Evaluation of Impervious Surface Estimates in a Rapidly Urbanizing Watershed

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Abstract

Accurate measurement of impervious surface (IS) cover is an essential indicator of downstream water quality and a critical input variable for many water quality and quantity models. This study compares IS estimates from a recently developed satellite imagery/land cover approach with a more traditional aerial photography/land use approach. Both approaches are evaluated against a high-quality validation set consisting of planimetric data merged with manually-delineated areas of soil disturbance. The study area is the rapidly urbanizing 127 km² Cub Run watershed in northern Virginia, located on the fringe of the Washington, D.C. metropolitan region. Results show that photo-interpreted IS estimates of land class are higher than satellite-derived IS estimates by 100 percent or more, even in land uses conservatively assigned high IS values. Satellite-derived IS estimates by land class correlate well with planimetric reference data (r = 0.95) and with published ranges for similar sites in the region. Basin-wide mean IS values, difference grids, and regression and density plots validate the use of satellite-derived/land cover-based IS estimates over photo-interpreted/land use-based estimates. Results of this site-specific study support the use of automated, satellite-derived IS estimates for planning and management within rapidly urbanizing watersheds where a GIS system is in place, but where time-sensitive, high quality planimetric data is unavailable.

Introduction

Urban growth, frequently occurring in the form of urban or suburban "sprawl" has been a consistent process in the Baltimore-Washington, D.C. metropolitan region over the last 50 years. Several authors (Crawford-Tilley, *et al.*, 1996; Masek, *et al.*, 2000; Jantz, *et al.*, in press) have documented methods and data collection criteria to define urban growth in this region, which currently makes up ten percent of the 168,000 km² Chesapeake Bay watershed and includes over forty percent of its total population. Masek, *et al.* (2000) presented urban change detection methods that minimize confusion between urban green space and agriculture, reporting a notable increase in "built-up area" in the Washington, D.C. metropolitan region during the late-1980s. Jantz, *et al.* (in press) predicted future sprawl in the Washington, D.C.-Baltimore area, at current growth and policy trends, of more than 7,200 additional km² by 2030.

This paper evaluates the use of a newly developed approach to quantify a specific landscape feature, impervious surface (IS) cover, to support watershed management at the development or zoning level. The study compares two fundamentally different methods of estimating IS cover; a traditional aerial-photography/land use approach and a satellite imagery/land cover approach. Throughout this paper, the term *land use* refers to the economic or social function of the land, while *land cover* refers to the physical properties of the land surface (Aspinall, 2002). Photography, as used in this paper, is the process from which the results are photographs.

The use of IS percent (from remotely-sensed or other data) as a measure urbanization and as an effective means for managing land and aquatic resources has been reviewed by a number of authors, including Schueler and Claytor (1996), Arnold and Gibbons (1996), CWP (1998), Prisloe, *et al.* (2000), Cappiella and Brown (2001), and Civco, *et al.* (2002). Accurate measurement of IS provides an essential indicator of downstream water quality and a critical input variable for many water quality and quantity models such as TR-20, TR-55, Storm Water Management Model (SWMM), Source Loading and Management Model (SLAMM), and Hydrologic Simulation Program Fortran (HSPF) (USDA, 1982, 1986; Huber, *et al.*, 1988; Pitt and Vorhees, 1989; Bicknell, *et al.*, 1995).

In recent years, mean watershed imperviousness has become an indicator for assessing water quality impacted by urban growth. According to Schueler (1994), adverse water quality effects above the 10 percent imperviousness threshold appear as increased pollutant loads from urban washoff, warmer stream temperatures from reduced canopy cover, and increased scour and channel instability with accompanying loss of pool and riffle sequences. Long-term changes in a stream brought about by increased IS areas (such as parking lots, rooftops, airports, and sidewalks) can lead to reduced stream habitat and loss of biodiversity. In addition, pollutants transported downstream end up in the receiving water body. In the present study, the receiving water body was Cub Run and its tributary streams, which flow into the Occoquan Reservoir, and eventually into the Chesapeake Bay.

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Study Area

Cub Run is a 127 km^2 watershed in northern Virginia, on the current urban fringe of greater metropolitan Washington, D.C., approximately 20 km west of the Washington, D.C. beltway (Figure 1a, 1b). The Cub Run watershed is part of the larger Occoquan basin draining into the Occoquan Reservoir, an important water supply and recreational resource for more than one million people in northern Virginia. A report assessing growth in the Occoquan basin (Schueler, 1996) cited as a top priority the need for timely, coordinated estimates of basin land use and impervious cover. Quantification of IS area in the Cub Run watershed has particular value as input for lumped parameter, linked watershed-reservoir modeling currently underway in the Occoquan basin (Stein, *et al.*, 1998).

Data Sets

Predefined land use data for this study were supplied by the Northern Virginia Regional Commission (NVRC) as a hard copy base map, circa 1990 (Figure 2), and as polygon shapefiles, circa 1995 and 2000 (Figure 3a). Satellite impervious area estimates for the years 1990, 1996, and 2000, extracted from those developed by Smith, *et al.* (in press) were utilized as the land cover data set. Validation data include high quality planimetric data from local jurisdictions merged with manually-delineated areas of soil disturbance from same-era digital orthophotos.

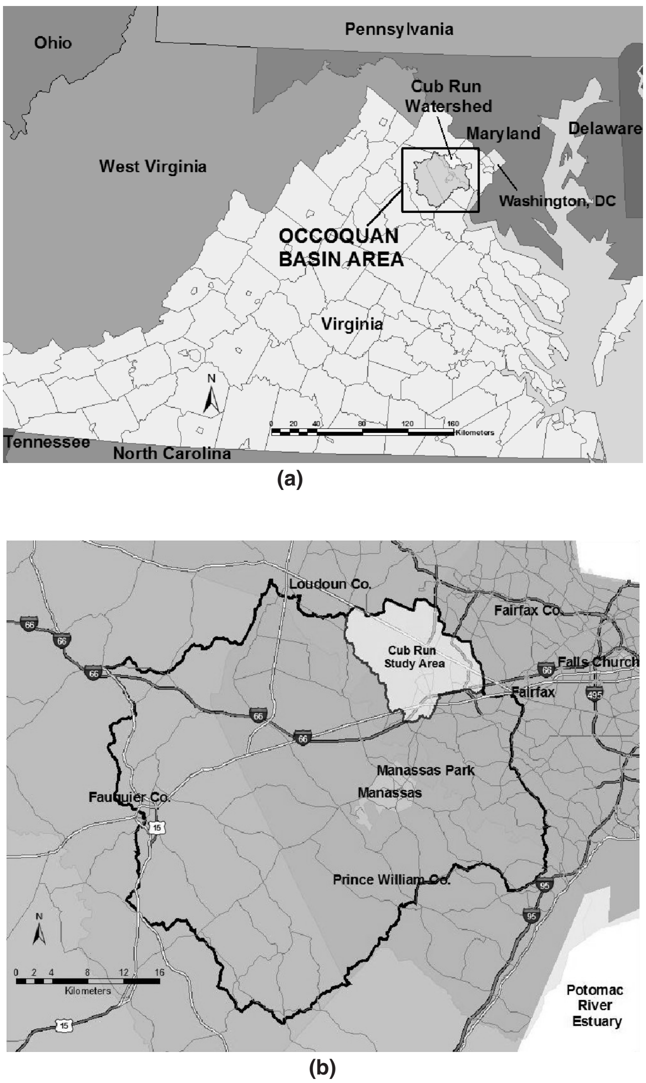


Figure 1. (a) Location map; (b) Occoquan basin map showing location of Cub Run study area, a highly urbanizing watershed approximately 20 km west of Washington, D.C.

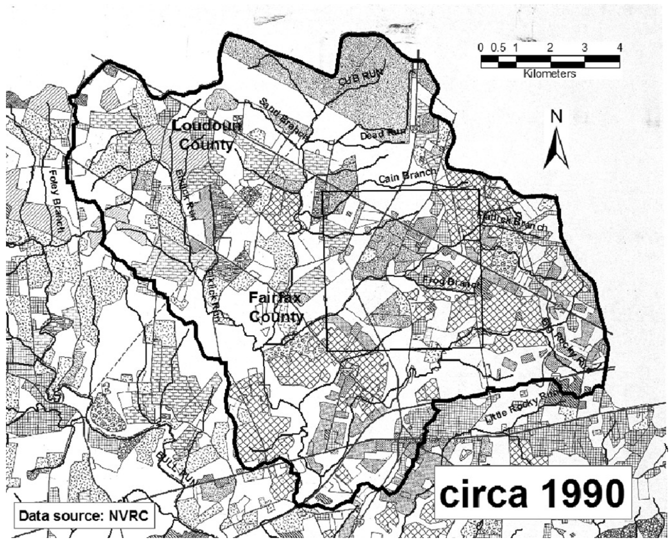
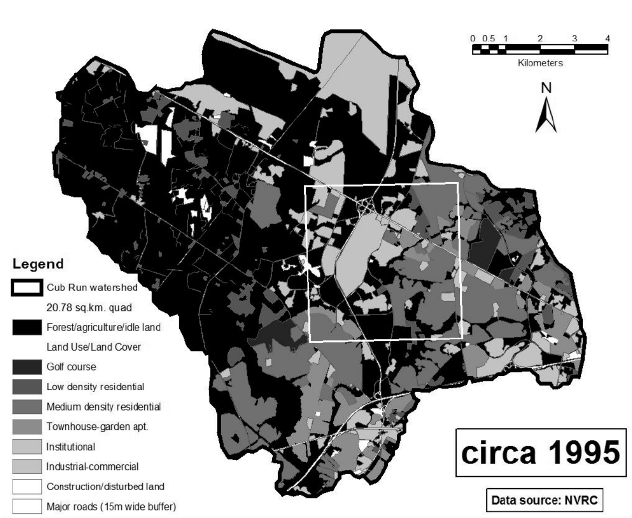


Figure 2. Georeferenced 14-class land use map of Cub Run watershed, showing 20.78 km^2 subset of Fairfax County.

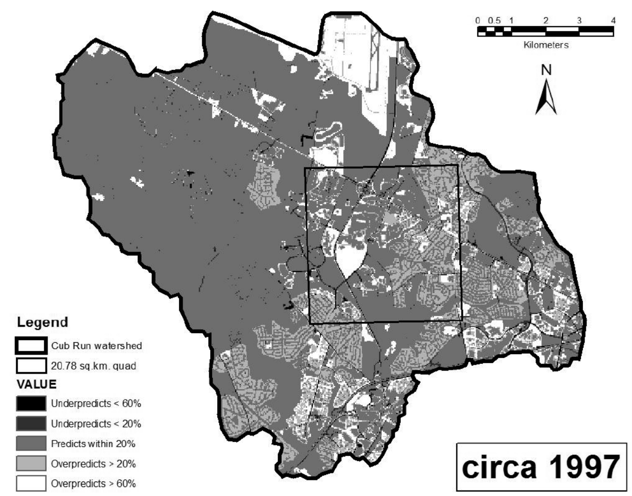
NVRC Land Use

Since 1979, the NVRC has used 14 land use classification types (8 urban, 5 agricultural, 1 forest/idle) for planning purposes within the Occoquan basin. For the present study, the five agricultural land use categories were merged with forest and idle land to form a single, pervious land use class. Institutional, commercial, and industrial land use classifications were merged into a single land use class and assigned equal estimates of IS area. Estate and low-density residential land use classifications were similarly combined. As a result, the following residential land use categories, similar to an Anderson Level III classification (Anderson, *et al.*, 1976), were formed: (1) low density residential land use (0–5 dwelling units per hectare), (2) medium density residential land use (5–20 dwelling units per hectare), and (3) townhouse-garden apartment land use (>20 dwelling units per hectare). In comparison, Crawford-Tilley, *et al.* (1996) used a residential density of three houses per hectare as a threshold for urbanized land use.

The 1990 land use data used in this study were derived from an historic NVRC base map dated December 1989, assembled from local land use maps, Master Plans, infrared (IR) photography (dated April 1974), field surveys, and information from the Virginia Department of Forestry and local Soil & Water Conservation Districts. The 1995 land use data supplied by NVRC consists of land use polygons delineated by NVRC staff from color IR aerial photography at a nominal scale of 1:40000, taken during leaf-off conditions with airborne photo centers and ground points identified by in-flight, differential GPS. The resulting digital orthophotography had a map scale of 1:12000 (1″ = 1,000′), at 25 micrometer scan resolution (approximately 1000 dpi), and a ground resolution of 1 m. The 1995 land use polygons for Cub Run basin had a minimum mapping unit of 500 m^2. The 2000 land use data were derived similarly, but from airborne true color photography at 0.6 m (2-foot) resolution with a minimum mapping unit of 300 m^2.



(a)



(b)

Figure 3. (a) Cub Run watershed land use classification showing 20.78 km^2 subset of Fairfax County; (b) Difference grid (30 m) showing 7-class aerial IS estimate minus planimetric reference data. Areas where aerial IS estimates overpredict are lighter.

Photo-interpreted Land Use and Impervious Area

Fauss (1992) used archived aerial photography and a modified Anderson classification scheme to delineate IS area for land use classes in the Cub Run watershed as input for lumped parameter watershed modeling. In that study, residential land use was divided into three Anderson Level III categories; low-density, medium-density, and high-density. Residential and other land use classifications used by Fauss correspond closely to those used by NVRC.

Fauss (1992) utilized color photography in 9-inch by 9-inch format from the years 1979, 1984, and 1988 at scales from 1:20000 to 1:80000. Manually identified land uses were traced onto a clear overlay on a light table using a minimum mapping unit of 2.8 hectares (168 m × 168 m), then transferred to a map base of six individual USGS 7.5-minute topographic maps. Roads, houses, buildings, and other impervious surfaces were traced from color photographic enlargements onto drafting film overlays, then digitized and summed within a geographic information system (GIS) to produce average per-class IS estimates.

Fauss (1992) noted several biases and assumptions in the above delineation method. For example, in order to insure consistency in the determination of IS percent for each residential category, residential land use delineations included only those areas affected by housing, roads, sidewalks, and minor open or forested areas (such as residential yards). Alternately, institutional, commercial, and industrial land use delineations were biased to select only those areas dominated by parking areas, sidewalks, building rooftops, and other impervious areas. Construction and other disturbed areas (including barren areas such as rock quarries) were assigned a maximum impervious value of 100 percent based on the conservative assumption that these areas were characterized by highly exposed and compacted soils. Runways and airport facilities were delineated as a special land use class that included all intervening open land. In contrast, Crawford-Tilley, *et al.* (1996) identified airports using only impervious areas such as airport facility runways, terminals, and parking lots, without including surrounding, open land.

Satellite-derived Impervious Area

Subpixel impervious surface area estimates of the Baltimore-Washington metropolitan area were developed at 30 m resolution using Landsat satellite imagery (path 15, row 33). Details of the approach are provided by Smith, *et al.* (in press) and are briefly summarized here. Numerous Landsat scenes were orthorectified to within 0.5 pixel RMSE using the 30 m National Elevation Data DEM and at least five ground control points. Scenes were radiometrically corrected to limit topographic and seasonal differences due to solar illumination (Varlyguin, *et al.*, 2001). In order to provide reliable, high-resolution training data for automated IS extraction, vector data of impervious features for Montgomery County, Maryland (derived from 1:14400 scale digital orthophotos from Spring 1993–2000) were rasterized to 3 m resolution. The resulting grid was aligned with the Landsat grid system for subsequent matching of Landsat spectral values. Zonal aggregation from 3 m to 30 m produced a continuous training grid of actual IS cover that corresponded to each Landsat pixel. Additional training data consisting of high resolution GIS data sets of agricultural field plots, non-impervious point data, and other data from the Mid-Atlantic region were collected and incorporated for improved IS extraction.

Using assembled training data, a decision tree classifier was used to recursively partition the satellite observations into separate impervious classes for the year 2000. Decision tree processing defines traceable paths until reaching terminal nodes beyond which the data can no longer be accurately partitioned using the predictor variables (Breiman, 1984). To produce the most efficient algorithm, predictive variables are evaluated based on given inputs, retaining those variables that effectively precipitate splits. Inputs to the decision tree included the multitemporal Landsat TM/ETM+ bands, as well as the normalized difference vegetation index (NDVI), and the Brightness, Greenness, and Wetness components of the Tasseled Cap transformation.

Accuracy of the resulting impervious cover data was assessed using matching Ikonos imagery (4 m resolution) and color-IR Digital Ortho Quarter Quads (DOQQ). The across adjacent-class overall accuracy of the Montgomery County impervious cover data set was 87.7 percent (Kappa = 0.77), with some evidence for systematic commission errors resulting from residual bare or plastic-covered agricultural fields, and beaches (Smith, *et al.*, in press).

Impervious surface maps for 1990 and 1996 were derived using binary impervious/pervious decision trees, effectively producing maps of urban extent. The subpixel 2000 IS values were then passed through to the 1990 and 1996 urban extent maps, assuming that pixel-level IS intensity remained constant through time. Resulting grids for all years had values ranging from zero through 100 percent IS (Figure 4c).

Cub Run Watershed Validation Data

Validation data for this study consisted of jurisdictional vector data merged with manually-delineated areas of soil disturbance. Planimetric data from Loudoun and Fairfax County GIS departments located buildings, roads, and other paved surfaces within the study area. Fairfax County vector data was derived from 1997-era, 6-inch resolution orthophotography having a positional accuracy of +/− 0.6–0.9 m. Vector IS data from Loudoun County, current as of January 2001, was manually edited to match 1997-era DOQQs. Disturbed impervious areas including cleared construction sites and rock quarries were identified using digital orthophotos, assigned an IS value of 100 percent, and added to countywide validation sets. Resulting IS data sets from both counties were merged then rasterized to 3 m to retain near-vector quality resolution (Figure 4a). A 30 m grid aggregation of the 3 m planimetric reference data was used for subsequent analysis to represent actual percent IS in the 127 km^2 Cub Run watershed (Figure 4b).

Methods

Impervious surface estimates from a conventional aerial-photography/land use classification approach and a satellite imagery/land cover approach were compared against high quality validation data using a variety of spatial and statistical tools. In order to better discern differences between IS estimation methods, two land use classifications were developed, a seven-category and a nine-category classification system. Impervious surface estimates from prior photo-interpretation (Fauss, 1992) were assigned to land classes in both classification systems for comparison with both satellite-derived data and planimetric reference data. Land use summaries and corresponding mean IS values for the entire 127 km^2 Cub Run watershed are reported for all years and data sets. Mean IS values for a 20.78 km^2 subset of the watershed in Fairfax County are also presented for all years and data sets.

Land Use Classification

In order to characterize the rapidly urbanizing Cub Run landscape, land use and land use changes were summarized for the years 1990–2000. To account for all impervious surface areas within the study area, two new land use categories were developed: (1) major roads (representing four-lane highways), and (2) disturbed land (representing urban expansion not otherwise identified by NVRC land use mapping). Land use in the Cub Run watershed was divided into seven generalized impervious surface classes, ranging from zero to 100 percent. This seven-class system was contrasted with a more detailed nine-class system by appropriate addition/substitution of the following three detailed land use categories: disturbed land, major roads, and airport and adjoining land (Table 1).

Map Data Preparation

To produce 1990 land use polygons for this study, the existing 1989 NVRC land use base map (90 cm × 152 cm) was digitally photographed then georeferenced within ESRI® ARCMAP™ 8.2 using over 20 control points to match previously mapped watershed boundaries and road intersections. The georeferenced base map was used to back-classify existing 1995 NVRC land use polygons to 1990 land use by deleting areas identified as urban in 1995, but rural in 1990. DOQQs of the same era, as well as matching USGS 7.5-minute topographic maps in Digital Raster Graph (DRG) format were used to verify revisions to the NVRC land use polygons. A minimum mapping unit of 700 m^2 was used for the 1990 Cub Run land use data.

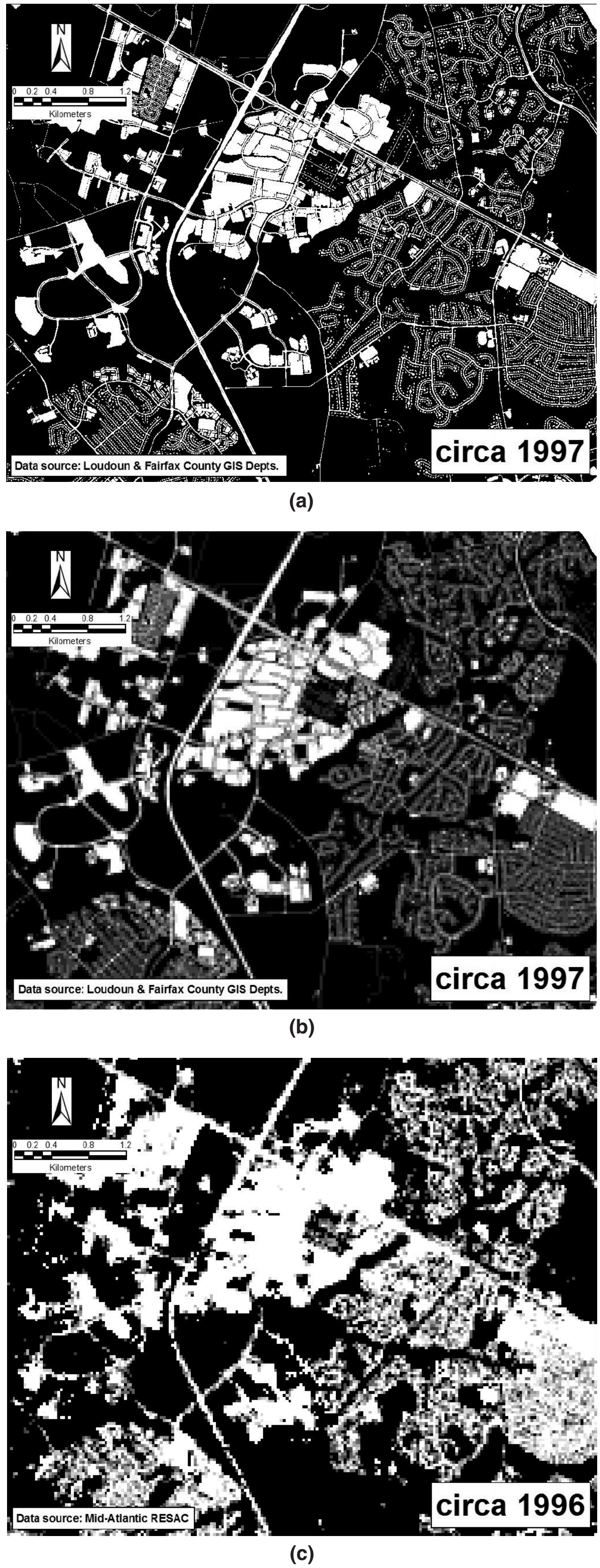


Figure 4. Reference vs. satellite-derived IS grids, 20.78 km^2 subset of Fairfax Co. (a) 3 m raster of planimetric reference data; (b) 30 m aggregation of planimetric reference data; (c) Landsat 30 m satellite-derived data.

TABLE 1. IMPERVIOUS SURFACE CLASSIFICATIONS OF CUB RUN WATERSHED FROM PHOTO-INTERPRETATION

Land Use Category Used for Impervious Surface Area Estimation	Characteristics	Aerial IS Estimate (percent)
Generalized land use categories:		
Major roads/disturbed lands[1]	Four-lane hwy, construction	100
Institutional/ commercial/ industrial[2]	Includes airports, quarries	87
Townhouse-garden apts.	Multi-family dwellings (>20 du/ha)	82
Medium density residential	Single family subdivisions (5–20 du/ha)	41
Low density residential	Large lots, no subdivisions (0–5 du/ha)	12
Agriculture/forest/ idle land	Crop, pasture, open woods	0
Golf course	Similar to agriculture	0
Detailed land use categories:		
Disturbed lands	Construction, rock quarries	100
Major roads	Four-lane highways	66
Airport and adjoining land	Runways and all property	34

Table adapted from Fauss (1992).

Note 1: Major roads identified by the authors using a 15 meter road centerline buffer. Disturbed lands approximated using available imagery and planimetric data.

Note 2: Due to variability in degree of imperviousness between individual facilities, land segments used for photo-interpretation were biased to select areas dominated by parking areas, sidewalks, building rooftops, and other impervious surfaces.

The Landsat impervious cover estimates were used to visually cross-check NVRC rural land use polygons to identify obvious areas of imperviousness such as major industrial expansions and new construction sites. Verified areas of disturbed land were subsequently added as polygons to the 1990, 1995, and 2000 data sets as a new land use classification and concurrently deleted from the agriculture/forest/idle land use category. An additional land use category, major roads, was added to the 1990, 1995, and 2000 data sets to delineate major highways located within the study area. Planimetric road centerline data from Virginia Department of Transportation (VDOT) was buffered by 15 m to approximate a nominal 100-ft highway right-of-way. Visual registration of the resulting major road polygon with Landsat impervious cover estimates was deemed acceptable to within 30 m.

Image Data Preparation

For convenience and ease of analysis, Landsat 30 m impervious cover estimates were binned at ten percent increments to form 11 classes, from zero to 100 percent, then clipped to the existing watershed boundary using ESRI® ARCINFOWORKSTATION™ 8. The extent of the resulting 141,297-cell (127 hectare) grid was used as a mask for subsequent rasterization. Spatial filtering may be helpful where there is a need to normalize maps of different spatial resolution, such as in change detection analysis, to make them more directly comparable (Pereira, *et al.*, 2002). However, filtering the Landsat 30 m data in this study would have removed important differences between the two data types being compared and, for example, eliminated many houses in low-density residential developments. Thus, no filtering of the 30 m satellite data to match the scale of the photo-interpreted impervious surface delineations was done, nor required.

Air photo land use polygons were assigned average IS estimates corresponding to Fauss (1992) (Table 1). All 1990, 1995, and 2000 land use polygon classes were subsequently converted to 30 m raster format to create *aerial* IS grids with matching watershed extent. Two sets of grids were created for 1990, 1995, and 2000 to represent both the seven-class and the nine-class system, resulting in six raster grids for comparative analysis.

Comparisons and Statistical Analyses

Photographically-interpreted and satellite-derived IS means were determined for each land use, year, and classification system. Comparison and statistical analysis of predicted IS values with validation data was accomplished using regression analysis, density plots, and spatial differencing. Regression analysis was carried out on a per-pixel, as well as a per-class basis, in order to quantify differences between IS estimates from the 1997-era validation data, the 1996-era Landsat land *cover*, and the 1995-era aerial photo land *use*.

Grid subtraction provided spatial differencing of IS estimates with validation data, affording a direct comparison between the two approaches being evaluated. In this process, planimetric reference data were subtracted from Landsat impervious cover grids and seven- and nine-class photo-interpreted IS area grids on a pixel-by-pixel basis. Mean differences provided a measure of how much the photo-interpreted IS estimates over-predict or under-predict IS cover within each land use class. Difference results were displayed spatially across the watershed for visual interpretation. Comparative density plots were used to visualize conformance between predicted IS distributions and planimetric reference data.

Results

Land use summaries from 1990 to 2000 reveal that the 127 km² Cub Run watershed continued changing from predominantly rural to predominantly urban (Table 2). Urban

TABLE 2. CUB RUN WATERSHED LAND USE SUMMARIES, 1990–2000

	1990		1995		2000	
Land Use	km²	% Total	km²	% Total	km²	% Total
Golf course	1.7	1.3	1.8	1.4	3.7	2.9
Low density residential	2.9	2.3	5.2	4.1	4.4	3.5
Medium density residential	18.0	14.1	20.2	15.9	23.1	18.2
Townhouse/ garden apts.	5.5	4.3	6.7	5.3	8.4	6.6
Institutional	1.1	0.9	2.4	1.9	2.8	2.2
Industrial/ commercial[1]	14.5	11.4	18.5	14.5	20.4	16.1
Disturbed land[2]	3.7	2.9	1.9	1.5	0.1	0.1
Major roads	1.6	1.2	1.6	1.2	1.6	1.2
Subtotal:						
Urban land use	49.0	38.5	58.3	45.8	64.5	50.7
Forest/agriculture/ idle land use	78.2	61.5	68.9	54.2	62.7	49.3
Total	127.2	100.0	127.2	100.0	127.2	100.0

Table adapted from Northern Virginia Regional Commission land use data and available imagery and planimetric data.

Note 1: Includes 5.5 km² airport and 1.1 km² rock quarry.

Note 2: Majority of disturbed land consists of land clearing for new building construction or industrial expansion.

Table 3. Summary of Mean Impervious Cover Estimates versus 1997 Planimetric Reference Data

	Circa 1990 IS Estimate	Circa 1995 IS Estimate	Circa 2000 IS Estimate	1997 Planimetric Data
Cub Run basin (127 km^2):				
Aerial 7-class	24	28	30	16
Aerial 9-class	22	26	28	16
Landsat	13	14	17	16
20.78 km^2 subset of Fairfax County:				
Aerial 7-class	35	41	45	26
Aerial 9-class	34	40	44	26
Landsat	23	24	27	26

Source: Aerial photographic interpretation of Cub Run watershed by Fauss (1992), Landsat 30 m impervious cover estimates, and planimetric data from Loudoun and Fairfax County GIS Departments.

land use in the watershed increased approximately 30 percent over the 10-year study period at an average rate of 1.6 km^2 per year. Land use conversion in the Cub Run watershed was faster in the early 1990s than the late 1990s, similar to growth trends reported by Masek, *et al.* (2000) for the Washington, D.C. metropolitan region. Mean impervious cover values for the entire Cub Run watershed revealed increasing imperviousness from 1990 to 2000 (13 percent to 17 percent), with good conformance of Landsat data to 1997 planimetric reference data (Table 3). Photo-interpreted IS estimates demonstrate increased conformance with 1997 reference data upon addition of more land use classes. Similar results were found for the 20.78 km^2 subset of Fairfax County (Table 3).

Photo-Interpreted Versus Satellite-Interpreted IS Estimates

Comparison of photo-interpreted IS estimates with Landsat impervious cover estimates for all years and data sets in this study revealed differences between the two approaches. Photo-interpreted IS estimates for all urban land uses except golf courses were up to 100 percent higher than satellite-derived estimates for most years (Table 4), with differences more pronounced in land use classes conservatively assigned higher IS values. The townhouse-garden apartment land use category was identified as having the largest difference of all residential land use categories. Satellite-derived IS estimates from Landsat generally fell within directly-measured impervious cover ranges reported by Cappiella and Brown (2000) for selected jurisdictions in the Chesapeake Bay watershed.

Spatially distributed grid differencing between the two methods of IS estimation and planimetric reference data revealed widespread overestimation of IS cover by aerial-interpretation of land use in much of the urbanized portion of Cub Run basin (Figure 3b). Areas of highest overestimation were located in pervious areas classified as urban, such as the open and forested land surrounding Dulles International Airport (along the northern boundary of the watershed) and numerous other, widely dispersed urban land segments. Forest/agriculture/idle land and golf course land use categories, which presently make up approximately 50 percent of the land area of the Cub Run watershed, had the lowest differences (i.e., highest conformance) with planimetric reference data (Figure 3b) and correspond most closely to Landsat impervious cover estimates (Table 4).

IS Estimates versus Validation Data

Comparison of per class impervious cover estimates with 1997 planimetric reference data (Table 5) resulted in somewhat better correlation between Landsat IS estimates and the validation data ($r = 0.97$), relative to the aerial-photo IS estimates ($r = 0.93$) (Figure 5a). The higher slope of the Landsat estimates ($m = 0.80$) compared to the seven- and nine-class aerial-interpreted estimates ($m = 0.48$ and $m = 0.57$, respectively) provided additional evidence of IS overestimation by aerial-interpretation of land use compared to the Landsat and validation data sets. The higher slope for the nine-class system over the seven-class system demonstrated that IS estimates resulting from the nine-class aerial-interpreted system more closely corresponded, on a per-pixel basis, with planimetric reference data. Density plots representing IS cell-value distribution (Figure 5b) support linear regression results, illustrating the distributional similarity of 1996 Landsat IS estimates to the 1997 planimetric reference data.

Table 4. Comparison of Photo-interpreted versus Satellite-interpreted Impervious Cover Estimates, by Land Class

Land Use Category/Source Data (date)	Aerial[1] (1979–88)	Landsat[1] (1990)	Landsat[1] (1996)	Landsat[1] (2000)	CWP[2] (1993–00)
Generalized land use categories:					
Major roads/disturbed lands	100	47	53	49	NA
Institutional/commercial/industrial[3]	87	35	37	40	31–74
Townhouse-garden apts. (>20 du/ha)	82	31	34	37	40–46
Med. density residential (5–20 du/ha)	41	19	20	22	20–34
Low density residential (0–5 du/ha)	12	7	4	5	10–20
Agriculture/forest/idle land	0	3	4	4	2
Golf course	0	2	2	3	NA
Detailed land use categories:					
Disturbed lands (includes quarries)	100	49	57	59	NA
Institutional/commercial/industrial[4]	87	46	44	46	31–74
Major roads	66	46	47	47	NA
Airport and adjoining property	34	14	15	18	NA

Note 1: Aerial photographic interpretation of Cub Run watershed by Fauss (1992) and Landsat 30 m impervious cover estimates of Cub Run watershed.

Note 2: Ranges of directly-measured impervious cover reported by Center for Watershed Protection for targeted land use categories at both development and zoning area levels for four jurisdictions within the Chesapeake Bay watershed (Cappiella and Brown, 2000).

Note 3: Airports and rock quarries are included as industrial.

Note 4: Excludes airports and rock quarries.

Table 5. Impervious Cover Estimates versus 1997 Planimetric Reference Data, Cub Run Watershed, by Land Class

Land Use Category/Source Data (date)	Aerial[1] (1979–88)	Landsat[2] (1996)	Landsat[2] (1996)	Planimetric Data[3] (1997)	
Generalized land use categories:		7-class	9-class	7-class	9-class
Major roads/disturbed lands	100	50	NA	80	NA
Institutional/commercial/industrial	87	37	46	40	48
Townhouse-garden apts.	82	34	34	40	41
Medium density residential	41	20	20	22	23
Low density residential	12	5	5	5	5
Agriculture/forest/idle land	0	4	4	3	3
Golf course	0	2	2	3	3
Detailed land use categories:					
Disturbed lands (includes quarries)	100	NA	55	NA	96
Major roads	66	NA	47	NA	60
Airport and adjoining property	34	NA	16	NA	10

Note 1: From aerial photographic interpretation of Cub Run watershed by Fauss (1992).

Note 2: Mean of 1990, 1996, and 2000 Landsat 30 m impervious cover grids.

Note 3: From directly measured 1997 planimetric data supplied by Loudoun and Fairfax County GIS Depts., verified with circa 1997 DOQQs from Virginia Economic Development Partnership.

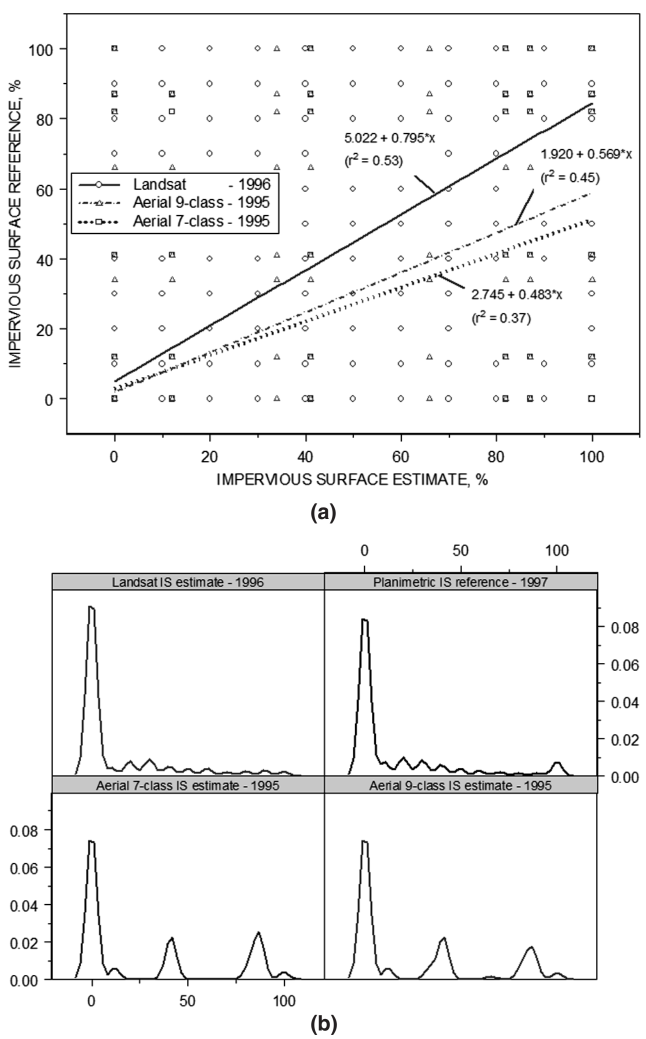


Figure 5. (a) Per pixel regression analysis (entire basin, N = 141,297 cells); (b) Density plots showing derived IS estimates and planimetric reference data (entire basin, N = 141,297 cells).

Fairfax County Subset

In order to increase the number of high quality data set comparisons, additional per pixel regression, density plot, and difference grid analyses were run on a 20.8 km^2 subset of Fairfax County having a more intricate suburban land cover mixture (mean IS = 26 percent). Resulting linear regression slope values show that all IS subset estimates generally over-predicted compared with planimetric reference data, with aerial seven- and nine-class estimates over-predicting more than satellite-derived IS estimates. The satellite-derived IS estimates had a better fit (higher r^2) with planimetric reference data than photo-interpreted estimates ($r^2 = 0.56$ versus $r^2 = 0.35$). Comparative density plots of the 23,083-cell subset (Figure 6) revealed the conformance of 1996 Landsat IS estimates with 1997 planimetric reference data. Mean IS estimates and reference values, by class, are presented for comparison with basin-wide means (Table 6).

Difference grid analysis of the Fairfax County subset (Figure 7a) provides a more detailed visual analysis of IS over- and under-prediction in an urbanized section of the Cub Run

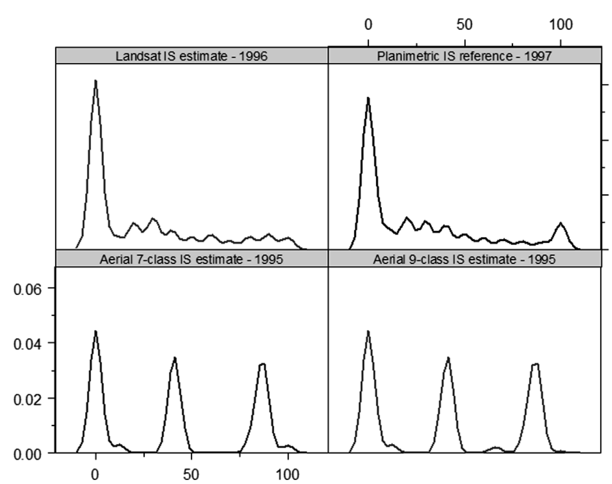


Figure 6. Density plots showing derived IS estimates and planimetric IS reference data (20.78 km^2 subset of Fairfax County, N = 23,083 cells).

Table 6. Impervious Cover Estimates versus 1997 Planimetric Reference Data, 20.78 km^2 Subset of Fairfax County, by Land Class

Land Use Category/Source Data (date)	Aerial[1] (1979–88)	Landsat[2] (1996)	Landsat[2] (1996)	Planimetric Data[3] (1997)	
Generalized land use categories:		7-class	9-class	7-class	9-class
Major roads/disturbed lands	100	49	NA	70	NA
Institutional/commercial/industrial	87	51	51	53	53
Townhouse-garden apts.	82	30	30	37	37
Medium density residential	41	22	22	23	23
Low density residential	12	6	6	6	6
Agriculture/forest/idle land	0	7	7	6	6
Golf course	0	7	7	6	6
Detailed land use categories:					
Disturbed lands (includes quarries)	100	NA	65	NA	94
Major roads	66	NA	44	NA	63
Airport and adjoining property	34	NA	NA	NA	NA

Note 1: From aerial photographic interpretation of Cub Run watershed by Fauss (1992).
Note 2: From Landsat 30 m impervious cover grid.
Note 3: From directly measured 1997 planimetric data supplied by Loudoun and Fairfax County GIS Departments, verified with circa 1997 DOQQs from Virginia Economic Development Partnership.

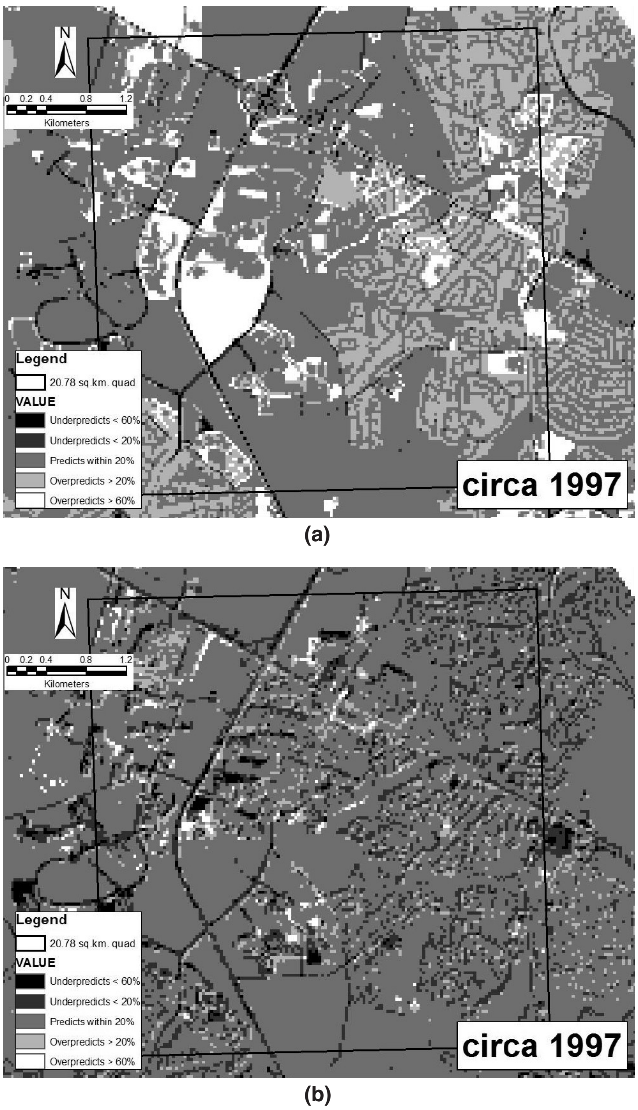


Figure 7. Difference grids: (a) Aerial 7-class 1995—Planimetric reference 1997; (b) Landsat 1996—Planimetric reference 1997. Areas of overprediction are lighter.

watershed. Over-prediction was more apparent and widespread in the aerial-interpreted IS estimates than in the Landsat estimates (Figure 7b). In spite of a general under-prediction in the Landsat map at low IS values (Figure 6), the Landsat IS distribution provides a better match of the intricate suburban land cover represented by the reference data.

Discussion

Assignment of a single, photo-interpreted estimate of IS to land segments having homogeneous land *use*, but heterogeneous land *cover* is inherently problematic. Depending upon the minimum mapping unit used, the skill of the photo analyst, the quality of available equipment and photography, and the extent of representative sampling done to capture land cover(s) expected within a given land use, resulting IS estimates can vary widely. With the advent of synoptic imagery such as provided by Landsat TM and ETM+, landscape information related to impervious cover can be derived using automated classification techniques at a higher resolution, and at more regular intervals. The present study shows that a "unique land use-impervious cover estimate" approach to impervious surface estimation runs the risk of overestimation in urbanizing areas.

Results of this study, which further validate the use of Landsat IS estimates, show that the 100 percent IS assignment for areas delineated from aerial photography as disturbed/construction may be unrealistic. Based on validated Landsat estimates, IS values for disturbed/construction sites in the Cub Run watershed ranged from 50 to 70 percent, with major four-lane highways (including median strips) falling in a similar range. Recommended ranges of impervious cover resulting from this study, by land class, are summarized in Table 7.

Spatial analysis of grid differences identify areas where IS estimates over- or under-estimated compared to validation data, for example, the large area of over-prediction by the photo-interpreted/land use approach in the forested buffer south of Dulles International Airport (Figure 3b). In spite of noted uncertainties in the satellite-derived data, results suggest than an average imperviousness value closer to the Landsat impervious cover estimate of 16 percent (Table 5) would be more realistic for the combined airport/adjoining property land use classification in this watershed. Grid differences in the vicinity of the airport raise the question of whether a single land use value for urban IS estimation has a strong physical meaning, given the accepted heterogeneity of all but the

TABLE 7. EXPECTED RANGE OF IMPERVIOUS PERCENT, BY LAND USE CLASS, CUB RUN WATERSHED

Land Use Category	Impervious Surface Range (percent)
Disturbed/construction	50–70
Major roads/highways w/median	50–70
Institutional/commercial/industrial	35–55
Townhouse-garden apts.	35–45
Medium density residential	20–25
Dulles Airport w/adjoining land	10–20
Low density residential	5–10
Ag/forest/golf/idle land	2–7

most impervious urbanized land covers (such as, shopping mall parking lots and industrial warehousing).

The most prominent examples of urban heterogeneity in the Cub Run watershed were the residential areas in the more densely developed, eastern (Fairfax County) portion of the basin. In this study, aerial IS estimates for residential street patterns compare more favorably to validation data than the interspersed expanses of suburban lawn and forest, where widespread over-prediction occurs (Figure 7a). These high IS estimates appear to be the result of noted bias and assumptions inappropriate for a watershed having such a complex mix of urban land cover. In spite of scattered under-prediction, satellite-derived IS estimates (Figure 7b) demonstrate better overall conformance to validation data. Under-prediction of satellite-derived IS estimates may be attributed to the inability of Landsat 30 m observations to discern portions of small roads and other impervious surface features as discrete entities, particularly where there is obscuration by tree cover and associated shadows, even in leaf-off imagery.

Of the two approaches and data sources evaluated in this study, the 30 m Landsat land cover data has the advantage of using a much smaller MMU than the photo-interpreted land use data set. NVRC accommodates for the uncertainty in photo-interpreted land use coefficients by assigning and utilizing high and low ranges of IS for each land class. However, in lieu of using IS ranges to account for varied land cover, decreasing the MMU in photo-interpreted products, or increasing the number of manually-delineated land use classes, it appears reasonable and reliable to transition to a land cover approach for IS cover estimation using satellite data available at more frequent intervals, at least for those jurisdictions capable of using geospatial data sets.

Of all photo-interpreted IS estimates, agriculture/forest/idle land and golf course land use categories corresponded best with the validation data set (Table 5). As a result, inevitable reductions in rural land area in this watershed will further reduce the reliability of photo-interpreted IS estimates. At present, rural and idle lands make up approximately 50 percent of the Cub Run basin. As urban land conversion continues, with increasing segments of interspersed, heterogeneous land cover, the need for synoptic current satellite-derived estimates of impervious cover also increases. Stated in general terms, as a rural landscape increases in complexity with increased urbanization, so does the need for a land cover approach for IS estimation.

Recent work based on even higher resolution satellite imagery (4 m Ikonos) suggests that indicators of stream health based on the amount of IS within watersheds may need to be revised to reflect the discrimination between land cover and land use map products (Goetz, *et al.*, in press). They suggest, for example, that guidelines for an excellent stream health rating would be no more than 6 percent impervious with at least 65 percent forested buffers; and for a rating of good there should be no more than 10 percent impervious and at least 60 percent forest buffer. Above guidelines are impacted by landscape configuration in relation to stream buffers, which is another advantage of using maps based on satellite observations.

Conclusions

This study documented how impervious cover estimation based on a traditional photo-interpreted land use approach can vary considerably from a more automated Landsat-based land cover approach. High quality reference data validated the use of Landsat 30 m IS estimates in the rapidly urbanizing 127 km^2 Cub Run watershed in northern Virginia. Increasing the number of land use classes for photo-derived IS delineation was shown to increase conformance with actual IS coverage. Thus, at least one way to increase the reliability of a land use approach for IS estimation would be to increase the number of manually-delineated land use classes. However, a more reasonable alternative, and the one suggested by our results, would be to transition to a synoptic land cover approach using satellite observations. As satellite-derived IS cover estimates become increasingly more reliable and widely available, they will also increasingly become the tools of choice for a growing assortment of comprehensive watershed modelers, urban planners, and land use managers.

Given the limited spatial extent and sampling used in this study, however, the results found in the Cub Run basin may not hold for other areas. There are many factors that can affect the outcome of land use-based estimates of impervious surface, including interpretation skill, land use classification scheme, and data resolution. Consequently, we encourage additional validation and comparative studies under an even broader range of conditions.

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