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Quantifying the Components of Impervious Surfaces

By Janet S. Tilley and E. Terrence Slonecker

In collaboration with the
U.S. Environmental Protection Agency
Office of Research and Assessment

U.S. Department of Transportation
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Abbreviations

BMP	Best Management Practices
CWA	Clean Water Act
CWP	Center for Watershed Protection
DOT	U.S. Department of Transportation
DOQ	Digital Orthophoto Quadrangle
EROS	U.S. Department of the Interior, U.S. Geological Survey, EROS Data Center
ETM	Enhanced Thematic Mapper
FHWA	U.S. Department of Transportation, U.S. Federal Highway Administration
GAM	U.S. Department of the Interior, U. S. Geological Survey, Geographic Analysis and Monitoring Program
GAO	U.S. Government Accounting Office
GIRAS	Geographic Information Retrieval and Analysis System for Handling Land Use and Land Cover Data
GIS	Geographic Information System
LC	Land Cover
LU	Land Use
MRLC	Multi-Resolution Land Characteristics
NLCD	National Land Cover Data
NLCD92	National Land Cover Data – 1992 product
NLCD2000	National Land Cover Data – 2000 product
NPS	Nonpoint source pollution
ORD	U.S. Environmental Protection Agency, Office of Research and Development
RESAC	Mid-Atlantic Regional Earth Science Applications Center
RIA	Road Impervious Area
TIA	Total Impervious Area
TM	Thematic Mapper
USEPA	U.S. Environmental protection Agency
USGS	U.S. Geological Survey
VAT	Value Attribute Table
WSIA	Watershed Impervious Area
WSTA	Watershed Total Area

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Executive Summary

Since the early 1970s our Nation has been experiencing a growing awareness of the complex relationships between the transportation infrastructure and environmental quality. One notable concern has been the potential for water quality degradation as a result of stormwater runoff over paved highway surfaces. Laws, executive orders, and government polices designed to minimize and mitigate the potential negative consequences of highway runoff have been enacted. These include the National Environmental Policy Act, the Intermodal Surface Transportation Efficiency Act, the Coastal Zone Reauthorization Amendment, the National Wild and Scenic Rivers Act, and the Clean Water Act of 1972, as amended, including the National Pollutant Discharge Elimination System and the Nonpoint Source Management Programs.

The Federal Highway Administration (FHWA) has designated environmental protection and enhancement are high-priority program areas that stress the evaluation of highway-related water quality impacts, as well as avoiding, mitigating, or managing such impacts, and coordinating with other agencies to ensure that Federal environmental policies are placed in perspective with other primary highway missions. The FHWA, the U.S. Geological Survey (USGS), and the U.S. Environmental Protection Agency (USEPA) are currently cooperating on research and development projects related to the minimization of water quality impacts from highway runoff.

Past research sponsored by the FHWA identified and measured various pollution sources and developed techniques to lessen their impact on water resources. This research has been used by project development personnel to plan and implement highway improvements that minimized the impacts of pollution. The improved understanding of pollution sources and solutions to water quality problems has greatly increased the ability of States to plan and construct highways that have minimal effects on water quality (Bank, 1993).

The issues of highway stormwater runoff and its consequences were refocused in the early 1990s by the emergence of a new environmental water quality indicator called impervious surfaces. Impervious surfaces represent all materials and structures that inhibit the penetration of precipitation into the ground and divert its flow over the land surface and eventually into surface waters. In general, impervious surfaces are manmade structures such as buildings, roads, parking lots, sidewalks, and other land covers.

Research has shown that land development and the addition of impervious surfaces can increase streambank erosion, loss of aquatic habitat, and other changes, as the percentage of total impervious area increases in watershed (Arnold and Gibbons, 1996; Schueler, 1994).

As impervious surfaces emerged as an important indicator of water quality, researchers began to use numerous statistical, census-based, and land-use mapping methods to estimate the total impervious area (TIA) of a given area. None of these techniques, however, had been tested rigorously for the fundamental mapping accuracy of the measurement. Furthermore, in the literature and in discourse, road surfaces were often cited as the leading cause, the driving force, or the major component of the impervious surface problem. To better understand, plan, and control the effects of road surfaces to water quality, a quantitative assessment of the component makeup of total impervious cover is needed. Also, an assessment is needed of the accuracy of the current methods used by the scientific community to compute total impervious area.

The objectives of this study are to (1) determine the makeup of total impervious area and the relative contribution of individual components; and (2) assess the accuracy of various techniques in use for determining total impervious area.

Six urban and suburban watersheds were selected for study that represent a wide geographic distribution across the country. High-resolution orthoimagery (1 meter or better) was obtained for each watershed. Six classes of impervious cover were manually digitized as polygon features in a geographic information systems (GIS) environment. Relevant GIS data were obtained from County or City GIS departments. The six classes of cover were roads, buildings, parking lots, driveways, sidewalks, and other (such as sport courts). Quality control was provided by independent validation and mapping spot checks. The total area for each impervious surface class was totaled for the six watersheds and the percentage of each class was calculated against the total area of impervious cover.

The largest area class of impervious cover was *buildings* at 29.1 percent, followed by *roads* (28.3 percent), and *parking lots*

(24.8 percent). Three minor classes of impervious surfaces were driveways (9.0 percent), sidewalks (3.2 percent), and other (1.8 percent).

Three significant observations were apparent. First, *roads* were *not* the leading contributor to total impervious area. Second, *parking lots* represented a much larger than anticipated percentage of the area. Parking lots represent a different level of responsibility and a different set of environmental problems. Third, the three minor classes, *driveways*, *sidewalks*, and *other*, in total represented 14 percent of total impervious area. These three classes are rarely accounted for in impervious calculation methods, leading to the possibility of a statistically significant under-representation of minor class TIAs as compared to the impact of larger areas.

As part of the second objective of this study, to evaluate other TIA calculation methods, the high-resolution data from the six watersheds were used as control data to evaluate other methods. Three methods were tested. The first was, subpixel mapping of impervious area, land use coefficients and land cover coefficients. Subpixel estimates of impervious areas are derived from advanced image processing techniques using Landsat Thematic Mapper 30-meter multi-spectral and high-resolution digital orthophoto quarter quads. The result is a percentage of impervious area within each 30-meter pixel. Subpixel estimates of impervious area will be a nationally available, standard product of the USGS/USEPA National Land Cover Data (NLCD) set and could be a consistent base layer for a rapid method of TIA estimation. The results of testing this method showed a consistent underestimation of TIA, although usually within 10 percent. However, in one watershed, Difficult Run, Va., over 40 percent of TIA was not accounted for. This is likely due to coniferous tree cover in this area that masks the spectral reflectance of impervious materials underneath.

The second method, the land-use coefficient method, is widely used and is based on multiplying the area of each vector-based land use polygon by a predetermined coefficient that represents the average amount of impervious area for that particular land use class. Results from testing in four watersheds showed that the TIA derived from the land-use coefficient method were, on average, within 7 percent of the area derived from the high-resolution mapping.

The third method, the land cover method, involves generating an estimate of TIA from land cover data that is typically in a raster model generated from satellite-based image processing methods. Land cover data, like land use, is a thematic representation of surface phenomenon, but is based on the environmental cover or spectral reflectance properties of the surface instead of on an anthropogenic-based utilization of land. In general terms, land cover is generally less detailed than the type of land use data used in the second method and is generally mapped on a raster-based GIS model derived from the satellite imagery pixel size. It does, however, offer the advantage of a national, thematically consistent and regularly updated dataset from which many other spatial relationships, such as impervious surfaces, can be derived on a consistent, national basis.

Two methods were utilized to calculate TIA from National Land Cover Data (NLCD). Both methods use coefficients to calculate a percentage of impervious area per each pixel in the NLCD land cover classes. The results for both methods showed that the land-cover coefficient method delivered an average of 96 percent accuracy when compared to the high-resolution mapping data.

The high-resolution compilation of impervious surfaces begins to show us the component relationship of similar features that, as a whole, make up the functional impervious surface area. Roads, while often being the primary focus for impervious area, are only one of the three major components of TIA that also include buildings and parking lots. The contribution of Road Impervious Area to overall Total Impervious Area ranged from a low of 20.8 percent in the 1992 Black River watershed to a high of 35.6 percent in the 1998 Tuscarora Creek watershed. Driveways, often unaccounted for in impervious surfaces research, make up an average of 9 percent of the total impervious surface area in this study. Further, these data show that even very minor classes of impervious cover are important. Very few studies on impervious surface area have taken into account sidewalks, patios, and or other sport courts. Yet in this study, these are responsible for 5 percent of TIA.

This study shows the component composition of impervious areas in six selected watersheds. While roads, buildings, and parking lots, make up the majority of impervious areas, driveways, sidewalks, and other covers make up 14 percent of TIA and should not be ignored in calculating TIA. Also, TIA is affected by regional or individual differences in land use in the watershed. Further research is needed to extend these findings to the entire nation.

Four of the common methods of computing impervious area show significant variability when measured against high-resolution truth data. Overall, the four methods tested here generally produced an estimate of TIA within 10 percent of the truth value. These methods could be refined further and result in an even better estimate of TIA.

Introduction

Why Impervious Surfaces Are Important

Impervious surfaces are manmade objects that prohibit the infiltration of rainwater into the ground and cause increased surface flow. Impervious surfaces are a major concern for the quality of a community's surface water and aquatic ecosystem resources. A number of well documented studies have shown the negative effects of increased imperviousness on stream morphology, water quality, and ecosystem health. However, beyond the basic science of the environmental effects of imperviousness, there is a growing and complex debate about the best practices for mitigating their negative effects.

At the core of this debate is the often cited belief that imperviousness is largely the result of roadway surfaces (or the overall transportation infrastructure). Roads are sometimes cited as making up as much as 80 percent of all imperviousness in a given area. This belief influence local and national transportation policy, including calls for more comprehensive environmental impact studies and new and expensive *best management practices* that are often required for new road construction (Center for Watershed Protection, 1998).

At the local level, policies that establish *stormwater utility fees* are based on the area of impervious surface in a given property parcel. Even the basic land use policy and the nature of urban-suburban-exurban expansion are now being rethought with an eye towards reducing automobile-centric development patterns and increasing high-density communities.

Yet throughout this debate is a lack of detailed studies and scientific quantification of what actually makes up the whole of impervious surfaces and how those components vary across the political and physical landscape. Further, the methods of measuring and computing impervious surface area are varied and complex and similarly have no established quality control associated with their use.

Any effort that helps to define the component nature of imperviousness and (or) helps to assess the accuracy of the various methods used to compute impervious area is critically needed. This study addresses some of these issues.

Impervious Surfaces Defined

A formal definition of an impervious surface can be found in the U.S. Environmental Protection Agency's *Draft Report on the Environment* (2003a): *"Impervious surface: A hard surface area that either prevents or retards the entry of water into the soil mantle or causes water to run off the surface in greater quantities or at an increased rate of flow. Common impervious surfaces include, but are not limited to rooftops, walkways, patios, driveways, parking lots, storage areas, concrete or asphalt paving, and gravel roads."*

The increase in impervious surfaces is directly related to human activity through the construction of manmade structures. As precipitation is diverted from natural soil infiltration, the overland flow results in significant increases in surface water runoff as well as a rise in the acquisition of sediment and anthropogenic chemical contaminants. The subsequent surge in the inflow rate and volume in the receiving stream brings about an enlargement of bank-full and stream scour events and significantly influences a stream's morphological structure. The instream and riparian ecology is thus altered because of changes in structural habitat and the related increases in sedimentation and pollution loadings (Arnold and Gibbons, 1996).

A National Problem

The USEPA now classifies urban runoff from impervious surfaces as a significant cause of impairment to water quality; local governments are required to address urban runoff through the National Pollutant Discharge Elimination System Storm Water Program (U.S. Environmental Protection Agency, 2003a). According to the U.S. Department of Agriculture, between 1945 and 1997 land devoted to urban areas in the United States increased by approximately 237 percent; paved road mileage increased by 278 percent (fig. 1).

Impervious Surfaces as an Environmental Indicator

The study of impervious surfaces has become one of the emerging areas of scientific interest in the control of Nonpoint Source Pollution (NSP), and as

Figure 1. Photograph showing a typical suburban impervious surface cover in one of the study areas of this project: the Tuscarora Creek watershed located in Leesburg, Loudoun County, Virginia.

an indicator of terrestrial and aquatic ecosystem quality. NSP runoff from urban surfaces has been recognized as a leading threat to water quality, and the percentage of impervious surface within a particular watershed has been shown to correlate strongly with water quality, species diversity, and trophic status (Arnold and Gibbons, 1996; U.S. Environmental Protection Agency, 2001). The imperviousness issue has been suggested as one of the main unifying themes for overall study of watershed protection (Schueler, 1994) and as part of an urban ecosystems analytical model (Ridd, 1995). Problems with NSP include its sporadic and diffuse nature, a lack of monitoring capability, and the difficulty of assigning responsibility for the NPS pollution. Generally it is very difficult to identify the amount of discharge from individual or suspected pollution sources and to infer NPS levels from observable ambient pollutant levels (Wood and Bernknoph, 2003).

In USEPA's *Draft Report on the Environment*, impervious surfaces and the extent of urban and suburban development are mentioned prominently as potential key indicators of ecological condition of both water and terrestrial ecosystems (U.S. Environmental Protection Agency, 2003a and 2003b). The environmental protection of water quality has generally evolved away from end-of-pipe regulation to a more comprehensive watershed management approach in which the interface between human and ecological systems is better understood. Stormwater runoff has always been of concern to planners and civil engineers, but until recently the emphasis was on human safety, not ecological consequences. However, comprehensive watershed management techniques that seek to understand and balance ecological factors, classic stormwater management, and local land use policy are now being widely implemented. Several researchers have shown the direct effect of impervious surfaces on the water quality of receiving streams (Klein, 1979; Todd, 1989; Booth and Reinfelt, 1993; Schueler, 1994). Numerous cities have adopted comprehensive water-quality planning efforts that integrate control of impervious surfaces as a central planning theme (Monday and others, 1994; Kienegger, 1992; Plunk, 1989). There are numerous other examples of impervious surfaces as a prime consideration in local planning processes.

Correlation Between Impervious Surfaces and Aquatic Ecosystem Conditions

Literature indicates that irreversible environmental degradation of an aquatic ecosystem occurs when a watershed contains more than 25 percent impervious surfaces. Schueler (1994) and Arnold and Gibbons (1996) both observe that research over the last 20 years has consistently reported a correlation between watershed imperviousness and the health of the receiving stream ecosystem. Schueler proposes (and Arnold and Gibbons concur with) a three-tiered threshold classification scheme of urban instream quality potential based on watershed imperviousness levels:

Stressed = 1 to 10 percent imperviousness
Impacted = 11 to 25 percent imperviousness
Degraded = more than 25 percent imperviousness

These classes were described in further detail by the Center for Watershed Protection (1998), which also modified the names of the first level from *stressed to sensitive*, and the third level from *degraded to non-supporting*.

A summary of the descriptions of the three classes follows:

Sensitive streams are of high quality and are typified by stable channels, have an excellent habitat structure, good to excellent water quality, and diverse communities of fish and aquatic insects. In addition, they do not experience frequent flooding.

Impacted streams show clear signs of degradation due to watershed urbanization. Because of the greater storm flows due to the higher intensity of flooding and runoff from impervious surfaces, the stream geometry becomes wider due to more rapid erosion and also causes unstable banks. The physical habitat declines noticeably and the water quality transitions from good to fair. Biodiversity declines to fair levels with most sensitive fish and insects disappearing.

Non-supporting streams become a conduit for conveying stormwater flows and can no longer support a diverse stream community. The stream channels become highly unstable while the stream reaches experience severe widening, down cutting, and streambank erosion. Pool and riffle structures needed to sustain fish are diminished or eliminated, and the stream substrate can no longer provide habitat for aquatic insects or spawning areas for fish. Water quality is consistently fair to poor and water contact for people is no longer possible due to the high bacteria levels. Sub-watersheds in the non-supporting category will generally display increases in nutrient loads to downstream receiving waters, even if effective urban Best Management Practices are installed and maintained. Biological quality is generally considered poor and is dominated by pollution tolerant fish and insects.

Each of these classes has corresponding Best Management Practices associated with them. These categories could be used as a foundation for a watershed-based zoning approach, using impervious cover as the key measure and unifying theme in the municipal land-use zoning process (Schueler, 1994).

Impervious Surface Impacts

Stream Morphology. The immediate and direct ecological consequence of watershed imperviousness is the effect on stream morphology. Increased water flow and volume destabilize streams through widening and incision, as well as streambank erosion and habitat degradation. Channel instability correlates with sub-bank full floods (Anderson, 1968; Leopold, 1968; Hammer, 1972; Hollis, 1975; Booth, 1993) and is characterized as loss of critical instream and riparian ecostructures such as pool and riffle networks and vegetative cover, in addition to an increase in the width of a channel during high flows (Schueler, 1994).

Conveying Urban Pollution. Impervious surfaces efficiently convey urban pollution to receiving streams and directly impact stream water quality. Prior to modern stormwater mitigation techniques, urban effluence transported sediments at a rate of an order of magnitude greater than comparably sized rural watersheds. For instance, sediment transport from a hectare of urban development and highway construction activity can yield 20,000 to 40,000 times the sediment of a comparably sized agricultural or woodland area (Wolman and Schick, 1967; Burton and others, 1977; Klein, 1979). Modern erosion and sediment controls now employed at highway construction projects significantly reduce sediment load from highway construction. Nevertheless, sediment load from other urban activities is still a significant obstacle to improving water quality. Monitoring studies in Wisconsin (Bannerman and others, 1993) revealed specific relationships between pollutants and types of impervious surfaces (for example, *E. coli* with residential streets, phosphorous with residential lawns, metals with industrial zones). Impervious surface runoff of hydrocarbons (Whipple and Hunter, 1979; Schueler, 1994), metals (Randall and others, 1978), and road salt (Crowther and Hynes, 1977) and their related effects on instream water quality have also been addressed. The hydrologic science community has consistently used the parameter of imperviousness both to model pollutant runoff and as a gauge to measure the relative level of instream water quality (Schueler, 1994).

Thermal Properties. Imperviousness has a two-fold effect on the thermal properties of a stream. First, impervious surfaces hold and retain more heat than the natural features they replace. Their heat is transferred downslope (via runoff) and warms the receiving stream. Schueler (1994) notes that impervious surfaces may be 10 to 12 degrees warmer than the fields and forests they replace. Galli (1991) compared urban related streams in Maryland with a forested reference stream and found a correlation between urban imperviousness and higher relative instream temperatures. Secondly, this instream warming reduces streamside vegetative cover, that shades the stream. This loss is often due to urban encroachment, as well as to erosion from flooding. Klein (1979) notes a 6- to 11-degree Celsius variation in shaded and unshaded areas on the same Maryland stream.

Stream Biodiversity. Perhaps the strongest environmental indicator of instream health is stream biodiversity. A change of instream characteristics due to watershed development (for example, increased water flow volume, pollutant runoff, and change in thermal characteristics) plays a systematic role in altering an aquatic ecosystem. Schueler (1994) cites 18 studies associated with the effects of imperviousness on stream biodiversity. The focus of these studies is aquatic insect and fish surveys; results provide an overall characterization of ecosystem change as related to imperviousness of a watershed at the 10- to 15-percent level. These surveys reveal a consistent pattern of biodiversity decline as well as a concurrent relationship of a decline in pollution-sensitive species and an increase in pollution-tolerant species. Watershed impervious thresholds of 10- to 15-percent have also been shown to have a relationship to freshwater wetland health. Taylor (1993) and Hicks (1995) relate imperviousness around 10- to 15-percent to a decline in freshwater habitat quality and plant and amphibian diversity.

Science and Policy Issues

While the combined effect of imperviousness in a watershed and the direct relationships to measurable ecosystem and water quality parameters are generally accepted, the overall value of impervious surfaces as a key environmental indicator is currently being debated as researchers in this field have identified a number of science and policy issues.

Pertinent science and policy issues include:

Natural Setting. If impervious surfaces are to be a valid indicator of watershed condition, some way of taking into account existing environmental conditions and watershed settings must be developed. Watersheds in relatively flat terrain with sandy soils will have a very different surface water runoff potential than a watershed with clay soils and significant topographic relief.

Mitigation Efforts. Surface runoff can be controlled by a number of engineering techniques (such as storm sewers, catchment basins, and retention ponds), all of which would alter the surface flow and ecological effects of the receiving stream. The relationship between impervious surfaces percentage and these mitigation efforts is not fully understood.

Land Use Policy. A greater understanding of the ecological consequences of urbanization should inevitably lead to changes in land use policy at all levels. However, a number of questions must be asked and answered quantitatively in order to realize urban/suburban development with a minimum of negative ecological effects. How might the understanding of impervious surfaces affect local land use policy? What steps might local planners take in order to minimize the ecological effects of urban/suburban development and at what cost? Of the various sub-classes of impervious surfaces, which ones are most responsible for overall imperviousness? And, of the various impervious surfaces, which have the most negative impact on the ecosystem?

These questions focus much of this research effort. While there is a significant and increasing level of scientific understanding about the effects of total imperviousness, there appears to be little information about the relative contribution of buildings, parking lots, roads, and other features. From a review of the literature, the transportation infrastructure appears to receive an inordinate amount of blame for the impervious surfaces problem. A Draft General Accounting Office Report (2001) cited roads as responsible for as much as 66 percent of the runoff in urban watersheds. Schueler (1994) attributes 63 to 70 percent of imperviousness to transportation land uses. Southworth and Ben-Joseph (1997) asserted a now infamous statistic that "…the automobile consumes close to half the land area in cities." Shoup (1997) traces the origin of this statistic through several scientific works back to Sale (1980) and shows that it is not based on any scientific study, and most relevant data today puts the contribution of roads of around 25 percent.

The Emerging Science of Measuring Impervious Surfaces

Perhaps the most fundamental issue in the debate over impervious surfaces is simply the method of measuring and quantifying impervious surfaces with defensible precision and accuracy. There exists no uniform methodology, and there are a variety of methods that range from statistical estimates from Census population data to laborious mapping of surface features from very high to moderately high spatial resolution aerial imagery (Slonecker and others, 2001). Given the potential of impervious surfaces to serve as an indicator of ecological condition, the and sensitivity of the metric to indicate impairment, greater understanding of the methods and accuracies of computing impervious surfaces values is needed.

Although the effects of land use, population, and impervious surfaces on water quality has been generally known for many years, a basic problem exists in quantifying the detailed spatial extents and distribution of various classes of impervious surface phenomena. Accurate and quantifiable measurements of impervious area remain elusive and expensive (Slonecker and others, 2001). Determining the area of imperviousness is primarily a mapping issue, and it is in mapping methods that the base data for determining the contribution of individual components for evaluating the other methods of imperviousness will be found. While there are a number of viable methods, such as statistical estimates, spectral reflectance methods, and GIS algorithms, there must necessarily be some set of 'reference' data in order to measure the accuracies of other methods.

Objectives

One of the primary purposes of this study is to develop quantitative information about the spatial extent of various classes of imperviousness through detailed mapping from high-resolution imagery sources. Numerous studies differentiated between rooftops and transportation systems, some without supporting or additional data. In some of these studies buildings and roads are identified as the entire contribution of all impervious surfaces. If the components of impervious surfaces are broken down into more detailed components within watersheds, methodologies can be better evaluated to control and mitigate the impacts from these components. This report presents quantitative results that detail how much each impervious feature is contributing to the total imperviousness for six selected urbanized watersheds throughout the United States.

The objectives of this research were:
Objective 1 – to determine the relative contribution of the individual components that comprise the total area of impervious surfaces in six selected watersheds in the United States by locating or collecting impervious surfaces data from high spatial resolution aerial imagery. *This objective is addressed by Task One (below).*

Objective 2 - to demonstrate scale dependent and efficient methods for mapping impervious areas by using remote sensing and Land Use/Land Cover and other detailed GIS data. Potentially, reliable and efficient methodologies could be developed for use by State and local governments as well as Federal agencies to efficiently measure the imperviousness in any given watershed, thereby correlating road impact upon the quality of the environmental conditions. *These objectives are addressed by Tasks Two and Three.*

Scope and Approach

Six watersheds were selected, based on degree of urbanization and the availability of GIS data. Three primary tasks were completed:

Task 1 - Quantifying Components of Impervious Surfaces: Reference Data

The impervious surfaces for each watershed were mapped at highly detailed levels (see data source examples in fig. 2). Existing detailed GIS datasets were acquired from the local governments where available and spatially explicit classes of impervious surfaces were digitized from high spatial resolution orthoimagery to compile highly detailed GIS datasets for six classes of impervious surface cover. From this product, the relative contribution of each class of impervious cover was determined. This task addresses *Objective One*.

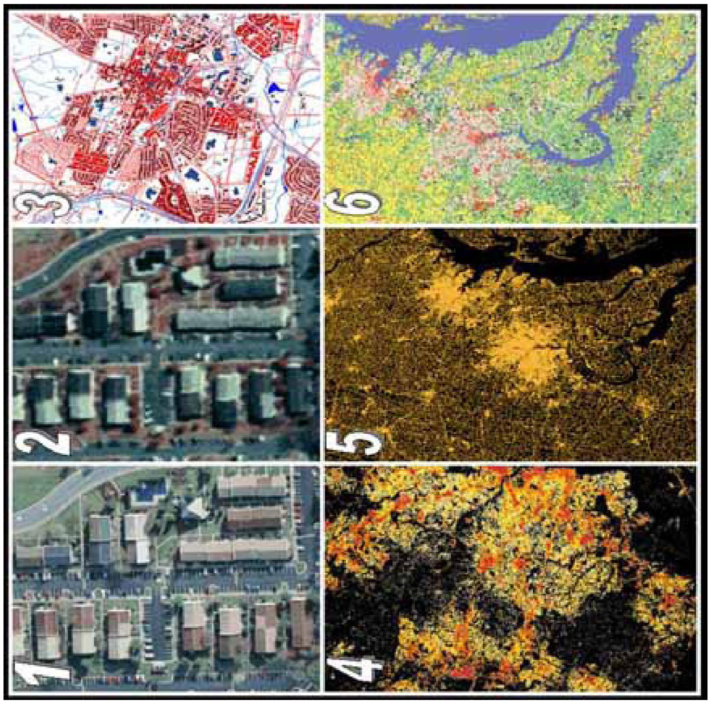


Figure 2. Examples of data used in this research: (1) high spatial resolution imagery at 1-foot resolution, Vargis, LLC Aerial Imagery ©2002 Commonwealth of Virginia; (2) digital orthophoto quadrangle image at 1-meter resolution, USGS; (3) local government GIS data, courtesy of Loudoun County Government, Virginia; (4) RESAC sub-pixel data, courtesy of the University of Maryland, Geography Department; (5) vector road GIS data, *The National Map*; and (6) 1992 National Land Characteristics data.

Task 2 - Intermediate Scale Analysis

Total impervious surface area can be determined using various methods from remote sensing and Land Use data. These methods are both efficient and widely accepted for the quantification of the impervious surface area for many applications, including GIS/Land Use coefficient techniques and subpixel satellite remote sensing techniques. Satellite remote sensing instruments, such as the Landsat Thematic Mapper, collect data in different bands of the electromagnetic spectrum, and this permits the identification of materials on the Earth's surface based on their spectral reflectance characteristics. The identification of impervious areas lends itself well to this type of analysis because impervious surface materials are generally very different from most natural features. Further, new techniques in the field of digital image processing permit the derivation of information at the subpixel level. The standard 30-meter pixel size of the Landsat Thematic Mapper sensor has inherent limitations with respect to mapping small objects or areas. However, classification techniques such as spectral mixture modeling (Ji and Jensen, 1999; Ward and others, 2000; Phinn and others, 2000) and neural network-based classification methods (Civco and Hurd, 1997) are capable of extracting subpixel information (RESAC, 2003). *This task addresses Objective Two*.

Task 3 - Synoptic Scale Analysis

Because of the appeal of being able to quickly compute impervious cover from nationally consistent and regularly updated datasets, the National Land Cover Data (NLCD) and *The National Map* (U.S. Geological Survey, 2003) road data were used to compute impervious cover via coefficient methods and were tested for overall accuracy and efficiency. Although this is a regional view of the detail and statistics of the impervious surface extents, this task is designed to produce rapid results and quick assessments. This task addresses *Objective Two*.

Study Areas

The criteria used for selecting the six watersheds, the locations, and the relevant characteristics about each watershed are described below. Two low, two moderate, and two high intensity urban watersheds were selected for this study.

Watershed Selection Criteria

A watershed is the area drained by a stream and its tributaries. Watersheds range in size from under a square mile to hundreds of thousands of square miles (for example, the Chesapeake Bay watershed, in which two of our watersheds are located, has an area of 66,388 square miles). Precipitation that falls within a watershed will eventually drain from the bottom of the basin through the main stream channel.

The U.S. Department of Transportation, the agency this research was prepared for, requested that areas from each quadrant of the United States be represented in this study. A list of locations from which data were available from *The National Map* was used to choose the areas. Originally, six to eight study areas, each one square mile in size were to be selected. However, the value of working in watershed areas rather than the one-square-mile areas was compelling and very important in data sharing. Ultimately the watersheds ranged from very dense urban (four of the watersheds) to suburban (two of the watersheds).

Local Data Availability

The team located contacts interested in this research who were willing to share their data. Use of existing datasets saved the project from the expensive, labor intensive, and time consuming process of collecting all reference data, and allowed datasets to be finished only slightly. The Appendix shows the sources and additional information about the various datasets used in this research.

Watershed Locations

In cooperation with the U.S. Department of Transportation, Federal Highway Administration, the following watersheds were selected for study: Black River within King County, Washington; Difficult Run within Fairfax County, Virginia; North Walnut Creek within Polk County, Iowa; Oak Creek within Lancaster County, Nebraska; Tuscarora Creek within Loudoun County, Virginia; and Wares Creek within Manatee County, Florida (fig. 3).

Figure 3. On the map of the United States are the watershed locations for this study, as represented by orange dots.

Watershed Characteristics

The following section describes each watershed in further detail. Size, population, and area characteristics are briefly summarized in table 1.

Black River Watershed, King County, Washington

The Black River watershed is located in King County, Wash., and is within the greater Seattle-Tacoma Metropolitan Region (fig. 4). It is part of the larger Duwamish-Green watershed and encom-

Table 1. Basic characteristics of the selected watersheds and the counties they reside in (U.S. Census Bureau, 2001). There are 3,141 counties in the United States. [CO=County; Hi-Res= High-Resolution; Pop=Population; est=estimated to be at x-percent built-up/year]

Watershed Name	Watershed Size (km^2 / $miles^2$ / acres$^{)}$	CO Size ($miles^2$ / acres)	Greater Watershed Name and Hydrologic Unit	CO Pop Percent Change from 1990-2000*	CO Ranking in Pop for 2000* (out of 3,141 COs)	CO Ranked by Numeric Pop Change from 1990-2000* (out of 3,141 COs)	Visual Assessment of the Watershed's Urbanization as Observed on Hi-Res Imagery (Percent Built-up/year)
Black River, Washington (King CO)	70 / 26.89 / 17207.1	2,165	Duwamish 17110013	15.2	12	18 (increase of 229,715 people)	***Dense Urban*** - High/Low Density Residential and Commercial (est. 98%/1989)
Difficult Run, Virginia (Fairfax CO)	151 / 58.09 / 37179.4	397	Middle Potomac-Catoctin 02070008	18.5	36	35 (increase of 151,165 people)	***Dense Urban*** High/Low Density Residential and Commercial (est. 88%/1998)
North Walnut Creek, Iowa (Polk CO)	35 / 13.58 / 8691.7	595	N.Racoon 07100006	14.5	156	159 (increase of 47,461 people)	***Dense Urban*** High/Low Density Residential and Commercial (est. 55%/2001)
Oak Creek, Nebraska (Lincoln CO)	57 / 21.94 / 14042.1	844	Salt 10200203	6.5	1,261	1456 (increase of 2,124 people)	***Rural*** Residential and some Commercial (est. 20%/2002)
Tuscarora, Virginia (Loudoun CO)	40 / 14.42 / 9226.2	529	Middle Potomac-Catoctin 02070008	96.9	320	72 (increase of 169,599 people)	***Rural*** Residential and some Commercial (est. 25%/1998)
Wares Creek, Florida (Manatee CO)	21 / 8.00 / 5091.4	734	Manatee 03100202	24.7	209	145 (increase of 52,295 people)	***Dense Urban*** High Density Residential, Some Commercial (est. 99%)

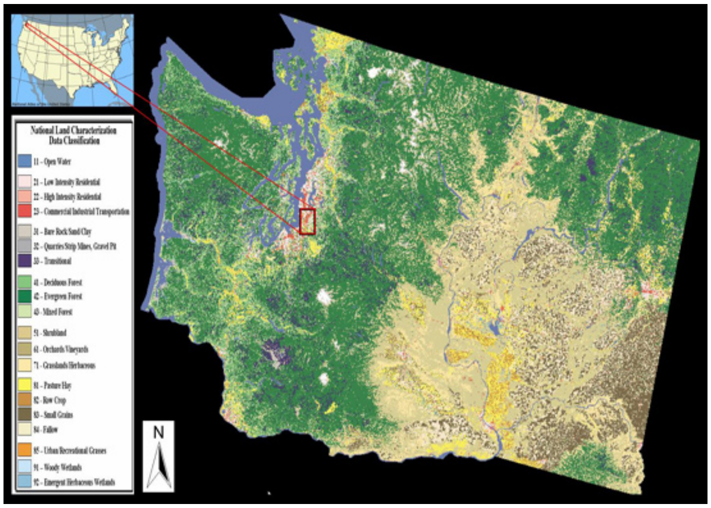


Figure 4. The Black River watershed is located in King County, Washington, and is approximately 27 square miles. It is part of the Seattle-Tacoma metropolitan region. The locator map, from the National Atlas of the United States, left, shows the State of Washington with the red box giving the location of the watershed. The land cover data, 1992 National Land Characteristics Data, right, shows an overview of the characteristics of the study sites and characteristics of the State of Washington.

passes parts of the cities of Kent and Renton. The Black River watershed is approximately 69.6 square kilometers in area. The watershed is highly developed (fig. 5) with approximately 60 percent of the area in dense urban and commercial land uses (King County, 2001). The County's population in 1990 was 1,507,319 and in 2000 it was 1,737,034, resulting in a 15.2 percent increase (U.S. Census Bureau, 2001). The Black River watershed contains the following major roads: Interstate 405, State Highways 546, 515, 167, 181, and 516, with no U.S. Highways. The only lake is Panther Lake. The west side of the watershed is bounded by Green River. Three main streams and rivers are within the watershed: Black River, Mill Creek, and Springbrook. Based on the NLCD92 (produced from 1992 source), the dominant Land Uses are (1) commercial, industrial, transportation, (2) low density residential, and, (3) deciduous forest, which has changed only slightly since this date.

Difficult Run Watershed, Fairfax County, Virginia

Difficult Run (fig. 6) is located just west of the greater Washington, D.C., metropolitan region, which has undergone massive expansion, with many people commuting into D.C. for work. The watershed drains approximately 150.5 square kilometers and flows directly into the Potomac River. It is contained within Fairfax County, the most populous urban county in both Virginia and in the Washington, D.C., metropolitan area. In 1990 the population for Fairfax County was 818,584; by 2000 the population reached 969,749, an 18.5 percent increase over the 10-year period (U.S. Census Bureau, 2001). Within the Difficult Run watershed (fig. 7) are four large and major transportation corridors including Interstate 66, U.S. Highway 50, and the Dulles Airport access and toll road (fig. 8). Other important roads in this watershed are State Highways 7 and 123. It is part of the larger Middle Potomac-Catoctin watershed and contains the following reservoirs: Lake Audubon, Lake Thoreau, Lake Anne, and Lake Fairfax. Many streams flow into Difficult Run, which in turn flows into the Potomac River, the main streams are: Colvin Run, Captain Hickory Run, Piney Run, Wolftrap Run, Piney Branch, Snakeden Branch, Little Difficult Run, South Fork, and Rocky Branch. Based on the 1990 and the 2000 NLCD, the primary Land Uses in Difficult Run are (1) deciduous forest, (2) pasture hay, (3) residential dispersed amongst the first two dominant features.

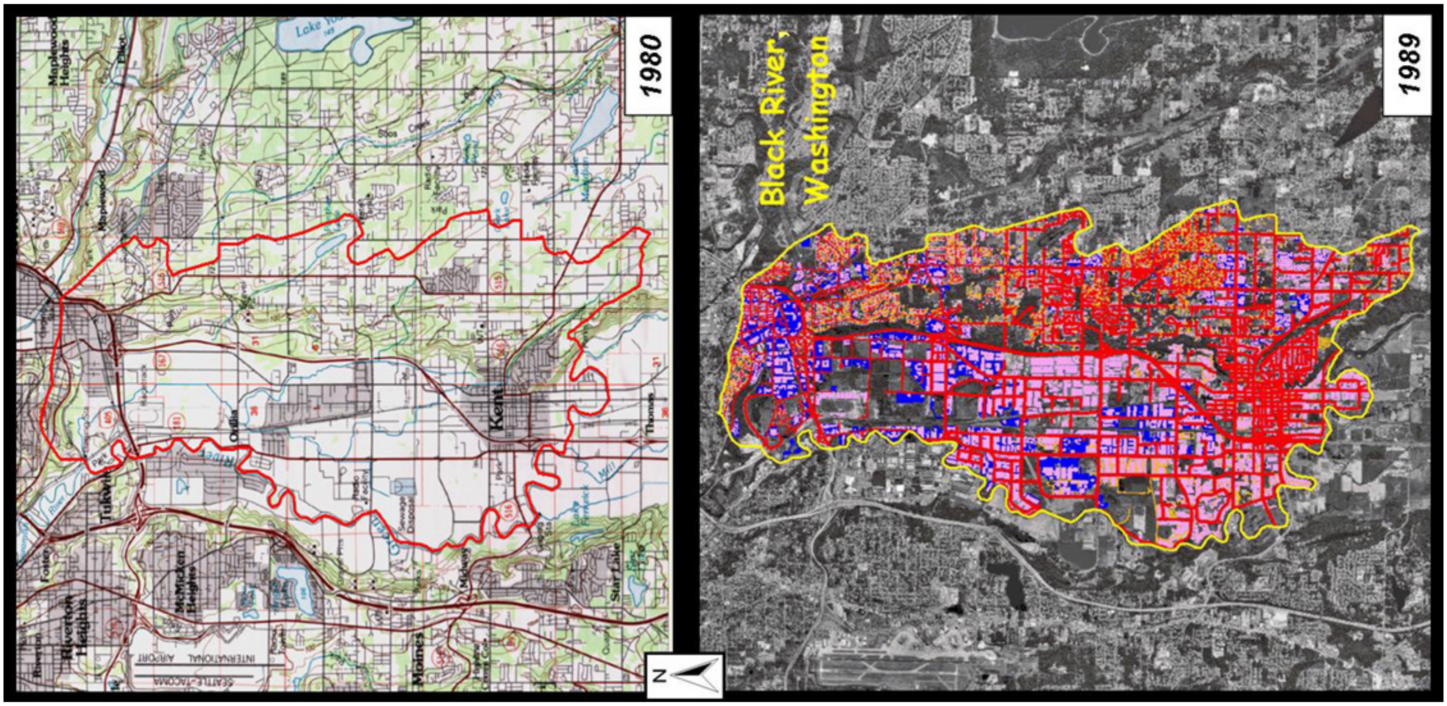


Figure 5. The nearly 28-square-mile Black River watershed in the top illustration shows a 1980, 1:100,000-scale map. Data and the imagery at 1-meter resolution, dated 1989, are USGS DOQs. Much of the data, as well as more recent higher-resolution imagery, were courtesy of King County, Washington. Other sources of data for this area were Army Corp of Engineers and Walker Aerial Survey.

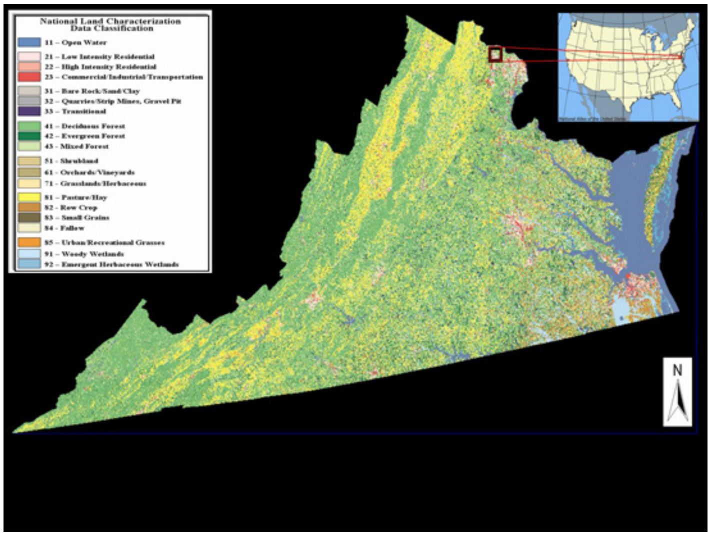


Figure 6. The Difficult Run watershed, located in Fairfax County, Virginia, is approximately 58 square miles and is west of the Washington, D.C., metropolitan region. The top image is the locator map from the National Atlas of the United States. The lower image shows 1992 National Land Characteristics Data.

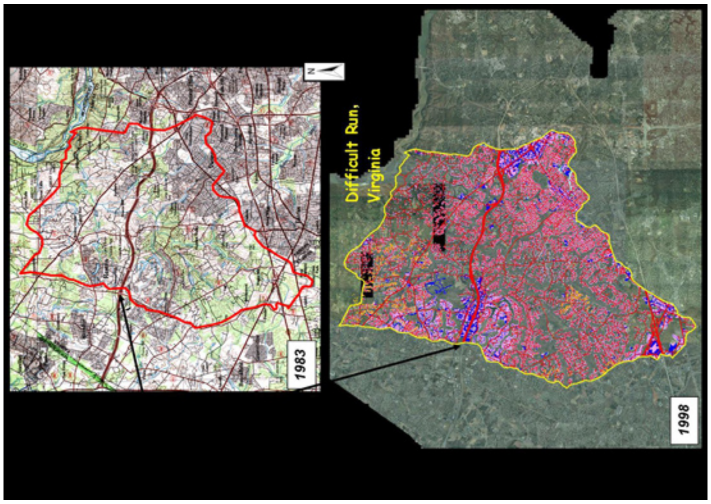


Figure 7. The top figure is of the 58-mile Difficult Run watershed shown on a 1983, 1:100,000-scale map. The bottom image shows the road data draped on the 1998, 1-foot resolution imagery, courtesy of Fairfax County, Virginia.

Figure 8. This photo was taken in early 2004 of the Dulles Toll Road, Route 267, a private highway, looking to the east from the Fairfax County Parkway in the western portion of the Difficult Run watershed, Virginia. The toll road is 14 lanes wide at this location. Buildings to the left are the growth centered around the Reston Town Center. This area's growth trend is similar to that of the Tysons Corner area, a high retail and high density area also in Fairfax County. The Tysons Corner area is on the east side of the Difficult Run watershed.

North Walnut Creek Watershed, Polk County, Iowa

The North Walnut Creek watershed (fig. 9) is situated on the north-western edge of the City of Des Moines, Iowa, in Polk County. It is approximately 35.17 square kilometers in area. Most of the south two-thirds of the watershed are developed as medium-intensity residential with growth trending further northwest (fig. 10). In 2000 the population of Polk County was 374,601, compared to 1990 when it was 327,140, for a 14.5 percent increase (U.S. Census Bureau, 2001). The population for the city of Des Moines in 2000 was 198,682 (ranked 92nd most populated out of 239 cities with a population over 100,000), and in 1990 was 193,333 (ranked 81st most populated out of 239 cities with populations over 100,000 people) (U.S. Census Bureau, 2001). The major roads contained in the North Walnut Creek watershed are the following: overlapping Interstates 35/80, State Highway 141, and the smaller U.S. Highway 6. North Walnut Creek Watershed is contained within the larger North Raccoon

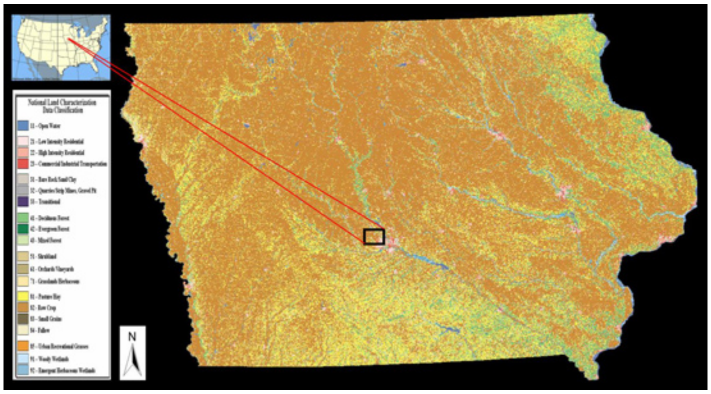


Figure 9. The North Walnut Creek watershed, almost 14 square miles, is located in Polk County, Iowa, and extends into the city of Des Moines. The locator map from the National Atlas of the United States (left) shows the watershed relative to the United States, while the 1992 National Land Characteristics Data shows the land cover characteristics surrounding the watershed and for the State of Iowa, predominantly agriculture.

watershed. The watershed's namesake, North Walnut Creek, flows toward the central part of Des Moines into Walnut Creek and after about 5 kilometers, it flows in turn, into the Raccoon River, which joins the Des Moines River after about another 5 kilometers. The one lake in the watershed is Lake Halice with a limited number of small reservoirs and numerous intermittent streams. The dominant Land Use is low-intensity residential, followed closely by row crop and high-intensity residential (as determined by the NLCD92).

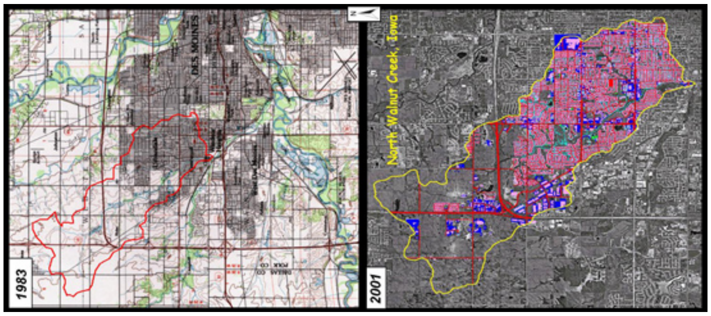


Figure 10. The nearly 14 square mile North Walnut Creek watershed is shown on a 1983, 1:100,000-scale map. The 2001 bottom image has vector data draped on it and is better than 1-foot resolution. The 2001 imagery and building data were courtesy of Polk County as well as the buildings' data layer. The research team collected information on roads, buildings, driveways, sidewalks/paths, parking lots, and all of the other features that do not fall into the categories listed.

Oak Creek Watershed, Lancaster County, Nebraska

The Oak Creek watershed (fig. 11) is located in the northwest area of Lincoln, Nebr., in Lancaster County and is approximately 56.82 square kilometers in area. The Lincoln Municipal Airport is situated in the center of the watershed, with most of the commercial and residential areas in the eastern portion of the watershed (fig. 12). Newer residential areas are beginning to develop just west of the airport. In 2000, the Lancaster County population was 34,632, compared to 1990 when it was 32,508, for a 6.5 percent population increase since 1990 (U.S. Census Bureau, 2001). The Lincoln City population in 2000 was 225,581 (ranked 76th most populated out of 239 cities with a population over 100,000) and in 1990 it was 192,722 (ranked 82nd most populated out of 239 cities with a population over 100,000). The major roads in the watershed are the following: Interstates 180 and 80, U.S. Highways 6 and 34, and a small portion of U.S. Highway 64. The main water features are Oak Creek, Oak Lake, and Salt Lake, with several intermittent streams and small reservoirs and is contained in the larger Salt watershed. The dominant Land Use is pasture/hay with a small, second use of herbaceous grass lands, followed by fallow lands (as determined with the NLCD92).

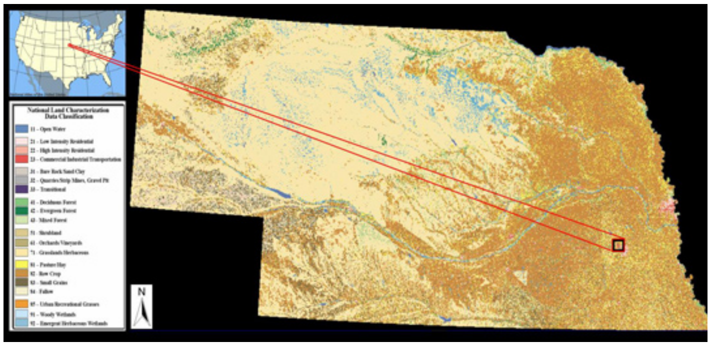


Figure 11. The Oak Creek watershed, nearly 14 square miles, is located in Lancaster County, Nebraska, and extends into the city of Lincoln. The locator map from The National Atlas of the United States shows the watershed relative to the United States while the 1992 National Land Characteristics Data shows the land cover characteristics surrounding the watershed and for the State of Nebraska to be predominantly agriculture and pasture.

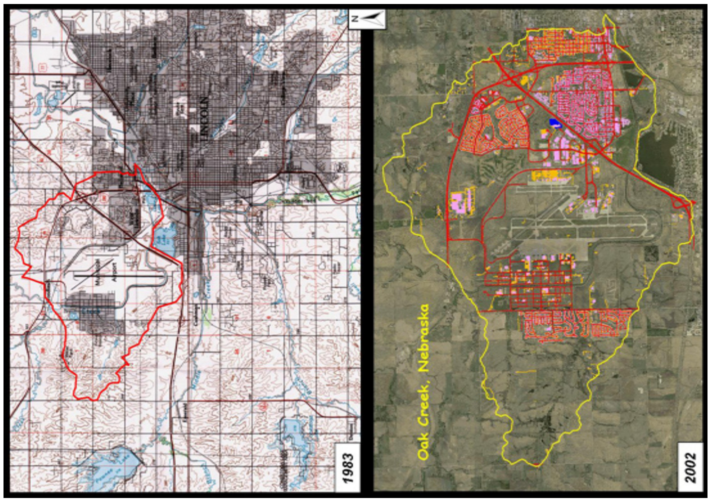


Figure 12. The top illustration shows the 22-square-mile Oak Creek watershed draped on a 1983, 1:100,000-scale map. Below it is draped on a 2002 National Map image that offers 1-foot resolution in natural color. All data layers needed to be collected for this watershed.

Tuscarora Creek Watershed, Loudoun County, Virginia

The Tuscarora Creek watershed (fig. 13), over 36 square kilometers in area, is located in Loudoun County, Va., about 40-kilometers west of the Washington, D.C., metropolitan area (fig. 14). Tuscarora Creek is 1.6 kilometers from the Potomac River and

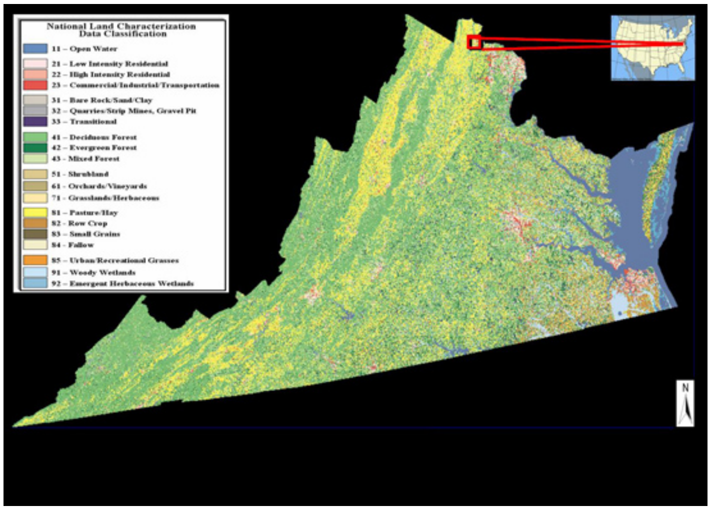


Figure 13. The Tuscarora Creek watershed, over 14 square miles, located in Loudoun County, Virginia, is about 25 miles west of the Washington, D.C., metropolitan area. The locator map is from the National Atlas of the United States and the land cover data are 1992 National Land Characteristics Data (available free and nation wide by State at http://www.mrlc.gov/).

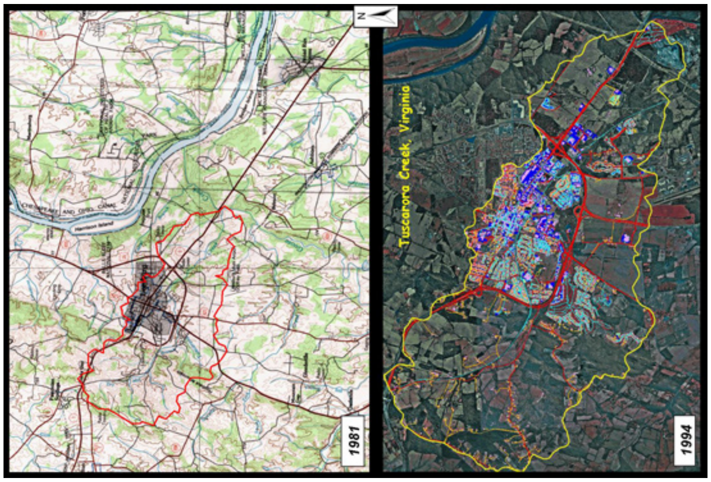


Figure 14. The 14-square-mile Tuscarora Creek watershed draped on the 1981, 1:100,000-scale map. The vector data, courtesy of Loudoun County, are draped on a USGS 1994 color infrared digital orthophoto quarter quadrangle image at 1-meter resolution.

contains most of the town of Leesburg. The U.S. Census Bureau has estimated Loudoun County to be the fastest growing county in the nation (U.S. Census Bureau, 2003). The population for Loudoun County in 1990 was 86,129; by the year 2000 the population grew to 169,599, for a 96.9 percent population increase over that 10-year period. By 2002, the estimated population was 204,054 (U.S. Census Bureau, 2001), a 136-percent increase since 1990 and a 20-percent increase since 2000. The main roads in the watershed are private highway 267, State Highway 7, U.S. Highway 15, State Highway 621, and State Highway 9, which starts at the northern edge of this watershed. The Tuscarora Creek watershed is part of the larger Catoctin watershed and the still larger Potomac River Basin where the water flows into the largest estuary in the United States, the Chesapeake Bay. There are no lakes, but there are several small reservoirs that are less than 0.25 square kilometers.

The main streams in the Tuscarora watershed are Town Branch, Dry Mill Branch, and its namesake the Tuscarora Creek, where the beginning is only 8 kilometers from Goose Creek, which when the Tuscarora Creek flows into it, is only 2.4 kilometers from the Potomac River. The Tuscarora Creek watershed is in the path of the urban growth that is rapidly occurring in the eastern portion of the county (fig. 15). Within the watershed the NLCD92 indicates the dominant covers are agricultural use, slightly leading the amount of forest. The community is a prime location for urbanization, especially with the availability of the convenient private highway 267. Maryland owns the water rights to the Potomac River, which is a challenge when planning for enough water to support the growing community.

Wares Creek Watershed, Manatee County, Florida

The Wares Creek watershed (fig. 16) is contained within the County of Manatee, Florida, and is approximately 9 kilometers north of Sarasota and contains part of the city of Bradenton. The county is 1,919.2 square kilometers, while the small Wares Creek watershed is approximately 20.7 square kilometers. It is extremely flat terrain and is less than 16 kilometers from the Gulf of Mexico (fig. 17). The county's population in 1990 was 211,707, and in 2000 it was 264,002, an increase of 24.7 percent over the 10-year period (U.S. Census Bureau, 2001). The main roads contained within the watershed are the following: U.S. Routes 301 and 41, State Routes 55, 45, and 684, where 684 is the road that takes tourists directly to the Gulf of Mexico beaches within 12.9 kilometers. The Wares Creek watershed is 3.2 kilometers north of the Sarasota Bay and is directly off the Manatee River and drains into both by way of the Cedar Hammock Drainage Canal. The canal flows into north and south flowing segments, where the branch traveling south drains into the Sarasota Bay, while the branch traveling north drains into the Manatee River. The Manatee River flows directly into the Tampa Bay, which in turn flows into the Gulf of Mexico. The Wares Creek watershed

Figure 15. Photographs showing views within the Tuscarora Creek watershed, Virginia, in the Leesburg area.

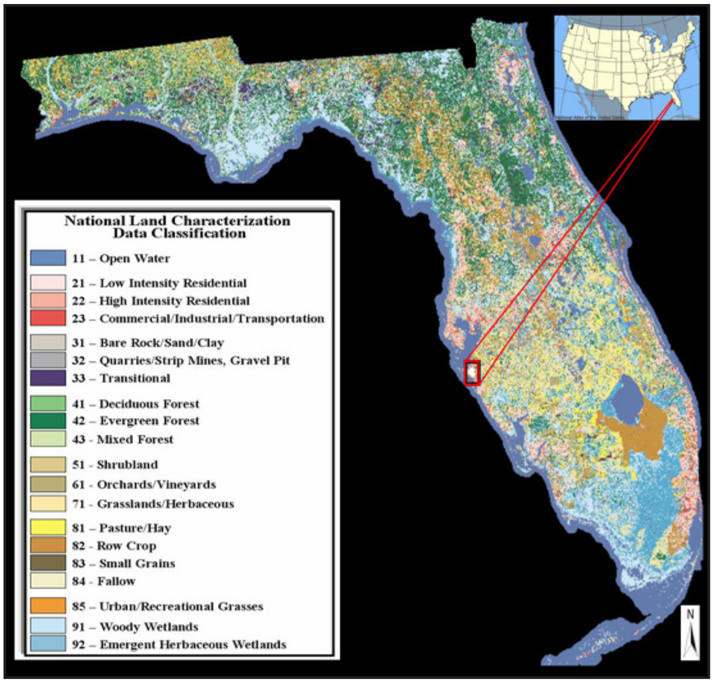


Figure 16. The Wares Creek watershed, approximately 8 square miles, is located 25 to 30 miles south of the metropolitan area of Tampa on the Gulf coast of Florida, in Manatee County. The locator map is from the National Atlas of the United States and the land cover data are 1992 National Land Characteristics Data.

is located in the larger watershed of the Peace-Tampa Bay. There are approximately nine small man made lakes. Wares Creek is completely developed and has high-density residential areas as the predominant land use. The northern portion has more residential tree cover rather than the grasses and the occasional palm trees in the southern portion of the watershed. Any areas that are not residential are commercial areas serving the communities. The open lands are a golf course, lakes, and a few educational facilities. The NLCD92 shows the following three, respectively, as the primary features in the watershed: (1) low-intensity residential, (2) high-intensity residential, and (3) commercial, industrial, and transportation.

Methodology

Overall Process

In order to achieve objectives one and two, three tasks were designed to accomplish them:

Task 1 – Quantifying Components of Impervious Surfaces: Reference Data, was used to build and assemble GIS reference data, designed to fulfill the first objective; Task 2 - Intermediate Scale Analysis: Subpixel Image Processing Techniques and Land Use Coefficients Method addressed the needs of the second objective, as did Task 3 – Synoptic Scale Analysis, which allowed for the

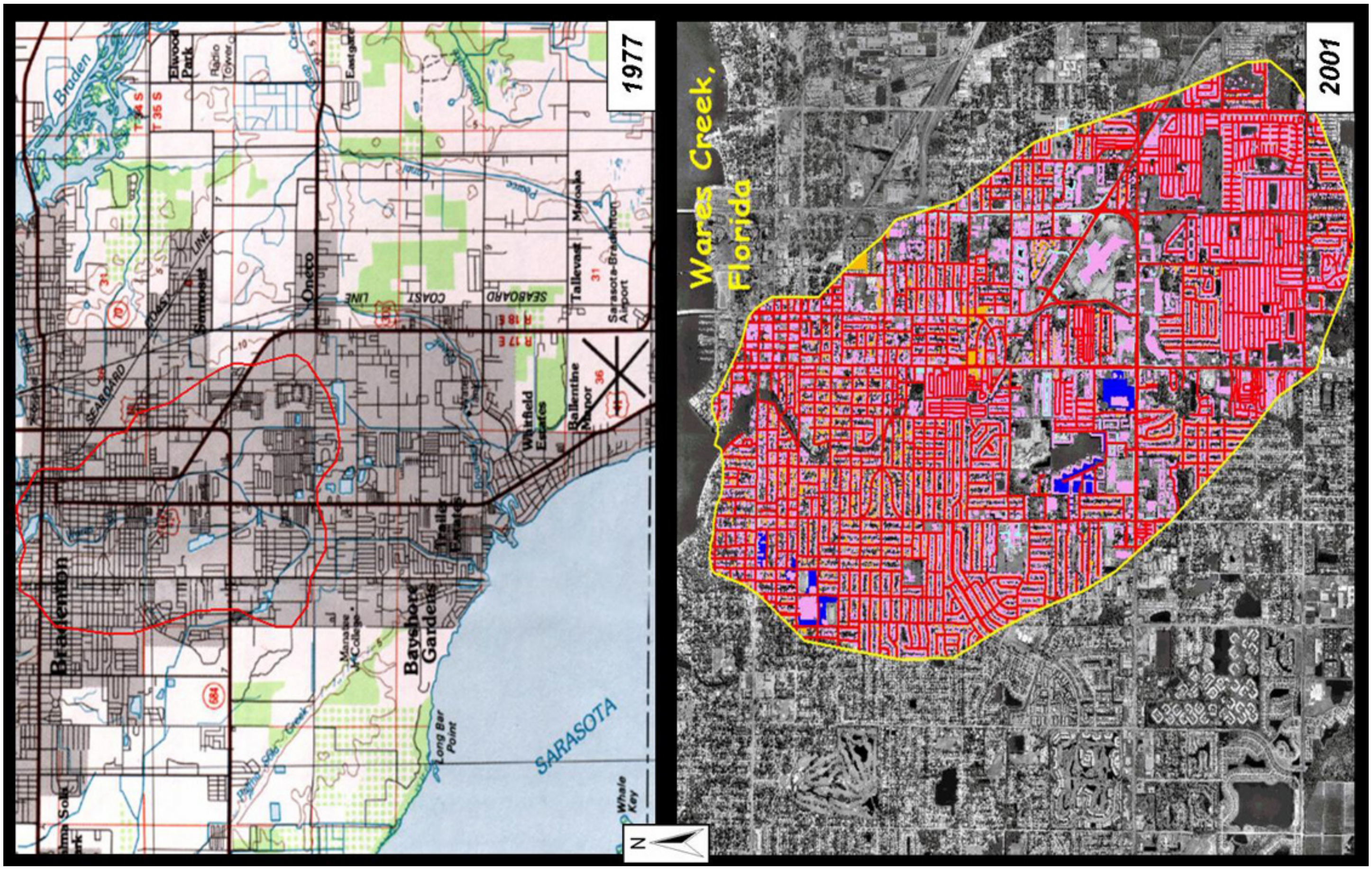


Figure 17. The Wares Creek watershed draped on the 1977, 1:100,000-scale map and on the 1-foot resolution image is from 2001, shown above courtesy of Manatee County. All data were available from the county except for the sidewalks and parking lots.

quick regional assessment of imperviousness and also to compare with the reference data from Task One.

To complete the tasks, six phases were nested in the three tasks: (1) Watershed Selection, (2) GIS Data Acquisition, (3) High Spatial Resolution Imagery Acquisition, (4) Reference Data Match Process, (5) Components Summations, and (6) Accuracy Comparisons.

Task 1 - Quantifying Components of Impervious Surfaces: Reference Data

Data modification and collection in assembling the reference datasets for this work involved the completion of one to three GIS datasets per watershed in order to obtain a match with both the NLCD92 (1992 product) and with the subpixel contemporary products, NLCD2000 (produced from the year 2000 source). By digitizing spatially explicit components (table 2) of impervious surfaces from high spatial resolution imagery and especially by utilizing existing detailed GIS datasets provided by local governments and *The National Map*, this task encompassed mapping and quantifying the impervious surfaces for each feature in the selected watersheds, at extremely detailed levels primarily for the years 1992 and 2000. The results showed temporally the relative contribution in area of each component's impervious surface for all six watersheds. For each watershed, preliminary research was conducted to identify sources for both GIS data and high spatial resolution imagery from public or private sources (see appendix). In some cases, aerial photographs were acquired, scanned, georegistered, and orthorectified for use as the base sources. After all GIS data were acquired, local data were reviewed for consistency and accuracy, and were updated (heads-up digitizing/editing) to match the high spatial resolution imagery source for the years 1992 and 2000. When no existing GIS data could be found, as in the Oak Creek watershed, the features were digitized from high spatial resolution imagery sources. Figure 18 shows an example of the end product with all the features delineated after the modi-

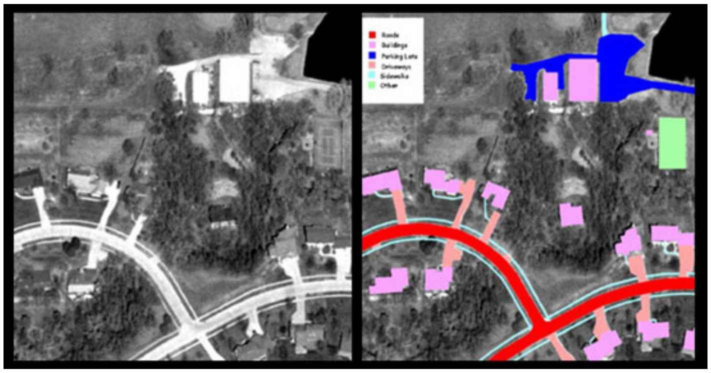


Figure 18. The six types of impervious surfaces are digitized from rectified high spatial resolution imagery. These show buildings, roads, sidewalks, driveways, parking lots, and other covers (a sport court is shown).

Table 2. Table showing the six principal components features of impervious surfaces. See the appendix for sources of data.

Impervious Surface Components	Component/Feature Descriptions
Buildings	All roofed structures including storage sheds and trailers (with the assumption that trailer's foundations were concrete pads). As often the base of structures are obscured by camera angle or vegetation, roof tops were digitized rather than the structure bases.
Roads	Long, narrow areas of gravel, paved or other hard surfaces that are utilized primarily for public transportation by automobile and are maintained and regulated by Federal, State or local government.
Parking Lots	Paved or hard surfaced areas that exist primarily for the temporary storage for automobiles and other vehicles, equipment, and materials. In commercial/industrial/business/institutions/apartment areas, entryways into these complexes were referred to parking lots to include the parking areas that often ran off the entryways.
Driveways	Hard surface or gravel areas that connect a house, garage, or other structure to a road surface for the purpose of automobile access and storage. In residential areas entryways, into homes were put in this category.
Sidewalks	Narrow hard surface areas that are generally found parallel to roadways and exist primarily for pedestrian traffic. Recreational trails, home and business entryways, park and golf course cart paths are included in this category.
Other	Hard surface recreation areas, such as basketball or tennis courts, patios, swimming pools - to include surrounding patio, any other impervious surface that does not fit in any of the above categories.

fication/collection process. Figure 19 shows one of the researchers comparing the acquired data with the imagery.

Once the base datasets were completed, the features were subtracted to construct the 1992 reference data for the NLCD92 with the appropriate dates from the metadata. For the match with the contemporary subpixel products, the team updated the base dataset to the appropriate date of those products as well. The areas of the different components were calculated for both 1992 and 2000 reference datasets. The Task 1 results were compared with the NLCD92 products and the RESAC subpixel product (Smith and others, 2003).

Figure 19. A team member is modifying the acquired data in the match process with the high resolution imagery.

Task 2 - Intermediate Scale Analysis

Two separate techniques were used to calculate impervious surface area at an intermediate scale. These two techniques were selected for their efficiency and frequent mention in the literature. The first, Task 2A, subpixel processing, is a relatively recent advance in spectral analysis that utilizes a combination of spectral processing and statistical tools to derive information on the components makeup of an individual pixel. The second technique makes use of land use coefficients that are commonly used by hydrologists and watershed protection specialists working on impervious surfaces research.

Task 2A - Intermediate Scale Analysis: Subpixel Image Processing Techniques

For many years, satellite remote sensing and image processing techniques were limited by the spatial resolution of these remotely sensed products. Typical systems such as the Landsat Thematic Mapper, with 30-meter pixel size, exhibited significant limitations on minimum mapping units, spatial accuracy, and general detail of derived products. However, a relatively new class of image processing techniques has been developed in the last decade that can be used to classify the pixel into relative abundance of materials within it based on statistical analysis and spectral unmixing (a process enables the user to derive more information from a 30-meter pixel than before). The end result is a better resolution product than the original 30 meters (fig. 20).

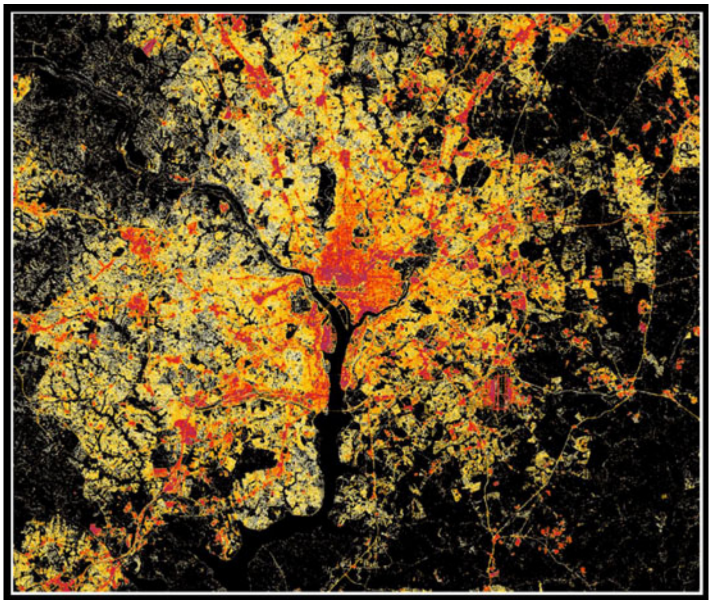
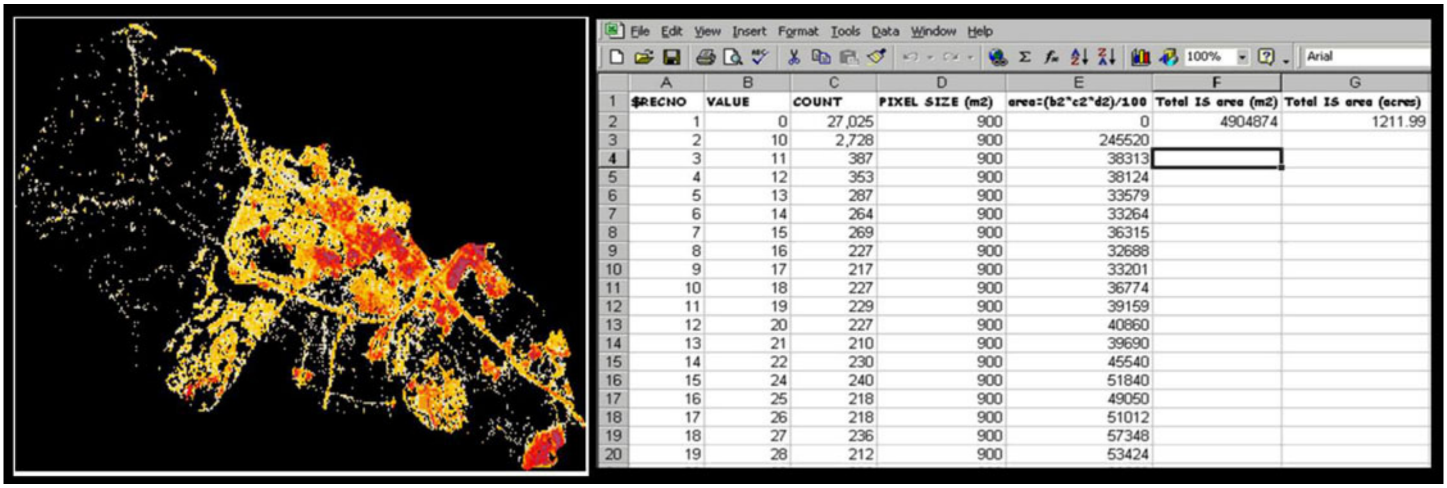


Figure 20. A subpixel impervious surface image of the Washington, D.C., area as derived from Landsat Thematic Mapper imagery by the University of Maryland RESAC. Red areas indicate pixels of high levels of impervious surfaces, yellow areas are less imperviousness than the red, while the black areas indicate no impervious cover.

This technique has shown to be successful when applied to high spectral resolution imaging data (hyperspectral offers more than 200 bands), where subtle diagnostic absorption features largely determine the spectral characteristics (Van der Meer, 2002). Spectral unmixing techniques strive to find proportions of end-members, spectrally ‘pure’ pixels, within a pixel from the observed mixed pixel spectrum and a number of pure end-member spectra of known composition (Ji and Jensen, 1999; Ward and others, 2000). When used in conjunction with advanced image classification techniques such as neural networks or decision tree classifiers, subpixel techniques can return data that are more accurate and have more spatial detail, compared to traditional classification techniques, such as Task 1-Reference Data.

In determining the impervious surface percentage per pixel from subpixel products, the following two fundamental steps are involved. First, impervious surface products using subpixel image processing are generally released in a raster format in which the cell value is the percentage of imperviousness calculated for that pixel. The raster image is assigned color values by some percentage class of imperviousness. Second, after clipping the extent of the area of interest (in this case the Tuscarora Creek watershed) product (fig. 21) from the large raster the values from the value attribute table, which are the ‘value’ and ‘count,’ can be easily input to a spreadsheet for calculation of total imperviousness. The value represents the percentage of imperviousness and the count represents the total number of occurrences in these datasets. These steps are similar to those applied in Task 3-Synoptic Scale Analysis.



	A	B	C	D	E	F	G
1	$RECNO	VALUE	COUNT	PIXEL SIZE (m2)	area:(b2*c2*d2)/100	Total IS area (m2)	Total IS area (acres)
2	1	0	27,025	900	0	4904874	1211.99
3	2	10	2,728	900	245520		
4	3	11	387	900	38313		
5	4	12	353	900	38124		
6	5	13	287	900	33579		
7	6	14	264	900	33264		
8	7	15	269	900	36315		
9	8	16	227	900	32688		
10	9	17	217	900	33201		
11	10	18	227	900	36774		
12	11	19	229	900	39159		
13	12	20	227	900	40860		
14	13	21	210	900	39690		
15	14	22	230	900	45540		
16	15	24	240	900	51840		
17	16	25	218	900	49050		
18	17	26	218	900	51012		
19	18	27	236	900	57348		
20	19	28	212	900	53424		

Figure 21. To the left, the subpixel impervious surface raster derived using subpixel digital image processing for the Tuscarora Creek watershed, Virginia. A geographic information system coverage of the watershed boundary was used to clip the larger raster, resulting in the impervious surface data for just the watershed. The value attribute table from the impervious surface raster, from which the total impervious area is easily calculated, is shown on the right.

The reflectance characteristics of impervious surfaces lend themselves well to delineation via spectral remote sensing. Concrete, macadam, and other substances that are utilized in human construction efforts generally have significantly different spectral profiles from natural surfaces. With the ability to potentially acquire information at the subpixel level, this method of classification can provide more accurate measures of composition. Subpixel processing of widely available satellite imagery could become an important new source of impervious surface data. Several organizations and institutions now regularly process 30-meter subpixel impervious surface data, such as the Mid-Atlantic Regional Earth Science Applications Center (RESAC) at the University of Maryland, Geography Department (fig. 20 and 21). The USGS EROS Data Center (EDC) has completed national subpixel products, NLCD2000, for different ecoregions across the United States with some still in progress (U.S. Geological Survey, 2000). The potential accuracy and national availability of these data sources made them excellent candidates for testing in this study. This task used the RESAC and NLCD2000 products, which were only available for the Tuscarora Creek and the Difficult Run watersheds at the time of analysis.

Task 2B - Intermediate Scale Analysis: The Land Use Coefficient Methodology

The coefficient method can be used to derive impervious surface estimates from land use (Task 2B) and land cover (Task 3) data separately from different sources. An important distinction must be made between land use and land cover data: land use data describes the anthropogenic utilization and purpose of various land parcels. It is usually derived from detailed maps and aerial photographs and is digitized in a vector GIS format. The work by Anderson and others (1976) has for many years served as the basis for land use classification and mapping from remotely sensed data. Land cover data are somewhat different, as they describe the natural surface and condition based on biophysical characteristics. Table 3 shows examples of the differences between land use and land cover for the same parcels of land.

Table 3. Comparison of land-use versus land-cover features. impervious surfaces. See the appendix for sources of data.

Land Use (NLCD92)	Land Cover (NLCD2k)
Golf Course	Herbacceous Grasses
Orchard	Tree Cover
Retention Pond	Open Water
Quarries/Strip Mines	Barren

The Land Use Coefficient method, applied in Task 2B, may be used to determine the impervious surface area of a watershed (Capiella and Brown, 2001). Land use mapping involves the delineation of similar land uses as interpreted from a digital image or cartographic base using moderately-high spatial resolution scale. Each specialized land use polygon is then multiplied by a specific, previously determined coefficient that represents the average fractional percentage of impervious cover for that particular land use. The sum of this area for all land use polygons is then the impervious amount for the watershed. For example, table 4 lists the land use classes and coefficients that were developed for the Chesapeake Bay watershed (Capiella and Brown, 2001).

Task 3 – Synoptic Scale Analysis: Calculation of Impervious Surface Area from Regional and National Synoptic Land Cover Data Sources

The NLCD92 product for which the coefficients were applied is typically generated from satellite-based image processing methods. Land cover data, like land use, is a thematic representation of surface phenomenon but is based on the biophysical cover and its spectral reflectance properties of the surface features instead of an anthropogenic-based utilization of land. The NLCD92 and the subpixel products are extremely important for the second objec-

Table 4. Land Use Codes and Coefficients (Capiella and Brown, 2001).

Land Use Classes	Land Use Code	Impervious Coefficients
Open Urban land	10	0.086
Residential – 2 acre lot	11	0.106
Residential – 1 acre lot	12	0.143
Residential – 0.5 acre lot	13	0.212
Residential – 0.25 acre lot	14	0.278
Residential – 0.125 (1/8) acre lot	15	0.326
Townhome Residential	16	0.409
Multifamily Residential	17	0.444
Agriculture	20	0.019
Institutional	30	0.344
Churches	31	0.399
Schools	32	0.303
Municipal	33	0.354
Golf Courses	34	0.050
Cemeteries	35	0.083
Parks	36	0.125
Light Industrial	40	0.534
Commercial	50	0.722

tive as it is anticipated that a combination of these methods and products could offer a more accurate quantification of imperviousness of a watershed.

The final task in this research was the determination of impervious area from a regional or national synoptic data source, which incorporated the Land Use Coefficient methodology previously discussed. The Multi-Resolution Land Consortium's National Land Cover Dataset (NLCD) was selected and was available for the 1990 timeframe (NLCD92), with some variation in scene date from 1988 to 1993. Unlike land use data, the big advantage of land cover in this application is that it can be derived spectrally from remotely sensed data with any one of several automated image classification techniques, which can be very efficient over large areas. The computation of impervious area from land cover offers two distinct advantages. First, land cover can be derived from spectral satellite data and computed mostly using automated digital classification routines. Second, the availability of a nationally consistent land cover data source allows for the rapid and efficient analysis of any watershed or area of the United States, conserving valuable resources that would be expended on the data acquisition and processing steps used in other methods.

The computation of total impervious cover from this type of data source is similar to the subpixel processing discussed in Task 2A-Intermediate Scale Analysis: Subpixel Image Processing Analysis in the analysis of the UMD-RESAC and NLCD2000 product. Rather than using the UMD-RESAC or NLCD2000 data, the NLCD92 was used and processed exactly the same way to extract the impervious surfaces. But before applying the coefficients to the different classes within the watershed, basic calculations were used to determine which type of urban intensity the watershed has, one of three categories based on the number of urban pixels. Once the values from the value attribute table have been put in the spreadsheet the total impervious area is calculated using the coefficients (table 5) for each of the class watershed. The coefficients are then multiplied times the total area for each class and summed, yielding an estimate of total impervious area.

The use of coefficients for impervious surface determination in this context implies that there are similarities in landscape structure that would make this method of computing impervious surfaces feasible. Developing the coefficients is accomplished by a sampling technique in the Mid-Atlantic region for these coefficients, where higher spatial resolution data are used to determine the average amount of imperviousness in each land cover category. This average is then used to compute a coefficient for a 'per pixel' amount of imperviousness for each class. In this task, two sets of coefficient methods were used for computing imperviousness from NLCD92. The details of the two techniques are found in Center for Watershed Protection (1998), as implemented in the Arcview Extension 'Attila' (Ebert and Wade, 2003; Jennings and others, 2004) (table 6).

Results

All five methods in the three different tasks enabled the quantification of the different components of impervious surfaces – at different scales and accuracies with some interesting results.

Task 1 – Quantifying Components of Impervious Surfaces: Reference Data

After compiling all temporal datasets on the six watersheds, overall, buildings led all other categories at 29.2 percent of the total imperviousness, followed closely by roads at 28.3 percent, with parking lots in third place at 24.6 percent. These three cat-

Table 5. The 1992 National Land Cover Dataset coefficients for the Chesapeake Bay region (Jennings and others, 2004). The watershed can be a Type 1- rural/sub-urban, Type 2 - suburban, or a Type 3 - urban. Type is determined by the built-up intensity using the imperviousness/class for: Low Intensity Residential (21), High Intensity Residential (22), Commercial/Industrial/Transportation (23).

Class Name	Codes	Type 1 Coefficient (Low Intensity)	Type 2 Coefficient (Moderate Intensity)	Type 3 Coefficient (High Intensity)
Open Water	11	0.0070	0.0440	0.0950
Low Intensity Residential	**21**	**0.1820**	**0.2500**	**0.3060**
High Intensity Residential	**22**	**0.6920**	**0.6200**	**0.4900**
Commercial/Industrial/Transportation	**23**	**0.3480**	**0.4500**	**0.6280**
Bare Rock/Sand Clay	31			
Quarries/Strip Mines/Gravel Pits	32	0.0620	0.1380	0.4470
Transitional	33	0.0580	0.2400	0.5000
Deciduous Forest	41	0.0130	0.0550	0.1190
Evergreen Forest	42	0.0100	0.0940	0.1530
Mixed Forest	43	0.0180	0.0870	0.1110
Shrubland	51			
OrchardsVinards/Other	61			
Grass Lands/Herbaceous	71			
Pasture/Hay	81	0.0350	0.0580	0.1140
Row Crop	82	0.0450	0.1160	0.1400
Small Grains	83			
Fallow	84			
Urban / Recreational Grasses	85	0.0880	0.0900	0.2100
Woody Wetlands	91	0.0070	0.0130	0.0360
Woody Wetlands	92	0.0080	0.0370	0.2110

Table 6. Center for Watershed Protection (1998) coefficients. Each land use area is measured and multiplied by the coefficient resulting in an estimate of imperviousness for that feature.

Class Name	Density (dwelling/acre)	Coefficients
Forest	--	0.01
Agriculture	--	0.01
Urban Open Land	--	-
Water/Wetland	--	-
Low Density Residential	<0.5	0.06
	0.5	-
	1	0.12
Medium Density Residential	2	0.18
	3	0.20
	4	0.25
High Density Residential	5 -7	0.35
Multifamily	(Townhouse) >7	0.35 - 0.50
	(Highrise) >20	0.60 - 0.75
Industrial		0.60 - 0.80
Commercial		0.90 - 0.95

egories accounted for the majority of total impervious area for all the watersheds. Table 7 summarizes the area measurements for each category in acres and table 8 summarizes the percentages of total impervious surfaces area. Figure 22 shows the cumulative percentages of each category.

Task 2 - Intermediat Scale Analysis

Task 2A - Intermediate Scale Analysis: Subpixel Image Processing Techniques

The results are shown in table 9. In the Tuscarora Creek watershed, both the RESAC and the EDC data compiled total impervious area to within 10 percent of the Task 1-Reference Data values. For the Difficult Run watershed, however, both the RESAC and EDC datasets significantly under reported the total impervious area. The 1996 RESAC data were only 52 percent in agreement with the 1997 reference data, while the 200 EDC data were 59 percent in agreement with the 1997 reference data.

Task 2B - Intermediate Scale Analysis: Land Use Coefficient Methodology

The application of Land Use coefficients performed best in the Black River watershed where the use was predominantly industrial and commercial, with some residential running from north-to-south on the eastern side of the watershed (table 10). The Task 1-Reference Data resulted in 35.2 percent impervious surfaces for the entire watershed. Visual observation (fig. 5) indicates that the watershed was nearly 100 percent built-up, with no open-

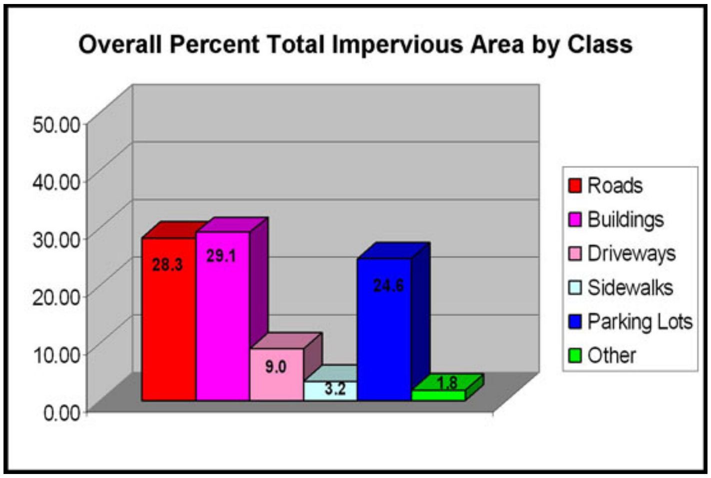


Figure 22. Task 1-Components Quantification - Truth Data. The percent of Total Impervious Area as calculated from eleven separate mappings of the six watersheds. Buildings, roads and parking lots account for the majority of total impervious surfaces area.

Table 7. Task 1- Component Quantification - Truth Data. The Impervious Surface (IS) Area Measurements, in acres, for all the watersheds with dates used in this study. [Bldg=Buildings, DW=Driveways, SW=Sidewalks, PL=Parking Lots, and PCT=Percent]

			Impervious Surface Area (In Acres)							
Watershed Name	**Image Source Date**	**Total Area**	**Watershed**	**Roads**	**Bldg**	**DW**	**SW**	**Parking Lot**	**Other**	**Airport**
Black River	1992	17207.1	6054.5	1257.1	1870.7	250.5	111.3	2508.9	55.9	N/A
Difficult Run	1997	37179.4	6516.1	2043.6	1955.1	786. 0	226.2	1295.2	210.1	N/A
Difficult Run	1988	37179.4	5786.0	1877.4	1691.0	686.9	187.6	1150.7	192.5	N/A
N. Walnut Creek	2001	8691.7	2201.1	578.8	727.1	222.1	92.6	563.5	16.9	N/A
N. Walnut Creek	1990	8691.7	1716.0	500.3	573.5	193.5	75.9	358.2	14.6	N/A
Oak Creek	2000	14042.1	2421.9	607.7	521.3	152.9	86.8	401.7	24.5	626.8
Oak Creek	1990	14042.1	1873.6	525.8	307.2	109.1	56.9	236.3	11.6	626.8
Tuscarora Creek	2000	9226.2	1165.1	409.4	279.4	128.0	66.9	267.4	14.0	N/A
Tuscarora Creek	1998	9226.2	984.2	350.8	252.2	99.6	50.2	219.6	11.7	N/A
Tuscarora Creek	1988	9226.2	806.8	282.6	203.2	86.8	38.2	188.8	7.2	N/A
Wares Creek	2001	5091.4	2311.1	560.9	898.5	146.5	37.2	653.2	14.9	N/A
Totals	N/A	169803.5	31836.4	8994.4	9279.1	2862.0	1029.9	7843.5	573.8	1253.6
Overall PCT per Component	N/A	N/A	18.75	28.25	29.15	8.99	3.23	24.64	1.80	3.94

space lands, and the area being predominantly industrial and commercial.

In the Wares Creek watershed, where this method performed furthest from the reference data, the use was entirely residential. Task 1-Reference Data resulted in 45 percent impervious surfaces for the entire watershed. The development covered the watershed homogeneously, visually appearing to be nearly 100 percent built-up, with the area being predominantly residential.

The two remaining watersheds with percent agreements between Wares Creek and Black River had a combination of uses and undeveloped lands that covered at least 50 percent of the watershed. Task 1-Reference Data resulted in, for both, less than 25 percent impervious surfaces for their entire watersheds.

Task 3. Synoptic Scale Analysis

Task 3-Synoptic Scale Analysis results for both methods are summarized in table 11. Both methods simply multiply a coefficient against the area of satellite image-derived land cover for each class. The coefficient represents the average impervious area for that land cover class. Both methods had overall percent agreements that fell within 5 percent of the reference data. The minimum percent agreement was 90.0 percent and the maximum was 99.9.

Conclusions

This study documented quantities of total impervious areas (table 2) as components in six watersheds (fig. 3). While roads, buildings, and parking lots make up the majority of impervious areas, driveways, sidewalks, and other covers make up 14 percent of total impervious area and should not be ignored in calculating the total impervious surface. Parking lots tended to be large connected, areas unlike the other components that tended to be fairly linear and fragmented.

Four of the common methods for computing impervious area showed significant variability when measured against the high spatial-resolution ground-reference information developed in Task 1. Overall, the four methods tested generally produced an estimate of total impervious area within 10 percent of the reference value. Figure 23 shows a simple regression of the derived, the various methods and years applied, versus the reference data for all four methods tested. There were 24 independent observations from all the methods and the different dates plotted against the Task 1-Reference Data percentages of imperviousness, resulting in a regression correlation R2 = 0.89. Ten-percent variability in the accuracy of the total impervious area value is important, considering that 10 to 25 percent and greater than 25 percent impervious area in a watershed was considered to result in an ecological condition of ‘potentially impacted’ or ‘non-supportive.’ The correlation from Schueler (1994) and Arnold and Gibbons (1996) has been supported by numerous other studies. Research over the last 20 years has consistently reported a correlation between imperviousness of a watershed and ecosystem quality.

Task 1 – Quantifying Components of Impervious Surfaces: Reference Data

This method was supported by the abundance of geo-registered digital imagery at 1-meter resolution or better that is now widely available from the U.S. Geological Survey, other government sources, and educational institutions, as well as from private mapping vendors. The reference data provided excellent and reliable sources of detailed impervious surfaces in correlating them with the condition of the watershed, as well as the valuable and critical assessment of important new techniques.

The high spatial resolution compilation of impervious surfaces in this task revealed individual component features that made up functional impervious surface area. Roads, while often considered the main contributor to impervious area, are only one of the three major components of total impervious area that include buildings and parking lots. The contribution of road impervious area to overall total impervious area has been implied in the literature to be as high as 70 and 80 percent. In this research, the roads ranged from 20.8 percent, in 1992 Black River watershed (dense built-up commercial/industrial with some residential), to 35.6 percent, in the 1998 Tuscarora Creek watershed (low-density residential with a significant amount of open space). Driveways, often unaccounted for in impervious surfaces research, made up an average of 9 percent of the total impervious surface area. Thus, these data show that even very minor classes of impervious cover are important. Very few studies on impervious surface area take into account sidewalks and other components. Yet in this study, these components were responsible for approximately 5 percent of total impervious area (table 8).

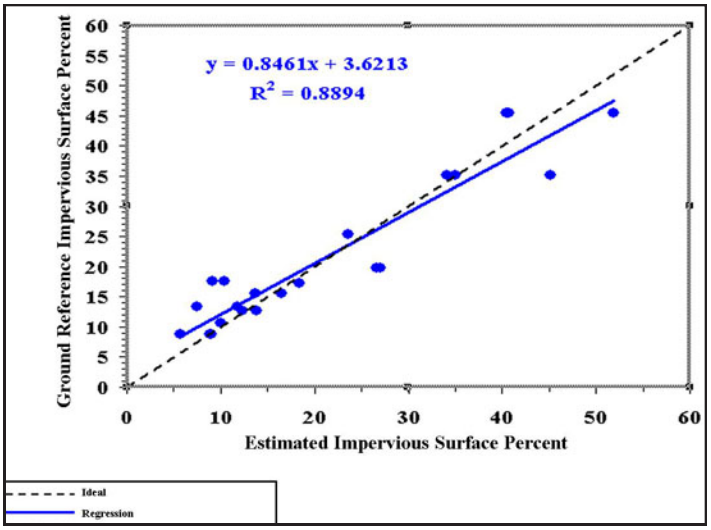


Figure 23. In this regression plot the estimated impervious surfaces percents were derived from all the methods and their 24 observations. These estimations were plotted against the actual impervious surfaces percent. Though the points are scattered along the ideal from low to high density, notice that in this research the techniques examined tended to overestimate the impervious surfaces in the less developed watersheds (for example, greater than 20 percent impervious surfaces).

Road Contribution/Watershed Urbanization

In the two watersheds in the suburban Washington, D.C., metropolitan area, roads were the leading components of impervious cover; even though one watershed was fairly rural and the other more built-up. In contrast, in the more rural Oak Creek watershed in Nebraska, the airport/air force base was the dominant component in both years of analysis, with roads being second. In the highly industrialized Black River watershed with Seattle to its north and Tacoma to its south, parking lots were the leading component of imperviousness (41.4 percent). In both the Wares Creek watershed, Fla., and the North Walnut Creek watershed, Iowa, extending into Des Moines, buildings were the largest component of impervious cover. Buildings were the lead impervious

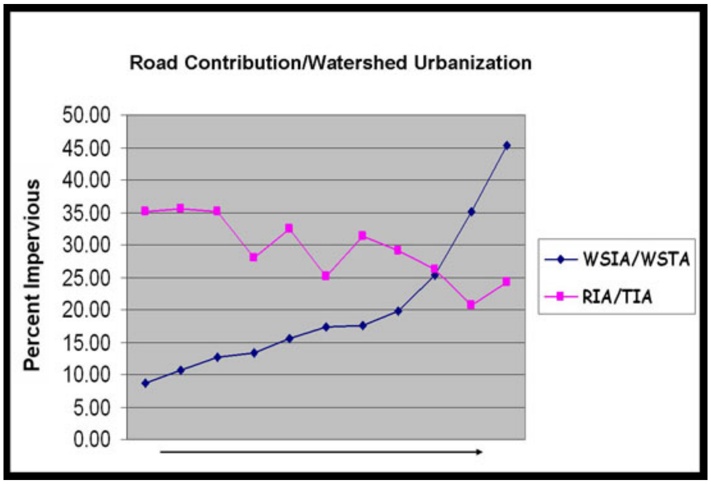


Figure 24. The relationship between road impervious area to watershed impervious area. As the watershed becomes more developed (resulting in increases in the percentage of impervious area) the contribution of roads to the total impervious area declines. WSIA = Watershed Impervious Surfaces Area, WSTA = Watershed Total Area, RIA = Road Impervious Area, and TIA = Total Impervious Area.

Table 8. Task 1-Truth Data. The percent contribution of each component to the total impervious surface for each watershed/year. The highlighted percentage indicates these are the largest contributor of imperviousness in that watershed for that year.
[IS=Impervious Surfaces, TIS=Total Impervious Surfaces, Bldg=Buildings, DW=Driveways, SW=Sidewalks, and PL=Parking Lots]

Watershed	Image Source Date	Watershed and Components Impervious Surface Percentages								
		Water-shed	Road	Bldg	DW	SW	PL	Other IS/TIS	Airport	DW, SW, and Other Combined
Black River	1992	35.19	20.76	30.90	4.14	1.84	**41.44**	0.92		0.69
Difficult Run	1997	17.53	**31.36**	30.00	12.06	3.47	19.88	3.22		18.75
Difficult Run	1988	15.56	**32.45**	29.22	11.87	3.24	19.89	3.33		18.44
N. Walnut Creek	2001	25.32	26.30	**33.03**	10.09	4.21	25.60	0.77		15.07
N. Walnut Creek	1990	19.74	29.16	**33.42**	11.27	4.42	20.87	0.85		16.54
Oak Creek	2000	17.25	25.09	21.52	6.31	3.58	16.59	1.01	**25.88**	10.9
Oak Creek	1990	13.34	28.06	16.40	5.82	3.04	12.61	0.62	**33.46**	9.48
Tuscarora Creek	2000	12.63	**35.13**	23.98	10.99	5.74	22.95	1.20		17.93
Tuscarora Creek	1998	10.67	**35.64**	25.63	10.12	5.10	22.31	1.19		16.41
Tuscarora Creek	1988	8.74	**35.03**	25.19	10.76	4.74	23.40	0.89		16.39
Wares Creek	2001	45.39	24.27	**38.88**	6.34	1.61	28.26	0.64		8.59
Overall PCT per Components	N/A	18.75	28.25	**29.15**	8.99	3.23	24.64	1.80	3.94	14.0

surface component of all these watersheds combined (table 8).

A significant relationship can be found in the correlation of road impervious area to total impervious area (RIA/TIA). TIA correlates with the level of development of the watershed. Figure 24 shows the linear relationship between road impervious area and total impervious area. Recognizing total impervious area as a general indicator of the level of human development in a watershed, we can see that at lower percentages of imperviousness that the road impervious area is around 35 percent. But as the watershed becomes more and more developed, the contribution of roads tends to decline. However, when examining the relationship of the percent impervious surface contribution of all of the other components, separately, to increasing urbanization, there was no apparent trend with the increase in urbanization.

Task 2 - Intermediate Scale Analysis

Task 2A - Intermediate Scale Analysis: Subpixel Image Processing Techniques

Subpixel image processing produced mixed results. Although both methods, RESAC and EDC impervious surfaces results provided good estimates of total impervious area in Tuscarora Creek, both methods significantly under estimated total impervious area in Difficult Run. This may be due to the extensive tree cover and older, large-lot development in some parts of this watershed of Fairfax County, Va. As compared to the Tuscarora Creek watershed, it is much less built-up at this time, but has become one of the fastest growing counties in the United States. These methods may need to incorporate ancillary sources such as current vector road data. The availability of subpixel Land Use/Land Cover data, as derived from satellite imagery, is currently limited but will likely become widely available in the near future, and more accurate as techniques are improved.

Table 9. Task 2A-Intermediate Scale Analysis - Subpixel Image Processing Techniques. Subpixel image processing results above are in acres. Subpixel data are not yes available for the remaining watersheds of this study. [TIA=Total Impervious Surfaces Area, PCT = Percent, and AGR = Agreement]

Watershed	Task 1 Reference Data Image Source Date	Task 2A Subpixel Data Source/Date	Task 1 Reference Data TIA	Task 2A Subpixel TIA	Difference Btwn Task 1 and Task 2A TIA	PCT AGR with Reference
Tuscarora Creek	*2000*	*RESAC / 2000*	*1165.1*	*1132.6*	*32.5*	*97.2*
Tuscarora Creek	*1998*	*RESAC / 1996*	*984.2*	*922.2*	*61.9*	*93.7*
Tuscarora Creek	*1988*	*RESAC / 1990*	*806.8*	*835.1*	*-28.3*	*96.5*
Difficult Run	1997	RESAC / 1996	6516.1	3403.6	3112.5	52.2
Tuscarora Creek	*2000*	*EDC / 2000*	*1165.1*	*1280.9*	*-115.8*	*90.1*
Difficult Run	1997	EDC / 2000	6516.1	3866.5	2649.6	59.3
Average Accuracy	--	--	--	--	--	81.5

Table 10. Task 2B-Intermediate Scale Analysis: Land Use Coefficients (Capiella and Brown, 2001). [TIA=Total Impervious Surfaces Area, and LUC=Land Use Coefficients]

Watershed	Image Source Date	Task 1-Reference Data PCT IS of Watershed / size (mi^2)	Task 1-Reference Data TIA	Task 2B-Land Use Coefficients TIA	Difference Btwn. Reference and Land Use Coefficients	Percent Agreement w/Reference Data
Black River	1992	35 / 26	6054.45	5866.37	188.08	96.89
North Walnut Creek	2001	25 / 13	2201.13	2045.37	55.76	92.92
Oak Creek	2000	17 / 2	421.87	2585.84	163.97	93.23
Wares Creek	2001	45 / 7	2311.09	2062.19	248.90	89.23
Average Accuracy	--	--	--	--	--	93.1

Task 2B - Intermediate Scale Analysis: Land Use Coefficient Method

Task 2B produced results generally within 10 percent of Task 1 for total impervious area. If this technique used a remotely sensed product to derive the land use features using semi- or automated techniques, the 89 percent agreement for Wares Creek result from table 10 could be explained by the vegetation obscuring the sensors view of the surface and structures. However, high spatial resolution images were used to collect these data. The average of the percent agreement for all of the watersheds, though only four watersheds in this comparison, for this method was 93.1 percent. Since the land use was derived from high spatial resolution imagery, the percent agreement was expected to be greater than the average agreement results, at 96 percent agreement, from Task 3-Synoptic Scale Analysis, which only used a product derived from 30-meter resolution satellite imagery. Only Black River met this expectation, although there were still good results from all tested watersheds. Clearly, further testing is needed as only four watersheds were examined in application of this process. This method is more time consuming, as the land use needs to be collected at a fairly detailed level (table 4). Some of the classes include the following: Residential 2-acre lots, Residential 1-acre lots, Residential 0.5-acre lots, Residential 0.25-acre lots, Residential 0.125-acre lots, Townhomes Residential, Multifamily Residential, and other very detailed classes based on lot size discrimination.

Task 3 - Synoptic Scale Analysis

In this technique in the application of land cover coefficients, basic calculations were used to determine the watershed type (urban, suburban, suburban/rural) based on the number of urban pixels in its watershed from the NLCD92. Once the type of watershed was determined, the coefficients were then multiplied against the total area for each class and summed yielding an estimate of total impervious area. One of the main drawbacks of any NLCD-based method is sensitivity to misclassification of these urban pixels in the dataset.

The two land-cover coefficient methods resulted in some interesting patterns. The Center for Watershed Protection (CWP) method over estimated total impervious surface area in five of the six watersheds, while the Jennings and Jarnagin (J&J) method under estimated total impervious area in five of the six cases. Each method calculated total impervious area extremely accurately in one watershed; CWP did so in the smaller, more rural watershed at 9 percent impervious surfaces of the Tuscarora Creek watershed; the J&J method did so in the 35 percent impervious surfaces of the much larger Black River watershed. Overall, the average accuracy for the CWP was 95.6 percent and the J&J method was 96.3 percent. Given the small-scale source of 30-meter resolution, these results seemed impressive. Applying the coefficients to the NLCD product offers a tremendous advantage to all of the methods in that the NLCD-based product with its derivatives products is a fast method of analysis with results in less than an hour. Applying these methods does require the use of GIS software. Potentially, the CWP and the J&J methods could be combined, resulting in an even more accurate technique in determining the impervious area in any given watershed.

Table 11. Task 3-Synoptic Scale Analysis. Comparison of total impervious area calculations from NLCD92 Data in acres with the other two methods in Task 3, Center for Watershed Protection (CWP) and Jennings & Jarnagin (J&J). [TIA=Total Impervious Surfaces Area, AGR=Agreement, and PCT = Percent. * There was no significant change since 1992 in the Black River watershed]

				Task1 Reference Data		Center for Watershed Protection				Jennings and Jarnagin			
Watershed	**Image Source Date**	**NLCD Scene Date**	**Total Area**	**TIA**	**PCT TIA**	**TIA**	**PCT IA**	**Diff Btwn Reference**	**PCT AGR**	**TIA**	**PCT IA**	**Diff Btwn Reference**	**PCT AGR**
Black River	1992*	5/92 8/92	17207.1	6054.5	**35.2**	2735.0	**45.2**	10.0	90.0	6016.4	**35.0**	-0.2	99.8
Difficult Run	1988	3/89 5/90	37179.4	5786.0	**15.6**	955.9	**16.5**	1.0	99.0	5072.0	**13.6**	-1.9	98.1
N. Walnut Creek	1990	4/91 8/92	8691.7	1716.0	**19.7**	463.0	**27.0**	7.2	92.8	2310.8	**26.6**	6.8	93.2
Oak Creek	1990	5/88 8/91	14042.1	1873.7	**13.3**	222.0	**11.9**	-1.5	98.5	1052.2	**7.5**	-5.8	94.2
Tuscarora Creek	1988	3/92 9/93	9226.17	806.8	**8.7**	71.6	**8.9**	0.1	99.9	531.3	**5.8**	-3.0	97.0
Wares Creek	2001	3/92 12/91	5091.4	2311.1	**45.4**	1198.8	**51.9**	6.5	93.5	2073.5	**40.7**	-4.7	95.3
Average Accuracy	--	--	--	--	--	--	--	--	95.6	--	--	--	96.3

Additional Research

This project has taken an initial look at two important issues: the component makeup of total impervious area and the accuracy of various methods used to compute total impervious area. A logical progression of this initial research would entail construction of a larger, statistically significant sampling frame in order to establish defensible inferential relationships about the component structure and the relationship of road surfaces to the scientific discussion of impervious surfaces and water and ecosystem quality. A larger sample of the accuracy assessment of other methods would likely yield similar scientific results.

A larger sample size might be well-served by an initial research inventory of high-resolution datasets available from municipal and county governments. As noted in this report, the availability of local, high spatial resolution GIS datasets represents a major savings of research resources.

This research also indicates that the component structure of impervious area varied by region and differences appeared to be significant. Establishing a regional, economic and (or) ecoregion-based approach to impervious surface and water quality issues could be extremely useful in understanding the spatial context of impervious development in different parts of the country, but could also provide operational information on critical ecosystems and the potential benefit of mitigation efforts.

Further developing the concept presented in figure 24, understanding the changes and trends to total impervious area that road surfaces contribute over time would be a valuable contribution to transportation science. Impervious surfaces developed over a timeframe using historical imagery, correlated with population statistics and water quality parameters, could lead to a better understanding of the relationship between roads, mitigation efforts, best practices, and eventual water quality issues.

Finally, a comparative, time-series, watershed analysis of total impervious area in the United States and in similar watersheds in other parts of the world could provide an increased understanding of the efficiency of construction practices and best practices.

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Web Sites for Additional Information

Anderson Classification Level II:	http://landcover.usgs.gov/pdf/anderson.pdf
American Planning Association:	http://www.planning.org/
Bureau of Transportation Statistics:	http://www.bts.gov/
Center for Watershed Studies:	http://depts.washington.edu/cwws/
How to Find a Watershed Address:	http://www.epa.gov/win/address.html
International Institute for Geo-Information Science and Earth Observation:	http://www.itc.nl/research/policy/spearhead1/vdmeer.asp
Nonpoint Source Pollution: The Nations Largest Water Quality Problem:	http://www.epa.gov/OWOW/NPS/facts/point1.htm
National Land Cover Data 1992:	http://landcover.usgs.gov/natllandcover.html
Maryland's Surf Your Watershed:	http://www.dnr.state.md.us/watersheds/surf/index.html
Multi Resolution Land Consortium:	http://www.epa.gov/mrlc/
National Land Cover Data 1992	http://www.mrlc.gov/
National Land Cover Data 21-classes:	http://landcover.usgs.gov/classes.php
National Academies:	http://www.nationalacademies.org/environment/
National Land Cover Data 2001:	http://www.mrlc.gov/mrlc2k_nlcd.asp
The Brookings Institute:	http://www.brook.edu/index/research.htm
University of Maryland, College Park Department of Geography:	http://www.geog.umd.edu/
University of Maryland, College Park, RESAC:	http://www.geog.umd.edu/resac/index.html
People would walk if it wasn't so far and dangerous:	http://www.transact.org/report.asp?id=205
Science in Your Watersheds:	http://water.usgs.gov/wsc/index.html
Soil and Water Conservation – Virginia Nonpoint Source Pollution Management Program: Surface Transportation Policy:	http://www.transact.org/
Soil and Water Conservation – Virginia Nonpoint Source Pollution Management Program Surface Transportation Policy Program Update:	http://www.dcr.state.va.us/sw/npsupdt.htm
Transportation Research Board:	http://trb.org/
U.S. Department of Transportation:	http://www.dot.gov/

U.S. Department of Transportation Federal High Administration:	http://www.fhwa.dot.gov/
U.S. Environmental Protection Agency:	http://www.epa.gov/
U.S. Geological Survey:	http://www.usgs.gov
U.S. Geological Survey, Geography:	http://geography.usgs.gov/
U.S. Geological Survey: Geographic Analysis & Monitoring	http://gam.usgs.gov/
Water Quality Assessment Database 2000 305(b) Data:	http://www.epa.gov/waters/305b/index.html

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Appendix A: GIS Data Source Information

GIS DATA SOURCE INFORMATION

Selected Watersheds	GIS Data Source (Date / Resolution)	Themes Available in GIS Data (metadata yes / no)	Modification To, or Creation of, Each Theme with Best Available Imagery		Provide Products & Results Back to Interested Local Government and Other Interested Contacts
			Modification	Created New Themes	
Black River, Washington	King County (2000) Data covered city limits but not north 1/3 portion of the watershed	Buildings – lines	Buildings convert to polygons, closed, and add missing	Top 1/3 ws	King Co.
		Roads – lines	Roads convert to polygons, closed, and add missing	Top 1/3 ws	
		Parking Lots – None	N/A	Parking lots	
		Driveways - line	Driveway convert to polygons, closed, and add missing	Top 1/3 ws	
		Sidewalks – None	N/A	Sidewalks	
		Other – None	N/A	Other	
		Watershed	N/A	Top 1/3 ws	
Difficult Run, Virginia	Fairfax County (2000)	Buildings – polygon	Adjusted and made some additions	N/A	Fairfax Co.
		Roads (major, minor) – polygon	Adjusted and made some additions	N/A	
		Parking Lots – polygon	Adjusted and made some additions	N/A	
		Driveways – None	N/A	Driveways	
		Sidewalks – lines	Adjusted and made *many* additions, and buffered	N/A	
		Other (pools) - polygons	Adjusted and additions made (all recreation trails added, pool patios added)	N/A	
		Watershed	N/A	N/A	

Continued.....

Appendix A: GIS Data Source Information (continued)

GIS DATA SOURCE INFORMATION (continued)					
Selected Watersheds	**GIS Data Source (Date / Resolution)**	**Themes Available in GIS Data (metadata yes / no)**	**Modification To, or Creation of, Each Theme with Best Available Imagery**		**Provide Products & Results Back to Interested Local Government and Other Interested Contacts**
			Modification	**Created New Themes**	
North Walnut Creek, Iowa	Some Added Converted to Polygons, Many Added and Others Adjusted N/A Added and Adjusted N/A Patios around pools added	N/A	Manatee Co.	N/A	Polk Co.
		N/A	Combined, converted to polygon file closed polygons, added many more	N/A	
		Parking Lots	N/A	Parking Lots	
		N/A	Closed Polygons	Driveways	
		Sidewalks	N/A	Sidewalks	
		N/A	N/A	Other	
		Watershed	N/A	N/A	
Oak Creek, Nebraska	*The National Map* (2002)	None	N/A	Roads, Parking Lots, Buildings, Driveways, Sidewalks, Other	None.

Continued....

Appendix A: GIS Data Source Information

GIS DATA SOURCE INFORMATION (continued)					
Selected Watersheds	**GIS Data Source (Date / Resolution)**	**Themes Available in GIS Data (metadata yes / no)**	**Modification To, or Creation of, Each Theme with Best Available Imagery**		**Provide Products & Results Back to Interested Local Government and Other Interested Contacts**
			Modification	**Created New Themes**	
Tuscarora Creek, Virginia	Loudoun County (1998)	Buildings	N/A	N/A	Larry Stepik
		Roads	N/A	N/A	
		Parking Lots	N/A	N/A	
		Driveways	N/A	N/A	
		Sidewalks	N/A	N/A	
		Other	N/A	N/A	
		Watershed	N/A	N/A	
Wares Creek, Florida	Manatee County (2001)	Buildings - polygon	N/A	N/A	Manatee Co.
		Roads – lines	N/A	N/A	
		Parking Lots – None	N/A	N/A	
		Driveways - polygon	N/A	N/A	
		Sidewalks - – None	N/A	N/A	
		Other (pools present)	N/A	N/A	
		Watershed	N/A	N/A	

Appendix B: High Spatial Resolution Imagery Source Information

HIGH-SPATIAL RESOLUTION IMAGERY SOURCE INFORMATION			
Selected Watersheds	**Hi-Resolution Imagery Source used for Base IS Completion (resolution/ date)**	**Imagery Source for NLCD92 Match (resolution/date)**	**Hi-Resolution Imagery Source for Subpixel Data – RESAC and EDC Impervious Surfaces Data Match (Resolution/ Vintage)**
Black River. Washington	King County (1992)	USGS/DOQ (1-meter/1989) Scanned Aerials (1.5'/1992)	No Significant Change Since 1992 EPA CIR Aerial Photographs
Difficult Run, Virginia	Fairfax County (1'/1997) *The National Map* 2002	USGS/DOQ (1-meter/1988)	*The National Map* (1'/2002)
North Walnut Creek, Iowa	Polk County (6"/2001/BW)	EPA/Scanned Aerial Photos (1.5'/1992/BW) 1990	Polk County (6"/2001/BW)
Oak Creek, Nebraska	*The National Map* (1'/2002/Natural Color)	EPA/Scanned Aerial Photos (1.5'/1987/CIR) USGS/ DOQs (1-meter/1990)	*The National Map* (1'/2002/Color)
Tuscarora Creek, Virginia	Private Source (1'/1998/Color) and USGS DOQs (1-m/1998/CIR) Eyemap™ 1998; DOQs 1990, and 2000 Eyemap ™)	USGS/DOQ (1-meter/1988)	EPA/Scanned Aerial Photos (~1.5'/2000)
Wares Creek, Fllorida	Manatee County (~2'/2001)	EPA Aerial Photos 1992/CIR	No Significant Change Since 1992

Appendix C: Small Scale Source Information

SMALL SCALE SOURCE INFORMATION				
Selected Watersheds	**NLCD Path/ Row**	**NLCD92 Scene Date**	**UMD RESAC Scene Date**	**EDC Impervious Surfaces Date**
Black River, Washington	46/27	5/1992 8/1992	Unavailable	Unavailable
Difficult Run, Virginia	15/33	3/1989 5/1990	2000	2000
North Walnut Creek, Iowa	26/31	4/1991 8/1992	Unavailable	Unavailable
Oak Creek, Nebraska	28/32	5/1988 8/1991	Unavailable	Unavailable
Tuscarora Creek, Virginia	15/33	3/1992 9/1993	2000	2000
Wares Creek, Florida	17/41	3/1992 12/1991	Unavailable	Unavailable