A Comparison of Approaches to Impervious Surface Characterization

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Abstract — **Impervious surface estimates derived from different modeling approaches and data types were compared to highly accurate and precise planimetric calibration and validation data. A linear regression model using population density and percent land cover class per unit area produced the most accurate results, with an overall RMSE of 3.2% for the 82 census tracts studied. Two methods using just land cover-based impervious coefficients yielded results with an RMSE of 4.8% and 5.4%, while the subpixel estimates had an RMSE of 5.8% and 7.5%.**

Keywords-impervious surface; land cover; population density; subpixel analysis

I. INTRODUCTION

Nonpoint source pollution (NPS) has been cited as one of the top contributors to water quality problems in the United States [1]. It has been well-documented that urbanization increases the volume, duration, and intensity of stormwater runoff [2]. Resulting imperviousness not only increases concentrations of nitrogen and phosphorous in surface waters, but also influences hydrology, stream habitat, chemical water quality, and biological water-quality [3,4,5]. Research has suggested that the amount of urban runoff and its impacts on stream conditions and water quality are strongly correlated to the percent area of impervious surfaces within a watershed [4,5,6]. This strong relationship implies impervious surfaces can serve as an important indicator of water quality because it can be readily measured at a variety of scales (*e.g.,* from the parcel level to the watershed and regional levels) [4].

Research has demonstrated a positive correlation among percentage of urban land or imperviousness and select water quality parameters [6, 7, 8, 9, 10]. Within the past few years, numerous research projects have been undertaken to develop methods to measure impervious surfaces at the watershed scale or larger [11, 12, 13, 14, 15, 16, 17]. Past efforts to determine watershed imperviousness have been hampered by inconsistent methods and outdated or unavailable data. There is a need for a consistent and replicable technique to calculate easily and quickly watershed imperviousness from readily available and cost effective remote sensing information and other geo-spatial data that achieves an acceptable level of accuracy.

This paper reports on several approaches to estimating percent imperviousness and is part of ongoing research aimed at developing a suite of analysis tools for effective land management [18, 19].

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A. Study Area

Ten towns in the state of Connecticut served as the study sites for calibrating and validating impervious surface models (Fig. 1). They range from rural (Chaplin, Marlborough, Woodbridge), to suburban (Groton, Stonington Suffield, Waterford), to urban (Milford, Stamford, West Hartford).

B. Data

Planimetric data portraying the built landscape served as validation data for each of the methods examined, and as calibration for all but one – the NLCD 2001 impervious surface data set which was developed independently of this project. These planimetric data are photogrammetrically-derived layers that delineate building footprints, roads, driveways, parking lots, and other anthropogenic impervious surfaces (Fig. 2). Tracts for the 2000 census TIGER (Topologically Integrated Geographic Encoding and Referencing) files served as the analysis unit over which actual and estimated imperviousness was summarized. For the ten towns there were a total of 82 census tracts. Landsat ETM+ data, from Sept 8, 2002, was used for the extraction of CCL (*Connecticut's Changing Landscape*) land cover [20] and subpixel imperviousness [21]. Springtime leaf-off and summertime leaf-on Landsat ETM was used for NLCD (*National Land Cover Dataset*) landcover [22] and imperviousness [23].

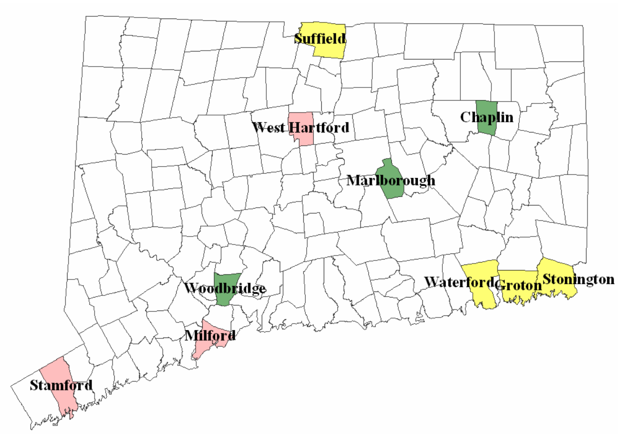


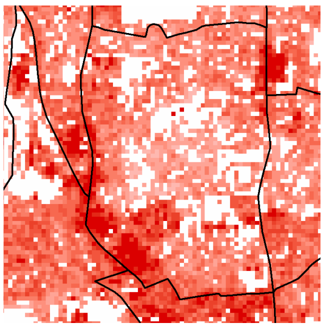
Figure 1. Location of the ten study towns in Connecticut.

C. Approaches

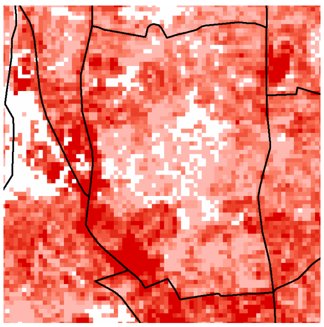
The methods for estimating percent imperviousness examined included: (1) spectral unmixing using a subpixel classifier; (2) general classification and regression tree (CART) sub-pixel analysis; (3) land cover-specific percent impervious coefficients using both CCL and NLCD land cover; and (4) regression modeling using land cover and population density.

1) *Subpixel Classification*

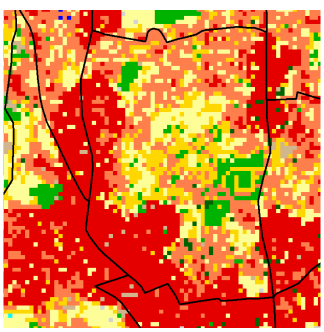
Impervious surface estimates were derived directly from Landsat Thematic Mapper imagery using the Sub-pixel Classifier™, an add-on module to Leica Geosystems' ERDAS Imagine software and engineered by Applied Analysis Inc. The Sub-pixel Classifier (SPC) enables the detection of materials of interest as a whole or fractional component of an image pixel at 10 percent increments beginning with a detectable threshold of 20 percent (*i.e.*, 20-30%, 30-40%, … 90-100%).



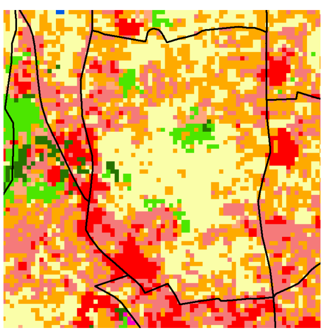
(a) CCL 2002 sub-pixel impervious surface estimate



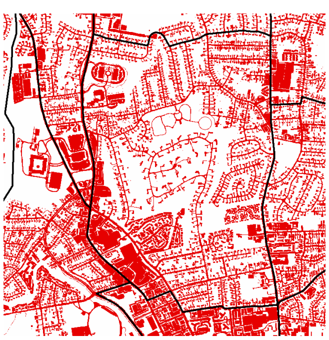
(b) NLCD 2001 sub-pixel impervious surface estimate



(c) CCL 2002 land cover



(d) NLCD 2001 land cover



(e) Planimetric impervious surface data.

Figure 2. Examples of calibration and validation data used in this study. Tract boundaries are outlined in black. This area is from Stamford, one of the urban study towns.

The general process consists of image preprocessing steps that prepare the image for sub-pixel classification, signature derivation, and classification. Signature derivation is conducted manually using Areas-of-Interest (AOI) to identify pixels with a minimum of 90 percent imperviousness (*i.e.*, end members). Because of the diverse reflectance characteristics of impervious surfaces, signatures were individually created for bright, medium, dark, and very dark sub-classes of impervious surfaces. These sub-classes were grouped into a single signature file known as a 'family' using the optional Signature Combiner function in the SPC. Classification utilizes the initial preprocessed image, corresponding environmental correction file, and derived signature file. A function within the SPC allows for the adjustment of the classification tolerance. Based on several tests of the classifier on a sample of Landsat image data, this parameter was set to increase slightly the number of detections reported. A sample of the CCL sub-pixel impervious surface estimate can be seen in Figure 2a.

2) *General Classification and Regression Tree (CART)*

As part of the NLCD 2001 program, along with land cover and forest canopy closure, estimates of percent imperviousness are being developed [23]. Landsat ETM+ data and derived Tasseled Cap transform, along with ancillary data including elevation, slope, and a soil index, are used in a general classification and regression tree (CART) algorithm to produce rule-based models for prediction of continuous measures of imperviousness. Yang *et al.* [23] report an average error of predicted versus actual percent impervious surface from 8.8 to 11.4% for three test areas – Sioux Falls, SD, Richmond, VA, and the Chesapeake Bay area. A sample of the NLCD sub-pixel impervious surface estimate can be seen in Figure 2b.

3) *Land Cover Coefficients*

The Impervious Surface Analysis Tool (ISAT), an extension for ESRI's ArcView and ArcGIS, was developed by the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center in collaboration with the University of Connecticut's *Nonpoint Education for Municipal Officials* (NEMO) program for use by water resource managers and planners. It must be loaded into the ArcView project along with the Spatial Analyst extension and requires the use of land cover data in an ESRI GRID format, analysis units in an ESRI shapefile format, and a set of impervious surface coefficients, defined as the percent impervious surface per land cover class. To calculate the impervious surface coefficients, land cover data for each town were overlaid on the impervious surface calibration (planimetric) data. The database containing summary statistics was produced to show the total area of each land use land cover class and the total area of imperviousness within this class in each town [24]. To calculate the percent of impervious surface for each watershed, ISAT overlays the polygon data on land cover data and calculates the area of each land cover category within each polygon. ISAT allows the application of the impervious surface coefficients to calculate the percentage of imperviousness for each polygon:

$$IS_w = \frac{\sum_{i=1}^{n} Area_i \cdot IS_i}{TotalArea} \qquad [1]$$

where IS_w is the percent of imperviousness per each analysis unit, $Area_i$ is the area of the particular land cover category within this tract, IS_i is impervious surface coefficient for this specific land cover category, and Total Area is the area of the region.

4) Land Cover and Population Density Regression

A regression model for calculating the amount of imperviousness was developed using JMP Statistical Discover Software. There were 21 independent variables selected: population density and the percentage of each NLCD land cover class per tract. A linear regression model was created:

$$IS = b_1 + b_2 \cdot PopDen + \sum (b_i \cdot \% A_i) \qquad [2]$$

where b_1 is an intercept, b_2 is the coefficient for population density expressed in persons per square mile, and b_i are those for the percentage of the NLCD category area within the tract. Actual percent imperviousness was calculated from the *Union* of the planimetric data layer with the tract boundaries, and the amount of each NLCD 2001 landcover class present in the study area was derived using the *Tabulate Areas* command from the *ArcToolbox Spatial Analyst Tool* for each tract. Approximately eighty percent of the tracts (n = 65 of 82) were randomly selected from the sample and used as calibration data for regression analysis. The remaining tracts (n = 17 of 82) were used for the testing and validation.

II. Results

Figure 3 contains scatter plots of estimated *versus* actual percent imperviousness for each of the five methods. Also shown is a linear fit line and its R^2, as well as overall RMSE for each method. Of these five methods, and given these 82 census tracts, the land cover and population density-based approach yielded the highest degree of agreement with the reference planimetric data, with an RMSE of 3.2%, followed by the two land cover coefficient methods implemented with ISAT (RMSE of 4.8% and 5.4%,), and then the two direct sub-pixel methods (RMSE of 5.8% and 7.5%).

Table 1 presents the linear regression coefficients to calculate percent impervious from population density and percent area of NLCD classes. It was found that only seven of the possible 20 land cover classes were significant contributors to the regression model. Shown, too, are the impervious surface coefficients for both NLCD 2001 and CCL 2002 land cover data. It should be noted that these sets of impervious surface coefficients are not stratified by population densities, as enabled by ISAT (high, medium, and low), but are the overall averages of imperviousness by land cover type.

The land cover-based coefficients for use with ISAT express a similar pattern for the NLCD and CCL land cover data, but there are substantial differences in the values themselves. The NLCD-based impervious cover coefficients are higher for the developed categories (63%, 49%, and 29% for high, medium, and low density developed) than the corresponding CCL-based classes (54%, 34%, and 19%, respectively). This disparity is due in part to a difference in the definitions of those classes, as well as a difference in the land cover mapping procedures. Overall, the CCL coefficients are lower than the NLCD counterparts.

The coefficients for land cover and population density-based regression model parallel in magnitude and relative importance those of the simple land cover-based values. It is interesting to note the inverse relationship between percent imperviousness and the barren land category as well scrub/shrub wetland.

III. Conclusions

There are advantages and disadvantages to each of the impervious surface estimation methods examined. The higher accuracy achieved with the population and land cover-based regression model becomes even more appealing because of the wide availability of NLCD and population data, and the model is fairly easy to implement within a GIS. It can be adapted and recalibrated to different analysis units such as census blocks or watersheds [25]. The subpixel methods, while seemingly less accurate when examined at the tract level, do offer the advantage of being spatially explicit – that is, they provide positionally-specific (at the pixel resolution) imperviousness estimates, rather than a homogenous (*lumped*) measure as do the other methods.

Efforts continue to refine all of the techniques discussed in this paper, to extend their application geographically to other regions of the United States, and to implement at a finer analysis unit (*e.g.*, local watershed or some regular zonal area circa 150 meters across).

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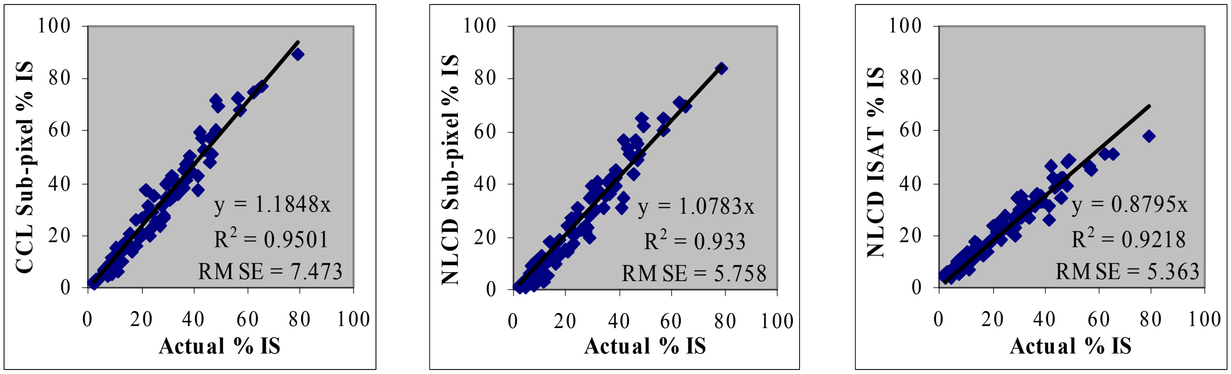
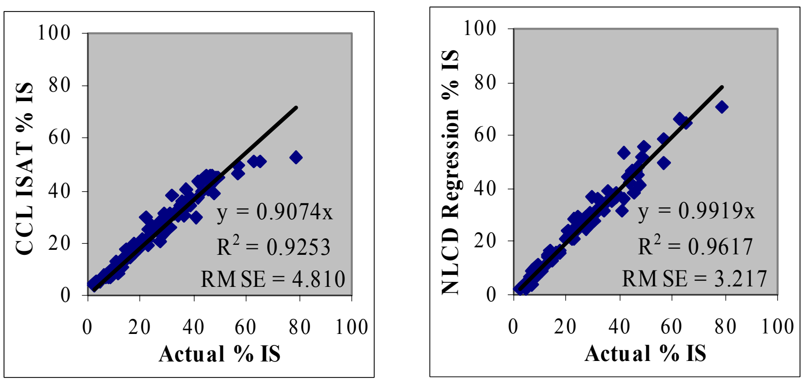


(a) (b) (c)



(d) (e)

Figure 3. Scatter plots comparing actual impervious surfaces for 82 census tracts *versus* estimates from each of the following five impervious surface estimate methods: (a) Sub-pixel classification directly from Landsat TM imagery using CCL land cover, (b) NLCD sub-pixel analysis, (c) ISAT applied to NLCD land cover, (d) ISAT applied to CCL land cover, and (e) Regression analysis applied to NLCD land cover.

Table 1. Regression coefficients for (a) estimating p percent imperviousness from population density and percent coverage of NLCD land cover classes and (b) use with the Impervious Surface Analysis Tool (ISAT) and NLCD and CCL land cover

NLCD Category	NLCD #	Coefficient			CCL #	CCL Category
		Regression $_{NLCD}$	ISAT $_{NLCD}$	ISAT $_{CCL}$		
High Intensity Developed	24	0.735641	63.0%	53.9%	1	High Density Developed
Medium Intensity Developed	23	0.428519	48.7%	33.6%	2	Medium Density Developed
Low Intensity Developed	22	0.274385	29.1%	19.3%	3	Low Density Developed
Developed Open Space	21	0.179453	13.4%	12.5%	4	Turf & Grass
Grassland	71		5.2%			
Pasture/Hay	81		5.8%	4.2%	5	Other Grasses & Agriculture
Cultivated	82		5.8%			
Deciduous Forest	41		2.9%			
Mixed Forest	43		2.5%	2.1%	6	Deciduous Forest
Scrub/Shrub	52		6.8%			
Evergreen Forest	42	0.517378	8.0%	3.2%	7	Coniferous Forest
Water	11		1.1%	1.3%	8	
Palustrine Aquatic Bed	98		0.6%			Water
Palustrine Emergent Wetland	96		1.5%	1.2%	9	Non-forested Wetland
Palustrine Forested Wetland	91		1.8%	0.7%	10	
Palustrine Scrub/Shrub Wetland	92	-1.213820	0.7%			Forested Wetland
Estuarine Scrub/Shrub Wetland	94		1.4%	1.6%	11	
Estuarine Emergent Wetland	97		3.5%			Tidal Wetland
Bare Land	31	-0.867190	24.7%	15.3%	12	
Unconsolidated Shore	32		16.7%			Barren
Utility ROW	N/A	N/A	N/A	1.6%	13	Utility Rights-of-way
Population Density	N/A	0.000424	N/A	N/A	N/A	

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