JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
AUGUST AMERICAN WATER RESOURCES ASSOCIATION 2006

WATERSHED IMPERVIOUSNESS IMPACTS ON STREAM CHANNEL CONDITION IN SOUTHEASTERN PENNSYLVANIA[1]

Christina M. Cianfrani, W. Cully Hession, and Donna M. Rizzo[2]

ABSTRACT: Forty-six independent stream reaches in southeastern Pennsylvania were surveyed to assess the relationships between geomorphic and habitat variables and watershed total impervious area (TIA) and to test the ability of the impervious cover model (ICM) to predict the impervious category based on stream reach variables. Ten variables were analyzed using simple and multivariate statistical techniques including scatterplots, Spearman's Rank correlations, principal components analysis (PCA), and discriminant analysis (DA). Graphical analysis suggested differences in the response to TIA between the stream reaches with less than 13 percent TIA and those with greater than 24 percent TIA. Spearman's Rank correlations showed significant relationships for large woody debris and sinuosity when analyzing the entire dataset and for depth diversity and the standard deviation of maximum pool depths when analyzing stream reaches with greater than 24 percent TIA. Classification into the ICM using DA was 49 percent accurate; however, the stream reaches did support the ICM in other ways. These results indicate that stream reach response to urbanization may not be consistent across geographical regions and that local conditions (specifically riparian buffer vegetation) may significantly affect channel response; and the ICM, used in the appropriate context, can aid in the management of stream reaches and watersheds.
(KEY TERMS: urbanization; urban hydrology; impervious cover model; stream habitat; geomorphology; rivers/streams; channel morphology; statistics)

Cianfrani, Christina M., W. Cully Hession, and Donna M. Rizzo, 2006. Watershed Imperviousness Impacts on Stream Channel Conditions in Southeastern Pennsylvania. Journal of the American Water Resources Association (JAWRA) 42(4):941-956.

INTRODUCTION

Urbanization has significant impacts on stream systems (Leopold, 1968; Hammer, 1972; Klein, 1979; Booth, 1991; Schueler, 1994; Booth and Jackson, 1997; Pizzuto *et al.,* 2000; Booth *et al.,* 2002; Hession *et al.,* 2003). This is mainly due to changes in storm hydrographs observed in developed areas. Urban watersheds show increased surface runoff, in terms of both magnitude and frequency (Horner *et al.,* 1997; MacRae, 1997). Peak flows after a storm can increase up to five times the predevelopment level (Neller, 1988; Booth, 1991). Conversely, because less water infiltrates into the ground, less water reaches the stream through the ground water, reducing the amount of water during low flow periods (DNREC, 1997; Finkenbine *et al.,* 2000). As a result, the balance of water and sediment supplied to stream channels changes, resulting in geomorphological alterations (Leopold, 1968; Hammer, 1972; Booth and Jackson, 1997; Pizzuto *et al.,* 2000). Urban streams show increased bed and bank erosion, causing enlarged widths and cross sectional areas as compared to nonurban streams (Hammer, 1972; Trimble, 1997; Pizzuto *et al.,* 2000; Hesson *et al.,* 2003).

Urbanization also impacts aquatic habitat quality. Urban channels tend to be morphologically "simpler," having less defined pool/riffle structure and more uniform depth (Booth, 1991; Sovern and Washington, 1997; Pizzuto *et al.,* 2000), and bed grain size distributions shift toward smaller particles during watershed level construction due to increased sedi-

[1]Paper No. 04164 of the *Journal of the American Water Resources Association* (JAWRA) (Copyright © 2006). **Discussions are open until February 1, 2007.**
[2]Respectively, Assistant Professor, School of Natural Science, Hampshire College, 893 West Street, Amherst, Massachusetts 01002; Associate Professor, Biological Systems Engineering, Virginia Tech, 315 Seitz Hall, Blacksburg, Virginia 24061; and Assistant Professor, Department of Civil and Environmental Engineering, University of Vermont, 213 Votey Building, Burlington, Vermont 05405 (E-mail/Cianfrani: ccianfrani@hampshire.edu).

mentation (Wolman, 1967; Wolman and Schick, 1967; Booth and Jackson, 1997). A decrease in large woody debris (LWD) has also been observed in Pacific Northwestern streams (Booth, 1991; Booth *et al.,* 1997; Sovern and Washington, 1997; Finkenbine *et al.,* 2000). These changes affect the ability of a stream to support a variety of biota, including fish and macroinvertebrates (Kemp and Spotila, 1997; Horner *et al.,* 1999).

Urban best management practices (BMPs) have been adopted in many watersheds in an attempt to lessen the downstream effects of urbanization. The types of BMPs vary widely and include riparian buffers, infiltration, swales, and wet and dry detention ponds (USEPA and ASCE, 2005). Measuring the impacts of these practices on downstream hydrology, aquatic habitat and biota, and water quality has been difficult (CWP, 2003). Studies involving detention ponds have shown mixed results (Jones *et al.,* 1997; Maxted and Shaver, 1997; Horner *et al.,* 1999; Booth *et al.,* 2002). These structures have been widely used to reduce peak flows to predevelopment levels (Booth, 1991). Using data from Montgomery County, Maryland, Horner *et al.* (1999) found that while structural BMPs such as ponds can reduce the impacts of high flows on downstream habitat, macroinvertebrate community health declined with increased imperviousness. This may in part be due to increased temperatures (Horner *et al.,* 1999) or the increased duration of high flows (Booth and Jackson, 1997) reported downstream of detention ponds. Maxted and Shaver (1997) similarly used macroinvertebrates to compare the physical habitat and biological quality of watersheds with storm water detention ponds to those without ponds. The preliminary results showed the ponds did not reduce the effects of urbanization on macroinvertebrate communities, especially in watersheds with greater than 20 percent TIA (Maxted and Shaver, 1997).

Impervious cover within urban watersheds is often cited as the main characteristic driving changes in hydrology and channel morphology (Hammer, 1972; Booth, 1991; Schueler, 1994; Booth and Jackson, 1997; Booth *et al.,* 2002). Impervious cover may be connected or disconnected, depending on how water is conveyed to the drainage system. For example, most roads are directly connected to a drainage system and are thus considered connected impervious surfaces. Rooftops may be disconnected if gutters drain to pervious lawn areas. Most often, TIA, including both connected and disconnected surfaces, is calculated for watersheds because of the availability of data and ease of calculation (CWP, 2003). Effective Impervious Area (EIA) (Sutherland, 1995), which includes only connected impervious surface, has been shown to be more accurately correlated with urbanization effects than TIA is (Booth and Jackson, 1997; Booth *et al.,* 2002; Lee and Heaney, 2003). However, the additional data necessary for computing EIA often is unavailable or too time-consuming and costly to obtain.

Empirical studies have attempted to relate levels of impervious cover with instream geomorphic and aquatic habitat conditions (Klein, 1979; Booth and Jackson, 1997; Maxted and Shaver, 1997; Horner *et al.,* 1999; MacRae and DeAndrea, 1999; Morse, 2001). These studies were used in developing the ICM, which identifies three levels of stream quality based on watershed TIA (Schueler, 1994; CWP, 1998). Streams whose watersheds contain 0 to 10 percent impervious cover are considered sensitive; those with 11 to 25 percent are considered impacted; and those with greater than 25 percent TIA are considered nonsupporting. However, the ICM has some limitations, including the following: it should only be applied to first-order to third-order streams in tested ecoregions; it predicts potential rather than actual quality; and the defined thresholds are not set breakpoints but indicate transition zones (CWP, 1998). Further, relationships between TIA and stream quality have been shown to be relatively weaker at lower levels of imperviousness (e.g., less than 10 percent) where local conditions may play a larger role in determining stream health than watershed level TIA (CWP, 2003). Where validated, however, this type of model can prove useful in the management and classification of watersheds.

In general TIA data are readily available or easily calculated for most land areas in the United States. However, many of the underlying mechanisms relating stream change to impervious cover are poorly understood. In addition, little is known about which stream characteristics or combinations of characteristics are most sensitive to changes in watershed impervious cover. Specifically, the relationship between habitat parameters, both composite measures and individual measures (e.g., pool depth and sinuosity), and watershed TIA has been identified as a research need (CWP, 2003). Field data from 46 stream reaches in southeastern Pennsylvania were used to test hypothesized relationships between stream geomorphic and habitat characteristics and watershed TIA and to determine whether the ICM provides a reasonable method for classifying streams based on field geomorphic and habitat data.

METHODS

Study Area

The 46 stream reaches are in the Piedmont Uplands Physiographic Province in southeastern Pennsylvania (Figure 1). The Piedmont Uplands were formed mostly on schist and receive about 110 cm of precipitation annually. Within Philadelphia County, Bucks County, and most of Montgomery County, Pennsylvania, land cover is predominantly suburban and urban. The Delaware Regional Planning Commission (1994) reported that developed and residential lands in this area increased by 30 percent from 1970 to 1990; the commission predicted an increase of an additional 47 percent from 1990 to 2020. In Chester County, Pennsylvania, the rural areas include mixed hardwood deciduous forests and mixed agricultural lands. Presettlement Philadelphia and the surrounding area was forested. However, as settlers began to arrive in the late 1600s, land was cleared for agriculture, a trend that continued into the next two centuries. By the mid-1800s, most of the forest in and around the city had been cleared and was replaced by either farms or urban land uses. This same conversion occurred throughout much of the Mid-Atlantic during the 1700s and 1800s. Areas where soils became unproductive were left fallow and eventually returned to forest (Sweeney, 1992).

Field Data

Stream reach geomorphic and physical habitat data were collected as part of three previous stream research efforts (Hession *et al.,* 2003; Pizzuto *et al.,* 2000; Sweeney *et al.,* 2004). For all variables excluding large woody debris (detailed below), field data collection methods were identical among the three studies. Stream reaches were chosen across a gradient of urbanization (Hession *et al.,* 2003). Watershed TIA ranged from 0 percent to 75 percent (Table 1). Riparian zone cover for all stream reaches was predominantly forested, with 38 of the 46 stream reaches having greater than 18 m width of forested buffer on at least one bank.

Geomorphic Surveys. Channel geomorphic surveys were conducted during base flow periods in the summers of 1997 to 1999 following procedures outlined by Pizzuto *et al.* (2000) and Hession *et al.* (2003). Locations of the top and bottom of the reaches were recorded using a global positioning system (GPS) (Trimble, Sunnyvale, California). Sinuosity (S) was calculated using the straight line valley distance, determined by using the GPS points of the top and bottom of the reach, and the measured thalweg distance. Stream reaches were 10 to 20 bankfull widths in length. All survey measurements were made using a laser level and survey tapes. The surveys included longitudinal profiles of all major features and breaks

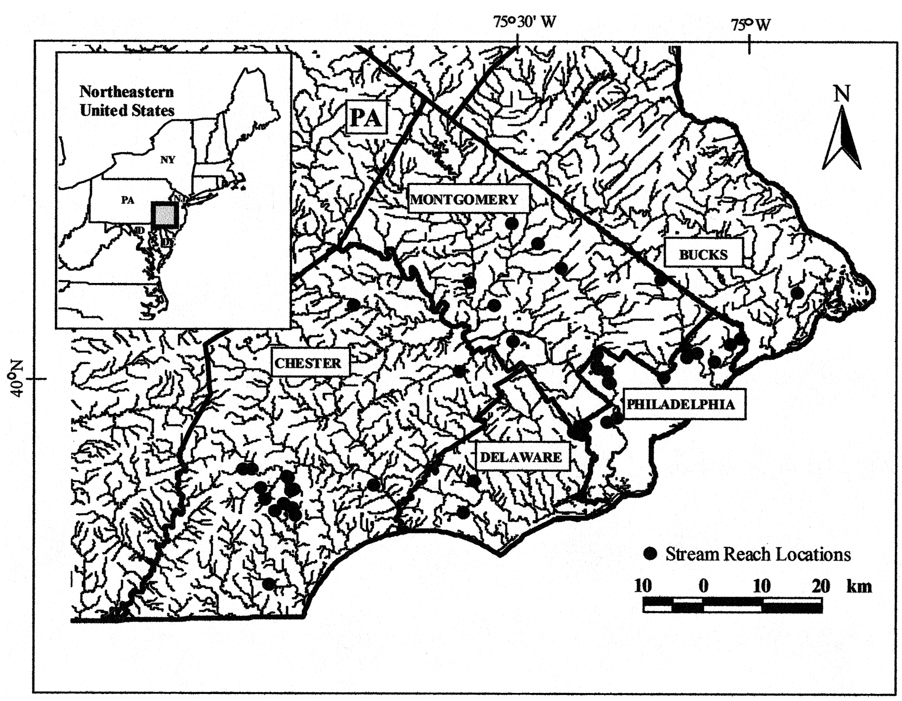

Figure 1. Location of Stream Reaches.

TABLE 1. Stream Reach Characteristics.

Site Name	Watershed Total Impervious Area (percent)	Drainage Area (km^2)*	Reach Length (m)	Channel Slope (m/m)	Bankfull Width (m)	Bankfull Depth (m)	Bankfull Cross Sectional Area (m^2)	Mean Pool Depth (m)	Max Pool Depth (m)	Large Woody Debris Count
Pennypack Creek Trib. 15	0	0.08	62	0.052	4.08	0.37	1.52	0.05	0.07	N/A
Sedden's Creek Trib. 1	0	0.05	71	0.018	2.41	0.21	0.51	0.12	0.19	N/A
Three Springs Creek	0	0.09	104	0.032	3.29	0.27	0.89	0.11	0.15	N/A
Carpenter's Run	4	0.68	79	0.019	5.67	0.19	1.06	0.19	0.32	N/A
Beaver Run	5	11.60	147	0.012	7.42	0.32	2.37	0.37	0.71	0
West Trib. 4	6	0.62	61	0.030	5.00	0.29	1.34	0.13	0.16	N/A
West Br. White Clay	7	1.33	150	0.012	3.73	0.25	0.91	0.31	0.70	16
Hannum's Run	7	0.69	203	0.030	3.94	0.18	0.78	0.15	0.19	31
White Clay Creek	7	6.56	155	0.005	6.91	0.45	2.97	0.36	0.60	9
Teeter's Run	8	1.92	224	0.005	3.78	0.33	1.24	0.31	0.50	44
Pocopson Creek	8	21.55	150	0.007	10.11	0.55	5.48	0.53	0.65	4
Big Springs	8	2.10	150	0.011	5.46	0.29	1.68	0.35	0.52	21
West's Run	8	1.44	170	0.021	5.70	0.26	1.51	0.31	0.55	26
East Trib. 3	8	0.17	74	0.056	4.66	0.31	1.47	0.14	0.24	N/A
Moorehead's Run	8	1.61	147	0.009	5.22	0.34	1.84	0.48	0.82	36
Birch Run	8	8.11	204	0.007	9.12	0.37	3.36	0.43	0.48	25
Fisher's Run	8	12.94	146	0.008	8.26	0.41	3.46	0.83	0.83	15
Wise's Mill Creek	10	0.69	120	0.032	5.70	0.40	2.27	0.22	0.51	N/A
Doe Run	10	26.43	264	0.004	10.98	0.52	5.47	0.86	1.20	23
Sharitz Creek	12	4.48	147	0.007	6.81	0.31	2.04	0.48	0.81	50
Doe Laurels Creek	12	45.56	150	0.002	15.38	0.71	10.98	0.79	0.88	15
Bell's Mill	13	1.26	97	0.030	6.71	0.42	2.87	0.25	0.98	N/A
Cresheim Creek	24	5.67	218	0.026	11.70	0.45	5.21	0.60	0.94	N/A
Rockledge Creek	27	1.70	124	0.008	5.61	0.42	2.40	0.38	0.49	N/A
Green Creek	30	8.30	125	0.004	8.42	0.53	4.46	0.27	0.43	60
Indian Creek	32	3.84	158	0.012	11.64	0.51	6.03	0.58	0.92	N/A
Rocky Run	33	7.90	133	0.008	10.90	0.36	3.98	0.31	0.92	85
Indian Run	34	4.38	116	0.024	9.75	1.42	10.17	0.33	0.47	N/A
Tacony Creek	35	40.13	245	0.002	17.56	0.71	12.33	0.54	0.70	N/A
Donny Brook	39	3.50	103	0.006	6.12	0.37	2.30	0.29	0.59	46
Wissahickon Creek Trib. 26	41	0.20	44	0.104	4.88	0.48	2.39	0.08	0.16	N/A
Little Valley	41	13.00	95	0.007	6.19	0.30	1.88	0.35	0.67	28
Wooden Bridge Creek	43	6.73	201	0.004	10.24	0.47	4.75	0.43	1.00	N/A
W. Branch Skippack Creek	48	4.00	209	0.003	7.75	0.34	2.59	0.30	0.50	8
Poquessing Creek Trib. 3	49	1.31	76	0.005	5.67	0.42	2.35	0.25	0.41	N/A
Queen Anne Creek	50	15.30	174	0.003	7.91	0.46	3.65	0.37	0.64	22
Bocci Trib.	50	0.06	70	0.025	3.44	0.38	1.31	0.12	0.23	N/A
Towamencin Creek	52	6.90	84	0.005	6.93	0.42	2.91	0.26	0.38	9
Wissahickon Creek	53	11.80	114	0.004	9.86	0.37	3.70	0.45	0.57	15
Abrams Run	57	11.00	140	0.003	8.14	0.57	4.58	0.41	0.50	52
Wise's Mill Run	58	0.90	119	0.036	5.30	0.36	1.90	0.16	0.24	22
Eagelville Run	61	1.10	122	0.016	5.36	0.38	1.96	0.18	0.29	17
Indian Creek 2	63	4.10	157	0.006	11.41	0.44	5.12	0.36	0.52	59
Cobb's Creek	66	0.40	132	0.024	5.17	0.38	1.96	0.13	0.37	43
Pennypack Creek	66	4.60	79	0.008	7.13	0.40	2.83	0.33	0.48	78
Cobb's Creek Trib. 3	75	0.28	79	0.028	3.98	0.27	1.25	0.18	0.31	N/A
Mean	28	6.68	135	0.02	7.20	0.41	3.22	0.33	0.54	30.68
Median	25	3.67	132	0.01	6.45	0.38	2.38	0.31	0.51	24.00
Standard Deviation	22	9.75	52	0.02	3.18	0.19	2.56	0.19	0.27	21.84

*Upstream from bottom of reach.
N/A indicates data not available for that stream reach for that variable.

in slope including top of riffle, top of pool, and deep point in pool. Pools were counted for each reach based on the longitudinal survey.

Five to six cross sections per site were surveyed and used to compute mean reach level characteristics (widths, depths, cross sectional areas, etc.). Cross section locations were determined on site and, on average, included two riffles, two pools, and at least one run. Bankfull elevations were identified using field indicators including point bar elevations, changes in vegetation, topographic breaks, change in size of distribution of materials, and debris remnants (Leopold, 1994). Bankfull widths and depths for the nonurban sites were verified using regional curves (Cinotto, 2003) to ensure accurate field assessment.

Sediment Surveys. A modification of the Wolman (1954) method (Pizzuto *et al.,* 2000) was used to calculate median bed grain size (d_{50}) for each reach. Average reach embeddedness (E) was assessed visually according to procedures outlined by Barbour *et al.* (1999) and was classified using four categories: 0 to 25 percent, 25 to 50 percent, 50 to 75 percent, and 75 to 100 percent. Three stream reaches were missing E values and were not used in computations involving this variable.

Large Woody Debris. For 28 of the 46 sites, LWD pieces greater than 0.10 m in diameter and greater than 1 m in length within the bankfull channel were counted (Montgomery *et al.,* 1995). For 31 of the sites, a separate qualitative LWD survey was completed using four categories – none, some/few, moderate, and abundant – based on relative differences between the reaches (LWD_{cat}). Qualitative categories were assigned to the remaining 15 sites based on the LWD count data for those sites.

Computed Variables

In addition to the variables directly collected (d_{50}, LWD_{cat}, E, and S), six variables were computed from the collected field data for use in statistical analyses (Table 2 and Table 3). Bankfull widths and depths were not used directly due to varying drainage sizes. To adjust for this, enlargement ratios (Hammer, 1972; Morisawa and LaFlure, 1979) were computed using regional curves for nonurban streams in the Piedmont physiographic province of Pennsylvania and Maryland developed by Cinotto (2003). The regional geometry curves were first tested on the stream reaches with low watershed TIA (less than 13 percent) to assess their suitability and were deemed adequate (bankfull width: $R^2 = 0.89$, $p < 0.0001$; bankfull depth: $R^2 = 0.64$, $p < 0.0001$). The enlargement ratios were computed by dividing the actual bankfull width (or depth) by the bankfull width (or depth) predicted for a nonurban stream based on the drainage size of the watershed.

$$W_{BF} = \frac{\textit{Measured bankfull width}}{\textit{Computed bankfull width}} \tag{1}$$

$$D_{BF} = \frac{\textit{Measured bankfull depth}}{\textit{Computed bankfull depth}} \tag{2}$$

The resulting dimensionless enlargement ratios were used in further analyses. Higher enlargement ratios for width (or depth) indicate channels with greater width (or depth) than predicted.

Three measures were used to assess depth variability throughout the stream reaches. First, to compare the influence of the number of pools on habitat across

TABLE 2. Ten Variables Used in Statistical Analyses.

Variable	Description	Units
W_{BF}	Enlargement ratio for bankfull width	m/m
D_{BF}	Enlargement ratio for bankfull depth	m/m
P_{cw}	Pools per channel width	pools
D_{div}	1 - (mean thalweg depth / mean pool depth)	m/m
D_{SDMax}	Standard deviation of reach maximum pool depths	unitless
d_{50}	Median bed sediment diameter for stream reach	mm
LWD_{cat}	Category of LWD (none, few/some, moderate, abundant)	0-3
LWD_{cw}	Number of large woody debris pieces per channel widths of stream	LWD
E	Embeddedness (0-25 percent, 25-50 percent, 50-75 percent, 75-100 percent)	1-4
S	Sinuosity	m/m

TABLE 3. Variables Used in Data Analyses.

Site Name	W_{BF}	D_{BF}	P_{cw}	D_{div}	D_{SDMax}	d_{50} (mm)*	LWD_{cw}	LWD_{cat}	S (m/m)	E**
Pennypack Creek Trib. 15	5.10	4.32	0.26	0.21	0.02	10	N/A	3	0.86	2
Sedden's Creek Trib. 1	3.87	2.99	0.24	0.48	0.04	28	N/A	2	1.21	1
Three Springs Creek	3.92	3.11	0.19	0.45	0.04	60	N/A	2	1.29	2
Carpenter's Run	2.57	1.10	0.50	0.45	0.07	11	N/A	1	1.24	2
Beaver Run	0.89	0.70	0.51	0.42	0.14	64	0.00	2	1.51	3
West Trib. 4	2.35	1.67	0.49	0.28	0.04	9	N/A	2	1.09	1
West Br. White Clay	1.23	1.11	0.20	0.48	0.16	16	0.40	2	1.16	3
Hannum's Run	1.77	0.99	0.14	0.46	0.04	64	0.60	3	1.26	2
White Clay Creek	1.08	1.19	0.31	0.20	0.12	23	0.40	2	1.32	2
Teeter's Run	1.05	1.31	0.17	0.56	0.09	45	0.74	2	1.99	1
Pocopson Creek	0.90	0.96	0.07	0.53	0.12	90	0.27	1	1.01	3
Big Springs	1.45	1.10	0.18	0.58	0.08	16	0.76	3	1.11	2
West's Run	1.81	1.14	0.23	0.52	0.09	55	0.87	2	1.51	2
East Trib. 3	4.04	2.82	0.69	0.46	0.05	50	N/A	1	1.10	3
Moorehead's Run	1.57	1.43	0.21	0.63	0.13	23	1.28	3	1.46	2
Birch Run	1.29	0.89	0.22	0.52	0.07	45	1.12	2	1.01	2
Fisher's Run	0.94	0.86	0.11	0.65	0.15	64	0.85	2	1.05	3
Wise's Mill Creek	2.55	2.26	0.38	0.46	0.10	65	N/A	2	1.11	4
Doe Run	0.89	0.84	0.25	0.53	0.22	45	0.96	2	1.69	2
Sharitz Creek	1.27	0.93	0.23	0.44	0.24	16	2.31	3	1.13	3
Doe Laurels Creek	0.97	0.97	0.21	0.51	0.20	45	1.54	2	1.07	3
Bell's Mill	2.26	1.95	0.55	0.48	0.17	20	N/A	1	1.09	3
Cresheim Creek	1.95	1.23	0.38	0.57	0.23	40	N/A	3	1.15	4
Rockledge Creek	1.65	1.73	0.27	0.50	0.15	29	N/A	3	1.33	N/A
Green Creek	1.18	1.28	0.40	0.47	0.11	22.6	4.04	3	1.03	4
Indian Creek	2.34	1.60	0.29	0.58	0.25	24	N/A	1	1.14	2
Rocky Run	1.56	0.90	0.33	0.31	0.19	16	6.97	3	1.14	2
Indian Run	1.84	4.28	0.51	0.49	0.11	71	N/A	1	1.04	1
Tacony Creek	1.17	1.01	0.22	0.43	0.17	16	N/A	1	1.03	3
Donny Brook	1.28	1.21	0.47	0.49	0.13	45	2.72	3	1.16	3
Wissahickon Creek Trib. 26	3.91	4.15	0.22	0.41	0.06	65	N/A	1	1.18	3
Little Valley	0.70	0.63	0.26	0.44	0.15	22.6	1.82	2	1.07	N/A
Wooden Bridge Creek	1.58	1.21	0.25	0.46	0.24	16	N/A	1	1.16	2
West Branch Skippack Creek	1.52	1.04	0.26	0.43	0.14	11	0.30	1	1.10	3
Poquessing Creek Trib. 3	1.88	1.88	0.37	0.47	0.11	13	N/A	1	0.97	2
Queen Anne Creek	4.71	4.77	0.32	0.33	0.13	22.6	1.00	2	1.05	2
Bocci Trib.	0.83	0.90	0.34	0.46	0.06	32	N/A	1	1.18	2
Towamencin Creek	1.06	1.08	0.16	0.55	0.15	22.6	0.74	1	1.02	2
Wissahickon Creek	1.17	0.80	0.43	0.55	0.18	64	1.29	2	1.04	2
Abrams Run	1.00	1.25	0.35	0.43	0.14	22.6	3.02	3	1.10	N/A
Wise's Mill Run	2.10	1.84	0.40	0.42	0.05	90	0.98	2	1.07	3
Eagelville Run	1.93	1.80	0.22	0.57	0.06	32	0.75	2	1.16	2
Indian Creek 2	2.22	1.37	0.29	0.39	0.15	22.6	4.30	3	1.20	2
Cobb's Creek	2.99	2.55	0.55	0.38	0.07	32	1.69	3	1.10	2
Pennypack Creek	1.31	1.18	0.36	0.44	0.13	16	7.04	3	1.03	3
Cobb's Creek Trib. 3	2.70	2.05	0.20	0.43	0.07	52	N/A	2	1.91	2
Mean	1.92	1.66	0.31	0.46	0.12	36.17	1.74	2.02	1.19	2.37
Median	1.58	1.22	0.27	0.46	0.13	28.50	0.99	2.00	1.12	2.00
Standard Deviation	1.08	1.04	0.13	0.09	0.06	21.93	1.83	0.77	0.22	0.76

*Median bed sediment diameter for stream reach (mm).
**1 = 0-25 percent, 2 = 25-50 percent, 3 = 50-75 percent, 4 = 75-100 percent.
N/A indicates data not available for that site for that variable.

channels of different size, the number of pools was converted to number per channel width (P_{cw}) (Jackson and Sturm, 2002). Each reach length was divided by the bankfull channel width to determine the number of channel widths per stream reach. Next, the count of pools was divided by the channel widths to result in a measure expressed in pools (Jackson and Sturm, 2002).

$$P_{cw} = \frac{\#\ Pools}{Length\ /\ Channel\ width} \quad (3)$$

Second, depth diversity (D_{div}) was calculated using the formula

$$D_{div} = 1 - \frac{Mean\ Thalweg\ Depth}{Mean\ Pool\ Depth} \quad (4)$$

This measure was created to provide an indication of the variety of depths throughout the stream reach. Higher values of D_{div} indicate higher depth diversity along the longitudinal profile, while low values indicate the absence of deep pools relative to the average thalweg depth.

Finally, depth was also assessed by using the standard deviation of the maximum pool depths for each stream reach (D_{SDMax}). Maximum pool depths were measured during the longitudinal profile surveys by measuring the deep point in pool for every pool. Streams with higher D_{SDMax} have higher depth variability throughout the reach.

For the sites having quantitative LWD counts (28 of the 46 stream reaches), the amount of LWD per channel width (LWD_{cw}) was computed in the same fashion as P_{cw} (Jackson and Sturm, 2002).

$$LWD_{cw} = \frac{\#\ LWD}{Length\ /\ Channel\ width} \quad (5)$$

This enabled comparison of LWD across channels of differing size. While a smaller sample size was used for this measure, stream reaches represented a broad range of watershed TIA (5 percent to 66 percent).

Watershed Total Impervious Area

Watershed total impervious area was generated for each stream reach using the best available data. Three sources of impervious cover were used: Multi-Resolution Land Characteristics Consortium (MRLC) land cover based on 1992 Landsat Thematic Mapper data (Vogelman *et al.,* 1998) converted to impervious cover using loading factors described by Prisloe *et al.* (2001); Delaware Valley Regional Planning Commission (DVRPC) impervious land cover layers created from 1995 aerial photography (DVRPC, 1998); and Philadelphia Water Department (PWD) impervious cover data layers created from 1996 aerial photos (PWD, 1996). The MRLC data were used for all 13 nonurban sites. Testing of watersheds where overlapping data sources existed showed that the MRLC data were adequate for predicting land use in rural areas but less accurate in urban and urbanizing areas. The DVRPC data covered 15 of the sites outside the county boundaries of Philadelphia. The PWD data were used for the 18 sites within Philadelphia County. If watershed boundaries extended beyond the Philadelphia County boundary, either DVRPC data (when available) or MRLC data were used for that portion of the watershed.

As part of the analysis, stream reaches were categorized into watershed TIA categories based on the ICM (Schueler, 1994). In this study, only two of the three ICM groups were well represented – 0 to 10 percent (19 stream reaches) and greater than 25 percent (23 stream reaches). Four stream reaches (12 percent, 12 percent, 13 percent, and 24 percent, respectively), fell outside those two categories, and due to the proximity to the cutoffs these were assigned either to the 0 to 10 percent or greater than 25 percent categories. As these thresholds are not set "breakpoints" by design, this adjustment was deemed appropriate (CWP, 2003).

Statistical Methods

Ten stream reach variables were used in the statistical analyses (Table 2). As a first test, scatterplots were used to assess relationships between the stream reach geomorphic and habitat data and watershed TIA. Since 8 of the 10 variables failed the Shapiro-Wilk test for normality (Afifi *et al.,* 2004), nonparametric Spearman's Rank correlation coefficients (Mendenhall *et al.,* 1986) were computed to assess the statistical correlation between the variables and watershed TIA. Spearman's Rank correlations were computed for all stream reaches and two subsets – stream reaches less than 13 percent TIA and stream reaches greater than 24 percent TIA.

Principal components analysis (PCA) was used to assess the relationships among and reduce the number of interrelated variables and ensure that the new reduced number of variables used in the subsequent regression and discriminant analysis (DA) were independent and uncorrelated. The PCA technique often used in biological and social sciences (Townsend *et al.,* 1997; McGarigal *et al.,* 2000; Nerbonne and Vondracek, 2001) and more recently in stream studies

(Sawyer *et al.,* 2004) to gain an understanding about the relationships among a large set of variables, reduce the dimensionality of a dataset, and produce independent, uncorrelated variables for use in further statistical analysis. Commonly, numerous variables are measured during stream field surveys, but only a few are used to develop regression relationships. While the researcher must choose which variables to measure in the field, PCA produces linear combinations of the original variables that convey information (i.e., variance) to discover the underlying linear structure of the data. It is, therefore, possible to explore the relationships among sets of new independent variables using PCA as well as use the principal components (PCs) for prediction purposes such as regression and discriminant analysis. Where consistent patterns emerge, it may be possible to reduce redundancy in field collection efforts. Each PC is ranked in proportion to the amount of variance explained in the original data. Therefore, the PCs are arranged in order of decreasing variance, the first few PCs being the most informative. For this study, the number of PCs necessary to explain at least 80 percent of the total variance was retained (Afifi *et al.,* 2004), thereby reducing the dimensionality of the problem. Variables were considered to load significantly on a PC if the correlation with that PC was higher than 0.50 (Afifi *et al.,* 2004). For each PC, the significant loading threshold was calculated using the formula

$$Loading\ Threshold = \frac{0.50}{\sqrt{Eigenvalue}} \tag{6}$$

Stepwise DA, a multivariate technique, was then used to classify stream reaches according to impervious cover category based on the ICM (Schueler, 1994; Afifi *et al.,* 2004). While the ICM has three major categories, two categories of imperviousness were used: 0 to 13 percent and greater than 24 percent. The PCs were used in a stepwise process to assign stream reaches to categories. Cross validation was used to test the DA model's accuracy and predictive capability.

Spearman's Rank correlations and PCA were performed using JMP 5.0.1.2 Statistical Discovery Software (SAS Institute Inc., Cary, North Carolina). Stepwise DA was completed using SAS System Software 8.02 (SAS Institute Inc., Cary, North Carolina).

RESULTS

Scatterplots

Visual inspection of the scatterplots for bankfull width versus drainage area and D_{SDMax}, P_{cw}, and D_{div} versus watershed TIA data suggest that the variables respond differently to watershed TIA beyond 13 percent TIA (Figure 2). While Figure 2a shows the

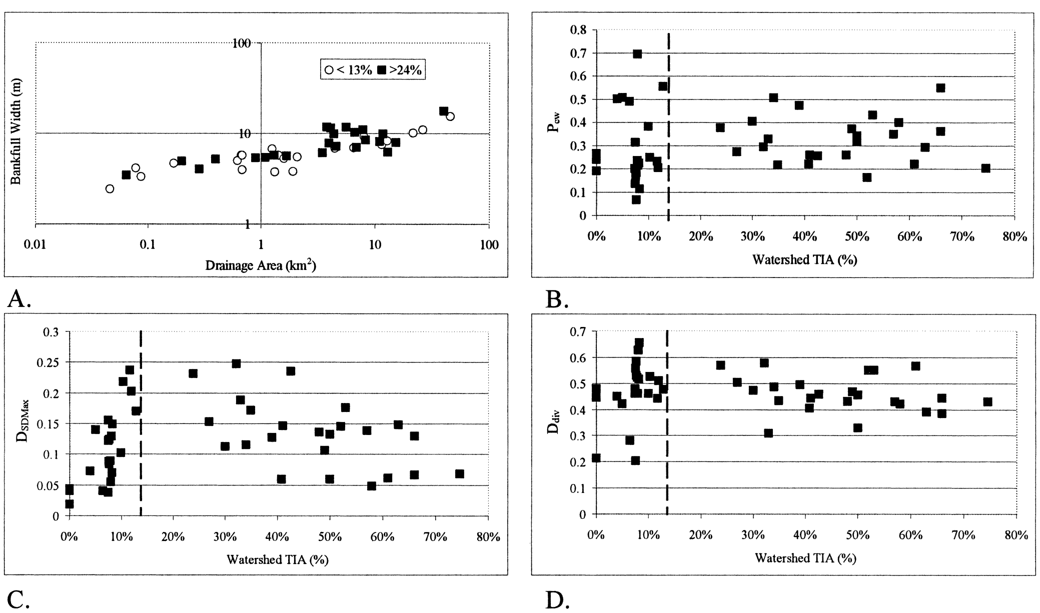

Figure 2. Scatterplots of Selected Geomorphic and Habitat Variables. (A) Bankfull Width Versus Drainage Area; (B) Number of Pools Per Channel Widths (P_{cw}) Versus Watershed Total Impervious Area (TIA); (C) Standard Deviation of Maximum Depth (D_{SDMax}) Versus Watershed TIA; and (D) Depth Diversity Along the Longitudinal Profile (D_{div}) Versus Watershed TIA.

generally accepted relationship of increasing bankfull width with increasing drainage area, it also depicts a subtle shift upward of the greater than 24 percent TIA stream reaches. Increased relative variability and scatter were seen in the low TIA stream reaches for five of the variables including D_{SDMax}, P_{cw}, D_{div}, S, and W_{BF}.

Spearman's Rank Correlations

Spearman's Rank correlations for the variables and watershed TIA are shown in Table 4. All data were tested at the $\alpha = 0.05$ and $\alpha = 0.10$ levels. First, all stream reaches were used for the analysis (0 to 75 percent TIA). LWD_{cw} was significantly correlated with watershed TIA ($\rho = 0.60$, $p = 0.0006$). The correlation was positive, indicating that LWD_{cw} increased as watershed TIA increased. However, LWD_{cat} was not significantly correlated with TIA. Sinuosity was negatively correlated at the $\alpha = 0.10$ level ($\rho = -0.25$, $p = 0.096$), indicating that sinuosity decreased as watershed TIA increased.

In the second analysis, stream reaches with less than 13 percent TIA were used (22 stream reaches). Four of the 10 variables were correlated at the $\alpha = 0.05$ level. Two depth variability measures were positively correlated (D_{div}: $\rho = 0.43$, $p = 0.0483$; D_{SDMax}: $\rho = 0.67$, $p = 0.0004$), as were LWD_{cw} ($\rho = 0.89$, $p = 0.0001$) and E ($\rho = 0.51$, $p = 0.0146$). Enlargement ratios for both bankfull width and depth were negatively correlated (W_{BF}: $\rho = -0.37$, $p = 0.0941$; D_{BF}: $\rho = -0.36$, $p = 0.1009$).

Finally, the correlations were assessed for the stream reaches of greater than 24 percent TIA (24 out of 46 stream reaches). Both LWD_{cw} and S had close to a 0 correlation coefficient. Only D_{SDMax} ($\rho = -0.45$, $p = 0.027$) had a significant correlation at the $\alpha = 0.05$ level. In the higher watershed TIA stream reaches, D_{SDMax} decreased as watershed TIA increased, indicating that channels became more uniform in depth as imperviousness increased. D_{div} was significant at the $\alpha = 0.10$ level ($\rho = -0.37$, $p = 0.076$), indicating a statistically weaker but corresponding relationship between the diversity in depths along the thalweg profile and watershed TIA. There was no consistent pattern in how the correlations changed among the three analyses.

Principal Components Analysis

The PCA of the variables for all stream reaches (PC_{All}) (all variables except LWD_{cw}) revealed five PC axes that explained 82 percent of the variance (Table 5). $PC1_{All}$ explained 30 percent of the variance in the stream reaches and contained significant loadings for characteristics associated with size of the stream reaches and depth variability including W_{BF}, D_{BF}, D_{div}, and D_{SDMax}. The size characteristics loaded positively and the depth variables negatively, indicating that a high value of $PC1_{All}$ for a stream reach corresponds to higher enlargement ratios and

TABLE 4. Spearman's Rank Correlations for Geomorphic and Habitat Variables and Watershed TIA (bolded entries are significant at the $\alpha = 0.05$ or $\alpha = 0.10$ level).

Variable	All Stream Reaches		Stream Reaches < 13 Percent TIA		Stream Reaches > 24 Percent TIA	
	ρ	*p*	ρ	*p*	ρ	*p*
W_{BF}	-0.04	0.7961	**-0.37**	**0.0941**	0.13	0.5556
D_{BF}	0.06	0.6880	**-0.36**	**0.1009**	0.14	0.5100
P_{cw}	0.19	0.1973	-0.02	0.9423	-0.08	0.7010
D_{div}	-0.14	0.3701	**0.43**	**0.0483**	**-0.37**	**0.0761**
D_{SDMax}	0.23	0.1202	**0.67**	**0.0004**	**-0.45**	**0.0271**
d_{50}	-0.02	0.8897	0.17	0.4404	0.06	0.7829
LWD_{cat}	-0.01	0.9326	-0.06	0.7899	0.07	0.7346
LWD_{cw}	**0.60**	**0.0006**	**0.89**	**0.0001**	-0.02	0.9524
E	0.11	0.4801	**0.51**	**0.0146**	-0.30	0.1905
S	**-0.25**	**0.0963**	-0.18	0.4160	0.01	0.9509

TABLE 5. Principal Components for All Stream Reaches and for Stream Reaches > 24 Percent TIA (variables loading significantly on a PC axis shown in bold).

All Stream Reaches	**$PC1_{All}$**	**$PC2_{All}$**	**$PC3_{All}$**	**$PC4_{All}$**	**$PC5_{All}$**
Eigenvalue	2.670	1.534	1.331	1.038	0.821
Percent	29.669	17.048	14.785	11.533	9.126
Cum. Percent	29.669	46.717	61.502	73.035	82.161
W_{BF}	**0.549**	0.018	0.074	0.037	-0.160
D_{BF}	**0.542**	0.084	0.180	-0.045	-0.145
S	-0.086	**0.549**	-0.300	0.075	0.520
D_{div}	**-0.309**	0.363	0.358	-0.111	-0.169
d_{50}	0.003	**0.446**	**0.528**	0.369	0.197
D_{SDMax}	**-0.448**	-0.245	0.072	-0.300	0.084
P_{cw}	0.219	**-0.410**	0.173	0.020	**0.768**
LWD_{cat}	-0.108	-0.117	-0.407	**0.771**	-0.120
E	-0.203	-0.345	**0.514**	0.398	-0.072
Stream Reaches >24% TIA	**$PC1_{>24\%}$**	**$PC2_{>24\%}$**	**$PC3_{>24\%}$**	**$PC4_{>24\%}$**	**$PC5_{>24\%}$**
Eigenvalue	2.766	1.696	1.321	1.081	0.838
Percent	30.732	18.847	14.680	12.014	9.309
Cum. Percent	30.732	49.579	64.259	76.274	85.583
W_{BF}	**0.506**	-0.054	-0.099	0.076	-0.271
D_{BF}	**0.549**	-0.019	0.185	-0.079	-0.195
S	0.223	-0.131	**-0.564**	0.399	0.474
D_{div}	-0.080	-0.188	**0.546**	**0.605**	0.104
d_{50}	**0.346**	0.277	0.241	0.361	0.328
D_{SDMax}	**-0.429**	-0.223	0.171	0.043	0.206
P_{cw}	0.058	**0.609**	0.370	-0.212	0.184
LWD_{cat}	-0.186	**0.602**	-0.313	0.091	0.164
E	-0.213	0.290	-0.134	**0.527**	**-0.665**

lower depth variability. $PC2_{All}$ contained significant loadings for S, d_{50}, and P_{cw} with positive values of S and d_{50} associated with decreasing values of P_{cw}. $PC3_{All}$ contained significant loadings for d_{50} and E. $PC4_{All}$ and $PC5_{All}$ each had one significant positive loading, LWD_{cat} and P_{cw}, respectively, and contributed 12 percent and 9 percent of the overall variance.

The scores for the first two PCs for the stream reaches are shown in Figure 3. The first two PCs account for 47 percent of the variance seen in the dataset. The sites were grouped into the two impervious classes according to the ICM (Schueler, 1994) with the modifications previously described for this study. The stream reaches show a significant amount of overlap with no general clustering tendencies on either $PC1_{All}$ or $PC2_{All}$. This indicates that the variables used in the study were unsuccessful in grouping stream reaches according to watershed TIA.

A PCA was performed again using the stream reaches with greater than 24 percent TIA ($PC_{>24\%}$) to determine if the variables loaded differently for higher impervious sites (Table 4). For this subset, five PCs were retained explaining 86 percent of the variance. $PC1_{>24\%}$ contained significant loadings for W_{BF}, D_{BF}, d_{50}, and D_{SDMax}. $PC2_{>24\%}$ contained significant loadings for P_{cw} and LWD_{cat}. For the higher TIA stream reaches, LWD explained a relatively higher level of variance than in the first PCA. $PC3_{>24\%}$ contained significant loadings for S and D_{div}, $PC4_{>24\%}$ for D_{div} and E, and $PC5_{>24\%}$ for E. The variables explaining the most variance in the data (those that loaded on $PC1_{>24\%}$) remained consistent between the two PCAs;

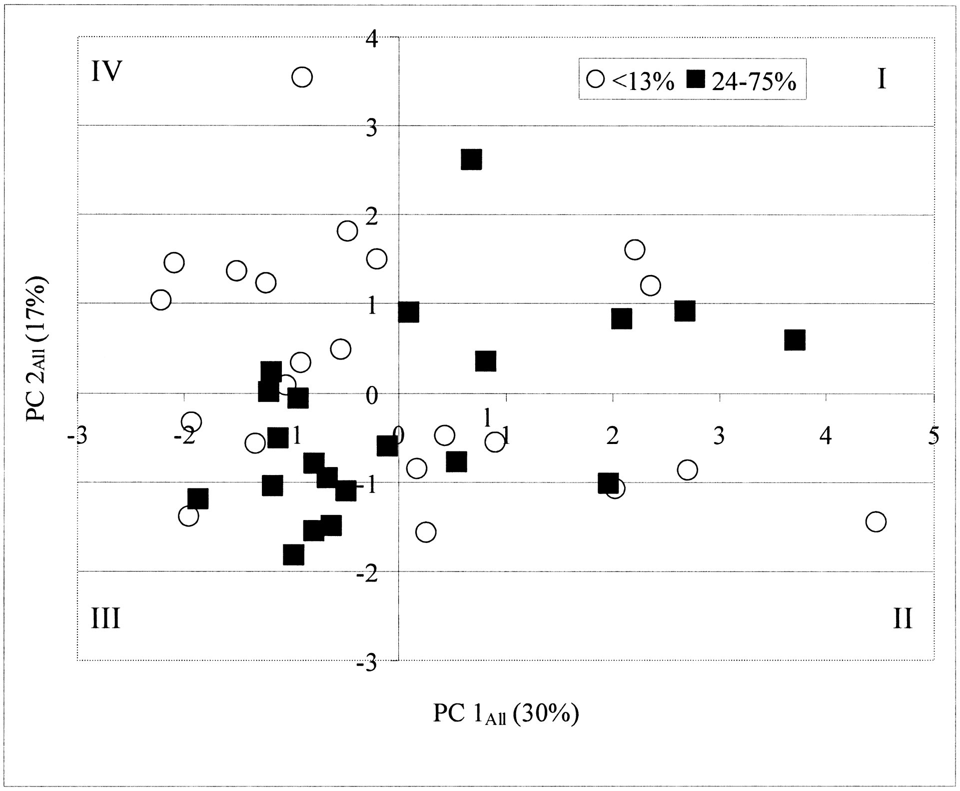

Figure 3. Plot of the First Two Principal Components for All Stream Reaches. $PC1_{All}$ contained significant loadings for width and depth enlargement ratios (W_{BF}, D_{BF}), depth diversity (D_{div}), and standard deviation of maximum depth (D_{SDMax}). $PC2_{All}$ contained high loadings for sinuosity (S), median bed sediment diameter (d_{50}), and pools per channel widths (P_{cw}).

however, the associations changed for the remaining PCs. As with the Spearman's Rank correlations, the PCA results suggest that when separated by impervious group, the associations between the variables change.

Multiple Linear Regression

Both sets of PCs were used in an attempt to develop multiple regression models to explore the relationship between TIA and stream reach geomorphic and habitat variables. No significant models were built using either set.

Discriminant Analysis

The ability of the ICM (CWP, 1998) to predict categories of impervious cover using the PCs developed from all the stream reaches (PC_{All}) was tested in a stepwise DA. The discriminant function was developed using two categories of impervious cover: 0 to 13 percent and greater than 24 percent. All sites were classified using the function developed from the five retained PCs (Table 6). During the stepwise addition of PCs, only $PC2_{All}$ (significant loadings for S, d_{50}, and P_{cw}) entered the model and was used in generating the discriminant model. This model generated an overall 68 percent accuracy in assigning stream reaches to impervious categories. Using cross validation, classification accuracy dropped to 49 percent. The ICM was not accurate in classifying stream reaches into impervious classes based on the variables.

DISCUSSION

Correlation Analysis

The data support the results of previous studies which found that streams with less than 10 percent watershed TIA show greater relative scatter and variability for a variety of geomorphic and habitat variables than those with higher levels of imperviousness (Booth *et al.,* 1997, 2002; Horner *et al.,* 1997; Booth,

TABLE 6. Categories Used and Number and Percent of Stream Reaches Classified Correctly Using Discriminant Analysis.

Total No. Stream Reaches*	Category	Impervious Level (percent)	No. of Samples Classified Correctly	Percent of Samples Classified Correctly	No. of Samples Classified Correctly Using Cross Validation
22	1	< 13	13	59	41
21	2	> 24	16	76	57
TOTAL			29	68	49

*Three stream reaches not used in this analysis due to missing data.

2000; Stepenuck, 2002; CWP, 2003). While the data do not show the same decreasing nonlinear trend for LWD as Horner *et al.* (1997), they do show a similar broad range of LWD at lower levels of TIA. The results also appear to support studies which have shown that in watersheds with less than 10 percent imperviousness, factors other than impervious cover tend to have a greater impact on stream channel geometry and condition (Booth and Jackson, 1997; CWP, 2003).

While the scatterplots of the raw data show differing responses between the two categories of TIA with the sampled geomorphic and habitat variables, the statistical analyses using Spearman's Rank correlation coefficients did not reveal significant relationships for most variables except when the stream reaches of less than 13 percent TIA were used alone (Table 3). Many studies have concluded that as watershed level impervious cover increases, channel widths and depths increase (Hammer, 1972; Booth, 1991; Gregory *et al.,* 1991; Pizzuto *et al.,* 2000; Doll *et al.,* 2002; Hession *et al.,* 2003). Pizzuto *et al.* (2000) show this to be case for channel widths but not depths using paired urban/rural streams (a subset of the data used in this study) in southeastern Pennsylvania. Others, looking more specifically at enlargement ratios, have found similar trends of increasing enlargement as watershed imperviousness increases (Hammer, 1972; MacRae and DeAndrea, 1999; Caraco, 2000). In the present study, 21 of the 24 stream reaches (for W_{BF}) and 20 of 24 stream reaches (for D_{BF}) with greater than 24 percent TIA had enlargement ratios greater than 1, indicating enlargement as compared to nonurban streams. However, the enlargement ratios for bankfull width and depth for these study reaches did not show significant correlation with watershed TIA either when all stream reaches were included or when the stream reaches of greater than 24 percent TIA were used. This may be due in part to the type and extent of riparian vegetation found at these stream reaches. All stream reaches in this study had intact forested buffers of an average of 18 m in width. Hession *et al.* (2003) show in a related study using a subset of this data, pairing forested and nonforested reaches, that riparian vegetation exerted a significant influence on channel geometry regardless of level of urbanization. The effect of riparian vegetation on channel geometry has been reported by others as well (Davies-Colley, 1997; Montgomery, 1997; Trimble, 1997). Additionally, May *et al.* (1997) reported a significant trend of decreasing riparian buffer width with increasing watershed TIA. While only measured qualitatively for the present study, even the stream reaches with the highest TIA had intact forested riparian buffers. The effect of these buffers was not a focus of the study; however, this may explain, in part, the lack of significant relationships between enlargement ratios and TIA in these stream reaches.

A number of studies have attempted to relate watershed TIA with composite and individual stream habitat variables (see review in CWP, 2003). Much of this research has been done in the Pacific Northwest focusing on habitat variables important for salmon (e.g., Horner *et al.,* 1997; May *et al.,* 1997). Individual habitat variables were used to assess relationships with watershed TIA. Channel complexity and depth variability throughout the stream reaches were assessed using P_{cw}, D_{div}, and D_{SDMax}. When using all stream reaches in the study, no significant correlations were observed between any of the depth diversity measures and watershed TIA. However, when using the stream reaches with greater than 24 percent watershed TIA, significant negative correlations between D_{SDMax} and D_{div} and watershed TIA were observed (ρ = -0.45, p = 0.027 and ρ = -0.37, p = 0.076 respectively). In this set of stream reaches, depth variability decreased as watershed TIA increased. This finding supports previous research that has shown that urbanized channels are simpler and more uniform and provide fewer habitat units for aquatic biota (Booth, 1991; Booth and Jackson, 1997; Sovern and Washington, 1997; Pizzuto *et al.,* 2000; CWP, 2003).

Two measures of LWD presence – LWD_{cw} and LWD_{cat} – were used due to data availability. When using all the stream reaches, LWD_{cw} was significantly positively correlated ($\rho = 0.60$, $p = 0.0006$), indicating increased amounts of LWD_{cw} with increased TIA. Most studies have reported losses of LWD with increases in watershed TIA (Booth *et al.,* 1997; Horner *et al.,* 1997; May *et al.,* 1997; Finkenbine *et al.,* 2000). As specified previously, this analysis was completed using 28 of the 46 stream reaches due to data availability. One explanation for this result may be increased LWD loading due to increased bankfull widths in stream reaches with intact forested riparian buffers, as evidenced by enlargement ratios greater than 1 in stream reaches with TIA greater than 24 percent. As the streams become wider, tree roots may be exposed and become unstable, resulting in increased wood loading to the stream reach. While significantly correlated, the data also show a range of scatter. Also of note is the lack of correlation with the LWD_{cat}. This may indicate that using broad qualitative categories of LWD presence may not be adequate for all assessment purposes.

Embeddedness is also often measured in composite habitat assessments, with higher levels indicative of reduced habitat suitability (Barbour *et al.,* 1999). In these stream reaches, neither d_{50} nor E showed any correlation with watershed TIA. This is in contrast to the research of Horner *et al.* (1997) and May *et al.* (1997) that showed increased fine sediment deposition in streams with increased TIA. The amount of sedimentation has been shown to change over time, with streams undergoing increased sediment inputs during watershed level construction and increased bed and bank erosion as increased flows move sediment from the stream channel (Wolman, 1967; Wolman and Schick, 1967). As the exact timing of watershed imperviousness construction was not documented for each of the stream reach watersheds, these competing processes may have caused the increased variability in the collected data.

While often not explicitly testing sinuosity, research has shown that increased urbanization often results in the straightening of stream reaches either directly by channelization or indirectly as the result of altered hydrology (Booth and Jackson, 1997; Pizzuto *et al.,* 2000; CWP, 2003). Using all the stream reaches, the data show a weak negative correlation of S with TIA ($\rho = -0.25$, $p = 0.096$), which is consistent with previous research. When using the higher TIA stream reaches, no correlation was observed.

Principal Components Analysis

Principal components analysis was used in an attempt to reduce the number of variables employed in analyses and to understand the interrelationships of the geomorphic and habitat variables. The latter goal can aid further studies by helping to eliminate redundancy in field data collection. In this study, to maintain 80 percent of the variance measured in the stream reaches, five PC axes were retained when using the entire dataset and when using the stream reaches with greater than 24 percent TIA. Use of PCA reduced the number of variables from nine to five. PCA is most useful when the axes can be interpreted in meaningful ways. When using all stream reaches, $PC1_{All}$ (30 percent of the variance) was interpreted as channel size and depth variability. Decreasing depth variability has been associated with increasing enlargement ratios in studies of urbanizing streams, as previously described. In terms of sampling effort, it is also useful to know that W_{BF} and D_{BF} are interrelated, as these variables are more easily collected, in terms of time and money, than are specific measures of depth throughout the longitudinal profile. Interpretation of the remaining PCs was not as straightforward, since $PC2_{All}$ and $PC3_{All}$ both had multiple variables loading on the axes. However, this analysis is useful in identifying variables that may be more easily collected in the field. $PC2_{All}$ contained significant loadings for S, d_{50}, and P_{cw}, with S usually requiring the least effort to collect. It is interesting to note that in the first PCA, LWD_{cat} loaded on $PC4_{All}$, which was only helpful in explaining a total of 12 percent of the variance seen in the stream reaches. For this dataset, LWD, at least at the categorical level, was not among the most significant variables in explaining the variance seen in the stream reaches across the urban gradient.

$PC1_{>24\%}$ (31 percent of the variance) retained similar loadings in the second PCA after the stream reaches of less than 13 percent were removed. Stream channel size and depth variability, as represented by D_{SDMax}, as well as d_{50} had significant loadings. However, $PC2_{>24\%}$ in this PCA was interpreted as a habitat axis with significant loadings for P_{cw} and LWD_{cat}. This association is supported in the literature linking LWD with pool formation and habitat diversity (Booth *et al.,* 1997). LWD, even at the categorical level, explained an increased amount of variance seen in the data when the lower impervious stream reaches were removed. The loadings for the remaining PCs changed between the two PCAs as well. That the variance structure changed is not surprising, given the results from the correlation analysis.

Discriminant Analysis

Discriminant analysis has been used in a variety of contexts for classification when the classes are known *a priori* (Poff and Allan, 1995; Ludvigsen *et al.,* 1997; Merritt and Wohl, 2003; Santos-Roman *et al.,* 2003). In this study, DA using the PCA_{All} results was not accurate in predicting imperviousness based on the collected field data. This may in part be due to the complexity of the stream system and show that the amount of impervious cover alone does not explain the natural groupings based on these particular geomorphic and habitat variables. Choosing another set of variables may alter the results significantly. Additionally, the majority of the stream reaches had intact forested riparian buffers, which may affect how they are responding to increased TIA. For example, research in the Pacific Northwest has shown that forest cover and riparian continuity may be useful in predicting channel response to land cover change (May *et al.,* 1997; Horner *et al.,* 2001; Booth *et al.,* 2002).

SUMMARY AND CONCLUSION

Forty-six stream reaches with varying watershed TIA were surveyed in southeastern Pennsylvania. Ten stream channel characteristics were analyzed using scatterplots, Spearman's Rank correlations, and multivariate statistical methods in an attempt to understand the relationships among and between the variables and TIA. Specifically, the project had two objectives: to test hypothesized relationships between stream geomorphic and habitat characteristics and watershed TIA and to determine if the ICM provides a reasonable method for classifying streams based on field geomorphic and habitat data.

First, relationships between geomorphic and habitat variables and watershed TIA were assessed. Significant relationships were found for only two variables, both when analyzing the entire dataset (LWD_{cw}, S) and when using the stream reaches with greater than 24 percent TIA (D_{div}, D_{SDMax}). Three of the four significant correlations observed were consistent with those reported in the literature. However, a positive correlation between LWD_{cw} and TIA was found, which is opposite to correlations previously reported. This difference may in part be due to differing local conditions, given that all the stream reaches in this study had intact forested riparian buffers. The lack of significant correlation for the remaining variables is contrary to results reported in the literature, often from studies in the Pacific Northwest. This may indicate differing response to urbanization in different geographic locations.

Secondly, the ICM, as evaluated with DA, was not successful in classifying stream reaches based on the assessed variables used in this study. The ICM was only 49 percent accurate using cross validation. Therefore, roughly half the sites were misclassified using TIA and the collected stream geomorphic and habitat variables. While the stream reaches were not classified correctly using the ICM, the data analysis did support the ICM in other ways. A visual and statistical difference was detected in the manner in which streams with less than 13 percent TIA and greater than 24 percent TIA responded to urbanization. This finding is consistent with prior research indicating that at low levels of imperviousness, other factors (such as riparian land cover) may be more important in determining the shape and condition of a steam channel (Booth and Jackson, 1997; CWP, 2003).

These results indicate that stream reach response to urbanization may not be consistent across geographical regions and local conditions (specifically riparian buffer vegetation) may significantly affect channel response; and that the ICM, used in the appropriate context, can aid in the management of stream reaches and watersheds. Further research is needed in both of these areas across multiple geographic regions to more fully understand the effects and impacts of urbanization on the condition of stream reaches.

ACKNOWLEDGMENTS

Research was supported in part by grants from the U.S. Environmental Protection Agency STAR Grants program No. R 825798-01-0, National Science Foundation Grant DEB 96-1388, and Vermont NSF Experimental Program to Stimulate Competitive Research (EPSCoR) Graduate Student Research Assistantship grant No. EPS 0236975. Data collection was completed by the Stroud Water Research Lab and the Patrick Center for Environmental Research. The authors would also like to acknowledge the helpful comments of three anonymous reviewers.

LITERATURE CITED

Afifi, A., V.A. Clark, and S. May, 2004. Computer-Aided Multivariate Analysis (Fourth Edition). Chapman and Hall/CRC, New York, New York, 489 pp.

Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling, 1999. Rapid Bioassessment Protocols for Use in Streams and Wadable Rivers: Periphyton, Benthic, Macroinvertebrates, and Fish (Second Edition). EPA 841-B-99-002, U.S. Environmental Protection Agency, Washington, D.C.

Booth, D.B., 1991. Urbanization and the Natural Drainage System - Impacts, Solutions, and Prognoses. The Northwest Environmental Journal 7(1):93-118.

Booth, D.B., 2000. Forest Cover, Impervious-Surface Area, and the Mitigation of Urbanization Impacts in King County, Washington. University of Washington, Seattle, Washington.

Booth, D.B., D. Hartley, and R. Jackson, 2002. Forest Cover, Impervious-Surface Area, and the Mitigation of Storm water Impacts. Journal of the American Water Resources Association (JAWRA) 38(3):835-845.

Booth, D.B. and C.R. Jackson, 1997. Urbanization of Aquatic Systems: Degradation Thresholds, Storm water Detection, and the Limits of Mitigation. Journal of the American Water Resources Association (JAWRA) 33(5):1077-1090.

Booth, D.B., D.R. Montgomery, and J. Bethel, 1997. Large Woody Debris in Urban Streams of the Pacific Northwest. *In:* Effects of Watershed Development and Management on Aquatic Ecosystems, L.A. Roesner (Editor). American Society of Civil Engineers, Snowbird, Utah.

Caraco, D., 2000. The Dynamics of Urban Stream Channel Enlargement. Watershed Protection Techniques 3(3):729-734.

CWP (Center for Watershed Protection), 1998. Rapid Watershed Planning Manual. Center for Watershed Protection, Ellicott City, Maryland.

CWP (Center for Watershed Protection), 2003. Impacts of Impervious Cover on Aquatic Systems. Monograph Center for Watershed Protection, Ellicott City, Maryland.

Cinotto, P.J., 2003. Development of Regional Curves of Bankfull-Channel Geometry and Discharge for Streams in the Non-Urban Piedmont Physiographic Province, Pennsylvania and Maryland. Water Resources Investigations Report 03-4014, U.S. Department of the Interior and U.S. Geological Survey, New Cumberland, Pennsylvania.

Davies-Colley, R.J., 1997. Stream Channels Are Narrower in Pasture Than Forest. New Zealand Journal of Marine and Freshwater Research 31:599-608.

DNREC (Delaware Department of Natural Resources and Environmental Control), 1997. Conservation Design for Storm water Management. Delaware Department of Natural Resources and Environmental Control, Newark, Delaware.

DVRPC (Delaware Valley Regional Planning Commission) , 1998. Delaware Valley Data - 1995 Land Use Information: Philadelphia, Pennsylvania. Bulletin 59, Delaware Valley Regional Planning Commission, Philadelphia, Pennsylvania.

Doll, B.A., D.E. Wise-Frederick, C.M. Buckner, S.D. Wilkerson, W.A. Harman, R.E. Smith, and J. Spooner, 2002. Hydraulic Geometry Relationships for Urban Streams Throughout the Piedmont of North Carolina. Journal of the American Water Resources Association (JAWRA) 38(3):641-651.

Finkenbine, J.K., J.W. Atwater, and D.S. Mavinic, 2000. Stream Health After Urbanization. Journal of the American Water Resources Association (JAWRA) 36(5):1149-1160.

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins, 1991. An Ecosystem Perspective of Riparian Zones: Focus on Links Between Land and Water. Bioscience 41(8):540-551.

Hammer, T.R., 1972. Stream Channel Enlargement Due to Urbanization. Water Resources Research 8(6):1530-1540.

Hession, W.C., J.E. Pizzuto, T.E. Johnson, and R.J. Horwitz, 2003. Influence of Bank Vegetation on Channel Morphology in Rural and Urban Watersheds. Geology 31(2):147-150.

Horner, R.R., D.B. Booth, A. Azous, and C.W. May, 1997. Watershed Determinants of Ecosystem Functioning. *In:* Effects of Watershed Development and Management on Aquatic Ecosystems, L.A. Roesner (Editor). American Society of Civil Engineers, Snowbird, Utah.

Horner, R., C. May, E. Livingston, D. Blaha, M. Scoggins, J. Tims, and J. Maxted, 2001. Structural and Non-Structural BMPs for Protecting Streams. *In:* Linking Storm water BMP Designs and Performance to Receiving Water Impact Mitigation, B. Urbonas (Editor). ASCE, Snowmass, Colorado, pp. 60-77.

Horner, R., C. May, E. Livingston, and J. Maxted, 1999. Impervious Cover, Aquatic Community Health, and Storm water BMPs: Is There a Relationship? *In:* Proceedings of the Sixth Biennial Storm water Research and Watershed Management Conference. Southwest Florida Water Management District, Tampa, Florida.

Jackson, C.R., and C.A. Sturm, 2002. Woody Debris and Channel Morphology in First- and Second-Order Forested Channels in Washington's Coast Range. Water Resources Research 38(9):1177-1190.

Jones, R.C., A. Via-Norton, and D.R. Morgan, 1997. Bioassessment of the BMP Effectiveness in Mitigating Storm water Impacts on Aquatic Biota. *In:* Effects of Watershed Development and Management on Aquatic Ecosystems, L.A. Roesner (Editor). American Society of Civil Engineers, Snowbird, Utah.

Kemp, S.J. and J.R. Spotila, 1997. Effects of Urbanization on Brown Trout Salmo Trutta, Other Fishes and Macroinvertebrates in Valley Creek, Valley Forge, Pennsylvania. The American Midland Naturalist 138(1):55-68.

Klein, R.D., 1979. Urbanization and Stream Quality Impairment. Water Resources Bulletin 15(4):948-963.

Lee, J.G. and J.P. Heaney, 2003. Estimation of Urban Imperviousness and Its Impacts on Storm Water Systems. Journal of Water Resources Planning and Management 129(5):419-426.

Leopold, L.B., 1968. Hydrology for Urban Land Planning: A Guidebook on the Hydrologic Effects of Urban Land Use. U.S. Geological Survey Circular 554:1-18.

Leopold, L.B., 1994. A View of the River. Harvard University Press, Cambridge, Massachusetts, 298 pp.

Ludvigsen, L., H.J. Albrechtsen, H. Holst, and T.H. Christensen, 1997. Correlating Phospholipid Fatty Acids (PLFA) in a Landfill Leachate Polluted Aquifer with Biogeochemical Factors by Multivariate Statistical Methods. FEMS Microbiology Reviews 20(3-4):447-460.

MacRae, C.R., 1997. Experience From Morphological Research on Canadian Streams: Is Control of the Two-Year Frequency Runoff Event the Best Basis for Stream Channel Protection. *In:* Effects of Watershed Development and Management on Aquatic Ecosystems, L.A. Roesner (Editor). American Society of Civil Engineers, Snowbird, Utah.

MacRae, C.R. and M. DeAndrea, 1999. Assessing the Impact of Urbanization on Channel Morphology. Second International Conference on Natural Channel Systems, Niagara Falls, Ontario.

Maxted, J., and E. Shaver, 1997. The Use of Retention Basins to Mitigate Storm water Impacts on Aquatic Life. *In:* Effects of Watershed Development and Management on Aquatic Ecosystems, L. A. Roesner (Editor). American Society of Civil Engineers, Snowbird, Utah.

May, C., R. Horner, J.R. Karr, B. Mar, and E. Welch, 1997. Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion. Watershed Protection Techniques 2(4):483-494.

McGarigal, K., S. Cushman, and S. Stafford, 2000. Multivariate Statistics for Wildlife and Ecology Research. Springer-Verlag, New York, New York, 283 pp.

Mendenhall, W., R.L. Scheaffer, and D.D. Wackerly, 1986. Mathematical Statistics With Applications (Third Edition). Duxbury Press, Boston, Massachusetts, 750 pp.

Merritt, D.M. and E.E. Wohl, 2003. Downstream Hydraulic Geometry and Channel Adjustment During a Flood Along an Ephemeral, Arid-Region Drainage. Geomorphology 52(3-4):165-180.

Montgomery, D.R., 1997. River Management; What's Best on the Banks? Nature 388(6640):328-329.

Montgomery, D.R., J.M. Buffington, R.D. Smith, K.M. Schmidt, and G. Pess, 1995. Pool Spacing in Forest Channels. Water Resources Research 31(4):1097-1105.

Morisawa, M. and E. LaFlure, 1979. Hydraulic Geometry, Stream Equilibrium, and Urbanization. *In:* Adjustments of the Fluvial System, D.D. Rhodes and G.P. Williams, (Editors). Kendall-Hunt, Dubuque, Iowa, pp. 333-370.

Morse, C., 2001. The Response of First and Second Order Streams to Urban Land-Use in Maine, USA. Master's Thesis, University of Maine, Orono, Maine.

Neller, R.J., 1988. A Comparison of Channel Erosion in Small Urban and Rural Catchments, Armidale, New South Wales. Earth Surface Processes and Landforms 13(1):1-7.

Nerbonne, B.A. and B. Vondracek, 2001. Effects of Local Land Use on Physical Habitat, Benthic Macroinvertebrates, and Fish in the Whitewater River, Minnesota, USA. Environmental Management 28(1):87-99.

PWD (Philadelphia Water Department) , 1996. Impervious Surfaces. Philadelphia Water Department, City of Philadelphia. *Available at* http://www.pasda.psu.edu/documents.cgi/philacity/phila-impervious.xml. *Accessed in* 1999.

Pizzuto, J.E., W.C. Hession, and M. McBride, 2000. Comparing Gravel-Bed Rivers in Paired Urban and Rural Catchments of Southeastern Pennsylvania. Geology 28(1):79-82.

Poff, N.L. and J.D. Allan, 1995. Functional-Organization of Stream Fish Assemblages in Relation to Hydrological Variability. Ecology 76(2):606-627.

Prisloe, S., Y. Lei, and J. Hurd, 2001. Interactive GIS-Based Impervious Surface Model. ASPRS 2001 Annual Convention, St. Louis, Missouri.

Santos-Roman, D.M., G.S. Warner, and F. Scatena, 2003. Multivariate Analysis of Water Quality and Physical Characteristics of Selected Watersheds in Puerto Rico. Journal of the American Water Resources Association (JAWRA) 39(4):829-839.

Sawyer, J.A., P.M. Stewart, M.M. Mullen, T.P. Simon, and H.H. Bennett, 2004. Influence of Habitat, Water Quality, and Land Use on Macro-Invertebrate and Fish Assemblages of a Southeastern Coastal Plain Watershed, USA. Aquatic Ecosystem Health and Management 7(1):85-99.

Schueler, T., 1994. The Importance of Imperviousness. Watershed Protection Techniques 1(3).

Sovern, D.T. and P.M. Washington, 1997. Effects of Urban Growth on Stream Habitat. *In:* Effects of Watershed Development and Management on Aquatic Ecosystems, L.A. Roesner (Editor). American Society of Civil Engineers, Snowbird, Utah.

Stepenuck, K.F., R.L.Crunkilton, L. Wang, 2002. Impacts of Urban Landuse on Macroinvertebrate Communities in Southeastern Wisconsin Streams. Journal of the American Water Resources Association (JAWRA) 38(4):1041-1051.

Sutherland, R.C., 1995. Methodology for Estimating the Effective Impervious Area of Urban Watersheds. Watershed Protection Techniques 2(1):282-284.

Sweeney, B.W., 1992. Streamside Forests and the Physical, Chemical, and Trophic Characteristics of Piedmont Streams in Eastern North America. Water Science and Technology 26(12): 2653-2673.

Sweeney, B.W., T.L. Bott, J.K. Jackson, L.A. Kaplan, J.D. Newbold, L.J. Stanley, W.C. Hession, and R.J. Horwitz, 2004. Riparian Deforestation and Stream Channel Narrowing: Loss of Stream Ecosystem and Its Services. Journal of the National Academy of Sciences 101(39):14132-14137.

Townsend, C.R., C.J. Arbuckle, T.A. Crowl, and M.R. Scarsbrook, 1997. The Relationship Between Land Use and Physicochemistry, Food Resources, and Macroinvertebrate Communities in Tributaries of the Taieri River, New Zealand: A Hierarchically Scaled Approach. Freshwater Biology 37:177-191.

Trimble, S.W., 1997. Contribution of Stream Channel Erosion to Sediment Yield From an Urbanizing Watershed. Science 278(5342):1442-1444.

USEPA (U.S. Environmental Protection Agency) and ASCE (American Society of Civil Engineers), 2005. International Storm water Best Management Practices (BMP) Database. *Available at* http://www.bmpdatabase.org/index.htm. *Accessed in* July 2005.

Vogelman, J.E., T.L. Sohl, P.V. Campbell, and D.M. Shaw, 1998. Regional Land Cover Characterization Using Landsat TM Data and Ancillary Data Sources. Environmental Monitoring and Assessment 51:415-428.

Wolman, M.G., 1954. A Method of Sampling Coarse River-Bed Material. Transactions - American Geophysical Union 35(6):951-956.

Wolman, M.G., 1967. A Cycle of Sedimentation and Erosion in Urban River Channels. Geografiska Annaler Series A: Physical Geography 49(2-4):385-395.

Wolman, M.G. and A.P. Schick, 1967. Effects of Construction on Fluvial Sediment, Urban and Suburban Areas of Maryland. Water Resources Research 3(2):451-464.