Effects of urbanization on watershed hydrology: The scaling of discharge with drainage area

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ABSTRACT

This study examines the effects of impervious surfaces within urbanized land on the scaling of river discharge with drainage area. Discharge in a river channel grows as drainage basin area increases following the general equation $Q = kA^c$, where Q is river discharge, k is a measure of river base flow, A is upstream drainage area, and c is the scaling power dependency. Land use is a critical variable in the examination of river discharge; discharge has significant geologic and ecologic influences on fluvial systems. Discharge is assumed to scale linearly or nearly linearly with drainage area ($c \sim 1$), but in spite of its widespread application, the relationship has not been explicitly tested with respect to urbanization. Here we show that in small urban settings the scaling is nonlinear for peak flows. It is proposed that effective water loading occurs through a combination of increased runoff and an increase in the rate of transport to the rivers. These higher discharges in urban rivers have the potential to increase erosion, degrade aquatic habitats, and significantly alter channel forms.

Keywords: discharge, drainage area, land use, watershed, urbanization.

INTRODUCTION

Fluvial research and restoration efforts are growing in importance (Hession et al., 2003; Fleckenstein et al., 2004; Bernhardt et al., 2005), but both research and restoration tend to be concentrated at the channel reach scale, even though the hydrology of the entire watershed drives channel evolution and is most directly affected by forces external to the channel reach, including land use (Miller et al., 1993; Clark and Wilcock, 2000; Pizzuto et al., 2000; Kondolf et al., 2002; Brooks and Brierley, 2004). Discharge in a river grows as drainage basin area increases following the general equation:

$$Q = kA^c, \quad (1)$$

where Q is river discharge (m^3/s), k is a measure of river base flow (m/s), A is upstream drainage area (m^2), and c is the scaling power dependency. Discharge appears to scale linearly or nearly linearly with drainage area ($c \sim 1$) (Dunne and Leopold, 1978; Pazzaglia et al., 1998), an observation consistent with the simple notion that every unit increase in area (m^2) contributes a unit volume of water (m^3) to the channel. A value of 1 or nearly 1 for c enjoys widespread application, including modeling the longitudinal profiles of bedrock channels using the stream power erosion law (Snyder et al., 2000; Finnegan et al., 2005). In spite of its common use, the scaling relationship between discharge and drainage basin area across different spatial and temporal scales, variable geographic or geologic settings, and different land uses is lacking. This study focuses on human dimension time and space scales and is designed to provide insight into how discharge scales with drainage basin area for small watersheds, in a humid-temperate tectonically stable setting, that are undergoing an acute change in land use practices.

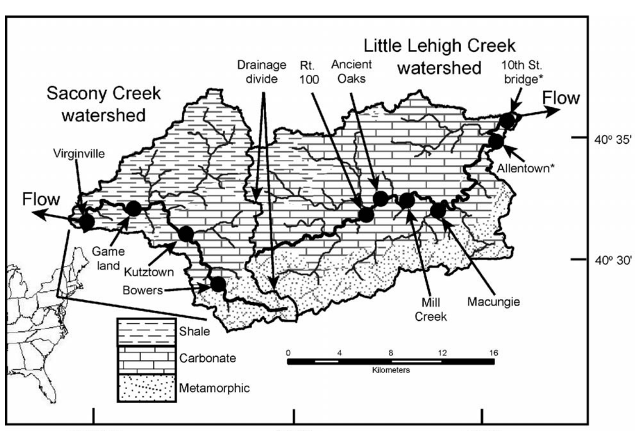

Figure 1. Simplified bedrock geology map locating Sacony Creek and Little Lehigh Creek watersheds in east-central Pennsylvania, U.S. Majority of bedrock in Little Lehigh Creek watershed is carbonate; Sacony Creek has mixed carbonate and shale substrate. Sacony Creek generally flows from east to west and Little Lehigh Creek flows from west to east. Gauging stations listed in Table 3 are labeled; two U.S. Geological Survey gauging stations are marked with asterisks.

METHODS

We selected two contiguous and physically similar watersheds in east-central Pennsylvania, Little Lehigh Creek and Sacony Creek (Fig. 1), that have different land use practices. The two watersheds are similar in drainage area (Little Lehigh, 254 km^2; Sacony, 141 km^2), trunk channel stream order (Strahler), annual precipitation (1.08 m for both), relief (Little Lehigh, 315 m; Sacony, 290 m), and underlying substrate (Fig. 1). Both watersheds also lack dams or reservoirs that would significantly affect the surface runoff. The relatively small size, low relief, and contiguous nature of the watersheds minimize the possibility that rainfall is unequally distributed. The main land use difference is expressed in the amount of urbanized land. The Little Lehigh Creek watershed has been and continues to be rapidly urbanizing, while the Sacony Creek watershed remains mostly rural and agricultural. We proceed on the assumption that urbanization results in more impervious surfaces as well as artificial pathways for rapid transport of runoff to the trunk channels. We expect that, when scaled to drainage area, discharge will increase at a faster rate along the Little Lehigh Creek than along its rural counterpart Sacony Creek.

TABLE 1. SUMMARY OF RATING CURVES

Gauge Name	Number of measurements	Min. Q* measured (m^3/s)	Max. Q* measured (m^3/s)	Rating curve ($d = y + x\text{Ln}Q$)	r^2 of rating curve
Little Lehigh Creek					
Rt. 100	8	0.40 ± 0.02	1.14 ± 0.07	(0.67 ± 0.10) + (0.33 ± 0.16)LnQ	0.74 ± 0.09
Ancient Oaks	6	0.97 ± 0.06	2.89 ± 0.17	(0.69 ± 0.03) + (0.34 ± 0.07)LnQ	0.96 ± 0.06
Mill Creek	6	0.96 ± 0.06	2.73 ± 0.16	(0.64 ± 0.04) + (0.40 ± 0.08)LnQ	0.91 ± 0.08
Macungie	6	1.07 ± 0.06	3.20 ± 0.19	(0.52 ± 0.06) + (0.30 ± 0.10)LnQ	0.91 ± 0.08
Sacony Creek					
Bowers	8	0.53 ± 0.03	3.94 ± 0.24	(0.47 ± 0.03) + (0.13 ± 0.04)LnQ	0.87 ± 0.09
Kutztown	8	1.08 ± 0.06	2.91 ± 0.17	(0.20 ± 0.02) + (0.22 ± 0.04)LnQ	0.94 ± 0.03
Game land	6	1.57 ± 0.09	6.58 ± 0.39	(0.34 ± 0.05) + (0.21 ± 0.04)LnQ	0.96 ± 0.04
Virginville	6	1.74 ± 0.10	5.24 ± 0.31	(0.16 ± 0.08) + (0.30 ± 0.06)LnQ	0.95 ± 0.05

*Q = discharge

Note: Data for the USGS gauging stations were not included because they were not constructed as part of this study.

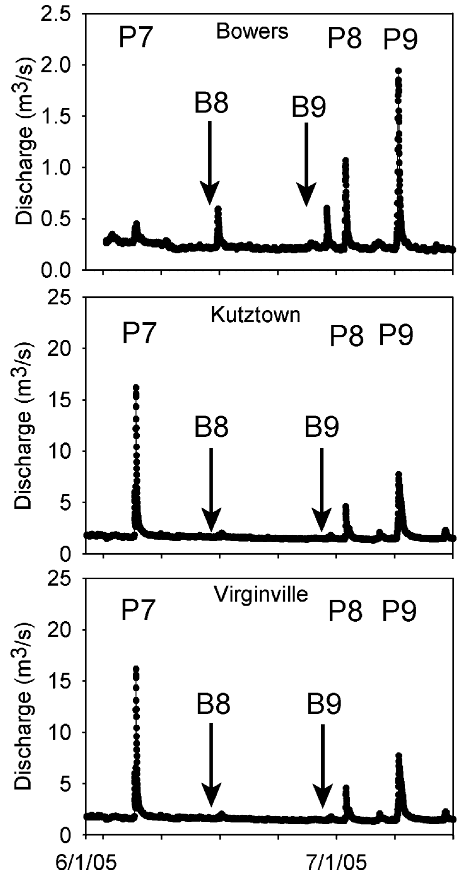

Figure 2. Gauge data from three stations in Sacony Creek watershed from December 2004 to January 2005. These data illustrate how discharge data are compiled moving downstream for both peak and base flow events. Discharge labels correspond with either peak flows (e.g., P7, P8, P9) or base flows (Table 3).

Our approach was to install instruments in a river as it flows through its watershed. Pressure sensors act as gauging stations, each one with a calibrated rating curve, so that the discharge-area relationship can be examined in detail along the length of the river. The sensors were distributed to maximize the variation in upstream drainage area A; they remained in the river for at least five months and in some cases as many as eight months. The sensors (Solinst Levelogger Model 3001, precision ±0.6 cm) recorded depth measurements at 15 min intervals and were calibrated before installation on the surface of the river bed. A rating curve was developed to calculate river discharge from the recorded water depth at each site (Table 1). The rating curves were compiled by manually measuring water velocity and depths at either 0.5 m (for channels 6–8 m wide) or 1 m (channels 10–19 m wide) increments across the channel and integrating the cross-sectional area and water velocity. Pressure sensor data are supplemented by two U.S. Geological Survey gauging stations (01451500 and 01451650) near the mouth of the Little Lehigh Creek that also record discharge at 15 min intervals. These gauging stations provide discharge measurements that are used to supplement the discharge and/or drainage area measurements compiled from the pressure sensors for both peak and base flows.

Data were compiled for both storm events and base flows. For storm events the peak discharge was calculated using the largest recorded depth (stage) for that event and the rating curve for each site and then compiling them (Fig. 2). Storm events were recorded in Sacony Creek from 28 November 2004 to 8 August 2005, and in the Little Lehigh Creek from 1 August 2004 to 27 September 2004, and 1 August 2005 to 31 October 2005. For base flows, the discharge was calculated from simultaneously recorded depths at each site, often at times immediately preceding a storm event, allowing for the lowest possible depth to be recorded and the river to be as close to base flow as possible under prevailing conditions. To determine the scaling variable c for each river (equation 1), a linear regression using dummy variables (Pindyck and Rubinfeld, 1998) through the logarithm of discharge Q and drainage area A was estimated for the storm peak flow or base flow set of data. Dummy variables ($n - 1$ for each regression) were used to account for the different environmental conditions such as antecedent soil moisture, base flow, and precipitation intensity and distribution that create different values for c for each peak or base flow event. The value of c for any given indicated river is the sum of the constant term estimated by the regression plus the estimated coefficient of the relevant dummy variable. Variance is calculated and reported at the 95% confidence interval.

RESULTS

Upstream drainage area for each discharge measurement site was calculated from 10 m digital elevation models using a geographic information system (GIS). Similarly working in a GIS, land use was summarized (into urban, agricultural, and forest) using the most recent publicly available data in the 1992 National Land Cover Database (NLCD) (EROS Data Center, 1993) and from a percent-impervious surface area coverage (Carlson, 2003). The 1992 NLCD demonstrates that the most important land use difference between the watersheds was the degree of urbanization, i.e., 20% coverage in the Little Lehigh Creek drainage and only 3% in the Sacony Creek drainage (Table 2). In 1992, the amount of forest cover in the two watersheds was roughly equal (16% and 18%, respectively); the Sacony Creek watershed has greater agricultural cover (79%) than the Little Lehigh Creek watershed (64%). Differences also exist in the spatial distribution of the impervious surfaces within each watershed (Fig. 3). In the Little Lehigh Creek watershed most of the impervious surfaces are near the mouth and mid-section of the river, while the headwaters have remained mostly undeveloped. In contrast, the percentage of impervious surfaces within the Sacony Creek watershed is relatively low throughout, even decreasing toward the mouth (Fig. 3). Being more recent, it is assumed that the 2003 percent-impervious data more accurately reflect the current urbanization patterns within the watershed than the 1992 NLCD.

For base flow conditions, drainage area and discharge scale linearly for both Sacony Creek ($c = 0.91 \pm 0.03$, $r^2 = 0.98$, n = 12) and

TABLE 2. 1992 NATIONAL LAND COVER DATA

Land Use	km^2	Area %
Little Lehigh		
Urban	52	20
Agriculture	162	64
Forest	40	16
Sacony Creek		
Urban	4	3
Agriculture	121	79
Forest	27	17

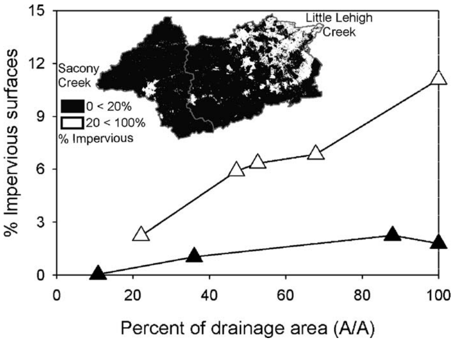

Figure 3. Distribution of percent-impervious surfaces within Sacony Creek (black triangles) and Little Lehigh Creek (white triangles) watersheds as percentage of upstream drainage area. Triangles represent points where pressure transducers were installed in two rivers. Percentage of impervious surface is fairly consistent for Sacony Creek (0.1%–2.2%), whereas it steadily increases downstream to almost 12% in Little Lehigh Creek watershed. Inset shows distribution of impervious surfaces within each watershed used to generate graphical data. Watershed names have been placed at mouth of each stream. See Figure 1 for more spatial detail on each watershed.

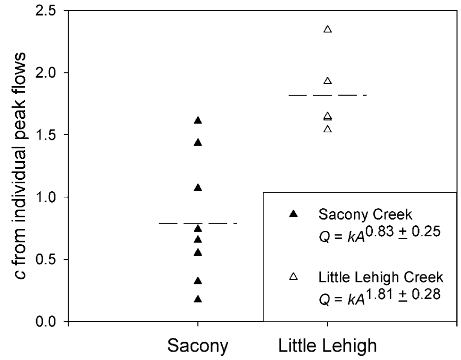

Figure 4. Regression values of each peak flow event (logarithm *A* vs. logarithm *Q*, using minimum of three data points for each regression; see text) as well as compiled linear regression (*c*, dotted line) using dummy variables (Pindyck and Rubinfeld, 1998) for all peak flow events for Sacony Creek (black triangles) and Little Lehigh Creek (white triangles). Discharge increases at faster rate for Little Lehigh Creek (*c* = 1.81 + 0.28) than for Sacony Creek (*c* = 0.83 ± 0.25), represented by larger value for Little Lehigh Creek regression.

Little Lehigh Creek ($c = 1.31 \pm 0.15$, $r^2 = 0.90 \pm 0.24$, n = 9; see GSA Data Repository[1]). However, peak flow discharge scales differently between the Sacony Creek ($c = 0.83 \pm 0.25$, $r^2 = 0.88$, n = 9) and Little Lehigh Creek watersheds ($c = 1.81 \pm 0.28$, $r^2 = 0.90$, n = 5) (Table 3; Fig. 4).

DISCUSSION

Linear scaling of discharge with drainage area implies that all parts of the drainage basin contribute nearly the same volume of water at nearly the same rate as either runoff or as recharge to the water table (Fleckenstein et al., 2004). As a hydrograph recedes to base flow conditions, the groundwater supplied to the river decreases as the elevation of the water table declines, which is the process that occurs in both the rural Sacony Creek and urban Little Lehigh Creek watersheds during base flow conditions. The peak flow scaling relationship for Sacony Creek ($c = 0.83 \pm 0.25$) similarly argues for equal contribution of all watershed area to river discharge.

In contrast, we argue that the greater amount of impervious surfaces and their distribution within the Little Lehigh Creek watershed are the critical variables causing discharge to scale nonlinearly ($c = 1.81 \pm 0.28$) with drainage basin area for peak flow conditions. Urbanization drives this response presumably because of (1) higher percentage of impervious surfaces leading to increased Hortonian overland flow (Wolman, 1967; Leopold, 1968; Hollis, 1975), and (2) anthropogenic sources and pathways strategically distributed in the watershed that not only increase the volume of discharge delivered to the river but also the rate of that delivery (Ferguson and Suckling, 1990).

In the Little Lehigh Creek watershed, anthropogenic activities are responsible for increasing *c* to values >1. The higher percentage of impervious surfaces in the watershed creates not only an increase in the volume of surface water delivered but also the rate of that delivery. There is a well-documented body of research illustrating how urbanization and the increase in impervious surfaces affect peak discharge (Leopold, 1968; Ferguson and Suckling, 1990; Booth and Jackson, 1997), but we believe that our research is unique in its presentation of the effects of urbanization on the discharge–drainage area relationship.

[1]GSA Data Repository item 2006149, base flow discharges, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

TABLE 3. PEAK FLOW DISCHARGES AND REGRESSIONS

	Drainage area (km^2)	Peak *Q* #1 (m^3s)	Peak *Q* #2 (m^3s)	Peak *Q* #3 (m^3s)	Peak *Q* #4 (m^3s)	Peak *Q* #5 (m^3s)	Peak *Q* #6 (m^3s)	Peak *Q* #7 (m^3s)	Peak *Q* #8 (m^3s)	Peak *Q* #9 (m^3s)	*c* value using dummy variables
Little Lehigh Creek gauges											
Rt. 100	55	0.69 ± 0.12	0.59 ± 0.04	1.03 ± 0.54	0.77 ± 0.20	0.93 ± 0.39					
Ancient Oaks	118	2.71 ± 0.90	1.91 ± 0.47	9.18 ± 6.15	1.62 ± 0.33	2.41 ± 0.72					
Mill Creek	132	1.88 ± 0.47	1.52 ± 0.30	7.45 ± 4.49	N.D.*	N.D.*					
Macungie	170	2.97 ± 1.03	5.52 ± 2.43	10.89 ± 5.75	2.15 ± 0.62	2.92 ± 1.00					
Allentown	209	6.12	14.97	13.45	6.23	8.13					
Allentown 10th St.	254	7.40	16.44	23.71	10.82	13.22					
$Q = kA^{c\dagger}$											
c		1.54 ± 0.40	2.33 ± 0.81	1.93 ± 0.49	1.62 ± 0.74	1.64 ± 0.62					1.81 ± 0.28
k		−2.84 ± 0.88	−4.45 ± 1.76	−3.24 ± 1.06	−3.03 ± 1.61	−2.96 ± 1.35					NA
r^2		0.93 ± 0.21	0.89 ± 0.43	0.94 ± 0.26	0.86 ± 0.39	0.90 ± 0.33					0.90 ± 0.33
Sacony Creek gauges											
Bowers	16	57.86 ± 39.30	8.11 ± 3.97	10.39 ± 5.39	1.62 ± 0.80	8.11 ± 3.97	6.52 ± 3.01	0.45 ± 0.01	1.94 ± 1.12	1.07 ± 0.33	
Kutztown	51	N.D.*	N.D.*	11.62 ± 4.27	2.78 ± 1.35	19.33 ± 8.04	N.D.*	N.D.*	N.D.*	N.D.*	
Game land	126	84.01 ± 50.40	29.19 ± 15.33	N.D.*	N.D.*	N.D.*	6.12 ± 2.39	12.87 ± 5.90	5.06 ± 1.87	4.14 ± 1.45	
Virgin	141	152.21 ± 99.88	52.73 ± 31.06	35.86 ± 20.14	40.82 ± 23.31	88.25 ± 51.00	9.06 ± 4.05	16.15 ± 8.05	7.72 ± 3.34	4.58 ± 1.74	
$Q = kA^{c\dagger}$											
c		0.32 ± 0.46	0.74 ± 0.39	0.54 ± 0.57	1.43 ± 1.26	1.07 ± 0.44	0.19 ± 0.67	1.61 ± 0.04	0.55 ± 0.30	0.65 ± 0.01	0.83 ± 0.25
k		1.37 ± 0.84	0.02 ± 0.74	0.31 ± 0.98	−1.65 ± 2.19	−0.42 ± 0.76	0.47 ± 1.34	−2.25 ± 0.07	−0.37 ± 0.56	−0.75 ± 0.03	NA
r^2		0.67 ± 0.17	0.87 ± 0.30	0.78 ± 0.38	0.84 ± 0.86	0.92 ± 0.30	0.25 ± 0.23	1.00 ± 0.27	0.93 ± 0.23	1.00 ± 0.01	0.88 ± 0.52

*N.D. = not determined.
†*Q* is river discharge (m^3/s), *k* is a measure of unit river base flow (m^3/s). *A* is upstream drainage area (m^2), and *c* is the scaling power dependency.

The impervious surfaces present in urban environments decrease infiltration and increase the rate and volume of water delivered to the river. Perhaps the key observation is that in the Little Lehigh Creek watershed, the percent of land covered with impervious surfaces increases downstream (Fig. 3). There is variation in the bedrock composition between the two watersheds; the lower Sacony Creek watershed has more shale than the predominantly carbonate bedrock of the Little Lehigh Creek watershed. The probable effect of the more impermeable shale in Sacony Creek would be to increase runoff and subsequently increase downstream river discharge, increasing its c value and reducing the difference in c values between the two watersheds. Because the variation in bedrock lithology acts to minimize the observed difference in c values and the other hydrologic variables are relatively constant across the watersheds, the remaining variation in percent-impervious surfaces is proposed as the cause of the different scaling in discharges. These impervious surfaces efficiently convert precipitation to runoff and deliver that runoff quickly to the river. The contribution of water from each unit of drainage area is not equal in the Little Lehigh Creek watershed because the downstream urbanized regions are contributing a greater volume per unit area than upstream, forested, or rural areas over the time period represented by the peak flows ($c = 1.81 \pm 0.28$) (Fig. 4). Qualitative observation suggests that a pattern of more impervious surfaces near the mouth or midsections of a watershed is common throughout the eastern United States and would produce similar discharge scaling patterns.

There are natural analogs outside the study area of eastern Pennsylvania to the discharge patterns found in both Sacony Creek and Little Lehigh Creek. In addition to representing watersheds with low amounts of impervious surfaces, the Sacony Creek watershed is an analog for natural settings where the distribution of precipitation throughout the watershed is uniform and all unit areas deliver approximately the same unit of water to the river. In contrast, we envision the Little Lehigh Creek watershed as mimicking natural settings, where the distribution of precipitation increases downstream, and/or return flow via groundwater taps a deep or extrabasinal source and scaled discharge increases downstream ($c > 1$). Downstream increase in precipitation is a phenomenon known to occur in mountainous terrain where the range is both tall and broad and the precipitation at high elevation is limited by the moisture content (Smith, 1979). Scaled peak flows that slightly decrease downstream ($c < 1$) can be thought of as occurring in those natural settings where drainage basins are more arid near their mouths, resulting in less water loading and both evaporative and channel bed seepage loss.

The higher downstream discharges in rivers with higher percentages of impervious surfaces that we document here may have unwelcome and cascading effects for sediment transport, erosion, and aquatic ecology. Discharges that increase nonlinearly downstream will drive greater channel bed incision and significantly alter channel features such as pools, riffles, and meanders. Restoration efforts often scale bankfull stream dimensions with drainage area (Rosgen, 1996), with the assumption that discharge and drainage area are substitutable (i.e., $c \sim 1$). However, this assumption is not valid when the c value of the river is closer to 2 (e.g., Little Lehigh Creek). Common local efforts to rehabilitate rivers and reverse the debilitating effects of land use change ultimately will not be effective unless the channel restoration is approached at the watershed scale.

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