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MEASURING THE IMPACT OF URBANIZATION ON CHANNEL WIDTHS USING HISTORIC AERIAL PHOTOGRAPHS AND MODERN SURVEYS[1]

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ABSTRACT: Land use in a watershed is commonly held to exert a strong influence on trunk channel form and process. Land use changes act over human time-scales, which are short enough to measure effects on channels directly using historic aerial photographs. We show that high-resolution topographic surveys for the channels of paired watersheds in the Lehigh Valley, Pennsylvania, are comparable, but have channel widths that have changed dramatically in the past five decades. The two watersheds, Little Lehigh Creek and Sacony Creek, are similar in most aspects except in their respective amount of urban land use. Aerial photographs of the urbanized Little Lehigh Creek show that a majority of the measured widths (67 of 85) were statistically wider in 1999 than in 1947. In contrast, the measured widths from the agricultural Sacony Creek are more evenly distributed among those that widened (18), narrowed (28), and those that were statistically unchanged (6) from 1946 to 1999. From 1946 to 1999 the only section of Sacony Creek that widened was that reach downstream of the only sizable urban area in the watershed. The current land use in Sacony Creek watershed resembles that of 1946, while the Little Lehigh Creek watershed has more than tripled its urban area. These data, in concert with other recent hydrologic data from the watersheds suggest that the increase in urban area-generated peak discharges is the mechanism behind the widening that occurred in the Little Lehigh Creek. These wider channels can affect water quality, aquatic habitat, suspended sediment loads, and river esthetics.

(KEY TERMS: erosion; runoff; urbanization; fluvial processes; watersheds; geographic information system; fluvial geomorphology).

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INTRODUCTION

Throughout the middle-Atlantic states, a recurring observation is that channels are widening over human time spans (Wolman, 1967; Wolman and Schick, 1967; Hammer, 1972; Jacobson and Coleman, 1986; Trimble, 1997; Kondolf *et al.*, 2002). Widening is typically viewed as a problem that needs to be addressed in terms of the engineering challenges wider channels present for bridges and related structures, the loss of private property, the alteration of ecologically sensitive riparian zones, and the mobilization of legacy sediments from floodplains to sinks further down

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basin. Claims of widespread channel widening lack one or both of two key components: (1) isolation of the process or processes that are primarily responsible for driving the widening and (2) understanding if the widening is a transient, perhaps even cyclic process, or if it represents a truly secular trend for all reaches of the trunk channel. The second possibility is particularly interesting because the channels undergoing change are already profoundly altered forms of what they were before European colonization. Recent work (Merritts *et al.*, 2006) strongly suggests that we do not know if the observed channel widening is simply a natural response driving the channels back towards a precolonization form. Certainly, the conclusions of the benchmark studies on this topic (e.g., Wolman, 1967; Wolman and Schick, 1967; Hammer, 1972; among others) are being revisited and reinterpreted in the context of a large, emerging body of data that shows that the mid-Atlantic states are virtually devoid of natural channels and that changes in channel form and process have as much to do with the effects of legacy sediments from agricultural practices as they do from urbanization (Merritts *et al.*, 2006).

In this paper, we avoid these problems by documenting the channel widening phenomena through both a paired watershed study and the direct measurement of channel widths preurbanization and posturbanization. Additionally, we offer an explanation of the key driving process based on detailed hydrologic data we have previously collected for these watersheds (Galster *et al.*, 2006). Rather than repeat the results of the evaluation of changes in stream hydrology through time here, the interested reader is directed to Galster *et al.* (2006).

Comparative studies using multiple watersheds to determine the effects of land use change on channels are numerous and wide in their scope. Some recent studies in the mid-Atlantic states have examined how changes in vegetation (Hession *et al.*, 2003; Allmendinger *et al.*, 2005) and sediment supply (Kondolf *et al.*, 2002; Brooks and Brierley, 2004) influences channel morphology and river processes. One of the most studied changes in land use is urbanization and the role of increased impervious surfaces within a watershed. Increased discharges (Arnold *et al.*, 1982; Doll *et al.*, 2002; Burns *et al.*, 2005) channel widening and/or meandering (Arnold *et al.*, 1982; Pizzuto *et al.*, 2000; Brooks and Brierley, 2004; Cianfrani *et al.*, 2006) and fluctuations in sediment supply (Trimble, 1997; Clark and Wilcock, 2000; Nelson and Booth, 2002) have all been documented as the percentage of impervious surfaces within a watershed increases due to urbanization. Most of these studies are comparative in design (i.e., compare two sites with one variable changing), which is useful but presents difficulties because of the inherent complexity across watersheds and rivers (Schumm, 2005), even at small spatial and temporal scales. Like other studies, two watersheds with different amounts of urbanized land are compared here, but this study also directly measures the changes in stream width before and after the increase in urbanization rather than using indirect space-for-time methods. Land use change and channel responses operate over human time-scales allowing for direct observation and measurement and eliminating some of the difficulties from using multiple watersheds.

The specific land use change tested here is the increase in urbanization of which the most obvious change is an increase in the percentage of impervious surfaces. Impervious surfaces tracks closely with population density (Arnold and Gibbons, 1996), and it is these surfaces that increase peak discharges in a river (Galster *et al.*, 2006). A significant increase in impervious surfaces decrease infiltration, increase runoff, and decrease transit time to the channel, resulting in larger peak flows (Ferguson and Suckling, 1990; Booth and Jackson, 1997; Wang *et al.*, 2001). We hypothesize that these larger peak flows cause a river channel to adjust to the new hydrologic regime by widening its channel. We test this hypothesis using two methods: (1) comparing the current channel morphologies of two similar streams with different amounts of impervious surfaces in their watersheds and (2) using historic aerial photographs to measure stream widths before and after land use change over a decadal time-scale. The combination of comparative measurements over different time-scales helps distinguish our approach from most published comparative studies (e.g., Pizzuto *et al.*, 2000; Hession *et al.*, 2003; Iroume *et al.*, 2005).

Watershed Characteristics and Land Use

The Little Lehigh Creek and Sacony Creek watersheds in eastern Pennsylvania share many characteristics in common, but vary considerably in their land use. Each watershed has a long (>50 years) record of aerial photographs, which allows for the direct comparison of trunk channel widths before and after land use change. The two watersheds are similar in drainage area (Little Lehigh: 254 km^2 and Sacony: 152 km^2), trunk channel stream order (fourth, Strahler), annual precipitation (1.08 m for both), relief (Little Lehigh Creek: 315 m and Sacony Creek: 290 m), and underlying bedrock geology (Table 1) (Figure 1). The upper part of Sacony Creek watershed is carbonate and the lower shale, while most of the Little Lehigh watershed is underlain by carbonates. Neither watershed has any large dams or reservoirs that would significantly affect the surface runoff.

TABLE 1. Watershed Characteristics.

	Little Lehigh Creek	Sacony Creek
Area (km^2)	254	152
Length (km)	39.1	28.3
Stream order	4th	4th
Relief (m)	312	287
Bedrock Geology	Carbonate	Carbonate and shale

TABLE 2. Land Use Data.

Watershed	Little Lehigh Creek		Sacony Creek	
Land use	Area, 1947 km^2 (%)	Area, 1992 km^2 (%)	Area, 1946 km^2 (%)	Area, 1992 km^2 (%)
Urban	16 (6)	52 (20)	3 (2)	4 (3)
Agriculture	197 (78)	162 (64)	126 (83)	121 (80)
Forest	41 (16)	40 (16)	23 (15)	27 (17)

The most significant difference between the two watersheds is their current land use (Table 2). The 1992 National Land Cover Database (NLCD) data shows that the Little Lehigh Creek watershed is more urbanized (20%) than the rural Sacony Creek watershed (3%). There are roughly equal percentages of forest cover within each watershed, with the Sacony Creek watershed having a higher percentage of rural land. In contrast, the land use pattern was similar for the two watersheds in 1946/1947, although the Little Lehigh Creek was slightly more urbanized than the Sacony watershed (6% *vs*. 2%).

Another significant difference between these watersheds is their discharge characteristics. The peak discharges during storm events scale at a much faster rate downstream for the Little Lehigh Creek than for Sacony Creek (Galster *et al.*, 2006). Discharges were recorded at multiple sites along the trunk channel in each watershed. The discharge increased at a much faster rate in the Little Lehigh watershed when scaled with drainage area than for Sacony Creek watershed, indicating that more discharge per unit drainage area is generated in the lower portions of the watershed with respect to the headwaters.

METHODS

The oldest aerial photographs for the Little Lehigh Creek and Sacony Creek watersheds are from 1947 and 1946, respectively. The black and white photo-

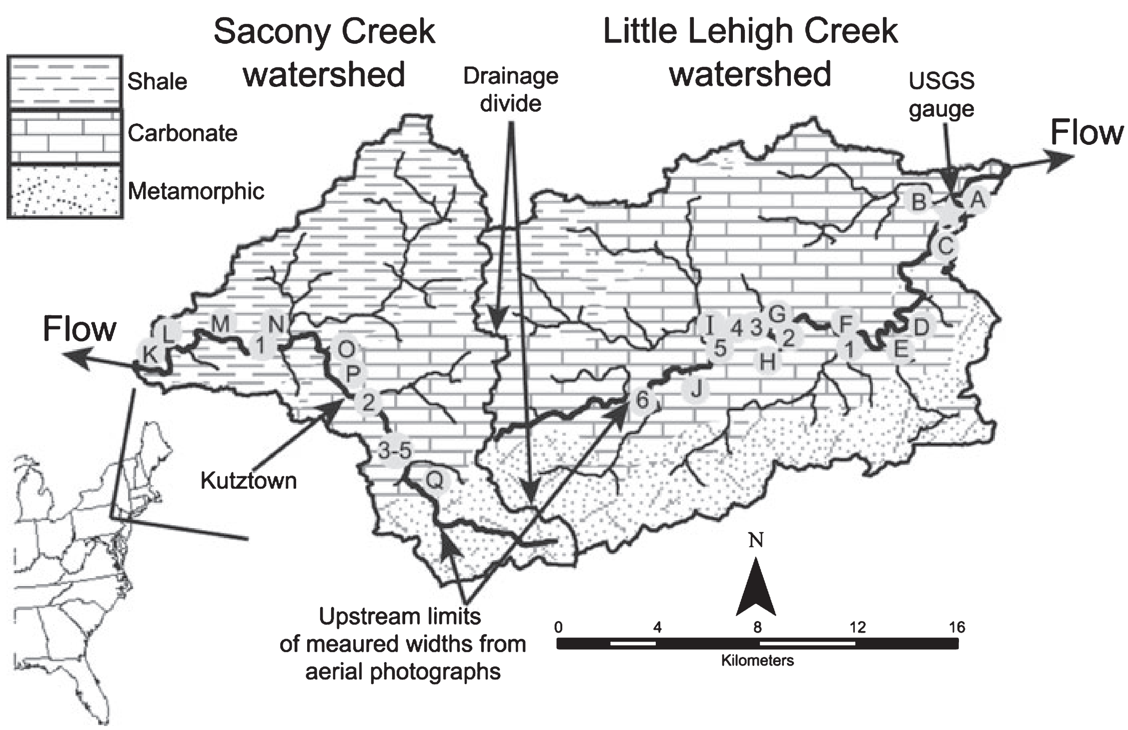

FIGURE 1. Location and Bedrock Geology Map of the Sacony Creek and Little Lehigh Creek Watersheds. The numbered circles correspond to the surveys listed in Table 3, the letters to the building control points (Figure 8), and the gray star to the USGS gauge near Allentown, Pennsylvania.

graphs (1:20,000) were originally taken by the U.S. Department of Agriculture for their Agricultural and Stabilization Conservation Series (Pennsylvania Geological Survey Library, 1946, 1947). The photographs for Little Lehigh Creek were taken on June 22, 1947, for the downstream section (points 1-55) and August 1, 1947, for points 56-86. The Sacony Creek photographs were taken either on November 19 or 27, 1946.

The 1946/1947 photographs were digitized on a flat-bed scanner at either 600 dots per inch (dpi) or 300 dpi, depending on their location relative to the river channel. Photographs containing the main trunk channel were scanned at 600 dpi whereas the remaining photographs were scanned at only 300 dpi, which was sufficient resolution for land use classification. The digitized photographs were imported into a Geographic Information System (GIS) and georeferenced in Earth Science Research Institute's (ESRI) ArcMap 8.3 (ESRI, Redlands, CA) using at least six ground control points from spatially referenced (usually road intersections) GIS layers. The ground control points were selected to avoid a clustering of the points in one section of the photograph, and georeferencing continued until the root mean square error was less than 12. A first-order (affine) transformation was used on all photographs.

Modern channel widths were measured from the 1999 digital orthophotographs from the National Aerial Photography Program, Series III. They were obtained from the Pennsylvania Geospatial Data Clearinghouse (Pennsylvania Spatial Data Access, 2000), have a 1-m ground resolution, and were already georeferenced. The photographs, taken from April 13-24, 1999, each cover one quarter of a quadrangle and overlap with the adjacent photograph 50-300 m. Photographs from the Fleetwood, Manatawny, and Kutztown quadrangles were used for Sacony Creek, and Allentown East, Allentown West, and Topton for Little Lehigh Creek.

The width of the Sacony and Little Lehigh trunk channels was measured using the georeferenced aerial photographs and a GIS. Points were established for each stream for the old (1946/1947) and new (1999) photographs at locations where both streambanks were visible for both sets of years. The need for visible banks results in the points being placed at places where there are sparse or no tree cover. Points were kept a minimum of 80 m apart to make each width measurement independent of the nearest upstream or downstream neighbor. Where there was overlap between more than one photograph the width was measured on the photograph whose center was nearest to avoid the edge of a photograph where the distortion is highest. The channel width was measured in a GIS at 1:900 (Figure 2) a minimum of 10 times on the same photograph in order to determine precision. Widths were measured at 83 points over 31.8 km length of the Little Lehigh Creek (Figure 3), and 52 points on 24.9 km of the shorter Sacony Creek (Figure 4). Bankfull widths were determined by the using the change from dark shaded pixels to light shaded pixels (Mount *et al.*, 2003) (Figure 2). Using the means of the replicate measurements for each year *t*-test were run to determine the statistical significance of any differences in measured width and

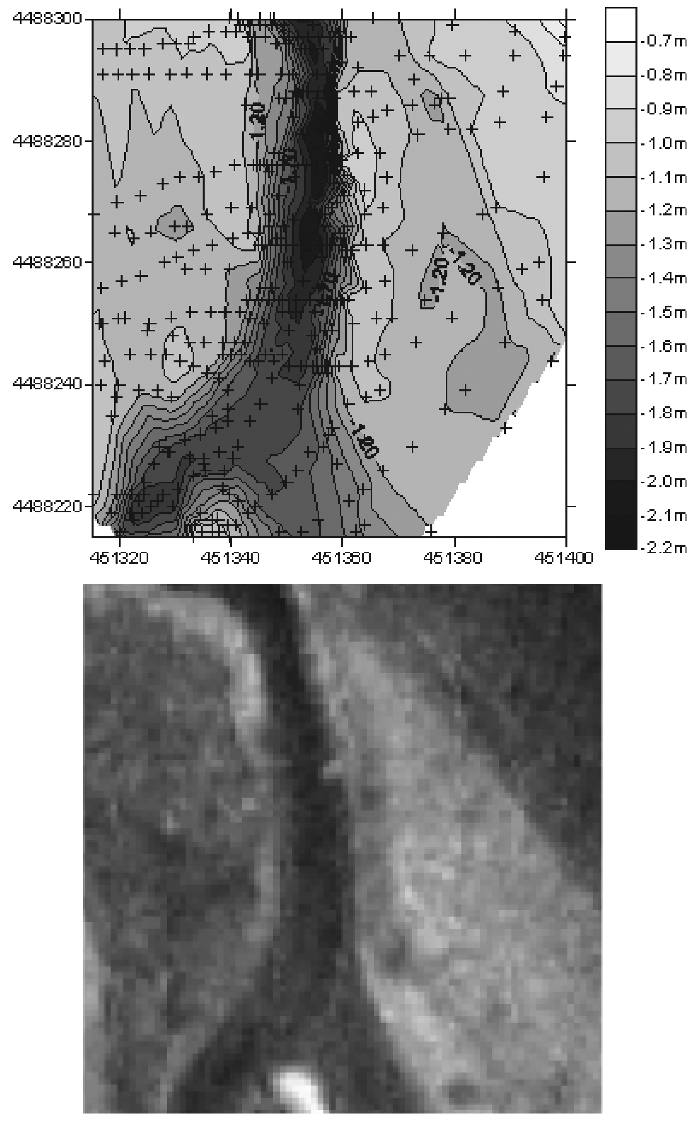

FIGURE 2. The Top Image Is a Contour Map Produced From Survey 3 on the Little Lehigh Creek and Bottom Image Is the Corresponding 1999 Aerial Photograph. The stream flow is from top (north) to bottom (south) with the channel dividing around an island at the bottom of the image. The elevations in the survey are relative to the location of the total station, and the symbols (+) represent the survey points used to build the contours. The 1999 image is shown at 1:900, the scale that was used to measure the bankfull widths from all aerial photographs.

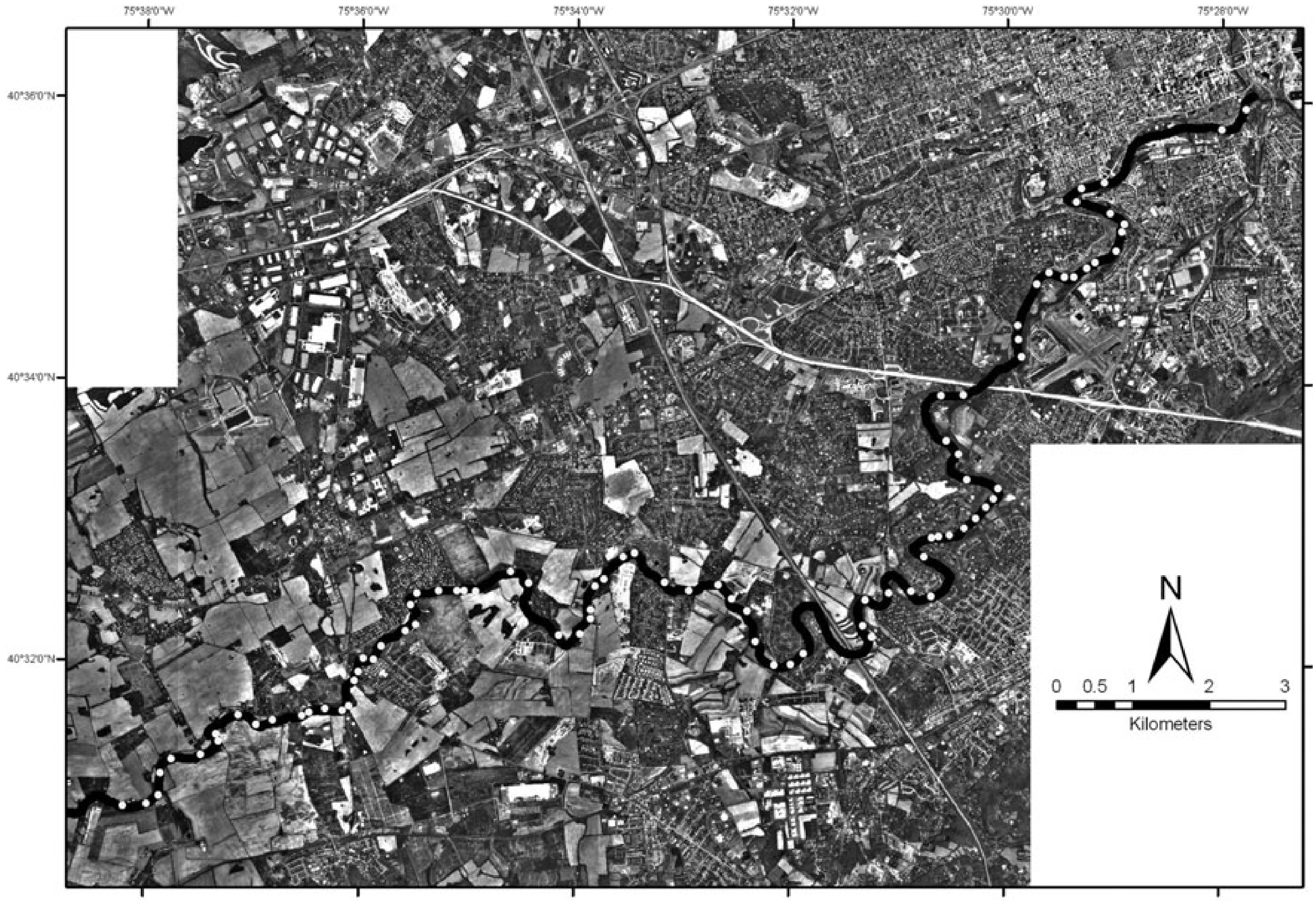

FIGURE 3. The Location of the Width Measurements (circles) From Little Lehigh Creek. The background image is from 1999, and the river has been shaded black for identification in this figure.

the 95% confidence interval. The 95% confidence interval is used as the expression of variance throughout. From the same set of aerial photographs the planform of the stream channel was traced using the channel midpoint to test for changes in channel length over the stretch of measured widths.

Ten control points were established to test for distortions in the georeferencing process. The control points consisted of 10 buildings that did not change size from 1947 to 1999. The lengths of their roofs were measured in both years to determine if there were systematic errors in how the aerial photographs were georeferenced. These buildings were selected so that they were near the stream channel and distributed along the section of width measurements. Reproducibility of these fixed structure measurements validates our methodology and offers high-resolution aerial photography as a complement to emerging, but still expensive and locally available light detection and ranging (LiDAR) data.

Land use was classified in the GIS from the 1946/1947 photographs into three categories: urban, agricultural/open, and forest. These three categories are broader than those typically used for land use/land classification, but simpler categories were used to reduce the chance of misclassification. The land use was classified by digitizing polygon coverages (at 1:3000 scale) for urban and forest areas, and subtracting the sum of their areas from the total watershed area to obtain the agriculture/open area.

The 1992 NLCD for Pennsylvania is the most recent version of land use data that is publicly available (EROS Data Center, 1993). The NLCD was derived from Landsat Thematic Mapper images taken from 1989 to 1994, and has a spatial resolution of 30 m. The database was already digitized and georeferenced, and the process described above for the 1946/1947 dataset was not needed.

Lastly, the modern channel morphologies were reconstructed and compared through high-resolution

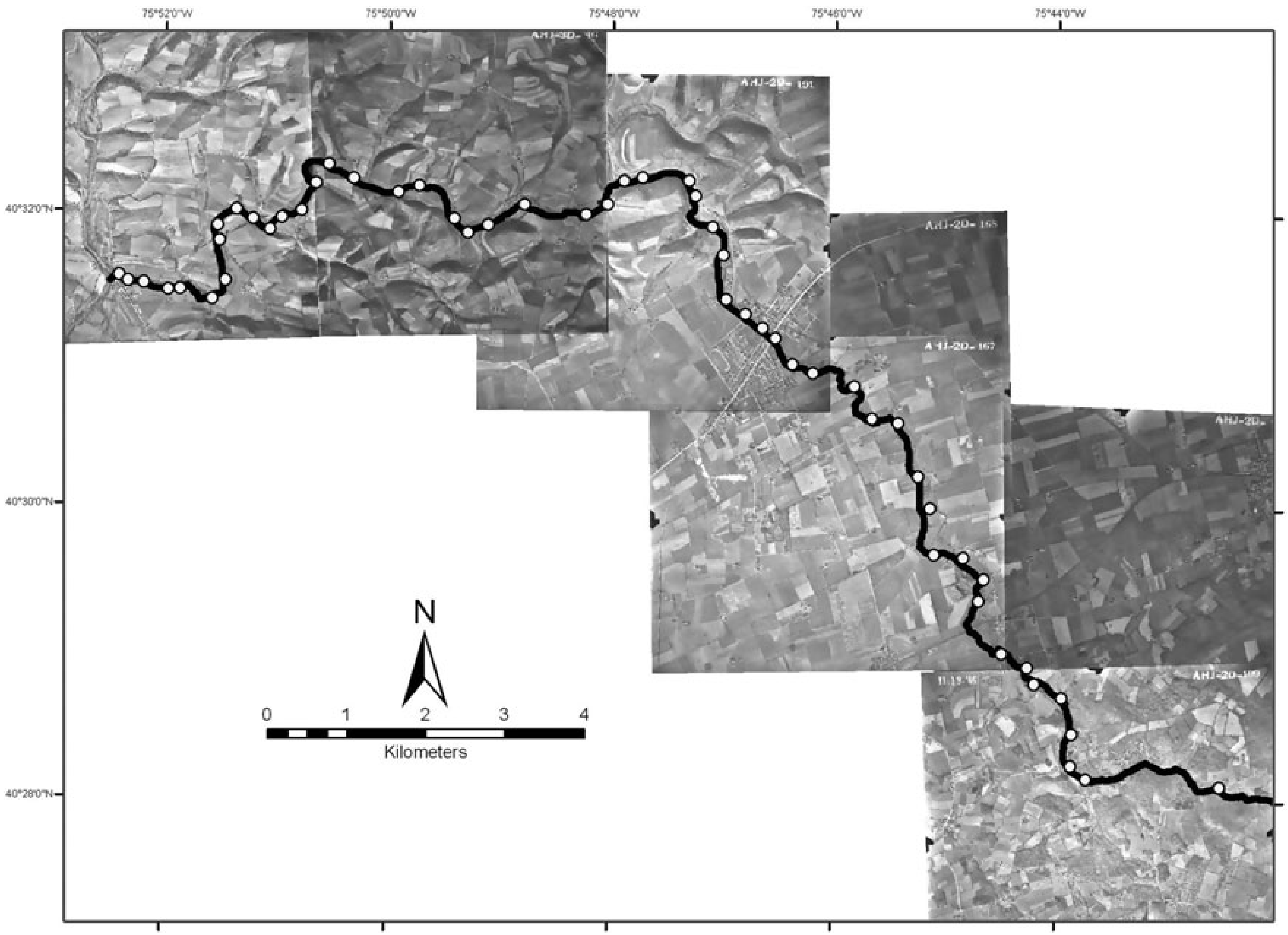

FIGURE 4. The Location of the Width Measurements (circles) on Sacony Creek.
The background image is from 1946, and the river itself has been darkened for identification.

topographic surveys of channel reaches. These reaches were selected so that an 80-100 m reach could be surveyed using a total station (Topcon GTS-211D). Points were surveyed along each bank, along the thalweg, and for multiple cross-sections (Figure 2). These points were used to generate a digital elevation model (DEM) of the channel in Surfer (v. 6.03). This DEM was then used to measure the bankfull widths and depths along the reach, as well as to calculate the reach volume and area. Width and depth measurements were made approximately every 10 m on the DEM and averaged for each reach. The reach volume and area were measured by constructing a planar surface using the bankfull elevations at the upstream and downstream boundaries of the reach and calculating the volume and area between this plane and the river channel surface. A range of bankfull elevations were used to determine the error of the reach volumes and areas. The total volume and area were scaled by dividing each value by the length of the thalweg to produce a unit volume (m^3/m) and a unit area (m^2/m) that integrates these measurements over the scale of each measured reach.

RESULTS

The Little Lehigh Creek generally widened along the length of the measured channel from the 1947 measurements to the 1999 measurements (Figure 5). A majority of the measured widths (67 of 85) were statistically ($p < 0.05$) wider in 1999 than in 1947, and the width increased approximately the same amount along the length of the measured channel (Figure 5). Although the magnitude of increase was roughly the same along the channel, the percentage

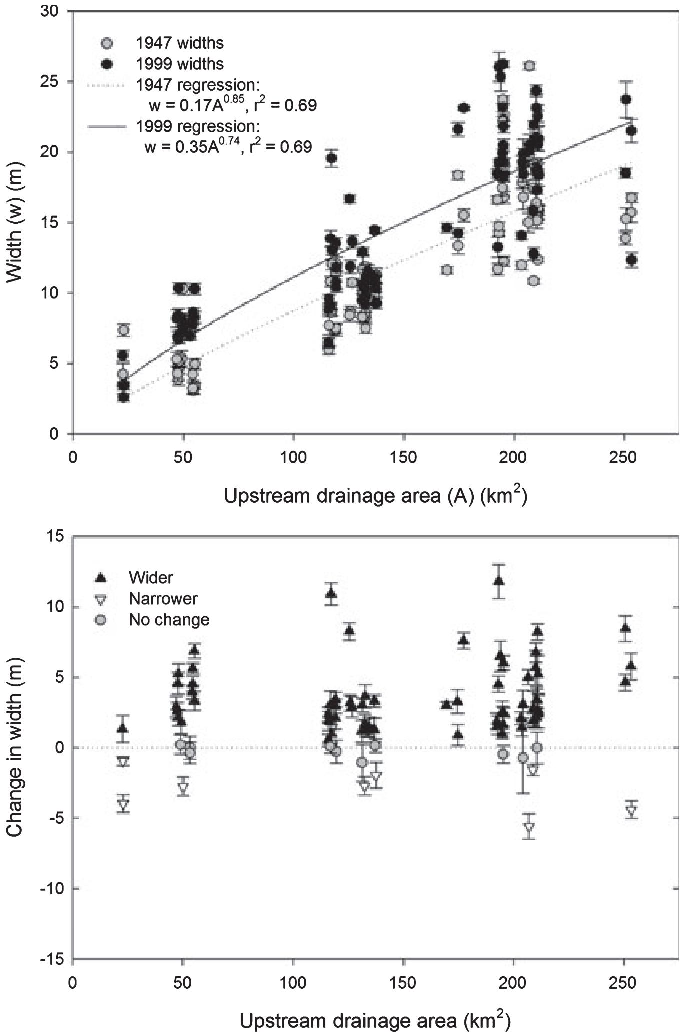

FIGURE 5. The Measured Widths (top) of the Little Lehigh Creek From 1947 (gray circles) and 1999 (black circles), and the Change in Widths (bottom) Over That Time. The widths increased on 67 of the 85 measured sites. The gaps in measured widths are from tributaries increasing the upstream drainage area, not from large distances between width measurements (Figure 3).

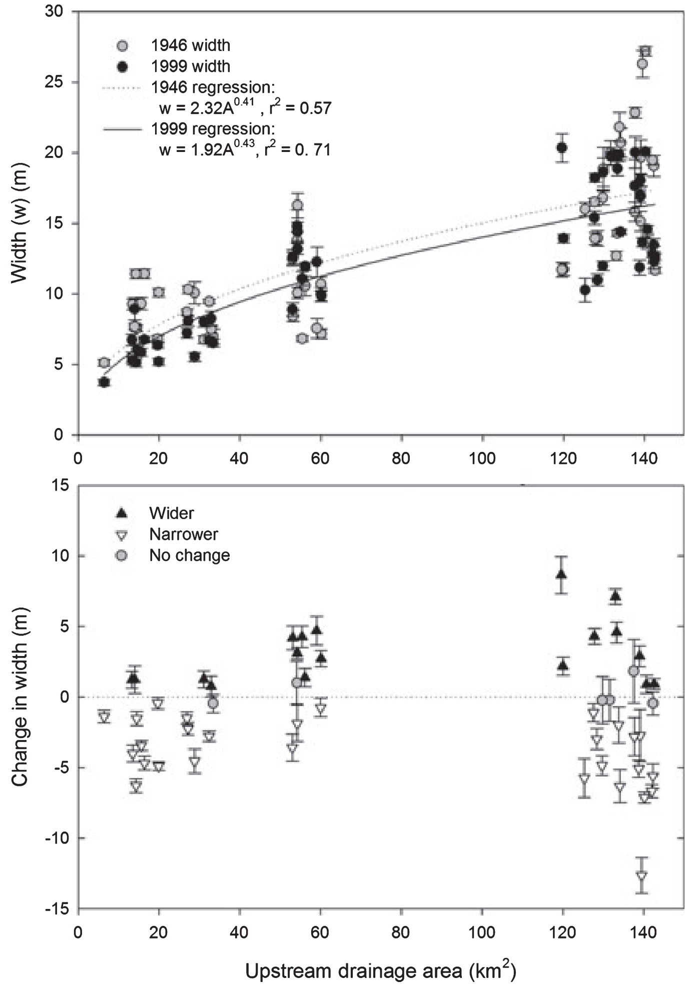

FIGURE 6. The Measured Widths (top) for Sacony Creek From 1946 (gray circles) and 1999 (black circles), and the Change in Widths (bottom) Over That Time. The widths did not systematically change in Sacony Creek. The gaps in measured widths are from tributaries increasing the upstream drainage area, not from large distances between width measurements (Figure 4).

increase was higher upstream. Eight of the widths narrowed over the 52 years, while 10 were not statistically significantly different.

In contrast, the 52 measured widths on Sacony Creek are more equally divided among those that narrowed or widened (Figure 6). Eighteen widths were wider and 28 were narrower in 1999 than in 1946, with six widths measuring the same from 1946 to 1999 (Figure 6). At the upstream and downstream ends of the measured channel the widths decreased from 1946 to 1999. In the middle is a section of the stream where the widths increase moving downstream and then decrease again, peaking at an increase of over 70% at 9.5 km from the mouth. Downstream of this location the magnitude of the increase in widths progressively diminishes to a point of inflection, from where channel widths decrease downstream.

The amount of precipitation prior to each set of aerial photographs is within 20% of long-term averages (Allentown, Pennsylvania, weather station) (National Climatic Data Center, 2006). The total precipitation in the six months prior to each photograph was summed and compared with the longer-term average during that period. Abnormally high or low precipitation levels might skew the width measurements, as high precipitation would result in wider channels appearing in the photographs. However, the 1946/1947 photographs had only 14% larger precipitation totals in the six months preceding the photographs, and only 20% lower precipitation prior to the 1999 photographs.

The spatial accuracy and precision of the aerial photographs are described in Figures 7 and 8. Channel widths measured in a GIS from 1999 aerial photographs and modern ground truth survey widths show good accuracy (Figure 7). The method of measuring identical buildings in 1947 and 1999 also demonstrated precision in the georeferencing of the photographs (Figure 8).

There were not significant differences between the surveyed channel morphologies of the Little Lehigh Creek and Sacony Creek (Table 3). The bankfull widths and depths (Figure 9) increase downstream, as expected. However, there is enough variability in the measurements that there are not discernible differences between the two rivers. The unit area also exhibits a consistent trend of increasing downstream, but the unit volume does not (Figure 10). There is also no shift in the channel planforms between the two time periods. For both rivers the channels have lengthened by less than 1% between 1946/1947 and 1999, suggesting that there has not been much change in sinuosity during this time.

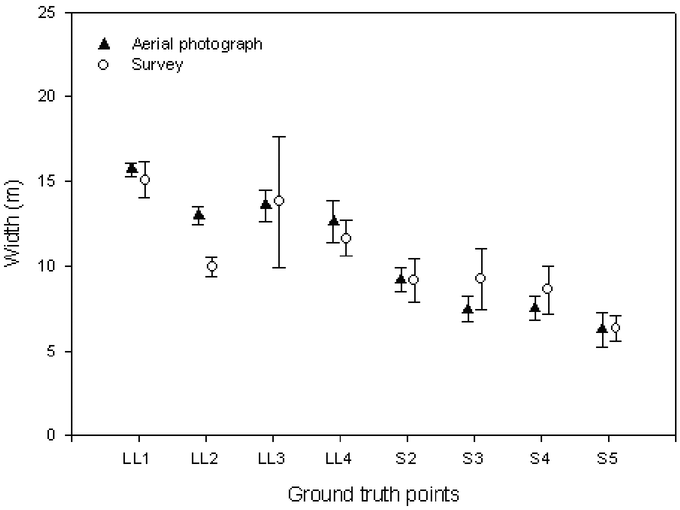

FIGURE 7. The Comparison of Survey Measurements of the Channel Width Along a Reach to the Widths Measured From Aerial Photographs. The *x*-axis labels refer to the survey positions listed in Figure 1 for Little Lehigh Creek (LL) and Sacony Creek (S).

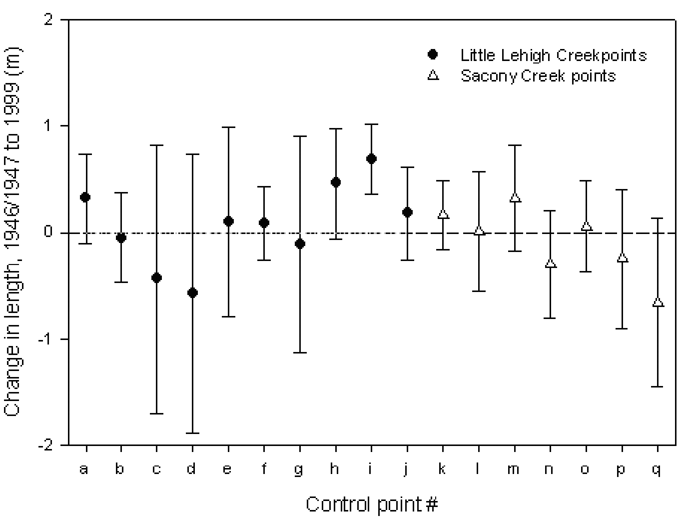

FIGURE 8. The Comparison of Measured Ground Controlled Points From the 1947 and 1999 Georeferenced Aerial Photographs From the Two Watersheds. The measurements do not systematically change between the two sets of photographs, implying that there are not spatial differences due to georeferencing errors.

DISCUSSION

Channel Widths Through Time

The direct measurement of river channel change over time using aerial photographs eliminates many of the complexities of comparative studies. The number of possible channel metrics is limited to width when using aerial photographs, but an accurate illustration of the effects of the increase in impervious surfaces can be obtained. The sample size can be large enough when using aerial photographs to produce statistically robust results.

A sample of measured channel widths over time would be expected to be roughly equally distributed into three groups if the climatic and hydrologic characteristics of a watershed remain constant. Those groups would be: (1) the channels widths that increased, (2) those that decreased, and (3) those that were not statistically different. This distribution is due to the dynamic nature of river channels: gravel bars migrate, channel bends meander, and any single channel reach (or, at a smaller scale, a discrete width measurement) might dynamically respond over time even though the external hydrologic forces remain constant.

The change in the widths of Sacony Creek from 1946 to 1999 demonstrates this even distribution between those widths that widened, narrowed, and remained the same. Eighteen widths widened and 28 narrowed, while six did not change (Figure 6). There are not any basin-wide changes in land use that could result in a systematic change in channel width. There is random widening and narrowing along the length of Sacony Creek, with the exception of the notable section from 9 to 13 km upstream of the mouth where the channels consistently have widened. Upstream and downstream of this section more channel segments narrowed, but there are still examples of channel widening at the ends of the measured section.

The section of Sacony Creek having wider channels in 1999 corresponds exactly with the only sizable

TABLE 3. Channel Metrics From Surveys.

Survey	Drainage Area (km^2)	Date of Survey	Width (m)	Depth (m)	Width/ Depth	Reach Volume (m^3)	Reach Area (m^2)	Thalweg Length (m)	Unit Volume (m^2)	Unit Area (m)
Little Lehigh Creek										
1	175	7/17/2003	15.1 ± 0.9	1.2 ± 0.2	13.6 ± 2.4	1011 ± 131	1058 ± 15	122 ± 8	122 ± 8	8.7 ± 0.6
2	127	7/1/2003	9.9 ± 0.5	0.9 ± 0.1	11.0 ± 1.3	374 ± 49	604 ± 8	52 ± 5	52 ± 5	11.7 ± 1.1
3	126	6/26/2003	13.8 ± 3.2	0.6 ± .1	23.4 ± 6.5	530 ± 69	1661 ± 23	69 ± 5	69 ± 5	24.0 ± 1.9
4	118	7/31/2003	11.6 ± 0.8	1.0 ± 0.2	12.4 ± 2.6	572 ± 74	933 ± 13	97 ± 7	97 ± 7	9.6 ± 0.7
5	55	4/10/2005	11.0 ± 1.9	1.1 ± 0.1	10.0 ± 2.0	275 ± 36	448 ± 6	36 ± 4	36 ± 4	12.5 ± 1.3
6	19	8/3/2003	7.8 ± 0.6	0.8 ± 0.1	10.0 ± 1.5	211 ± 27	385 ± 5	48 ± 4	48 ± 4	8.0 ± 0.7
Sacony Creek										
1	126	5/10/2005	17.3 ± 1.0	1.1 ± 0.1	16.9 ± 0.1	314 ± 41	365 ± 5	44 ± 4	44 ± 4	8.3 ± 0.8
2	51	6/29/2004	9.2 ± 0.9	0.7 ± 0.2	15.4 ± 0.3	144 ± 19	550 ± 8	60 ± 5	60 ± 5	9.1 ± 0.8
3	29	6/18/2004	9.3 ± 1.1	0.7 ± 0.1	13.4 ± 0.2	212 ± 28	618 ± 8	69 ± 5	69 ± 5	9.0 ± 0.7
4	29	6/4/2004	8.6 ± 1.1	0.9 ± 0.1	10.3 ± 0.2	471 ± 61	908 ± 12	96 ± 7	96 ± 7	9.4 ± 0.7
5	29	7/1/2004	6.3 ± 0.6	0.9 ± 0.2	7.0 ± 0.1	268 ± 35	455 ± 6	64 ± 5	64 ± 5	7.1 ± 0.6

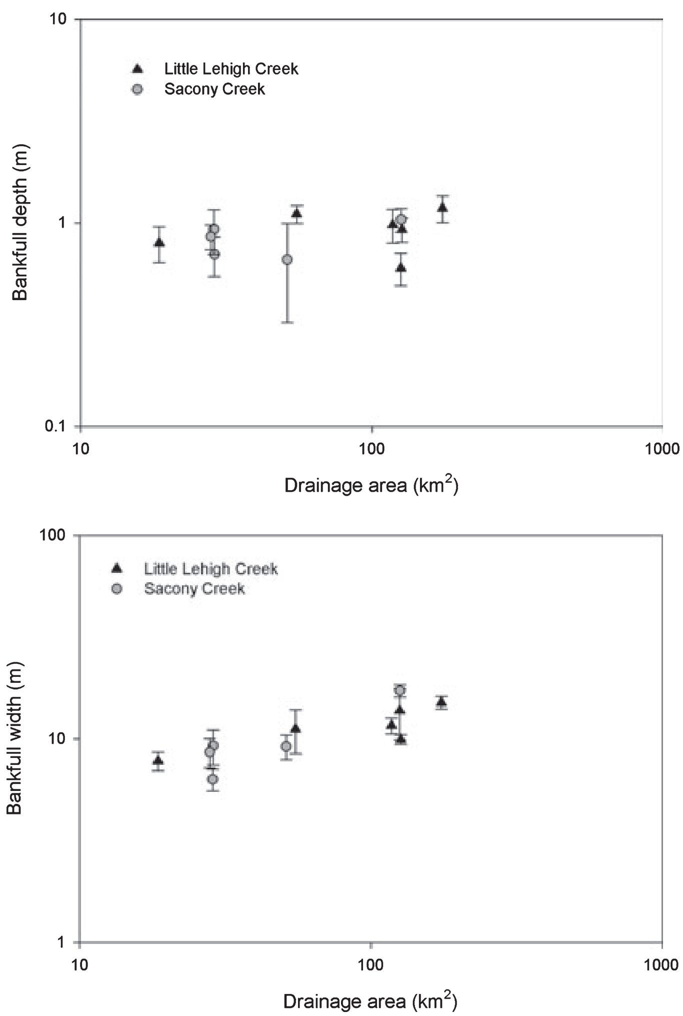

FIGURE 9. The Bankfull Widths (top) and Depths (bottom) for Little Lehigh Creek (black triangles) and Sacony Creek (grey circles). The 95% confidence intervals illustrate the range of measurements found at similar drainage areas, especially ~125 km^2 for the Little Lehigh Creek and ~30 km^2 for Sacony Creek, and are not due to any systematic error.

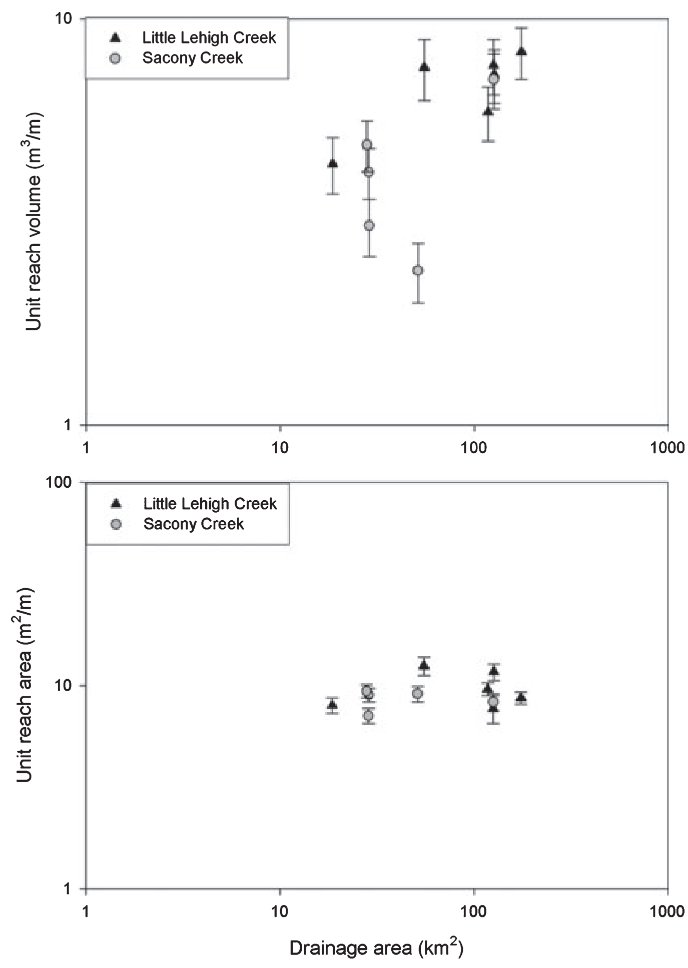

FIGURE 10. The Unit Areas and Unit Volumes From Little Lehigh Creek (black triangles) and Sacony Creek (grey circles).

urban area in the watershed, the small town of Kutztown, Pennsylvania (Figure 11). The upstream end of the segment where channels widened (at 13 km) is the south edge of the town. The urban area

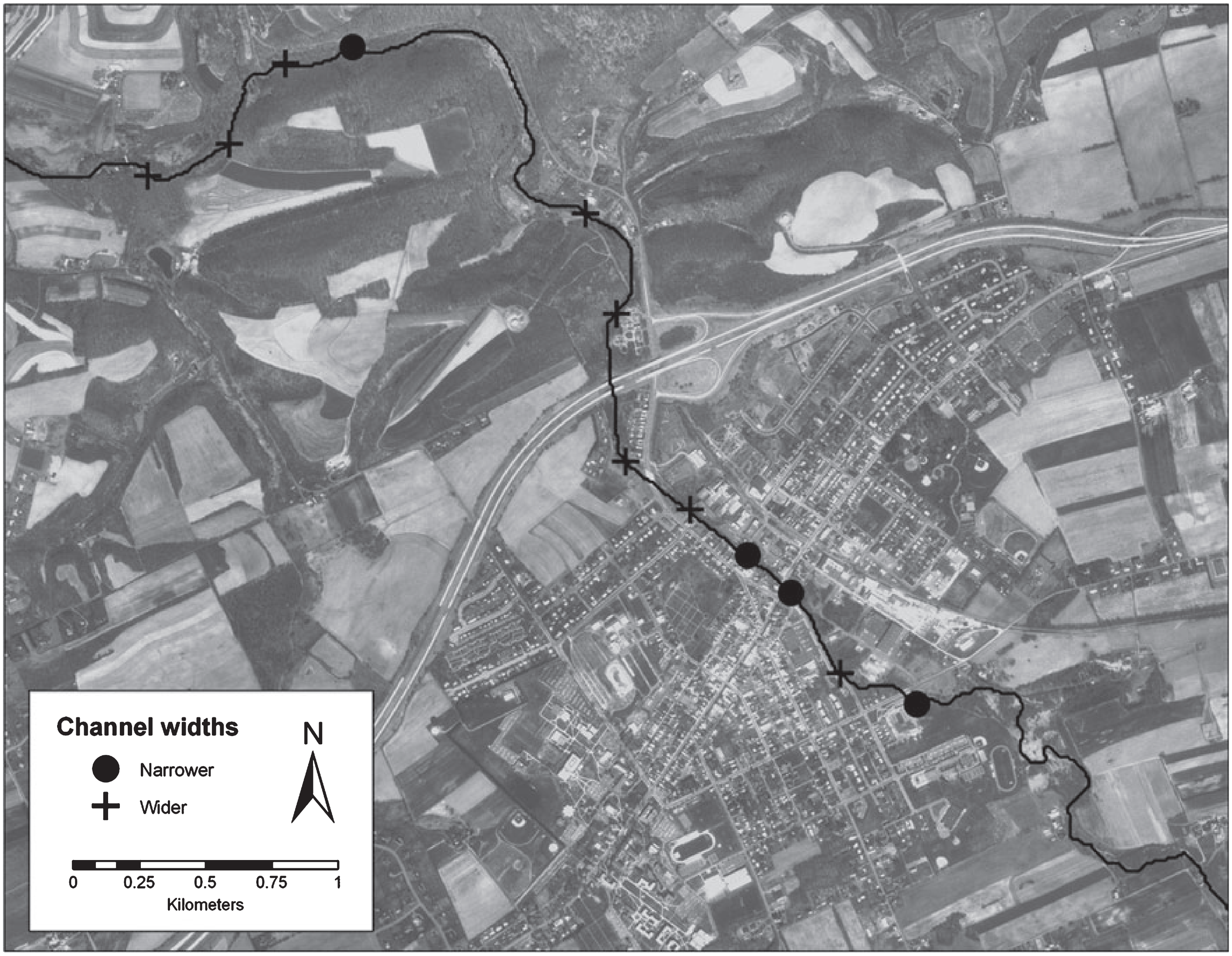

FIGURE 11. The Town of Kutztown, Pennsylvania (the gridded pattern in the central portion of the photograph), and Sacony Creek With Its Measured Widths. The widths that increased (+) from 1946 to 1999 are concentrated downstream of Kutztown, while those that narrowed (●) are distributed along the entire river. The widened channels extend for 3.8 km downstream of Kutztown, and suggest a downstream limit to the effects of Kutztown's increased urban area.

has expanded over the 52 years, and it can safely be assumed that the larger urban area in 1999 has a larger area of impervious surfaces, which produces larger runoff volumes and higher peak discharges. One response of a river channel to the higher flows is a widening of its channel, as seen in this stretch of Sacony Creek. The wider channels continue for 3.8 km downstream of Kutztown, which indicates that the effects of more impervious surfaces can extend for significant distances downstream of the urban area before the higher peak flows are attenuated. It may be that as the higher peak discharges from the impervious surfaces move downstream the peak of the hydrograph will be attenuated and stretched, and the "natural" channel growth through the normal downstream increase in drainage area will be able to transport the higher flows without needing to adjust its channel width.

Similarly, the data suggests that an increase in urban areas is the mechanism behind the widening that occurred in the Little Lehigh Creek. Of the 85 measured channel widths, 79% of them widened an average of 3.6 ± 0.6 m (Figure 5). Over the intervening 52 years between the two sets of width measurements the amount of urbanized land increased by more than a factor of three from 16 to 52 km^2 (Table 2). The increase in urban area would logically increase the amount of impervious areas within the watersheds, a safe assumption even though the amount of impervious area in the watershed in 1947 is not available. It is the increase in impervious area that most influences increased runoff and peak discharges from storms, assuming that other variables such as climate and precipitation remained constant. The implication is that larger, and more frequent large discharges drive the bank widening response. Previous studies support these interpretations as they clearly show that discharge in the Little Lehigh Creek watershed grows downstream following a power function as opposed to discharge in the Sacony Creek watershed, which grows downstream following a normal linear function (Galster *et al.*, 2006).

Other responses to land use directly or indirectly related to urbanization should be considered. For example, a decrease in agriculture and increase in impervious surfaces have collectively worked to decrease the sediment supply to the Little Lehigh Creek causing the stream to stop sequestering legacy sediments through floodplain construction and begin cannibalizing those sediments through bank erosion. It is also possible that there are additional fluvial responses to the change in land use, such as a shift in the pool-riffle sequence or a change in depth, or that the widening is not linear from 1946/1947 to 1999. However, such a change is impossible to test from the aerial photograph record.

The larger, post-urbanization discharges for the Little Lehigh Creek cause the stream to widen its channel to accommodate the larger flows. The relative amount of widening also increases going upstream in the Little Lehigh Creek for two reasons. First, the downstream sections of the watershed were already urbanized in 1947. These downstream sections would have already been affected by larger discharges caused by urban runoff and the stream would have already widened its channel by 1947 in response to these higher flows. Second, the downstream valleys are narrower and have steeper sides than the upstream sections. These narrower valleys have less accommodation space for floodplains and for the stream to widen and may have constrained how the stream responded to the larger, post-urbanization discharges.

The gauging station record for the Little Lehigh Creek shows that peak annual discharges from 1947 to the present have increased, especially since 1970. The only USGS gauging station in either of these watersheds that has a length of record approximating the aerial photographs is #01451500 (Allentown, Pennsylvania), located near the mouth of the Little Lehigh Creek. The period of $\sim$1955-1970 corresponds to a drier climate, and after 1970 the precipitation increases. It is unlikely that the wider channels in the Little Lehigh Creek are primarily the result of higher discharges from climate change and are not the result of a change in land use because a similar shift in channel width should appear in both the Little Lehigh Creek and Sacony Creek watersheds. The watersheds are small (<250 km^2), contiguous, and have low relief ($\sim$300 m) so it is highly unlikely that there are measurable climatic and precipitation differences between the two. The difference between the responses of the two rivers since 1946/1947 suggests that climate change was not the driving factor.

Variability in Field-Surveyed Channel Metrics

The replicate surveys along each river demonstrate the range of observable channel morphologies at relatively constant drainage areas. The comparative method of employing a space-for-time substitution across multiple watersheds with different land uses increases the possibility that the inherent complexity and variability within and across river systems will overshadow any change due to shifts in land use. The difficulty of constraining variables using paired watersheds increases the likelihood of results not being uniquely interpretable. The high-resolution surveys show the range of channel morphometries within a given channel reach ($\sim$75 to 100m length), with select width and depth measurements having 95% confidence intervals greater than 2.5 and 0.25 m, respectively (Table 3) (Figure 2). The three surveys completed along a stretch of the Little Lehigh Creek with a fairly constant drainage area (118 to 127 km^2) show the variability that occurs at a larger scale. These reaches have average widths that vary by 2.8 m and depths that vary by 0.4 m (Figure 9). This represents 28% variability in width and 63% in width over a length of stream that does not change significantly in drainage area. A similar amount of variability between nearby reaches is shown by the Sacony Creek surveys at 29 km^2.

This variability in channel morphology at different scales suggests that site selection could significantly influence the final results. Many comparative studies measure width and depth at a limited number of sites, and a small sample size may not adequately reflect the variability inherent in a river channel. The amount of variability visible in the high-resolution stream surveys is large enough that it can overshadow any change due to a shift in land use and make the rivers appear similar (Figures 9 and 10) or worse, produce misleading differences that are not due to any systematic change in land use but rather are only an expression of the natural variability within a stream. Caution should be used in order to produce robust results that are not just a product of a small sample size but are a result of different mechanisms operating in the watersheds.

CONCLUSIONS

The two methods presented here offer different insights into current attempts to quantify the effects of urbanization on rivers. The aerial photographs enabled the direct measurement of channel widths before (1947) and after (1999) urbanization occurred within these watersheds. The urbanization and accompanying increase in impervious surfaces increased the discharges, which consequently drives the widening of the channel. This widening (3.6 ± 0.6 m) was subtle enough and the modern channels complex enough that only through the comparison of a large number of widths from 1947 and 1999 was the change discernable. The widening that occurred in part of Sacony Creek suggests that the downstream spatial impacts of urbanization is quantifiable, and in this river is roughly 4 km downstream of the urban area.

There are many implications for wider channels in urban areas. Lateral erosion can damage property and infrastructure, and the increase in suspended sediment can adversely affect water quality and aquatic habitats. The wider channels can be viewed as esthetically unpleasing and decrease the river's recreational value, especially since these are urban rivers and are located near large populations. Restoration efforts in urban streams would also be affected, as the rehabilitators would need to consider the wider channels when designing new channel dimensions. These wider channels in rivers with increasing urbanization may be inevitable unless the effects of the increase in impervious area are mitigated through the engineered control of runoff and/or strict land use planning.

The survey data, even though it is high-resolution and measures channel metrics in three dimensions (reach volume and reach area) as opposed to two dimensions (width and depth), was still not able to distinguish between these rivers with different amounts of urbanization. Comparative methods that use a space-for-time substitution across multiple watersheds have inherent problems with variability and complexity at multiple spatial scales, from the reach to the watershed. These changing variables can possibly overshadow the effects of urbanization on a river, as exhibited by the survey data. Comparative methods still can be useful where long-term records do not exist, but the direct measurement of change before and after urbanization should be utilized whenever possible.

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