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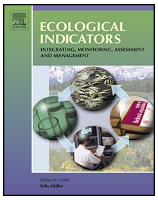

Spatial patterns of watershed impervious cover relative to stream location

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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.

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