzell, 2005; Hyndman *et al.*, 2007; Li *et al.*, 2008) and may be even greater in drought years. Mukammal and Neuman (1977), in a study in proximity to our study area, determined that actual evapotranspiration rates for forested areas could be as high as 6.5 mm/day. Hyndman *et al.* (2007) found that virtually all of the rainfall that fell in an area had the potential to be absorbed by either forests, or agriculture, during the peak growing season. Further, Zhang *et al.* (2001) found that the greatest variability in the relationship between flows and forest cover is within the deciduous and mixed-deciduous forest types, common to this study area. Finally, we acknowledge that using the amount of rainfall prior to an event rainfall as our surrogate measure of antecedent soil moisture provides only a crude estimate of these conditions. We justify its use as being something that is measurable across a broad geographic extent. That this factor did not correlate with peak flows provides some support for the conclusion that antecedent soil moisture measured during a drought period, at least as we measured it, had little influence on peak flows in this study. These findings suggest that future efforts to quantify land-use/land-cover effects on flow might benefit from a measure of potential evapotranspiration rates and techniques to better measure soil moisture across the landscape.

The methods used here to estimate discharge are adaptations of traditional approaches used in larger streams and likely underestimates velocities at high flows. Although we are reasonably confident that our measures of the wet area of the channel are reliable, we are much less sure of our measures of velocity and cannot account for flows in the flood plain, outside the bankfull channel. Our misgivings about our estimates of velocity are based on two main themes. First, velocity estimates using Manning's equation were based on the full-channel estimate of roughness. However, in most streams, coarse materials tend to be located in the periphery of the channel and would only be in contact with water under higher flow conditions, which was generally not the case for the comparison dataset, which was obtained at lower levels of flows. This condition ensures that even small differences in true channel roughness would result in significant reductions in the estimated velocity of a site and hence reduced discharge at lower depths of flow. Lee and Ferguson (2002) also found that the back-calculated n values were very high and greatly variable and that, at high flows, there could be as much as a one order magnitude reduction in n, as discharge increased over the observed range. Second, discharge and cross-sectional area were measured at one location in each site, whereas Manning's equation represents the average of conditions throughout the site. We have no means of evaluating the degree to which this mismatch of scales influences the velocity as measured, or whether the relationship of roughness to velocity is different in small channels as were sampled here. Clearly, these findings ensure that our measures of discharge per event are but a relative measure of flows at a site. We take some confidence in the conclusions in the knowledge that velocity is only one factor in the estimate of discharge and that even if our estimates of velocity are wrong they are consistently wrong because of the approaches used. A priority of future studies in headwater streams should be to resolve the factors that influence the various components of Manning's equation, so that reliable estimates of peak discharges can be obtained.

Scale of Measurement Is Important

Measuring rainfall with fine spatial resolution across a landscape is a difficult task, but one that is improving all the time (Sevruk, 1996; Heinemann *et al.*, 2002). Like many studies (Young *et al.*, 2000; Morin *et al.*, 2003; Vieux and Bedient, 2004), we found that the magnitude of the variability in both the quantities and spatial distribution in rainfall were large. We employed a volunteer network and could not control the timing of rain-gauge readings and that introduced more variability in rainfall readings (i.e., effectively uncontrolled error) than desired. However, the approach used in this study provided higher resolution interpolations than are typically available from agency-derived data alone (see Sampson and Guttorp, 1992; Teegavarapu and Chandramouli, 2005, for examples), or from what might have been possible if NEXRAD estimates were used (Jayawickreme and Hyndman, 2007). We also acknowledge that GIS data limitations such as the 25-m resolution in the DEM introduced an unknown amount of variance in the dataset that is likely to be more important in headwater systems than in larger catchments and likely contributed to the weak correlations observed. We acknowledge that improvements can be made to the methodology employed, but we believe that the approach used provided reasonable measures of the rainfall to each catchment and cannot account on their own for the poor correlations between discharges and rainfall that we observed. The implications of these findings for efforts to model and protect hydrologic properties of streams in this scale size are considerable, because it is at the medium- and fine-scale land unit size that managers are called upon to make detailed land-use plans. However, drawing generalizations of the factors that effect flows requires the field and predictor data to be collected with sufficient accuracy to ensure observed patterns are not artifacts of scale or field collection methods.

Although we are unaware of another spatially extensive study of the factors that influence headwater stream peak flows, there are several retrospective case studies from catchments of comparable size that have been compiled and synthesized by Moore and Wondzell (2005) from which we can draw comparisons. Moore and Wondzell (2005) compared the findings of 20 paired studies, conducted in small catchments (12 to 101 ha) from a broad geographic range, and determined that there can be considerable variation (−22 to +194% change) in the change in flow conditions between treatment (mainly forest clear cut) and untreated catchments. Many factors are identified in the various studies to account for the observed variability in peak flows between catchments including: local climate and geology, vegetation types, and duff layer, along with their historic patterns of disturbance and geologic processes. Further, at this small scale, smoothing effects on measured flows that are apparent in larger catchments are minimized. That we also observed high variability in peak flows and their correlations with the various predictor variables supports the contention that these same factors are also important in a local geographic setting, although teasing out the relationships is hampered by the influence of methods used.

As we discovered, working in small headwater systems is challenging, requiring unique approaches, especially where spatially extensive comparisons are required. The challenge is twofold. First, working in smaller systems requires methods that accurately measure the predictor variables. Even with our enhanced network of weather watchers the estimates of rainfall were deemed coarse and the poor correlations between both rainfall and antecedent soil moisture conditions suggest that we cannot discount the conclusion that our methods were too coarse to capture the effect of rainfall on peak flows. Ideally, we would have had a rain gauge and a means to measure soil moisture in each sample catchment, but this level of control was beyond the scope of our study. It is also likely that better measures of land use/land cover and surficial geology would increase the variance explained in the models. Second, this study demonstrates measuring peak flows in small systems can be less precise and have greater variability than data collected from sites located in larger systems. This increased intrinsic variability, along with the fact that no standard approaches exist for use in small catchments, makes it difficult to decouple the natural scaling from methodology effects. Clearly more effort is required to better understand the effect of scaling and methods used to generalize or predict how stream peak flows will change in various scenarios of drought, land use, and geology.

CONCLUSIONS AND IMPLICATIONS

This study demonstrated that at the scale at which plans of subdivision are typically made (i.e., ~100 ha), stream responses to storm events during the growing season of drought years show general patterns of similarity related to both geology and land use. Patterns such as greater responses in sites with poorly drained soils and high LDI values were found, but there was no consistent pattern of responses in flows for sites with lower levels of development. A surprise finding of this study was the poor correlation between peak flows and both rainfall and antecedent rainfall (as a surrogate of soil moisture). This result is difficult to fully explain because of the combined influences of drought conditions, scale of measurement, and the methods used. Having measurements for only a few extensive rain events during a period of extreme drought and using coarse methods to measure the key controlling properties in the watersheds limited the analytical approaches and the broad transferability of the findings. Certainly, more intensive and finer resolution data collected over a longer time frame would provide better input data for describing patterns and building predictive models. We encourage these efforts and look forward to seeing future studies that address these issues and use methods that are applied consistently across a large spatial extent, over several seasons, and that cover a range of catchment sizes and hydrologic conditions. Our more modest goal was to test the degree to which field methods that could be applied in short-term monitoring or environmental impact studies and using GIS datasets that are readily available to agency staff responsible for plan review could elucidate the factors that influenced peak flows. That these relatively coarse approaches were not better predictors of peak flows is a concern for management agencies for two reasons.

First, it is not clear how much of the poor correlation between peak flows and rainfall is attributable to our measures of the controlling watershed variables, the anomalous weather conditions, or natural variability in rainfall and flow. The field techniques used here are intensive, relative to what is routinely carried out in Ontario, and it is clear that for at least some of the approaches (measuring channel roughness) even more effort might be required in the future. These methods were sufficient to document, at a minimum, a coarse measure of stream response and rainfall. More study is required to determine the right balance between field sampling effort and model prediction capabilities. Second, we are concerned that the increases in model accuracy that generally accompany improvements in model data (e.g., more intense sampling of additional properties, such as rainfall intensity, soil moisture, local storage capacity, and evapotranspiration) may not be sufficient to provide adequate direction to protect habitats that are highly sensitive to seasonal changes in rainfall patterns, especially drought. The challenge of developing sufficient accuracy in predictions of the hydrological response in watersheds during rare events like drought, without the use of spatially and temporally intensive monitoring and modeling, is of great concern to ecologists (Tallaksen and van Lanen, 2004; Freeman and Marcinek, 2006) because of (1) the lack of resources to capture the more detailed data that might be required (e.g., catchment specific rain-gauge data) and (2) the potential impact that extreme weather conditions could have on the biota in these fragile habitats. An imprecise understanding of how flow patterns in fish-rearing headwater systems will respond to altered land use or climatic conditions could result in the loss of fish or other biota, as it is these extreme conditions that determine some of the fish residing in a system (Matthews and Marsh-Matthews, 2003). As climate change makes drought events more common in some areas (Lofgren *et al.*, 2002), the impacts from these occurrences on streams will be greater and the fact that science has yet to demonstrate an ability to predict the outcomes is worrisome.

The implications of these findings for our goal of understanding the sources of variation in sites that are below the 10% impervious cover threshold for loss of sensitive fish taxa (Stanfield and Kilgour, 2006) are large. First, these findings suggest that it will be very challenging to develop a clear cause and effect relationship between alterations in flow conditions within headwater streams and the fish in downstream reaches, at least based on the kinds of datasets that are easily available to resource managers in Ontario. In fact, these findings support Richardson and Danehy's (2007) contention that variability in the hydrology of headwater drainage features help explain variations in stream condition in downstream areas. Second, we wish to be clear that our conclusions do not preclude the possibility that flow patterns in headwater drainage features can be modeled. Rather, future efforts to develop predictive models will require even more rigorous and precise measurements than could be used here and we hope our study will provide a useful starting point for these initiatives.

Addressing these concerns within this study area in a timely fashion will be critical, as Toronto and surrounding municipalities are projected to grow by another 2 million people in the next 20 to 25 years (Sahely *et al.*, 2003) and much of this development is planned in the areas that this study has shown are the most vulnerable to generating flashy stream responses. Predictive models may not be feasible to the level of accuracy often demanded by planning processes. Rather, perhaps a new, more iterative approach that combines model estimations based on typical or mean responses in combination with a sensitivity analysis to the effects of extreme weather events may be essential, if future development is to occur in ways that prevent the continued degradation of streams from urbanization.

APPENDIX

Quantifying Manning's Equation

Manning's equation (Manning, 1891) is as follows:

$$V = \frac{1}{n}\left(R^{2/3} S^{1/2}\right), \qquad (A1)$$

where V is the velocity (m/s), R is the hydraulic radius (m), S is the slope of the channel (dimensionless change in elevation over a distance), and n is channel roughness in $m^{1/3}$/s.

Site boundaries were defined as beginning at a point of constriction or "nick point" (usually a culvert) and progressing up or downstream to the first crossover that was at least 20 m from that location. In a few instances, there was a stream feature, such as a tributary inlet or a gradient control structure, within the 20 m length and, in these situations, the site ended at this location. In this study, the approach offered by Cowan (1956) was used to estimate Manning's roughness coefficient:

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m, \qquad (A2)$$

where n is the channel roughness, n_b is the base value contribution to n for a straight uniform and smooth channel, n_1 is the contribution value for the effect of surface irregularities, n_2 is the contribution value for variations in shape and size of the channel cross-section, n_3 is the contribution value for the effect of obstructions, n_4 is the contribution value for vegetation and flow conditions, and m is a correction factor for meandering of the channel.

Recognizing the inherent variability in measuring n, we followed the advice of Marcus *et al.* (1992) and measured the various components of this formula to remove individual bias that would be present if only visual estimates were used. Values were matched to the criteria offered by either Cowan (1956) or Gore (1996) (Table A1), on the assumption that parameters increased linearly in value within each category. Data were collected once at each site during low flow periods. For all parameters except n_2, data were collected using a point-transect survey design using 10 equally spaced transects and 6 equally spaced points along each transect. Further details for each parameter are available in Stanfield (2009). On each transect the bankfull width and maximum depth of the channel was measured (see n_1). Any vegetative material that intersected the transect within the bankfull channel and exceeded 20 cm in length and was at least 5 cm wide that was dense enough to block 70% of light penetration was inventoried. These data contributed to measures of channel roughness (n_3) and the effect of vegetation on flows (n_4). Channel roughness (n_3) was determined as the sum of all obstructions within the bankfull channel including, the volume of vegetation and woody material, depth of undercut banks and other materials, provided they were > 5 cm wide and were intersected by the transect. Following the recommendation by Leopold *et al.* (1995), the D_{50} or median of the substrate particle distribution was used to estimate the value for n_b. Substrate size was determined from the median axis of each sampled substrate particle, collected by extending the index finger to the stream bed at each point location along a transect. The derivation of each roughness value obtained by these measurements was determined by using the average of all transect measurements. Mean sinuosity (n_2) was evaluated at site, visually classifying the sites from 0.0 to 1.0, where 0.0 represents a straight channel and 1.0 is highly sinuous with meanders almost connecting. The second classification was conducted using photographs taken at each site.

The hydraulic radius for each event (R) was calculated from the cross-sectional area divided by the wetted perimeter of the stream. To generate the wetted perimeter, the bed distances between observation points were calculated and summed and added to the wetted channel width, to provide the overall channel perimeter for each rain event. Data were obtained from the cross-sectional profiles conducted at the location of each CSG.

Cowan (1956) suggested that a correction factor (m) is required to account for up to a 0.03 increase in roughness associated with highly meandering streams. Therefore, each site was multiplied by a base factor of 1 plus from 0 to 0.03 depending on the sinuosity rating as described above.

TABLE A1. Criteria Used to Define the Roughness Coefficient Values, "*n*" for Each Parameter in the Cowan's (1956) Estimate of Manning's *n*.

Cowan Classification	**Field Summary Conditions**	***n* Value**
n_b substrate type		
Earth	$D_{50} \leq 2$ mm	0.020
Fine gravel	$2 < D_{50} \leq 15$ mm	0.020-0.024 (increase by 0.00031/mm increase in D_{50})
Coarse gravel	$16 < D_{50} \leq 63$ mm	0.024-0.028 (increase 0.000085/1 mm increments)
Cobble and boulder	$D_{50} > 63$ mm	0.030 + (0.00025/mm > 63 mm to a maximum of 0.07)
n_1 degree of irregularity		
Smooth	width/depth > 10	0.000
Minor (minimal scouring)	5 < width/depth ≤ 10 and <0.1 m undercut/transect	0.005
Moderate	5 < width/depth ≤ 10 and >0.1 m undercut/transect	0.01
Moderate with potential for severe erosion	width/depth ≤ 5 and 0.1 m < undercut/transect ≤ 0.2	0.015
Potentially severe: eroding banks	width/depth ≤ 5 and undercut/transect ≤ 0.1	0.02
Severe: eroding banks	width/depth ≤ 5 and >0.1 m undercut/transect	0.025
n_2 variation in channel cross-section (location of thalweg)		
Gradual	sinuosity < 0.3 (add 1 unit per unit)	0.000-0.003
Alternating occasionally	0.3 ≤ sinuosity < 0.5 (sinuosity/100)	0.005
Alternating frequently	0.5 ≤ sinuosity < 0.8 (sinuosity/80)	0.010
Alternating very frequently	0.8 ≤ sinuosity (sinuosity/66.5)	0.015
n_3 effect of obstructions (roughness)		
Negligible	No obstructions	0.000
Minor	≤1 m^3/obstructions/site	<0-0.015 (volume × 0.015)
Appreciable	1 < m^3/obstructions/site ≤ 10	0.015 + 1.67×10^{-3} per unit additional volume
Severe	>10 m^3/obstructions/site	0.030 + 0.003 per unit additional volume (maximum of 0.06)
n_4 vegetation		
No grass	0	0
Low	0 < average proportion of bankfull channel < 0.25	0.04 per unit increase
Medium	0.25 ≤ average proportion of bankfull channel < 0.50	0.01 + 0.06 per unit increase
High	0.50 ≤ average proportion of bankfull channel < 75	0.025 + 0.1 per unit increase
Very high	75 ≤ average proportion of bankfull channel	0.05 + 0.2 per unit increase
m correction factor for sinuosity		
Sinuosity	0.0-1.0	1 + (0.03 × sinuosity)

Note: Substrate types are based on Gore (1996) and all other criteria come from Chow (1959).

ACKNOWLEDGMENTS

We would like to thank the Oak Ridge Moraine Foundation, Toronto Region Conservation Authority, Ontario Ministry of Natural Resources, and the Department of Fisheries and Oceans for provided funding for this project. Additionally, Central Lake and the Ganaraska Region Conservation Authorities provided in-kind support to the project. Laura Del Guidice, Scott Jarvie, and Silvia Strobl provided administrative and logistic support. The Ontario source-water protection program supported the acquisition of the tile drainage layer for this study area. Graham Smith and Andrew Carnegie helped with some of the GIS work. Pedro Peres-Neto helped with the partitioning analysis. To my dedicated field crew of Sarah Ross, Mike Brestansky, Amie Cousins, and Christina Abengoza, we cannot say enough. The paper also benefited by the helpful comments of Tim Haxton, Danijela Puric-Mladenovic, and three anonymous reviewers.

LITERATURE CITED

Alexander, R.B., E.W. Boyer, R.A. Smith, G.E. Schwarz, and R.B. Moore, 2007. The Role of Headwater Streams in Downstream Water Quality. Journal of American Water Resources Association 43:41-59.

Allan, J.D., D.L. Erickson, and J. Fay, 1997. The Influence of Catchment Land Use on Stream Integrity Across Multiple Spatial Scales. Freshwater Biology 37:149-161.

Beckers, J. and E.O. Frind, 2001. Simulating Groundwater Flow and Runoff for the Oro Moraine Aquifer System. Part II. Automated Calibration and Mass Balance Calculations. Journal of Hydrology 243:73-90.

Bradford, A., 2008. Water Policy for Ecosystem Integrity: Oak Ridge Moraine Conservation Plan, Ontario, Canada. Water International 33:320-332.

Buttle, J.M., 1994. Hydrological Response to Reforestation in the Ganaraska River Basin, Southern Ontario. The Canadian Geographer 38:240-253.

Canada, 1985. The Fisheries Act. Government of Canada, R. S., c. F-14, Ottawa, Ontario.

Chow, V.T., 1959. Open Channel Hydraulics. McGraw-Hill Book Co., New York, New York, 680 pp.

Cook, D.J. and W.T. Dickinson, 1986. The Impact of Urbanization on the Hydrologic Response of a Small Ontario Watershed. Canadian Journal of Civil Engineering 13:620-630.

COSEWIC, 2007. COSEWIC Assessment and Update Status Report on the Redside Dace Clinostomus Elongates in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa, 59 pp.

Cowan, W.L., 1956. Estimating Hydraulic Roughness Coefficients. Agricultural Engineering 37:473-475.

DFO, 1986. Policy for the Management of Fish Habitat. The Department of Fisheries and Oceans, Publication No. 4486, Ottawa, Ontario, 28 pp.

Dinicola, R.S., 1990. Characterization and Simulation of Rainfall-Runoff Relations for Headwater Basins in Western King and Snohomish Counties, Washington. Water Resources Investigations Report 89-4052, 52 pp., U.S. Geological Survey, Tacoma, Washington.

Dunne, T., 1978. Field Studies of Hillslope Flow Processes. *In:* Hillslope Hydrology, M.J. Kirkby (Editor). Wiley-Interscience, New York, pp. 227-293.

Dunne, T. and L.B. Leopold, 1978. Water in Environmental Planning. Freeman, New York, 618 pp.

Ebel, B.A., K. Loague, W.E. Dietrich, D.R. Montgomery, R. Torres, S.P. Anderson, and T.W. Giambelluca, 2007. Near-Surface Hydrologic Response for a Steep, Unchanneled Catchment Near Coos Bay, Oregon: 1: Sprinkling Experiments. American Journal of Science 307:678-708.

Finch, J.W., 1998. Estimating Direct Groundwater Recharge Using a Simple Water Balance Model – Sensitivity to Land Surface Parameters. Journal of Hydrology 211:112-125.

Freeman, M.C. and P.A. Marcinek, 2006. Fish Assemblage Responses to Water Withdrawals and Water Supply Reservoirs in Piedmont Streams. Environmental Management 38:435-450.

GBA, 2005. Green Belt Act, S. O. Chapter 1. Province of Ontario, Toronto, Ontario.

Gerber, R.E. and K. Howard, 2002. Hydrogeology of the Oak Ridges Moraine Aquifer System: Implications for Protection and Management From the Duffins Creek Watershed. Canadian Journal of Earth Science 39:1333-1348.

Gomi, T., R.C. Sidle, and J.S. Richardson, 2002. Understanding Processes and Downstream Linkages of Headwater Systems. BioScience 52:905-916.

Gore, J.A., 1996. Discharge Measurements and Streamflow Analysis. *In:* Methods in Stream Ecology, F.R. Hauer and G.A. Lamberti (Editors). Academic Press, San Diego, California, pp. 53-74.

Hauer, F.R., and G.A. Lamberti, 1996. Methods in Stream Ecology. Academic Press, San Diego, CA, 674 pp.

Heinemann, A.B., G. Hoogenboom, and B. Chojnicki, 2002. The Impact of Potential Errors in Rainfall Observation on the Simulation of Crop Growth, Development and Yield. Ecological Modeling 157:1-21.

Henderson, F.M., 1966. Open Channel Flow. MacMillan, New York, New York, 522 pp.

Hughes, R.M. and J.R. Gammon, 1987. Longitudinal Changes in Fish Assemblages and Water Quality in the Willamette River, Oregon. Transactions of the American Fisheries Society 116:196-209.

Hunt, R.L., 1976. A Long-Term Evaluation of Trout Habitat Development and Its Relation to Improving Management-Related Research. Transactions of the American Fisheries Society 105:361-364.

Hyndman, D.W., A.D. Kendall, and N.R.H. Welty, 2007. Evaluating Temporal and Spatial Variations in Recharge and Streamflow Using the Integrated Landscape Hydrology Model (ILHM). Geophysical Monograph 171:121-141.

Hynes, H.B.N., 1970. The Ecology of Running Waters. University of Toronto Press, Toronto, Ontario, 555 pp.

Jayawickreme, D.H. and D.W. Hyndman, 2007. Evaluating the Influence of Land Cover on Seasonal Water Budgets Using Next Generation Radar (NEXRAD) Rainfall and Streamflow Data. Water Resources Research 43:1-11.

Karr, J.R. and E.W. Chu, 1999. Restoring Life in Running Waters: Better Biological Monitoring. Island Press, Washington, D.C., 206 pp.

Kassenaar, J.D.C. and E.J. Wexler, 2006. Groundwater Modelling of the Oak Ridges Moraine Area. CAMC-YPDT Technical Report 01-06. http://www.ypdt-camc.ca.

Klaassen, J., M. Vanhoucke, S. Fernandez, and N. Comer, 2008. Drought Hazard in Southern Ontario: A Historical Drought Indicator Analysis. Environment Canada, Toronto, Ontario, 124 pp.

Lee, A.J. and R.I. Ferguson, 2002. Velocity and Flow Resistance in Step-Pool Streams. Geomorphology 46:59-71.

Legendre, P. and M.J. Anderson, 1999. Distance-Based Redundancy Analysis: Testing Multispecies Responses in Multifactorial Ecological Experiments. Ecological Monographs 69:1-24.

Legendre, P. and S. Durand, 2008. Compute a Canonical Redundancy Analysis. Published for R software, Package: sonarX version 0.1-6. http://esapubs.org/archive/.

Legendre, P. and L. Legendre, 1998. Numerical Ecology. Elsevier Science, Amsterdam, The Netherlands, 853 pp.

Leopold, L.B., 1968. Hydrology for Urban Land Planning: A Guidebook on the Hydrological Effects of Urban Land Use. U.S. Geological Survey, Circular 554, USGS, Washington, D.C., 18 pp.

Leopold, L.B., M. G Wolman, and J.P. Miller, 1995. Fluvial Processes in Geomorphology. Freeman, San Francisco, California, 522 pp.

Li, Q., A.J.A. Unger, E.A. Sudicky, D. Kassenaar, E.J. Wexle, and S. Shikaze, 2008. Simulating the Multi-Seasonal Response of a Large-Scale Watershed With a 3D Physically-Based Hydrologic Model. Journal of Hydrology 357:317-336.

Lofgren, B.M., F.H. Quinn, R.A. Assel, A.H. Clites, A.J. Eberhardt, and C.L. Luukkonen, 2002. Evaluation of Potential Impacts on Great Lakes Water Resources Based on Climate Scenarios of Two GCMs. Journal of Great Lakes Research 28:537-554.

Maidment, D.R., 2002. Arc Hydro GIS for Water Resources. ESRI Press, Redlands, California, 220 pp.

Manning, R., 1891. On the Flow of Water in Open Channels and Pipes. Institute of Civil Engineering. Ireland Transactions 20:161-207.

Marcus, W.A., K. Roberts, L. Harvey, and G. Tackman, 1992. An Evaluation of Methods for Estimating Manning's n in Small Mountain Streams. Mountain Research and Development 12:227-239.

Matthews, W.I. and E. Marsh-Matthews, 2003. Effects of Drought on Fish Across Axes of Space, Time and Ecological Complexity. Freshwater Biology 48:1232-1253.

McCuen, R.H., 1989. Hydrologic Analysis and Design. Prentice Hall, New York, New York, 867 pp.

Moller, A.P. and M.D. Jennions, 2002. How Much Variance Can Be Explained by Ecologists and Evolutionary Biologists? Oecologia 132:492-500.

Montgomery, D.R., W.E. Dietrich, R. Torres, S.P. Anderson, J.T. Heffner, and K. Loague, 1997. Hydrologic Response of a Steep, Unchanneled Valley to Natural and Applied Rainfall. Water Resources Research 33:91-109.

Moore, R.D. and S.M. Wondzell, 2005. Physical Hydrology and the Effects of Forest Harvesting in the Pacific Northwest: A Review. Journal of the American Water Resources Association 41:753-784.

Morin, W., W.F. Krajewski, D.C. Goodrich, X. Gao, and S. Sorooshian, 2003. Estimating Rainfall Intensities From Weather Radar Data: The Scale-Dependency Problem. Journal of Hydrometeorology 4:782-797.

Morrison, M.M., B.G. Marcot, and R.W. Mannan, 2006. Wildlife-Habitat Relationships: Concepts and Applications. Island Press, Washington, D.C., 493 pp.

Morse, C.C., A.D. Huryn, and C. Cronan, 2003. Impervious Surface Area as a Predictor of the Effects of Urbanization on Stream Insect Communities in Maine, U.S.A. Environmental Monitoring and Assessment 89:95-127.

Mosley, M.P., 1979. Streamflow Generation in a Forested Watershed, New Zealand. Water Resources Research 15: 795-806.

Mukammal, E.I. and H.H. Neuman, 1977. Mechanical Balance-Electrical Readout. Application of the Priestley-Taylor Evaporation Model to Assess the Influence of Soil Moisture on the Evaporation From a Large Weighing Lysimeter and Class A Pan. Boundary Layer Meteorology 12:243-256.

Ng, H.Y.F. and J. Marsalek, 1989. Simulation of the Effects of Urbanization on Basin Streamflow. Journal of the American Water Resources Association 25:117-124.

OMAFRA, 2008. Ontario Ministry of Agriculture and Food. Tile Drainage Layer. Managed by Ontario Ministry of Natural Resources, Land Information Ontario, Guelph, Ontario.

OMNR, 2006. Digital Elevation Model – Version 1.1.0 – Provincial Tiled Data Set (DEM). Managed by Ontario Ministry of Natural Resources, Land Information Ontario, Guelph, Ontario.

OMNR, 2007. Southern Ontario Land Resource Information System (2000-2002), Edition 1.2. Managed by Ontario Ministry of Natural Resources, Land Information Ontario, Guelph, Ontario.

Ontario Geological Survey, 1997. Quaternary Geology, Seamless Coverage of the Province of Ontario, ERLIS Data set 14. Ontario Ministry of Northern Development and Mines, Sudbury, Ontario.

ORMCA, 2001. Bill 122, An Act to Conserve the Oak Ridges Moraine by Providing for the Oak Ridges Moraine Conservation Plan. Government of Ontario, S.O. 2001, Chapter 31, Toronto, Ontario.

Paul, M.J. and J.L. Meyer, 2001. Streams in the Urban Landscape. Annual Review of Ecological Systems 32:333-365.

Peres-Neto, P.R., P. Legendre, S. Dray, and D. Borcard, 2006a. Variation Partitioning of Species Data Matrices: Estimation and Comparison of Fractions. Ecology 87:2614-2625.

Peres-Neto, P.R., P. Legendre, S. Dray, and D. Borcard, 2006b. Supplement 3: An Executable Program for Conduction Variation Partitioning With Adjustments, Test of Fractions in Redundancy Analysis (RDA) and Canonical Correspondence Analysis (CCA). Ecological Archives, Washington, D.C., E087-158-S3.

Piggott, A., D. Brown, and S. Moin, 2002. Calculating a Groundwater Legend for Existing Geological Mapping Data. Proceedings of the 55th Canadian Geotechnical and 3rd Joint IAH-CNC and CGS Groundwater Specialty Conference, Southern Ontario Section of the Canadian Geotechnical Society, Burlington, Ontario, pp 863-871.

Post, D.A. and A.J. Jakeman, 1996. Relationships Between Catchment Attributes and Hydrological Response Characteristics in Small Australian Mountain Ash Catchments. Hydrological Processes 10:877-892.

Prudic, D.E., 1989. Documentation of a Computer Program to Simulate Stream-Aquifer Relations Using a Modular, Finite-Difference, Ground-Water Flow Model. U.S. Geological Survey, Open-File Report 88-729. http://water.usgs.gov/ogw/MODFLOW_list_of_reports.html.

Puric-Mladenovic, D., 2003. Predictive Vegetation Modeling for Forest Conservation and Management in Settled Landscapes. Ph.D. Thesis, University of Toronto, Toronto, Ontario, 282 pp.

Richardson, J.S. and R.J. Danehy, 2007. A Synthesis of the Ecology of Headwater Streams and Their Riparian Zones in Temperate Forests. Forest Science 53:131-147.

Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, Colorado.

Sahely, H.R., S. Dudding, and C.A. Kennedy, 2003. Estimating the Urban Metabolism of Canadian Cities: Greater Toronto Area Case Study. Canadian Journal of Civil Engineering 30:468-483.

Sampson, P.D. and P. Guttorp, 1992. Nonparametric Estimation of Nonstationary Spatial Covariance Structure. Journal of the American Statistical Association 87:108-119.

Schlosser, I.J., 1991. Stream Fish Ecology: A Landscape Perspective. BioScience 41:704-712.

Sevruk, B., 1996. Adjustment of Tipping-Bucket Precipitation Gauge Measurements. Atmospheric Research 42:237-246.

Shaver, E.J. and J.R. Maxted, 1995. The Use of Impervious Cover to Predict Ecological Condition of Wadeable Nontidal Streams in Delaware. Delaware County Planning Department, Ellicott City, Maryland, 7 pp.

Shuster, W.D., J. Bonta, H. Thurston, E. Warnemuende, and D.R. Smith, 2005. Impacts of Impervious Surface on Watershed Hydrology: A Review. Urban Water Journal 2:263-275.

Stanfield, L.W., 2009. Understanding the Factors That Influence Headwater Stream Flows in Response to Storm Events. Masters Thesis, University of Toronto, Toronto, Ontario, 75 pp. https://tspace.library.utoronto.ca/handle/1807/17446.

Stanfield, L.W., S.F. Gibson, and J.A. Borwick, 2006. Using a Landscape Approach to Identify the Distribution and Production of Tributary Habitats for Juvenile Salmonids. *In:* Landscape Influences on Stream Habitats and Biological Assemblages, R.M. Hughes, L. Wang, and P. Seelbach (Editors). American Fisheries Society, Symposium 48, Bethesda, Maryland, pp. 601-621.

Stanfield, L.W. and B.W. Kilgour, 2006. Effects of Percent Impervious Cover on Fish and Benthos Assemblages and In-Stream Habitats in Lake Ontario Tributaries. *In:* Landscape Influences on Stream Habitats and Biological Assemblages, R.M. Hughes, L. Wang, and P. Seelbach (Editors). American Fisheries Society, Symposium 48, Bethesda, Maryland, pp. 577-599, 601-621.

Stendera, S. and R.K. Johnson, 2006. Multiscale Drivers of Water Chemistry of Boreal Lakes and Streams. Environmental Management 38:760-770.

Sturm, T.W., 2001. Open Channel Hydraulics. McGraw Hill, Boston, Massachusetts, 493 pp.

Tallaksen, L.M. and H.A.J. van Lanen, 2004. Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater. Elsevier Science, Amsterdam, 579 pp.

Teegavarapu, R.S.V. and V. Chandramouli, 2005. Improved Weighting Methods, Deterministic and Stochastic Data-Driven Models for Estimation of Missing Precipitation Records. Journal of Hydrology 313:191-206.

TRCA, 2007. Rouge River State of the Watershed Report. Chapter 5: Surface Water Quantity. Toronto and Region Conservation Authority, Ontario, Canada, 36 pp.

Vieux, B.E. and P.B. Bedient, 2004. Assessing Urban Hydrologic Prediction Accuracy Through Event Reconstruction. Journal of Hydrology 299:217-236.

Wang, L., P.W. Seelbach, and R.M. Hughes, 2006. Introduction to Landscape Influences on Stream Habitats and Biological Assemblages. *In:* Landscape Influences on Stream Habitats and Biological Assemblages, R.M. Hughes, L. Wang, and P. Seelbach

(Editors). American Fisheries Society, Symposium 48, Bethesda, Maryland, pp. 1-24.

Ward, R.C., 1984. Response to Precipitation of Headwater Streams in Humid Areas. Journal of Hydrology 74:171-189.

Weight, W.D. and J.L. Sonderegger, 2001. Manual of Applied Hydrogeology. McGraw Hill, New York, New York, 599 pp.

Winsor, H.L., G.E. Likens, and M.E. Power, 2006. Linking Scales in Stream Ecology. BioScience 56:591-597.

Young, C.B., A.A. Bradley, W.F. Krajewski, A. Kruger, and M.L. Morrissey, 2000. Evaluating NEXRAD Multisensor Precipitation Estimates for Operational Hydrologic Forecasting. Journal of Hydrometeorology 1:241-254.

Zhang, L., W.R. Dawes, and G.R. Walker, 2001. Response of Mean Annual Evapotranspiration to Vegetation Changes at Catchment Scale. Water Resources Research 37:701-708.