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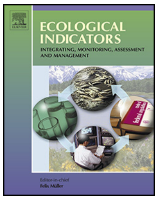

Spatial patterns of watershed impervious cover relative to stream location

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ABSTRACT

The urban stream syndrome may not be limited to streams in urbanized watersheds. We measured the spatial pattern of impervious cover in ~82,800 small watersheds across the conterminous United States by comparing watershed-based and stream-based measures of imperviousness. The watershed-based measure was the commonly used watershed percentage impervious cover. The stream-based measure was the percentage of watershed stream length flowing through impervious cover. Spatial pattern of impervious cover was classified on a watershed basis as proximal to streams, distal to streams, and uniform by comparing the two measures of impervious cover. We used a classification threshold of ±5% to assign watersheds to the three classes (i.e., stream-based minus watershed-based ≥5% = proximal; watershed-based minus stream-based ≥5% = distal; else = uniform). We then applied the classification to two impervious cover thresholds, ≥5% and ≥15%. For ≥5% and ≥15% thresholds, impervious cover was distributed uniformly across ~70% and ~86% of the watersheds, respectively. For the remaining watersheds, the proximal spatial pattern was ~12× and ~4× greater than the distal spatial pattern for the ≥5% and ≥15% impervious cover thresholds, respectively. The proximal spatial pattern of impervious cover occurred predominantly in non-urbanized watersheds, resulting in a widespread occurrence of a relatively high percentage of streams flowing through relatively high impervious cover in watersheds where the total percentage impervious cover was relatively low. The spatial pattern of change in impervious cover between ca. 2001 and ca. 2006 did not avoid streams. Impervious cover increased in the vicinity streams in ~55% of the watersheds with increases in impervious cover. During this period, the length of streams flowing through ≥5% and ≥15% impervious cover increased by ~9800 km and ~6900 km, respectively.

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1. Introduction

Over the last 20 years impervious cover has been accepted as an informative indicator of stressors that cause water-quality degradation (Schueler, 1994; Arnold and Gibbons, 1996; Paul and Meyer, 2001; Brabec et al., 2002). Where it occurs, impervious cover reconfigures rainfall-runoff relationships and often increases pollutant transport (Arnold and Gibbons, 1996; Shuster et al., 2005). A greater fraction of precipitation contributes to runoff, which increases overall and peak discharges, reduces the time of concentration during storm events, and, in turn, a smaller fraction of precipitation tends to infiltrate, which can reduce baseflow discharges. The hydrologic impacts of impervious cover are accompanied by increased pollutant loads, increased stream temperatures, increased streambank erosion, and adverse affects on stream biota (Schueler, 1994; Brabec et al., 2002; Walsh et al., 2005). Because impervious cover is typically found at higher levels in urban areas, the numerous adverse impacts that arise from it have motivated some researchers to collectively refer to these effects as the urban stream syndrome (Meyer et al., 2005; Walsh et al., 2005).

Adverse impacts often occur at low levels of impervious cover. Surveys of impervious cover impacts on water quality generally find that adverse impacts are detectable when percentage impervious cover is as low as 5–15% (Brabec et al., 2002; Schueler et al., 2009). The low percentages at which adverse impacts begin to appear has led some to postulate that stream response to

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impervious cover exhibits threshold effects (Schueler et al., 2009). Others have found that stream response to impervious cover is linear rather than non-linear (Booth et al., 2002; Moore and Palmer, 2005), and Walsh et al. (2005) point out that stream response to impervious cover could take on a variety of functional forms. Regardless of the form of the quantitative relationship between stream response and impervious cover, some jurisdictions in the United States are now using impervious cover thresholds to identify impaired waters. The State of Connecticut has established a threshold of 12% impervious cover to identify streams that are not likely to meet water quality standards for aquatic life use (Bellucci, 2007), and the State of Maine has established aquatic life use thresholds for impervious cover of ≥5%, ≥9%, and ≥15% for different classes of waters (Maine, 2012).

Impervious cover is most commonly expressed as a percentage of watershed area (Arnold and Gibbons, 1996; Brabec et al., 2002; Schueler et al., 2009), which does not account for spatial pattern. Others have recognized that spatial pattern is an important element of the degree to which impervious cover degrades water quality (Brabec et al., 2002; Shuster et al., 2005; Alberti et al., 2007; Schiff and Benoit, 2007). The idealized conceptual model of the influence of spatial pattern is that impervious cover proximal to a water body is more likely to cause adverse impacts than impervious cover distal to a water body (Brabec et al., 2002), but there are few studies of the effect of the spatial pattern of impervious cover on stream and aquatic condition (Alberti et al., 2007). Schiff and Benoit (2007) found that the amount of impervious cover in riparian areas was a better predictor of stream and aquatic condition than the amount of impervious cover in the entire watershed. Similarly, Alberti et al. (2007) found that the number of road-stream crossings provided additional explanatory power of stream and aquatic condition that was not realized when using only the amount of impervious cover in the entire watershed. Hammer (1972) found that the negative impact of impervious cover on stream channel form tended to decline as the distance between the impervious cover and the stream channel increased. Perhaps the most well established conceptualization of the importance of spatial pattern is the "derivative, directly connected impervious cover (Alley and Veenhuis, 1983). Directly connected impervious cover is the subset of the total impervious cover area that is directly connected to streams through conveyances such as storm sewers. By directly connecting impervious cover to a stream, it becomes more proximal to the stream network than it otherwise would be.

Under the assumption that proximal and distal areas of impervious cover have differential impacts on surface water response, measures of impervious cover that account for spatial pattern are needed to complement the commonly measured indicator, watershed total percentage impervious cover. The primary objective of this paper is to report on the development and nationwide measurement of an impervious cover indicator that accounts for stream location as a complement to reporting watershed total percentage impervious cover alone. The indicator developed is the percentage of the watershed stream length that flows through to impervious cover. Although watershed impervious cover is associated with alteration of runoff volume and timing even without accounting for proximity to streams, it is plausible that other impervious cover-related stressors such as road salt, metals, elevated heat, conductivity, nitrogen, and sediment could vary in magnitude and duration due to differences in the proximity of impervious cover to surface waters. The potential value of the indicator is demonstrated conceptually by comparing this stream-based indicator of impervious cover to watershed percentage impervious cover to identify spatial patterns of impervious cover across watersheds for the conterminous United States. We add to the demonstration by comparing change in each indicator between ca. 2001 and ca. 2006. Based on the comparisons, we relate the potential implications of impervious cover spatial patterns to water-quality monitoring, assessment, and management under the Clean Water Act (CWA) (P.L. 92-500).

2. Methods

2.1. Data

Impervious cover data were from the MultiResolution Land Characteristics (MRLC) Consortium's National Land Cover Database (NLCD) (http://www.mrlc.gov). The most recent release of NLCD data (2006) provides percentage impervious cover estimates for each 30 m × 30 m (0.09 ha) pixel in 1% increments from 0% to 100% (Fry et al., 2011; Xian et al., 2011). NLCD 2006 is a change detection database that provides percentage impervious cover for the target years 2001 and 2006 and the change between 2001 and 2006. Change in impervious cover can be either new impervious cover (pixels whose impervious cover was 0% in 2001 but greater than 0% in 2006) or an increase in impervious cover (2006 percentage impervious cover > 2001 percentage impervious cover). Comparison of the two datasets indicated that ~94% of impervious cover change was new impervious cover. Description of the NLCD 2006 impervious cover database is found in Xian et al. (2009, 2011).

Digital streams and shorelines were from the 1:100,000-scale National Hydrography Dataset Plus, Version 2 (NHDPlus) (http://www.horizon-systems.com/nhdplus/NHDPlusV2_home.php). NHD data include linear and area (polygon) features. The linear features are smaller streams and the area features include shorelines of larger streams and rivers, as well as estuaries, lakes, and reservoirs. The area features for streams (i.e., larger streams) were overlaid with the linear streams to form a single streams data set. We removed features that were not labeled as streams, such as canals/ditches and connectors (Electronic Supplementary Material, Table S1). Thus, our streams dataset included only features classified as streams in the NHD data. Analyses for streams and water bodies (lakes, reservoirs) were conducted separately. For simplicity, we hereafter use the term stream to refer to stream and water body. For example, phrases such as "streams flowing through impervious cover" should be interpreted as "streams flowing through impervious cover and impervious cover in the vicinity of lake and reservoir shorelines."

The Watershed Boundary Dataset (WBD) (http://datagateway.nrcs.usda.gov) 12-digit Hydrologic Unit Code (HUC12) served as the analysis unit for the comparison of stream-based and watershed-based expressions of impervious cover. WBD watersheds are small and therefore more likely to serve as a management unit than larger watersheds. There are ~82,800 WBD watersheds for the conterminous US. The average watershed size, average watershed stream length, and average watershed shoreline length are ~9000 ha, ~66 km, and ~8 km, respectively.

2.2. Analyses

Analyses were conducted for the conterminous US using standard GIS routines. Stream and shoreline percentage impervious cover were estimated by overlaying the stream and shoreline data with a buffered impervious cover dataset. Buffering was done to accommodate the reality that streams often flow adjacent to but not coincident with impervious cover (e.g., roads). We chose to buffer the impervious cover map rather than opting for the intuitive choice of buffering the stream map because it was necessary to estimate the stream length "flowing" through impervious cover to identify proximal, distal, and uniform spatial patterns. GIS buffering of streams results in a polygon map of riparian areas that can be

Table 1
Classification of buffered impervious cover map using a maximum rule. An X indicates that buffering introduced that class to a pixel that was 0% impervious in the original map. The column "% of U.S." is the percentage of pixels in the conterminous NLCD 2006 impervious cover map. Buffering changed ∼7% of the contiguous U.S. from 0% impervious to >0% impervious.

Original map	Buffered impervious cover maps				New map	% of U.S.
Impervious class	1–4%	5–14%	15–25%	≥25%	Impervious class	
0	X				1	2.639
0	X	X			2	1.105
0	X		X		3	0.086
0	X			X	4	0.044
0	X	X	X		3	0.133
0	X	X		X	4	0.049
0	X		X	X	4	0.031
0	X	X	X	X	4	0.022
0		X			2	1.175
0		X	X		3	0.481
0		X		X	4	0.132
0		X	X	X	4	0.124
0			X		3	0.333
0			X	X	4	0.262
0				X	4	0.401

used to estimate the amount of impervious cover in the area of the watershed defined as riparian. GIS buffering of a stream map and intersection of the output of the buffering operation with an impervious cover map does not provide an estimate of the stream length "flowing" through impervious cover. GIS buffering of the impervious cover map allowed us to "bring" the impervious cover to the streams to estimate the amount of stream length "flowing" through impervious cover.

To simplify the GIS buffering computations, the impervious cover map was first simplified to five classes: 0%, 1–4%, 5–14%, 15–24%, and ≥25%. The class choices are consistent with adverse impacts on water quality at low levels of impervious cover reported in the literature (King and Baker, 2010; Miltner et al., 2004; Ourso and Frenzel, 2003; Stanfield and Kilgour, 2006; Schiff and Benoit, 2007; Uphoff et al., 2011), the conceptual model of impervious cover impacts proposed by Schueler et al. (2009), and impervious cover thresholds recognized by states (Bellucci, 2007; Maine, 2012). Buffering of the impervious cover dataset expanded impervious cover pixels in the NLCD 2001 and 2006 maps by one pixel (30 m) in all directions. The buffer analysis was done separately for each of the impervious cover classes to control for expansion of impervious into pixels that were already impervious. The class-specific buffered maps (e.g., 1–4%) were then recombined into a single map that contained the original class assignments and the expanded values. The recombined map was then reclassified. The re-classification assigned the maximum impervious cover class value to pixels that were 0% impervious cover in the original map but greater than 0% in one of the buffered maps. Pixels that were greater than 0% impervious cover in the original map were not reclassified.

Classification of the re-combined buffered impervious cover map was accomplished using a maximum rule (Table 1). For example, if the re-combined map indicated that both the 1–4% class and the ≥25% class could occupy the same 0% impervious cover pixel, the pixel was classified as ≥25% in the buffered impervious cover map. Use of a maximum rule assigned a higher proportion of re-classified pixels to the ≥25% class than would have been realized if a minimum rule had been used. The percentage changes in the class assignments between the maximum and minimum rules provide an estimate of how the percentages of stream and shoreline lengths assigned to each class would have changed if we had used the minimum rule classification scheme (Table 2).

Table 2
Change in class assignments between maximum and minimum classification rules. The percentages for the maximum and minimum rules are from the column "% of U.S." in Table 1.

Class	Maximum rule (%)	Minimum rule (%)	Difference (%)	Percentage change
1–4%	2.64	4.11	1.47	55.7
5–15%	2.28	1.91	−0.37	−16.2
15–24%	1.04	0.60	−0.42	−40.4
≥25%	1.06	0.40	−0.66	−62.3

Streams and water bodies were then overlaid on the buffered impervious cover map to estimate the proportion of watershed total stream length in each impervious cover category. Stream-based impervious cover is conceptualized differently than watershed impervious cover. Watershed impervious cover is often summarized as a simple percentage, whereas summarizing our stream-based impervious cover indicator requires two percentages, i.e., the percentage of stream length that flows through impervious cover of at least *X*%. Simplifying the stream-based indicator of impervious cover to a single percentage would have required very high spatial resolution impervious cover data (e.g., 1 m^2) such that each pixel could be classified as homogenously impervious cover or not. Very high spatial resolution impervious cover data do not exist nationally. For consistency, our watershed-based impervious cover indicator was also expressed as a double percentage, i.e., the percentage of the watershed that is at least *X*% impervious cover. The watershed-based impervious cover indicator was the sum of all pixels (converted to area) greater than or equal to a specified threshold divided by watershed area. Watershed percentages were based on the original (i.e., not buffered) impervious cover map.

Comparison of watershed- and stream-based indictors of impervious cover can be used to identify spatial patterns of impervious cover in a watershed. If impervious cover is distributed uniformly throughout a watershed, the percentage of stream length flowing through impervious cover will be approximately equal to the percentage of impervious cover in the watershed. Conversely, watershed impervious cover could be non-uniformly distributed such that it tends to be either proximal or distal to a watershed's streams. We used an equivalence threshold of ±5% to distinguish the three spatial pattern classes. Watershed- and stream-based percentages that were within 5% were classified as a uniform spatial pattern. Watershed percentages that exceeded stream-based percentages by at least 5% were classified as a distal spatial pattern, and stream-based percentages that exceeded watershed percentages by at least 5% were classified as a proximal spatial pattern (Fig. 1). Mapping of impervious cover spatial patterns (i.e., comparison of stream- and watershed-based impervious cover) is based on two thresholds, ≥5% and ≥15%. For example, the percentage of watershed stream length flowing through ≥5% impervious cover is compared to the percentage of the watershed that is ≥5% impervious cover.

3. Results

The total length of streams and lake and reservoir shorelines in the NHDPlus2, 1:100,000-scale data is ∼6 million km (Tables 3 and S2). Approximately 8% and 4% of the total conterminous U.S. stream length flows through impervious cover ≥5% and ≥15%, respectively. On a percentage basis, high impervious cover (i.e., ≥15%) tends to be more prominent in the vicinity of lakes and reservoirs than streams, which may reflect a tendency for development around larger water bodies.

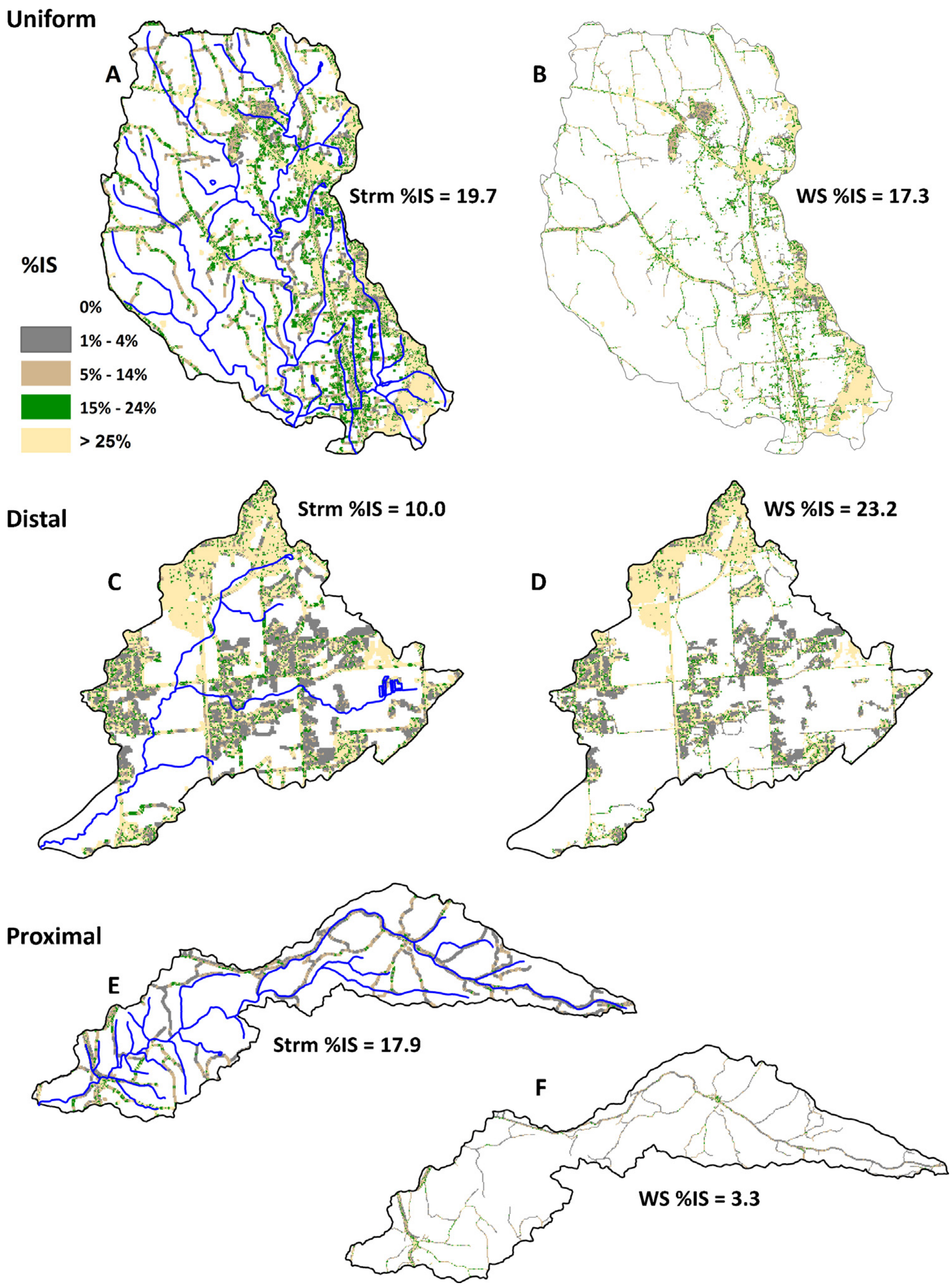

Fig. 1. Geographic examples of uniform, distal, and proximal distributions of impervious cover. The label "Strm %IS" is the percentage of the watershed stream length that flows through impervious cover ≥5%, and the label "WS %IS" is the percentage of the watershed that is ≥5% impervious cover. Panels A, C, and E, show the expanded impervious cover used for the stream analysis, and panels B, D, and F show the unexpanded (i.e., original) impervious cover used for the watershed analysis. Streams are not shown on panels B, D, and F.

Based on the ≥5% threshold, ~70% of the watersheds had a uniform spatial pattern of impervious cover in that the stream-based and watershed-based values per watershed differed by less than 5%. Of the remaining ~30%, the spatial pattern was such that impervious cover was much more likely to be proximal to streams than distal to streams (Fig. 2a). There were ~12× more watersheds with a proximal spatial pattern of impervious cover than a distal spatial pattern of impervious cover. For the ≥15% threshold, the percentage of watersheds with a uniform spatial pattern increased from ~70% to ~86%, but the dominance of the proximal spatial pattern over the distal spatial pattern remained (Fig. 2b). There were ~4× more watersheds with a proximal spatial pattern of impervious cover than a distal spatial pattern of impervious cover for the ≥15% threshold. The distal spatial pattern characterized urbanized watersheds regardless of the threshold used. The majority of the United States major metropolitan areas have a distal spatial pattern of impervious cover (e.g., Fig. 1c),

Table 3
Lengths of stream and lake or reservoir shorelines within 30 m of ≥5 and ≥15% impervious cover.

Date	Class	Total (km)	IS ≥ 5%	IS ≥ 15%
2006	Stream	5,306,128	424,809 (8%)	215,590 (4%)
	Lake, reservoir	681,638	60,133 (8%)	40,896 (6%)
Change	Stream		8026 (0.10%)	5542 (0.10%)
	Lake, reservoir		1788 (0.26%)	1344 (0.20%)

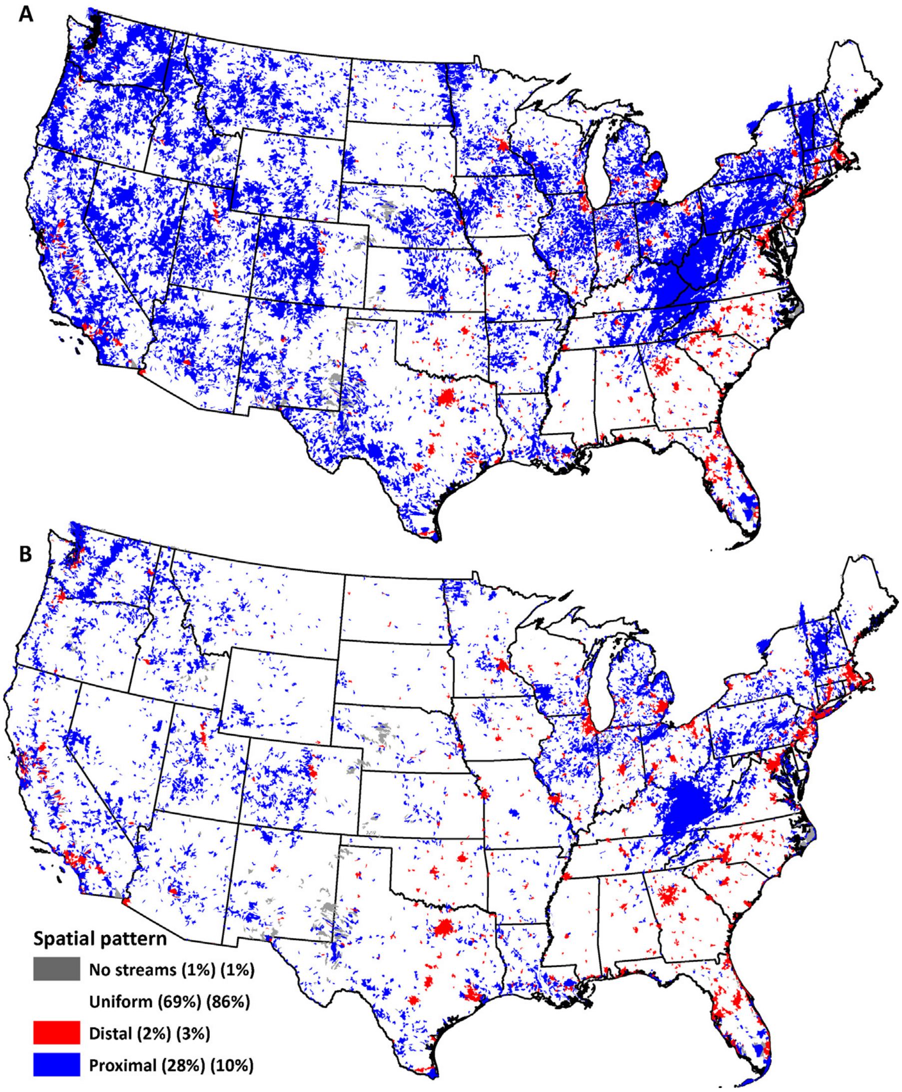

Fig. 2. Uniform, distal, and proximal spatial patterns of impervious cover for the $\geq$5% (A) and $\geq$15% (B) thresholds. The numbers in parentheses are the percentage (rounded to the nearest integer) of watersheds in the spatial pattern classes for the $\geq$5% and $\geq$15% thresholds, respectively.

which may be attributable to lack of adequate mapping of streams in urban areas or the “burial” of streams in urban areas.

Roads and topography appear to be important factors contributing to the predominance of the proximal spatial pattern in many non-urban watersheds. Most of the watersheds where impervious cover is proximal to streams appear to occur in areas where topographic factors “force” urbanized areas and streams to co-occur in valleys or where roads are predominantly adjacent with streams. In eastern Kentucky and West Virginia, for example, topographic factors result in co-located concentrations of streams and impervious cover. Watersheds in central Colorado (north-south orientation), central Nebraska northwest to Wyoming, and Shreveport, LA northwest to Texas are other examples of areas where roads and streams appear to be co-located (Fig. 2a and b).

Many of the areas where impervious cover is proximal to streams have a high percentage of their stream lengths flowing through impervious cover that equal or exceed the $\geq$5% and $\geq$15% thresholds (Fig. 3). Most of the watersheds in the northeastern quadrant of the United States (Iowa to New Hampshire) have at least 5% of their streams flowing through impervious cover $\geq$5% (Fig. 3a), and many of the watersheds in eastern Kentucky and southern West Virginia have at least 25% of the watershed’s stream length flowing through impervious cover $\geq$ 15% (Fig. 3b). Of the $\sim$82,800 watersheds in the conterminous United States, $\sim$54% have at least 5% of their stream length flowing through $\geq$5% impervious cover and $\sim$25% have at least 5% of their stream length flowing through $\geq$15% impervious cover.

Impervious cover increased in the vicinity of streams in $\sim$55% of the watersheds in which there were increases, based on the 5% threshold. The geography of impervious cover increase is dominated by the expected pattern of urban sprawl, but also has a consistent scattering of non-urban watersheds where a portion of the increase occurs in the vicinity of streams (Fig. 4). Development in the vicinity of roads appears to be a factor contributing to increases in the stream length flowing through impervious cover in non-urban watersheds. There is a linear orientation to the increase that tracks the road network for several locations in the continental United States.

4. Discussion

The spatial pattern of impervious cover throughout the conterminous U.S. is such that streams affected by impervious cover may be common in watersheds that would not be considered urbanized. Depending on the impervious cover threshold, there were $\sim$4× to

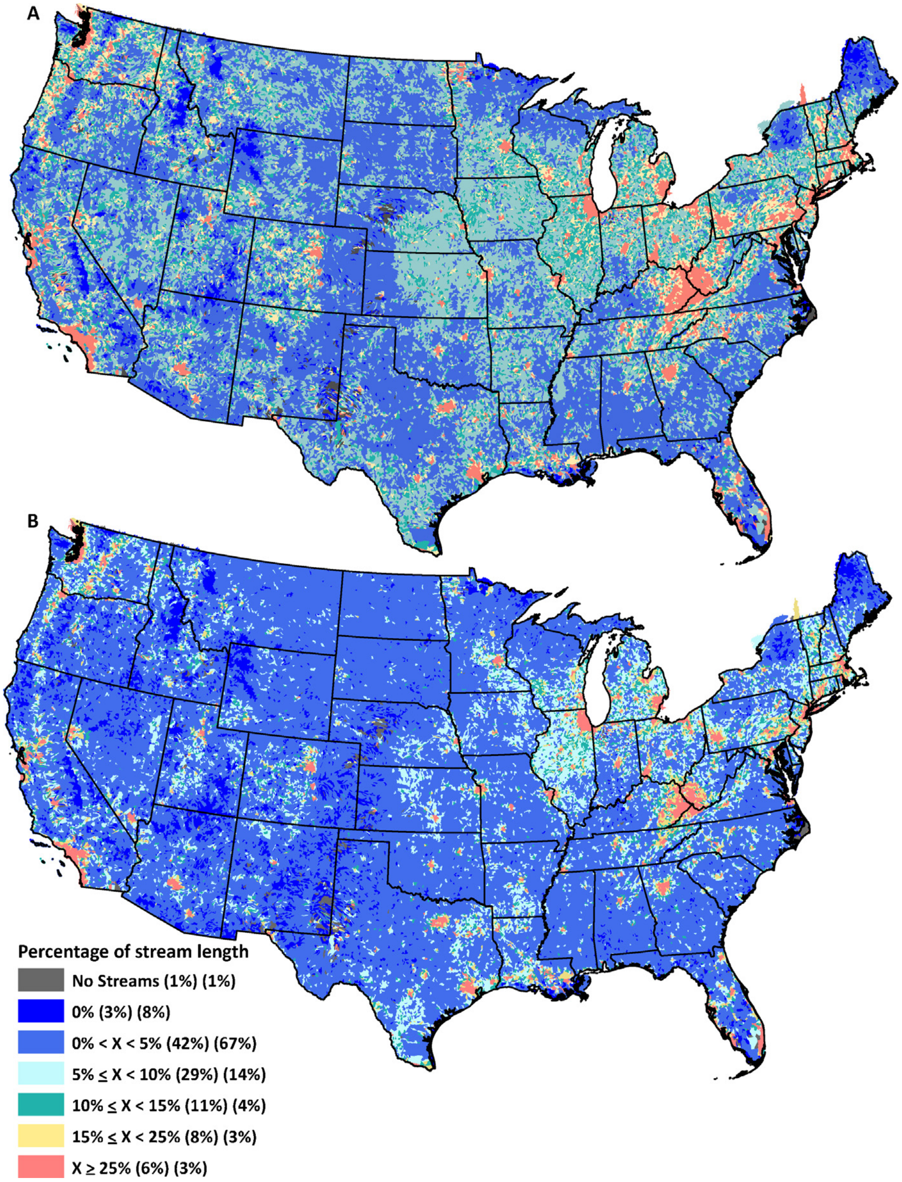

Fig. 3. Percentage of watershed stream length (e.g., $0\% < X < 5\%$) flowing through impervious cover ≥5% (A) and ≥15% (B). The numbers in parentheses are the percentage (rounded to the nearest integer) of watersheds in each category for the ≥5% and ≥15% thresholds, respectively.

~12× more watersheds with impervious cover concentrated near streams than watersheds with impervious cover concentrated far from streams, and most of the watersheds with impervious cover concentrated near streams are not urbanized watersheds (Fig. 2). The total length of streams flowing through impervious cover ≥5% and ≥15% would be substantially less if the distal spatial pattern was more prominent than the proximal spatial pattern.

Our use of two indicators of impervious cover provides information on the spatial pattern of imperviousness that can be used to inform planning and management. The state of Kentucky contains ~1300 watersheds. For the ≥5% threshold, impervious cover was configured as uniform, proximal, and distal spatial patterns for 55%, 42%, and 2% of the watersheds, respectively. At 42%, the proximal distribution is ~1.5× more frequent in Kentucky than it is nationwide due to the co-occurrence of streams and impervious cover in the narrow valleys of the highly dissected topography of the Appalachian Plateau in the eastern half of the state (Fig. 2). Using only the watershed-based expression, there are 36 watersheds in Kentucky with greater than 25% of their area with ≥5% impervious cover, whereas using only the stream-based expression, there are 309 watersheds with greater than 25% of their stream length flowing through ≥5% impervious cover. Using the watershed-based expression alone would underestimate the occurrence of impervious cover above a target threshold and would have no apparent sensitivity to detect a common impervious cover exposure setting in the state. Spatial patterns similar to those in Kentucky are likely to present in other states. Five states and the District of Columbia have more than 10% of their stream length flowing through impervious cover ≥15% (Table S2).

The number of watersheds in our uniform, proximal, and distal classes is, of course, dependent on the classification threshold used to define the classes. Reducing the classification threshold would increase the number of watersheds in the proximal and distal classes and reduce the number of watersheds in the uniform class, whereas increasing the classification threshold would reduce the number of watersheds in the proximal and distal classes and increase the number of watersheds in the uniform class (Table S3). For the ≥5% impervious cover threshold, for example, reducing the classification threshold from ±5% to ±4% would increase the number of watersheds assigned to the proximal and distal classes by

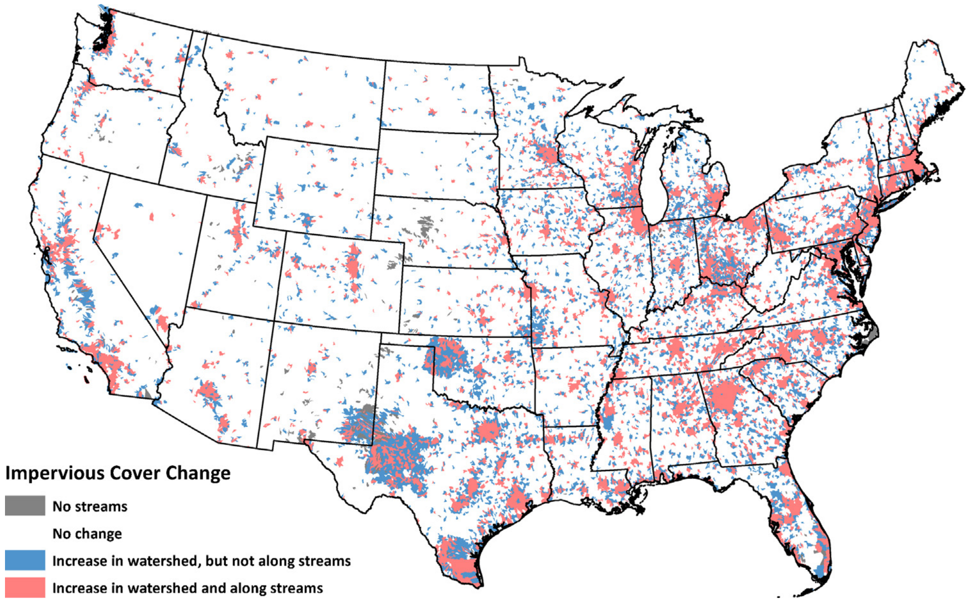

Fig. 4. Spatial pattern of impervious cover change.

~8%, and reduce the number of watersheds assigned to the uniform class by the same amount. We chose a logical and reasonable threshold for the purpose of illustrating the classification and its utility for understanding spatial patterns of impervious cover in a watershed.

Roads appear to be an important factor contributing to the widespread occurrence of impervious cover in the vicinity of streams. The total length of roads and streams in the conterminous U.S. is approximately equivalent, and, as a result of the ubiquity of roads, ~12% of all land in the conterminous U.S. is within ~30 m of road (Riitters and Wickham, 2003), which is consistent with our result that ~8% of water bodies in the conterminous United States is within 30 m of ≥5% impervious cover (Tables 3 and S2). Roads are often “crowned” to promote runoff during precipitation events and the runoff is often directed to streamside ditches that may be directly connected to streams (McBride and Booth, 2005). These construction practices alter hydrologic processes and expose streams to pollutants (Foreman and Alexander, 1998; Trombulak and Frissell, 2000).

Impacts that arise from streams flowing through impervious cover linger for some distance downstream. Therefore, our indicator, stream length flowing through impervious cover, is an underestimate of the stream length affected by impervious cover because it does not account for downstream impacts. Decline of in-stream concentrations of nitrogen is inversely correlated with stream size (Alexander et al., 2000; Peterson et al., 2001), suggesting that in-stream nitrogen concentrations will tend to abate over shorter downstream distances for smaller streams and longer downstream distances for larger streams. McBride and Booth (2005) have shown that the physical condition of streams improves downstream from urban areas when the downstream reach is forested and has few road crossings. However, without comprehensive assessments of lag distances for all downstream impacts of impervious cover over a wide range of environmental settings, it is impossible to estimate the total length of streams impacted by impervious cover from the total length of streams flowing through impervious cover. Our percentage estimates (i.e., 4% and 8%) of stream length impacted by impervious cover would increase if downstream lag distances could be estimated reliably.

Much smaller amounts of impervious cover change are required to increase watershed stream length flowing through impervious cover than watershed impervious area. The average area and average total stream length for the watersheds used in this study were ~9000 ha, and ~66,000 m, respectively. Using the 30 m buffer width (90 m diameter) adopted in this study as a baseline to compare these areal and linear statistics, a 1% increase in watershed impervious area (90 ha) would be equivalent to a rectangle of dimensions 90 m × 10,000 m, whereas the rectangle size to increase watershed stream length flowing through impervious cover by 1% would be 90 m × 660 m. As impervious cover increases over time, watershed stream length flowing through impervious cover will likely experience more dramatic percentage increases than the watershed itself, unless the spatial pattern of change avoids riparian areas.

The spatial pattern of impervious cover change did not avoid riparian areas between ca. 2001 and ca. 2006. Approximately one-half of the watersheds in which impervious cover increased also had increases in impervious cover in close proximity to streams. The number of non-urbanized watersheds with streams exposed to impervious cover will continue to increase if the spatial pattern of impervious cover increase between 2001 and 2006 (Fig. 4) continues into the future.

Directly connected impervious cover was introduced to improve accuracy and precision in hydrologic modeling (Alley and Veenhuis, 1983). Water quality monitoring under the CWA is more commonly based on streams, lakes, and reservoirs than watersheds. Similarly, stream length flowing through impervious cover is an indicator that is more closely aligned with the object being monitored (streams, lakes, reservoirs) than watershed percentage impervious area. Combining the indicators stream length flowing through impervious cover and watershed percentage impervious cover area provides information on spatial pattern that can be used to further inform management of aquatic resources. NLCD’s nationwide impervious cover data (Fry et al., 2011; Xian et al., 2011) make a significant contribution to the breadth of available impervious cover metrics that can be calculated and used for watershed monitoring, planning, and management.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.01.013.

References

Alberti, M., Booth, D., Hill, K., Coburn, B., Avolio, C., Coe, S., Spirandelli, D., 2007. The impact of urban patterns on aquatic ecosystems: an empirical analysis in Puget lowland sub-basins. Landsc. Urban Plan. 80, 345–361.

Alexander, R.B., Smith, R.A., Schwartz, G.E., 2000. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. Nature 403, 758–761.

Alley, W.M., Veenhuis, J.E., 1983. Effective impervious area in urban runoff modeling. J. Hydrol. Eng. 109, 313–319.

Arnold Jr., C.L., Gibbons, C.J., 1996. Impervious surface coverage: the emergence of a key environmental indicator. J. Am. Plann. Assoc. 62, 243–258.

Bellucci, C., 2007. Stormwater and aquatic life: making the connection between impervious cover and aquatic life impairments for TMDL development in Connecticut streams. In: Proceedings of the Water Environment Federation, TMDL 2007, http://dx.doi.org/10.2175/193864707786619819, pp. 1003–1018 (16).

Booth, D.B., Hartley, D., Jackson, R., 2002. Forest cover, impervious-surface area, and the mitigation of stormwater impacts. J. Am. Water Resour. Assoc. 38, 835–845.

Brabec, E., Schulte, S., Richards, P.L., 2002. Impervious cover and water quality: a review of current literature and its implications for watershed planning. J. Plan. Lit. 16, 499–514.

Foreman, R.T.T., Alexander, L.E., 1998. Roads and their major effects. Ann. Rev. Ecol. Syst. 29, 207–231.

Fry, J.A., Xian, G., Jin, S., Dewitz, J.A., Homer, C.G., Yang, L., Barnes, C.A., Herold, N.D., Wickham, J., 2011. Completion of the 2006 National Land Cover Database for the conterminous United States. Photogramm. Eng. Remote Sensing 77, 858–864.

Hammer, T.R., 1972. Stream channel enlargement due to urbanization. Water Resour. Res. 8, 1530–1540.

King, R.S., Baker, M.E., 2010. Considerations for analyzing ecological community thresholds in response to anthropogenic environmental gradients. J. N. Am. Benthol. Soc. 29, 998–1008.

Maine, 2012. Maine Impervious Cover Total Maximum Daily Load (TMDL) for Impaired Streams. Maine Department of Environmental Protection, DEPLW-1239, Augusta, Maine, USA http://www.maine.gov/dep/water/monitoring/tmdl/2012/IC%20TMDL_Sept_2012.pdf

McBride, M., Booth, D.B., 2005. Urban impacts on physical stream condition: effects of spatial scale, connectivity, and longitudinal trends. J. Am. Water Resour. Assoc. 41, 565–580.

Meyer, J.L., Paul, M.J., Taulbee, W.K., 2005. Stream ecosystem function in urbanizing landscapes. J. N. Am. Benthol. Soc. 24, 602–612.

Miltner, R.J., White, D., Yoder, C., 2004. The biotic integrity of streams in urban and suburbanizing landscapes. Landsc. Urban Plan. 69, 87–100.

Moore, A.A., Palmer, M.A., 2005. Invertebrate biodiversity in agricultural and urban headwater streams: implications for conservation and management. Ecol. Appl. 15, 1169–1177.

Ourso, R.T., Frenzel, S.A., 2003. Identification of linear and threshold responses in streams along a gradient of urbanization in Anchorage, Alaska. Hydrobiologia 501, 117–131.

Paul, M.J., Meyer, J.L., 2001. Streams in the urban landscape. Ann. Rev. Ecol. Syst. 32, 333–365.

Peterson, B.J., Wollheim, W.M., Mulholland, P.J., Webster, J.R., Meyer, J.L., Tank, J.L., Martí, E., Bowden, W.B., Valett, H.M., Hershey, A.E., McDowell, W.H., Dodds, W.K., Hamilton, S.K., Gregory, S., Morrall, D.D., 2001. Control of nitrogen export from watersheds by headwater streams. Science 292, 86–90.

Riitters, K.H., Wickham, J.D., 2003. How far to the nearest road? Front. Ecol. Environ. 1, 125–129.

Schiff, R., Benoit, G., 2007. Effects of impervious cover at multiple spatial scales on coastal watershed streams. J. Am. Water Resour. Assoc. 43, 712–730.

Schueler, T.R., 1994. The importance of imperviousness. Watershed Protect. Tech. 1, 100–111.

Schueler, T.R., Fraley-McNeal, L., Cappiella, K., 2009. Is impervious cover still important? Review of recent research. J. Hydrol. Eng. 14, 309–315.

Shuster, W.D., Bonta, J., Thurston, H., Warnemuende, E., Smith, D.R., 2005. Impacts of impervious surface on watershed hydrology: a review. Urban Water J. 2, 263–275.

Stanfield, L.W., Kilgour, B.W., 2006. Effects of percent impervious cover on fish and benthos assemblages and instream habitats in Lake Ontario tributaries. Am. Fish. Soc. Symp. 48, 577–599.

Trombulak, S.C., Frissell, C.A., 2000. Review of the ecological effects of roads on terrestrial and aquatic communities. Conserv. Biol. 14, 18–30.

Uphoff Jr., J.J., McGinty, M., Lukacovic, R., Mowrer, J., Pyle, B., 2011. Impervious cover, summer dissolved oxygen, and fish distribution in Chesapeake Bay subestuaries: linking watershed development, habitat conditions, and fisheries management. N. Am. J. Fish. Manage. 31, 554–566.

Walsh, J.W., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan II, R.P., 2005. The urban stream syndrome: current knowledge and search for a cure. J. N. Am. Benthol. Soc. 24, 706–723.

Xian, G., Homer, C., Fry, J., 2009. Updating the 2001 National Land Cover Database land cover classification to 2006 by using Landsat imagery change detection methods. Remote Sens. Environ. 113, 1133–1147.

Xian, G., Homer, C., Dewitz, J., Fry, J., Hossain, N., Wickham, J., 2011. Change of impervious cover area between 2001 and 2006 in the conterminous United States. Photogramm. Eng. Remote Sensing 77, 758–762.