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Urbanization affects the extent and hydrologic permanence of headwater streams in a midwestern US metropolitan area

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Abstract. Headwater streams dominate natural landscapes and provide essential functions for downstream waters. However, because of minimal legal protection, they often are piped or buried to accommodate urban growth. Urbanization also alters stream base flows. The combined impact of these factors on channel location is unknown. We assessed the effects of urbanization on the location and length of ephemeral, intermittent, and perennial streams. We randomly selected 150 of 6686 potential channel origins in Hamilton County (Cincinnati), Ohio, USA, for field assessments, and mapped 122 ephemeral, 74 intermittent, and 45 perennial flow origins in these channels. On average, 1:100,000- and 1:24,000-scale US Geological Survey maps underestimated channel length by 85% and 78%, respectively. Mean catchment areas for ephemeral and intermittent flow origins were smaller in forested (0.66 ha and 3.60 ha, respectively) than in urban areas (5.13 ha and 6.79 ha, respectively). These values indicate 93% and 46% county-wide losses of ephemeral and intermittent channel length, respectively, with urbanization. In contrast, the mean catchment area for perennial flow origins was larger in forested (48.12 ha) than in urban (31.22 ha) areas, resulting in a 22% gain in perennial channel length with urban development. Increased perennial channel length was partially explained by reduced forest cover, a result suggesting that reduced evapotranspiration can significantly increase stream base flows. Most variation (59–74%) in catchment area of ephemeral, intermittent, and perennial flow origins was explained by catchment relief, with higher relief corresponding to smaller catchments. Urbanization can decrease (e.g., via reduced infiltration) or increase (e.g., via lawn irrigation and septic tanks) the permanence of flows, thus confounding any overall effect of urban land cover on hydrologic permanence. Site-specific differences in physiography (e.g., bedrock, springs) and landscape management (e.g., stream impoundments) suggest that field surveys are necessary for accurate stream delineation. These results highlight the extensive effects of urbanization on the presence and hydrologic permanence of headwater streams, raise issues with current jurisdictional policy in the US, and emphasize the need to examine the cumulative effects of headwater stream loss on downstream ecosystems.

Key words: headwater streams, flow permanence, hydrology, urban, forest, ephemeral, intermittent, perennial, mapping.

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Headwater streams dominate the riverine landscape and constitute >½ of total stream length (Leopold et al. 1964, Nadeau and Rains 2007). These small streams transport nutrients and organic material from terrestrial uplands to large streams and rivers and provide essential ecosystem functions (Meyer and Wallace 2001, Freeman et al. 2007). For example, headwaters transport and transform organic material, such as invertebrates (e.g., drifting and emerging insects), organic matter (dissolved and particulate), and wood, thereby providing food resources for downstream ecosystems (Meyer et al. 2007, Wipfli et al. 2007). Small streams can effectively retain sediments and transform and retain nutrients and contaminants, thereby providing water-quality benefits downstream (Meyer and Wallace 2001). Temperature regulation from groundwater-fed springs provides thermal refuge for fauna in summer and winter months (Power et al. 1999, Meyer et al. 2007) and can moderate the thermal regime of downstream waters. In addition, small streams provide unique habitat for many biota that require headwaters for all or part (e.g., for spawning) of their life cycle (Doppelt et al. 1993, Vannote et al. 1980, Meyer et al. 2007).

Headwater streams have been extensively eliminated by human activities that disturb landscapes because of their predominance in the landscape and the fact that they receive minimal legal protection. Small streams often are filled or diverted through pipes to accommodate residential, commercial, and industrial development. For example, in Atlanta, Georgia, drainage density of natural channels is ~⅓ less in urban and suburban catchments than in forested catchments (Meyer and Wallace 2001). Many areas presently experiencing urban, suburban, and exurban growth were previously farmed, and agriculture also results in filling and burying of stream channels (Meyer and Wallace 2001). Headwater streams are buried more extensively than larger streams and ~70% of streams in Baltimore City with catchments <260 ha are buried (Elmore and Kaushal 2008).

The loss of stream channels probably is underestimated because many headwater streams are not explicitly mapped (Meyer and Wallace 2001, Hansen 2001, Colson et al. 2008). For example, only 21% of stream channels in the Chattooga River basin in the Blue Ridge Mountains are included on US Geological Survey (USGS) standard 1:24,000-scale maps (Hansen 2001). About ¾ of perennial, but virtually no intermittent or ephemeral, stream length was mapped (Hansen 2001). The fact that the blue lines representing streams on these maps were not drawn based on stream flow, but were drawn subjectively to "fill a rather personalized aesthetic," contributes to the inaccuracy and inconsistency of 1:24,000 maps across the US (Leopold 1994). Technological advances in geographic information systems (GIS) in the last decade have helped standardize hydrologic maps via use of digital elevation models (DEMs). However, topographic information is not sufficient to characterize hydrologic permanence (ephemeral, intermittent, or perennial) or to account for channel loss.

Urban development can have profound effects on baseflow hydrology, and thus, can affect the hydrologic permanence of streams. Urbanization decreases the magnitude and increases the duration of low flows by reducing infiltration and groundwater recharge (Ferguson and Suckling 1990). Furthermore, groundwater pumping has lowered the water table in many areas of the country (Postel 2000) and has caused previously perennial streams to dry. However, some evidence suggests that reduced base flows might not be a characteristic symptom in urban headwater streams (Nilsson et al. 2003, Konrad and Booth 2005, Walsh et al. 2005). For example, high densities of septic systems, leaky pipes, and lawn irrigation in urban areas might provide sufficient water to offset losses from increased runoff from impervious surfaces (Lerner 2002). At the extremes, changes in base flow can cause perennial streams to dry or ephemeral streams to flow continuously, and thereby alter ecosystem functions and biotic communities adapted to various degrees of flow permanence (Lytle and Poff 2004).

Our objective was to evaluate the effects of urbanization on channel length and permanence of flows in headwater streams. We define ephemeral streams as channels with distinct stream bed and bank that carry water only for a short period of time during and briefly after storms; intermittent streams as channels that carry water during the wet season (e.g., winter and spring) and dry to pools, interstitial flow, or no flow during dry summer months; and perennial streams as channels that carry flow all year (Hansen 2001). We conducted field assessments of headwater streams to map channels and determine hydrologic permanence across a gradient of urbanization because flow permanence of most headwater streams cannot be determined directly from aerial photographs or other available geographic data. We used regression models to identify natural and anthropogenic predictors of channel location and extent, but we could not use these models to infer causes of increases or decreases in ephemeral, intermittent, and perennial channel length. We conclude by discussing the regulatory implications of

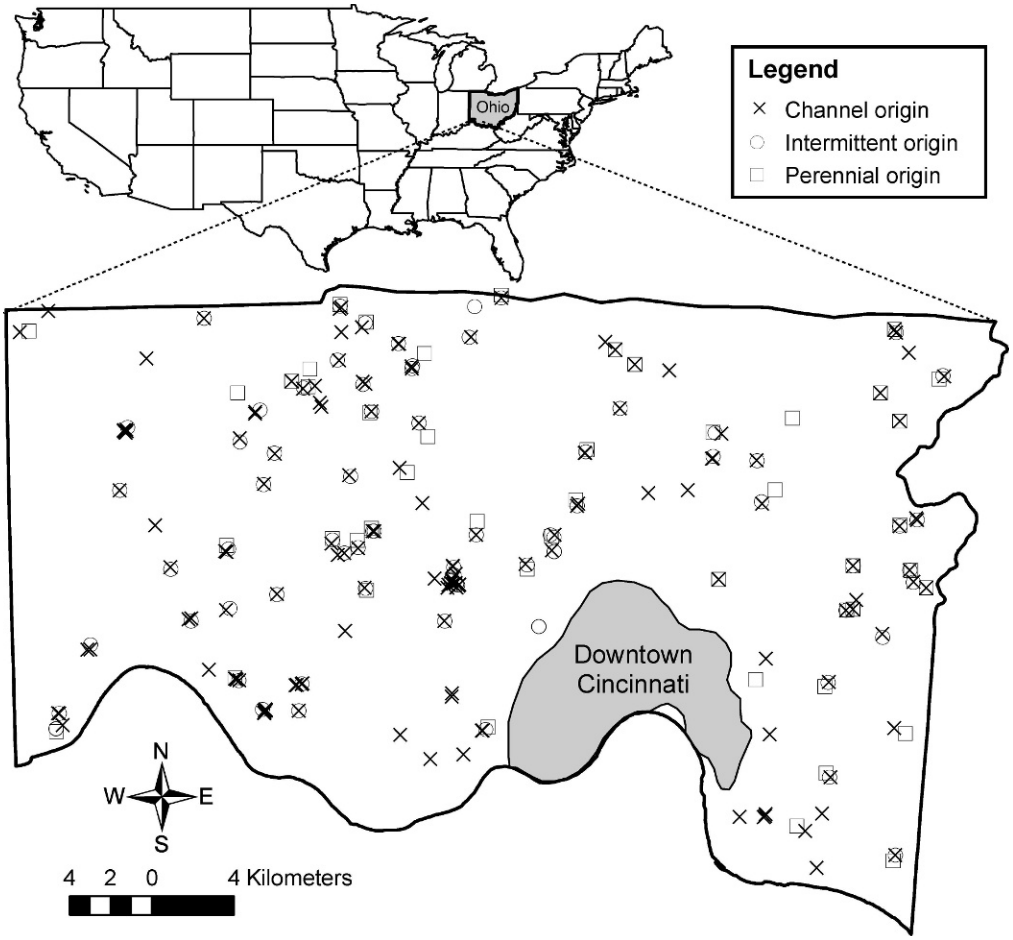

FIG. 1. Map of surveyed channel origins and origins of intermittent and perennial flow within Hamilton County, Ohio (US). Ephemeral stream origins occur where channel origins do not overlap with intermittent and perennial flow origins. Multiple adjacent X's indicate >1 ephemeral flow origin.

using hydrologic permanence as criteria for stream protection and the potential ecological impacts of changes in flow permanence associated with disturbance.

Methods

Study area

Our study was conducted in Hamilton County, a 1074-km^2 area in the southwestern corner of Ohio, USA (Fig. 1). The county includes a variety of land covers, from high-density urban land use in the center of Cincinnati to mature forests in parks, nature preserves, and old estates. Based on the 2001 USGS National Land Cover Data (NLCD), the county has 50.2% developed land, 36.1% forested land, and 11% agricultural land. The city has a mixture of combined sanitary and storm sewers (built starting in the 1800s), and separate sanitary sewers routed to wastewater treatment plants and storm sewers routed to streams (built since the 1960s). The urban water infrastructure in the county includes various combinations of private wells, public drinking-water pipes, and private septic tanks that outlet to leach fields.

The region has a continental climate, with cold winters and hot summers. Mean annual precipitation in the county is ~100 cm (Lerch et al. 1982) and evapotranspiration is 73 cm (Shuster et al. 2007). Hamilton County is in the Central Lowland physiographic province, and dominant features are gently rolling glacial uplands, steep hillsides, glacial river terraces, and flood plains (Lerch et al. 1982). About ⅔ of the county (southwestern part) is in the Interior Plateau level III ecoregion, and dominant features are rolling to rugged terrain underlain by sandstone, siltstone, shale, and limestone (Omernik 1987). The northeastern part of the county is in the Eastern Corn Belt Plains ecoregion and has rolling till plains set on glacial deposits (Omernik 1987).

Field data collection

We began with a stream network for Hamilton County that had been created by Cincinnati Area GIS (CAGIS) from DEMs (0.61-m contours). The network was fitted to approximate most channels, and CAGIS personnel had hand-edited part of the stream network on or near culverts and eliminated all streams in downtown Cincinnati that were known to have been piped, but the map had not been ground-truthed. We selected a random subset of 150 channel origins from the 6686 channel origins in the CAGIS stream network. We visited each randomly selected channel origin twice: 1) during the wet season (winter/spring 2006 and 2007), and 2) during the dry season (summer/autumn 2006). We waited at least 48 h after large rainfall events to ensure that ephemeral streams were not flowing. We used a handheld personal digital assistant (PDA) and geographical positioning system (GPS; Axim X5 with World Navigator Global Positioning System; Dell, Boston, Massachusetts) with navigator software (Pocket Navigator 4.0; Maptech, Amesbury, Massachusetts) and USGS 1:24,000 topographic maps to aid field surveys.

During the first visit, we walked or drove upstream or downstream of the point of channel origin identified from the map until we found the actual channel origin. Channel origins or heads are the upslope boundary between the hillslope and channel, where a channel has defined banks and bed material (Dietrich and Dunne 1993, Fritz et al. 2006). If the channel split into multiple tributaries, then we recorded the coordinates of all channel origins for tributaries >10 m long. If we found no channel at the point of channel origin selected from the map (i.e., the channel was piped or buried), then we moved downslope until we reached the actual channel origin (e.g., where the pipe returned to the surface or the stream began) and recorded the coordinates. We recorded the diameter of the pipe at channel origins that had pipe outlets. If we were unable to access a channel origin (e.g., no landowner permission), we surveyed the nearest accessible channel origin.

We also mapped and recorded ephemeral, intermittent, and perennial flow origins in each channel. We classified channel origins as ephemeral, intermittent, or perennial flow origins, depending on when they were flowing. Intermittent flow origins had continuous flow in spring but not in summer. Perennial flow origins had continuous flow in spring and summer. Ephemeral flow origins had no flow in spring or summer. We walked downstream of ephemeral flow origins until we reached the intermittent and perennial flow origins in the channel. We identified intermittent or perennial origins based on presence of continuous surface flow for a distance longer than the length of the adjacent dry section. We recorded coordinates, pipe diameter(s) (when applicable), bankfull width, bankfull height, and floodprone width (i.e., width at 2× bankfull height; Fritz et al. 2006) of all intermittent and perennial flow origins. If intermittent or perennial flow origins were inaccessible, we did not survey additional points. We resurveyed all channels and identified flow origins in both seasons. For example, when we returned in summer to resurvey channels that had been surveyed in spring, we started at the mapped intermittent flow origin and walked downstream to locate the perennial flow origin. We compared permanence designations from the 2 visits in 2006 to designations based on surveys made 5 times/y for 4 to 6 y between 2003 and 2008 to assess the accuracy of our method for determining flow category in 4 intermittent and 3 perennial stream reaches.

GIS calculations

We used ArcGIS® (version 9.2; Environmental Systems Research Institute, Redlands, California) to calculate catchment areas, land cover, and other geographical information for catchments of channel and ephemeral, intermittent, and perennial flow origins. We used ArcHydro® tools with a National Elevation Dataset DEM (⅓ arc second, seamless, ~10-m resolution) to identify catchments for each mapped origin. We verified all catchments against hand-drawn maps to check for correspondence to the correct location and redigitized, as necessary, from 3-m (10-ft) contour maps. We calculated % land cover as forest (deciduous, evergreen, and mixed forest; emergent and woody wetlands), agriculture (cultivated/exposed, pasture hay), and urban (high-, medium-, and low-intensity urban; open space developed) within 1) catchments and 2) 100-m buffers around randomly selected channel origins from the USGS 2001 NLCD (30-m pixels). Urban land cover increased between the collection of NLCD data and our field collection (5–6 y later), but we used NLCD because of its regional coverage and widespread use around the country. We also calculated % impervious surface area from the NLCD imperviousness layer (created from 2001 Landsat 7 ETM+ data). We calculated road and sewer densities (m/km^2) and septic densities (no. tanks/km^2) for each catchment with data obtained from the Department of Transportation and Cincinnati Metropolitan Sewer District. We determined elevation and relief ratio (i.e., difference in elevation between highest and lowest point in the catchment divided by the catchment area) from 3-m contour maps. We used the National Resources Conservation Service Soil Survey Geographic (SSURGO) Database to determine the % area of each soil type and multiplied % area by average soil depth for each type (Lerch et al. 1982) to obtain average catchment soil depth.

We used ArcHydro® (Environmental Systems Research Institute) to determine the flow accumulation coefficient (FAC) for the mapped stream network that corresponded to each mapped origin. The flow accumulation grid records the number of cells that drain into an individual cell ($\sim$10 m $\times$ 10 m), and the coefficient is the threshold number of cells required for initiation of a stream. Our goal was to determine the unique FAC associated with each origin, so we created stream networks with various FAC values and matched them to the mapped origins. The FAC for an origin was the value (within increments of 25) that created a stream network that reached but did not extend upslope of the mapped origin. Where a network could not be created from the DEM for the channel, we considered the FAC to be 0. FAC values were less precise than catchment areas, particularly for smaller catchments, for which FAC $=$ 0 and catchments were hand-drawn. Therefore, we used the relationship between FAC and catchment areas for origins with FAC $>$ 0 to convert catchment areas to FAC values:

$$\text{Area}\ (\text{m}^2) = (81.334 \times \text{FAC}) + 1511.4 \quad (r^2 = 0.999,\ p < 0.001,\ n = 184) \qquad [1]$$

We used FAC values based on our field data to generate stream networks and to estimate ephemeral, intermittent, and perennial channel length (all length downstream of ephemeral, intermittent, or perennial flow origins, respectively) in the county based on median catchment area for each type of flow origin. We compared these lengths to lengths determined from USGS National Hydrography Dataset (NHD) 1:100,000-scale maps and USGS 1:24,000 topographic maps to quantify the differences in length among stream maps of various scales and derivation methods.

Data analysis

We tested all variables for normality and transformed them as necessary. We used an arcsine($\sqrt{[x]}$)-transformation for all percentage variables. We used *t*-tests (2-tailed, assuming unequal variances) to compare catchment characteristics for channel and ephemeral, intermittent, and perennial flow origins between the 2 ecoregions (Eastern Corn Belt Plains and Interior Plateau). We used *t*-tests to compare % urban, % forested, and % agricultural land cover within the 100-m buffer around randomly selected channel origins at sites where a channel was present and where a channel was absent (i.e., the channel was buried). We used *t*-tests to compare catchment areas of channels with ephemeral, intermittent, and perennial flow origins between primarily forested (75–100% forest, depending on origin type) and primarily urban (75–100% urban cover) catchments. We also used *t*-tests to compare bankfull width:depth ratios and entrenchment ratios (i.e., flood-prone width divided by bankfull width) at intermittent and perennial flow origins between sites with and without pipes.

We developed linear regression models to predict mean catchment area of channel and ephemeral, intermittent, and perennial origins using catchment characteristics. Catchment area served as a surrogate for location of origins relative to ridge tops. Independent variables included measures of anthropogenic disturbance (road density, sewer density, septic density, % urban, % agriculture, % imperviousness) and natural factors (relief, elevation, soil depth, and % forest cover) that were expected to influence catchment area. We included relief ratio, which captures the gradient of the entire catchment, in all models because several studies had indicated the importance of local or valley slope in predicting channel origins (e.g., Montgomery and Dietrich 1989, Tucker and Bras 1998). We expected positive relationships between road density, % urban, % agriculture, and % imperviousness and catchment areas because these variables indicate decreased infiltration and routing of runoff to downstream locations. We also expected a positive relationship between sewer density (a combination of both sanitary and storm sewers) and catchment area, although water can leak both into and out of unpressurized pipes. On the other hand, we expected an inverse relationship between septic tanks and catchment area because septic systems contribute novel water sources to the catchment and should increase flows of headwater streams (thereby decreasing catchment area).

We compared models with Akaike's Information Criterion adjusted for small sample size (AIC_c). We considered the model with the highest Akaike weight (w_i) for each model set to be the best supported model, but we regarded all models with $\Delta AIC_c \leq 2$ as plausible alternatives (Burnham and Anderson 2002). We report adjusted r^2 values and parameter estimates for the best supported models for the Eastern Corn Belt Plains, Interior Plateau, and combined ecoregions. We did all analyses with JMP (version 5.1; SAS Institute, Cary, North Carolina).

Results

We mapped 148 channel origins distributed throughout Hamilton County, 122 that were ephemeral flow origins and 26 that had intermittent or perennial flow (Fig 1). In total, we identified 74 intermittent and 45 perennial flow origins. Land cover and other catchment characteristics varied widely among channel and flow origins (Table 1). Mean catchment areas were much smaller for ephemeral (2.55 ha) and intermittent (5.23 ha) than for perennial (28.39 ha) flow origins. Catchment areas of channel origins (0.03–27.29 ha) and of ephemeral (0.03–25.52 ha), intermittent (0.30–27.15 ha), and perennial (1.21–125.3 ha) flow origins ranged widely.

We used the FAC corresponding to median catchment areas for surveyed ephemeral, intermittent, and perennial flow origins to map a total of 7062 km of channel length in Hamilton County. This length is nearly 7× greater than the channel length included in the 1:100,000 NHD network (1052 km; Table 2). We mapped 2250 km of perennial channel length. Thus, the NHD appears to include $<$½ of perennial channel length and no ephemeral or intermittent channel length (Fig. 2). USGS 1:24,000 maps show 1575 km of channel length and appear to exclude all ephemeral channel length, ~50% of intermittent channel length, and ~75% of perennial channel length. The CAGIS map includes 4368 km of total channel length, but excludes 2694 km of channel length, which corresponds to almost all of the ephemeral channel length (2952 km, Table 2).

Percent urban land cover was significantly higher at randomly selected channel origins where the channel was absent (i.e., because it was buried) than where the channel was present (Fig. 3). Percent forest cover was significantly higher at randomly selected channel origins where the channel was present than where the channel was absent.

Mean catchment areas draining to channel and flow origins were used to indicate where channels were located in the landscape relative to ridge tops. Catchment areas of ephemeral flow origins were significantly smaller in completely (100%) forested catchments (mean = 0.66 ha) than in completely urbanized catchments (mean = 5.13 ha) (Table 3). Catchment areas for intermittent and perennial flow origins did not differ significantly based on land cover. We used the FACs corresponding to these urban and forested catchment areas to map channel networks. Total channel length was ~3× greater in models of forested than of urban catchments (Table 3, Fig. 4). At the scale of the entire county, modeled ephemeral channel length was 93% lower, intermittent channel length was 46% lower, and perennial channel length was 22% higher in urban than in forested catchments (Fig. 5).

Pipes were present at 24 (20%) ephemeral, 22 (30%) intermittent, and 18 (40%) perennial flow origins (Table 4). Mean catchment areas did not differ between locations with and without pipes at flow origins of any type. Bankfull width:depth ratios and entrenchment ratios also did not differ between intermittent or perennial flow origins with and without pipes (Table 4).

Most of the variation (59–74%) in catchment area was explained by relief ratio (Table 5). The best-supported models for catchment areas of channel and ephemeral flow origins included relief ratio and soil depth (Table 6). Higher relief ratios were associated with smaller catchments, and deeper soils were found in smaller catchments (Table 5). Several equally plausible models ($\Delta AIC_c \leq 2$) included urban variables (e.g., road density, sewer density, % impervious cover). The best-supported models for catchment areas of intermittent flow origins included relief ratio, soil depth, and elevation, but no urban variables. The best-supported model for catchment areas of perennial flow origins included relief ratio and % forest cover (perennial channel length decreased with increasing forest cover), and this model was ~2.5× better supported than were alternative models (Table 6). Overall, the regression models explained 72–84% of the variation in catchment areas of the various origins (Table 5).

Catchment characteristics (e.g., relief ratio, soil depth, sewer density, % forest, % urban) differed between the 2 ecoregions for channel and ephemeral, intermittent, and perennial flow origins (Table 1). Therefore, we constructed regression models for origins within each ecoregion. Catchments in the Eastern Corn Belt Plains had significantly lower mean relief ratios than did catchments in the Interior Plateau, but the relationship between relief ratio and catchment area was significant for each ecoregion and origin type (Fig. 6A–D). In general, the best-supported ecoregion-specific models used the same predictor variables as the models with all sites included, with 3 exceptions (Table 5). In the Eastern Corn Belt Plains, the best-supported model for catchment area of ephemeral flow origins also included road density (catchment area increased with road density). For the Interior Plateau, the best-supported model for catchment area of perennial flow origins included relief ratio and road density rather than relief ratio and % forest cover (catchment area decreased with road density) (Table 5).

TABLE 1. Summary statistics for ephemeral, intermittent, and perennial flow origins and comparison between Eastern Corn Belt Plains and Interior Plateau ecoregions (2-tailed t-test, assuming unequal variances).

Origin type	Area[a] (ha)	Relief ratio[a] (m/km^2)	Elevation (m)	Soil depth (cm)	Road density[a] (m/km^2)	Sewer density[a] (m/km^2)	Septic density[a] (no./km^2)	% forest[b]	% agriculture[b]	% urban[b]	% impervious[b]
Ephemeral											
All sites (n = 122)											
Mean	2.55	1876	232	188	5464	6969	52	36.9	9.0	51.8	12.8
Median	1.14	1231	235	199	2271	0	0	14.2	0.0	62.9	5.8
SE	0.40	187	3	4	706	1204	13	3.7	2.2	3.9	1.5
Eastern Corn Belt Plains (n = 38)											
Mean	4.49	895	221	200	6060	12,188	21	24.8	7.4	65.8	16.8
SE	0.93	180	5	7	903	2496	13	5.7	3.6	6.5	2.9
Interior Plateau (n = 84)											
Mean	1.67	2319	237	182	5194	4608	67	42.3	9.7	45.4	11
SE	0.36	244	3	5	942	1264	18	4.6	2.7	4.8	1.7
Ecoregion comparison											
t	5.52	−5.35	−2.84	2.08	3.49	4.33	−1.31	−2.35	−0.54	2.58	2.07
p	<0.001	<0.001	0.006	0.041	0.001	<0.001	0.193	0.021	0.590	0.012	0.042
Intermittent											
All sites (n = 74)											
Mean	5.23	867	230	40	5875	9071	56	32.2	9.6	56.8	14.3
Median	3.29	645	244	40	5296	0	0	16.4	0.0	61.6	8.0
SE	0.69	94	4	1	585	1684	12	4.0	2.6	4.4	1.8
Eastern Corn Belt Plains (n = 30)											
Mean	7.69	597	229	42	6669	15,140	15	18.1	13.3	67.6	18.3
SE	1.49	135	6	1	931	3281	11	5.0	5.0	6.8	2.8
Interior Plateau (n = 44)											
Mean	3.55	1051	231	38	5333	4934	85	41.8	7.1	49.5	11.5
SE	0.40	122	4	1	750	1472	18	5.5	2.7	5.6	2.3
Ecoregion comparison											
t	2.57	−4.19	−0.35	2.18	1.17	2.78	−3.91	−3.26	1.04	2.10	1.99
p	0.013	<0.001	0.725	0.033	0.246	0.007	<0.001	0.002	0.303	0.040	0.051
Perennial											
All sites (n = 45)											
Mean	28.39	355	219	179	4937	10,164	38	31.5	9.0	57.9	13.5
Median	11.77	242	219	186	4658	2594	2	22.6	0.0	66.7	10.2
SE	4.89	75	4	7	525	1965	11	4.2	2.8	4.9	1.3
Eastern Corn Belt Plains (n = 28)											
Mean	32.94	271	225	197	5713	13,363	13	21.8	9.4	67.5	16.6
SE	7.04	53	5	9	708	2764	7	4.8	3.9	5.7	3.0
Interior Plateau (n = 17)											
Mean	20.90	493	208	149	3659	4896	79	47.5	8.3	42.0	8.4
SE	5.52	177	8	10	673	2020	25	6.3	4.1	7.9	1.7
Ecoregion comparison											
t	0.45	−2.68	1.77	3.63	0.75	2.41	−4.30	−3.40	0.01	2.70	2.36
p	0.652	0.010	0.087	0.001	0.459	0.022	<0.001	0.002	0.995	0.011	0.023

[a] log(x)-transformed for analysis
[b] arcsine($\sqrt{[x]}$)-transformed for analysis

TABLE 2. Stream network lengths for Hamilton County, Ohio, based on publically available Geographical Information System (GIS) data sources and median catchment area for ephemeral, intermittent, and perennial flow origins from field data collected in our study. USGS = US Geological Survey, NHD = National Hydrography Dataset, DEM = digital elevation model, FAC = flow accumulation coefficient, ArcHydro® = tools in ArcGIS software.

Source	Description	Total length (km)	Ephemeral length (km)	Intermittent length km)	Perennial length (km)
USGS NHD	Based on 1:100,000-scale map	1052	–	–	–
USGS topographic maps	Blue lines on 1:24,000-scale map	1575	–	977	598
Cincinnati Area GIS	Created from 0.61-m DEM with hand edits	4368	–	–	–
Ephemeral, intermittent, and perennial	Created in ArcHydro®; FAC = 143	7062	2952	–	–
Intermittent and perennial only	Created in ArcHydro®, FAC = 385	4110	–	1860	–
Perennial only	Created in ArcHydro®; FAC = 1429	2250	–	–	2250

Discussion

Mapping headwater streams

Commonly used stream maps greatly underestimate actual stream length (Mueller 1979, Meyer and Wallace 2001). Inaccuracies are biased toward under-representation of the smallest, intermittently flowing headwater streams. In our study (in the eastern US), 1:100,000-scale maps identified only ½ of perennial channel length, and ~1/7th of the total channel length, whereas 1:24,000-scale maps identified 22% of the total channel length. These underestimations are comparable to those reported for a field assessment in the Chattooga River watershed in the Blue Ridge Mountains of Georgia, South Carolina, and North Carolina (Hansen 2001). However, Colson et al. (2008) found that accuracy of maps can vary by ecoregion. USGS 1:24,000-scale maps underestimated stream length in the Southwestern Mountain ecoregion of North Carolina by 54% and overestimated stream length in the Coastal Plain ecoregion by 31% (Colson et al. 2008). This difference could be caused by higher drainage densities in mountains than in lower elevations, or cartographic guidelines that require minimum lengths and distances from ridges before identifying streams (Drummond 1974, Colson et al. 2008). The substantial underestimation of streams based on nationally available maps can lead to inaccurate scientific understanding of ecosystem processes. For example, riparian buffers calculated

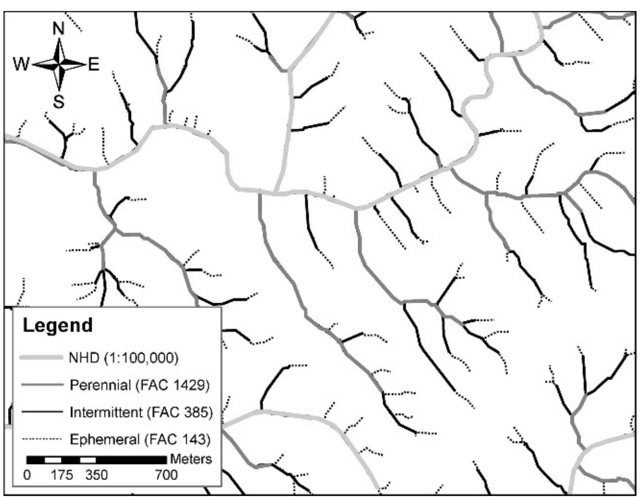

FIG. 2. Stream networks in a representative section of Hamilton County, Ohio, based on the US Geological Survey National Hydrography Dataset (NHD, 1:100,000 scale) and extended networks created in ArcHydro® using flow accumulation coefficients (FAC) corresponding to the median catchment area (ha) of ephemeral, intermittent, and perennial flow origins based on field surveys.

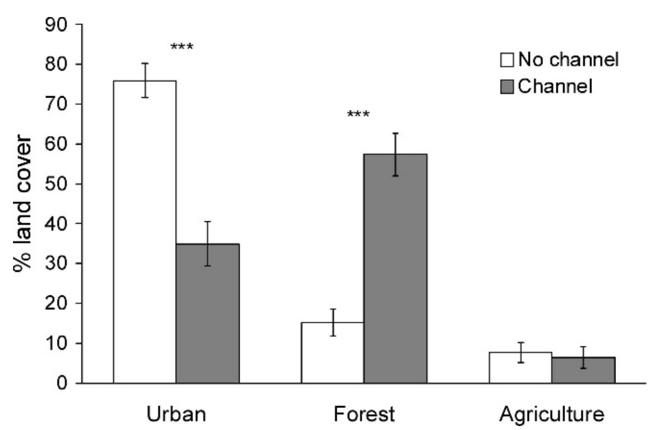

FIG. 3. Mean (±1 SE) % urban, forest, and agriculture land cover in a 100-m buffer around randomly selected channel origins within Hamilton County based on the Cincinnati Area Geographic Information System (CAGIS) map. *** = $p < 0.001$ (2-tailed t-test, assuming unequal variances).

TABLE 3. Comparison of mean catchment areas draining to ephemeral, intermittent, and perennial flow origins between forested and urban catchments (2-tailed *t*-test assuming unequal variances). Flow accumulation coefficients (FAC) were calculated from catchment areas based on a formula (see text) and were used to generate county-level stream networks using ArcHydro® tools in ArcGIS. Stream network length includes the entire network below flow origins; i.e., the length indicated under ephemeral includes ephemeral, intermittent, and perennial streams, and the length under intermittent includes intermittent and perennial streams. Drainage density (Dd) was calculated based on stream lengths and total area for Hamilton County, Ohio.

Flow origin	*n*	FAC	Length (km)	Dd (km/km^2)	Area (ha)	SE	*t*	*p*
Ephemeral								
100% forest	22	62	10,006	9.36	0.66	0.20	−3.68	0.001
100% urban	26	613	3310	3.10	5.13	1.20		
Intermittent								
100% forest	8	424	3923	3.67	3.60	1.09	−1.53	0.140
100% urban	18	817	2907	2.72	6.79	1.78		
Perennial								
>75% forest	6	5898	1175	1.10	48.12	19.30	0.81	0.445
>75% urban	19	3820	1435	1.34	31.22	7.97		

from coarse-scale maps overestimated buffer prevalence and led to artificially high estimates of watershed-scale nutrient retention potential (Baker et al. 2007). In regions where headwater streams have retained their forested buffers, coarse-scale maps could underestimate riparian buffers. Accurate delineation of stream networks also is a critical first step for identifying anthropogenic impacts within catchments and developing watershed management plans that protect headwater streams and, thus, downstream ecosystems.

We used catchment area and corresponding DEM-derived FACs to estimate channel length and to indicate relative locations of origins and channels in the landscape. Thus, our method depended on our ability to predict catchment area. Relief ratio can accurately predict catchment areas of ephemeral, intermittent, and perennial flow origins. Other researchers have reported strong relationships between local slope or valley gradient, which are comparable to relief ratio, and catchments areas of channel origins (Montgomery and Dietrich 1989, Tucker and Bras 1998, Vogt et al. 2003, Colombo et al. 2007; but see Jaeger et al. 2007). These results suggest that DEMs can be effective tools for mapping stream networks. In our study, soil depth also was included in the best-supported models for catchment areas of ephemeral and intermittent flow origins, a result suggesting that interflow might be critical for maintaining stream flows. These 2 geographic variables are easily obtained from topographic and soil maps and predicted 71 to 77% of the variation in catchment area for channel origins. Our predictive models were relatively strong, but we emphasize that channel and flow origins were highly variable across sites (even in natural settings) because locations of origins are related to local headcuts, bedrock, springs, and other site-specific variables (Adams and Spotila 2005). Thus, precise locations of origins are not likely to be mapped accurately and consistently from regional landscape variables. However, locations of origins might be easily and more accurately predicted in some regions, such as areas strongly influenced by groundwater.

With the exception of forest cover, few of the variables describing anthropogenic disturbance were included in the best supported models explaining catchment areas of origins. General indicators of urban anthropogenic disturbance (e.g., % urban land cover, % impervious surface area) encompass factors that could increase (e.g., via landscape irrigation) or decrease (e.g., via reduced infiltration) base flows. These opposing effects might prevent variables indicating urban disturbance from predicting catchment areas of origins. Sanitary sewer lines commonly are positioned near headwater channels and have the potential to infiltrate local soil water or exfiltrate wastewater, potentially confounding our ability to detect a consistent pipe effect across all streams. Depending on the location of pipe outlets relative to flow origins, storm sewers could increase (if upstream) or decrease (if downstream) flow in channels. Septic tanks, which are likely only to increase water supply to headwater streams, were not included in the best supported models. The only urban disturbance variable included in the best supported models was road density, which was positively related to catchment area of ephemeral channels and reflected burial or piping of channels in areas with many roads. Road density was inversely related to catchment area

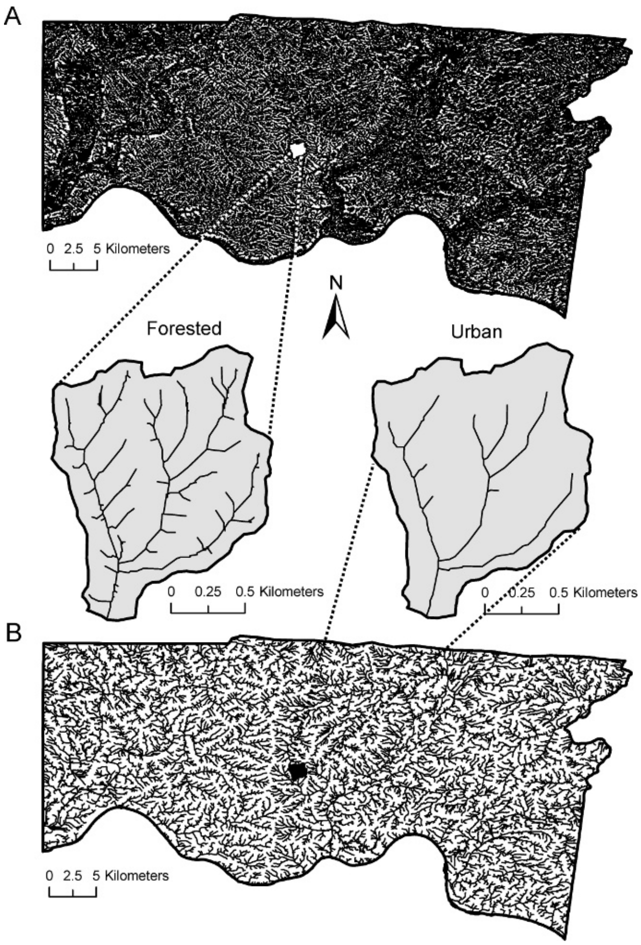

FIG. 4. Stream networks in a small (1.9 km^2) catchment in Hamilton County, Ohio, modeled in ArcHydro® with flow accumulation coefficients (FAC) corresponding to the mean catchment area for forested (FAC = 62, n = 22) (A) and urban (FAC = 613, n = 26) (B) catchments. The forested map portrays ephemeral, intermittent, and perennial stream channels with minimal human influence.

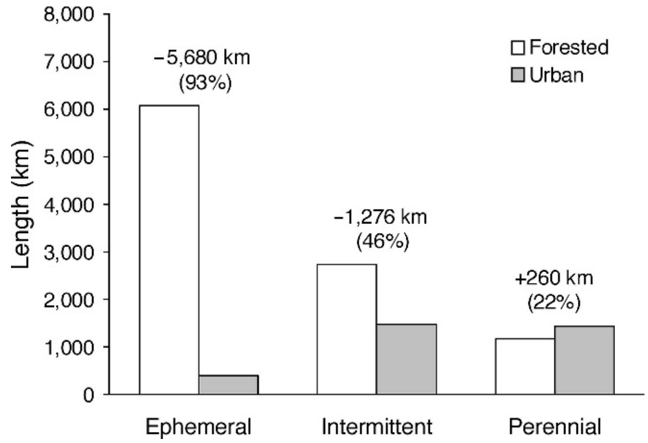

FIG. 5. Total ephemeral, intermittent, and perennial channel length within Hamilton County, Ohio, based on modeled stream networks corresponding to mean flow accumulation coefficients (FAC) for forested vs urban catchments. Numbers above bars indicate the absolute and % difference in channel length in forested and urban catchments.

of perennial channels in the Interior Plateau. This relationship might reflect a sustained water supply from gullies adjacent to roads. Despite regulations, individual landowners decide whether to fill, pipe, dredge, channelize, impound, or otherwise alter stream channels. In areas where most property is privately owned (as in this study), these personal decisions probably are an important source of variability of stream burial in urban environments and decrease our ability to predict catchment area based on anthropogenic disturbance variables. In catchments with relatively uniform, publicly operated water infrastructure, relationships between anthropogenic disturbance variables and catchment area might be stronger.

We used DEMs (10-m resolution) to generate stream lines. DEM-derived stream networks are likely to be more accurate than other national stream network sources, such as USGS NHD and topographic maps (depending on map scale), but DEMs also have potential inaccuracies. Advanced Light Detection and Ranging (LiDAR) technology probably would have provided a more accurate account of ground elevation than DEMs and, consequently, improved our ability to generate stream network maps. However, elevation maps based on 10-m DEMs and LiDAR are comparable except where little topographic relief exists in the Coastal Plain (Colson et al. 2006). Depending on the source and year of the data, DEMs might not reflect recent landscape transformations associated with urbanization, which can occur quickly and can drastically change valley slopes. Even when streams are buried or the landscape is recontoured to route water to detention basins, new stream channels (especially ephemeral channels) are likely to be carved into the landscape. Thus, stream maps created from DEMs should not be seen as static, but rather should be continuously updated with the most recent and accurate GIS data.

Given the variability in locations of channel and flow origins observed in our study, we think that field surveys are necessary to produce accurate maps of ephemeral, intermittent, and perennial stream networks. Field surveys are particularly important in catchments where researchers want to understand processes, such as nutrient or sediment dynamics, occurring downstream that might depend on up-

TABLE 4. Comparison of catchment area and channel cross-sectional area at channel and ephemeral, intermittent, and perennial flow origins with and without pipes (2-tailed t-test assuming unequal variances). Entrenchment ratio is flood-prone width (width at 2× bankfull height) divided by bankfull width. Entrenchment ratios were limited to ≤2.2. na = not applicable.

	With pipe(s)		Without pipe(s)			
Origin type/variable	Mean	SE	Mean	SE	t	p
Channel						
No. sites	41		107			
Pipe area (m^2)	0.20	0.04	na	na		
Catchment area (ha)	3.37	0.54	3.04	0.54	0.434	0.665
Ephemeral						
No. sites	24		98			
Pipe area (m^2)	0.14	0.03	na	na		
Catchment area (ha)	2.56	0.65	2.54	0.47	0.022	0.983
Intermittent						
No. sites	22		52			
Pipe area (m^2)	0.27	0.06	na	na		
Catchment area (ha)	5.21	1.39	5.24	0.79	−0.020	0.984
Bankfull width:depth ratio	8.08	0.90	8.07	0.65	0.009	0.993
Entrenchment ratio	1.64	0.10	1.57	0.06	0.663	0.513
Perennial						
No. sites	18		27			
Pipe area (m^2)	1.10	0.24	na	na		
Catchment area (ha)	31.60	8.19	26.25	6.13	0.522	0.605
Bankfull width:depth ratio	7.63	0.84	8.18	0.83	−0.462	0.649
Entrenchment ratio	1.58	0.10	1.79	0.08	−1.586	0.123

stream drainage density, connectivity, and flow. For particularly large catchments, researchers could consider mapping streams initially based on empirical formulas (e.g., from our study for eastern US streams) and conducting field surveys to adjust actual locations.

Field-survey methods come with caveats. First, observations of hydrologic permanence are highly dependent on season and precipitation. We avoided sampling immediately after large rain events, but the amount of rain, time since rainfall, level of ground saturation, and depth of the water table all affect whether and for how long a particular stream reach is flowing after a storm (Hunter et al. 2005). In addition, interannual differences in climate will affect mapping results (see Paybins 2003). Our study was conducted in a year with slightly higher than average rainfall (125 cm) for the years 2000 to 2007 for the study region (average 120 cm; National Oceanic and Atmospheric Administration National Climatic Data Center, Cheviot, Ohio). Consequently, the 2 observations in 2006 correctly classified 3 of the 4 intermittent reaches and all 3 perennial reaches according to data collected on 7 streams over 6 y. However, had our study been in summer 2007, a drier year (104 cm rainfall), many of the perennial streams would have been considered intermittent (HRL, unpublished data). An alternative to point surveys is long-term, continuous monitoring of the presence and duration of flow (as done by Svec et al. 2005), which should accurately determine hydrologic permanence of headwater streams and eliminate some of the problems of intra- and interannual variability. However, gauges placed at single points in a catchment cannot capture longitudinal differences in permanence within stream networks. Geomorphic and biological indicators also could be used as surrogate measures of hydrologic permanence. For example, the North Carolina Division of Water Quality assigns point values to geomorphic, hydrologic, and biologic characteristics of the stream reach to classify streams as intermittent and perennial (NCDWQ 2005). However, these alternatives are more time-consuming and expensive than the approach we used, and these problems minimize their usefulness for large geographic areas. Last, our methods did not account for situations in which long sections of channel downstream of flowing reaches are dry (i.e., discontinuous or interrupted surface flow). In a temporal assessment of flow in headwater streams, Hunter et al. (2005) found no predictable pattern of longitudinal drying along a stream reach. Instead, dry-season recession typically was characterized by a transition from long segments of surface flow to short segments of dry

TABLE 5. Best-supported linear regression models predicting log(x)-transformed catchment area for channel origins, and ephemeral, intermittent, and perennial flow origins after model comparisons with Akaike's Information Criterion. Adjusted r^2 values (bold) are reported for whole models. Relief ratio and road density were log(x)-transformed; % forest land cover (% forest) was arcsine($\sqrt{[x]}$)-transformed.

All sites			Eastern Corn Belt Plains			Interior Plateau		
Variable	Estimate	r^2	Variable	Estimate	r^2	Variable	Estimate	r^2
Channel								
Model (n = 148)		**0.77**	Model (n = 54)		**0.71**	Model (n = 94)		**0.75**
Intercept	7.651		Intercept	7.147		Intercept	8.051	
Relief ratio	−1.044	0.74	Relief ratio	−0.826	0.65	Relief ratio	−1.199	0.73
Soil depth	−0.002	0.03	Soil depth	−0.003	0.07	Soil depth	−0.002	0.02
Ephemeral								
Model (n = 121)		**0.77**	Model (n = 38)		**0.80**	Model (n = 83)		**0.74**
Intercept	7.634		Intercept	7.125		Intercept	7.910	
Relief ratio	−1.026	0.73	Relief ratio	−0.736	0.67	Relief ratio	−1.153	0.72
Soil depth	−0.003	0.04	Soil depth	−0.005	0.11	Soil depth	−0.002	0.02
			Road density	0.067	0.04			
Intermittent								
Model (n = 74)		**0.72**	Model (n = 30)		**0.74**	Model (n = 44)		**0.70**
Intercept	7.899		Intercept	7.480		Intercept	9.143	
Relief ratio	−0.805	0.59	Relief ratio	−0.741	0.60	Relief ratio	−1.190	0.56
Soil depth	−0.003	0.11	Soil depth	−0.005	0.15	Soil depth	−0.002	0.09
Elevation	−0.003	0.03				Elevation	−0.004	0.07
Perennial								
Model (n = 45)		**0.84**	Model (n = 28)		**0.84**	Model (n = 17)		**0.89**
Intercept	7.156		Intercept	7.113		Intercept	9.414	
Relief ratio	−1.002	0.71	Relief ratio	−0.999	0.75	Relief ratio	−1.502	0.83
% forest	0.572	0.13	% forest	0.580	0.11	Road density	−0.158	0.07

areas with scattered pools. Despite these caveats, the random sampling and methods of on-the-ground observation used in our study were cost-effective, enabled us to gather data efficiently over a wide area, and allowed us to estimate the locations of ephemeral, intermittent, and perennial streams. However, the methods should be tested elsewhere to determine their appropriateness and to test the generality of the predictive models in other regions of the world.

Urbanization effects on headwater stream length

Catchment areas of ephemeral and intermittent channel origins were larger in urban than in forested areas. We estimate that urban areas have lost 93% of historical ephemeral channel length and 46% of historical intermittent channel length (Fig. 7). These estimates might be slightly high because most forested catchments in Hamilton County were logged (Bryant and Held 2004), and logging can cause headcut migration up tributaries and increase channel length in forested catchments relative to unlogged natural conditions (Schumm 1999). The differences in area between urban and forested catchments might have arisen because developments typically occur on flatter landscapes, which have naturally larger catchments. However, the correlation between relief ratio and urban land cover was weak ($r = -0.33$, $n = 240$). The loss of ephemeral and intermittent stream length also might be a consequence of increased flow in urban areas. For example, naturally ephemeral or intermittent streams could become perennial if flow increased. However, our study was not designed to distinguish among the causes of reductions of channel length, and hydrologic monitoring would be necessary to understand changes in baseflow hydrology with urbanization.

Catchment area of perennial channels was smaller in urban than in forested areas, despite the fact that the remaining forests in Hamilton County are on steep slopes where catchments are small. We estimate that urban areas gained 22% of perennial channel length relative to historical perennial channel length, a result suggesting that some naturally intermittent streams had been converted to perennial streams (Fig. 7). Our predictive models indicate that the increase in perennial channel length in urban catchments is related to deforestation. In the eastern US,

TABLE 6. Linear regression models predicting catchment area for channel and ephemeral, intermittent, and perennial flow origins. Models were compared using Akaike's Information Criterion for small sample size (AIC_c). Akaike weights (w_i) indicate the relative support for each model type. Asterisks indicate the best model for each stream type ($\Delta AIC_c = 0$), and bold indicates equally plausible models ($\Delta AIC_c \leq 2$). k is the number of parameters, including the intercept and residual variance. Relief = relief ratio, soil = soil depth, road = road density, sewer = sewer density, septic = septic density, urban = % urban land cover, agriculture = % agricultural land cover, forest = % forest land cover.

Model	k	Channel			Ephemeral			Intermittent			Perennial		
		Adj r^2	ΔAIC_c	w_i	Adj r^2	ΔAIC_c	w_i	Adj r^2	ΔAIC_c	w_i	Adj r^2	ΔAIC_c	w_i
Relief	3	0.74	6.2	0.01	0.73	7.0	0.01	0.59	9.3	0.00	0.70	9.8	0.00
Relief + elevation	4	0.75	6.3	0.01	0.73	8.0	0.00	0.65	5.7	0.02	0.75	8.5	0.00
Relief + elevation + soil	5	0.77	1.4	**0.10**	0.77	2.0	**0.07**	0.72	0.0	**0.28***	0.76	9.5	0.00
Relief + elevation + forest	5	0.75	8.2	0.00	0.73	10.1	0.00	0.66	6.2	0.01	0.83	2.5	0.08
Relief + elevation + road	5	0.75	8.1	0.00	0.73	10.2	0.00	0.64	8.0	0.01	0.74	11.0	0.00
Relief + elevation + sewer	5	0.75	6.7	0.01	0.74	8.3	0.00	0.65	7.7	0.01	0.74	11.0	0.00
Relief + elevation + septic	5	0.75	8.4	0.00	0.73	9.6	0.00	0.65	8.0	0.01	0.78	8.2	0.00
Relief + elevation + urban	5	0.75	7.5	0.00	0.74	9.3	0.00	0.65	7.5	0.01	0.77	8.7	0.00
Relief + elevation + agriculture	5	0.75	8.4	0.00	0.73	10.0	0.00	0.65	7.6	0.01	0.76	9.3	0.00
Relief + elevation + impervious	5	0.76	6.0	0.01	0.75	7.0	0.01	0.64	8.0	0.01	0.75	10.2	0.00
Relief + soil	4	0.77	0.0	**0.20***	0.77	0.0	**0.19***	0.69	1.7	**0.12**	0.70	12.2	0.00
Relief + soil + forest	5	0.77	2.1	0.07	0.77	2.2	0.06	0.71	1.2	**0.16**	0.84	1.7	**0.11**
Relief + soil + road	5	0.77	1.0	**0.12**	0.77	1.8	**0.08**	0.69	3.7	0.05	0.72	12.7	0.00
Relief + soil + sewer	5	0.77	1.0	**0.12**	0.78	0.5	**0.15**	0.69	3.5	0.05	0.72	12.9	0.00
Relief + soil + septic	5	0.77	2.1	0.07	0.77	1.6	**0.09**	0.69	3.4	0.05	0.74	11.4	0.00
Relief + soil + urban	5	0.77	2.0	0.07	0.77	1.8	**0.08**	0.70	2.5	0.08	0.78	7.8	0.01
Relief + soil + agriculture	5	0.77	2.1	0.07	0.77	2.0	0.07	0.69	3.8	0.04	0.71	13.4	0.00
Relief + soil + impervious	5	0.77	1.4	**0.10**	0.78	0.4	**0.16**	0.69	3.7	0.05	0.77	8.6	0.00
Relief + forest	4	0.74	8.3	0.00	0.73	9.1	0.00	0.64	6.2	0.01	0.84	0.0	**0.26***
Relief + forest + road	5	0.74	10.3	0.00	0.72	11.3	0.00	0.64	8.5	0.00	0.83	2.5	0.07
Relief + forest + sewer	5	0.75	8.8	0.00	0.74	9.3	0.00	0.65	7.7	0.01	0.83	2.5	0.07
Relief + forest + septic	5	0.74	10.4	0.00	0.73	10.6	0.00	0.64	8.5	0.00	0.84	1.8	**0.10**
Relief + forest + urban	5	0.74	10.0	0.00	0.73	10.2	0.00	0.64	8.5	0.00	0.84	2.3	0.08
Relief + forest + agriculture	5	0.74	10.4	0.00	0.73	11.2	0.00	0.64	8.5	0.00	0.84	2.2	0.09
Relief + forest + impervious	5	0.75	7.8	0.00	0.75	6.8	0.01	0.65	7.3	0.01	0.84	2.2	0.09
Relief + road	4	0.74	8.2	0.00	0.73	9.1	0.00	0.59	10.7	0.00	0.70	12.2	0.00
Relief + sewer	4	0.75	6.8	0.01	0.74	7.2	0.01	0.58	11.5	0.00	0.71	11.5	0.00
Relief + septic	4	0.74	8.3	0.00	0.73	8.4	0.00	0.58	11.3	0.00	0.73	9.7	0.00
Relief + urban	4	0.74	8.1	0.00	0.73	8.8	0.00	0.62	8.3	0.00	0.77	6.4	0.01
Relief + agriculture	4	0.74	8.3	0.00	0.73	9.0	0.00	0.58	11.5	0.00	0.70	12.0	0.00
Relief + impervious	4	0.75	6.9	0.01	0.74	6.9	0.01	0.59	10.8	0.00	0.73	9.7	0.00

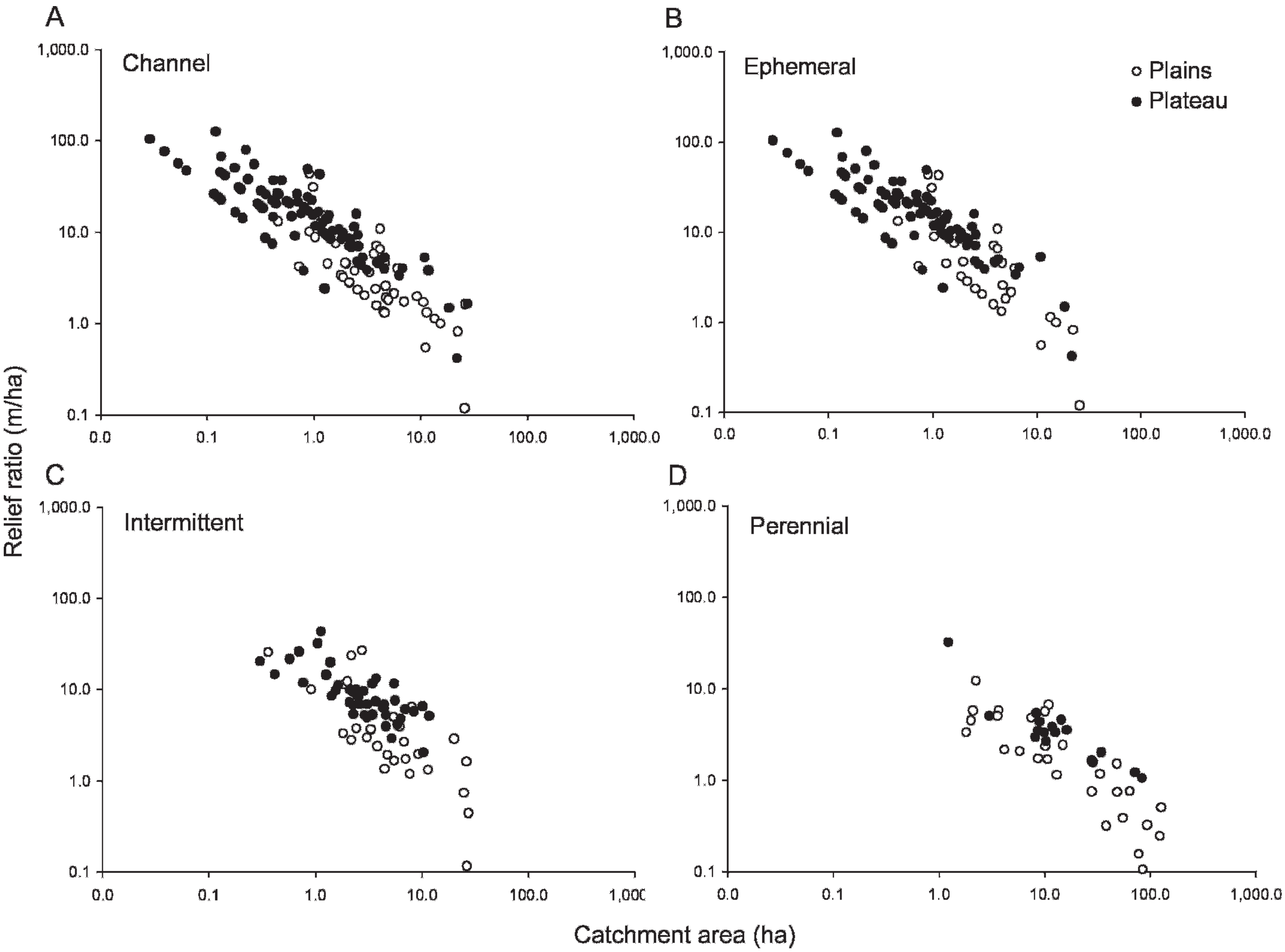

FIG. 6. Scatter plots between catchment area and relief ratio for channel (A), and ephemeral (B), intermittent (C), and perennial (D) flow origins in Eastern Corn Belt Plains and Interior Plateau Omernik Type III ecoregions.

deforestation increased water yield (i.e., surface-water discharge) because of decreased evapotranspiration (Hewlett and Hibbert 1961, Bosch and Hewlett 1982, Sun et al. 2005). Increased water yield in urban catchments might explain why perennial channels have smaller catchments in urban than in forested landscapes. Alternatively, urban and forested land cover are strongly negatively correlated ($r = -0.83$, $n = 240$) in Hamilton County, and more urban land cover (rather than less forest land cover) could have contributed to increased flows in urban catchments. However, the likely sources of increased flows in urban catchments (e.g., leaky sewers, septic tanks; Lerner 2002) did not improve the ability of our models to predict catchment area of perennial flow origins in urban catchments.

The increased perennial channel length in urban catchments does not indicate that perennial streams were not piped. In fact, 18 of the 64 channel origins with pipes had perennial flow, and 40% of perennial flow origins were in pipes. Thus, piping of perennial streams was widespread in urban catchments. Moreover, we did not account for the many streams (perennial and otherwise) in downtown Cincinnati that have been converted to sewer lines. Multiple mechanisms affect the length of perennial channel in urban areas, including piping of channels and conversion of ephemeral and intermittent channels to perennial channels.

Regulatory implications in the US

Our study highlights the inaccuracies of existing stream maps and the risks of using USGS NHD or 1:24,000-scale topographic maps as a basis for stream regulation and landuse planning. USGS topographic maps typically are used as a source when defining regulatory boundaries, such as riparian buffer re-

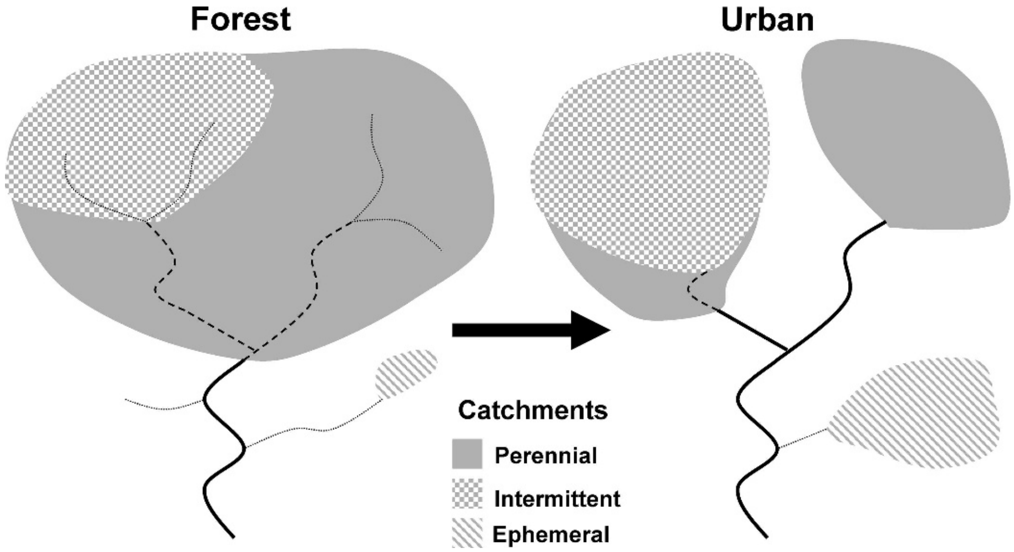

FIG. 7. Conceptual representation of study results. Urbanization results in a loss of ephemeral (dotted lines) and intermittent (dashed lines) stream length through channel burial/piping, as indicated by larger drainage areas. Perennial catchments are smaller in nonforested areas, associated with an increase in channel length (solid lines) resulting from reduced evapotranspiration.

quirements (Russell 2008) and forestry best-management practices (Svec et al. 2005). Thus, regulations are not likely to provide any protection for ephemeral and intermittent streams, and insufficiently protect perennial streams. To our knowledge, North Carolina was the first state to have developed field protocols for mapping headwater streams. The new, field-based maps have been used for stream regulation in North Carolina and for jurisdictional determinations in other states (Russell 2008). Regulations frequently are based on estimated catchment area for intermittent (e.g., 4.9 ha, West Virginia permitted valley fills; Paybins 2003) or perennial (e.g., 5.3 ha, Washington State forest practices; Jaeger et al. 2007) streams. However, differences in catchment area associated with different types of flow origin mean that use of any standardized area as a cutoff is likely to result in incomplete protection of headwater streams. Regardless of the method used to map streams, the smallest headwater streams must be included in planning and management plans to ensure comprehensive stream protection.

Our results also have implications for federal regulations pertaining to stream protection. The larger catchment areas for ephemeral and intermittent channels in urban landscapes might indicate that small streams have been piped and filled, perhaps because of misperception of these temporary waters as valueless ecosystems and minimal legal protection. In the US, the Army Corps of Engineers (USACE) oversees permits for discharge of dredge or fill material through Section 404(b) of the Clean Water Act (CWA), but permits are required only for "waters of the United States", which might not include ephemeral and intermittent channels. Moreover, nationwide permits allow disturbance of streams if the length of stream or catchment area buried or disturbed is small (e.g., 91 m of stream or 0.2 ha area for residential, commercial, and industrial development), and these limits can be waived for streams classified as intermittent or ephemeral. The jurisdictional authority to protect headwater streams under the CWA has also recently come under scrutiny in the US Supreme Court in *Rapanos* (consolidated *Rapanos v. United States* and *Carabell v. United States*, 126 S. Ct. 2008; Nadeau and Rains 2007, Leibowitz et al. 2008). Following the split decision in *Rapanos*, the US Environmental Protection Agency (EPA) and US Army Corps of Engineers (ACE) issued a joint memorandum describing how "waters of the United States" will be assessed for inclusion under the CWA (USEPA and USACE 2007). In accordance to Justice Scalia's opinion, the agencies state that surface water connection (i.e., perennial flow) warrants protection under the CWA. Based on the increase in perennial channel length with urbanization, more stream length is likely to be covered by this criterion in urban areas than before. Nonetheless, the requirement for perennial flow would leave many streams unprotected in US arid zones where many large rivers are intermittent (Nadeau and Rains 2007). A "significant nexus" to waters of the US is an alternate criterion for protection based on Justice Kennedy's opinion. However, it is not clear what data will be required for determining this connection (Leibowitz et al. 2008). The lack of criteria for determining a significant nexus is likely to lead to inconsistent protection, at best, and, at worst, a tendency for managers to ignore disturbances in temporary waters.

Ecological implications

Changes in the hydrologic permanence of streams can greatly affect stream communities and ecosystem functioning. Decreased flow caused by reduced infiltration in urbanized catchments can result in a loss of habitat for plants and animals that require water for all or part of their life cycle (Freeman et al. 2007, Meyer et al. 2007). The pools that remain are likely to support fewer taxa (Boulton and Hancock 2006), partially because of increased competition and predation in an unnaturally restricted habitat (Power et al. 1988). Increased flow (i.e., making streams more perennial) might increase habitat for some organisms and could lead to additional processing of nutrients and C (Richardson 1990, Stanley et al. 2004, Chadwick and Huryn 2005), but would negatively affect organisms that rely on temporary habitats for protection from fish and other predators. For example, perennial streams are more likely to harbor fish that can reduce the abundance of predatory invertebrates and salamanders, which are typical top predators in intermittent streams (Wilkins and Peterson 2000, Meyer et al. 2007). Wigington et al. (2006) reported that juvenile coho salmon are common in intermittent reaches, and overwintering smolts were larger than those from perennial reaches. The cumulative loss of ephemeral and intermittent streams also could negatively affect population recovery dynamics via reduced potential for recolonization (Fritz and Dodds 2004, Meyer et al. 2007). Last, urbanization might alter the variability of base flows, which could negatively affect organisms that require a certain number of continuously wet days (e.g., for breeding) or wet days during certain seasons (e.g., for nursery ground; Boulton and Hancock 2006). However, flow in temporary streams is stochastic by nature, and many organisms in these streams are adapted to drying and might be able to adjust to altered flow regimes (Lytle and Poff 2004, Boulton and Hancock 2006). Several studies have examined effects of drying on stream ecosystems, but most such studies addressed large droughts or were in areas where organisms are adapted to intermittent flow regimes (e.g., Lytle and Poff 2004). More research is needed on the effects of urban-induced hydrologic alteration on ecosystem processing and the ability of intermittent stream biota to adapt to altered timing, frequency, and duration of drying.

In urban streams, the challenge will be to isolate the effects of hydrologic permanence from the myriad of other urban impacts. We also need to understand better the cumulative effects of stream burial on downstream ecosystems. Some estimates of altered ecosystem processing with stream channel loss have been made using data in small streams (Meyer and Wallace 2001, Freeman et al. 2007). However, to our knowledge, no studies have assessed communities and ecosystem functions in water bodies receiving urban headwaters with and without piping. An understanding of the locations of headwater streams in the landscape is critical as scientists work to determine indicators of hydrologic permanence (e.g., Fritz et al. 2008) and the cumulative effects of headwater stream loss on downstream waters.

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