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ESTIMATING THE EXTENT OF IMPERVIOUS SURFACES AND TURF GRASS ACROSS LARGE REGIONS[1]

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ABSTRACT: The ability of researchers to accurately assess the extent of impervious and pervious developed surfaces, e.g., turf grass, using land-cover data derived from Landsat satellite imagery in the Chesapeake Bay watershed is limited due to the resolution of the data and systematic discrepancies between developed land-cover classes, surface mines, forests, and farmlands. Estimates of impervious surface and turf grass area in the Mid-Atlantic, United States that were based on 2006 Landsat-derived land-cover data were substantially lower than estimates based on more authoritative and independent sources. New estimates of impervious surfaces and turf grass area derived using land-cover data combined with ancillary information on roads, housing units, surface mines, and sampled estimates of road width and residential impervious area were up to 57 and 45% higher than estimates based strictly on land-cover data. These new estimates closely approximate estimates derived from authoritative and independent sources in developed counties.

(KEY TERMS: impervious surface; turf grass; land cover; Chesapeake Bay.)

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INTRODUCTION

In this article, we introduce a new method to consistently estimate the area of impervious surface and turf grass area across the Chesapeake Bay watershed over a 22-year timeframe. While the methods were developed to improve the accuracy of the Chesapeake Bay Watershed Model (WSM) (Shenk and Linker, this issue) and to inform the development of state Watershed Implementation Plans required in the Chesapeake Bay Total Maximum Daily Load (TMDL) (USEPA, 2010b), they are largely based on nationally available datasets and are therefore transferrable to other parts of the United States (U.S.).

Land cover, use, and management are essential data inputs to WSMs because they reflect sources of nutrients and sediment and directly impact watershed hydrology (Booth *et al.*, 2002; Moglen and Kim, 2007; Law *et al.*, 2009). Changes in the estimated area of land cover, use, and management practices directly impact modeled estimates of nutrient and sediment loads to the Chesapeake Bay from all sources. For watershed and stormwater management, accurately assessing the extent of impervious surfaces (e.g., roads, rooftops, and parking lots) and pervious developed surfaces (e.g., lawns and landscaped areas) is critical (Law *et al.*, 2009). Impervious surfaces route precipitation to streams directly through storm drains or indirectly through overland flow. The

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percent area of impervious surfaces in a watershed is correlated with increases in stream flow flashiness and declines in stream benthic conditions (Snyder *et al.*, 2005; Jacobson, 2011). As streamflow volume and velocity increase, so do the hydraulic forces causing streambank and bed erosion and the transport of sediment downstream (Booth *et al.*, 2002). Pervious surfaces in developed areas are by definition not impervious, but they may function similarly to impervious surfaces when compacted during the development process or when saturated during large storm events (Gregory *et al.*, 2006; Law *et al.*, 2009). Nutrients from fertilizers applied to pervious developed surfaces such as turf grass may migrate to streams and groundwater depending on fertilizer nutrient concentrations, application and plant uptake rates, soil characteristics, and weather (Law *et al.*, 2004). Given the dominant use of turf grass as ground cover in developed areas and its likely presence under trees in small-lot residential subdivisions, we consider pervious developed surfaces to be mostly composed of turf grass and refer to them as "turf grass" in this article.

While both impervious surfaces and turf grass can be accurately measured using field mapping or high-resolution imagery interpretation techniques (Slonecker and Tilley, 2004), applying such approaches across the 165,760-km^2 Chesapeake Bay watershed can be labor and cost intensive. Moreover, the development of accurate retrospective estimates suitable for comparing over time and space is hindered by the lack of historical high-quality high-resolution imagery. The use of Landsat-derived land-cover data to characterize the developed area of large watersheds is supported by other studies (Goetz *et al.*, 2004; Jennings *et al.*, 2004; Jacobson, 2011) and is reproducible. For these reasons, the U.S. Geological Survey published the Chesapeake Bay Land Cover Data (CBLCD) series for the years 1984, 1992, 2001, and 2006 (Irani and Claggett, 2010). The CBLCD series were developed to provide a spatially consistent and temporally comparable set of land-cover information to support Chesapeake Bay restoration objectives and to provide data on impervious surfaces and turf grass as inputs to the calibration of the Chesapeake Bay Program's Phase 5.3.0 (P530) WSM used to establish the Chesapeake Bay TMDL (USEPA, 2010a, b).

Landsat-derived land-cover data, however, have known limitations representing impervious surfaces associated with low-density residential development (McCauley and Goetz, 2003; Jantz *et al.*, 2005; Irwin *et al.*, 2007; Moglen and Kim, 2007; Jones and Jarnagin, 2009) and narrow linear features such as 2-lane roads (Lu and Weng, 2004). In recognition of these limitations and the fact that the estimates of impervious surface used in the P530 were 18% lower than previous estimates, which relied on the 2001 National Land Cover Dataset (NLCD) impervious surface data in combination with the CBLCD and ancillary data on road density and residential housing (Peter R. Claggett, 2009, unpublished data), the Chesapeake Bay Program Partners requested a more complete accounting of impervious surface and turf grass area to inform the current Phase 5.3.2 (P532) WSM (USEPA, 2010c).

METHODS

Estimating Impervious Surface and Turf Grass Area for the P530 WSM

For the P530 WSM, only the CBLCD and NLCD impervious data were used to assess impervious surface and turf grass area. The CBLCD series were derived from Landsat satellite imagery and consist of 30 meter (m)-resolution raster datasets classified into 16 land-cover classes (Table 1) using the level-2 Anderson classification system (Anderson *et al.*, 1976). To estimate impervious area, the areas of the four CBLCD developed classes, High-Intensity Developed (HID), Medium-Intensity Developed (MID), Low-Intensity Developed (LID), and Developed Open Space (DOS) were calculated using ESRI® ArcGIS™ (Redlands, California) software and multiplied by watershed-wide estimates of the mean percent

TABLE 1. Chesapeake Bay Land Cover Data Series Classification.

Level	Class Name	Code	Level	Class Name	Code
11	Open Water	OW	42	Evergreen Forest	EF
21	Developed Open Space	DOS	43	Mixed Forest	MF
22	Low-Intensity Developed	LID	52	Scrub/Shrub	SS
23	Medium-Intensity Developed	MID	71	Grassland/Herbaceous	GH
24	High-Intensity Developed	HID	81	Pasture/Hay	PH
31	Barren	BN	82	Cultivated Crops	CC
32	Unconsolidated Shore	US	90	Woody Wetlands	WW
41	Deciduous Forest	DF	95	Emergent Wetlands	EW

impervious cover for each developed class derived from the NLCD (Table 2). The remaining non-impervious portion of each developed pixel was considered to be pervious and consist mostly of turf grass. Milesi *et al.* (2005) found a strong inverse relationship between the fractional impervious and fractional turf grass area within a 1-km grid. While urban trees may be present within a partially developed 30-m cell, the full extent of urban tree canopy is not accurately represented in 30-m resolution land-cover products (Moskal *et al.*, 2011) and the potential presence of urban trees does not preclude the presence of lawns underneath the canopy.

Estimating Impervious Surfaces and Turf Grass Area for the P532

The process for developing new estimates of impervious surface and turf grass as inputs to the P532 WSM involved refining the characterization of developed lands in the CBLCD, dividing the watershed into three distinct analysis zones, estimating impervious surface and turf grass areas separately within each zone, and summarizing the results within each of the 2,692 WSM modeling segments that have a median size of 3,200 hectares (ha) and encompass the entire Chesapeake Bay watershed and adjoining counties (Figure 1). Distinguishing separate zones was necessary because the best available data for estimating impervious and turf grass area varied among zones (Table 3). Therefore, different methods and data were used in the three zones that were loosely characterized as "urban," "suburban," and "rural" for the purposes of this study (Figure 2). The terms "urban," "suburban," and "rural" were not meant to conform to or reflect existing definitions of such areas developed by the U.S. Census Bureau or other entities (U.S. Census Bureau, 2002). Rather they merely represented zones where different analytical techniques and data were employed to estimate impervious and turf grass areas. Large patches of contiguous developed lands in the 2006 CBLCD were used to define and map the urban zone and include the majority of places that are conventionally viewed as "suburban." Outside of the urban zone, where the potential was high for under-detection of impervious surfaces and turf grass in the CBLCD, secondary road density was used to map the suburban zone. The suburban zone is small because it represents only residential developments underrepresented in the land-cover data. By default, all remaining lands were considered to be in the rural zone. ESRI® ArcGIS™ software was used to conduct all of the spatial analyses discussed in this article.

Refining the Representation of Developed Lands in the CBLCD

The CBLCD was refined to improve the spatial representation of developed "land use" in contrast to developed "land cover." The refinements were conducted to address some of the common limitations of Landsat-derived land-cover datasets in representing institutional properties and residential subdivisions. They were also performed to address potential misclassifications of developed lands as barren or surface mines.

Mapping Institutions. Identifying institutional properties with Landsat imagery results in similar issues and concerns as those associated with mapping residential areas. Institutional properties used in this study include airports, airport roads, cemeteries, golf courses, hospitals, industrial complexes, shopping centers, sports complexes, and universities/colleges. While some of these features, such as airports and shopping centers are identifiable with Landsat imagery as LID, MID, or HID, associated small buildings, narrow roads, and sidewalks are often missed and adjacent lawn areas are commonly confused with pasture or cropland. Recreational fields on school properties in addition to cemeteries and landfills are particularly prone to misclassification as pasture or cropland. For these reasons, the above-mentioned institutional features in the 2006 NAVTEQ Landuse database (NAVTEQ, 2006) were overlaid on the CBLCD and used to reclassify underlying herbaceous and barren land-cover classes (e.g., barren, scrub/shrub, grassland, pasture, and cropland) to DOS based on the assumption that sidewalks, narrow roads, and other features typically associated with the DOS class are also typical characteristics of

TABLE 2. National Land Cover Dataset Impervious Surface and Turf Grass Coefficients for Developed Land Cover Classes in the Chesapeake Bay Watershed.

Land Cover Class	Description	Impervious Surface (%)	Turf Grass (%)
Developed Open Space	Ball fields and parks	5.82	94.18
Low-Intensity Developed	½ acre lot residential areas	20.18	79.82
Medium-Intensity Developed	Multifamily residential areas, townhomes	44.60	55.40
High-Intensity Developed	Commercial areas	71.04	28.96

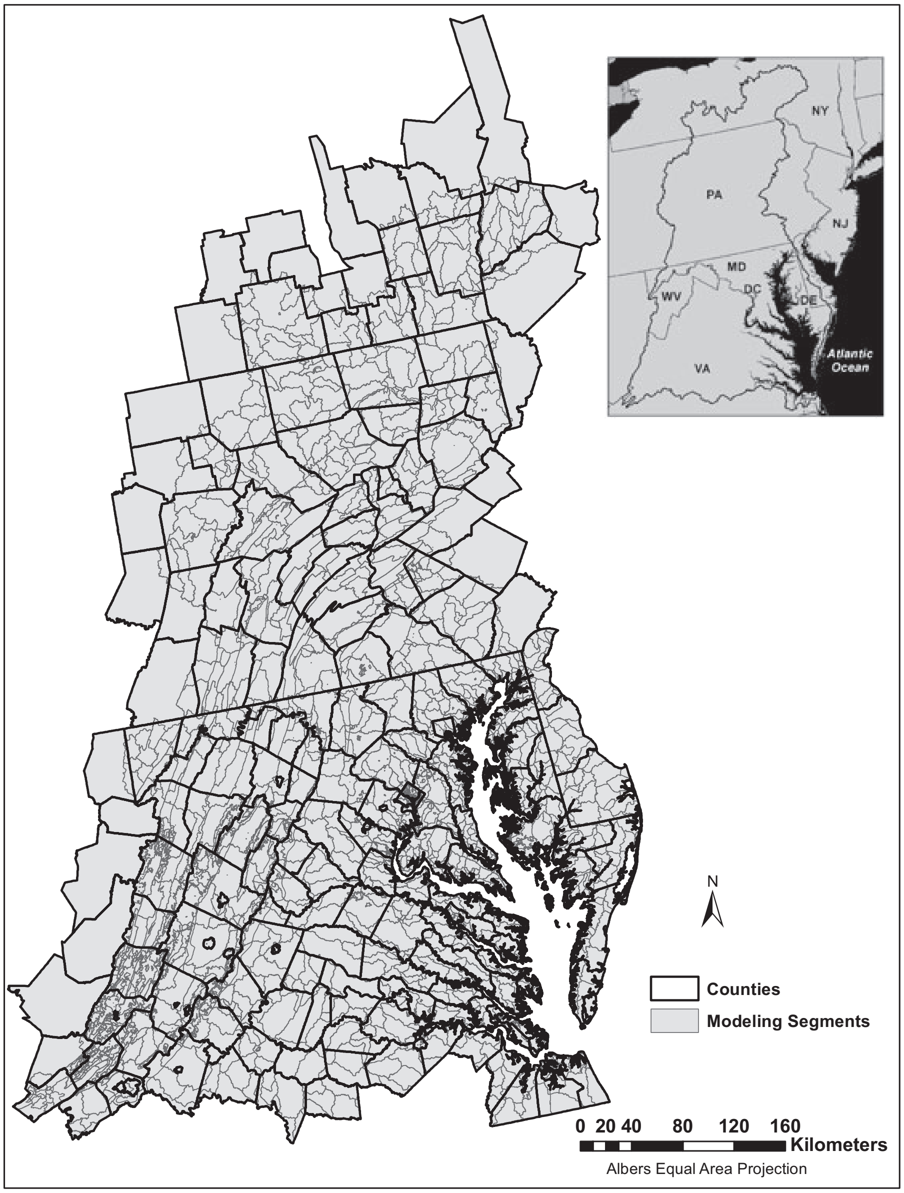

FIGURE 1. Chesapeake Bay Program Phase 5.3.2 Watershed Model Segmentation.

TABLE 3. General Equations Used to Estimate Impervious Surface and Turf Grass Area for P532.

Urban zone	Impervious surface area =	Area of developed land per CBLCD land-cover class * NLCD coefficients of impervious surface per class
	Turf grass area =	Area of developed land per CBLCD land-cover class * (1 − NLCD coefficients of impervious surface per class)
Suburban zone	Impervious surface area =	Suburban road area + (# of single-detached houses * coefficients of impervious surface for suburban residential lots)
	Turf grass area =	Total suburban area − (suburban impervious surface area + suburban forests)
Rural Zone	Impervious surface area =	Rural road area + (# single-detached houses * coefficients of impervious surface for rural residential lots)
	Turf grass area =	([# of single-detached houses * mean rural residential lot size] − [# of single-detached houses * coefficients of impervious surface for rural residential lots]) * proportion of herbaceous cover to forest cover along residential roads

Note: CBLCD, Chesapeake Bay Land Cover Data; NLCD, National Land Cover Dataset.

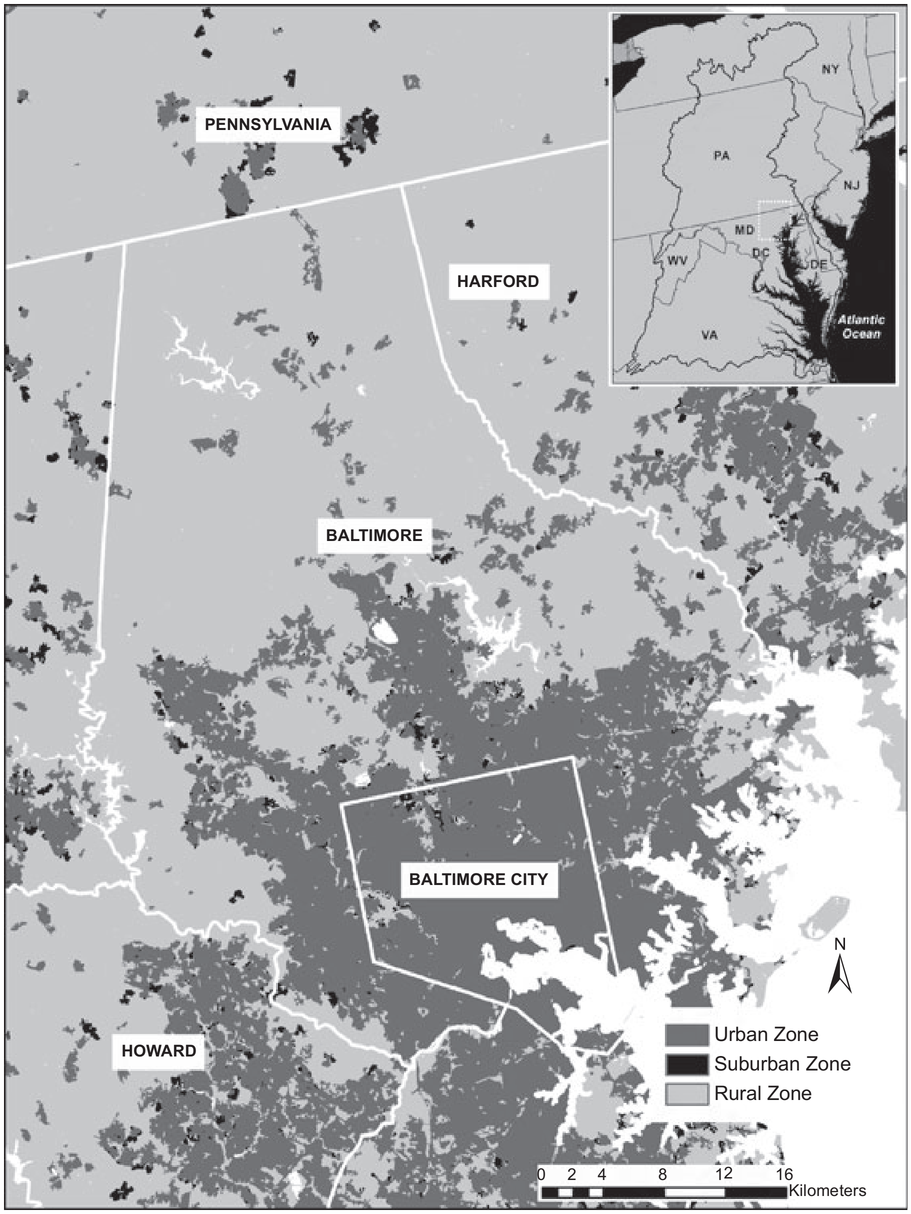

FIGURE 2. Example of Urban, Suburban, and Rural Zones in Baltimore County and Surrounding Areas.

institutional properties. However, this assumption was not tested as part of this study.

Mapping Low to Medium-Density Residential Areas. Generally, the land within large residential lots (>0.2 ha) is a combination of lawns and landscaped areas planted with herbs, shrubs, and trees. These land-cover types are typically classed as pasture, cropland, or forests in Landsat-derived land-cover datasets because of their similar spectral characteristics. To identify and map low to medium-density residential subdivisions, all potential residential roads were identified from the 2006 NAVTEQ Streets database. Residential roads included roads that have low to moderate traffic volumes and permit automobile access. Service roads, highway access ramps, bridges, and tunnels were excluded. The line density of residential roads was calculated for circular radii of 100, 200, 500, and 1,000 m, each resulting in a 30-m resolution raster dataset of residential road density. Each of these datasets was classified using Jenks' natural breaks algorithm (Jenks, 1967) and overlaid on aerial images to visually determine the optimum radius and classification threshold for mapping residential subdivisions.

As a result of this exercise, the length of roads within a 200-m radii circle was determined to best approximate the extent of residential subdivisions while minimizing commission errors (classifying undeveloped areas as residential) and omission errors (excluding residential lands from the residential class). The 200-m road-density raster was divided into nine natural break classes. Classes six through nine represented areas of highest road density and were expanded into adjacent lower density classes four and five to establish a potential residential extent. Residential roads intersecting these potential residential areas were buffered by 60 m, clipped to the potential residential extent, and then expanded 100 m into adjacent buffered residential road areas. A 60-m buffer width was chosen based on the assumed average lot size of 0.2 ha, which roughly corresponds to a 35-m × 60-m rectangular lot with 35 m of road frontage. The resulting raster dataset of potential residential land use was overlaid on the 2006 CBLCD and incorporated into it by reclassifying all developed, cropland, pasture, grassland, scrub/shrub, and forest CBLCD classes overlapping residential areas and outside of urban areas to a new class called "residential." The remaining CBLCD land-cover classes (e.g., open water, unconsolidated shore, and emergent wetlands) were unchanged. Barren and undeveloped residential pixels within 30 m of urban areas were reclassified to match the nearest urban developed pixel value (21-24) based on the assumption that these areas were more likely to exhibit hydrologic functions typical of developed areas compared to functions typical of barren, forest, or agricultural land uses. The resulting raster dataset was renamed the Phase 5.3.2 Land Cover Dataset (P532).

Mapping Forests in Low-Density Residential Areas. Landsat-derived land-cover datasets like the CBLCD and NLCD include four "forest" classes that represent areas with mature tree canopy and a scrub/shrub class that, in the Mid-Atlantic region, typically represents the early to mid-successional stages of forest growth (Homer *et al.*, 2004). The characteristics of the forest understory are not evident in the CBLCD because dense tree canopy obscures the underlying land cover. In residential areas, the understory is assumed to be composed of impervious surfaces and/or turf grass. In large unfragmented wooded areas, however, the understory is assumed to be unmanaged with hydrologic functions more similar to forests than lawns. Based on these assumptions, interior forest/scrub areas within patches greater than or equal to 1 ha in the original 2006 CBLCD that were classified as residential in the P532 were reclassed back to their original forest or scrub/shrub values. To identify interior forest/scrub areas, contiguous CBLCD forest and scrub/shrub pixels were grouped together and buffered inward by 30 m. The interior patches were then fragmented using a 30-m raster dataset representing all roads in the 2006 NAVTEQ Streets database. The remaining unfragmented interior forest and scrub/shrub areas greater than or equal to 1 ha were then reincorporated back into the P532.

Correcting Misclassifications of Developed Lands as Barren or Surface Mines. The CBLCD barren class generally represents areas denuded of vegetation. Such areas might be quarries, rock outcrops, surface mines, clear-cut forests, beaches, mudflats, areas cleared for agriculture, or represent the initial stages of residential or commercial developments. Likewise, areas classed as developed could actually be quarries or surface mines. To accurately estimate the extent of developed lands in the Chesapeake Bay watershed in 2006, misclassification among the CBLCD developed, extractive, unconsolidated shore, and barren land-cover classes had to be minimized.

First, discrepancies between barren and extractive were addressed using state mining permit data that were assumed to be spatially and categorically accurate. The CBLCD does not contain an "extractive" (quarries and surface mines) land-cover class. To fill this data gap, spatial information on the type and extent of permitted, restored, and active surface mines was obtained from each state (Table 4). Only West Virginia and Delaware provided spatial polygon information delineating the size and shape of their mining operations. New York, Pennsylvania,

TABLE 4. Surface Mine Data Sources.

State	Agency	Dataset
Delaware	Office of Management and Budget Geographic Data Committee	2007 Extractive
Maryland	Department of Environment Minerals, Oil and Gas Division	2009 Surface Mines
New York	Department of Environmental Conservation Division of Mineral Resources	Geographic Information System (GIS) Mines through 2009
Pennsylvania	Department of Environmental Protection Bureau of Mining and Reclamation	Reclaimed or Forfeited Mines in PA, 2009-09-29
Virginia	Department of Mines, Minerals and Energy	Active Permits
West Virginia	Office of Abandoned Mine Lands and Reclamation (AMLR) of the West Virginia (WV) Department of Environmental Protection	WV Permit Boundaries

Maryland, and Virginia provided attributed point locations.

All six states reported permitted acres and, except for Maryland, all reported some measure of active or disturbed acres (USEPA, 2010a, b). West Virginia provided a polygon dataset delineating the extent of disturbed areas. Delaware provided a detailed land-cover map with an extractive class. Pennsylvania's dataset contained an "authorized" category corresponding to portions of permitted acres actively mined. The New York and Virginia datasets had "permitted" and "disturbed" field entries. Maryland's dataset included only information on permitted acres, not active or disturbed acres. Because permitted acres may vastly exceed the area of active mining, active acres for Maryland were approximated using a nonlinear regression equation derived from relating permitted and disturbed mining areas reported in Virginia. There was a positive correlation (R^2 = 0.79) between the extent of permitted and disturbed mining areas in Virginia.

Surface mine data that were spatially represented as points were converted into circular polygons equal in size to the reported or modeled active acreage at each site. The circles were merged together with the extractive data provided originally as polygons to form an extractive land-use mask. Overlaying the extractive mask on the P532 revealed areas of potential misclassification where patches of contiguous clusters of barren-classed pixels were recognized as quarries or surface mines in the ancillary state datasets. All patches of barren land in the P532 that intersected the extractive land-use mask were reclassed as "extractive." All patches of barren land in the P532 that intersected patches of developed land-cover pixels, but did not intersect the extractive land-use mask or patches of unconsolidated shore pixels were reclassified as "residential."

Overlaying the extractive mask on the P532 also revealed quarries or surface mines that were misclassified as development. Unfortunately, the methods used to identify extractive areas misclassified as barren do not work effectively for identifying extractive areas misclassified as development. Quarries and small surface mines can be nested within large spatially contiguous developed areas and therefore it is inaccurate to assume that a large patch of developed land partially intersecting an area presumed to be extractive should be reclassified in its entirety as extractive. Therefore, only the portions of developed patches that underlay the extractive mask were reclassed as extractive.

Mapping Urban, Suburban, and Rural Zones

In densely developed areas, residential lot sizes tend to be small and man-made structures typically dominate the spectral reflectance within 30-m resolution Landsat pixels. In such regions, we assumed that developed lands were accurately represented in the CBLCD. Therefore, only Landsat-derived land-cover datasets were used to characterize densely developed areas defining the urban zone.

Densely developed areas include all interior patches of developed lands (i.e., patches of contiguous developed pixels in the 2006 CBLCD within 60 m from the patch edge) with a minimum area of 1 ha and intersecting major roads. These criteria eliminate small patches of developed lands and narrow linear features from inclusion in the urban category. Major roads are roads that provide for high volumes of traffic as defined using the functional class attributes in the NAVTEQ streets database (NAVTEQ, 2006). To eliminate small gaps between patches of development and densely developed areas resulting from the above process, all developed lands within 500 m and contiguous to densely developed areas were incorporated into the urban zone.

The suburban zone was defined as all areas classed as "residential" in the P532. All areas outside of the urban and suburban zones were considered to be part of the rural zone.

Estimating Impervious Surfaces and Turf Grass Area in the Urban Zone

In each WSM modeling segment, the extent of impervious surfaces within the urban zone was estimated by multiplying the area of each developed land-cover class in the P532 by county-level estimates of the mean percent imperviousness for each developed class derived from the NLCD. Average county-level impervious surface percentages per developed land-cover class, i.e., impervious coefficients, were used in place of calculations derived from overlaying the 2001 NLCD on the 2001 CBLCD due to spatial disagreement between the developed pixels in the CBLCD and impervious pixels in the NLCD. The spatial disagreement was particularly influential in sparsely developed counties. Due to the high degree of coefficient variation at the county level, county-level coefficients were preferred for use at the modeling segment scale compared to more generalized state-level coefficients (Tables 5 and 6). Note that in some counties, the impervious coefficient values were below the minimum value of the range used in the NLCD to define the developed classes. For example, by definition LID impervious values range from 21 to 50% (Homer *et al.*, 2004, 2007) yet in some counties, LID areas in the CBLCD averaged less than 1% impervious. To minimize the impact of spatial disagreement on impervious coefficient values, the first quartile of

TABLE 5. State-Level Mean Percent Impervious Coefficients per Developed Land-Cover Class.

Development Class	District of Columbia	Delaware	Maryland	New York	Pennsylvania	Virginia	West Virginia
DOS	8.7	5.2	4.8	7.5	7.3	6.0	4.9
LID	27.7	20.0	20.4	21.0	20.1	19.9	17.3
MID	53.7	43.4	44.6	50.6	41.7	45.3	40.7
HID	78.9	74.6	75.8	76.2	64.9	71.0	64.9

Note: DOS, Developed Open Space; LID, Low-Intensity Developed; MID, Medium-Intensity Developed; HID, High-Intensity Developed.

TABLE 6. County-Level Mean Percent Impervious Coefficients per Developed Land-Cover Class.

Development Class	Minimum (%)	First Quartile (%)	Mean (%)	Maximum (%)
DOS	0.27	2.11	6.30	19.15
LID	0.73	11.38	18.58	37.15
MID	0	32.45	41.98	68.72
HID	19.0	53.01	64.72	90.78

Note: DOS, Developed Open Space; LID, Low-Intensity Developed; MID, Medium-Intensity Developed; HID, High-Intensity Developed.

TABLE 7. Median Impervious Surface Area of Residential Lots from Sample Data.

	Suburban			Rural		
Jurisdiction	Count	Median (ha)	Mean (ha)	Count	Median (ha)	Mean (ha)
District of Columbia	25	0.029	0.041	n/a[1]	n/a	n/a
Delaware	34	0.046	0.050	44	0.060	0.099
Maryland	17	0.054	0.060	43	0.072	0.154
New York	21	0.039	0.041	41	0.046	0.054
Pennsylvania	31	0.031	0.039	39	0.060	0.084
Virginia	24	0.035	0.036	35	0.061	0.098
West Virginia	22	0.031	0.045	21	0.044	0.054
All states	174	0.037	0.044	223	0.057	0.095

[1]There were no rural zone areas within the District of Columbia.

county-level coefficients was calculated for all counties in each state and set as the minimum coefficient values for each state. Pervious portions of each developed land-cover pixel were used to represent the extent of turf grass in the urban zone.

Estimating Impervious Surfaces on Suburban and Rural Residential Lots

The county-level impervious surface coefficients coupled with the CBLCD developed land-cover classes were not used in suburban and rural areas because the developed classes in the CBLCD do not sufficiently capture all suburban and rural developed lands. Instead, information on roads, single-detached housing units, and sampled estimates of impervious area per residential lot were used in suburban and rural areas. As an initial step, impervious surfaces associated with suburban and rural residential lots were sampled. Fifty sample points were randomly allocated at least 1.6 km apart (to minimize spatial autocorrelation effects) along residential roads within the suburban zone in each state and 50 additional points were similarly allocated per state along residential roads within the rural zone. Sampling was not conducted within the rural zone in the District of Columbia due to its minimal extent in the District. For each sample point, impervious surfaces associated with the nearest residence including the house, driveway, and associated outbuildings were heads-up digitized at a 1:200 scale from 1-m aerial imagery using 2005-2009 leaf-on imagery collected by the Farm Service Agency's National Agriculture Imagery Program (NAIP) or leaf-off imagery collected by state resource agencies. Of the 650 original sample points, impervious surfaces were digitized for 397 suburban and rural residences. Sample points were eliminated from consideration if they were further than 0.16 km from the nearest residence or if they landed within nonresidential areas (e.g., parks, cemeteries, airports, surface mines, farms, or apartment complexes). The final sample size in each state in the suburban zone ranged from 17 to 34 and from 21 to 44 in the rural zone (Table 7). The median values of impervious surface area within suburban and rural zones in each state were used as the best measure of central tendency because of the relatively small sample sizes and the presence of a few high-value outliers in each state's sample set.

Single-detached housing units as reported by the U.S. Census Bureau were used to represent the number of residential lots within the suburban and rural zones. Within each WSM modeling segment, the numbers of single-detached houses within both zones were estimated using dasymetric aerial interpolation techniques (Wright, 1936). Dasymetric mapping involves disaggregating spatial data (e.g., U.S. Census polygons attributed with housing unit data) to a finer unit of analysis (e.g., 30-m cells) using ancillary data to weight the disaggregation of the spatial data (Eicher and Brewer, 2001; Mennis, 2003). The normative approach for disaggregating population and housing data is to use land-cover data to weight the disaggregation (Reibel and Agrawal, 2007). The developed land-cover classes represented in regionally consistent land-cover datasets such as the CBLCD and NLCD, however, do not differentiate between residential, commercial, and industrial land uses and as previously discussed under-represent the presence of low-density development. Therefore, for this study, residential road density was used to weight the disaggregation of data on total housing units and single-detached housing units to 30-m raster cells. Road density has been used previously for fine-scale mapping of U.S. Census attributes (Claggett and Bisland, 2004; Reibel and Bufalino, 2005) and is further supported by the strong log-linear relationship between residential road density and total housing units within Census Block Groups in the Chesapeake Bay watershed (R^2 = 0.80). Data from the 2009 American Community Survey (ACS) 5-Year Estimates (U.S. Census Bureau, ACS, accessed January 5, 2011, http://www2.census.gov/) were used to approximate the total number of housing units in the year 2007 within 2000 Census Block Groups. Data from the 2000 Decennial Census (U.S. Census Bureau, Decennial Population and Housing Censuses, accessed July 1, 2010, http://www2.census.gov/) were used to represent the total number of housing units and the total number of single-detached housing units within 2000 Block Groups. While Census Blocks represent the finest geographic level for reporting Census information (U.S. Census Bureau, 1994), Block Groups were used for this analysis to ensure consistent mapping procedures for allocating both total and single-detached housing unit values and to ensure consistency between allocating data from the ACS and Decennial Census.

To create 30-m resolution raster datasets of total housing units in 2000 and 2007 and single-detached housing units in 2000, potential residential areas in the watershed were identified by excluding all public and protected lands, open water, emergent wetlands, beach areas, and slopes greater than 21% from the 200-m radii residential road density dataset used to map the suburban zone. The remaining road density values were summed within every 2000 Census Block Group. Block Groups were then converted to a 30-m resolution raster dataset using the total road density attributes as the raster value. The residential road density raster was divided by the Block Group total road density raster to produce a relative road density dataset with the value of each pixel representing the percentage of a Block Group's total residential road density falling within it. Finally, the Census Block Groups were converted to three 30-m rasters using the total number of housing units in 2000, 2007, and single-detached housings in 2000, as the raster values. These rasters were multiplied by the relative road density raster to produce the final dasymetric maps of single-detached housing units and total housing units. The values of these three raster datasets were totaled within each WSM modeling segment. The total numbers of single-detached housing units in 2007 within suburban and rural areas were estimated by multiplying the total number of housing units in 2007 by the ratio of single-detached to total housing units in 2000. The estimated number of single-detached housing units in 2007 was then multiplied by the sampled state-level suburban and rural residential impervious surface coefficients to estimate suburban and rural impervious area associated with residential development. Note that the CBLCD developed pixels outside of urban areas were not considered in the estimates of suburban and rural impervious surface area due to the inability to avoid double counting impervious surfaces associated with roads and houses that are incompletely detected in the CBLCD.

Estimating Impervious Surfaces for Suburban and Rural Roads. In addition to estimating the extent of impervious surfaces associated with residential lots, the area of impervious surface associated with suburban and rural roads was assessed. To measure road area, information on road length and the combined widths of paved lanes and compacted shoulders were needed. Road length was obtained from the 2006 NAVTEQ Streets database. Information on road and shoulder width was inferred and varied substantially by road type. The NAVTEQ Streets database included attributes on the number of lanes, direction of travel, controlled access, functional class (e.g., a classification based on levels of access, traffic volume, and speed changes), and travel speed for all roads. These data were used to develop 17 unique possible road "types." Ninety percent of the total road and

TABLE 8. Selected Combined Road and Shoulder Width Estimates by Road Type.

Road Type	Road Area (%)	Recommended Road Width (m)	Modeled Road Width (m)
1-lane/1-way	0.37	3.7	3.7
Suburban 2-lanes/2-way	10.53	6.7-11.0	7.9
Rural 2-lanes/2-way	79.66	6.7-11.0	6.7
4-6 lanes/2-way	3.00	12.8-25.6	7.9, 11.0, or 17.7
8+ lanes/2-way	6.44	17.7-18.3	17.7

shoulder area in the watershed was composed of 2-lane/2-way noncontrolled access roads followed by 8+ lane roads (~6% of road area) and 4- to 6-lane roads (3% of road area) (Table 8). The remaining road area, less than 1%, was composed of 1-lane/1-way roads. All roads not represented in the NAVTEQ Streets database, including most dirt and gravel roads, were not counted in this analysis.

Published recommendations for lane and road width varied. For example, recommended lane widths varied between 3.0 and 3.6 m (9.8-11.8 ft) and shoulder widths ranged from 1.2 to 4.9 m (4-16 ft) (AASHTO, 2004; VDOT, 2005; FHWA, 1997). Due to the variation in published recommended lane and shoulder widths, the combined lane and shoulder widths of the three major road types were randomly sampled in the three largest Chesapeake Bay watershed jurisdictions: Pennsylvania, Maryland, and Virginia (Table 9). The largest road class, 2-lane/2-way roads, was further divided into suburban and rural 2-lane/2-way roads based on the assumption that parking, turning, and bike lanes, hardened medians, and extra-wide residential streets may be prevalent in the suburban zone, but not in the rural zone.

In each of the three states, 50 sample points were randomly placed along the four classes of roads separated by a minimum distance of 1 km to reduce bias toward oversampling in areas with dense road networks. Of the 600 possible samples, 510 were classified using heads-up digital measurement of hardened road and shoulder surfaces from 2005 to 2009 leaf-on NAIP imagery or leaf-off state agency imagery. Generally, these measurements were conducted at a 1:200 scale. If trees or shadows obscured the roads within 0.16 km of the sample point locations, those samples were eliminated. The statistics developed from this sampling effort were used to inform selection of road and shoulder widths by road type from the range of published recommendations (Table 8). Due to the variability in the sampled widths of 4- to 6-lane/2-way roads, NAVTEQ database attribute

TABLE 9. Estimated Combined Width of Road Lanes and Shoulders by Road Type from Sample Data.

	Pennsylvania				Maryland				Virginia			
	Suburban 2-lanes/ 2-way	Rural 2-lanes/ 2-way	4-6 lanes	8+ lanes	Suburban 2-lanes/ 2-way	Rural 2-lanes/ 2-way	4-6 lanes	8+ lanes	Suburban 2-lanes/ 2-way	Rural 2-lanes/ 2-way	4-6 lanes	8+ lanes
Count	39	41	39	50	38	41	45	49	36	35	47	50
Median (m)	8.15	6.70	9.97	14.42	7.80	6.72	12.10	18.64	8.59	6.02	10.14	13.84
Mean (m)	8.75	6.48	10.62	15.48	8.66	7.14	13.04	18.82	8.72	6.20	11.43	14.58
1st Quartile (m)	6.73	5.00	8.64	12.62	7.09	6.00	7.83	14.81	6.59	5.06	7.73	10.89
3rd Quartile (m)	10.39	7.63	11.71	16.91	9.74	7.56	16.28	21.97	10.86	7.01	13.92	17.25

information on functional class and speed category were further used to refine the estimates of road lane plus shoulder widths. The area of impervious surface was estimated for each road type by multiplying road length by the estimated combined width of all lanes and shoulders based on the assumption that even gravel shoulders are compacted and therefore effectively function as impervious surfaces.

Estimating Turf Grass Area in Suburban and Rural Zones. To estimate turf grass extent in the suburban zone, the area of impervious surfaces associated with residences and roads was subtracted from the total suburban zone area. In the rural zone, replicating this process required a means to estimate the total area associated with rural residential development starting with an estimate of average rural residential lot size. The 2007 MdProperty View database (MDP, 2007) was used to estimate average rural residential lot size. MdProperty View contains data on lot size, land use, and structural attributes and represents all tax parcels in Maryland with pseudo-centroid points. All residential parcel points within areas defined as rural in this study were selected for analysis. From those data, all records that were described as "split foyer 2 levels of living area," "split level 3 or more levels of living area," or "standard single family unit 1, 2 or 3 story" were selected to approximate the U.S. Census Bureau's definition of "single-detached" housing units. The distribution of residential lot sizes was analyzed to identify a representative average measure (Figure 3). Low-value outliers in the lot size distribution were eliminated based on the assumption that rural lots less than the sampled median area of impervious surface on rural residential lots, 0.057 ha, are unrepresentative. Likewise, large lots, over 8 ha, were rare but exerted disproportionate influence on the mean of the distribution. Rather than exclude these data, the sizes of all large lots were reduced to 8 ha to partially reflect the presence and influence of large residential lots in Maryland.

After addressing the outliers, the mean of the distribution between 0.057 and 8 ha was calculated (0.91 ha) and used to represent the size of all rural residential lots in the Chesapeake Bay watershed. The mean lot size multiplied by the number of rural single-detached housing units in each modeling segment was used to estimate total rural residential area. Subtracting the area of impervious surface associated with rural residences yielded an estimate of total residential pervious area. Unlike denser suburban residential developments, however, the pervious portions of large rural residential lots may be wooded and unmanaged, performing nutrient and sediment processing functions more similar to forests than to lawns. To differentiate potential rural turf grass area from woodland, the relative proportions of forest to herbaceous land-cover types along rural roads were estimated within each modeling segment. For this analysis, it was assumed that the majority of rural houses were located close to roads and that if lawns were present on these lots, they would be located near the houses. Therefore, the 30-m raster dataset of residential roads in rural areas was buffered by

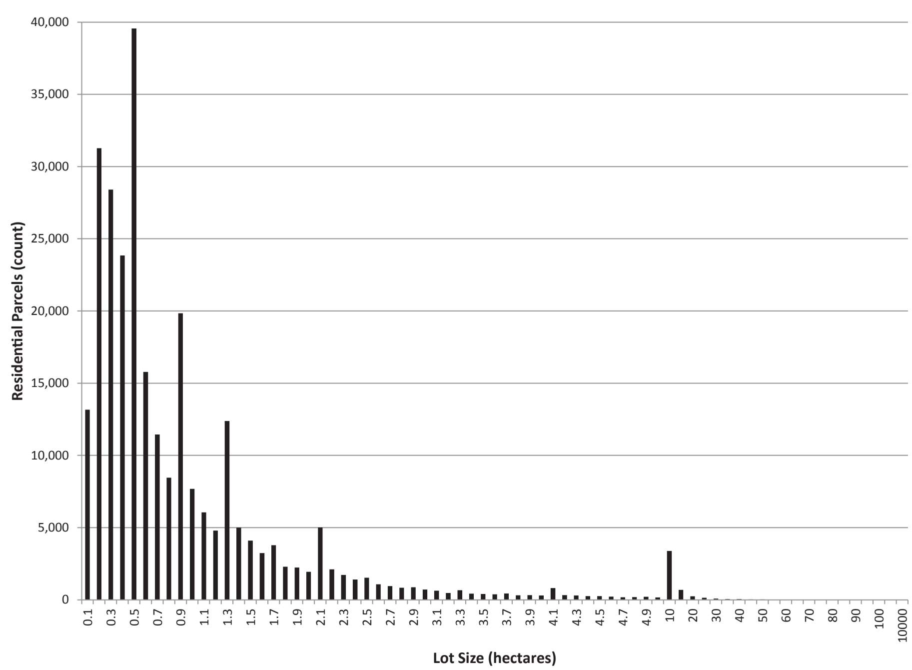

FIGURE 3. Distribution of Residential Lot Sizes in the State of Maryland.

60 m and the ratio of all barren, grassland, cropland, and pasture areas to wooded areas (deciduous, mixed, and evergreen forest, scrub/shrub and woody wetlands) was calculated within the buffer. This ratio was multiplied by the total pervious area associated with rural residential development in each modeling segment to estimate the acreage of rural turf grass. Turf grass associated with rural road medians and shoulders was not accounted for in this study.

Back-Casting Developed Land Area from 2006 to 1984

Due to the substantial underestimation of developed land and impervious cover in the CBLCD and the lack of historical road data comparable to the 2006 NAVTEQ Streets database, the extent of impervious surfaces and turf grass over the 20-year hydrologic calibration period (1985-2005) of the WSM was modeled rather than directly measured with satellite data. The CBLCD was used to establish the minimum extent of developed land in each WSM modeling segment for 1984, 1992, 2001, and 2006. Estimated changes in total housing units at the modeling segment level were used to assess decreases in developed land from 2006 to 1984 based on the strong correlation between total housing units to developed land cover at the modeling segment scale in the Chesapeake Bay watershed (R^2 = 0.78). Because the modeling segmentation is nested within counties, county-level estimates of total housing units were used as control totals for the segment level estimates. The estimated numbers of housing units in each county in 2006 and 2001 were obtained from the U.S. Census Bureau (U.S. Bureau of Census, Population Estimates, accessed October 1, 2010, http://www.census.gov/popest/estimates.html). The numbers of housing units in 1984 and 1992 were derived by multiplying the number of housing units reported in the 1980 and 1990 Decennial Censuses (Geolytics, CensusCD 1980, Release 2.15; U.S. Census Bureau, 1990 Census of Population and Housing, Summary Tape File 1, accessed October 1, 2010, http://www2.census.gov/), by the proportional change in county-level population estimates between 1980 and 1984 and between 1990 and 1992, respectively.

Methods used in the New Jersey Growth Allocation Model, GAMe (Reilly, 2003) were applied to estimate the total number of housing units in 1984 and 2006 to complement more direct estimates of the number of total housing units produced for 1992 and 2001. GAMe was originally developed in the mid-1990s for the New Jersey Office of State Planning. The model has been used effectively to generate municipal-scale forecasts of housing and office space demand that account for the availability of vacant housing, office space, and open land for development while maintaining consistency with county-scale projections of population and employment (Reilly, 1997, 2003). GAMe uses the Gompertz family of growth curves to represent development growth rates. Gompertz curves have an exponential “S” shape that makes them especially suitable for modeling situations in which: (1) growth is at first slow (such as when an agricultural or forested area is beginning to be developed); (2) growth takes place rapidly (such as when fairly large tracts are being developed into suburban housing subdivisions); and (3) growth trails off, but does not stop (such as when marginal areas within suburban areas or cities are developed or urban redevelopment entails marginal increases in housing density). In most modeling segments, extrapolations of development produced with a linear equation are similar to those produced using the Gompertz equation. However, the Gompertz family of curves is more suitable for use than linear growth functions for extrapolating future development in areas that experienced high historic growth rates and land availability is a constraining factor. Therefore, to ensure that the backcast of land use is methodologically consistent with planned forecast methods used in the Chesapeake Bay watershed, the Gompertz equation was used in place of linear extrapolation.

To estimate the number of total housing units in each WSM modeling segment for 1992, a 30-m resolution raster dataset of total housing units in 1990 was created using the dasymetric mapping methods described above and 1990 Census Block Groups. The total numbers of housing units in 1990 were then summarized by WSM modeling segment to complement the previously summarized housing unit totals for 2000 and 2007. The total number of housing units in 1992 and 2001 were estimated by linearly interpolating at the modeling segment scale between the years 1990, 2000, and 2007. This approach benefited from the fact that the geography of modeling segments is nested within county boundaries.

Total housing unit trends over the 1990s at the modeling segment scale were fit to a Gompertz curve, which was then used to extrapolate housing trends backward to 1984 and forward to 2006. The county-level population estimates for 1984 and 2006 were translated into estimates of total housing units to constrain the modeling segment scale forecasts generated using the Gompertz curve equation. To convert the 1984 Census population estimates to housing units, total housing units from the 1980 and 1990 Decennial Census were interpolated to 1984 based on the proportional annual change in county-level population estimates reported by the U.S. Census. County-level housing unit estimates for 2006 were obtained directly from the U.S. Census Bureau's Population Estimates Program. The Gompertz curve equation was used to estimate total housing units in 2006 and 2007. We then adjusted our 2006 estimates at the modeling segment scale using the ratio of the 2007 estimates to the 2009 ACS 5-Year Estimates.

To estimate the extent of development in 2001, 1992, and 1984 at the modeling segment scale, the area of developed land in 2006 was multiplied by the percentage change in total housing units from 2006 to previous years. The estimates of developed land area for 1984, 1992, 2001, and 2006 were then divided into subcategories of impervious and turf grass area using fixed proportions of impervious to pervious area by modeling segment developed for the year 2006 in this study.

This approach assumes that changes in rural, suburban, and urban areas are equally proportional to changes in total housing units. Despite the strong linear relationship between residential housing density and impervious surface land cover (Bierwagen *et al.*, 2010), local underestimates occur in urban areas dominated by commercial and industrial development. Overestimates occur in rural areas where tree canopy may obscure underlying impervious surfaces (Jantz *et al.*, 2005; Theobald *et al.*, 2009) or where the impervious features are smaller than the 30-m pixel resolution of Landsat imagery (O'Neill *et al.*, 1996). In this study, housing and impervious surfaces are correlated by definition because housing data were used in part to estimate impervious surfaces in rural areas. In urban areas, where localized areas may be dominated by commercial and industrial development, reliance on the CBLCD to represent the minimum historical extent of development prevented modeling reductions in historic developed area below that which can be discerned from Landsat satellite imagery.

Verification

These methods include numerous assumptions that impact the estimated extent of developed lands in the Chesapeake Bay watershed. To verify the estimates of impervious cover, high-resolution impervious surface data representing all roads, driveways, structures, and other impervious features in eight counties (i.e., Baltimore, Anne Arundel, Frederick, and Montgomery in Maryland; Lancaster in Pennsylvania; and all three counties in Delaware: Kent, New Castle, and Sussex) in the watershed circa 2004-2007 were obtained from county agencies. These counties represent a range of development intensities and patterns from mostly rural (Kent County, Delaware) to mostly developed (Montgomery County, Maryland). The data were converted to binary 1-m resolution raster datasets and summarized to a 30-m grid aligned to the P532. The percent impervious cover within each 30-m cell was calculated so that both the spatial footprint and level of impervious surface within developed areas could be compared. In addition, impervious surface area within each county was assessed separately in the urban, suburban, and rural zones to help identify the source of errors.

The proportions of rural residential lot area in turf grass in Baltimore County, Maryland were compared with similar proportions derived using high-resolution land-cover data developed by the University of Vermont from 2007 NAIP imagery and rural residential parcel boundaries obtained from the Baltimore County Office of Information Technology. Residential parcel boundaries within the rural zone were overlaid on the high-resolution land-cover data to assess the proportions of rural residential land in turf grass and to interpret the accuracy of the rural residential impervious surface coefficients.

To validate the overall estimates of turf grass in the watershed, state-level statistics on the area of agricultural land and turf grass produced by the USDA Natural Resources Conservation Service and National Agricultural Statistics Service were examined. These data were compared with estimates from this study to provide a state-level verification of turf grass estimates for Maryland.

RESULTS AND DISCUSSION

Including ancillary data on roads, institutions, housing units, and impervious surface and road width coefficients substantially increased the estimated area of developed land in the Chesapeake Bay watershed (Table 10). The methods outlined here produced estimates of impervious surfaces and turf grass that were 57 and 45% higher, respectively, for the Chesapeake Bay watershed than methods based solely on the CBLCD. For reference purposes,

TABLE 10. Comparison of Developed Land Use Extents for 2006 in the Watershed.

Land Cover/Use Dataset	Impervious Surface (ha)	Turf Grass (ha)
CBLCD	327,520	947,604
NLCD	397,707	1,456,540
P532 Land Use Dataset	513,559	1,375,420
P532-CBLCD difference	56.80%	45.15%
P532-NLCD difference	29.13%	−5.57%

Note: CBLCD, Chesapeake Bay Land Cover Data; NLCD, National Land Cover Dataset.

impervious and turf grass areas were also estimated from the 2006 NLCD impervious surface dataset for the Chesapeake Bay watershed. Impervious surface and turf grass areas estimated from the 2006 NLCD impervious surface dataset were 29% lower and 6% higher, respectively, compared with the P532 estimates. These findings appear to contrast with two previous studies that documented low actual errors in impervious surface estimates derived from the NLCD over large areas (Greenfield *et al.*, 2009; Nowak and Greenfield, 2010). However, they are consistent with the low actual, but high relative error rates outside dense urban areas documented through an analysis of error that was stratified by development intensity over sampled areas within the Chesapeake Bay watershed (Jones and Jarnagin, 2009). Our methods and results explicitly demonstrate the accumulation of large relative differences in small actual numbers across the majority of the Chesapeake Bay watershed that is not densely developed.

The NLCD provided a more accurate representation of total impervious surface and turf grass area compared with the CBLCD. The difference between how developed lands were represented in the CBLCD and NLCD was largely due to the use of buffered roads as part of an urban mask used to minimize commission errors in the NLCD impervious surface dataset (Homer *et al.*, 2007). An urban mask was not used in the development of the CBLCD. Rural tertiary roads are generally represented in the NLCD impervious surface dataset as pixels ranging from 1 to 10% impervious (Homer *et al.*, 2007). These pixels make up 45% of the total NLCD developed area in the Chesapeake Bay watershed and 56% of the NLCD turf grass area assuming that the non-impervious portion all developed pixels is turf grass. In contrast, the P532 land-use methodology allows for the independent assessment of impervious surfaces associated with residential lots and roads, assumes realistic road widths for different types of roads, and assumes that all of the turf grass in rural areas is associated with residences rather than mostly with roads.

We did not assess the impact of these increased impervious surface and turf grass area estimates on nutrient and sediment loads to the Chesapeake Bay as part of this study, however, given past performance of the WSM, initial estimates of nutrient and sediment loads to the Chesapeake Bay from these sources are expected to increase in proportion to their estimated areas. Increased loads from developed lands will result in a decrease in loads from land uses such as agriculture and/or forests that were converted to development. In the Chesapeake Bay watershed, 55% percent of development observed from 1984 to 2006 in the CBLCD series occurred on agricultural land and 45% on forested lands.

Because the WSM is calibrated to monitored loads in the rivers, the loads from all sources must be increased or decreased in proportion to the ratio of total source loads to total monitored loads while maintaining per-acre loading rates consistent with those published in the peer-reviewed literature. So while increasing the estimated area of impervious surfaces and turf grass will increase loads from development, the absolute increase may be magnified or reduced through the WSM calibration process. Furthermore, because development represents only 11.4% of the Chesapeake Bay watershed land area and previously was estimated to represent only 7% of the land area, compensatory changes in agricultural and forest loads are likely to be minor in most areas (Gary Shenk, U.S. Environmental Protection Agency, August 14, 2012, personal communication).

Approximately 51% of the impervious surfaces and 48% of the turf grass in the Chesapeake Bay watershed were identified within the urban zone using Landsat-derived land-cover data even though the urban zone covered less than 6% of the land area in the watershed (Table 11). The suburban zone covered only 1% of the watershed and accounted for 1.6% of the impervious surfaces and 13.5% of the turf grass in the watershed. The rural zone accounted for 93% of the land area, 17.7% of the impervious surfaces and 38.1% of the turf grass in the watershed. While the suburban zone did not account for a large percentage of the developed lands, it can be mapped at 30-m resolution and incorporated directly into satellite-derived land-cover datasets to improve the accuracy of those products. The same is true for ancillary spatial data on institutional properties.

Roads in both suburban and rural areas accounted for the remaining 29.3% of impervious surfaces. The majority of the difference between the P532 and P530 impervious surface estimates resulted from the

TABLE 11. Contribution of Residences and Roads to Regional Impervious Surface and Turf Grass Area Estimates for 2006 in the Chesapeake Bay Watershed.

Source	Zone Area (ha)	Impervious Surfaces (ha)	Impervious Surfaces (%)	Turf Grass (ha)	Turf Grass (%)
Urban zone	950,229	263,887	51.38	664,968	48.35
Suburban zone, residential lots	221,310	8,162	1.59	186,099	13.53
Suburban zone, roads		16,431	3.20	0	0.00
Rural zone, residential lots	15,295,590	90,779	17.68	524,353	38.12
Rural zone, roads		134,300	26.15	0	0.00
Total	16,467,129	513,559	100.00	1,375,420	100.00

inclusion of rural roads and residences in the estimates. This is because of the large size of the rural zone coupled with the presence of an extensive network of 2-lane roads and large numbers of dispersed residences, both of which are difficult to consistently detect in Landsat-derived land-cover datasets (Moglen and Kim, 2007; Jones and Jarnagin, 2009). Rural residential impervious surface coefficients were also consistently higher than suburban residential coefficients due to longer driveways and the presence of outbuildings and other structures on rural properties.

While the area of impervious surface estimated for the P532 WSM is substantially higher than that estimated using the CBLCD, the P532 estimates were lower than estimates derived from high-resolution impervious surface data for all eight counties examined to verify the P532 estimates (Figure 4). The P532 estimates were most accurate in the more developed counties where a large proportion of the impervious cover was located in the urban zone and estimated using the CBLCD. The majority of the underestimates occurred in the more rural counties and particularly in Delaware. The large underestimates in Delaware were partially due to a difference in imagery dates. Landsat satellite imagery used in the coastal plain to create the 2006 CLBCD was collected in 2005 and the imagery used to create the high-resolution impervious surface data was collected in 2007. While a two-year difference may seem minor and residential construction permits issued in the watershed declined in 2006 and 2007 from their peak in 2005 (Figure 5), there was still substantial construction activity during those years that could influence the underestimate of rural development. Another reason for the rural underestimate was that rural commercial and farm buildings were not represented in the road and residential housing data used to assess the extent of rural impervious area. Underestimates of rural impervious cover in Delaware were highest in Sussex County, the county with the most chickens and associated structures in Delaware. According to our analysis of the 2007 USDA Census of Agriculture, 85% (43.6 million) of broiler chickens in Delaware were located in Sussex County and the County contained 21% of all broiler chickens in the Chesapeake Bay watershed. Underestimates of impervious surfaces in the suburban zone contributed to only a minor proportion of the county-level underestimates.

The P532 estimates of impervious cover were also compared to the high-resolution county data separately within the urban, suburban, and rural zones to determine whether the increased accuracy achieved at the county level is supported by increased accuracies at the sub-county urban, suburban, and rural levels (Table 12). For example, in Baltimore County, the underestimate of impervious cover in the P532 dataset mostly occurred in urban areas. This could be due to an underestimate of the urban footprint or to an underestimate in the impervious surface coefficients associated with each of the four developed classes in the CBLCD. As shown in Table 13, the NLCD-derived county-level impervious surface

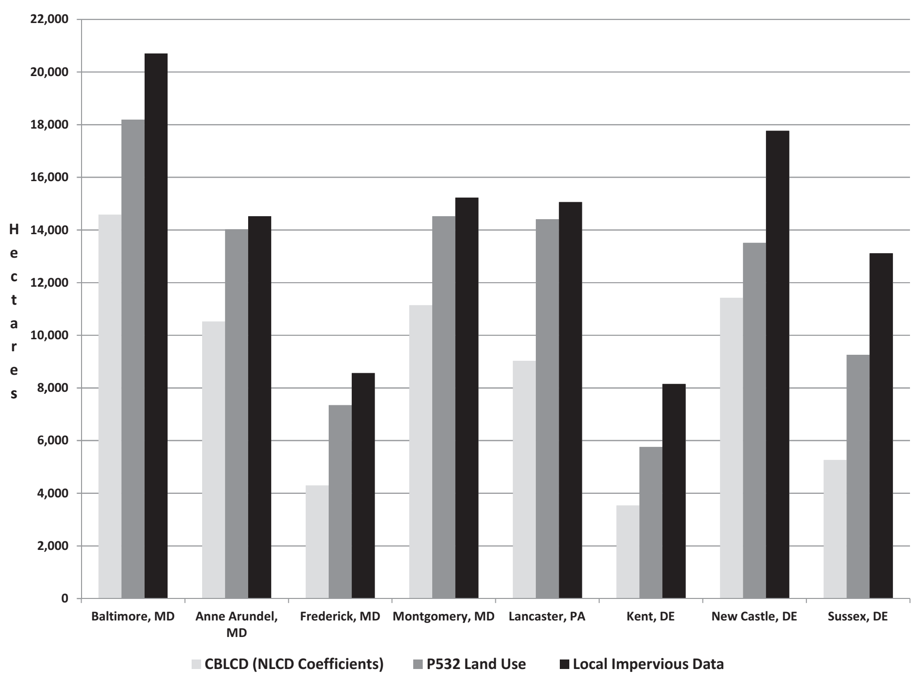

FIGURE 4. Comparison of Chesapeake Bay Land Cover Data (CBLCD), P532, and Local Impervious Data.

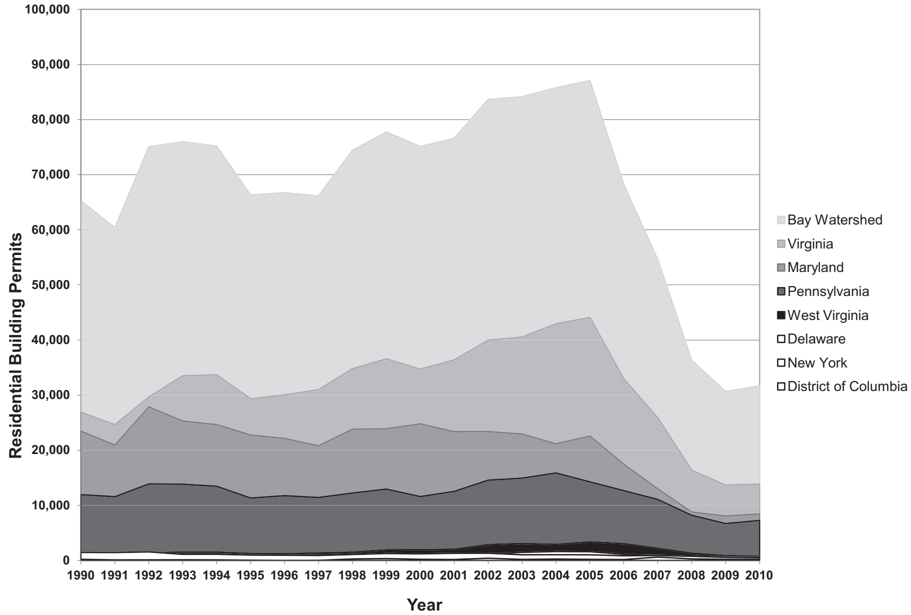

FIGURE 5. Residential Building Permit Trends, 1990-2010, in Chesapeake Bay Watershed Counties.

coefficient for DOS was much lower than the local coefficient for DOS derived from high-resolution county data and DOS composed 33% of the urban zone in Baltimore County. When the local coefficients were applied to the CBLCD developed classes the extent of impervious surface in the urban zone increased by over 1,000 ha and exceeded the P532 estimate, however, it was still more than 1,600 ha lower than the estimate based on local high-resolution impervious data. This indicates that in Baltimore County, the actual intensity of development in the urban zone was higher than could be estimated using the mean percent impervious surface per developed class. Median estimates of impervious surface percentages might provide more accurate representations of central tendency.

The suburban and rural residential impervious surface coefficients are generally lower than previously published impervious coefficients for residential land uses in the Chesapeake Bay watershed (Cappiella and Brown, 2001). Cappiella and Brown (2001) estimated impervious cover associated with different land uses and found values ranging from 0.043 ha of impervious surface for 0.2-ha residential lots up to 0.086 ha for 0.81-ha lots. The coefficients published by Cappiella and Brown (2001) included impervious surfaces associated with roads bordering residential parcels that were not included in our sampling of residential impervious cover. This discrepancy does not explain, however, all of the coefficient differences. In rural areas the mean residential impervious surface coefficients are substantially higher than the median coefficient values. Moreover, based on our analysis of high-resolution land cover and parcel boundaries in rural Baltimore County, the median amount of impervious surface on residential lots in the rural zone was 0.035 ha compared to 0.072 ha derived from our sampling approach. Surprisingly, however, our estimate of rural impervious surface area in Baltimore County was just 8% higher than the area of impervious surface as measured with high-resolution land-cover data (Table 12). This evidence suggests that our overestimate of impervious surfaces on rural residential lots may have been balanced by our not accounting for impervious surfaces associated with commercial, industrial, and agricultural operations and/or that our analysis underestimated impervious surfaces associated with rural roads.

The approach outlined in this article produced plausible estimates of turf grass area at the modeling segment, local, and regional scales. At the modeling segment scale, we found a strong linear relationship between our modeled estimates of turf grass and estimates derived from high-resolution land-cover data ($R^2 = 0.77$) excluding all small segments less than 40 ha. In Baltimore County, our analysis of high-resolution land cover and residential parcel data showed that 27% of rural residential land was grass and shrubs. Using an estimated average lot size of 0.91 ha and land-cover proportions adjacent to rural residential roads as a proxy for parcel data produced an estimate of 28% turf grass associated with rural residential lots in Baltimore County. Our analysis assumed that residences are evenly distributed along rural residential roads yet this is seldom the case given zoning, accessibility, and environmental

TABLE 12. Modeled and Measured Estimates of Impervious Surface Area within Urban, Suburban, and Rural Zones.

	Urban (ha)	Suburban (ha)	Rural (ha)	Total (ha)
Baltimore County, Maryland				
A. CBLCD (NLCD coefficients)	14,386	77	672	15,135
B. CBLCD (Local coefficients)	15,610	96	864	16,570
C. P532 Land Use	14,495	279	3,421	18,195
D. Local Impervious Data (2007)	17,259	277	3,168	20,704
CBLCD Absolute Error (A-D)/D	−16.65%	−72.06%	−78.79%	−26.90%
P532 Absolute Error (C-D)/D	−16.02%	0.72%	7.99%	−12.12%
Anne Arundel County, Maryland				
A. CBLCD (NLCD coefficients)	9,381	309	832	10,522
B. CBLCD (Local coefficients)	11,425	448	1,207	13,080
C. P532 Land Use	10,125	944	2,957	14,026
D. Local Impervious Data (2007)	10,759	967	2,793	14,518
CBLCD Absolute Error (A-D)/D	−12.81%	−68.00%	−70.21%	−27.52%
P532 Absolute Error (C-D)/D	−5.90%	−2.33%	5.89%	−3.39%
Frederick County, Maryland				
A. CBLCD (NLCD coefficients)	3,056	77	1,162	4,294
B. CBLCD (Local coefficients)	4,121	102	1,527	5,750
C. P532 Land Use	3,667	264	3,415	7,346
D. Local Impervious Data (2005)	3,959	301	4,306	8,566
CBLCD Absolute Error (A-D)/D	−22.83%	−74.51%	−73.01%	−49.87%
P532 Absolute Error (C-D)/D	−7.39%	−12.16%	−20.70%	−14.24%
Montgomery County, Maryland				
A. CBLCD (NLCD coefficients)	10,538	102	505	11,145
B. CBLCD (Local coefficients)	11,762	123	603	12,488
C. P532 Land Use	11,477	663	2,379	14,519
D. Local Impervious Data (2006)	12,616	554	2,058	15,229
CBLCD Absolute Error (A-D)/D	−16.48%	−81.55%	−75.44%	−26.81%
P532 Absolute Error (C-D)/D	−9.03%	19.61%	15.59%	−4.66%
Lancaster County, Pennsylvania				
A. CBLCD (NLCD coefficients)	7,541	122	1,368	9,030
B. CBLCD (Local coefficients)	7,017	111	1,262	8,390
C. P532 Land Use	8,110	518	5,779	14,407
D. Local Impervious Data (2008)	7,744	685	6,634	15,064
CBLCD Absolute Error (A-D)/D	−2.63%	−82.20%	−79.39%	−40.05%
P532 Absolute Error (C-D)/D	4.72%	−24.40%	−12.89%	−4.36%
Kent County, Delaware				
A. CBLCD (NLCD coefficients)	2,788	74	676	3,538
B. CBLCD (Local coefficients)	3,080	85	792	3,957
C. P532 Land Use	3,001	315	2,445	5,761
D. Local Impervious Data (2007)	3,428	618	4,101	8,147
CBLCD Absolute Error (A-D)/D	−18.65%	−88.09%	−83.51%	−56.57%
P532 Absolute Error (C-D)/D	−12.46%	−49.00%	−40.38%	−29.29%
New Castle County, Delaware				
A. CBLCD (NLCD coefficients)	10,821	84	519	11,425
B. CBLCD (Local coefficients)	14,055	127	710	14,892
C. P532 Land Use	11,450	331	1,730	13,511
D. Local Impervious Data (2007)	14,821	513	2,430	17,764
CBLCD Absolute Error (A-D)/D	−26.99%	−83.58%	−78.63%	−35.69%
P532 Absolute Error (C-D)/D	−22.74%	−35.49%	−28.81%	−23.94%
Sussex County, Delaware				
A. CBLCD (NLCD coefficients)	3,859	207	1,193	5,259
B. CBLCD (Local coefficients)	4,157	237	1,331	5,725
C. P532 Land Use	4,282	736	4,243	9,261
D. Local Impervious Data (2007)	4,738	1,274	7,106	13,117
CBLCD Absolute Error (A-D)/D	−18.55%	−83.76%	−83.20%	−59.91%
P532 Absolute Error (C-D)/D	−9.62%	−42.22%	−40.29%	−29.40%

Note: CBLCD, Chesapeake Bay Land Cover Data; NLCD, National Land Cover Dataset.

restrictions impacting residential development decisions. The suitability of forests and farms for development and other factors influencing the location of residential development also vary spatially and therefore their proportions along rural residential roads may not directly reflect the proportions of forests and

TABLE 13. Mean Impervious Surface Coefficients (% of a 30-m cell) Derived Using the National Land Cover Dataset (NLCD) and Local High-Resolution Impervious Data within Chesapeake Bay Land Cover Data (CBLCD) Developed Classes.

	Developed Open Space	Low Intensity	Medium Intensity	High Intensity
Baltimore County, Maryland				
NLCD (county-level)	6.9	27.1	54.5	78.8
Local Impervious Data	17.1	28.4	47.9	77.7
Anne Arundel County, Maryland				
NLCD (county-level)	8.7	23.6	51.4	75.0
Local Impervious Data	20.6	31.7	50.7	80.7
Montgomery County, Maryland				
NLCD (county-level)	6.4	23.5	50.3	79.1
Local Impervious Data	9.5	27.7	51.5	78.3
Frederick County, Maryland				
NLCD (county-level)	8.5	32.1	52.4	66.9
Local Impervious Data	19.6	38.7	62.2	79.9
Lancaster County, Pennsylvania				
NLCD (county-level)	9.7	19.8	46.9	70.5
Local Impervious Data	7.8	19.3	41.3	69.1
Kent County, Delaware				
NLCD (county-level)	11.0	27.0	60.9	85.3
Local Impervious Data	16.1	33.8	58.8	86.1
New Castle County, Delaware				
NLCD (county-level)	10.0	23.4	52.1	75.6
Local Impervious Data	17.1	37.0	58.8	80.7
Sussex County, Delaware				
NLCD (county-level)	11.1	25.5	56.0	72.8
Local Impervious Data	16.1	30.1	51.6	75.5

turf grass on residential lots in all counties. To fully verify the accuracy of this approach, the verification analysis should be expanded to include additional counties representing a range of development patterns. Using the dasymetric housing datasets to weight land-cover proportions along rural roads might yield further improvements in accuracy.

State agricultural statistics offices have independently assessed the extent of turf grass in Maryland, Virginia, Pennsylvania, and New York (Schueler, 2010). Only data for Maryland were used to verify the estimates of turf grass in this study, however, because the assessment date, 2005, was only one year previous to the average date of the imagery used to develop the 2006 CBLCD and because the P532 turf grass extent was assessed in all Maryland counties enabling a direct state-level comparison with industry statistics. For 2005, there was a reported 458,900 ha of turf grass in Maryland (NASS, 2006) compared to an estimated 394,000 ha of turf grass in 2006 based on P532. This comparison shows that while the P532 methods resulted in a 45% increase in turf grass estimates for 2006 compared to previous estimates for the same year based solely on the CBLCD, the new estimates do not exceed an independent statewide assessment of turf grass area.

Because turf grass associated with large-lot residential developments was commonly misclassified as agriculture in the CBLCD, improved accuracy and accounting of turf grass area should result in more accurate estimates of agricultural land. For 2007, the USDA Census of Agriculture reported 630,700 ha of agricultural land in Maryland. According to the 2006 CBLCD, there was 856,500 ha of cropland and pastureland in Maryland. After accounting for turf grass, we estimated that there was approximately 663,400 ha of cropland and pasture in Maryland in 2006. While we still overestimated the area of agricultural land by 5%, we believe that it is a reasonable approximation given that the error in the 2007 Census of Agriculture "Land in Farms" estimate is 1.7% root mean squared error (NASS, 2009). Moreover, in addition to improving the state-level estimates of agricultural land and turf grass, our methods spatially represent these data at the modeling segment scale.

Estimates of the area of rural turf grass varied in proportion to the assumed average rural residential lot size. For example, increasing the average rural lot size by 25% increased rural turf grass area proportionally and resulted in an 11% increase in the total turf grass area in the watershed. Changing the estimated median rural residential impervious coefficient by 25% (0.014 ha) resulted in a 23% change in rural residential impervious cover and a 4% change in the total impervious cover in the watershed. Assumptions about rural road and shoulder width also impacted our results. Varying the estimated combined road lane and shoulder width for 2-lane/2-way roads by less than 1 m (~10% change) resulted in a 2.6%

change in the total extent of impervious surfaces in the Chesapeake Bay watershed.

Users of these data should exercise caution with deriving or interpreting rates of change. The historic extents of impervious surfaces and turf grass in 1984, 1992, and 2001 were generally assumed to be proportional to changes in total housing units. This assumption is likely true in areas where commercial development (e.g., gas stations, restaurants, grocery stores) is dominated by the service sector. It may also be true in areas with mixed-use regional activity centers where commercial buildings are mixed with high-density residential condominiums and townhomes. The assumption may not be true, however, in areas with older commercial infrastructure and those dominated by industrial development such as airports, warehouses, and business parks. Setting a minimum value for historic developed area based on the CBLCD provided a control on estimates of historical development and served to increase the estimated total area of historical development by 0.6% compared to estimates based solely on changes in housing units.

Historical road development, lane expansions, increases in average home size, and direct measurement of changes in commercial, industrial, and agricultural structures were not accounted for in this analysis. Within the visible footprint of development identifiable in Landsat satellite imagery, some of these phenomena such as new roads, commercial buildings, and chicken houses may be represented. However, these features are incompletely represented and difficult to distinguish from the information on roads and residential development derived from ancillary data.

CONCLUSIONS

The methods outlined in this article produced more accurate impervious surface and turf grass area estimates at the modeling segment and county scales compared with estimates based solely on the CBLCD, a Landsat-derived land-cover dataset. Combining ancillary data on housing, roads, and regionally derived coefficients of road width, lot size, and residential impervious surfaces with Landsat-derived land-cover products greatly enhanced the accuracy of regional impervious surface and turf grass estimates and by default also improved the accuracy of agricultural land area estimates. Users of watershed impervious surface and turf grass area estimates derived solely from automated and semi-automated classifications of Landsat satellite imagery should be aware that those data may underestimate the extent of impervious surfaces and turf grass outside of densely developed areas. This caution is especially relevant to the use of impervious surface thresholds as indicators of watershed impairment as noted by Moglen and Kim (2007).

The methods used in this study are transferrable to other regions because the 2001 and 2006 NLCD and ancillary data used in this study are nationally available in the conterminous U.S. The methods and assumptions, however, may have to be uniquely adjusted in different regions of the country to accurately represent local variability and to ensure the use of the best available data. Variability in impervious surface coefficients for developed land-cover classes and residential lots, rural residential lot size, suburban road densities, and road median and shoulder management assumptions all impact regional estimates of impervious surfaces and turf grass based on our methods. If our methods are applied to other regions, consideration should be given to stratifying the region, increasing sample sizes, and examining local land-use and land-cover data across a rural-urban gradient to better understand and represent local variability. The frequency distributions of sampled parameters such as residential lot size and impervious surface area per lot could also be used in place of mean and median values. This would enable the production of a range of estimates based on the observed variability in sampled parameters.

While we used Census Block Group level data to develop our dasymetric maps of housing, we recommend the use of Census Block level data for mapping total housing units in future studies. These data are now available for the year 2010 from the U.S. Census Bureau and they could be used as a weighting factor for developing 30-m resolution dasymetric maps of single-detached housing from Census Block Groups.

Accurate estimates of the area of impervious surfaces and turf grass at a modeling segment scale are critical inputs to the Chesapeake Bay WSM. While the methods discussed in this article produce more accurate estimates of impervious surface and turf grass area, they do so by capturing impervious surfaces and turf grass in suburban and rural areas that are unobserved and/or misclassified in the CBLCD. Suburban and rural impervious surfaces are typically dispersed and disconnected from streams and may not influence stream hydrology or nutrient and sediment loads to the same degree as urban impervious surfaces that are well represented in Landsat-derived land-cover products (Mejia and Moglen, 2009; Yang *et al.*, 2011). Additional research on measuring the relative hydrologic connectivity of impervious surfaces and on understanding the effects of connectivity on hydrology and water quality is needed to improve the parameterization of regional WSMs.

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DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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