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ASSESSING IMPERVIOUS SURFACE CONNECTIVITY AND APPLICATIONS FOR WATERSHED MANAGEMENT[1]

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ABSTRACT: Although total impervious area (TIA) is often used as an indicator of urban disturbance, recent studies suggest that the subset of impervious surfaces that route stormwater runoff directly to streams via stormwater pipes, called directly connected impervious area (DCIA), may be a better predictor of stream ecosystem alteration. We evaluated the differences between TIA and DCIA in the Shepherd Creek catchment, a small (1.85-km^2), suburban basin in Cincinnati, Ohio. Imperviousness determinations were calculated based on publicly available geographic information system (GIS) data and parcel-scale field assessments, and these direct assessments were compared to DCIA calculated from published, empirical relationships. Impervious and semi-impervious area comprised 13.1% of the catchment area, with 56.3% of the impervious area connected. When summarized by subcatchments (0.26-1.85 km^2), TIA measured in the field (11-23%) was considerably higher than that calculated from the National Land Cover Data Imperviousness Layer (7-18%). In contrast, TIA calculated based on aerial photos was similar to TIA calculated from field assessments, thus indicating that photo interpretation may be adequate for catchment-scale (>25 ha) TIA determinations. While these GIS data sources can be used to calculate TIA, on-site assessments were necessary to accurately determine DCIA within residential parcels. There was a wide variation in percent connectivity across parcels, and, subsequently, DCIA was not accurately predicted from empirical relationships with TIA. We discuss applications of DCIA data that highlight the importance of parcel-scale field assessments for managing suburban watersheds.

(KEY TERMS: impervious surfaces; directly connected impervious area; disconnected impervious area; effective impervious area; stormwater management; watershed management; rivers/streams; urban areas.)

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INTRODUCTION

Urban and suburban landscapes are characterized by relatively high amounts of total impervious area (TIA), resulting in lower potential for infiltration, higher surface runoff, and reduced ground-water recharge compared to forested areas (Arnold and Gibbons, 1996; Konrad and Booth, 2005). Increased TIA in the landscape translates to altered storm-flow and base-flow hydrology in streams. For example, studies have demonstrated a reduced lag time among the initiation of precipitation and peak storm flow, increased peak discharge, and increased rise and fall

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rates or "flashiness" (Arnold and Gibbons, 1996; Paul and Meyer, 2001; Konrad and Booth, 2005). Base-flow responses to urbanization are more variable, as TIA can lead to reduced base flows from higher surface drainage and lower water tables, or increased base flows from imported water for landscape irrigation and septic tanks (Brandes *et al.*, 2005; Konrad and Booth, 2005). Due to changes in the quantity and quality of flows, catchments with high levels of TIA also exhibit geomorphic (Booth and Jackson, 1997; Bledsoe and Watson, 2001) and biotic alteration compared to vegetated watersheds where infiltration processes predominate (see reviews Schueler, 1994; Paul and Meyer, 2001; Walsh *et al.*, 2005b).

Although TIA has been used as an indicator of urban disturbance, recent studies suggest that the subset of impervious surfaces that route stormwater runoff directly to streams via stormwater pipes, called directly connected impervious area (DCIA) or effective impervious area (hereafter, DCIA), may be responsible for the majority of stream alteration due to urbanization (Booth and Jackson, 1997; Brabec *et al.*, 2002; Walsh, 2004; Walsh *et al.*, 2005a). For example, studies have found DCIA to be highly correlated with aspects of water quality, and algal, macroinvertebrate and fish assemblage integrity (Wang *et al.*, 2001; Hatt *et al.*, 2004; Taylor *et al.*, 2004; Walsh *et al.*, 2004; Newall and Walsh, 2005).

While DCIA may be a better predictor of stream ecosystem health than TIA in urbanizing areas, its determination presents several challenges. Some studies have predicted DCIA based on an empirical relationship with TIA (Alley and Veenhuis, 1983; Wang *et al.*, 2001; Wenger *et al.*, 2008), although the accuracy of such relationships has not been tested in a widespread manner (Brabec *et al.*, 2002). While delineation of DCIA is necessary to verify empirical relationships, very few studies have calculated DCIA independently of TIA (but see Rouge Program Office, 1994; Lee and Heaney, 2003). Independent calculation of DCIA involves overlaying stormwater conveyances on maps of impervious area to determine which impervious areas are connected to storm, sanitary, or combined sewer pipes (Krug and Goddard, 1986; Rouge Program Office, 1994; Walsh *et al.*, 2002). Although the increasing prevalence of digital mapping and more complete geographic information system (GIS) coverage at local and county levels makes this type of data more available than in the past (Brabec *et al.*, 2002), available maps and GIS data typically do not include information about actual runoff routing from impervious surfaces based on specific on-lot drainage patterns (e.g., discharge from roof downspouts, driveway slopes, etc.) (Lee and Heaney, 2003). Therefore, an accurate assessment of DCIA calls for field investigations to identify and verify where pipes are draining (Walsh *et al.*, 2002). Although the level of effort for on-site assessments can be quite high (Lee and Heaney, 2003), field campaigns to determine DCIA may be necessary so as to understand its extent and design optimal approaches to stormwater management.

The setting for this study was the Shepherd Creek catchment, a 1.85-km^2 (457-acre) basin in Cincinnati (Hamilton County), Ohio (Figure 1). The eastern one-third of the catchment lies within a city park with mature deciduous forest. The central and western two-thirds of the catchment represent a mix of residential parcels in the headwaters and horse pastures at downstream locations. The residential area consists primarily of single family homes and has a median lot size of 880 m^2 (0.22 acres). Over three-quarters of the 406 houses in the catchment were built between 1950 and 1990. There are also three apartment complexes (27 buildings) in the headwaters and several public buildings with parking lots (e.g., church, police station, park arboretum). The Shepherd Creek catchment is the focus of a multidisciplinary project investigating the use of economic incentives to install retrofit stormwater best management practices (BMPs) so as to mitigate the effects of excess stormwater runoff on stream hydrology, water quality, and biotic integrity (Roy *et al.*, 2006).

In this study we assess the importance of field-based delineation of impervious surfaces, as applied to the Shepherd Creek catchment. TIA and DCIA were delineated using a combination of GIS data compilation, aerial photo interpretation, and field assessments, and subsequently summarized within parcels (<10 ha) and subcatchments (0.26-1.85 km^2). The objectives of this study were: (1) to evaluate the primary sources of imperviousness and differences between TIA and DCIA data based on land ownership (public *vs.* private) and impervious surface type, and (2) to compare our results among data collected with various levels of effort (GIS only, field assessments, and published empirical formulas). We use these results to determine the best approach and potential for retrofit stormwater management within the catchment, and to discuss the applications of impervious area connectivity data for understanding and restoring stream ecosystems.

METHODS

Initial Geographic Information System Data Compilation

GIS data were acquired through the Cincinnati Area GIS (CAGIS), a city-level repository of geographic

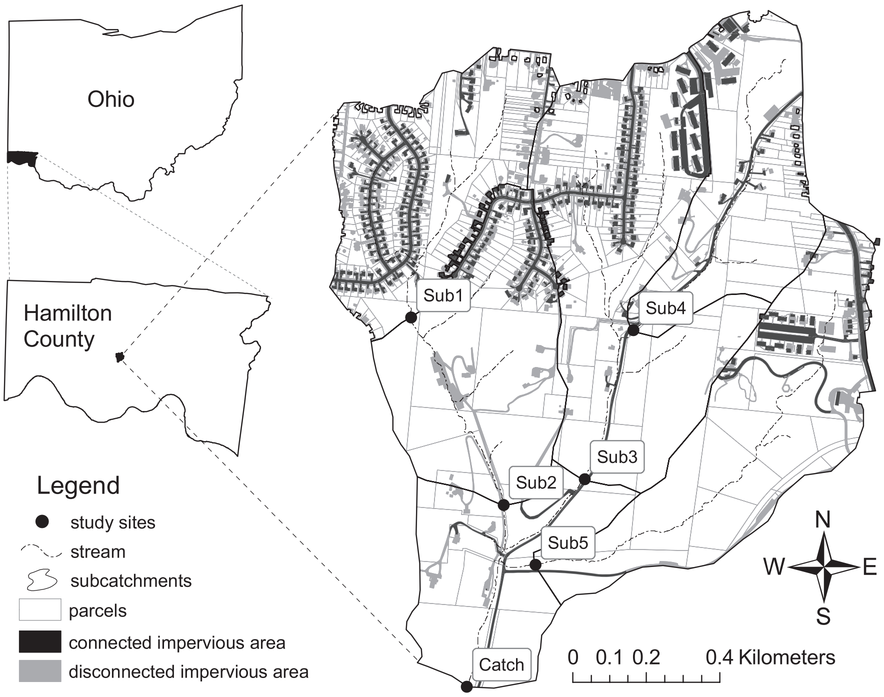

FIGURE 1. Map of Connected and Disconnected Impervious Areas Within the Shepherd Creek Catchment, Hamilton County, Ohio. Catchment (Catch) and subcatchment (Sub1-Sub5) boundaries are based on piped areas.

data. CAGIS provided a parcel layer and separate built layers for buildings, driveways, sidewalks, parking lots, and roads which were hand digitized based on 1989-1991 aerial photography. All of these built layers were manually updated using 2001 color orthorectified aerial photography (0.15-m resolution) as a reference. Sanitary, storm, and combined sewer data were also obtained from CAGIS and verified for this study area by city-level and county-level engineers familiar with the layout of the sewerage system. Topographic maps with two-foot (0.61-m) contours were initially used to delineate subcatchments for each of the six stream sampling locations. The U.S. Geological Survey's National Land Cover Database (NLCD) imperviousness layer [created from 2001 Landsat 7 ETM+ data following estimation methods by Yang *et al.* (2002)] was used for comparison to the more detailed impervious area data sources created based on CAGIS data and field assessments.

Field Assessments

In the summer of 2005, we conducted field assessments of impervious surfaces for every property within the Shepherd Creek catchment. Street addresses, homeowner names, and property age were acquired from the county-level, publicly available, property tax database. In two-person teams, we went door-to-door asking permission to conduct assessments. When residents were not home, a blank permission form and return envelope was left at the door. For properties that we were permitted to access, we then recorded type and dimensions of additional impervious areas (e.g., sheds, concrete patios, private sidewalks) and semi-impervious areas (e.g., wooden decks, gravel landscaping, gravel driveways), recording this information on field assessment sheets for each parcel that included known impervious data (i.e., built layers from CAGIS). All drains and downspouts were identified, recorded, and labeled as connected or disconnected (i.e., draining to grass or concrete then grass). If a building had gutter downspouts that were both connected and disconnected, the proportion of the roof area draining to each downspout was estimated. We also recorded slope direction for both driveway and yard areas. For properties where permission was either not granted or our request went unanswered, we conducted a visual assessment from the sidewalk or closest public easement (hereafter, referred to as "sidewalk assessments") wherein downspout connectivity, additional impervious surfaces, and driveway and yard slopes were recorded.

Geographic Information System Data Entry

A comprehensive impervious surface layer was created based on CAGIS data layers, field and sidewalk assessments, and aerial photo interpretation. First, CAGIS impervious surface layers (building, driveway, sidewalk, street, and parking) were merged into a single layer. The resulting composite layer was subsequently updated using field assessments, and some impervious surface locations were verified with 2001 aerial photography. For properties that had only sidewalk surveys, aerial photos were primarily used to update this new surface layer. All impervious surface features were attributed (i.e., assigned information) by surface type (e.g., pool, shed, sidewalk, etc.) and surface category (impervious or semi-impervious). Concrete patios, sheds, sidewalks, and pools were all attributed as impervious. As gravel driveways, landscaping pavers, and wooden decks all had some capacity for the abstraction of rainfall, these were attributed as semi-impervious.

Downspout and drain locations were digitized into separate GIS point shapefiles, and attributed according to downspout category (piped to sewer, piped to stream channel, or piped to landscape) and drainage status (connected or disconnected). Impervious areas that sloped toward drains that were assumed to be connected to the sewer system were always considered connected. Impervious areas that sloped toward yards or were piped to the landscape (based on visual inspection or as informed by a homeowner) were considered disconnected. Surface layer polygons were subdivided, as necessary, to reflect multiple levels of connectivity (e.g., part of roof draining to connected downspouts and part draining to disconnected downspouts). Where connectivity could not be determined (e.g., for some surfaces assessed from sidewalks), we estimated this attribute based on the characteristics of neighboring houses that were of similar age, occupied comparable topography, and were along streets with the same sewerage infrastructure.

After surface connectivity was defined, we manually adjusted topographic subcatchment boundaries to "piped" subcatchment boundaries to account for the direction of water flow based on stormwater conveyances. For example, impervious areas that were connected to sewers that flowed outside of the Shepherd Creek catchment were eliminated from the piped catchment. Similarly, impervious surfaces in Sub1 that were connected to sewers which drained into Sub2 were subsequently included in the Sub2 piped subcatchment.

Data Summarization and Analysis

The GIS impervious data were summarized at two scales: (1) the Shepherd Creek catchment ("Catch") and its five subcatchments ("Sub1" to "Sub5"; Figure 1) and (2) individual parcels. In ArcGIS® (ESRI, Redlands, California), we combined the surface, subcatchment, and parcel layers into a new output layer. We then determined the area and percent of pervious area, TIA, and DCIA, and proportion of TIA that is DCIA within subcatchments and for various surface types with standard ArcGIS® summarization tools. Mean and median pervious area, TIA, DCIA, and percent connectivity for individual parcels were calculated in MS Access (Microsoft Office Access, version 2003). We used a *t*-test (assuming unequal variances) to compare mean percent connectivity from older residences (1860-1959) to houses built more recently (1960-1999; JMP 5.1, SAS Institute, Inc., Cary, North Carolina).

We compared TIA and DCIA generated from data derived with various levels of effort. Subcatchment TIA was calculated using three data sources: (1) NLCD imperviousness layer, (2) CAGIS built layers derived from aerial photography, and (3) field assessments and subsequent data interpretation. DCIA was only available from field assessment data, but was calculated for both the topographic catchment and piped catchment to explicitly assess the effects of stormwater flow routing along catchment boundaries on catchment-scale DCIA.

Lastly, we determined the relationship between % TIA and % DCIA within parcels using linear regression analysis (JMP 5.1; SAS Institute). The linear regression model from this analysis was compared to other published models that predict DCIA based on TIA. We first derived % DCIA from an empirical formula developed by Alley and Veenhuis (1983) based on 14 urban catchments in Denver, Colorado

$$\mathrm{DCIA} = 0.15 \times \mathrm{TIA}^{1.41} \tag{1}$$

where TIA and DCIA units are percent of total area ($r^2 = 0.98$). Percent DCIA was also calculated from a formula developed by Wenger *et al.* (2008) for the Etowah River basin north of Atlanta, Georgia. For their study, TIA data were generated from the NLCD imperviousness layer and DCIA data were determined based on interpretation of high-resolution aerial photographs for 15 sites that ranged in size from 25 to 70 ha. The best fit model was

$$\mathrm{DCIA} = (1.046 \times \mathrm{TIA}) - 6.23\% \tag{2}$$

where DCIA is 0 for areas where TIA values are less than 6.23% ($r^2 = 0.98$). We applied the three models (one generated from our data and the two published formulas) to generate % DCIA predicted for each parcel in this study. Predicted % DCIA was compared with % DCIA observed in field assessments ($n = 524$ parcels with impervious surfaces), and coefficients of determination (r^2) for best fit linear models were used to determine the amount of variance explained by each of the three models.

RESULTS

Comparisons Between Total and Directly Connected Impervious Area

TIA for the Shepherd Creek piped catchment was 22.1 ha, and semi-impervious area was 1.8 ha, together comprising 13.1% of the catchment area (Table 1). Subcatchments (Sub1-Sub5) exhibited differences in the amount of pervious (80.1-88.8%), impervious (10.8-18.1%), and semi-impervious (0.4-1.9%) area. The catchment boundary adjustments for piped sewers resulted in a slightly smaller catchment size compared to the topographic catchment boundary (182.7 ha *vs*. 184.5 ha). This was due to subtraction of impervious areas on the catchment perimeter that were connected to sewers draining outside of the catchment (Figure 1). The subcatchment boundaries within the catchment were largely unaltered by the piping, with the exception of several houses along the boundary between Sub1 and Sub2, which drained into Sub1 with the topographic boundaries and Sub2 with the piped boundaries. Slightly more than half of the impervious area in Shepherd Creek catchment was connected (56.3%) (Table 2). Percent subcatchment DCIA ranged from 5.4 (Sub4) to 11.6 (Sub1).

TABLE 1. Pervious, Impervious, and Semi-Impervious Data for the Shepherd Creek Catchment and Subcatchments (Sub1-Sub5).

	Pervious		Impervious		Semi-impervious		Total	
Site	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Piped boundary								
Subl	22.4	80.1	5.1	18.1	0.5	1.8	28.0	100
Sub2	48.5	83.7	8.3	14.4	1.1	1.9	57.9	100
Sub3	59.8	86.9	8.8	12.7	0.3	0.4	68.9	100
Sub4	22.1	88.8	2.7	10.8	0.1	0.4	24.9	100
Sub5	30.6	87.9	3.9	11.3	0.3	0.8	34.8	100
Catchment	158.8	86.9	22.1	12.1	1.8	1.0	182.7	100
Topographic boundary								
Subl	22.6	76.8	6.3	21.5	0.5	1.7	29.5	100
Sub2	48.5	83.0	8.8	15.1	1.1	1.9	58.5	100
Sub3	60.2	85.3	10.1	14.3	0.3	0.4	70.6	100
Sub4	22.4	85.3	3.8	14.4	0.1	0.4	26.3	100
Sub5	30.4	88.5	3.7	10.7	0.3	0.8	34.3	100
Catchment	159.0	86.2	23.7	12.9	1.8	1.0	184.5	100

Note: Piped catchment boundaries reflect direction of flow within sewers, while topographic catchment boundaries exclusively reflect landscape elevation based on contour maps and field verification.

TABLE 2. Connected and Disconnected Impervious Area Within the Shepherd Creek Catchment and Subcatchments (Sub1-Sub5).

	Connected		Disconnected		
Site	Area (ha)	%	Area (ha)	%	% Connectivity
Subl	3.3	11.6	2.3	8.3	58.4
Sub2	5.2	9.0	4.3	7.4	54.9
Sub3	5.1	7.3	4.0	5.8	55.9
Sub4	1.3	5.4	1.4	5.8	48.2
Sub5	2.5	7.3	1.7	4.8	60.4
Catchment	13.5	7.4	10.5	5.7	56.3

Note: Percent connectivity is percent of total impervious area which is connected.

Of the 566 parcels in the Shepherd Creek catchment, 521 had impervious surfaces, of which 128 (25%) had exclusively disconnected impervious. The proportion of TIA that was DCIA varied widely across parcels. There were parcels with high imperviousness that were entirely disconnected, parcels that were entirely connected, and various levels of connectivity in between (Figure 2). For the 496 single family residential parcels, there was a median 210 m^2 (19.7%) impervious surface area, approximately half of which was disconnected (Table 3). The proportion of TIA that was connected was significantly higher for houses built between 1960 and 1999 (57.6%; $n = 305$) compared to those built prior to 1960 (15.6%; $n = 92$) (t-test assuming unequal variances, $t = 11.2$, $p < 0.001$; Figure 3).

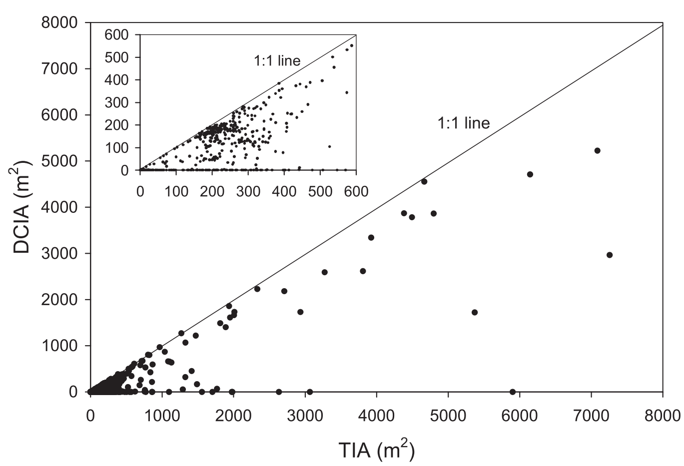

FIGURE 2. Comparison Between Directly Connected Impervious Area (DCIA) and Total Impervious Area (TIA) Within Parcels. Inset is an enlargement of parcels with 0-600 m^2 impervious area to show points at the bottom corner of the figure. One site with high impervious area (TIA = 16,732 m^2; DCIA = 14,741 m^2) was excluded for ease of presentation. Parcels falling on the 1:1 line indicate 100% connectivity.

TABLE 3. Median Pervious and Impervious Areas for Private, Single-Family Residential Parcels in Shepherd Creek.

	Area (m^2)	% Area
Pervious	642	80.3
Impervious	210	19.7
Disconnected	104	11.6
Connected	106	8.1

Note: Note that median percent area was calculated from the parcels (n = 496), rather than converting the median areas to percent, thus the areas and percentages do not correspond.

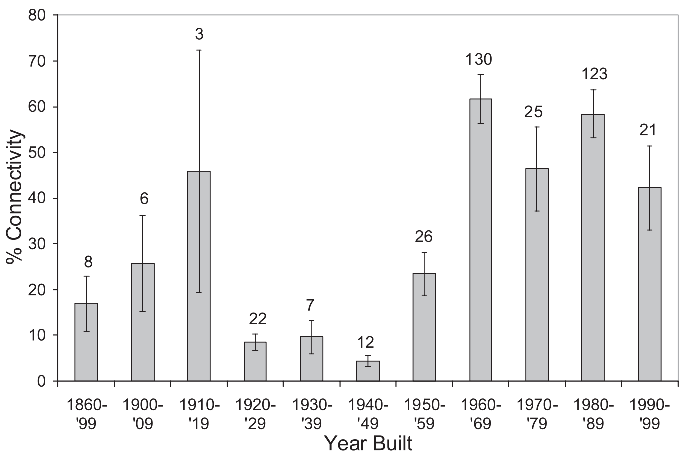

FIGURE 3. Percent Connectivity of Houses Based on Year Built, 1860-1999. Mean values and standard errors are reported for each decade since 1990. Numbers above bars indicate the number of houses within each year bracket.

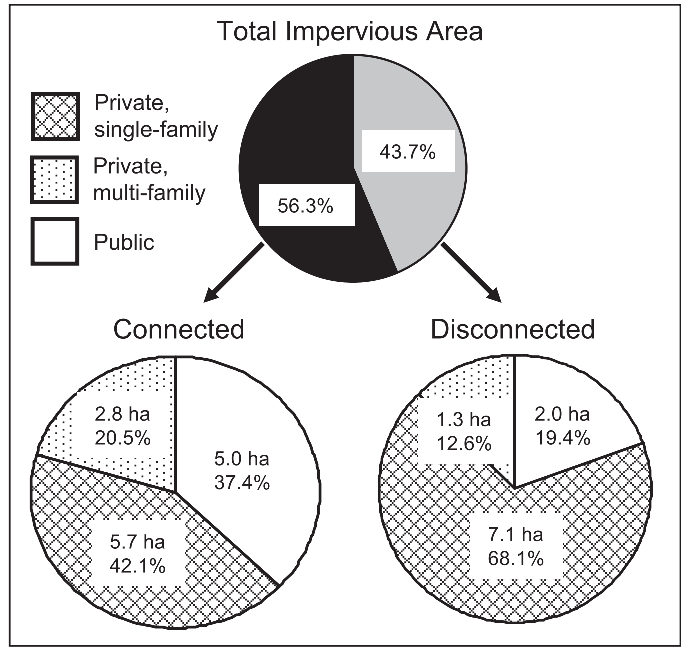

FIGURE 4. Total Impervious Area in the Shepherd Creek Catchment as Connected and Disconnected Based on Property Ownership.

The Shepherd Creek catchment consists of private property as single-family residential, multi-family residential (primarily low-rise apartment complexes), and pasture land, as well as public property (roads, city park, etc.). A majority of the TIA in Shepherd Creek was on private land (70.5%) compared to public land (29.5%). Public properties encompassed a larger proportion of the connected (37.4%) *vs.* disconnected (19.4%) impervious area (Figure 4). Conversely, single-family residential properties comprised a higher proportion of the TIA found to be disconnected (68.1%) than connected (42.1%). The public parcels and the private, multi-family residential parcels both had more than double the total amount of connected *vs.* disconnected impervious area, whereas single-family residential parcels had overall lower amounts of connected than disconnected impervious area (Figure 4).

We were also interested in determining what types of impervious surfaces were typically connected, to assess the potential for improvements from retrofitting properties with BMPs that disconnect impervious area from stormwater conveyances. Buildings

TABLE 4. Total and Directly Connected Impervious Area Categorized by Impervious Surface Type.

	TIA		DCIA		
Surface Type	(m^2)	(%)	(m^2)	(%)	% Connected
Building	66,168	27.6	44,364	32.9	67.0
Driveway	58,918	24.6	23,525	17.4	39.9
Street	54,432	22.7	48,551	36.0	89.2
Parking area	29,473	12.3	18,144	13.5	61.6
Sidewalk	13,097	5.5	3	0.0	0.0
Concrete	6,963	2.9	211	0.2	3.0
Wooden deck	4,984	2.1	0	0.0	0.0
Pool	2,363	1.0	0	0.0	0.0
Shed	882	0.4	12	0.0	1.3
Other	2,047	0.1	4	0.0	6.7

(27.6%), driveways (24.6%), streets (22.7%), and parking areas (12.3%) had the highest TIA (Table 4; Figure 5). A high proportion of the streets were connected (89.2%), while a comparatively lower proportion of the driveways were connected (39.9%). Overall, over two-thirds of the DCIA was in streets (36.0%) and buildings (32.9%), while the remainder of DCIA was divided among driveways (17.4%) and parking areas (13.5%). There were several other types of impervious surfaces (see Table 4); however, together these comprised less than 13% of TIA and 0.2% of DCIA, and were therefore considered to have minimal potential for improvements with retrofit management.

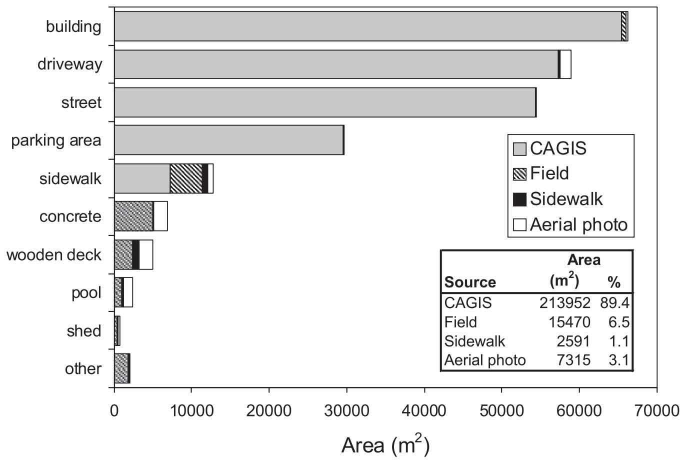

FIGURE 5. Cumulative Area of Impervious Surface Types Based on Sequential Data Sources. Inset shows total area and percent area for the four data sources. CAGIS = digitized from 1989-1991 aerial photos by Cincinnati Area Geographic Information System; field = detailed field assessment (excluding sidewalk); sidewalk = assessment from sidewalk where we did not have access permission; aerial photo = digitized from 2001 aerial photographs for parcels with sidewalk assessment.

Level of Effort

A majority of the TIA (89.4%) in the Shepherd Creek catchment previously had been delineated by CAGIS and was available in building, driveway, street, parking area, and sidewalk layers created from digital orthophotos. However, an additional 10.6% of TIA was revealed during the subsequent field assessments, sidewalk assessments, and aerial photo interpretation. Of the 441 properties assessed, 50% (222 properties) received complete field assessments, resulting in an additional 15,470 m^2 (6.5%) of TIA (Figure 5, inset). The field assessments took two people 54 h (excluding travel to and from the site), or approximately 15 min/property. The sidewalk surveys (for the properties that we did not have access to) required an additional 5 h of field time (1.4 min/property) and resulted in an additional 2,591 m^2 (1.1%) of TIA. Aerial photo delineation on parcels with only sidewalk assessments added 7,315 m^2 (3.1%) of TIA. In terms of types of impervious surface, the field and sidewalk assessments primarily added impervious and semi-impervious areas such as concrete, wooden decks, pools, sheds, and some other items (e.g., steps, pavers, play areas). Minor additions were also made to building, driveway, and street areas during the field and sidewalk assessments. The area of sidewalk nearly doubled as a result of our assessment as we accounted for sidewalks leading to houses, whereas only public sidewalks were included in the CAGIS layer (Figure 5). Note that the majority of the impervious areas that were added during the field assessment were found to be disconnected (Table 4, Figure 5).

There were some notable differences in TIA and DCIA when summarized across subcatchments. TIA calculated from the publically available NLCD imperviousness layer was considerably lower (7-18%) than actual TIA as determined from field assessments (11-23%) (Figure 6). Differences between aerial photos and field data were minimal and largely consistent across subcatchments; the data collected in the field added an average of 1.7% TIA to each of the sites compared to CAGIS data. Percent DCIA was on average 5.9% lower than TIA when summarized based on topographic catchments, and this difference was also relatively consistent across sites. However, when summarized based on the piped subcatchments, DCIA was between 0.7% higher and 4.1% lower than DCIA summarized using topographic subcatchments, leading to a different pattern of impervious cover across sites (Figure 6).

The field and sidewalk assessments were also necessary for determining impervious surface connection to stormwater pipes to calculate DCIA. An alternative to these time-intensive direct assessments is to estimate DCIA from TIA using empirical formulas. Compared to observed values, % DCIA calculated using the formulas by Alley and Veenhuis (1983) and Wenger *et al.* (2008) was generally higher (Figure 7). We also developed our own relationship based on fitting a linear regression to the parcel-scale % TIA *vs*. % DCIA

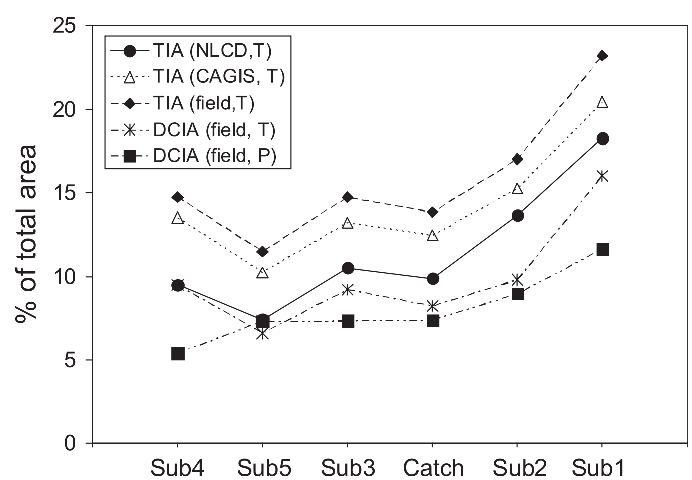

FIGURE 6. Subcatchment Percent Total (TIA) and Directly Connected (DCIA) Impervious Area Calculated From Different Data Sources. Catchment (Catch) and subcatchments (Sub1-Sub5) are ordered from lowest to highest % DCIA. NLCD = National Land Cover Data imperviousness layer from classified satellite imagery; CAGIS = Cincinnati Area Geographic Information System, digitized from 1989-1991 aerial photos; field = complete field assessment; T = subcatchment boundaries based on topography; P = subcatchment boundaries based on piped catchment (i.e., including stormwater conveyances).

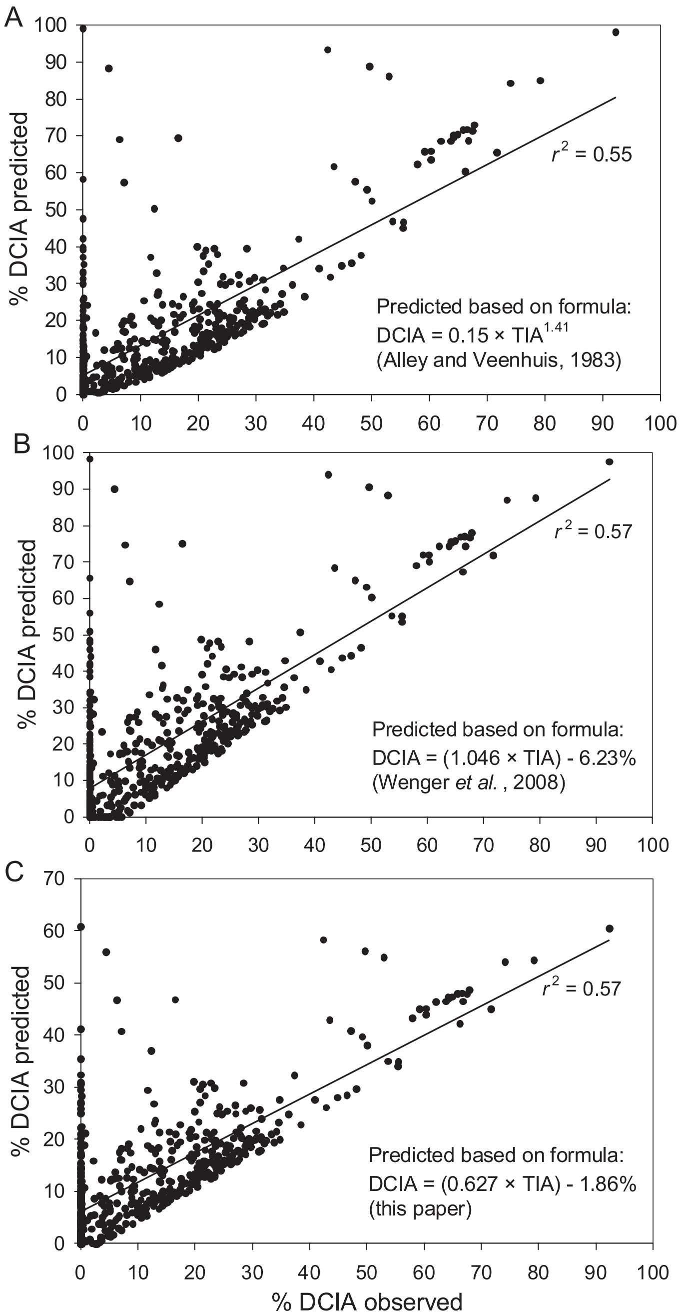

FIGURE 7. Relationship Between Directly Connected Impervious Area (DCIA) Observed From Field Assessments and DCIA Predicted From Empirical Formulas. DCIA was predicted from parcel-scale % total impervious area (TIA) at 521 parcels with impervious surfaces based on formulas (A) published by Alley and Veenhuis (1983), (B) published by Wenger *et al.* (2008), and (C) developed based on a linear regression relationship between % TIA and % DCIA within parcels for this study. Best fit linear regressions and corresponding r^2 values are reported.

$$\mathrm{DCIA} = (0.627 \times \mathrm{TIA}) - 1.86\% \tag{3}$$

which indicates that DCIA is 0 where TIA was less than 1.86% (r^2 = 0.57). Predicted % DCIA based on this model and the two published models were all similarly ineffective at predicting observed % DCIA (r^2 ranged from 0.55 to 0.57) (Figure 7).

DISCUSSION

Shepherd Creek Case Study

The Shepherd Creek catchment is a mixed-use, mixed-age area that reflects the diversity of impervious surfaces evident in many suburban settings. As such, the amount, types, and connectivity of the impervious surfaces in this study can provide comparative insights to other catchments. On average, slightly more than half of the impervious surfaces were connected to stormwater conveyances, although percent connectivity was highly variable across parcels. While residences built in more recent years (1960-1999) tended towards higher percent connectivity, there was high variability in percent connectivity regardless of house age (Figure 3). The variability in these measurements across parcels may be related to parcel topography and homeowner preferences (e.g., whether they have re-routed gutter downspouts), and precluded the derivation of a reliable, universally applicable empirical determination of DCIA from TIA. Public properties had higher percent connectivity, primarily because streets were 89% connected, and we expect that this pattern is typical of most suburban areas due to a compulsory adherence to city and county stormwater regulations that often require storm sewers along streets. In a similar study, Lee and Heaney (2003) used field measurements to assess impervious area in a much smaller (5.81 ha) subdivision in Boulder, Colorado, and they found lower percent connectivity (36%) compared to our study (56%). We attribute these differences to the fact that only 3% of buildings (all private residences) were connected in that subdivision compared to 67% of buildings in this study. Although the overall connectivity differed, both studies demonstrate that connectivity of buildings and driveways cannot be inferred solely based the presence of public storm sewers along streets.

We used our detailed assessment of impervious surfaces in the Shepherd Creek catchment to weigh stormwater management options and provide incentives for homeowners to manage runoff on their property. A majority of TIA was on private property (70.5%) and in buildings and driveways (52.2%), which resulted in targeting private properties for installation of BMPs in the form of rain gardens and rain barrels (Roy *et al.*, 2006). Using a so-called "reverse" auction, we offered homeowners the opportunity to submit bids for the amount of money they would accept to receive one free rain garden and up to four free rain barrels. We then used parcel-scale imperviousness data to evaluate potential benefits of installing BMPs on each parcel, and developed an environmental benefits index that was used in conjunction with costs (e.g., bid amount) to rank homeowners' bids for BMPs. Characteristics of impervious surfaces such as the type of imperviousness (e.g., road *vs*. rooftop), location in the catchment (e.g., distance from stream), and connectivity to stormwater conveyances, have been shown to qualify the extent of the impervious impact in streams (Brabec *et al.*, 2002; Walsh *et al.*, 2005a). We therefore considered parcels with high % TIA, low soil infiltrative capacity, and close proximity to the stream channel to yield the highest benefits for installing rain gardens, and, accordingly, gave these sites the highest environmental benefits scores. For rain barrels, higher rooftop connectivity was expected to result in higher potential benefits from installing the BMPs, and those residences subsequently received higher scores. Incorporating these data into the bid ranking process ensured that we were not just installing BMPs to the lowest bidders, but that the locations selected would result in maximum environmental benefits.

Comparison of Field-Based Assessments to Geographic Information System Approaches

In this study we used field assessments to accurately determine the spatial extent and types of impervious surfaces. The additional impervious surface area added from field assessments accounted for 10.6% of impervious surface area, primarily from sidewalks leading to houses, concrete patios, wooden decks, and pools. We expect that most of these impervious surfaces could have been digitized from high-resolution aerial photos without the need for on-site assessments. These additional surfaces measured were primarily disconnected from sewer conveyances, further suggesting that field assessments may not be critical for assessing imperviousness that can alter catchment hydrology and impair stream ecosystems. However, it is important to acknowledge that aerial photo interpretation is a time consuming process, and can account for just as much time and effort as field investigations (Lee and Heaney, 2003). The existing impervious surface data layers in the Cincinnati GIS allowed us to easily quantify buildings, driveways, streets, parking areas, and sidewalks. If our methods are to be applied elsewhere, similar information is essential for evaluating sources and solutions to stormwater runoff in a catchment.

We summarized subcatchment TIA and DCIA based on various GIS and field data sources to assess whether the additional effort could potentially increase our ability to predict instream conditions across sites. The NLCD imperviousness layer is the most widely available impervious surface data and is increasingly being used for catchment-scale impervious area assessments, although the coarse spatial resolution (30 m) limits its utility at fine spatial scales. The NLCD data greatly underestimated actual TIA, though given the small range in % TIA across subcatchments in this study, we are unable to determine whether a systematic adjustment of NLCD % imperviousness would result in a more accurate estimation of TIA. When compared to TIA assessed from aerial photography (the CAGIS dataset), the field and sidewalk assessments resulted in an additional 1.7% TIA, which was found to be consistent across the subcatchments. This suggests that a standard adjustment of % TIA (e.g., 1.7%) would account for additional sources, and field-based mapping of TIA may not be necessary when using the data for catchment-scale predictors of downstream conditions. Conversely, the range in percent connectivity across subcatchments in this localized area (48.2-60.4) (Table 2) suggests that percent connectivity would help explain additional variability in instream conditions beyond that explained by TIA, as observed by Walsh (2004). It is important to highlight that the inconsistent relationship between TIA and DCIA across subcatchments was primarily due to differences in the routing of water between subcatchments, as shown by the difference between the topographic and piped catchment (Figure 6). These differences were especially pronounced along roads adjacent to catchment boundaries. Accurate maps of stormwater conveyance and the direction of surface water flow are therefore likely to be critical datasets for accurately assessing catchment-scale DCIA.

Finally, we resolved the use of empirical relationships with % TIA to accurately estimate % DCIA, which would obviate the need for field-based assessments. Based on our assessments, none of the relationships can do better than explaining 57% of the variance in this nominal relationship. The formula from Alley and Veenhuis (1983) was developed based on aerial photos and, as deemed necessary, field inspections. While their relationship between TIA and DCIA was strong (r^2 = 0.98), the formula was not as accurate for predicting % DCIA based on data in this study. Wenger *et al.* (2008) exclusively used high-resolution aerial photographs to determine DCIA for a subset of locations and developed a relationship between TIA and DCIA that was similarly strong (r^2 = 0.98), but this strong relationship did not extend to predicting parcel-scale % DCIA using our data. There are several possible explanations for the lack of consistent performance of these models across datasets. First, the formulas were developed for predicting DCIA within catchments, and the authors did not address variability or discuss applications of the formula based on data at the parcel scale. Second, while high-resolution aerial photography can be used to determine whether there are sewers along roads, it cannot be used to determine slopes of driveways and resolve where sewers have outlets, which are apparently critical for accurate assessment of DCIA within catchments. Lastly, these studies were conducted in Denver, Colorado and north of Atlanta, Georgia that each had mixed urban land uses (commercial and residential), so the lack of commercial properties in Shepherd Creek and general differences in buildings and imperviousness across the United States (U.S.) may partially explain the consistency in model overestimation. However, the formula created in this study from highly reliable TIA was also unable to reliably predict % DCIA in parcels, and this is attributed to the high variability in parcel-scale DCIA. By definition, site-to-site variability in percent connectivity prevents reasonable prediction of DCIA from TIA, unless this can be explained by other factors that remain unresolved in this study. Our field visits and conversations with homeowners revealed that individual decisions are made by homeowners as to whether they will disconnect or connect rooftops, driveways, or patios to sewer inlets. This suggests that empirical formulas are unlikely to accurately predict parcel-scale DCIA, and that time and effort spent in structured field surveys will result in novel information not otherwise attainable.

The utility of field-based assessments *vs*. empirical formulas for obtaining DCIA data also depends on the temporal and spatial scale of the data and how it is summarized. The age of development in a region will likely regulate the accessibility and availability of GIS data. For example, recent developments may have GIS data on sewer pipes, though we found that records of older developments are often unavailable or incomplete. Homes within subdivisions built by a single developer are also likely more homogenous in relationships between TIA and DCIA, thus increasing the accuracy of empirical formulas and decreasing the importance of field-based assessments, offering potential for a "developer-shed" delineation. However, as educational campaigns and options for storing and infiltrating stormwater runoff via low impact development become more prevalent, there is likely to be additional increased variation in connectivity among parcels, even in newer developments.

In this study we have demonstrated that at a parcel scale, there is high variability in DCIA (Figure 2); however, when DCIA is summarized at the subcatchment scale (25-182 ha), the differences between TIA and DCIA are relatively uniform (Figure 6). This is because the relative importance of parcel- and street-level stormwater routing will necessarily decrease when averaged across these larger areas. Thus, when comparing data across catchments (e.g., >25 ha), it is possible that aerial photographs or classified satellite imagery, along with sewer conveyance information (to assess whether pipes flow into or out of the catchment), will adequately assess DCIA and predict in-stream conditions.

Further Applications for DCIA Data in Watershed Management

Characterization of DCIA represents an important shift in urban stream ecology from calculating disturbance *indicators* to identifying *mechanisms* of impact that can be linked to management. In the last 15 years, several studies have been published relating % urban and % impervious land cover to stream hydrology, geomorphology, habitat, biology, and ecosystem functions (see reviews by Schueler, 1994; Paul and Meyer, 2001; Walsh *et al.*, 2005b). More recently, studies have reported relationships with DCIA; there are greatly reduced macroinvertebrate assemblages above 6-14% DCIA (Walsh *et al.*, 2005a) and fish assemblages above 8-10% DCIA (Wang *et al.*, 2001). Much lower thresholds have been reported for water quality (1-5% DCIA), algae (2-5% DCIA) (Walsh *et al.*, 2005a), and sensitive fish species (2-4% DCIA) (Wenger *et al.*, 2008), and some of these relationships are linear for portions of the response (Walsh *et al.*, 2005a). From these and other studies, we now have an understanding of impacts of urbanization on stream ecosystems, although the exact nature of the relationship (e.g., linear, threshold, or stepped threshold) remains a subject of debate (Walsh *et al.*, 2005b). The differences in response curves and thresholds may be a function of biotic sensitivity to disturbance or specific response variables used, or may be a product of different methods used to calculate TIA and DCIA. Consistent and accurate delineation of impervious surfaces may help refine these relationships (Brabec *et al.*, 2002). Calculation of DCIA, in particular, provides data that represents a direct mechanistic link between urbanization and the impairment of stream ecosystems via piped stormwater runoff. Consequently, DCIA offers a similarly direct approach to watershed management through disconnection of impervious surfaces from storm sewers and streams (Walsh, 2004).

Another potential use of detailed, parcel-scale impervious area and connectivity data is for developing a market to encourage runoff-mitigating actions (Parikh *et al.*, 2005). Market-based mechanisms such as stormwater fees (Fullerton and Wolverton, 1999), tradable allowances (Thurston *et al.*, 2003; Ross-Rakesh *et al.*, 2006), and voluntary offsets administered via auctions (Roy *et al.*, 2006; Greenhalgh *et al.*, 2007) have been proposed for mitigating stormwater runoff. The effectiveness of these approaches depends on determining a price or payoff that encourages implementation of environmental management (Doll and Lindsey, 1999). For example, in many parts of the U.S., stormwater fees are minimal and are determined based on average imperviousness for certain property types (e.g., residential, commercial, etc.) rather than the actual amount of stormwater generated from individual properties (Keeley, 2007). If municipalities had parcel-specific information on TIA and percent connectivity, they could charge property owners based on stormwater generated across a reasonable annual rainfall distribution, which could be directly offset by stormwater-mitigating actions. This approach to fee-setting is used in Germany and being considered in several communities in the U.S. (Keeley, 2007); however, the expense of parcel-level imperviousness calculations remains a hurdle (Kaspersen, 2000). As local governments and municipal sewer districts face growing problems of aging stormwater infrastructure, combined sewer overflows, and declining water quality of streams and rivers, they will likely look toward private property owners to help offset the stormwater burden through source control retrofit and low impact development.

CONCLUSIONS

The detailed impervious assessment of the Shepherd Creek catchment presented in this paper and comparisons to other data sources offers several, important insights for calculating imperviousness in other areas.

1. *Digitizing impervious surfaces from aerial photos should provide an accurate assessment of TIA within parcels.* Further, if imperviousness is classified by type (e.g., building, street, sidewalk), this information can be used to assess the primary sources of imperviousness and develop watershed management plans according to TIA contributions.
2. *Classified satellite imagery (NLCD imperviousness layer) underestimates actual TIA.* Although we cannot determine whether a standard adjustment can improve TIA estimates across catchments, it is important to note that relationships between impervious area and stream ecosystem impairment will be affected by the source of impervious surface cover.
3. *Imperviousness connectivity can only be accurately assessed via field assessments.* The high parcel-scale variability in DCIA renders estimations from empirical relationships with TIA inaccurate. However, depending on study objectives, when calculating average DCIA at a catchment scale (e.g., >25 ha) over multiple parcels, estimates of DCIA based on TIA may be sufficiently accurate.

Although individual parcel assessments are considered time-consuming (15 min per property), the data gathered can contribute valuable information that can then play a key role in management of stormwater volume. For example, quantification of parcel-scale DCIA may be used to assess the extent of imperviousness linked to downstream ecosystems and to predict the potential hydrological and ecological responses to management by disconnection via retrofit BMPs. Parcel-scale DCIA can also be used to set fair stormwater fees and provide a basis for application of incentives that can encourage private property owners to mitigate stormwater on their property. Ultimately, assessment of impervious surface connectivity within parcels should result in more effective and efficient management of urban and suburban watersheds.

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