Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania

J. E. Pizzuto*
Department of Geology, University of Delaware, Newark, Delaware 19716, USA
W. C. Hession*
M. McBride*
Patrick Center for Environmental Research, Academy of Natural Sciences, 1900 Ben Franklin Parkway, Philadelphia, Pennsylvania 19103, USA

ABSTRACT

Surveys in eight paired urban and rural watersheds illustrate how urbanization changes fluvial morphology and processes. Our data also provide quantitative criteria for evaluating stream-restoration projects in urban areas. Bankfull depth, reach-averaged bed slope, and median grain size are similar in urban and rural watersheds. The median width of urban channels is 26% larger than the median width of rural channels. The median sinuosity is 8% lower in urban channels and pools are 31% shallower. The median composite Manning's *n* based on median grain diameter, pool depth, and channel sinuosity is 10% lower in urban streams, while the median bankfull discharge per unit drainage basin area is 131% higher in urban channels. Histograms of bed sediment-size distributions in urban channels lack a secondary mode in the size range 2–64 mm characteristic of rural channels, indicating that these sizes tend to be selectively removed from urban channels. However, bankfull Shields stresses in urban and rural channels exceed typical threshold values at most sites, indicating significant bedload transport at bankfull stage. Apparently, increased peak discharges caused by decades of urbanization have not removed all the transportable sediment from these urban stream channels. We speculate that the supply of sediment to urban channels from hillslope processes and channel erosion remains significant, even though much of the upland surfaces of these urban catchments are covered with nonerodible impervious surfaces.

Keywords: sediment transport, geomorphology, rivers, urbanization, watersheds, restoration.

INTRODUCTION

The effects of urbanization on watershed hydrology and river channel morphology have been studied for decades. Urbanization increases peak discharges (Leopold, 1968; Hollis, 1975) and influences the volume of sediment supplied to stream channels. Wolman (1967) suggested that sediment supply to channels should increase greatly during active construction, and Trimble (1997) demonstrated that stream channel erosion could provide a substantial fraction of the sediment produced during urbanization. Wolman (1967) suggested that after a watershed has been developed, sediment yields should decline, a hypothesis supported by Dawdy (1967). Sediment-starved stream channels subjected to increased discharges enlarge their widths and cross-sectional areas (Hammer, 1972; Leopold, 1973; Morisawa and LaFlure, 1979). Bank erosion rates and rates of knickpoint migration may also increase (Neller, 1988). Where streams flow over an erodible substrate, incision may occur (Booth, 1990; Trimble, 1997). Streams flowing near competent bedrock could become scoured of readily transportable sediment, creating coarse, armored beds that offer poor habitat characteristics.

There is a growing interest in restoring urbanized stream channels (Riley, 1998). However, because most previous studies have focused on a limited number of fluvial morphologic variables, the empirical basis for restoration of urbanized channels is unclear. As part of a restoration program for Philadelphia's Fairmount Park (Goldenberg, 1999), we measured a wide range of variables in paired urban and rural catchments to quantify geomorphic differences that could be used to design and evaluate stream-restoration projects. Our results indicate that urban stream channels of southeastern Pennsylvania are wider, straighter, and smoother than their rural counterparts. We also demonstrate that the beds of urban channels have not been extensively scoured of transportable sediment, suggesting that bed material continues to be supplied to these channels even after decades of urbanization.

STUDY AREAS AND EXPERIMENTAL DESIGN

The study reaches are located in forested areas of the Piedmont Province of southeastern Pennsylvania (Hunt, 1974) (Fig. 1). The study reaches are self-formed alluvial channels with gravelly beds and cohesive banks of composed sandy mud. Paleozoic gneiss and schist at shallow depth limits channel incision. Precipitation is evenly distributed throughout the year; the annual average is 1170 mm (Dailey, 1971).

We adopted a paired watershed experimental design. We selected eight watersheds in Philadelphia ranging in size from 6 to 4010 ha (Table 1). These watersheds are highly urbanized, with impervious fractions ranging from 34% to 50%. For each urban watershed, we then found a corresponding rural watershed with a similar drainage basin area in southeastern Pennsylvania (Fig. 1; Table 1). Five of the pairs have catchment areas within 5% of each other and two of the pairs have catchments within 14% (Table 1). Only one pair (the smallest) is not nearly equivalent in size.

Rural watersheds of southeastern Pennsylvania are appropriate controls for this study because urbanization has typically expanded into rural agricultural areas. If urbanization had not occurred, these urban watersheds would probably still be farmed, and therefore the rural watersheds represent conditions in urban watersheds before urban development. Our rural study area, however, is hardly pristine: watersheds of southeastern Pennsylvania have been influenced by deforestation and centuries of agricultural land use (Jacobson and Coleman, 1986). Nonetheless,

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*Present addresses: Hession, Department of Civil and Environmental Engineering, University of Vermont, 213 Votey Building, Burlington, Vermont 05405-0156, USA; McBride, Center for Urban Water Resources Management, Department of Civil and Environmental Engineering, Box 352700, University of Washington, Seattle, Washington 98195-2700, USA. E-mails: pizzuto@udel.edu; hession@emba.uvm.edu; mcbridem@u.washington.edu.

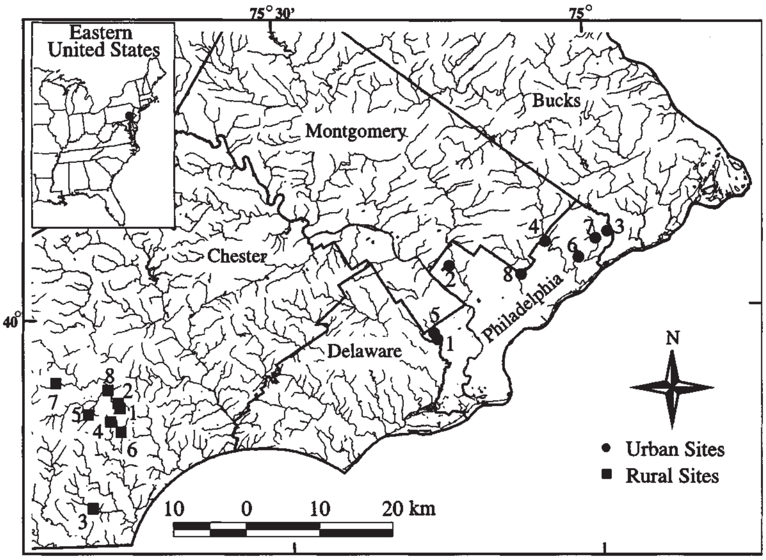


Figure 1. Locations of study areas. Site numbers correspond to pair numbers presented in Table 1.

streams in these rural watersheds are biologically healthy compared to urban streams and they therefore provide a useful reference condition for evaluating urban streams (Academy of Natural Sciences, 1999).

METHODS

In each catchment, we selected a study reach containing at least five riffle-pool pairs. All of the reaches were at least 100 m long. In each study reach, the longitudinal profile and five cross sections were surveyed during low-flow periods using a laser level and tape. The maximum water depth of each pool was also measured. The reach-averaged grain-size distribution was determined using the Wolman (1954) method. We collected samples of the bed material from the middle of the channel. The total sample size and sampling interval were varied to obtain a minimum of 200 gravel-sized clasts distributed evenly along the length of each study reach. Because sand was always present, the total sample size always exceeded 200 clasts. For example, if we estimated that the bed consisted of 50% sand, then a total sample of 400 clasts would be required. We used 200 as a minimum sample size for gravel because the results of Rice and Church (1996) suggest that this sample size should provide a precision of individual grain size percentiles within 10%. To determine the sinuosity of the channel we measured (1) the length of the channel using a tape measure and (2) the length of the valley along the study reach using a differential Global Positioning System. The length of the channel was divided by the length of the valley to obtain the sinuosity.

To better understand fluvial processes in urban and rural streams, we computed three parameters: the dimensionless Shields parameter based on the bankfull depth and the median sediment diameter, an estimated composite Manning's *n*, and an estimated bankfull discharge. The Shields parameter, τ_*, is defined as:

$$\tau_* = \tau/[(\rho_s - \rho)g\, d_{50}], \tag{1}$$

where τ is the shear stress exerted by the flow on the bed, ρ_s and ρ are the densities of the sediment and water, g is the acceleration of gravity, and d_{50} is the median diameter of the bed material. We used the normal flow approximation ρgDS (Chang, 1988, p. 39) to estimate τ (where D is the bankfull depth and S is the slope), and a constant value of 2650 kg/m^3 for ρ_s, providing a simple method for computing the Shields parameter:

$$\tau_* = DS/(1.65 d_{50}). \tag{2}$$

We estimated Manning's *n* using a modified version of the Natural Resources Conservation Service method (NRCS, formerly Soil Conservation Service), described by French (1985), that divides Manning's *n* into components related to morphologic variables. We considered the median grain size, mean pool depth (representing varia-

TABLE 1. CHARACTERISTICS OF PAIRED URBAN AND RURAL STUDY REACHES

Pair	Basin Area (ha)	% Impervious	Bed Slope (x10^{-2})	Width* (m)	Depth* (m)	Cross-sectional Area* (m^2)	d_{50}† (mm)	Sinuosity (m)	Pool Depth (x10^{-2}m)	Estimated n	Hammer number (x10^{-6} m/s)	Shields parameter
Pair 1	6/12	50/0	0.90/3.1	3.4/1.8	0.4/0.2	1.3/0.2	32/63	1.18/1.09	0.1/0.7	5.2/6.9	19.4/1.5	0.06/0.06
Pair 2	69/59	41/0	3.2/3.0	5.7/3.9	0.4/0.3	2.3/0.7	65/66	1.11/1.26	0.2/0.2	6.0/6.5	5.3/1.2	0.12/0.08
Pair 3	131/133	49/7	0.40/1.2	5.7/4.3	0.4/0.3	2.4/0.7	13/12	1.00/1.16	0.3/0.4	4.7/6.0	1.4/0.5	0.08/0.21
Pair 4	170/161	27/3	0.30/0.95	5.6/4.9	0.4/0.6	2.4/1.0	29/19	1.33/1.46	0.4/0.5	7.0/6.9	0.6/0.6	0.03/0.17
Pair 5	438/448	34/1	1.9/0.70	9.8/5.5	1.4/0.5	10.2/1.4	71/13	1.04/1.13	0.3/0.7	5.2/5.9	7.8/0.3	0.23/0.17
Pair 6	673/656	43/1	0.70/0.53	10.2/9.8	0.5/0.7	4.8/2.1	16/17	1.16/1.32	0.4/0.4	6.0/5.7	0.6/0.3	0.12/0.13
Pair 7	731/811	44/1	0.30/0.70	8.9/7.5	0.3/0.6	2.9/1.9	9/40	1.03/1.01	0.4/0.4	5.4/5.8	0.2/0.2	0.07/0.06
Pair 8	4010/4560	35/2	0.16/0.15	17.6/16.8	0.7/0.9	12.3/16.5	16/30	1.03/1.07	0.5/1.1	5.2/6.3	0.2/0.2	0.04/0.03
median % difference ††	NA **	NA	NA	26	0	180	-4	-8	-31	-10	131	NA
p§	0.31	0.01	0.48	0.01	0.67	0.12	0.57	0.05	0.05	0.09	0.07	0.93

Note: Slash indicates urban/rural parameter values.

* Average of 5 bankfull values determined at each site.

† Median bed sediment diameter.

§ Probability that urban and rural values are from the same population based on paired Mann-Whitney test (Davis, 1986). Values less than 0.1 indicate that urban and rural values are significantly different.

** Not applicable.

†† Percent difference is computed as 100 (urban value-rural value)/rural value (as in Figure 2). Only variables in Figure 2 are included.

bility in bed topography), and sinuosity. Because the bed sediment in our study reaches is not well rounded, we used the Federal Highway Administration's formula for riprap to compute n_{grain}, the contribution to Manning's n related to grain size (Chang, 1988, equation 3.43). The contribution of irregular bed topography, n_{bed}, to the total resistance was computed using the following equation adapted from the NRCS method:

$$n_{bed} = 0.02 \text{ mean pool depth/D}. \tag{3}$$

Following NRCS recommendations, values of n_{bed} greater than 0.02 were reduced to 0.02. The contribution of sinuosity, P, to Manning's n is provided by a sinuosity factor, F_p:

$$F_p = 0.6\,(P - 1). \tag{4}$$

The NRCS recommends that F_p should not exceed 0.3. The estimated Manning's n is then computed from the three components described here:

$$n = F_p\,(n_{grain} + n_{bed}) + n_{grain} + n_{bed}. \tag{5}$$

We refer to the value of Manning's n computed from equation 5 as the estimated Manning's n because it was impractical to verify these estimated values using field measurements.

Once Manning's n has been obtained from equation 5, the estimated bankfull discharge, Q_{bf}, may be computed using the Manning equation (Chang, 1988, equation 3.5). We scale the bankfull discharge by D_A, the drainage basin area defined at the downstream end of each study reach:

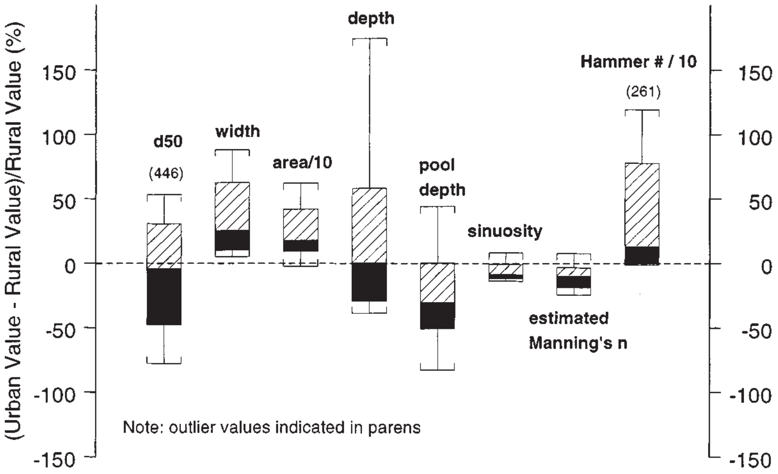
$$H = Q_{bf} / D_A. \tag{6}$$

We refer to H as the Hammer number in recognition of Hammer's (1972) pioneering studies of urbanization-related channel enlargement in the Philadelphia area. The Hammer number H is the discharge per unit drainage basin area conveyed by the channel at bankfull flow. H is a property of the channel, not the catchment.

RESULTS

Comparisons of the morphology of the paired reaches are summarized in Table 1 and Figure 2. The slope of the bed and the bankfull depth are not significantly different. Median bankfull widths and areas are 26% and 180% larger for urban channels than for rural channels (Table 1). Median sinuosities of urban channels are 8% lower than rural channels, and median pool depths are 31% smaller in urban channels than in rural channels.

The median grain size is not significantly different for urban and rural channels. Other statistics of the grain-size distribution, such as the percentages of sand, pebbles and granules, cobbles, and boulders, or cumulative grain-size percentiles such as D_{16}, D_{84}, and D_{95}, showed no significant differences between urban and rural streams.



Note: outlier values indicated in parens

Figure 2. Box plots of percentage differences between selected variables at paired urban and rural watersheds. Boundary between two patterns in each box indicates median value. Top and bottom of each box correspond to medians of all values greater than and lesser than overall median. Error bars are defined by range of data within 1.5 $Q_3 - Q_1$ (Q_3 is upper quartile and Q_1 is lower quartile). Outlier values are indicated in parentheses. Cross-sectional areas and values of Hammer number are divided by 10 so they will fit on same scale as other variables.

When comparing grain-size histograms of urban and rural channels, however, we observed an important difference: rural channels often exhibit a secondary mode somewhere in the range of 2–64 mm, with a primary mode typically from 64 to 256 mm. Urban channels exhibit a similar primary mode, but the secondary mode from 2 to 64 mm is often absent (Fig. 3) (the difference in the percentages of sand in the two histograms of Fig. 2 is *not* significant). The secondary grain-size mode is present in data from six of eight rural channels, and it is absent in data from seven of eight urban channels. A Mann-Whitney test indicates that the absence of the secondary mode from the urban channel data is significant at the 97.5% level. These results suggest that the beds of urban streams are depleted within the size range of 2–64 mm relative to rural streams.

Median estimated Manning's n values are 10% lower in urban streams than in rural streams (Fig. 2; Table 1) due to lower pool depths and sinuosities. Lower Manning's n values, when combined with increased channel areas, lead to median Hammer numbers that are 131% larger in urban streams than in rural streams (note that

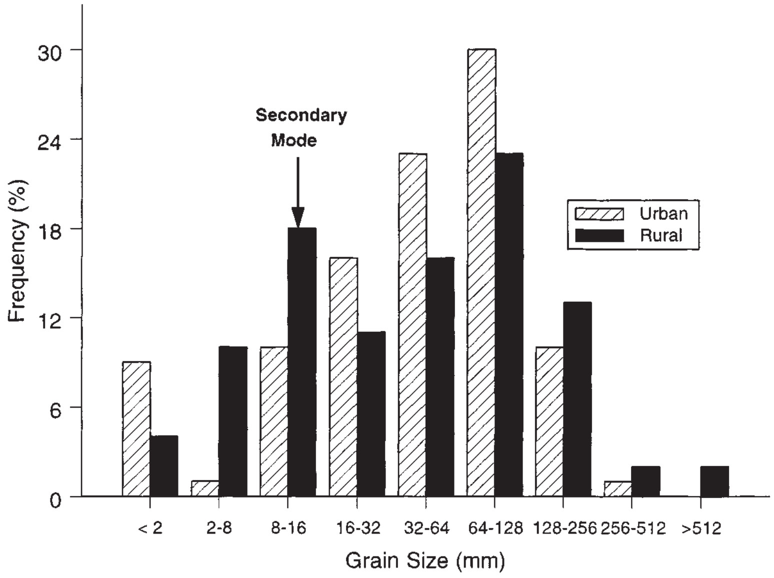


Figure 3. Typical grain-size histograms from urban and rural catchments. Urban data are from pair 1 and rural data are from pair 8. Secondary mode in range 8–16 mm is present at rural site, but not at urban site. Difference between percentages of sand between these two histograms is not significant.

values of the Hammer number are divided by 10 in Fig. 3 to facilitate plotting on the same scale as the other variables).

Shields parameters based on the bankfull depth and median grain size (equation 2) for urban and rural channels are not significantly different (Table 1). Furthermore, six of eight urban channels and seven of eight rural channels had Shields parameter values greater than 0.07, and several in each group had values greater than 0.1. These exceed values typically associated with the threshold of sediment motion. For example, Parker (1979) quoted a value of 0.03 for incipient motion of coarse gravel, and Buffington and Montgomery (1997) quoted a range of 0.03–0.07 for a variety of studies using visual methods to determine the threshold of sediment motion for gravel. These observations suggest that significant bedload transport should occur at bankfull stage in most of the urban and rural study reaches.

DISCUSSION AND CONCLUSIONS

The results presented here suggest that the urban stream channels of our study area have responded in a variety of ways to increased runoff caused by impervious surfaces. Urbanized channels have become wider, a result that has also been reported by many others (Hammer, 1972; Morisawa and LaFlure, 1979), but generally not deeper. We have also documented changes in other variables not as extensively demonstrated: urban channels have shallower pools and lower sinuosities, and they are therefore smoother, leading to lower values of estimated Manning's *n* in urban channels. All of these variables (including the median grain diameter) are combined when computing the Hammer number, which is significantly larger for urban than for rural channels, suggesting that urban channels have adjusted their size and overall frictional characteristics to convey increased peak discharges created by impervious surfaces.

When we began our study, we expected the finer size fractions of the bed to be greatly depleted in urban channels. We also expected the Shields parameter to be much lower, clearly indicating the development of threshold conditions in urbanized watersheds where channels are armored by large cobbles and boulders. Instead, our results indicate only a subtle difference in bed texture between urban and rural channels. The median grain sizes of the pairs are statistically indistinguishable, as are other grain-size statistics. The only significant difference is that urban channels lack a secondary mode in the range 2–64 mm, suggesting depletion of the bed sediment in this size range. Furthermore, Shields parameters for the urban and rural channels are larger than those characteristic of threshold gravel-bed rivers, indicating that bed material is likely to be transported during most bankfull discharge events.

After decades of urbanization, bedload transport can only remain significant if sediment continues to be supplied to the channel network. In particular, we speculate that erosion of the bed and banks and hillslope sources upstream provide enough sediment to keep the bed material sizes of urban streams nearly similar to those of rural streams. Field observations of eroding stream banks and hillslopes in Fairmount Park support this hypothesis, but further study is needed.

This study was motivated by a need to document the effects of urbanization on stream channels to guide and evaluate stream-restoration projects. If rural agricultural channels are accepted as the appropriate benchmark for comparison, then our results will help to achieve these goals. For example, Figure 2 suggests that restoration in Fairmount Park should attempt to decrease channel widths by 26% and increase pool depths and sinuosities by 31% and 18%, respectively. Resistance to flow, as summarized by Manning's *n*, should be increased by 10%. These changes should decrease the bankfull discharge per unit catchment area by ~131%.

These guidelines, however, cannot be used as a simple recipe for recreating stream channels: it would be futile to restore urban stream channels without considering the supply of water and sediment provided by the catchment upstream. Furthermore, our results do not provide any detailed blueprints for achieving the changes described here. However, by quantifying the differences between urban and rural stream channels, we have provided some useful measures for evaluating the results of stream-restoration projects in urbanized watersheds.

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