Limiting Imperviousness

Are Threshold-Based Policies a Good Idea?

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Research shows negative consequences for a stream when more than 10 to 15% of the land in its watershed is covered by impervious surfaces. Yet we find that how imperviousness is measured has a major effect on whether such thresholds are exceeded. First we show large differences between estimates of imperviousness obtained with land use and land cover data, and propose adopting a consistent standard for the future. Second, we illustrate very different results when watershed imperviousness is measured at a few discrete points on the drainage system or continuously along all stream segments. Based on these findings we recommend that planners allow a safety margin when regulating land based on imperviousness, steer development towards already urbanized locations and away from relatively undisturbed locations, and take advantage of methods that mitigate the deleterious effects of imperviousness on stream ecology.

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We define impervious surfaces as human-produced surfaces that are essentially impenetrable by rainfall. Imperviousness has been linked to water-related environmental degradation since the 1960s (see, e.g., Andersen, 1970; Carter, 1961; James, 1965; Klein, 1979; Leopold, 1968; Schueler, 1994; Viessman, 1966). There are at least three basic mechanisms for this degradation. First, imperviousness physically limits the infiltration of rainfall and snowmelt into the ground. Since this water cannot infiltrate, it instead becomes surface runoff. Impervious surfaces thus greatly increase the volume of surface runoff. Runoff moving along impervious surfaces also moves much faster on relatively smooth pavement than the natural, rougher surfaces that would otherwise be present, and therefore enters waterways more quickly. This combination of higher volumes and quicker arrival can increase stream bank erosion. Third, this water carries with it pollutants deposited by automobile traffic and commercial and industrial activities, including hydrocarbons and heavy metals from brake linings. In the summer, runoff from intense thunderstorms can also cause a large thermal shock in waterways it enters. Pollution and unnaturally quick temperature changes lead to an overall decline in biological abundance, richness, and diversity. Collectively, the increased volumes, faster arrival in streams, and poor quality of runoff degrade streams both physically and biologically.

As the population grows, demand for housing and commercial amenities naturally follows. The urbanization of the landscape adds roads, rooftops, parking lots, sidewalks, and other imperviousness to the landscape. The spatial extent of these surfaces may be directly measured through ground surveys, inferred from land use maps, or quantified remotely by using satellite imagery.

In recent years, researchers have reported that imperviousness is an effective predictor of environmental degradation, and that a distinct threshold separates the watersheds of degraded streams from those in good condition. These studies report that when imperviousness exceeds 10 to 15% of a watershed, various metrics of stream quality decline markedly. Planners and land managers have taken a keen interest in these findings, using them to develop policies to protect streams and aquatic resources while still accommodating strong pressures for land development.

We examine the results from different methods and data for measuring imperviousness, and find significant uncertainty. We also find that the natural organization of drainage in watersheds has important implications for the spatial distribution of aggregated imperviousness. We conclude by proposing a set of recommendations.

Imperviousness and Environmental Degradation

An extensive and growing body of literature has examined stream degradation as a function of urbanization. A first group of studies used percent impervious surface coverage as a measure of urbanization, and predicted physical, chemical, and biological indicators as functions of imperviousness. In many cases these studies found the onset of measurable degradation to occur at 10 to 15% imperviousness. Subsequently, a second group of publications cited this research to justify limiting imperviousness to protect stream conditions. This section provides a brief review of both groups of studies.

A handful of studies linked impervious cover to stream degradation.[1] Klein (1979) studied fish and macroinvertebrate diversity in urbanized areas of Maryland, finding it to decrease rapidly when imperviousness rose above about 10 to 15%. Booth and Reinelt (1993) showed a decline in aquatic insect diversity when imperviousness exceeded about 10%. May, Horner, Karr, Mar, & Welch (1997) developed a multimetric benthic index of biotic integrity in the Puget Sound lowland which declined as impervious cover increased, concluding that imperviousness must be limited to less than 5 to 10% to maintain stream quality unless other measures, such as best management practices or riparian corridor protection, are present. Wang, Lyons, & Kanehl (2001) looked at stream fish communities in southeastern Wisconsin, finding that connected imperviousness was the aspect of urbanization most strongly correlated with declines in fish density, species richness, and diversity. They identified a threshold region between 8 and 12% above which small changes in urbanization could result in large changes in stream conditions. Miltner, White, & Yoder (2004) focused on three streams in suburban Ohio over a decade of rapid urbanization. Their study showed a significant decline in an index of biotic integrity for imperviousness exceeding 13.8%. It is worth noting that given the imprecision of imperviousness measurements, Booth, Hartley, and Jackson (2002) express some doubt that a true threshold effect exists. They suggest that some results demonstrate a continuum of effects rather than a threshold response.

In an effort to protect streams from the degradation brought on by urbanization, many have recommended the establishment of policies to limit the amount of imperviousness in new development to values less than an identified threshold. Schueler (1994) examined many studies using various environmental indicators and concluded from these that streams draining areas with over 10% imperviousness generally exhibited negative impacts. He also made a case for using imperviousness for watershed-based zoning. Arnold and Gibbons (1996) identified imperviousness as a measure appropriate for planning and regulatory applications, noting that many municipalities across the country were using imperviousness in their policies. The U.S. Environmental Protection Agency (EPA, 1993) had already identified watersheds as planning units for this purpose. The EPA (2004) later identified cumulative impacts at 10% imperviousness, and advocated for the 10% threshold as a guideline for watershed-based zoning.

Different Approaches to Estimating Imperviousness Yield Different Results

As noted above, imperviousness can be estimated in a variety of ways, and using various data. To ascertain whether this creates enough variability in results to raise questions about using thresholds to plan and regulate land, we conducted an experiment, comparing two different approaches, both in common use. The first estimates the average percentage of each land use category that is covered by impervious surfaces, I_{LU}. This percentage may be estimated using ancillary information such as existing road networks or measured directly using on-site surveying or aerial photos. In the second approach, spectral measurements made by satellite sensors are used to assign a percentage value between 0 and 100 to indicate the imperviousness detected in the land cover of each 30 × 30 meter unit, or pixel, I_{LC}.

Land use records the human activities land is intended for, like agriculture, or recreation, and requires information not detectable from imagery alone, such as parcel boundaries. In contrast, *land cover* records what covers the land surface, like wetlands, grass, or roads, and can generally be determined from remote observation. These approaches are different. For example, the medium density residential land use might include residential, roads/transportation, and deciduous forest land covers. A land cover classification algorithm might choose forest as the dominant land cover for a number of pixels in an older residential neighborhood with rooftops, sidewalks, driveways, and storm drainage infrastructure, although a forest would generate runoff much differently than such a residential neighborhood. A system based on land use would recognize such an urban neighborhood in spite of the mature trees. Thus, land use and land cover are not interchangeable, and using one or the other to calculate imperviousness may lead to predictable biases.

Measuring Imperviousness Based on Land Use

We used land use data obtained from the Maryland Department of Planning (MDP, 2005). Each polygon in this data set represents a discrete land use based on a modified version of an Anderson Level II classification system (Anderson, Hardy, Roach, & Witmer, 1976). The imperviousness coefficients we used for each land use category were based on values reported in the Soil Conservation Service (SCS) TR-55 manual (1986), a method that remains broadly used in the engineering community today. While there are other sources for such coefficients (see, e.g., Capiella & Brown, 2001) they are generally quite comparable. The SCS land use categories are slightly different from those used by the MDP. Table 1 lists the imperviousness percentages (coefficients) for the MDP land use categories.

Measuring Imperviousness Based on Land Cover

It is also possible to assess land cover directly in order to calculate imperviousness. Impervious surfaces are a derived layer in the 2001 National Land Cover Dataset (NLCD), available for download from the U.S. Geological Survey (USGS) website (USGS, 2004). It is important to understand how this layer is produced from remotely sensed land cover data. Real images (from IKONOS from Space Imaging and USGS digital orthophoto quadrangles), that show actual spectral and spatial variability of impervious areas at 1 meter resolution are used for calibration (Yang et al., 2003). These are grouped into five land cover classes: impervious surface, forest, grass, water, or shadow. All 1-meter pixels classified as impervious surface are counted using a 30 × 30 meter grid based on 30-meter resolution Landsat ETM+ imagery to calibrate the relationships between percent imperviousness and Landsat spectral data (Yang et al., 2003). After the calibrated models are applied to all pixels in a mapping zone, urban classes are identified based on the value of I_{LC} as shown in Table 2.

Devising a Tool for Making Results Consistent

Since the two approaches yield inconsistent results, and both approaches are widely used, we sought a method for making results from each approach consistent with the other. To do this, we used data from our study area in the central third of the State of Maryland, as shown in Figure 1. According to the National Resources Inventory (National Resources Conservation Service, 2005), Maryland is one of the United States' most rapidly growing areas, and the sixth most urbanized state in the country. The counties that have the highest percentages and greatest areas of urban land are within the Baltimore-Washington-Annapolis triangle, which includes Montgomery, Prince Georges, Baltimore, and Howard counties. We chose our study area to include the most urbanized counties. As Figure 1 shows, the study area is divided into numerous square areas (hereafter called grid sampling cells). Each grid sampling cell contains a number of 30-meter cells, which are computational units used to develop separate estimates of I_{LU} and I_{LC}. We calculated aggregate imperviousness for each grid sampling cell by averaging the imperviousness values of all 30-meter cells within the grid sampling cell. We calculated estimates of both I_{LU} and I_{LC} for all the grid sampling cells in our study area.

Table 1. Imperviousness percentages (coefficients) for land use categories.

MDP Land use category	SCS Land use category	Coefficient (%)
Urban	Urban districts: commercial and business	85
Low density residential	Residential, ½ acre	25
Medium density residential	Residential, ¼ acre	38
High density residential	Residential, ⅛ acre or less	65
Commercial	Urban districts: commercial and business	85
Industrial	Industrial	72
Institutional		50
Open urban land		11
Miscellaneous transportation		75
Agricultural buildings		10

Source: SCS (1986) with additions by the authors for the last four land use categories.

Table 2. Imperviousness of remotely detected land cover categories.

Land cover categories	**Imperviousness**
Developed, open space	< 20%
Developed, low intensity	20% to 50%
Developed, medium intensity	50% to 80%
Developed, high intensity	80% to 100%

Figure 2 plots these values I_{LU} and I_{LC} for each study area grid cell, showing that, although there is considerable scatter, it is not unusual for I_{LU} to be 1.5 to 2 times greater than I_{LC}, especially at levels of imperviousness up to about 55%. This level of imperviousness corresponds to lower intensity urban land uses such as low and medium density residential land use categories, as shown in Table 1 and developed, low-intensity and developed, open space land cover classes, as shown in Table 2. These correspond to 2-, ½-, and ¼-acre residential lots according to the land use categories in TR-55 (SCS, 1986).

The relationship shown in Figure 2 led us to choose a power model to express the relationship I_{LC} and I_{LU}. When we regressed I_{LU} on I_{LC} and I_{LC} on I_{LU}, we estimated the following relationships, allowing conversion of I_{LU} to I_{LC} and vice versa.

$$I_{LU} = 6.725 \times I_{LC}^{\,0.5402} \qquad (1)$$

$$I_{LC} = 0.0806 \times I_{LU}^{\,1.5305} \qquad (2)$$

I_{LU} and I_{LC} are in units of percent. The R^2 values for equations 1 and 2 are 0.82 and 0.79, respectively, reflecting a good fit between these models and the data. These regressions are based on a sample size of 18,681 observations.

Drainage Networks Influence Imperviousness Measurements

Square grid sampling cells were useful for comparing two different approaches to calculating imperviousness and calibrating conversion equations in the preceding section, but do not capture the fundamental role that the drainage network plays in collecting runoff. Thus we aimed to characterize the spatial distribution of imperviousness in a way that would be meaningful for stormwater planning.

The percent imperviousness calculated using either approach detailed in the previous section is local, measured

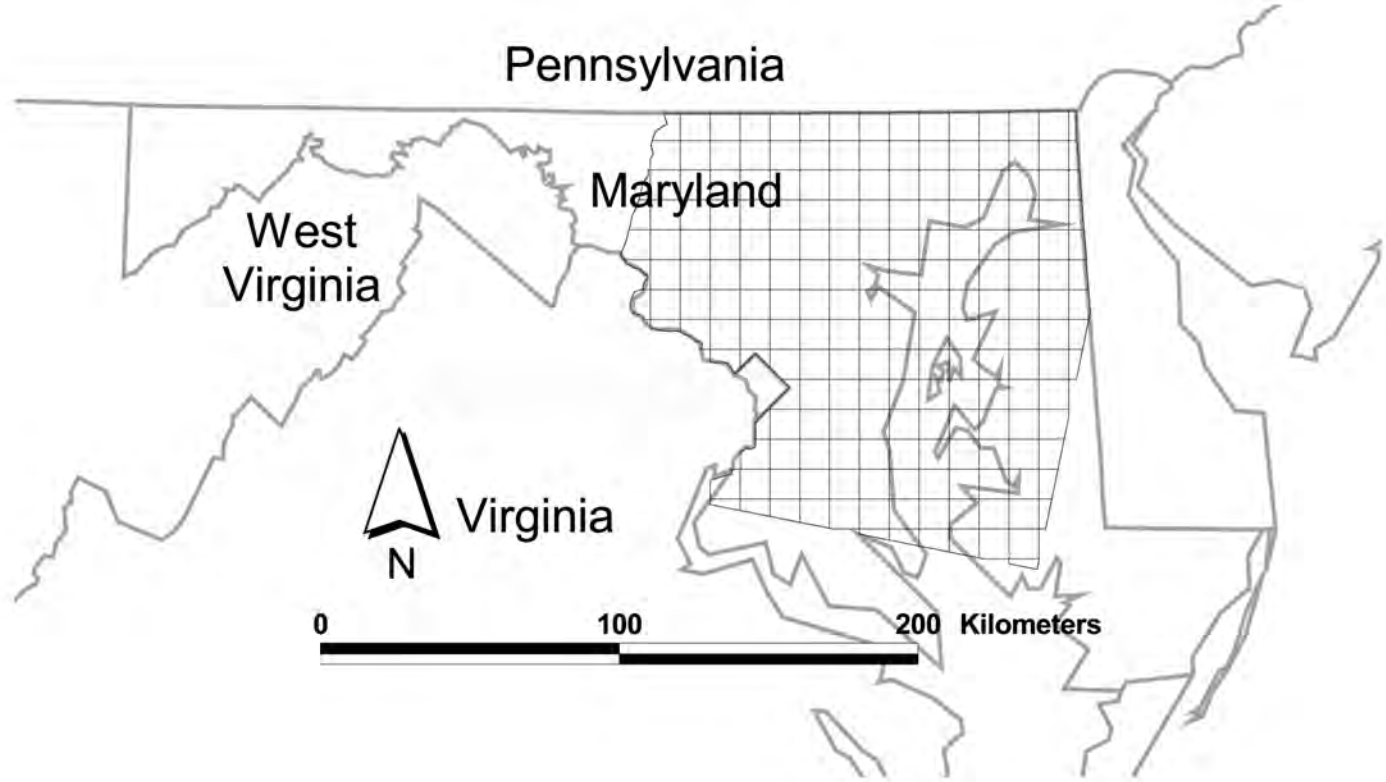


Figure 1. Study area for imperviousness estimates (grid sampling cell size: 10 km × 10 km).

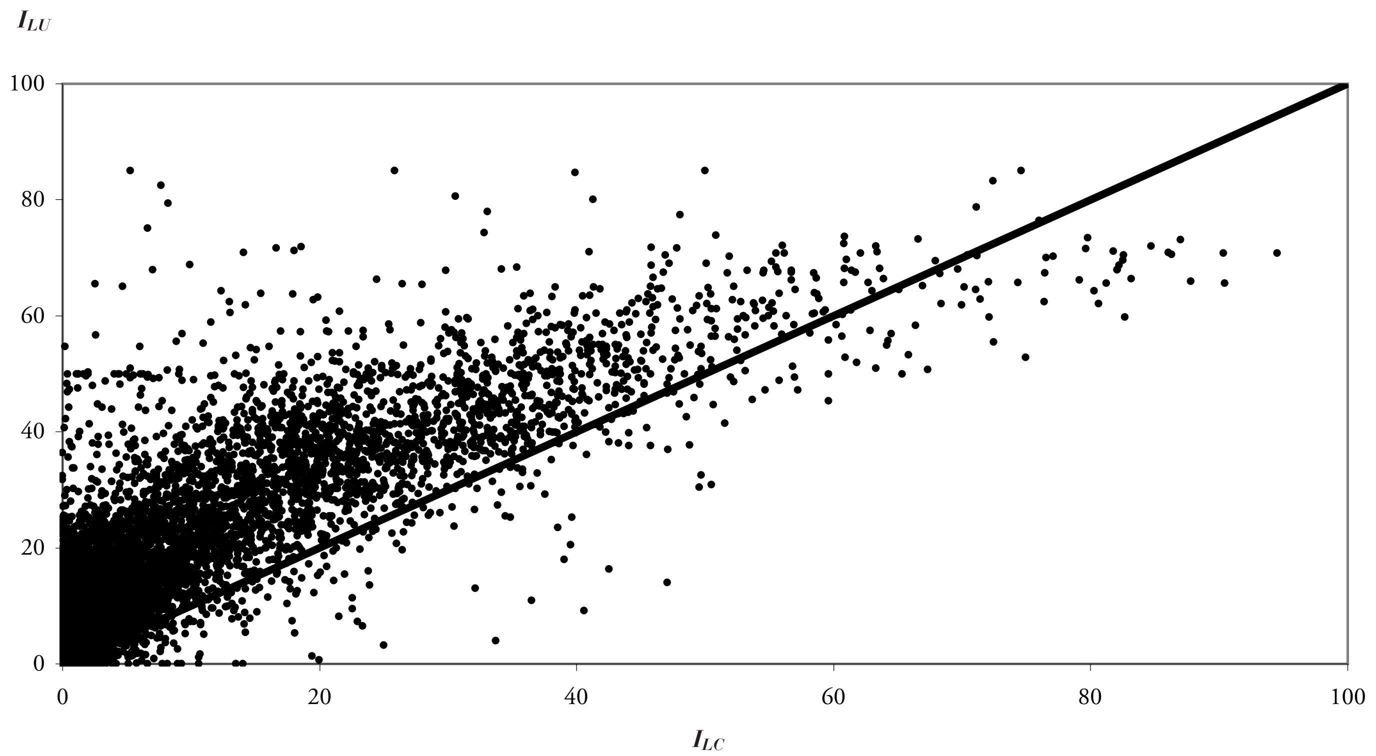


Figure 2. Aggregate grid cell percent imperviousness derived from land use (vertical axis) versus aggregate grid cell percent imperviousness derived from land cover (horizontal axis) for the region shown in Figure 1.

at the scale of the individual pixel (30 by 30 meters). Working within a GIS environment using a digital elevation model (DEM), we were able to determine flow directions at the same 30-meter resolution. With flow directions known, it is a straightforward process to identify the drainage area upstream from each individual pixel. Pixel A can thus be thought of as an outlet for its own upstream watershed, whose aggregate imperviousness can be calculated as the average of the local imperviousness values for all pixels upstream of pixel A.[2] In this way we can calculate the aggregate imperviousness of the area draining to each pixel of interest. For purposes of this study, we are interested in all pixels located along the stream network. Rather than measuring imperviousness at an arbitrarily selected watershed outlet, this approach measures imperviousness for each pixel located along the drainage network.

Figure 3 and Table 3 depict conditions in a small watershed in Howard County, Maryland. The overall watershed is 9.45 km^2 in area. Within this watershed are six subwatersheds ranging in size from 0.32 km^2 to 2.42 km^2. Measured at the outlet of the overall watershed shown in Figure 3, 28.8% of the channel length in this watershed exhibits aggregate imperviousness above a 10% threshold. However, as shown in Figure 3 and Table 3, these are far from uniformly distributed in space.

Subwatersheds C, D, and E exhibit variability that could be important for planning purposes. The identified channel in subwatershed C exceeds the 10% aggregate impervious area threshold everywhere, with a value of 18.5% aggregate imperviousness at the confluence of this subwatershed with the overall drainage network. In contrast, the drainage network in subwatershed D has aggregate imperviousness values less than the 10% threshold at all locations along the reach. From Table 3 we can see that the upper part of subwatershed E's channel (about 61%) exceeds the threshold, and the lower part falls below it, as does the aggregate imperviousness at the outlet (8.2%).

Figure 3 reveals that aggregate imperviousness changes only gradually along reaches with no significant tributaries, making it generally unimportant where along the stream imperviousness is compared to the threshold value. Four of the six subwatersheds are either wholly above or wholly below the 10% threshold. In the two other watersheds, aggregate imperviousness still changes gradually, but ends up exceeding the threshold slightly. For instance, in subwatershed B, the upstream end of the drainage network

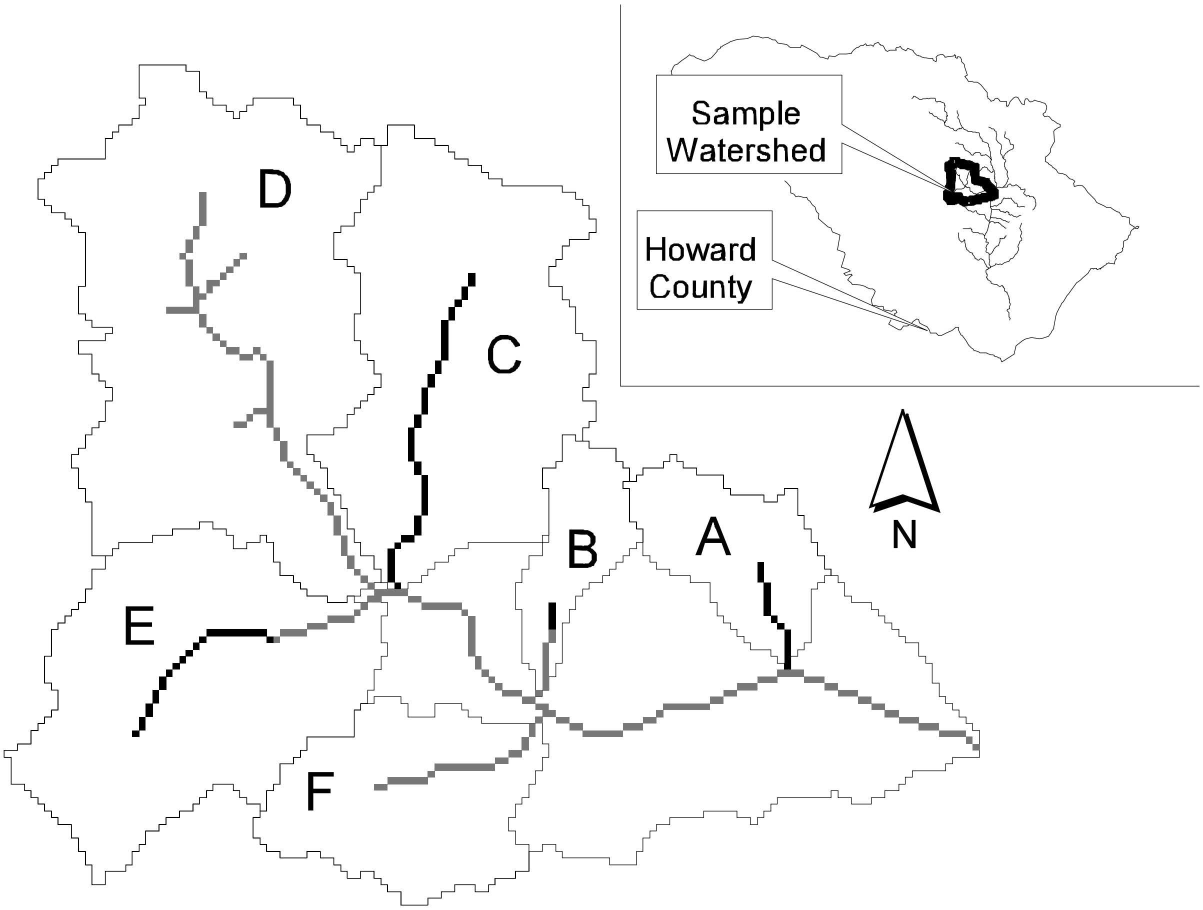


Figure 3. Illustration of a typical drainage network, with subwatersheds A through F. Darkest streams have an aggregate imperviousness (I_{LU}) exceeding 10%.

Note:
Inset shows location of watershed relative to Little Patuxent River and Howard County, MD.
▬ Streams draining areas with aggregate imperviousness (I_{LU}) > 10%
▬ Streams draining areas with aggregate imperviousness (I_{LU}) < or equal to 10%

has an aggregate imperviousness of 10.8%, which slowly diminishes to 8.9% at the outlet. In streams with tributaries, the location of the measurement could seriously mischaracterize the stream. Points of confluence with other streams often produce large changes in aggregate imperviousness if the joining reach is draining a watershed with much different aggregate imperviousness characteristics. This is the case for the confluence of subwatersheds A and C, which both exceed the threshold but join a drainage network which remains below the threshold. The opposite is true at the confluence of the watershed with the Little Patuxent River, as the joining watershed is below the threshold, but the Little Patuxent River (not shown in Figure 3) is above it.

Example: Howard County, Maryland

Our example measures imperviousness over the entire area of Howard County, Maryland. We do this both using 2002 generalized land use data from the MDP (2005), and using data from the 2001 National Land Cover Database (U.S. Geological Survey, 2004; Homer, Huang, Yang, Wylie & Coan, 2004). The former applies imperviousness coefficients to areas according to their land uses to calculate I_{LU}, while the latter estimates I_{LC} from land cover. The MDP data give an average imperviousness of 15.4% for the county, while the NLCD data indicates an average imperviousness of 5.7%.

Similar to the earlier example, here we examine again how imperviousness is distributed spatially in Howard

Table 3. Imperviousness and other characteristics of watersheds shown in Figure 3.

Watershed	**Drainage area (km^2)**	**Aggregate imperviousness at outlet (%)**	**Channel length above the 10% threshold (%)**
Subwatershed A	0.46	24.2	100.0
Subwatershed B	0.32	8.9	28.6
Subwatershed C	1.72	18.5	100.0
Subwatershed D	2.42	1.7	0.0
Subwatershed E	1.57	8.2	61.0
Subwatershed F	0.81	4.2	0.0
Overall watershed	9.45	9.8	28.8
Before confluence with Little Patuxent	46.18	23.4	85.4
After confluence with Little Patuxent	55.65	21.1	76.6

County. In this example, we identified the drainage network using 30-meter DEM data from the USGS National Elevation Dataset (U.S. Geological Survey, 2005a). We considered any pixel to be part of the drainage network if it drained an area greater than 0.25 km^2. This is approximately consistent with the 1:100,000 mapping of streams and rivers in the National Hydrography Dataset (U.S. Geological Survey, 2005b). At this scale, there were approximately 880 linear miles of drainage network identified in Howard County.

Using the methods described earlier, we identified those streams showing aggregate imperviousness in excess of thresholds of 5, 10, 15, 20, 25, and 30% imperviousness. The findings are summarized in Table 4. Focusing on the values for a 10% imperviousness threshold in this table shows that the two data sources indicate very different pictures of stream impacts. The MDP data show 57.2% of the drainage network in the county exceeds this threshold, while the NLCD data indicate only 18.5% exceed this threshold. We also identified stream segments in the county for which the MDP measure was above the examined threshold while the NLCD measure was below it, and expressed them as percentages of overall length for all stream segments in the far right column of Table 4. For a 10% imperviousness threshold, the two data sources were in disagreement for 38.8% of the length of all stream segments in the county. The table shows that a higher proportion of stream length violates the threshold when imperviousness is calculated with land use (MDP) data than with land cover (NLCD) data at all imperviousness thresholds, though the shares exceeding the threshold and the difference between the two measures both decrease as imperviousness thresholds increase.

Figure 4 shows Howard County, whose eastern extreme lies along a direct line between Baltimore, MD and Washington, DC, and is heavily urbanized. The degree of urbanization diminishes from east to west, with the western part of the county predominantly in agricultural or low-density residential land uses, adding another dimension to the imperviousness threshold issue. Figure 4a shows streams where I_{LU} is greater than 10%, while Figure 4b shows where I_{LC} is greater than 10%. These figures not only confirm the differences between the two measures in overall extent of presumably degraded streams, but also show that streams in the eastern, urbanized, part of the county are more likely to exceed the threshold than those in the less urbanized west. Figure 4c shows the locations where I_{LU} exceeds the 10% threshold and I_{LC} falls below the 10% threshold, mostly in the center of the county, which corresponds to the rural-urban fringe. Whether or not these fringe areas are above or below the imperviousness threshold depends on the data and methods used by the analyst.

Although the findings presented here are specific to the Howard County case, we believe that the issues illuminated through this case study apply more generally. We conclude that (1) imperviousness measures derived from land use (I_{LU}) and from land cover (I_{LC}) data can differ significantly, and (2) drainage patterns within watersheds can lead to profound differences in aggregate imperviousness from one stream reach to the next. As a result, we maintain that using a fixed threshold may lead to a poor assessment of actual watershed and stream conditions, and provide an unreliable guide to planning and policy.

Conclusions and Recommendations

In this study we compared measures of imperviousness based on two common forms of data describing the surface characteristics of the landscape. We also compared aggregate

Table 4. Fraction of total stream length in Howard County, MD draining areas exceeding indicated imperviousness thresholds.

Imperviousness threshold	**As measured based on NLCD (land cover) imperviousness**	**As measured based on MDP (land use) imperviousness**	**Exceeding threshold using MDP data, but not exceeding threshold using NLCD data**
5%	0.283	0.800	0.520
10%	0.185	0.572	0.388
15%	0.115	0.386	0.274
20%	0.072	0.279	0.208
25%	0.046	0.214	0.169
30%	0.030	0.146	0.117

imperviousness calculated for single points on a stream and along its entire length. Our results lead us to the following conclusions.

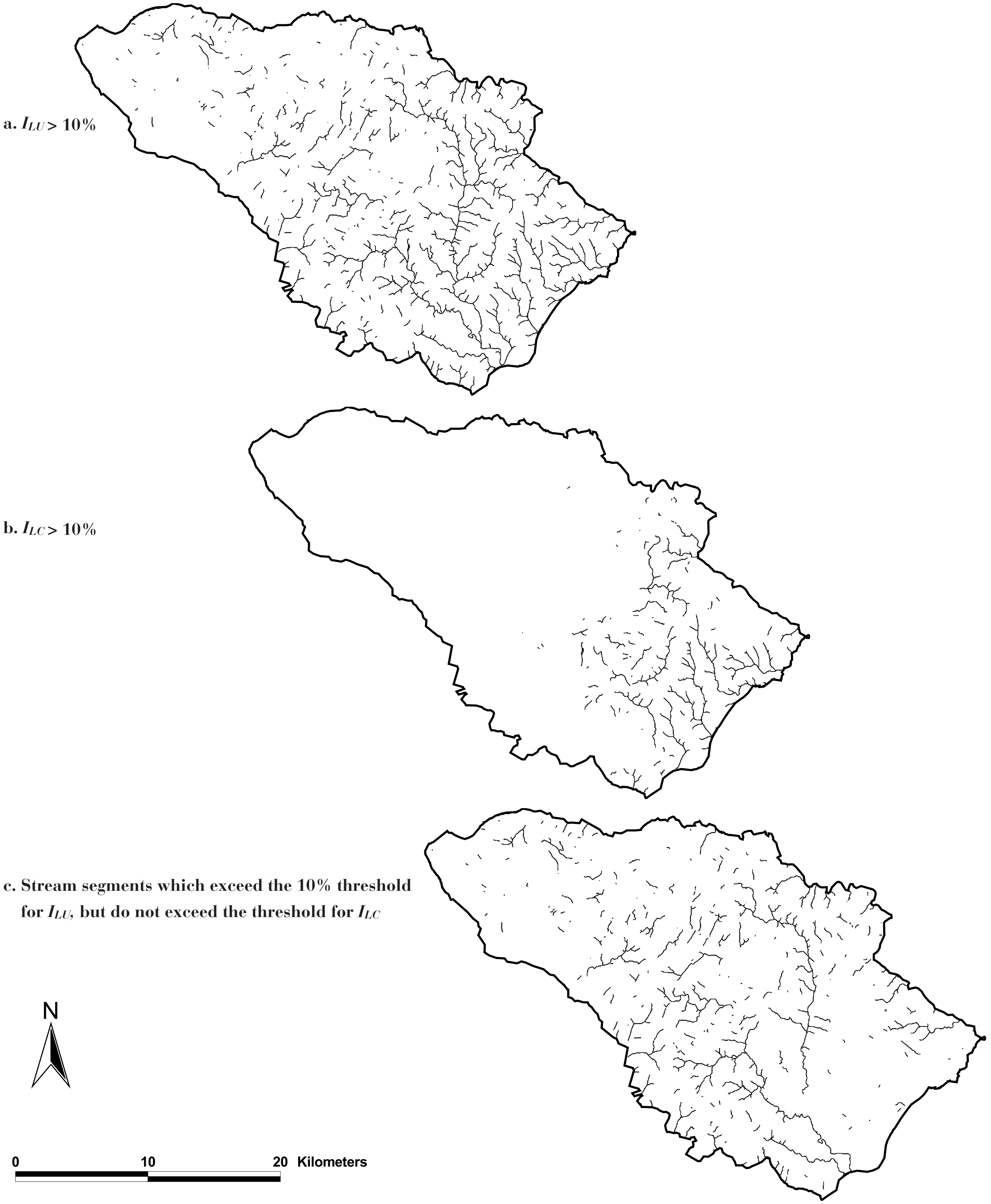
Conclusions

Different data sources and methods lead to different estimates of imperviousness. These results show that, depending on data sources and methods, estimates of imperviousness within a watershed can easily vary by as much as a factor of 1.5 or 2.0. To use such information responsibly, a decision maker must understand the methods being used to determine imperviousness both in the literature and in the region being managed. As discussed earlier, older studies tended to measure imperviousness based on land use using a coefficient method (I_{LU}). Newer studies tend to employ direct satellite measurements of imperviousness based on land cover (I_{LC}). Because these methods can differ so significantly, it is important to clearly state the methods used to generate estimates of imperviousness whenever findings are compared, and to make them consistent. As an aside, our anecdotal review of existing literature showed that many studies do not describe how they determined imperviousness in sufficient detail to permit appropriate comparison with other work, compromising the value of these studies for the future.

Our findings suggest there should be a standard measure for imperviousness. Once a standard is identified, data from existing studies can be adjusted, if necessary, to be consistent with the new standard. Adjustment methods would likely resemble our equations 1 and 2. If new studies all documented their methods and were consistent with this standard, comparing results across many studies would be easier and more meaningful. Since past research has not always been clear about the methods used to develop estimates of imperviousness, it is not clear that it is appropriate to draw conclusions from comparisons with or among past studies, or to apply their findings to planning strategies.

Point measurements do not characterize entire streams. Point measurements of imperviousness taken at arbitrary locations in the stream network are of limited value. Finding that aggregate imperviousness at a specific location is below the threshold does not necessarily imply that all locations in the watershed are below the threshold. Rather, such a measurement indicates the average imperviousness of all land area draining to that point, masking local extremes within the watershed. Good (below threshold) conditions at a downstream location can dominate this average even if poor (above threshold) conditions exist locally upstream, and the opposite is also true. As was illustrated in the Howard County, Maryland example summarized by Table 4, it is important to quantify stream conditions based on all stream reaches within a region rather than only isolated points at the outlets of major watersheds.

Planners should beware of misusing imperviousness thresholds. Planners at all levels of government know imperviousness thresholds are linked to stream degradation and have begun to act upon this linkage. Arnold and Gibbons (1996) cite imperviousness-based policies in Florida, Texas, and Maine as examples of using thresholds to guide or control land development. Federal agencies, such as the EPA (EPA, 1993, 2004), and nongovernmental organizations such as the Center for Watershed Protection (Schueler, 1994) have advocated planning and regulation based on watersheds. Although such actions are well intended, development should be planned so that it does not push streams over the imperviousness threshold at any scale. Failure to understand watershed organization and scale can result in land development that is well over the imperviousness threshold in one area, as in subwatersheds A and



a. $I_{LU} > 10\%$

b. $I_{LC} > 10\%$

c. Stream segments which exceed the 10% threshold for I_{LU}**, but do not exceed the threshold for** I_{LC}

Figure 4. Streams exceeding the 10% imperviousness threshold in Howard County, MD.

C, and to a lesser extent, B and E, in the example in Figure 3. If we considered only the overall watershed in this example, we would conclude that conditions were acceptable, although nearly 30% of the stream lengths in the watershed exceeded the 10% imperviousness threshold. Planners need the countywide view offered in Figure 4, including streams draining areas as small as 0.25 km^2 and as large as 350 km^2, to make appropriate assessments of, and plans for, watersheds under their jurisdiction.

Recommendations for Imperviousness-Based Land Use Planning

The problem with the threshold-based planning approach is that it represents an over-simplification of the imperviousness research. As a consequence, some planners may be making matters worse, though they intend well. We make the following recommendations that are consistent with the literature on imperviousness and that should be useful to planners.

Consider a safety factor. The literature indicates some uncertainty regarding the precise value at which stream degradation begins, and our research shows that there is also uncertainty in estimates of imperviousness for specific watersheds. We recommend adding a conservative safety factor of 2 or 3% (i.e., allowing only 7 or 8% total imperviousness) to provide a buffer against these sources of uncertainty when planning future development.

Place new development strategically in urbanized areas. In highly urbanized areas some streams drain areas that are well over the 10% threshold by any measure (as for example subwatersheds A and C in Figure 3). Steering more development to such areas would have small negative consequences at the margin, compared to directing the same development to watersheds where the streams are currently below the threshold and are ecologically healthy.

Protect relatively undisturbed natural areas. Planners should identify water resources that remain in a relatively undisturbed condition. Although in this article we have generally focused on 10% imperviousness as a threshold, some particularly sensitive species show decline well before this degree of imperviousness is reached. In regions where the current imperviousness is below 5% (see subwatershed D in Figure 3), consider preserving the landscape, particularly where rare or unique aquatic species are present.

Avoid development near headwaters. As illustrated earlier in Figure 3, there is a strong spatial component to the aggregate imperviousness measure. Planners should steer new development away from headwater locations, directing it instead to places where the local drainage would contribute immediately to a larger stream (see, e.g., the main channel downstream of the confluence with subwatersheds A, B, or F in Figure 3) The incremental influence of such development on the river is small because the upstream watershed is large, with relatively low aggregate imperviousness.

Mitigate impacts. Various methods have been developed to mitigate the negative effects of increased imperviousness. Best management practices (BMPs) such as grassed swales, green rooftops, rain gardens, porous pavement, and other forms of onsite detention should be used in all new development. Many of these BMPs work by disconnecting impervious areas from the urban drainage infrastructure, allowing storm runoff more opportunity to infiltrate. The result is a reduction in the effective imperviousness of the proposed new development, and is especially valuable in watersheds where the overall aggregate imperviousness is relatively low (below 10%).

Future Research

Future research is needed and likely both on how and where to locate development to minimize impacts on streams, and on effective methods for mitigating impacts. There has been some work on optimizing the location of urban development to minimize environmental impacts (Moglen, Gabriel, & Faria, 2003; Perez-Pedini, Limbrunner, & Vogel, 2005; Veith, Wolfe, & Heatwole, 2003), but more work is needed to develop practical tools that planners can use. There has also been significant research on quantifying the benefits of disconnected imperviousness and the effectiveness of many stormwater BMPs (Potter, 2003; Strecker, Quigley, Urbonas, Jones, & Clary, 2001). However, more such work is needed to predict BMP effectiveness when local conditions, techniques, goals, maintenance, and monitoring vary. Progress on these topics should help guide ecologically friendly land development.

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Notes

1. For more comprehensive reviews of this literature, see Schueler (1994) and Capiella and Brown (2001).

2. Some researchers have argued that connected imperviousness (imperviousness that is directly linked to the drainage network is more closely tied to environmental degradation than aggregate imperviousness. We did not examine connected imperviousness in this study because calculation of this quantity requires very high-resolution topographic data and information about the underground storm drainage network which, in general, is difficult to obtain for any significant spatial scale. (See also the article by Keeley in this issue.)

References

Andersen, D. G. (1970). *Effects of urban development on floods in Northern Virginia* (U.S. Geological Survey Water Supply Paper 2001-C). Washington, DC: United States Government Printing Office.

Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). *A land use and land cover classification system for use with remote sensor data* (U.S. Geological Survey Professional Paper 964). Washington, DC: United States Government Printing Office.

Arnold, C. L., Jr., & Gibbons, C. J. (1996). Impervious surface coverage: The emergence of a key environmental indicator. *Journal of the American Planning Association*, *62*(2), 243–258.

Booth, D. B., & Reinelt, L. (1993, March). Consequences of urbanization on aquatic systems—measured effects, degradation thresholds, and corrective strategies. In *Proceedings*, *Watershed '93: A National Conference on Watershed Management* (pp. 545–550). Washington, DC: U.S. Government Printing Office.

Booth, D. B., Hartley, D., & Jackson, R. (2002). Forest cover, impervious area, and the mitigation of stormwater impacts. *Journal of the American Water Resources Association*, *38*(3), 836–845.

Cappiella, K., & Brown, K. (2001). Land use and impervious cover in the Chesapeake Bay region. *Watershed Protection Techniques*, *3*(4), 835–840.

Carter, W. R. (1961). *Magnitude and frequency of floods in suburban areas* (U.S. Geological Survey Professional Paper 424-B). Washington, DC: U.S. Government Printing Office.

Homer, C., Huang, C. Q., Yang, L. M., Wylie, B., & Coan, M. (2004). Development of a 2001 national land-cover database for the United States. *Photogrammetric Engineering and Remote Sensing*, *70*(7), 829–840.

James, L. D. (1965). Using a digital computer to estimate the effects of urban development on flood peaks. *Water Resources Research*, *1*(2), 223–234.

Klein, R. D. (1979). Urbanization and stream quality impairment. *Water Resources Bulletin*, *15*(4), 948–963.

Leopold, L. B. (1968). *Hydrology for urban land planning: A guidebook on the hydrologic effects of land use* (U.S. Geological Survey Circular 554). Washington, DC: United States Government Printing Office.

Maryland Department of Planning. (2005). *Maryland Department of Planning land use mapping*. Retrieved October 14, 2005, from http://www.mdp.state.md.us/landmapping.htm

May, C. W., Horner, R. R., Karr, J. R., Mar, B. W., & Welch, E. B. (1997). Effects of urbanization on small streams in the Puget Sound lowland ecoregion. *Watershed Protection Techniques*, *2*(4), 483–494.

Miltner, R. J., White, D., & Yoder, C. (2004). The biotic integrity of streams in urban and suburbanizing landscapes. *Landscape and Urban Planning*, *69*(1), 87–100.

Moglen, G. E., Gabriel, S. A., & Faria, J. A. (2003). A framework for quantitative smart growth in land development. *Journal of the American Water Resources Association*, *39*(4), 947–959.

Natural Resources Conservation Service. (2005). *NRI information*. Retrieved October 14, 2005, from http://www.md.nrcs.usda.gov/technical/nritext.html

Perez-Pedini, C., Limbrunner, J. F., & Vogel, R. M. (2005). Optimal location of infiltration-based best management practices for storm water management. *Journal of Water Resources Planning and Management*, *131*(6), 441–448.

Potter, K. W. (2003). Managing stormwater at the source. *Proceedings, Wisconsin Academy of Sciences, Arts, and Letters*, *90* (pp. 67–74). Madison, WI: Wisconsin Academy of Sciences, Arts, and Letters.

Schueler, T. R. (1994). The importance of imperviousness. *Watershed Protection Techniques*, *1*(3), 100–111.

Soil Conservation Service. (1986). *Urban hydrology for small watersheds* (Technical Release 55). Washington, DC: U.S. Department of Agriculture.

Strecker, E. W., Quigley, M. M., Urbonas, B. R., Jones, J. E., & Clary, J. K. (2001). Determining urban stormwater BMP effectiveness. *Journal of Water Resources Planning and Management*, *127*(3), 144–149.

U.S. Environmental Protection Agency. (1993). The watershed protection approach: Annual report 1992 (#EPA840-S-93-001). Washington, DC: U.S. Environmental Protection Agency, Office of Water.

U.S. Environmental Protection Agency. (2004). Protecting water resources with smart growth (#EPA231-R-04-002). Washington, DC: U.S. Environmental Protection Agency, Office of Policy, Economics, and Innovation.

U.S. Geological Survey. (2004). *National land cover dataset 2001 (NLCD). EROS Data Center, Sioux Falls, South Dakota* [Data file]. Available from U.S. Geological Survey at http://seamless.usgs.gov/website/seamless/products/nlcd01.asp

U.S. Geological Survey. (2005a). *National elevation dataset, EROS Data Center, Sioux Falls, South Dakota* [Data file]. Available from U.S. Geological Survey at http://ned.usgs.gov/

U.S. Geological Survey. (2005b). *National hydrography dataset homepage, Rolla, Missouri*. Available from U.S. Geological Survey at http://nhd.usgs.gov/

Viessman, W., Jr. (1966). The hydrology of small impervious areas. *Water Resources Research*. *2*(3), 405–412.

Veith, T. L., Wolfe, M. L., & Heatwole, C. D. (2003). Optimization procedure for cost effective BMP placement at a watershed scale. *Journal of the American Water Resources Association*, *39*(6), 1331–1343.

Wang, L. Z., Lyons, J., & Kanehl, P. (2001). Impacts of urbanization on stream habitat and fish across multiple spatial scales. *Environmental Management*, *28*(2), 255–266.

Yang, L., Chengquan, H., Collin, G., Homer, B., Wylie, B. K., & Coan, M. J. (2003). An approach for mapping large-area impervious surfaces: Synergistic use of Landsat 7 ETM+ and high spatial resolution imagery. *Canadian Journal of Remote Sensing*, *29*(2), 230–240.