MEASURING IMPERVIOUS SURFACES FOR NON-POINT SOURCE POLLUTION MODELING

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ABSTRACT

The US EPA has reported non-point source pollution (NPS), which includes eroded sediments, toxic contaminants, nutrients, debris, and other pollutants, to be the number one threat to surface water quality nationwide. Numerous studies have established a direct relationship between the amount of impervious surface within a watershed and pollution of its surface waters. However, without detailed digital planimetric data, accurate watershed measurements of impervious surfaces are costly and time consuming to prepare. A method to determine percent impervious surface cover for different municipal zoning designations, parcel sizes and land uses (e.g. one-acre residential lots) was developed at the University of Connecticut. Large-scale digital planimetric data that included impervious surfaces from roads, parking lots, buildings, and other miscellaneous landscape features were obtained for West Hartford, Woodbridge, Marlborough, and Waterford, Connecticut. ArcInfo® 7.1.2 and ArcView® 3.1 (ESRI, Redlands, CA) GIS software were used to convert the data into a useable format (*i.e.* polygons) and perform overlay analyses. A relational database management system (RDBMS) was employed to analyze the data and produce summary statistics. Percent imperviousness coefficients were calculated for different zoning class and parcel size combinations. These data were analyzed with generalized land use and land cover data, previously prepared from 30 meter Landsat Thematic Mapper imagery, to produce percent imperviousness coefficients that easily can be used in watersheds without detailed planimetric data.

INTRODUCTION

The urban centers of the United States have rapidly expanded over the past 50 years. In addition, rural landscapes are being replaced with suburban communities. This rapid development has been referred to as urban sprawl, which has become synonymous with increased impervious cover. Impervious surfaces can be loosely defined as any surface through which water can not penetrate. These include paved roads, sidewalks, parking lots, buildings, rooftops, as well as many other land cover types. Most impervious surfaces common in an urban setting can be categorized as belonging either to the transportation system (roads, sidewalks, parking lots, *etc*.), or rooftops (residential housing, buildings, *etc*.). Of these two major components, the transportation system typically contributes the most to total impervious area (Schueler, 1994).

Polluted precipitation runoff has been identified as the leading threat to water quality in the United States (Environmental Protection Agency, 1994). Impervious surfaces are related to NPS pollution, which contributes to surface water degradation. NPS pollutants are generally spread over a relatively large area at low concentrations whereas a point source is located at a single location, such as a drainage outfall. It is estimated that 30% to 50% of the earth's surface is affected by non-point source pollution (Corwin *et al*., 1998). As water flows over the ground,

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it picks up debris and other contaminants that are carried into surficial water bodies or percolate through the soil and into ground water.

Impervious surfaces greatly increase the volume of runoff by preventing infiltration into the soil. The increased runoff volume can have numerous negative impacts upon a watershed. Land use planners can use impervious surface measurements as a means of estimating the environmental status of a particular watershed. Knowledge of the types of surfaces that comprise total impervious cover can be extremely beneficial. Planners can use this information to assist in the creation of future development plans and water resource protection programs (Schueler, 1994; Arnold and Gibbons, 1996). However, in order to be successful, accurate measurements of existing and future imperviousness are required. It was the purpose of this study to develop two sets if coefficients for these purposes:

1) Develop parcel size and zoning specific impervious surface coefficients as a means to estimate future impervious cover.
2) Develop land cover specific impervious surface coefficients as a means to estimate current impervious cover.

The scale at which to base a management plan of a natural system has been the subject of considerable debate. Management plans that are confined by political boundaries often fail because the natural systems they were designed to protect are influenced by factors that extend beyond any human-designated border. Watershed level management can be an effective means to protect the natural environment from the negative impacts of urbanization. However, the watershed level approach should not be considered "foolproof". One of the primary reasons for the failure of local watershed management programs is that the "real" issues about land use change are never addressed. A watershed level management plan is a comprehensive management process that should lead to the implementation of measures that collectively protect the watershed from the impacts of future development (*i.e.* land use, site planning, riparian management, and stormwater practices)" (Schueler, 1995). Schueler also states that a key flaw in many watershed protection programs is the failure to assess accurately current and future imperviousness. This is often due to budget restrictions, lack of data, or the failure to incorporate impervious surfaces into the original management plan. Arnold and Gibbons (1996) suggest methods by which surface water quality issues can be addressed by developing land use strategies that minimize impervious surfaces in the landscape. This concept is the heart of the Nonpoint Education for Municipal Officials (NEMO) program of the University of Connecticut Cooperative Extension Service. The purpose of the NEMO project is to educate local officials about the correlation between urbanization and decreased water quality. A geographic information system (GIS) is used to facilitate the teaching of others about the environmental impacts of urbanization. Percent impervious surface cover measures are used by NEMO to estimate the extent to which a watershed's water quality has been impacted. A three-tier classification scheme suggested by Schueler (1994) is used to classify the watershed (Figure 1). Currently, the NEMO project determines percent impervious cover by multiplying the total area of certain types of land cover by an impervious coefficient, specific to each land cover. IS coefficients express, as a percent, the typical imperviousness of the area of interest for which they were designed. These values have been derived from various studies found in the literature (City of Olympia, 1994; U.S. Soil Conservation Service, 1986). Coefficient values, derived from a comprehensive study of impervious cover from representative Connecticut towns, potentially could provide more accurate estimates of impervious cover. Land use planners can use impervious surface cover information to assist in the creation of sound watershed protection plans while minimizing the number of variables that can impede plan implementation. By planning for less impervious surface, managers are planning for better water quality.

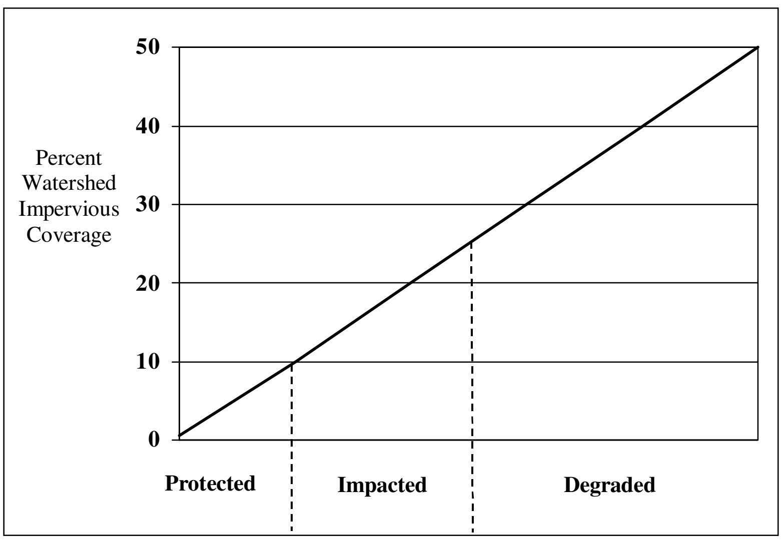

Figure 1. Relationship between percent watershed imperviousness and environmental quality (Arnold and Gibbons, 1996, Schueler, 1992).

BACKGROUND

The protection of surface water has been a long time concern at all levels of government. The previous decade has seen impervious cover emerge as an important indicator of environmental quality (Arnold *et al.*, 1996). Some land use planners have made a conscious effort to minimize impervious surfaces within their respective municipality. Prior to the development of any future development plans, an assessment of current imperviousness is usually required. In response to this need, numerous techniques have been devised to facilitate estimations of imperviousness. The most accurate measures of imperviousness can be achieved via traditional optical ground-based survey techniques or the global positioning system (GPS). In either case, extensive fieldwork is required to record the geographic location of all roads, buildings, sidewalks, *etc*. This method often is not feasible due to time and/or monetary constraints, especially in larger study areas.

In attempt to reduce cost and time requirements, several alternatives to traditional methods have been developed. Remotely sensed data, from both satellite and aerial platforms, have been used to determine impervious cover. The development of land use specific impervious surface coefficients has increased the effectiveness of estimating impervious cover form satellite data, especially in large study areas. These methods have resulted in varying degrees of success, but remain viable alternatives to traditional survey techniques. However, the benefit of reduced costs and timely results is often offset by reduced levels of accuracy in the output data (Figure 2)(Stocker, 1999).

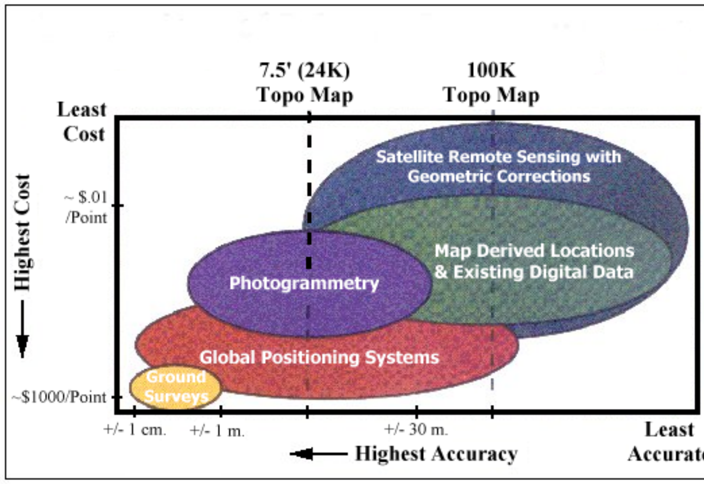

Figure 2. Cost versus Accuracy.

One of the most accurate methods to determine impervious cover is through aerial photograph interpretation (Draper and Rao, 1986). Determining impervious surfaces from aerial photographs is more practical for small study areas (*i.e.,* town-level or sub-regional watershed) than are most satellite data driven methods. Aerial photographs potentially can provide extremely high accuracy data depending on the interpretation method used.

The use of stereo photogrammetric techniques allows for the most accurate measurements from large-scale aerial photos. Using these methods, the numerous distortions that degrade accuracy are removed. A corrected photo can provide a wealth of information, and is limited only by the resolution of the photo. Given the same hardware (*i.e.*, camera lens, filters, etc.), the resolution of the photo is a factor of the altitude at which the photograph was taken. Generally, as altitude increases, resolution becomes coarser. At coarse-resolutions, individual small features are difficult to distinguish, even with the use of a stereo plotter and photogrammetric techniques (Lillesand and Kiefer, 1994).

When compiling a planimetric database of impervious surfaces, the need for high-resolution photographs is readily apparent. On a coarse-resolution photo, the boundaries of larger features (*i.e.*, buildings, or roads) can appear "fuzzy", which prevents accurate digitizing. Smaller features, such as sidewalk and patios, can become indistinguishable from the background features resulting in complete omissions of features from the final digitized data layer. The planimetric data used in this study were generated using stereo pairs of large scale (1" = 200') aerial photographs. This provides a sufficient resolution to allow for the differentiation of individual impervious surface types (*i.e.*, asphalt path versus concrete sidewalk). Data of this detail are imperative if precision analysis characterizing impervious cover is to be conducted. An inventory of the impervious surfaces within different zoning categories can assist local planners in identifying areas that have particularly high concentrations of impervious surface. The identification of problem areas is the first step in reducing impervious cover in future developments (City of Olympia, 1994).

Satellite remote sensing techniques provide an expedient and cost-effective means to estimate impervious cover over large study areas (*i.e.*, regional watershed or state level). Historically, the applicability of satellite data in small regions has been limited by their relatively coarse-resolution. For the most part, the few high-resolution satellites that exist have been restricted by the military and not available to the public. However, this is rapidly changing with the scheduled launching of numerous high-resolution satellites by companies in the private sector, as well as foreign governments. For example, the IKONOS satellite (Space Imaging, Thornton, Colorado), that was launched in September 1999, has a 1-meter panchromatic and 4-meter multi-spectral resolution. Although these data are at a fine enough resolution to allow the user to distinguish different impervious surface types, they are not yet commercially available for all areas. Additionally, high-resolution data sets usually cost more, increase processing times, cover a smaller area per scene, and require a large storage capacity. Continuing increases in computing power and disk storage capacity should help minimize processing times and make data storage a non-issue for all but extremely large study areas. Additionally, costs should decrease as more high-resolution satellites are launched and consumers have a greater number of choices when shopping for data.

Several alternatives to the "next generation" high-resolution satellites currently exist for the consumer (*i.e.*, LANDSAT, SPOT, AVHRR). Although the resolution of the data from these satellites is moderate to coarse, they are relatively inexpensive, and are available for nearly any geographic location. In addition, data are available for different time frames, which allows land cover change studies to be conducted. The LANDSAT series has been one of the most widely used satellites for discriminating urban surfaces. The LANDSAT satellite series' Multispectral Scanner (MSS), launched in 1972, and Thematic Mapper (TM), launched in 1982, have been successfully employed to classify various types of land cover (Arthur *et al*., 1998; Civco and Hurd, 1997; Haack and Adams, 1987; Toll, 1985). These studies have resulted in various degrees of success. Arthur *et al*. (1998) utilized LANDSAT Thematic data successfully to monitor the land cover change in Chester County, Pennsylvania. Comparison of remotely sensed information with that of land cover maps and ground truthing revealed an accuracy of 75% to 87%. It was noted that residential areas were difficult to classify due to land cover pattern complexity. In his evaluation of simulated LANDSAT data, Toll (1984) found the Thematic Mapper achieved a 50% to 80% level of accuracy in determining suburban/urban cover, as compared to 29% to 87% accuracy achieved using Multispectral Scanner data. Plunk *et al*. (1990) were able to attain an 85.1% accuracy, as compared to field measurements, of impervious surface in Fort Worth, Texas using a supervised, maximum-likelihood classification of LANDSAT TM data. It was noted that total impervious surface area was often underestimated.

Impervious surface coefficients express, as a percent, the typical imperviousness of the area of interest for which they were designed. Previous research has focused primarily on developing coefficients specific to 1) parcel size and zoning (Alley and Veenhuls, 1983; City of Olympia, 1994; U.S. Soil Conservation Service, 1986) or 2) satellite-derived land cover data (Deguchi and Sugio, 1994; NEMO, 1999). The parcel and zoning based method is useful for estimating imperviousness within politically defined areas, but are of limited value where parcel data are not available or the area of interest is defined by a natural boundary (*e.g.* watershed). As previously stated, various types of satellite data have been successfully used to determine land cover. Using coarse resolution, satellite-derived land cover data to estimate impervious cover can result in considerable error. For example, a 900 square meter pixel categorized as high-density residential is probably not 100% impervious. Studies have been conducted to determine the percent of impervious cover common to particular land uses (Deguchi and Sugio, 1994; NEMO, 1999). These percentages can be applied to satellite derived land cover data to improve the estimate of impervious cover. This approach benefits town planners because it allows an impervious cover study to be conducted in a timely manner and at very little expense.

METHODOLOGY

The Connecticut towns of West Hartford, Waterford, Marlborough, and Woodbridge served as the basis for this study. A town is a self-governed, politically defined unit comparable to a small county (~20-30 sq. miles). The towns represent different geographic regions of Connecticut and are in different developmental stages. Marlborough is a rural community, Woodbridge and Waterford are suburban, and West Hartford has both suburban and heavily urbanized areas. Considerable variation exists in average parcel size and parcel distribution.

Data availability was the primary reason these four towns were chosen. Unfortunately, the value of a town level geographic information system database has only been acknowledged over the past few years. In addition, it can be somewhat costly to develop a planimetric GIS database. As a result, very few towns in Connecticut had the data necessary for this study. The four study towns were chosen because they had recent and accurate digital planimetric data. These data were digitized from 1:2400 aerial photographs using stereographic techniques, by independent firms contracted by each of the towns. The data were converted into an ArcInfo 7.x format where editing and spatial joins were performed. Two sets of coefficients were developed using the GIS digital planimetric data. Statistics were calculated using a RDBMS.

The first set of coefficients is based on parcel size and zoning classification. This approach has been the focus of many studies (Alley and Veenhuls, 1983; City of Olympia, 1994; U.S. Soil Conservation Service, 1986), and is one of the more common methods used to estimate impervious cover.

The parcel and zoning specific coefficient approach made use of the planimetric database and parcel/zoning data layers acquired from each town. Percent imperviousness was first calculated for each individual parcel. The following equation was used to make the calculations.

$$(\text{ImperviousArea}_{\text{Parcel}} / \text{TotalArea}_{\text{parcel}}) \times 100 = \%\ \text{Impervious}_{\text{Parcel}}$$

Impervious surface coefficients were developed for different combinations of parcel size and zoning classification. Zoning categories vary considerably from one Connecticut town to another. To compare study areas, standard zoning categories were created. This involved reclassifying each town's current zoning with a standard, generalized classification scheme. Zones were reclassified based on designed use as specified by each town, using zoning regulations as a reference (Munilaw, Inc., 1999). Parcels were classified as commercial, industrial, or residential. Road right-of-ways were kept as a separate category.

Municipal Zoning Commissions in Connecticut establish zones within which specific land uses are allowed. Additionally, the commissions establish minimum lot sizes for each zone that must be met for development to occur. Due to the fact that the area of any individual parcel is rarely an integer multiple value, a system based on an area size range was devised to categorize the parcels of each town. Using the definition of an U.S. acre (43560 sq. ft.), parcel area value ranges were developed and assigned a unique code. This code value was then used to analyze how the impervious surface data varied between different size parcels with the same zoning designation.

Summary statistics were calculated to quantify the average percent imperviousness for parcels within each group. Impervious surface coefficients were based on the mean percent impervious value. The distribution of parcel imperviousness within size groups of residential parcels was normally distributed. The mean impervious value specific to each size group was used as the impervious coefficient for residential parcels. Parcel percent imperviousness within size groups of industrial and commercial parcels was uniformly distributed. It was determined that the mean parcel imperviousness was relatively consistent for different size groups of industrial and commercial parcels. Coefficients for industrial and commercial parcels were based on the mean impervious values for all parcels within each respective zone.

The second set of coefficients is based on Thematic Mapper satellite-derived land cover data. High-accuracy, digital planimetric data were used to determine the average percent imperviousness for each respective land cover category. This method attempts to reduce the limitations caused by the coarse resolution of the satellite data (30x30 meters).

The satellite-based impervious coefficient approach made use of the IS planimetric database and the LANDSAT TM-derived statewide Connecticut land cover map data (Civco and Hurd, 1999). These data contain 28 different land cover categories, of which, only three can be recognized as urban cover types. Due to the relatively coarse resolution of the land cover data, roads are often misclassified as non-developed land cover. This is primarily due to pixels containing a heterogeneous spectral signature. A "Road" category was created by rasterizing the roads from the planimetric IS data to a 10x10 meter grid. This coverage was then used to *update* the land cover dataset with a "Road" category.

Average percent imperviousness was determined for each land cover category for the towns of Marlborough, Woodbridge, Waterford, and West Hartford. Some similarity existed among the percent imperviousness per land cover type in the towns of Marlborough, Waterford, and Woodbridge. Percent imperviousness was generally greater for each corresponding land cover type in West Hartford as compared to the suburban study towns. Although some variability existed between the suburban towns, it was found that the majority of total impervious area could be traced to seven land cover categories in all four towns. Variability among these seven categories in the suburban towns was relatively low.

Based on population density, West Hartford was determined to be in an advanced stage of urbanization compared to the other study towns. The land cover values specific to West Hartford were consequently removed from the development of coefficients. Suburban coefficients were based on average percent impervious cover for each land cover type for the towns of Marlborough and Woodbridge. The town of Waterford was used to test the accuracy of the suburban IS coefficients. The land cover IS coefficient development process is summarized in figure 3.

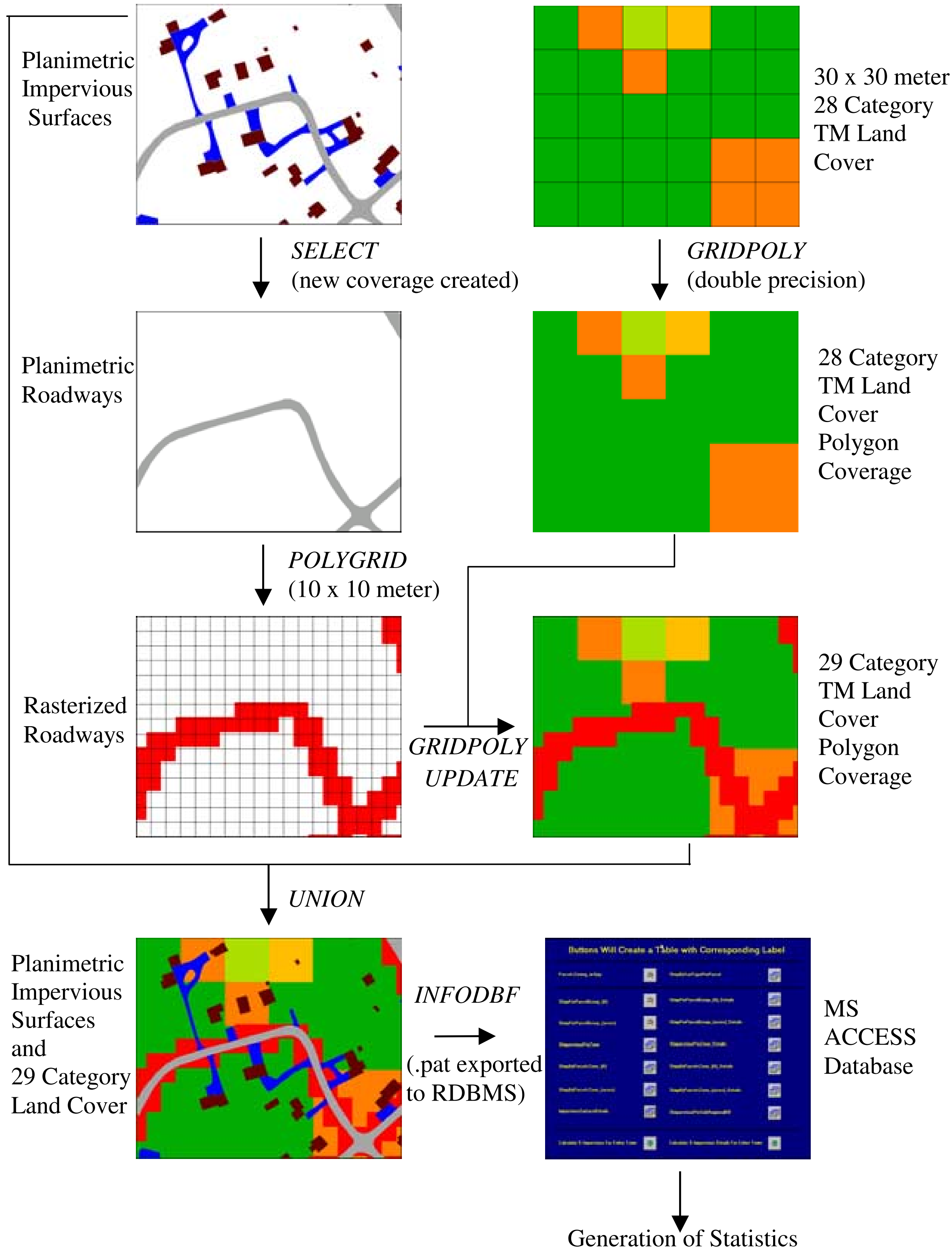

Figure 3. Land cover-specific IS coefficient development methodology.

To determine the validity of the IS coefficients, a comparison of predicted to known values was conducted. The planimetric impervious surface data provided high-accuracy measurements of IS cover in each of the four study towns. The parcel and zoning specific coefficients were used to estimate the percent imperviousness for each zone in West Hartford, Woodbridge, and Marlborough. Waterford was not included due to registration problems between the planimetric IS data and the parcel/zoning data coverages. The following equation was used to estimate the impervious cover for each of the simplified zones:

$$\frac{\sum (\text{ParcelArea}_{Zone} \times \text{IS Coefficient}_{ParcelSize,\ Zone})}{\text{Total Area}_{Zone}} = \text{Approximate \% Impervious}_{Zone}$$

where,

ParcelArea_{Zone} = Total area of each developed parcel in a specified zone,
$\text{IS Coefficient}_{Parcel,\ Zone}$ = Impervious surface coefficient specific to parcel size and zone,
Total Area_{Zone} = Sum of all parcel area for the specified zone, and
$\text{Approximate \% Impervious}_{Zone}$ = the estimated imperviousness for the specified zone.

These were then compared to the results achieved using the planimetric data.

Using the derived land cover specific coefficients in conjunction with the 1997 land cover data, an estimate of impervious cover was determined for each town and subregional drainage basin within each town. The following equation was used to estimate impervious cover:

$$\frac{\sum (\text{Land Cover Area}_{AOI} \times \text{IS Coefficient}_{LandCover})}{\text{Total Area}_{AOI}} = \text{Approximate \% Impervious}_{AOI}$$

where,

$\text{Land Cover Area}_{AOI}$ = the satellite land cover area within the area of interest,
$\text{IS Coefficient}_{LandCover}$ = Land cover specific impervious surface coefficient expressed as a decimal, and,
TotalArea_{AOI} = Total area of the area of interest.

The results were then compared to the results achieved using the planimetric data.

RESULTS

Percent imperviousness was determined for different combinations of parcel size and zoning designation (Figure 4). Average percent imperviousness decreased with increasing parcel size in the residential parcels of the suburban towns. A similar trend existed in parcels ranging <2 acres in West Hartford, however, average percent imperviousness increased in parcels >2 acres. This was believed to be due to the existence of multi-family apartment complexes with adjoining parking lots in these larger parcels. Parcel impervious percentages varied considerably in the industrial and commercial zones of all study towns.

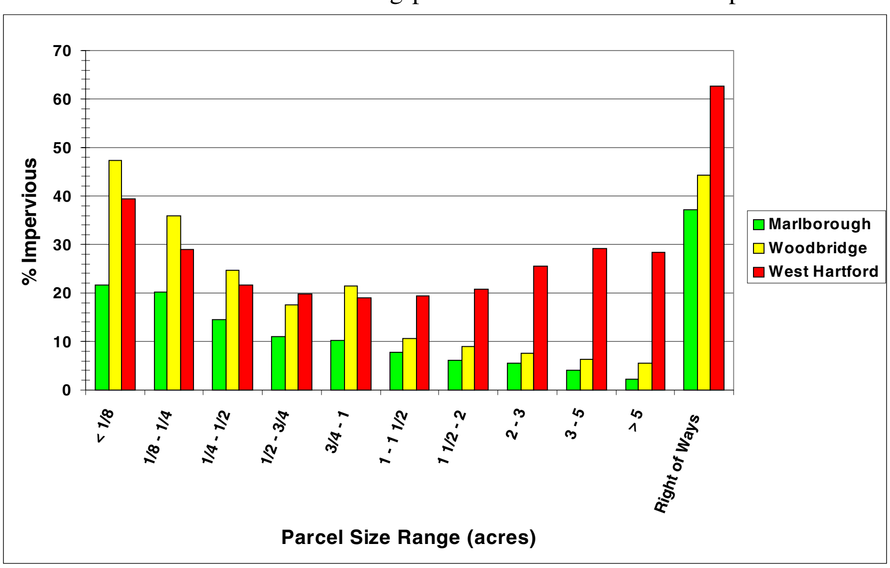

Figure 4. Average percent imperviousness per parcel.

Parcel and zoning specific coefficients were based on the average percent imperviousness for developed parcels in each size range category (Table 1). Percent imperviousness of residential parcels was normally distributed in each of the size categories. Average impervious percentages in industrial and commercial zones were uniformly distributed. Consequently, a single industrial coefficient and a single commercial coefficient were developed based on the mean percent imperviousness for all developed parcels.

Zone	*Parcel Size (acres)*	*Coefficient*
Residential	< 1/8	0.39
Residential	1/8 - 1/4	0.28
Residential	1/4 - 1/2	0.21
Residential	1/2 - 3/4	0.16
Residential	3/4 - 1	0.14
Residential	1 - 1 1/2	0.1
Residential	1 1/2 - 2	0.09
Residential	2 - 3	0.07
Residential	3 - 5	0.07
Residential	> 5	0.08
Industrial	all	0.53
Commercial	all	0.54

Table 1. Parcel and zoning specific IS coefficients.

Impervious surface coefficients were developed using the modified satellite-derived land cover data. Suburban coefficients were based on the percent impervious cover for each of the 29 land cover types in the towns of Marlborough and Woodbridge (Table 2).

Land cover	*Coefficient*
Road	43.3
Commercial & Industrial & Pavement	26.4
Exposed Soil	35.6
Residential & Commercial	20.5
Turf & Tree Complex	9.4
Nursery Stock	8.3
Pasture & Hay / Exposed Soil	7.3
Forest / Clear Cut	6.8
Rural Residential	6.5
Pasture & Hay & Grass	4.5
Coniferous Forested Wetland	4.0
Deciduous Shrub Wetland	2.1
Exposed Soil / Cropland	2.2
Deciduous Forest	2.0
Deciduous Forested Wetland	1.9
Shallow Water & Mud Flats	1.6
Turf & Grass	1.3
Coniferous Forest	1.1
Non-forested Wetland	0.8
Scrub & Shrub	0.5
Mixed Forest	0.2
Deciduous Forest & Mt Laurel	0.1
Dead & Dying Hemlock	0.1

Table 2. Land cover specific IS coefficients.

An accuracy assessment was conducted to assess the validity of the parcel and zoning specific IS coefficients and the land cover IS coefficients. Predicted impervious area was compared to the impervious area calculated using the IS planimetric data.

Overall, the parcel/zoning coefficients were relatively poor estimators of imperviousness. The residential coefficients appear to be the most precise with the margin of error ranging from 2.2% to 6.3%. The industrial zone coefficient was effective in predicting percent imperviousness in West Hartford and Woodbridge (±2.3%), but was highly inaccurate in Marlborough where imperviousness was overestimated by 26%. The commercial zone coefficient proved inaccurate for all three towns. Imperviousness was overestimated in Marlborough (+34.5%), and Woodbridge (+25.5%) and underestimated in West Hartford (-10.5%). These data are summarized in tables 3a-c.

a.

	Marlborough (%)	
Zone	*Predicted*	*Actual*
Residential	4.1	1.9
Industrial	35.5	9.5
Commercial	43.9	9.4

b.

	Woodbridge (%)	
Zone	*Predicted*	*Actual*
Residential	7.4	4.8
Industrial	53.0	55.3
Commercial	47.5	22.0

c.

	West Hartford (%)	
Zone	*Predicted*	*Actual*
Residential	11.8	18.1
Industrial	50.8	50.5
Commercial	53.6	63.1

Table 3a-c. Actual versus predicted zone imperviousness using parcel/zoning coefficients.

The land cover coefficients were used to estimate total town imperviousness in Marlborough, Woodbridge, and Waterford. Table 4 contains the actual percent town imperviousness and the predicted town imperviousness. The discrepancy between the actual and predicted values ranged from 0.2% to 1.4%.

	Actual Impervious Area (acres)	*Predicted Impervious Area (acres)*	*Actual %*	*Predicted %*
Marlborough	519.2	624.8	3.5	4.2
Woodbridge	948.2	726.4	7.3	5.9
Waterford	1539.3	1679.5	7.7	7.8

Table 4. Actual versus predicted town imperviousness using land cover coefficients.

The ability to assess current watershed imperviousness is the first step toward developing plans and possibly regulations to protect water quality. The percent impervious cover was determined for the portion of each subregional drainage basin that is within each of the suburban towns. Impervious cover was then estimated using the land cover specific impervious surface coefficients. The discrepancy between the actual and predicted values in Marlborough was less than 1.1% in 75% of the basins. The average difference was less than 1.5%. In Woodbridge, the discrepancy between actual and predicted values was less than 1.5% with an average difference of 1.2%. In

Waterford, the discrepancy between actual and predicted values was less than 1.2% with an average difference of 0.7% (Table 5).

Waterford			
Subregional DB	*SubDB Area (acres)*	*Actual %*	*Predicted %*
Hunts Brook	3591	4.8	6.1
Jordan Brook	4807	8.7	8.6
Latimer Brook	554	0.6	2.2
Niantic River	3052	7.5	8.0
Oil Mill Brook	2719	2.8	4.1
Oxoboxo Brook	3	17.8	18.5
Southeast Shoreline	5062	9.2	9.0
Thames River	2641	6.6	7.4

Table 5. Actual versus predicted sub-regional drainage basin imperviousness.

CONCLUSIONS

Many studies have focused on the development of impervious surface coefficients based on zoning and parcel size. This approach assumes that accurate parcel boundary and zoning data exists, ideally in digital format, and that an inventory of developed parcels is available. Efforts to assess imperviousness at the watershed level can be difficult using this method because natural, administrative, and political boundaries rarely coincide with one another. Continuous data sets, such as those provided by the Landsat Thematic Mapper, potentially offer a more accurate means to estimate impervious cover. Additionally, the parcel/zoning coefficients often fail to take into account impervious cover due to roads. Based on the results of this study, the parcel/zoning IS coefficients were poor estimators of impervious cover. This error was a result of the variation in zoning classes between each of the study towns. For instance, developed industrial zones in West Hartford had an average imperviousness of 50.5% as compared to Marlborough where average imperviousness was <10%. In order for the parcel/zoning IS coefficient approach to be successful a more accurate means to standardize zoning classes needs to be developed.

Assessing the validity of the land cover specific impervious surface coefficients was difficult due to the lack of high-accuracy planimetric data for towns outside of the study area. The coefficients were developed from the planimetric IS data of Marlborough and Woodbridge and then tested against values from Waterford. It was determined that the coefficients provided acceptable estimations of imperviousness at the town and sub-regional drainage basin level. It should be noted that the "deciduous forest" land cover category was responsible for much of the error in the estimations. Impervious cover in this category was over-estimated in Marlborough by approximately 75 acres and under-estimated in Woodbridge and Waterford by approximately 120 acres. Consequently, town-wide imperviousness was over-estimated in Marlborough and under-estimated in Woodbridge and Waterford. The discrepancy in the "deciduous forest" category is difficult to account for because the satellite data were collected during "leaf-off" conditions. Incorporating a "Roads" category into the data reduced some of the error caused by forest land cover. Impervious predictions at the sub-regional drainage basin level were on average ± 1.0 % of the planimetric derived values. The largest error (3.0 %) was within a heavily forested section of the Salmon River watershed within Marlborough. Based on these results, it was concluded that the methodology for developing the land cover specific coefficients for the suburban towns was valid.

The land cover IS coefficients developed by this study were based on the actual impervious cover for two suburban Connecticut towns (Marlborough and Woodbridge). When used in conjunction with TM land cover data, these coefficients successfully predicted percent impervious cover at the town and sub-regional drainage basin level for a third suburban town (Waterford). The difference in imperviousness in West Hartford as compared to the suburban towns suggests that a dichotomous approach might be an effective means to classify towns. Additional data potentially could be used to develop "urban" coefficients that can be used to estimate impervious cover in more developed communities. Another approach under consideration by these researchers involves a classification scheme based on population density. It is suggested that the application of these values to other communities in Connecticut would not be prudent until further research is conducted to refine and test their accuracy.

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