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

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Galster et al. (2006) use questionable data for two Pennsylvanian streams to misconstrue the dependence of streamflow on watershed area and urbanization. Their first equation, $Q = kA^c$, relates flow rate 'Q' (m^3/s) to drainage area 'A' (m^2), using 'k,' "a measure of river base flow (m/s)" and 'c', "the scaling power dependency" (Galster, et al., 2006, p. 713) Their Table 3 reports both positive and negative values for k, and redefines its units as m^3/s. Instead, Equation 1 requires that k be positive because both Q and A are positive, and that k has inconsistent units that depend on c. Because Table 3 reports that c ranges from 0.32 to 1.61 for different hydrographs in Sacony Creek (cf. Figure 1), k's units must vary from m$^{+2.36}$/s to m$^{-0.22}$/s. Such implausible and inconsistent units are one of many problems that arise when empirical relationships and log-log plots are misused in hydrology.

The values Galster et al. list for k in Table 3, e.g., –2.25 to +1.37 for Sacony Creek, actually are values of log k. Because the scale is logarithmic, this represents a >4,000 fold range for k, rendering it useless as a measure of base flow. Also, the various fits of Equation 1 to their data are poor and conflicting (Figure 1).

Dates of occurrence are not reported for most discharge events used by Galster et al., and when they are, inconsistencies abound. Their Figure 2 caption states that the results are for "December 2004 to January 2005," yet their x-axis encompasses only June and July, 2005. None of the points shown in Figure 2 correspond in any way to Table 3, which is referenced in the caption. Worse, of the three hydrographs in Figure 2, the two for "Kutztown" and "Virginville" are impossibly identical.

Galster et al.'s conclusions can be tested by comparing sites along Little Lehigh (Rt. 100) and Sacony Creeks (Kutztown) that have comparable drainage areas (see their Table 3). The five "peak flows" reported in Table 3 for the Rt. 100 site range only from 0.59 to 1.03 m^3/s, while the three peaks reported for Kutztown are much larger, at 11.62, 2.78, and 19.33 m^3/s. Similarly, a huge difference arises when data for the 132 km^2 catchment above the "Mill Creek" site in the Little Lehigh Creek watershed are compared with those for the 126 km^2 "Game land" site in Sacony Creek. The three flow peaks reported for Mill Creek are only 1.88, 1.52, and 7.45 m^3/s, while those for Game land are much larger on average, ranging from 4.14 to 84.01 m^3/s. These examples suggest that peak flows for similarly sized rural parts of two adjacent watersheds typically differ by ~10x, which is not plausible, and are greatest for the "most natural" watershed, which runs counter to common sense and to the conclusions of Galster et al.

Finally, robust data sets do not support the contention of Galster et al. that c can exceed unity (e.g., Costa, 1987a, 1987b). Our Figure 2 shows the relationship between mean or record flow and basin area for 550 gaging stations in Pennsylvania (USGS, 2006). The regression line between mean discharge and area has a unit slope, as expected, and indicates that the average runoff for Pennsylvania is close to 50 cm/yr. The slope for record flows is ~0.79, a value that would correspond to c in Galster's Equation 1. No evidence is seen for steep slopes of ~1.8 as estimated by Galster et al. If real, their steep slope could only reflect the monotonic downstream increase in the percentage of impervious area in this particular watershed (their Fig. 3). This is a special case, because an otherwise identical watershed with the

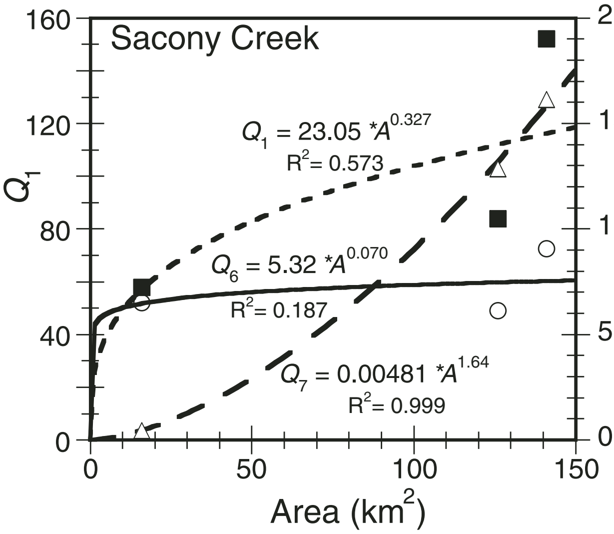

Figure 1. Graph of peak flows (m^3/s) versus catchment area for the Sacony Creek watershed, using data for events 1, 6, and 7 in Table 3 of Galster et al. (2006). Equation 1–type fits indicate exponents of 0.327, 0.07, and 1.64, which compare with 0.32, 0.19 (incorrect), and 1.61 reported by Galster et al. Values of "*k*" are positive as shown by our multiplicative factors (23.05, 5.32, 0.00481); these differ from Galster et al.'s values (1.37, 0.47, –2.25), which approximate log *k* in the first and third cases. Note the poor quality of the fits and the enormous range for *c* and *k* for only three events in this single creek.

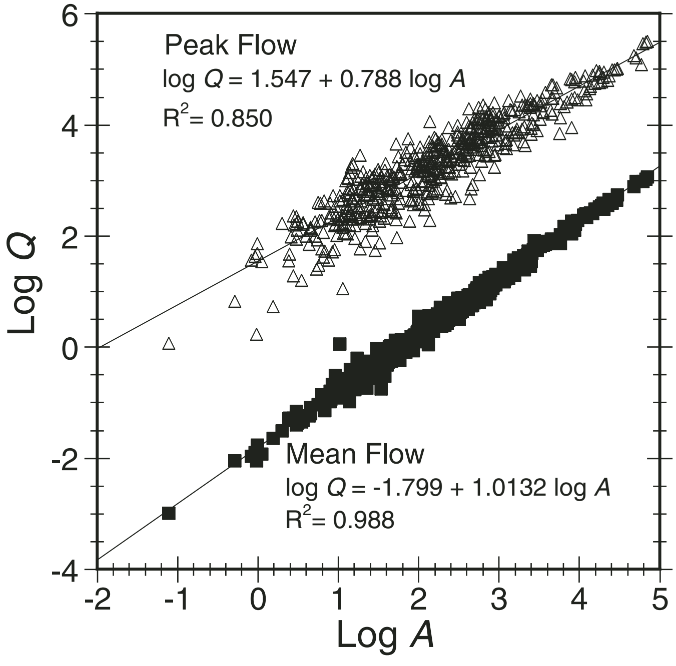

Figure 2. Log-log plot for discharge (*Q*, m^3/s) versus drainage area (*A*, km^2) for 550 USGS gaging stations in Pennsylvania. The linear relation for mean flow (squares) has a unit slope, so *c* = 1, but *c*~0.79 for maximum historic discharge (open triangles). A similar diagram for Missouri watersheds (Criss, 2003) also shows a unit slope for the mean flow relationship, but has *c*~0.5 for record flows. No data from either state suggest slopes greater than one.

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same impervious area, distributed differently, would not show such a slope. More likely, the high slope of 1.8 is an artifact that reflects an inappropriate combination of discharge determined by the U.S. Geological Survey and Galster et al., inaccurate peak flow estimations, or the different equations (exponential versus polynomial) used to calibrate the various rating curves.

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We thank Criss and Winston (2007) for their interest in and analysis of our manuscript on the interaction between discharge and drainage area. We feel that their points help strengthen the conclusions of our original article (Galster et al., 2006).

'*k*' Values: Criss and Winston begin by discussing the *k* values from Equation 1, which we characterized as a "measure of river base flow." In hindsight this was an oversimplification, as the units of *k* will vary, and we agree with their assessment that *k* is not a useful measure of discharge behavior. Watershed variables such as extrabasinal sources of groundwater, antecedent moisture conditions, and precipitation characteristics will change from one measurement of discharge to the next, and can result in different *k* values. Our goal was to characterize '*c*' from Equation 1 ($Q = kA^c$), not *k*, and we do not discuss or make any conclusions regarding *k* after our initial characterization. Criss and Winston accurately describe the *k* values in Table 3 as being log *k* values, but that description does not affect the *c* values, which are the focus of our paper and discussion. We urge caution when applying physical interpretations to empirically fitted equations.

Poor Fit of Equation 1 to Data: Criss and Winston comment that the regression of peak flow #6 (published at 0.19 ± 0.67) should be 0.07 (no published error or confidence interval). However, not only are these two values (0.19 ± 0.67 and 0.07) statistically the same given the large 95% confidence interval (0.67), but the difference can be explained by rounding issues—for publishing purposes, the values in Table 2 were shortened to two decimal places. For example, the listed discharge of event #6 for the Bowers station was 6.52, but a value of 6.516 was used in the linear regression. Other discrepancies noted by Criss and Winston are even smaller than the above example, and all are within the stated 95% confidence interval.

Figure 2: We agree that the caption and the x-axis of our Figure 2 are contradictory, with the x-axis being correct and the caption being wrong. The figure caption should read that these data are from June 2005 to mid-July 2005. In a drafting error, the hydrograph of Virginville was repeated and mislabeled "Kuztown" instead of "Game land." However, the data listed in Table 3 remain correct, as well as the statistical analyses derived from the data.

Comparison of Discharges from Similarly Sized Drainage Areas: Criss and Winston also note the disparity in our discharge data for similar drainage areas in the Sacony and Little Lehigh watersheds. Theses differences can be explained by the seasonality of the data. As we noted, most of the discharge data from Sacony Creek were collected in fall/winter, while most of the Little Lehigh discharges were collected in spring/summer. The fall/winter setting has lower evapotranspiration, higher soil moisture, and the possibility of frozen soil, all of which result in higher peak discharges given similar drainage areas.

Comparison of Other Data Sets to our Conclusions: As Criss and Winston show in their Figure 2, large data sets comparing river discharge and drainage area show linear, or close to linear, results. There are several important differences to note from their Figure 2 and the conclusions of our study. First, our study examines the increase in discharges within a single small watershed, using multiple gauging stations. Previously published research, as cited in both our article and in Criss and Winston's Comment, compiles data from multiple watersheds and concludes that *c* values are not greater than one. In our paired watershed study, we tried to carefully control for most of the watershed and hydrologic variables that plague large data sets. Our *c* value of 0.83 ± 0.25 for Sacony Creek watershed, in which the land cover is consistent throughout the watershed, not only agrees with Criss and Winston's Figure 2 but also validates our research methodology for measuring discharges.

Our study specifically set out to test how urbanization has affected the increase of discharge moving downstream in a single small watershed. The hypothesis was that changes in downstream urbanization levels in the Little Lehigh watershed would increase the flood peaks moving downstream. Our data show that the peak discharges in this watershed covary nearly with the square of drainage area ($c = 1.81 \pm 0.28$). We note that this particular pattern of downstream urbanization is not unique but is found in other similarly sized watersheds in eastern Pennsylvania. The distribution of impervious surfaces (Carlson, 2003) in the following watersheds (ranging in area from 128 to 906 km^2) was determined by dividing each watershed into upstream and downstream halves and calculating the average percent of impervious land cover for each half. Fourteen have increasing levels of impervious surfaces moving downstream (Aquashicola, Brandywine, Bushkill, Chickies, Darby, French, Jordan, Manatawny, Monocacy, Neshaminy, Pequea, Perkiomen, Saucon, and Tulpehocken), while only three (Little Schuylkill, Mahantango, and Tohickon) have less impervious surfaces downstream. We suggest that while our findings of $c > 1$ may only apply to similarly sized watersheds with urbanization concentrated downstream, this land use pattern is not unique to the Little Lehigh watershed (e.g., the 14 watersheds listed above) and that our conclusions are broadly portable.

In summary, we thank Criss and Winston for their interest and scrutiny of our original article. We appreciate the opportunity to further explore the covariance between discharge and drainage area in small watersheds undergoing acute urbanization pressure.

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