1. Introduction

Nonpoint source (NPS) pollution is defined by the U.S. Environmental Protection Agency (EPA) as pollution originating from urban runoff, construction, hydrologic modification, silviculture, mining, agriculture, irrigation return flows, solid waste disposal, atmospheric deposition, stream bank erosion, and individual sewage disposal (Corbitt, 1990). On a national scale, the U.S. EPA (1994) found most stream nutrient loads to be nonpoint source. According to the National Research Council (1999), a solid, scientific foundation of basic and applied research is needed to provide data, information, and tools for effective implementation of watershed management activities. In the Occoquan basin of northern Virginia, maintenance of local water resources for adequate waste assimilation, public water supply, recreation, and fishery and waterfowl habitat has been a state-mandated concern for more than 30 years. Water bodies enriched by nutrients and high biotic productivity such as the Occoquan reservoir are classed as eutrophic (Cole, 1994). Usually, eutrophic waters are impaired as a result of combined edaphic (soil), morphologic (shape), climatic, and anthropogenic (man-made) factors. Sediment delivery from nonpoint sources causes storage loss in water impoundments, making knowledge of suspended sediment in rivers and streams an important part of water resources management (Crawford, 1991).

The linkage between storm runoff and nonpoint source (NPS) pollution has been recognized since the late 1960s (Novotny and Chesters, 1981). Since then, the corresponding linkage between land use and NPS pollutant delivery has been investigated at a variety of temporal and spatial scales. ASCE (1998) noted that the development of data linking percent imperviousness thresholds to stream degradation in headwater areas has enhanced the potential for land-use planning as a tool for stormwater quality management. According to Novotny (1999), the evolving science of watershed management is positioned to become a dominating environmental issue. Synoptic records of land use/land cover (LULC) using remotely sensed imagery have the potential to provide nearly continuous landscape monitoring at geographies at or below the U.S. Census block level. Spatial data of relatively high temporal resolution (annual, seasonal, or monthly), when linked to long-term stream monitoring data, can provide an excellent opportunity to observe the impact of land use change on basin hydrology and NPS pollutant delivery.

According to ASCE (1998), long-term watershed monitoring programs provide valuable insights for targeting NPS pollutant sources. Empirical models are often used to identify possible indicators or sources of watershed influence on in-stream conditions (Tufford et al., 1998). Long-term watershed studies are often limited by the lack of consistent, historic landscape information or by periodic landscape data that is mismatched with higher temporal resolution water quality data. The present research attempts to close the gap between typically high temporal resolution water quality data and lower resolution landscape descriptions using statistical analysis including empirical modeling at an intermediate temporal scale. The goal of the dissertation is to quantify long-term annual and seasonal effects of LULC on basin hydrology and NPS sediment and nutrient flux in the four headwater basins of the Occoquan River, with a special focus on urbanization.

1.1. Background

Since the 1950s, rapid population increases in the northern Virginia region of the eastern United States have resulted in substantial land use changes. As a consequence of increased urbanization within the Occoquan River watershed throughout the 1960s, the waters of the Occoquan reservoir became increasingly eutrophic. A commissioned study by Metcalf & Eddy (1970) determined that a major cause of water quality impairment in the reservoir was nutrients from separate sewage treatment plant discharges and from natural drainage from forested, agricultural, and urban lands, particularly phosphorus.

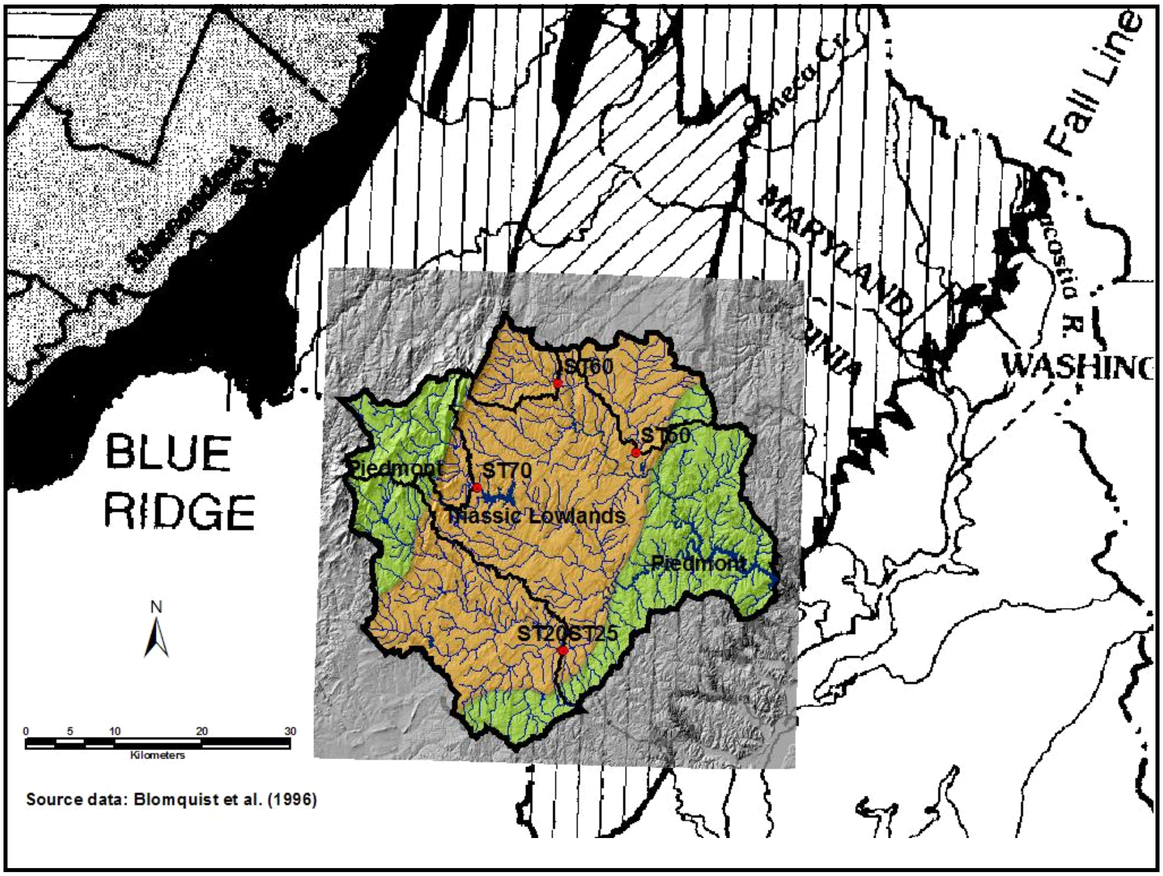
Water supply protection was begun in 1971 through the mandated replacement of the watershed's 11 wastewater treatment plants with an advanced wastewater treatment (AWT) facility and the establishment of the Occoquan Watershed Monitoring Program (Randall et al., 1977a; Randall and Grizzard, 1995). Early results from the monitoring program established nonpoint nutrient pollution as a major cause of water quality impairment. The AWT facility went on line in July of 1978, effectively removing point source contributions to the Cub Run basin. Continued monitoring in the basin has demonstrated that ongoing control of both point and nonpoint nutrients is necessary to protect the water quality of the Occoquan reservoir. Results of long-term basin monitoring have revealed that the majority of pollutants entering the Occoquan reservoir are from nonpoint sources (Table 1-1).

Table 1-1. Load sources and retention/conversion in Occoquan reservoir, 1983-1997.

	Average annual Load (kg)	NPS (% of total)	POTW's* (% of total)	Atmospheric deposition (% of total)
Total N	1.39e+06	68.4	31.2	0.4
Total P	8.98e+04	95.1	4.7	0.2
Total TSS	4.63e+07	100.0	0.0	0.0

Source: OWML (Occoquan Watershed Monitoring Laboratory), 1998.
*Publicly-owned treatment works.

The Occoquan drainage basin sits astride the Coastal Plain and Piedmont physiographic provinces, with the majority of the headwaters lying in the Piedmont. Miller et al. (1997) characterized the Occoquan region as part of the Piedmont and Triassic Lowlands subunit (Figure 1-1), a region of low baseflow alkalinity and hardness concentrations generally associated with lower hydraulic conductivities, as opposed to the carbonate groundwater systems of the Valley and Ridge Province of the Shenandoah Valley. Soils are predominantly sedimentary sandstones and shales which overlie Triassic shales of the middle Piedmont (Petry et al., 1970).



Source data: Blomquist et al. (1996)

Figure 1-1. Relief map of Occoquan watershed and four headwater study basins, Virginia, USA. Occoquan watershed boundaries are shown superimposed on a relief map of colorized physiographic provinces (Piedmont and Triassic Lowlands).

The Occoquan basin has two major sub-basins, Occoquan Creek basin (888 km^2) located in the southern portion of the watershed and Bull Run basin (479 km^2) to the north (Randall et al., 1978). The two tributaries draining these sub-basins meet approximately 26 stream kilometers (16 mi) above the Occoquan dam, which has a full pool elevation of 37m (122ft) mean sea level. Occoquan Creek, which forms at the confluence of Broad and Cedar Runs, drains predominantly agricultural land with increasing pockets of low-density residential housing (Figure 1-2). Bull Run, and its tributary Cub Run to the north, drains the developing urban areas in Fairfax and Loudoun counties. The Occoquan basin is sufficiently large to be subject to variable rainfall patterns, especially during summer months of convective precipitation.

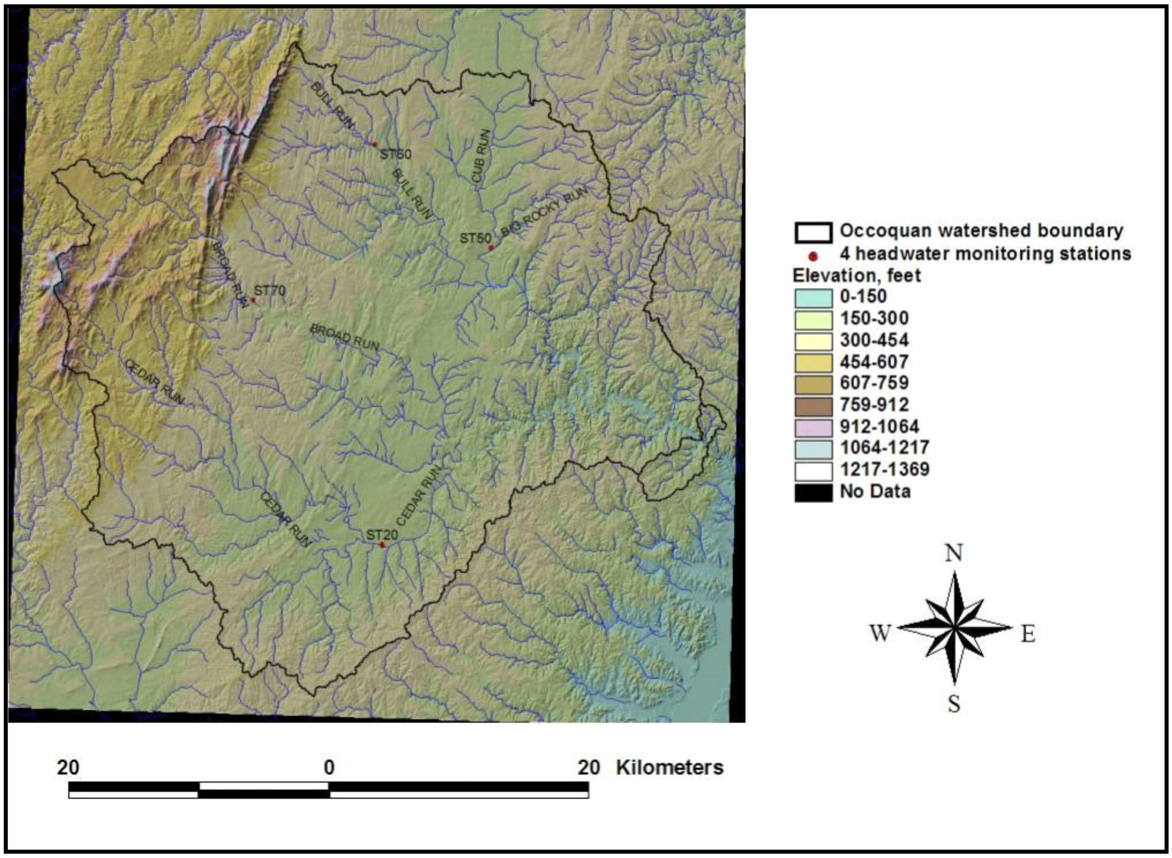


Figure 1-2. Relief map: Occoquan watershed, northern Virginia, USA.
(Station 20 was replaced by station 25 on 8/20/91).

Metcalf & Eddy (1970) reported that the morphology of the Occoquan reservoir allows high streamflows of January, February, and March to pass through while retaining the lower streamflows of May, June, July, August, and September for considerably longer periods of time.

1.2. Research Goals and Objectives

The principal goal of this research is to quantify the relationship between basin land use/land cover (LULC) and hydrologic and NPS sediment and nutrient flux in the four headwater basins of the Occoquan River, with a specific focus on the effects of urbanization. This goal is achieved by completion of the following objectives:

1. To develop methodologies summarizing historic LULC and water quantity/quality in the four study basins (using spatial and database tools).

2. To compare and contrast hydrologic and NPS pollutant summaries across basins, years, and seasons (using descriptive and nonparametric statistics).

3. To identify major physical processes related to LULC that are driving basin discharge and diffuse pollution delivery across all four study basins (using annual and seasonal multivariate linear regression models).

1.3. Scope and Limitations

The scope of this work is to answer the research question within the Occoquan watershed of northern Virginia using four headwater basins that contain no significant point source contributions. A major limitation of the research method is that only one of the four study basins is urbanized, and only one basin has become urbanized over the course of the study period – and they are the same basin. In addition, because the field method used to discriminate storm events changed in 1988 (from visual interpretation of a paper stage chart to automatic digital processing), an inconsistent data bias may be present. Consequently, comparison of storm response between pre- and post-1988 data is compromised; and statistical tests are limited to between-basin tests. Regression models developed in this study may be used for prediction within the bounds of observed data; however, their principal utility is to identify landscape-related physical processes that impact hydrologic and NPS pollutant flux across the four study basins. Deficiencies in empirical models are due to a limited capacity to characterize land use influences and changes through time, particularly agricultural land use on an annual time scale.

Swank and Waide (1998) note that long-term watershed monitoring tends to smooth out year-to-year variability in precipitation, evapotranspiration, nutrient deposition, and biological activity, thus reflecting the integrated behavior of natural landscape units. Complete accounting of nutrient inputs (agricultural fertilization, septic systems) and outputs (groundwater losses) is not completed in this research; therefore measurement of net nutrient budgets is not possible. As a result, an important means of characterizing biogeochemical processes and of quantifying system-level changes due to human activity is not available. Given the limitations described above, this dissertation identifies hydrologic and NPS pollution fluxes found to be associated with LULC change, based on observed, long-term data, with a focus on urbanization.

1.4. Outline

This dissertation is structured as an introductory chapter, four independent chapters, and a summary chapter. The introduction lays the framework for the research detailed in subsequent chapters, with chapters two through five written as independent manuscripts.

- Chapter 1 - Introduces the research study area and reviews literature current to integrated watershed monitoring and analysis. Specific objectives of the research are stated, as well as the overall goal, scope, and limitations of the study.
- Chapter 2 - *Evaluation of Impervious Surface Estimates in a Rapidly Urbanizing Watershed* - Compares impervious surface estimates from a recently developed satellite imagery/land cover approach with those from a traditional aerial-photography/land use approach. Resulting data sets are evaluated against a validation set consisting of planimetric data from the rapidly urbanizing Cub Run basin.
- Chapter 3 - *Quantifying Long-term Hydrologic Response in an Urbanizing Basin* Investigates hydrologic response to precipitation and basin characteristics, with specific focus on the effects of urbanization. Quantifies long-term hydrologic response within four Occoquan watershed headwater basins.
- Chapter 4 - *Quantifying Long-term NPS Pollutant Flux in an Urbanizing Basin* - Investigates NPS pollutant responses to precipitation and basin characteristics, with specific focus on the effects of urbanization. Quantifies long-term NPS pollutant response within four Occoquan watershed headwater basins.
- Chapter 5 - *Empirical Modeling of Hydrologic and NPS Pollutant Flux in an Urbanizing Basin* - Develops regression models of long-term hydrologic and NPS pollution flux response in the four headwater basins of the Occoquan watershed in order to identify significant landscape-related processes driving basin discharge and NPS pollutant flux in the urbanizing Cub Run and three rural basins.
- Chapter 6 – Concluding Summary and Recommendations – Provides a review of whether the objectives have been achieved, including clear statements regarding future research directions.

1.5. Literature Review

This section reviews literature related to watershed analysis in temperate climates under three main headings; previous studies in the Occoquan region, spatial analysis of watersheds, and modeling of hydrologic and NPS pollutant response. Major sub-sections include previous work related to integration of spatial data, quantifying urbanizing landscapes and land use change, and identifying relationships between landscapes and pollutant transport.

Previous Studies in the Occoquan Region

Randall et al. (1977b) reported that urban development and therefore urban runoff, was greatest along the portion of Bull Run that borders the Manassas area, along Flat Branch to Bull Run, and along Big Rocky Run, a tributary to Cub Run (Figure 1-2). Organic and nutrient contributions from urban runoff constituted a sizeable fraction of total quantities entering Bull Run. Randall et al. (1977b) recommended that the entire approach to pollution abatement and control in the Occoquan watershed be rethought, and concluded that the elimination of pollutants from treatment plant effluents would not be sufficient to accomplish desired water quality objectives in the Occoquan reservoir without controlling non-recorded (nonpoint) sources of pollution.

In 1978, the Metropolitan Washington Council of Governments (MWCOG) issued the final report of a study titled, "Land use/runoff quality relationships in the Washington metropolitan area." The study was prepared under Section 208 of the Federal Water Pollution Control Act using rainfall and runoff data from 303 site/storms collected in 1976 and 1977 at 21 small, relatively homogeneous watersheds in northern Virginia, thirteen of which were located in the Occoquan basin. At the time, the study represented the most comprehensive analysis of runoff characteristics based on local field data. Nonpoint pollutant loads were analyzed for several land use categories, including stabilized urban land use, transitional urban development (active construction sites), agricultural operations, and undeveloped land. Estimates of unit loading were determined by multiplying (mean concentration, from automated sampling) * (long-term runoff volume, from hydrologic modeling). The percentages of runoff nutrients and heavy metals in soluble and suspended forms were identified, as were storm runoff volumes produced from different land uses. Land use/runoff quality relationships were developed by statistical analysis of field data.

Results of the MWCOG study showed that urban runoff volumes were generally higher than those from nonurban land uses, resulting in higher unit pollutant loading from urban areas, although agricultural uses had higher mean nutrient and sediment concentrations. Conventional tillage had the highest instantaneous concentration of total suspended solids (2,814 mg/L), followed by active construction sites (700 mg/L). Agricultural areas had higher TSS concentrations than all urban land uses except for active construction sites. Conventional tillage agriculture, with its high fertilizer input, had the highest mean concentrations of total nitrogen and total phosphorus (15.5 mg/L and 3.34 mg/L, respectively). Unoxidized forms of nitrogen were found to be predominant over oxidized nitrogen forms in all land uses. Significant percentages of total nitrogen and total phosphorus loads from all land use categories appeared in the dissolved rather than suspended form. This result is important, given the fact that dissolved fractions are not affected by nonpoint pollution control measures that rely upon conventional sedimentation processes. Higher fractions of organic phosphorus were found in urbanized categories having higher impervious percentages. Apparent cause-effect relationships between impervious surface (IS) cover and total nonpoint pollutant loadings were attributed to vehicular sources, runoff from atmospheric deposition, and percentage of total runoff volumes generated by the watershed's impervious fraction.

Randall et al. (1978) reported that loads of available nutrients entering the Occoquan reservoir as a result of stormwater runoff were much greater than the loads from point sources. They also reported that the largest pollutant loads originated from the urbanized portion of the watershed compared to the agricultural portion, even though the agricultural area was 1.85 times larger than the area containing the urbanized sections. Significant fractions of nutrients were in the soluble inorganic or "available" form, 33% of total phosphorus and 26% of total nitrogen. Conclusions from their study set out priorities for upstream water quality control measures for the Occoquan reservoir in the following order: (1) primary treatment, (2) secondary treatment, (3) stormwater pollution, and (4) advanced wastewater treatment.

Randall et al. (1980) discussed relative contributions of nutrients by point and nonpoint sources as a function of land use and land development for the years 1976-1978. During this period, numerous nonpoint pollution control measures were implemented, including mandated construction of wet and dry stormwater detention ponds for commercial and suburban areas, swale drains rather than curb-and-gutter construction in residential subdivisions, porous pavements and subsurface drains for commercial parking lots, restrictions on cluster development in Fairfax County, and State Water Control Board (SWCB) imposed sewer moratoriums in some areas.

Northern Virginia Planning District Commission (NVPDC, 1979) developed NPS pollutant loading rate estimates based on correlations with land use and soil type. Robinson and Ragan (1993) used a GIS and NPS modeling approach to estimate NPS pollutant loading in nearby Montgomery County, Maryland in order to demonstrate integrated monitoring and management strategies at the regional scale. Corwin and Wagenet (1996), in their symposium overview regarding modeling of NPS pollutants with GIS, cautioned that the use of spatial mapping or environmental models should augment, but not replace actual observation.

Randall and Grizzard (1995) compared total NPS phosphorus loads to literature values for areas of similar land use; and reported that land use phosphorus contributions for 1977, 1979, 1984, and 1989 were similar to the lowest values recorded in the literature. Randall and Grizzard (1995) noted that the dominant pollution source during any period of the year is a function of the rainfall, especially during the growing season, with point sources dominating during dry periods and nonpoint sources dominating during wet weather. They also reported a general reduction in phosphorus loading from 1974 through 1991.

Most of the increase in new development in the Occoquan basin occurred after 1984 because of low-density residential land use regulations (i.e., restricted lot sizes) enacted by Fairfax County in 1980 (Randall and Grizzard, 1995). Upon lifting of a development moratorium in 1984 resulting from a legal challenge by developers, a massive wave of commercial and suburban development occurred in the Fairfax County segment of the watershed. Randall and Grizzard (1995) reported that as soon as construction began, suspended solids and total phosphorus concentrations in Cub Run increased dramatically and remained at elevated levels for several years. Construction resulted in large changes in land use patterns (Figure 1-3).

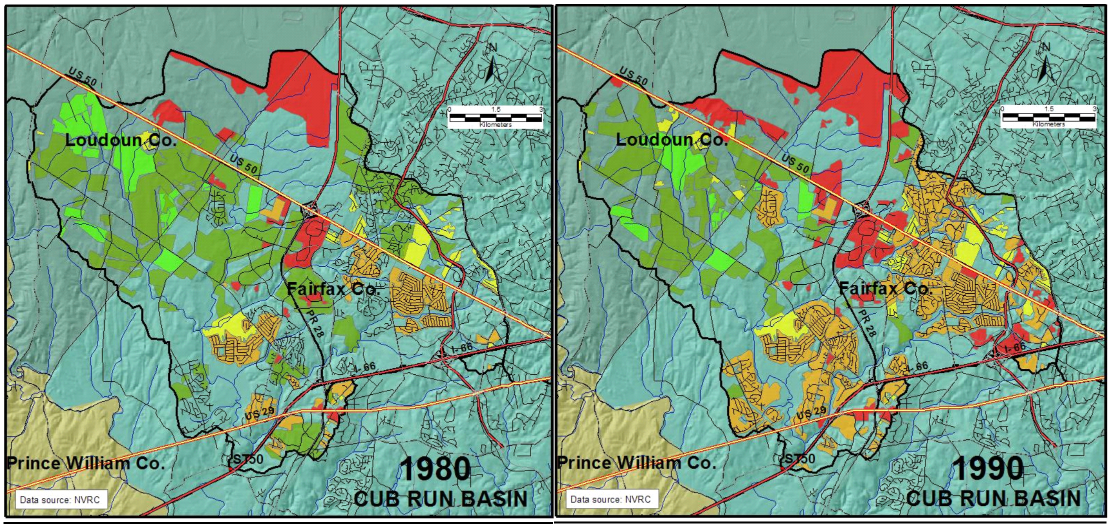


Figure 1-3. Land use time series, Cub Run headwater basin, 1980-1990.

Legend: mixed minimum till agriculture/pasture (dark green), mixed conventional till agriculture/livestock (light green), low density residential/golf course (yellow), townhouse/medium density residential (orange), commercial/ industrial/disturbed land/roads (red), forest/idle land (no color, blue).

In 1996, Schueler reported on the level of development sustainable within the Occoquan basin and concluded that the watershed was crossing an important rural to urban threshold. He stressed the cumulative impact of urbanization on the quality of the 1,300 stream miles draining the Occoquan basin and predicted that by the year 2020, more than 80 percent of the stream miles in the basin would fall into the impacted or non-supporting category. Schueler (1996) evaluated best management practices (BMPs) in the Occoquan basin, which was one of the first watersheds in the country to adopt urban BMPs to control phosphorus loadings from new development. Schueler (1996) urged a re-evaluation of urban BMP strategy to ensure that stormwater nutrient loads are reduced to comply with prescribed reductions under the Chesapeake Bay strategy. Schueler (1996) reported that the irreducible concentration of stormwater phosphorus exiting stormwater management facilities in the Occoquan basin is greater than recommended freshwater levels (Metcalf and Eddy, 1970), and that urban BMPs are only partially effective at reducing the large increase in phosphorus loads generated by urbanization. Schueler's report noted that the phosphorus removal rates assigned to dry extended detention ponds in the basin were higher than performance monitoring support, and that removal rates for nitrogen were also insufficient, since most urban BMPs have little capability to remove nitrogen in urban runoff (Schueler, 1996). Several streams in the Occoquan basin have been listed as impaired (VDEQ, 2000), including Bull Run (benthic impaired), Cedar Run (fecal coliform impaired), and Broad Run (NH_3-N impaired).

In the absence of a deterministic water quality-receiving model, the OWML (1998) used the empirical model of Vollenweider (1968, 1975) to relate long-term phosphorus loads to eutrophication in the Occoquan reservoir. Graphical analysis presented by OWML (1998) showed that although the Occoquan reservoir is highly eutrophic, substantial progress has been made since the AWT plant came on line in 1978. Hydrologic calibration of the Cub Run basin by Vilarino (1996) contributed to current watershed modeling efforts in the Occoquan watershed. OWML (1998) reported that when the reservoir response module of the revised and updated Occoquan Basin Model (Cole and Buchak, 1995; Bicknell et al., 1997; Stein et al., 1998; Godrej, 2000) is complete, a much more robust analytical tool will be available to assess water quality trends and predict future responses. Johnston (1999) developed methods to infill missing hydrologic and chemical watershed data using data from OWML for use in quantifying hydrologic and pollutant loads in the basin. In 2000, Dymond and Agbenowosi presented a GIS real-time working framework for monitoring and managing the Occoquan watershed.

In 1969, Jaworski et al. reported on the problematic nature of nutrients as a source of water quality impairment in the Potomac River basin. Over twenty-five years later, Blomquist et al. (1996) completed a water-quality assessment of the Potomac River basin based on nutrient data from the National Water-Quality Assessment (NAWQA) program, reporting that nutrient concentrations from 1970 to 1990 were highest in agricultural watersheds and near urban centers having large wastewater-treatment inputs. Blomquist et al. (1996) also reported that in agricultural and forest areas, nitrogen concentrations were highest during the winter, and phosphorus concentrations were highest during the summer. In areas having substantial wastewater inputs, concentrations of both nitrogen and phosphorus were highest during low streamflow (summer) conditions. Miller et al. (1997), as part of a related assessment of small streams in the Potomac River basin, compared baseflow nutrient concentrations to selected agriculture, urban, and forest land use categories. Miller et al. (1997) reported that among agricultural areas, streams draining areas of intense row cropping contained higher nitrate concentrations than those draining pastures, while streams draining forested areas typically had the lowest nutrient concentrations. Soluble phosphorus concentrations during baseflow were found to be generally low in all physiographic sub-units, including areas with potential for high phosphorus inputs.

The Occoquan basin sampling station network was not designed to quantify non-surface water sources of nutrients such as groundwater and septic systems. Estimates of atmospheric wetfall and dryfall nutrient inputs are available from two previous studies in the basin (OWML, 1998). The principal nutrient sources for the Occoquan Creek arm of the Occoquan reservoir were reported to be agricultural runoff because this basin receives essentially no urban drainage, nor does it have any significant wastewater discharges (OWML, 1998). Zipper et al. (2002), in their comparative water quality study of Virginia physiographic regions, noted that median total residue values from 1978 to 1995 in the Piedmont were low relative to other physiographic regions due to the general absence of saline coastal waters, coal mining, and soluble carbonate bedrock. Zipper et al. (2002) measured trends in water quality trend using Kendall's *tau* (Hirsch et al., 1982; Hirsch et al., 1991), with positive *tau* values indicating increasing trend. Although most total Kjeldahl nitrogen (TKN) *tau* values in the Piedmont were found to be highly negative, a number of high TKN *tau* values were recorded in Piedmont watersheds with relatively high percentages of cropland. Zipper et al. (2002) did not detect any significant correlation relationships between *tau* values for nitrate-nitrite and any land use variables.

Spatial Analysis of Watersheds

The concept of a watershed is based on surface landform and topography. Lavigne and Coyle (1995) defined a watershed as the land from which water, as rain, snow, or other form, drains into a river, stream, pond, or other water body. They note that because watersheds are easy to understand, they are a powerful tool for demonstrating the interconnections of natural systems; but that since science is not absolute, patience and professional judgment are required to quantify the long-standing and complex nature of environmental problems in a watershed. Accordingly, Lavigne and Coyle note that watershed science does not have to be perfect to be reliable and that sound decisions can be made with adequate science. The American Society of Civil Engineers (ASCE, 1998) affirms the watershed as an appropriate boundary for management of water resources, along with other approaches such as the groundwatershed and the airshed. ASCE notes that boundaries, once selected, are rarely absolute, and should be regarded as "diffuse."

Integration of Spatial Data

A geographic information system (GIS) is a platform that provides for integrated analysis of data from remote sensing (RS) and geographic positioning systems (GPS). Data manipulated within a GIS is either spatial, such as boundaries, or thematic, such as types of land cover. Limitations in GIS functionality due to incomplete, inaccurate, or obsolete data can be overcome ideally by integrating more current RS and GPS data. Gao (2002) describes how GIS, GPS, and RS are complementary to each other in their primary functions, with full utilization realized by providing all possible associations between any two represented components (Figure 1-4).

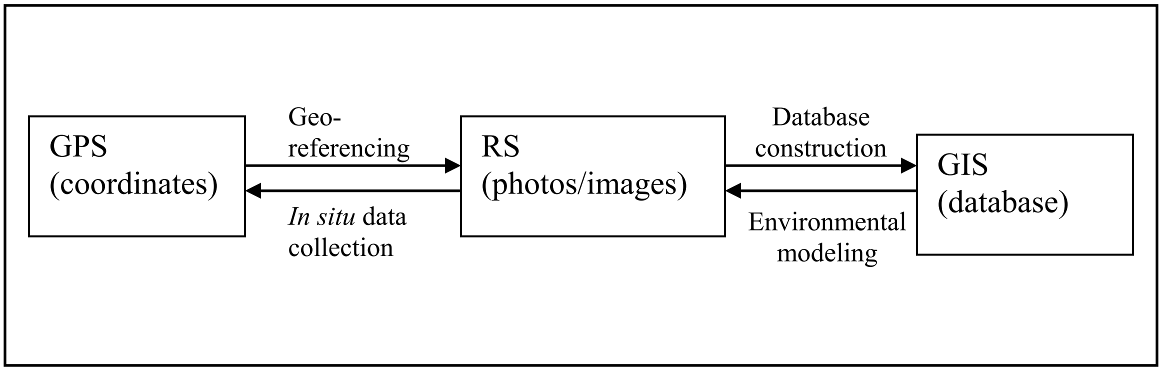


Figure 1-4. Interactive model of integration (from Gao, 2002).

Chen et al. (1997) showed how the integration of GIS, RS, and GPS in combination with ground monitoring systems is an efficient method of managing, analyzing, and outputting spatial data for regional water resources management. Change detection analyses reported by Welch et al. (1992), Haack et al. (1998), and Pereira et al. (2002) made use of integrated spatial analysis by overlaying historic and current land cover maps within a GIS. Other examples typifying spatial data integration include

Breiman et al. (1984) and Varlyguin et al. (2001), who used information stored in a GIS to facilitate RS image classification, and Monday et al. (1994), who derived percent impervious and pervious surfaces through integrated overlay analysis. Runyon (1994) integrated GIS, GPS, and aerial photography for environmental management during agricultural field inspections.

Gao (2002) notes that hydrology, especially watershed and stormwater management, is an area that can benefit considerably from a fully integrated spatial analysis approach, but has received insufficient attention. As more closely matched landscape and stream monitoring information becomes available, more detailed integration of spatial data across time is possible. Dymond et al. (2003, 2004) provide two good examples of the growing trend in watershed analysis to spatially integrate hydrologic, environmental, and economic models into a web-based problem solving environment. These powerful management tools are designed to serve as a spatial decision support system to assess water quality and social impacts of urbanization.

Geographical Analysis of Population

The impact of human development on natural landscapes generally increases with population, making it convenient to display and analyze population data. The U.S. Bureau of Census, the main governmental body charged with counting the population, developed a digital base map called Topologically Integrated Geographic Encoding and Referencing (TIGER). According to Tomasi (1990), TIGER provides the coordinate framework and topology (mapping network) for intersections, streets, and important feature names without which population data is of little value. A variety of proprietary spatial data products derived from U.S. Census data are available from sources such as Environmental Systems Research Institute, Inc. (ESRI®) and GeoLytics, Inc. (GeoLytics®). Plane and Rogerson (1994) list surrogate variables that are used in the absence of census data, including new residential building permits, active residential utility connections, auto license registrations, tax returns filed, children enrolled in schools, and elderly persons enrolled in government health-care programs.

Robinson (1982) states that the majority of techniques currently used to represent population data came into existence in the early to mid-19th century. Although current advances in GPS permit precise location of individual housing units, map scale limitations provide the same challenges for presentation of the data as existed 150 years ago. Standard cartography texts such as Robinson et al. (1984) and Dent (1990) discuss selection and placement of appropriate size symbols to represent varying numbers of persons. Often, maps of population density are useful. Two important characteristics of density as a measure are that density tends to smooth out the distribution of data, and the metric is areal-specific (Plane and Rogerson, 1994). In 1972, Stankowski made use of population density mapping to derive impervious surface regression relationships for various urban land uses in New Jersey. In 1992, Novotny reported that, based on analysis of many U.S. cities, regression formulas had been developed between population density and length of urban curb.

Clark (1951) showed the utility of a negative exponential model for mapping population distribution in a metropolitan area as a function of the distance from a densely populated hypothetical "center." In 1969, Newling pointed out that the negative exponent in Clark's model more closely represents daytime rather than nighttime urban population distribution. Based on his observation that residential densities are highest along a rim some distance away from the central business district (CBD), Newling modified Clark's model to include the entire CBD as a central position having a lower residential density.

The importance of scale was noted as early as 1934 by Gehlke and Biehl in their work with historic census tract data. Yule and Kendall (1950) confirmed Gehlke and Biehl's findings that comparative values for the same units over time is specific to the zoning area used. Openshaw (1984) reported that drastically different conclusions can be reached when data are aggregated to different scales, a phenomenon that is termed the modifiable areal unit problem (MAUP). A problem closely related to MAUP noted by Openshaw (1984) is the ecological fallacy problem, which occurs when a result is applied to individuals who form the zones or groups being studied. As most zoning systems studied by geographers are internally heterogeneous, the severity of the ecological fallacy problem is dependent upon the nature of the aggregation being applied (Openshaw, 1984).

Fotheringham and Wong (1991) examined the MAUP extended into multivariate statistical analysis and warned of the unpredictability of such analyses. Fotheringham and Wong mention that although many spatial analysts are aware of the MAUP, it is often conveniently ignored. The most likely solution offered by Fotheringham and Wong (1991) is to utilize GIS technology to rezone and re-aggregate data in a specified number of ways, reporting a summary of calibration results for each of the different zoning systems. The focus of the zoning scheme would then shift from a single scale for a particular zoning scheme towards an analysis of how the results change with scale and zoning. Literature cited above reveals the inconsistencies inherent in the use of population data as a variable in regression modeling.

Classifying Land Use Change

In 1975, Ragan and Jackson reported that automated spectral analysis of satellite-borne multi-spectral sensor (MSS) and Thematic Mapper (TM) data reduced the amount of labor necessary for manual IS delineation. Almost thirty years later, the Mid-Atlantic Regional Earth Science Applications Center (RESAC) (2002) reported that many of the methods using spectral information from satellite sensors are based on automated supervised and unsupervised classification techniques and other forms of spectral clustering, thresholding, and modeling. New techniques in digital image processing techniques such as neural network based classification (Civco and Hurd, 1997) and spectral mixture modeling (Ji and Jenson, 1999; Ward et al.; 2000 and Phinn et al., 2000) were developed to permit the derivation of information at higher resolution, sub-pixel levels.

In 1976, Anderson et al. published a paper titled, “A land use and land cover classification system for use with remote sensor data,” which became a catalyst for rapid advancements in land use classification and land use change detection. Federal efforts by Loelkes (1977), FGDC (1994, 1995), Vogelmann et al. (1998a, 1998b), Vogelmann and Wickman (2000), Ritters et al. (2000), Zhu et al. (2000), Yang et al. (2001), and others have since led to the creation of several national LULC data sets (USGS, 1990, 1992; Lunetta et al., 1998; Vogelmann et al., 2001), all of which have been developed using modifications to the Anderson et al. (1976) classification scheme. Vogelmann et al. (2001) describes the National Land Cover Data, the 23-class system that is based on the satellite-born Landsat thematic mapper (TM) sensor that began to revolutionize land use mapping in the mid 1980s.

According to Geoghegan et al. (1998) and Civco et al. (2000), remote sensing technologies are increasingly impacting urban land use change research. Since the late 1980s, there have been many improvements in automated mapping of heterogeneous landscapes. Moller-Jensen (1990), Civco (1993), Ji and Jensen (1996), Zhou and Civco (1996) and others developed enhanced classification approaches using knowledge-based expert systems, artificial neural networks, and genetic algorithms. Green et al. (1994), using remote sensing to detect and monitor LULC change, predicted the intensification of automated mapping that has since reinforced the relationship between RS data and GIS technology. In 2000, Steele reported new methods for combining multiple classifiers for increased accuracy in land cover mapping. DeFries and Chan (2000) provided multiple criteria for evaluating learning algorithms for automated land cover classifications.

The Mid-Atlantic RESAC (2002) extracted subpixel estimates of IS cover across the entire Baltimore-Washington Metropolitan area using Landsat TM imagery and a decision tree classifier, but was unable to identify small impervious features at scales below the sensor resolution such as single-lane rural roads. Hansen et al. (1996) previously described classification trees as a robust statistical method useful for mapping land cover types at regional to global scales. According to Quinlan (1993), decision tree classifiers are capable of "teasing out" hierarchical data structures and non-linear interactions between predictor variables by repetitive binary partitioning of predictor variables into smaller more homogeneous groups.

Pereira et al. (2002), in their spatial and temporal analysis of a tidal floodplain landscape in Brazil, used rasterized land-cover maps generated from photo-interpretation registered to a land-cover map generated from digital image classification. Land-cover mapping derived from 1970s aerial photography was overlaid with a land-cover map generated from 1995 Landsat TM imagery to compare 1995 satellite classification with 1976 photo-interpreted classification and perform temporal change detection. Similarly, Brondizio et al. (1994) used Landsat TM scenes from 1985 and 1991 to produce georeferenced mapping for their land use change study in the Amazon Estuary.

Characterizing Urbanizing Watersheds

Urban LULC, with its heterogeneous surface and large pixel variability, creates special challenges for the use of RS and other spatial technologies (Michalak, 1993;

Kam, 1995). For example, Ridd and Liu (1998) reported that the type of urban LULC change (for example, farmland to construction sites) impacts the method of change detection used. Yeh and Li (1996) and Campbell (1996) advised that procedures used for land use classification must be appropriately matched with specific project goals.

According to ASCE (1998), direct spatial effects of urbanization include loss of lands and direct alteration of stream channels, as well as the loss of natural features, groundwater recharge/discharge areas, and wildlife habitat. Schueler (1994a) reported that impervious surface (IS) delineation is useful as a measure of urbanization because of the widespread imperviousness associated with urbanized areas, but also because of its intuitive use as a physically defined unit. In 1995, Sutherland introduced a series of empirical equations that described the effective impervious area (EIA) of a basin as that portion of the mapped impervious area (MIA) that is directly connected to the urban drainage collection system. Sutherland's equations extended the single USGS equation developed by Laenen (1983), which was limited to catchments between ten and fifty percent MIA. As early as 1971, Rantz had noted that the entire impervious area in a watershed rarely has a direct connection with a principal watercourse. Horner et al. (1996) noted that the use of IS cover to express watershed conditions must be supplemented by other landscape measures, including riparian zone and drainage system characteristics. Arnold and Gibbons (1996) stated that althought impervious cover is rarely specifically identified or addressed in community goals, policies, or regulations, it should be.

Accurate estimation of IS provides an important indicator of downstream water quality and a critical input variable for many water quality and quantity models such as TR-20, TR-55 (USDA, 1982, 1986), Storm Water Management Model - SWMM (Huber et al., 1988), Source Loading and Management Model - SLAMM (Pitt and Vorhees, 1989), and Hydrologic Simulation Program Fortran - HSPF (Bicknell et al., 1997). The use of IS percent as a measure of urbanization and as an effective means for managing land and aquatic resources has been reviewed by a number of authors, including Deguchi and Sugio (1994), Schueler and Claytor (1996), CWP (1998), Prisloe et al. (2000), Cappiella and Brown (2001), and Civco et al. (2002). Before the availability of satellite-based imagery, determination of IS was a laborious and expensive process (Stankowski, 1972). Analysts counted individual structures from aerial photographs (Harris and Rantz, 1964) or superimposed transparent grids over detailed topographic maps of the study area (Martens, 1968).

Impervious cover can be estimated using lookup tables derived from property parcel size (Monday et al., 1994; Sleavin et al., 2000) or LULC information (Fauss, 1992; Deguchi and Sugio, 1994; Williams and Norton, 2000; Ward et al., 2000). While lookup tables can quantify relative IS cover across an entire watershed, they lack IS information at the subpixel level for specific locations. Dougherty et al. (in press) compare IS estimates from a satellite imagery/land cover approach with the more traditional aerial-photography/land use approach and report higher accuracies using the newer, synoptic approach, especially in suburban developments of heterogeneous land cover. Dougherty et al. (in press) evaluate IS estimates based on manually delineated residential land use categories ranging from low density residential land use (0-5 dwelling units per hectare) to high density, townhouse-garden apartment land use (>20 dwelling units per hectare). Crawford-Tilley et al. (1996) used a residential density of three houses per hectare as a threshold for urbanized land use in their development of a spatial database for the Baltimore-Washington, DC metropolitan region.

Sadler et al. (1991) extracted information from RS images for analysis of urban areas in the Netherlands. Masek et al. (2000) presented urban change detection methods in the Baltimore-Washington, DC region using modifications of the Normalized Difference Vegetated Index - NDVI ratio to minimize confusion between urban green space and rural agriculture. Earlier, Griffiths (1988) reported that image differencing of satellite imagery was the most successful technique for monitoring urban change. Studies by Jensen (1981), Jensen and Toll (1982), Howarth and Boasson (1983), and Quarmby (1987) had previously reached similar conclusions regarding the use of image differencing to detect urban change and encroachment. Yang (2002) established a six-part classification scheme using a modified version of Anderson et al. (1976) for his study of urban spatial growth in the Atlanta metropolitan area. The classification scheme was comprised of the following six classes; high-density urban use, low-density urban use, cultivated/exposed land, cropland/grassland, forest land, and water. High-density urban use consisted of approximately 80 to100 percent construction materials with a low percentage of residential development. Low-density urban use consisted of approximately 50 to 80 percent construction materials with local roads, small open space, and up to 20 percent vegetative cover. Cultivated/exposed land contained areas with less than 20 percent vegetative cover that are likely to be converted to other uses in the near future.

Yang (2002) monitored change along the widely dispersed Atlanta metropolitan urban fringe using a time series of satellite images from 1973 to 1999 (Landsat 1 to Landsat 7). Yang developed procedures to detect changes in the urban spatial pattern using two LULC conversion maps for the periods 1973-1987 and 1987-1999 to make map-to-map comparisons and note spatial patterns of urban growth. Yang's study focused on the conversion of forest, cropland/grassland, and cultivated/exposed land into urban uses using a two-way cross-tabulation matrix analysis to quantify and document LULC conversion. Yang (2002) carried out accuracy assessment using standard test methods of Congalton (1991) and was able to show that his image processing approaches can be effective in producing compatible, historic LULC data. Congalton's 1991 paper, cited by Yang (2002) describes the single-value KAPPA statistic and other methods for accuracy assessment now widely used in the field of RS data.

Modeling Hydrologic and NPS Pollutant Response

Sherwani and Moreau (1975) state that a stream is a dynamic, adaptive system, with a non-linear response to changes in input. They report that meteorological and hydrologic factors, physical, chemical, and biological processes, and land use changes and residential and economic activities, give rise to three types of movements in a quality constituent over time at a sampling location; 1) a general trend extending over many years, 2) cyclic variations showing a regular or variable pattern, and 3) a random variation with more or less stable characteristics. Sherwani and Moreau note that if all changes in water quality of a stream segment were the result of random variation, then the time of sampling would not be critical, and frequency of sampling could be arrived at from purely statistical considerations. However, recognizing that most water quality parameters exhibit a periodic structure (temporal variance), there is no single test that has a reasonably high power against all types of non-randomness that can arise in water quality data (Sherwani and Moreau, 1975).

Box and Jenkins (1976) presented a method of time series analysis that treats the serial correlation often present in water quality data. Helsel and Hirsch (1992), in their text on statistical methods in water resources, address most of the analytical challenges identified by Sherwani and Moreau (1975), including methods for parametric and nonparametric statistical comparison, tests for trend and serial correlation, treatment of missing or non-detectable data, and other topics. Numerous authors, including Montgomery and Peck (1992), Bowerman and O'Connell (1993), Huber (1993), Barnett and Turkman (1993, 1995), Ott (1995), Bierkens et al. (2000), and Zipper et al. (2000) have continued to contribute to the literature regarding statistical analysis of water quality and other environmental data.

The correlation of water monitoring results with watershed properties such as LULC requires simplification at some level because of the complex nature of the landscape. In the simplification process, properties of land segments and stream channels are spatially averaged or lumped so that each spatial object in the model is represented by a single set of descriptive properties. An example of spatial lumping is an attribute table in a GIS shapefile where a heterogeneous suburban development is classified as low-density as opposed to medium- or high-density residential. According to Maidment (1996), the level of spatial lumping is determined by the analyst, based on the resolution of the landscape data or the degree of precision desired. Regarding the interface of GIS with continuous simulation models, Maidment (1996) suggests that GIS be used solely as a spatial data source and that continuous simulation models, if used, remain separate from the GIS. Generally, since the state of continuous simulation flow modeling is more advanced than that of transport modeling, flows are computed first, then transport is modeled using precomputed flows. In the case of pollutant loadings (or fluxes) derived from regression equations, independent variables are mapped in GIS and then the loading (or flux) responses are determined based on a mathematical combination of GIS data (Maidment, 1993).

Numerous field studies, including Lowrance et al. (1984a, 1984b), Peterjohn and Correll (1984), Phillips (1989a, 1989b), and Correll et al. (1992), have focused on the movement of nutrients from the landscape into streams. Water quality parameters have been predicted using basin characteristics including geology, soils, climate, land use, and hydrology. Lystrom et al. (1978), Fannin et al. (1985), Osborne and Wiley (1988), and Tufford et al. (1998) all used multiple regression modeling to evaluate relationships between stream water quality and NPS pollutant contributions. According to ASCE (1998), long-term watershed monitoring programs provide insight for targeting diffuse pollutant sources and are typically preferable to the use of simulated data, especially for characterizing concentration/load ranges and to provide input to a receiving quality model. Poiani and Bedford (1995) noted that validation of NPS loading estimates from simulation models, although labor intensive and costly, is dependent upon the availability of long-term data.

Characterizing Hydrologic Processes in a Watershed

According to water balance theory (Bedient and Huber, 1992), the difference between precipitation input and outputs from deep percolation, evapotranspiration, and runoff from year to year represents the change in total watershed storage (Figure 1-5). To this simplified water balance approach can be added water supply contributions, withdrawals, and internal hydrologic cycling such as wastewater reclamation. Woodruff and Hewlett (1971), in their study of 90 test basins in the eastern United States ranging from five to 260 km^2 (2 to 100 mi^2), concluded that the response of a basin to actual rainfall may be the only accurate indicator of basin storage capacity. Likens and Bormann (1995) noted that considerable knowledge of a watershed ecosystem can be obtained from continuously monitored streamflows.

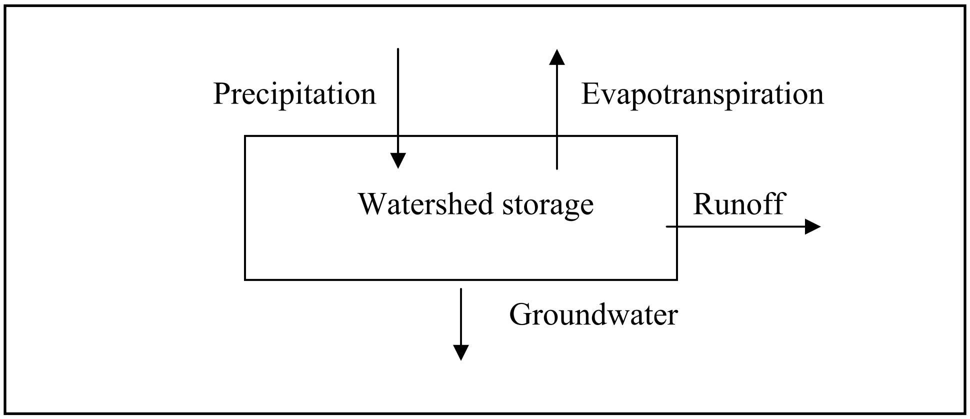


Figure 1-5. Water balance in a watershed (adapted from Bedient and Huber, 1992).

ASCE (1998) states that stormwater runoff is one means to analyze the impacts of urbanization, but that other impacts should also be considered, including reduction in infiltration to groundwater, increases in surface water flow, increased flooding and erosion potential, and greater risk of water quality and habitat degradation. As early as 1968, Brater and Sangal reported the effects of urbanization on peak flows. Rantz (1971), in his comparison of peak discharge estimation methods in the San Francisco Bay area, suggested that the location and characteristics of impervious areas be considered as important design criteria in reducing peak discharge in urban areas. In 1974, Stankowski developed flood frequency relationships in New Jersey using topographic characteristics and indexes of manmade impervious cover. Numerous authors, including Wheater et al.(1982), Laenen (1983), Booth and Reinelt (1993), Schueler (1994a), and Arnold and Gibbon (1996) have quantified shorter times of concentration, higher peak flows, larger storm volumes, and potentially lower baseflow volumes associated with urbanization.

Increased runoff volumes and reduced infiltration would be expected to result in lower groundwater recharge, with accompanying dry weather streams flows (ASCE, 1998); however, according to Schueler (1994a, 1994b) actual data that demonstrate this effect is rare. Although Simmons and Reynolds (1982) noted a reduction of dry weather flows after development in several urban watersheds in Long Island, New York, Evett et al. (1994) did not find any statistical difference in low stream flows between urban and rural basins in their study of 16 North Carolina watersheds. Belore (1991), in their 30-year comparison of low-flow rates in urbanizing watersheds in Toronto, Ontario, actually reported increased low-flow rates, but explained that results may have been impacted by water losses from lawn irrigation and sanitary sewer exfiltration. ASCE (1998) concluded that the impact of IS on baseflow is site-specific and that estimates of infiltration should be made independently from base flow.

Correll et al. (1999c), in their 25-year watershed study of a mid-Atlantic Coastal Plain agroecosystem, stated that a number of issues relating hydrology of small, headwater catchments can be adequately addressed only through long-term data. They quantified the relationship between annual and seasonal precipitation on water discharge per surface area for seven contiguous first-and second-order tributaries of the Rhode River in the Maryland Coastal Plain and found that, except in winter, the proportion of precipitation discharged into streams increased rapidly with increasing precipitation. Stream order in their study watershed showed a higher correlation with volume of discharge than vegetative cover.

Swift et al. (1988) described the results of fifty years of hydrologic study from thirty climatic stations at the 2185-hectare (8.4 mi^2) Coweeta Experimental Forest in the southern Appalachian Mountains Blue Ridge Physiographic Province. The six control sub-basins used for hydrologic study ranged in size from 12.3 to 48.6 ha (.05 to .19 mi^2). Precipitation, as modified by topography, is the dominant factor of the Coweeta climate, with precipitation generally increasing about five percent per 100m elevation. According to Swift et al. (1988), elevation can be used in Coweeta to represent the integrated effects of physiography and hydrology to determine rates and volumes of discharge. The original questions that initiated study at Coweeta included: 1) how is streamflow regulated by vegetative cover, and 2) how can erosion be controlled by vegetative cover?

Hewlett et al. (1984) strongly questioned the value of rainfall intensity as a predictor of stormflow at the Coweeta Experimental Forest. Swift et al. (1988) supported the conclusions of Hewlett et al. (1984), but acknowledged the use of both intensity and raindrop size for estimating erosion rates, noting that the erosivity index for the Universal Soil Loss Equation (USLE) is based on both the intensity and amount of rain. Swift et al. (1988) defined a storm as a period of precipitation separated by a rainless period of at least four hours; and reported that interception losses in Coweeta accounted for over 20 percent of rainfall input in half the storms each year.

In 1942, Hursh concluded that Horton's (1940) concept of rainfall excess and overland flow was not applicable to most forest land because of high infiltration, suggesting instead that runoff coefficients could be used to characterize watershed hydrology. Hewlett and Hibbert (1962) reported that many traditional runoff coefficients gave highly variable results between watersheds. Hewlett (1967) ultimately selected the ratio of annual mean storm runoff to mean precipitation as the most useful response characteristic; and Woodruff and Hewlett (1971) used this metric to develop a response map for the entire eastern United States. Owens et al. (1983) reported that large runoff events from five small pastured catchments in Ohio produced most of the total annual runoff volume.

Swift et al. (1988) referenced a number of studies in the 1960s and 1970s at Coweeta Experimental Forest that verified the importance of unsaturated flow through soils on steep slopes as a source of baseflow, based on the smaller cross-sectional area through which subsurface water flows. In 1966, Hewlett and Hibbert first presented the concept of a dynamic, contributory area adjacent to stream channels as the source of stormflow during rainfall events. Reckhow et al. (1985) expanded the theory of a partial contributory area to integrated watershed analysis in their review of pollutant runoff models.

Likens and Bormann (1995) reviewed the results of long-term hydrologic and biogeochemical monitoring in the small 0.12 km^2 (.05 mi^2) Hubbert Brooks Experimental Forest (HBEF) in New England. They defined a water-year as the successive 12-month period that most consistently gives the highest correlation between precipitation and streamflow; stating that wide rainfall extremes emphasize the need for a long-term record to more completely understand system hydrologic flux. At HBEF it was noted that monthly precipitation amounts exhibited extreme variation, however for the longer term monthly precipitation patterns became quite regular.

Likens and Bormann (1995) noted that seasonal streamflows in HBEF varied by orders of magnitude, whereas annual streamflows varied by no more than twofold. Sopper and Lull (1965, 1970) found that smaller, undisturbed, forested watersheds in the northeastern United States tended to have sharper streamflow peaks and shorter periods of sustained flow than larger watersheds, characteristics which can be exaggerated in steep, mountainous terrain with shallow bedrock (Likens and Bormann, 1995). Likens and Bormann (1995) noted the close correspondence between streamflow characteristics from HBEF and similar watersheds more than three orders of magnitude greater in size, which they used to validate the transfer of results from the HBEF to other areas.

According to Maidment (1993), all hydrologic models can be classified according to the assumptions made about three sources of variation: time, space (three dimensions), and randomness. Models that allow any one of the factors (time, one space dimension, or randomness) to be accounted for explicitly, such as regression modeling have existed since the 1970s. GIS can improve the accuracy of hydrologic modeling by increasing the number and description of spatial subunits, thereby solidifying the treatment of spatial variation. Frankenberger et al. (1999) developed a variable source area hydrologic model using GIS; and Rosenthal and Hoffman (1999) used GIS-based hydrologic modeling to locate future monitoring sites.

Two recent studies demonstrate the use of GIS as a spatial data source for hydrologic analysis and modeling. Brun and Band (2000) simulated runoff behavior using HSPF (Bicknell et al., 1997) after assessing twenty years of changing land use in Baltimore, Maryland with the GIS interface in Better Assessment Science Integrating point and Non-point Sources - BASINS (Lahlou et al., 1998). Resulting hydrologic simulations indicated that runoff ratio changed rapidly above 20% impervious surface, and that baseflow was reduced by as much as 20% from 1973 to 1990. Whittemore and Beebe (1998) cautioned against relying on a too simplistic approach to simulation models such as BASINS, but judged BASINS to be an excellent beginning tool to meet complex environmental modeling needs. In another study, Melesse and Shih (2002) used GIS and remote sensing to estimate 20-year spatial and LULC variations for estimation of storm runoff depth as a function of wetland and water-covered areas in south Florida. Spatial parameters used by Melesse and Shih such as hydrologic soil group, land use, land treatment, and hydrologic conditions were derived within the GIS for use in the Natural Resources Conservation Service Curve Number - CN method (U.S. Department of Agriculture, 1972). According to Melesse and Shih (2002), results of the study showed that land use changes determined from Landsat imagery were useful in studying the runoff response of the basin.

Hydrologic summaries from from OWML data are compared with four other long-term studies in small watersheds in the eastern United States (Table 1-2). Coweeta and Fernow watersheds are relatively high-rainfall experimental forests in North Carolina and West Virginia, respectively. Rhode River values represent the area-weighted mean of seven small agricultural sites in the Maryland Coastal Plain, and Little River values represent the sum of four agricultural sites in the Georgia Coastal Plain. Cub Run is the only urbanizing basin among the group, suggesting that consistent, long-term datasets from rural catchments are more widely available than those from urban catchments.

Table 1-2. Annual hydrologic balance for selected watersheds, mm/yr.

	Cedar Run, VA[1]	Cub Run, VA[1]	Upper Bull Run, VA[1]	Upper Broad Run, VA[1]	Rhode River, MD[2]	Fernow, WV (WS4)[3]	Little River, GA[4]	Coweeta, NC (WS2)[5]
Data period, years	24	24	24	24	25	40	11	37
Precipitation	1062	1021	1056	1054	1139	1458	1258	1772
Total runoff	341	382	344	344	332	640	379	854
Total runoff ratio	0.32	0.37	0.33	0.33	0.29	0.44	0.30	0.48
P-RO[6]	721	639	712	710	807	818	879	918

Table adapted from Correll et al. (1999c).

Discharge and precipitation means for Occoquan stations calculated using 24 years of data (water years 1979-2002).

[1] Data provided by the Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.

[2] Correll et al., 1999c (area-weighted mean of 7 watersheds).

[3] Adams et al., 1994 (watershed #4).

[4] Lowrance et al., 1985 (sum of watersheds N,O,J,K).

[5] Swift et al., 1988 (watershed #2).

[6] P-RO, precipitation minus total discharge (runoff), is equal to total non-discharge losses (evapotranspiration plus deep percolation).

Characterizing NPS Pollutant Delivery in a Watershed

A number of studies, including Omernik (1976), Jordan et al. (1986), Haith and Shoemaker (1987), Osborne and Wiley (1988), Kronvang (1992), and Correll et al. (1999b) have measured pollutant fluxes from mixed land use watersheds, demonstrating the impact of large storm events and land use practices on the magnitude of total suspended solids (TSS) and related nutrient fluxes. Numerous authors, including Richards and Holloway (1987), U.S.EPA (1990), Loftis et al. (1991), Dixon and Chiswell (1996), Longabucco and Rafferty (1998), and Correll et al. (1999a, 1999d) have cited the benefits of long-term, continuous watershed data for identifying pollutant sources. According to Novotny (1999), research in diffuse (NPS) pollution that includes both urban and rural sources is needed to develop models linking pollution loads to the probability of the exceedence of water quality standards. To complete the type of research recommended by Novotny (1999), long-term precipitation, integrated pollutant discharge, and mixed-land use LULC data is required.

Table 1-3 compares long-term summaries of OWML data with 11 other studies that determined TSS flux, in kg $ha^{-1}yr^{-1}$, from selected watersheds. The longest study lasted 18 years. This dissertation uses up to 24 years of continuous OWML data for a variety of constituent fractions, while quantifying both storm and nonstorm conditions. According to Correll et al. (1999a), broad variation in the range of reported values for

TSS flux is due to differences in the proportion of overland storm flow, erosion rates, and sampling methods used. Information related to the composition of TSS and particulate to soluble nutrients as a function of discharge and LULC makes a contribution to the literature regarding NPS sediment and nutrient delivery from mixed-land use catchments.

Table 1-3. Comparisons of selected annual TSS flux studies.

Location	Years of study	Number of watersheds	Mean flux (kg $ha^{-1}yr^{-1}$)	Range (kg $ha^{-1}yr^{-1}$)
Row cropped watersheds				
Iowa (corn)[1]	7	2	12,000	1,020-44,800
Iowa (terraced corn)[1]	7	1	3,050	110-14,700
Oklahoma (cotton)[2]	11	2	3,900	2,000-8,900
Oklahoma (wheat)[2]	11	2	1,200	100-3,900
Maryland (corn)[3]	17	1	546	18-3,880
Grazed watersheds				
Oklahoma (rotational)[2]	11	1	300	100-400
Oklahoma (continuous)[2]	11	1	8,100	1,500-23,000
Maryland (rotational)[3]	14	1	92	10-315
Forested watersheds				
North Carolina (hardwood)[4]	10	1	258	-
Maryland (hardwood)[3]	15	1	134	2-430
Mixed land use watersheds				
Rhode River, Maryland[3]	18	1	263	22-918
Cedar Run, Virginia[5]	21	1	230	22-754
Cub Run, Virginia[5]	21	1	503	26-1,794
Upper Bull Run, Virginia[5]	21	1	411	67-1,813
Upper Broad Run, Virginia[5]	21	1	235	60-870

Table adapted from Correll et al. (1999b).

[1] Alberts et al., 1978

[2] Menzel et al., 1978

[3] Correll et al., 1999b

[4] Swank and Walde, 1988

[5] Data provided by the Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.

Several national studies have quantified NPS pollution from urban and rural areas. Urban runoff was first mentioned in peer-reviewed literature in the late 1960s (Brater, 1968; FWPCA, 1969). In 1972, Sartor and Boyd reported the exponential washoff relationship of particles from urban streets. Omernik (1976) used National Eutrophication Survey (NES) data from 473 nonpoint source-type basins in the eastern United States to quantify the relationship between drainage area characteristics (particularly land use) and nutrient levels in streams. The Nationwide Urban Runoff Program (NURP) (U.S.EPA, 1983a, 1983b) utilized urban runoff contaminant data from 28 sites to provide a national perspective on the magnitude of urban NPS pollution, noting that land use category effects, if present, are eclipsed by storm-to-storm variability. Heaney and Huber (1984) summarized data from 248 urbanized areas of the United States to assess impacts of urban runoff on receiving waters. In 1989, Driscoll et al. developed a Federal Highway Administration (FHWA) procedure for estimating impacts on water bodies from direct highway stormwater runoff. According to ASCE (1998), the NURP and FHWA studies are considered the definitive studies characterizing urban runoff concentrations. In 1988, Driver and Tasker published national regression equations for estimating urban storm-runoff loads, volumes, and constituent concentrations as a function of several drainage area characteristics, including land use and impervious area.

Several subsequent studies have made use of long-term water quality data from the USGS National Water-Quality Assessment (NAWQA) Program and EPA's STORET database to summarize national stream characteristics. Lentenmeier et al. (1991) and Smith et al. (1994) reported on the status and trends of selected water quality indicators during the 1980s. Smith et al. (1997) designed a method of spatially referenced regressions of watershed attributes (SPARROW) to estimate the proportion of watersheds in the conterminous United States below a certain nutrient outflow criteria. In 2000, Clark et al. characterized NPS nutrient concentrations and yields in undeveloped stream basins of the United States.

ASCE (1998) noted five generally available methods for simulating water quality in urban watersheds; 1) constant concentration or unit loads, 2) spreadsheet, 3) statistical, 4) rating curve or regression, and 5) buildup/washoff. The simplest is the constant concentration or constant unit load method, which assumes that runoff volumes can be multiplied by a constant concentration, either from limited sampling or from existing databases such as the NURP study. Dolan et al. (1981) evaluated several methods of unit load estimation using 12 months of daily concentration and flow data from the Grand River into Lake Michigan. Rast and Lee (1983) are often cited as a source for average watershed nutrient export coefficients based on land usage. Marsalek (1991) reviewed methods for estimating pollutant loads from urban sources, noting that runoff monitoring methods provide the best estimate of existing loads, but unlike calibrated simulation models runoff monitoring alone cannot be used to predict load changes resulting from management or other changes to the urban system. Spreadsheet approaches to water quality simulation similar to Walker et al. (1989) are used to automate and extend constant concentration or unit load determinations based on changing land use.

Statistical methods for urban water quality simulation described by ASCE (1998) include the U.S.EPA Statistical Method (U.S.EPA, 1983b), which makes use of a derived frequency distribution to estimate the event mean concentration (EMC) of a storm. According to ASCE (1998), frequency distributions have been used extensively for urban runoff quantity, but not as often for quality predictions. The U.S. EPA method uses a log-normal frequency distribution with associated median and coefficient of variation to characterize non-constant EMCs. ASCE (1998) notes that although the log-normal assumption is good, the method is typically coupled with weak hydrologic assumptions such as estimating runoff from runoff coefficients, the accuracy of which is known to increase with increasing urbanization and imperviousness. The U.S. EPA Statistical Method was used as a primary screening tool in the NURP and FHWA studies.

Regression or rating curve approaches categorize a special form of regression analysis in which concentration or loads are related to flow rates or volumes (ASCE, 1998). Typically, storm mean concentration (EMC) is not well correlated with runoff flow or volume (Driscoll et al., 1989; U.S.EPA, 1983a), but load is typically well correlated with flow because load is the product of concentration times flow. This condition, referred to as spurious correlation (Bensen, 1962), is often ignored in urban runoff studies. ASCE (1998) notes that a linear relationship between load and flow indicates a constant concentration, otherwise some relationship between concentration and flow is implied. Cohn et al. (1989) and Crawford (1991) evaluated suspended-sediment rating curve methods and mean suspended-sediment loads using USGS stream monitoring data. Cohn et al. (1992) evaluated a log linear rating curve model to estimate fluvial transport of nutrients. According to ASCE (1998), rating curve results can be used for load and EMC estimates and are incorporated into some models.

Tasker and Driver (1988) developed a number of mostly log-linear multi-regression models of storm runoff constituent loads and runoff volumes that represent some of the best generalized regression equations available for urban runoff quality prediction (ACSE, 1998). These USGS equations for estimating loads are more accurate for the arid western U.S. for nitrogen and least accurate for suspended solids in areas of large mean annual rainfall (Tasker and Driver, 1988). A disadvantage of the USGS regression models compared to the EPA statistical approach is that the regression equations predict only the mean, while not providing the frequency distribution of the predicted variables, although error bounds can be calculated. Another limitation of the regression approach is that caution must be used when applying equations beyond the original data set from which they were derived (ASCE, 1998). Torno et al. (1986) noted that any given runoff pollution model established elsewhere but calibrated against local data, would not be expected to give better results than a statistically-based model developed from local data only. Thomas (1988) noted that the method of sampling has a large effect on rating curve parameters and resulting estimates of suspended sediment yield.

The fifth method described by ASCE (1998) for simulating water quality in urban watersheds is buildup/washoff. ASCE defines buildup as the inter-event processes that result in accumulation of materials subsequently washed off during rainfall events. Buildup of pollutants per curb kilometer of urban street surface was first shown by the American Public Works Association (1969) in a Chicago study. Sartor and Boyd's (1972) exponential pollutant washoff relationship was incorporated into several early models, including SWMM and other models (Huber, 1985). Manning et al. (1977) compiled a survey of generalized buildup data for many pollutants. According to ASCE (1998), field observations of concentrations and loads are often used as calibration parameters for subsequent buildup and washoff coefficients, since buildup-washoff models cannot be used to predict absolute values.

Butcher (1999) describes the assignment of average loads to a particular land area class as spatially and temporally lumped, with models at the other end of the complexity scale termed spatially and temporally distributed. A widely used example of lumped models is rainfall-runoff modeling, where the watershed or subwatershed is treated as a spatially-averaged entity (Maidment, 1996). Examples of distributed models are Soil and Water Assessment Tool - SWAT, Areal Non-point Source Watershed Environmental Response Simulation - ANSWERS, and Agricultural Non-Point Source - AGNPS. Endreny and Wood (1999) used distributed watershed modeling of design storms to identify nonpoint source loading areas. According to Butcher (1999), somewhere in between the two extremes are intermediate complexity models which are often more appropriate for watershed-water quality modeling because they combine spatial lumping of land uses at the sub-watershed scale with temporally distributed meteorology at the hourly or daily scale. Tomlin (1990) noted that it is also possible to create a discrete space representation in a continuous space model by assigning the same attribute value to a particular set of spatial elements, such as representing a stream and watershed, respectively, as lines and zones of cells in a grid-based watershed delineation.

The National Research Council (NRC, 1999) noted the spatial and temporal deficiencies of categorized annual export coefficients for effective NPS targeting; and Reckhow et al. (1985) pointed out similar weaknesses in hydrology-driven simulation models. Shoemaker et al. (1994) noted that the time step deficiency of categorized literature values is most pronounced during storm runoff events, which are known to result in variable watershed loadings from multiple sources. Maidment (1996) noted that the most complete representation of a continuous time model is to have a temporal data description using daily or hourly time steps over the whole time domain, such as a 10- to 20-year period. Maidment (1996) stated, however, that it does not seem productive to try to accomplish continuous simulations with GIS functions. Liao and Tim (1997) described a range of strategies, from loosely to tightly coupled, for integrating water quality models to a GIS. Loose coupling strategies are simplest to implement as they utilize the GIS only for generating, organizing, and displaying model input and output data. Tight coupling of water quality models to GIS removes the need for a GIS/model interface, but requires significant development and maintenance effort.

Liao and Tim (1997) successfully coupled the AGNPS water quality model with a GIS in an interactive modeling environment. Blaszynski (1993) integrated the Revised Universal Soil Loss Equation (RUSLE) with a GIS for a rangeland ecosystem. Engel et al. (1993) integrated GRASS GIS with the AGNPS and ANSWERS water quality models. In most of the above models, the GIS was used primarily to generate model input data and to display output data.

According to Klemes (1994), models are either analytical or synthetic. Klemes describes analytical models as investigative, making use of the scientific method, and asking questions. Synthetic models, on the other hand, are described as taking a descriptive approach that seeks to describe answers by predicting outcomes. Klemes states that the falsification of a truly analytical model is a good thing, as it can lead to further significant questioning. An example of analytical modeling is the regression work of Irish et al. (1998), who sought to identify the processes affecting NPS highway runoff loads, rather than a simple prediction of pollutant loads. The investigative regression models developed as part of this dissertation are examples of analytical modeling, while the predictive capabilities available from these models are applications of synthetic modeling.

An example of a synthetic model is the Simple Method procedure (Schueler, 1987) for estimating (predicting) urban NPS pollutant loads. The Simple Method procedure demonstrates that the degree of loading in recently stabilized urban development sites is a direct function of watershed imperviousness. ASCE (1998) has noted that with the development of data linking imperviousness thresholds to stream degradation in headwater areas, land-use planning has become a more commonly proposed tool for stormwater quality management.

Identifying Relationships Between Landscape and Pollutant Transport

A watershed can be viewed as an ecological system with a richly detailed, but imprecisely measured, budget of inputs and outputs. The lack of information about the relationships maintaining an *undeveloped* watershed ecosystem makes it difficult to assess the impact of human activities. As a result, land planners often cannot predict the full range of consequences resulting from cumulative land use changes over time. Likens and Bormann (1995), in their long-term studies at the Hubbard Brook Experimental Forest (HBEF) in the northern hardwood forests of New Hampshire, note that seasonal and year-to-year variations in water and nutrient flux rates require long-term analysis before reliable generalizations can be drawn. Therefore an ecosystem approach is used at the HBEF to study the linkage between chemical flux and the hydrologic cycle. Numerous others, including Novotny (1996), promote an integrated approach to water quality analysis and management. A common limitation noted by Likens and Bormann (1995) in many watershed studies is that subsurface flows are almost impossible to measure.

In spite of the challenges, numerous water-quality studies, including Osborne and Wiley (1986), Herlihy et al. (1988), Johnson et al. (1997), Parry (1998), Crosbie and Chow-Fraser (1999), and Zipper et al. (2002), have investigated relationships between land use and water quality. Others, including Smith et al. (1987a, 1987b, 1994) and Lentenmeir et al. (1991), have focused on changes in water-quality, due principally to the national scale of their studies. Fewer studies, such as Mattikali and Richards (1996) and Scott et al. (1998), have looked at water quality change in relation to documented land use change. Others, such as Tufford et al. (1998), have incorporated the effects of land-use proximity and seasonality in their predictions of NPS stream nutrients, documenting that land close to stream channels is a better predictor of nutrient concentration than land away from the channel, and that seasonal concentrations are dependent on the specific mix of land use.

Early literature reviews relating watershed characteristics to NPS nitrogen and phosphorus concentrations, including those by Uttormark et al. (1974), Loehr (1974), Dillon and Kirchner (1975), and Dornbush et al. (1974), describe data collected from a small number of watersheds within specific geographic regions. Omernik's (1976) macro-scale nationwide study relating land use (forest, agriculture, and urban) and other basin characteristics (geology, slope, and land resource region) to stream nutrient levels provided a uniform analysis procedure for establishing nutrient loading coefficients. Omernik (1976) reported that mean total and inorganic nutrient levels were considerably higher in streams draining agricultural watersheds than those draining forested watersheds; and mean nutrient levels were generally proportional to the percentages of land in agriculture, or the combined percentages of agriculture and urban land use. None of the 473 NES tributary sampling sites used in Omernik's study had identifiable point sources, similar to this disseration.

The NURP study was unable to identify a nationwide effect of any systematic factor except rainfall volume on EMC, however a relationship was found between runoff volume and degree of imperviousness. Novotny (1992) deduced that because unit load is determined as the product of runoff volume and EMC, there may be a relationship of unit loads to land use, even though the NURP relationship of EMCs to land use was not strong. Schueler (1992) associated changes in urban stream water quality with two phases of urbanization, an initial construction phase of high sediment loading, and a subsequent stabilized period of stream-bank erosion and accumulated washoff. ASCE (1998) reported that, in general, constituent concentrations in urban streams are one to two orders of magnitude greater than those reported in forested watersheds.

Correll et al. (1999a, 1999d) noted a large number of studies measuring nitrogen or phosphorus from various watersheds, focusing either on comparative effects of land use, differences in nutrient discharge between regions, or patterns of change in nutrient concentrations from a single storm event. Results of these studies have established that land use, particularly intensive agriculture, has a strong impact on nitrogen and phosphorus fluxes, with nitrogen fluxes in temperate regions generally peaking in winter and spring and phosphorus fluxes peaking in spring and summer. Correll et al. (1999a, 1999d) state that there is fairly good evidence of difference in nutrient discharge from a given land use between different regions. According to Correll et al. (1999a, 1999d), what is lacking are long-term studies that analyze the effects of interannual variations in precipitation and other variables on discharge of nutrient fractions. Lucey and Goolsby (1993) and Alexander et al. (1996) analyzed interannual variations in stream water discharge with nitrate fluxes, but these studies were on large rivers having complex land use, point sources, reservoirs, and water withdrawals.

Watershed studies conducted by Correll et al. (1999a, 1999d) sampled 25 years of nitrogen and phosphorus fluxes from seven small subwatersheds in Maryland having similar weather, soils, geology, and hydrology. Correlations of all nitrogen and phosphorus parameter discharges with precipitation were highly significant, with power function regressions explaining from 36 to 59 percent of the variation. Nitrogen and phosphorus fluxes from a cropland watershed were much higher and more variable with volume of precipitation, compared to those from a forested watershed, which were lower and primarily composed of organic species. Correll et al. (1999a) reported that correlations of nitrogen flux with precipitation were higher in winter and spring, while correlations of phosphorus fluxes were higher in the spring (Correll et al., 1999d). Annual and seasonal concentrations of nitrogen and phosphorus often increased significantly with precipitation (Correll et al., 1999a, 1999d).

Table 1-4 compares selected data from OWML with nine other studies that determined the proportion of total phosphorus discharged in the soluble phase. The comparison shows that the Occoquan headwater basins consist of several mixed-land use catchments that are not dominated by any single land use. Therefore, knowledge related to the ratio of particulate to soluble nutrients as a function of discharge and LULC makes a contribution to the literature regarding nutrient delivery from mixed-land use catchments, only one of which is urbanizing.

Table 1-4. Selected land use and phosphorus studies.

Location	Predominant land use	% soluble P[1]	Source
New Zealand	pasture	63	Cooke, 1988a,b
Mississippi	forest	29	Duffy et al., 1978
Denmark	row crops	66, 34	Kronvang, 1992
Oklahoma	cotton	16	Menzel et al., 1978
Oklahoma	wheat	14	Menzel et al., 1978
Oklahoma	grazing	3-7	Menzel et al., 1978
New Hampshire	forest	19	Meyer and Likens, 1979
Pennsylvania	row crops	28	Pionke and Kunishi, 1992
Nebraska	pasture	61	Scheppers and Francis, 1982
Cedar Run, Virginia	forest/mixed agric.	45	Tables M-1 and M-2 [2]
Cub Run, Virginia	forest/urban/mixed agric.	29	Tables M-1 and M-2 [2]
Upper Bull Run, Virginia	forest/mixed agric./resid.	23	Tables M-1 and M-2 [2]
Upper Broad Run, Virginia	forest/mixed agric.	23	Tables M-1 and M-2 [2]

Table adapted from Correll et al. (1999b).

[1] Values represent the proportion of mean annual total phosphorus flux discharged in the soluble phase from selected watersheds.

[2] Data provided by the Occoquan Watershed Monitoring Laboratory (OWML), Manassas, Virginia.

Schnabel et al. (1993) studied up to three years of nitrate, sulfate, and chlorine concentrations from a small, upland Pennsylvania watershed having shallow and deep groundwater flows. Their results suggest that temporal variations in stream flow composition are primarily hydrologically controlled, and that land use changes in parts of the watershed contributing to shallow groundwater had more impact on stream water quality. Owens et al. (1994), in their study of fertilized and grass-legume pastures having 1000 mm (39 in) annual precipitation, determined that subsurface flow was the main pathway for nitrogen loss, compared with surface runoff or sediment-attached nitrogen.

They also noted that relative contributions to total nitrogen transport, whether by surface runoff or deep percolation, were dominated by annual rainfall patterns.

Smith (1992) used 18 years of flow records in three headwater catchments in New Zealand to study the hydrologic and water quality effects of riparian forest. Study catchments were all less than seven hectares in size, located in an area with 1021 mm (40 in) of annual precipitation. Riparian forest was found to reduce peak flows in small events and increase peak flows during large events. Large reductions in water yield showed that the riparian zone had a greater than expected influence on catchment hydrology, due to high transpiration and interception losses in catchment pine plantings. Smith (1992) noted that the hydrologic consequences of riparian afforestation are likely to decrease as catchment area increases, and that water quality improvement planning requires a clear understanding of how catchment characteristics interact to regulate runoff quality.

Scott et al. (1998) quantified the impacts of historical change in agricultural land use on water quality in the Catskills Mountains of New York. Basnyat et al. (1999) incorporated remote sensing and GIS in their analyses of the joint contributions of multiple landscapes to NPS pollution problems. Clark et al. (2000) related nutrient loads to land use in undeveloped stream basins of the United States. Correll et al. (1999b, 1999c), reported hydrologic, sediment, and nutrient discharges from Rhode River watersheds in the Maryland Coastal Plain and reviewed a number of studies analyzing stream constituent response to land use. Jordan et al. (1993, 1997a, 1997b) reported on the impacts of riparian forest, land use, and agriculture on nutrient discharges in Piedmont and Coastal Plain watersheds of the Chesapeake Bay.

Swank and Waide (1998) summarized the long-term water record of seven control watersheds at the Coweeta Experimental Forest in North Carolina. Continuous chemistry data were available for at least 12 years for two low-elevation watersheds and two high-elevation watersheds, with nearly 50 years of corresponding hydrologic data. For three other control watersheds, stream chemistry for most ions spanned nine years. The Coweeta hardwood watersheds, which span a wide range of environmental conditions and overlay different bedrock formations, were analyzed for long-term annual and seasonal trends of stream constituents and average annual nutrient budgets. Swank and

Waide (1998) noted in their study that phosphorus is known to be immobile and strongly conserved by forest ecosystems; and NH_4-N and NO_3-N are immobilized by soil biota or taken up by root mycorrhizae.

Annual quantities of particulate cation export from control watersheds in Coweeta were found to be insignificant compared to dissolved export; however, suspended and bedload sediments were the dominant forms of nitrogen loss (Swank and Waide, 1998). Monthly flow accounted for at least 96 percent of the variation in monthly export of solutes. Nutrient export via sediments dominated the total export of nitrogen in Coweeta, but was relatively insignificant for other elements or ions. A relevant study by Kronvang (1992) reported on the export of particulate and dissolved phosphorus from two agricultural riversheds in Denmark from 1986-1987. The export of particulate matter was found to play a major role in the export of phosphorus, with sediment-associated transport of non-point source P of major importance. Concentrations of dissolved inorganic P were inversely related to discharge, demonstrating the dilution of P from point sources at higher flows. Higher concentrations of dissolved inorganic P were found during periods of storm run-off, suggesting the importance of surface runoff and P release during resuspension of river sediment. Kronvang (1992) cautioned that attempts to interpret sediment yield data in terms of upstream erosion require reliable measurements of the export of particulate matter and phosphorus, and must also take into account in-stream processes of retention and release.

Streams draining undisturbed watersheds in Coweeta showed distinct seasonal trends in concentrations of K^+, Ca^{2+}, SO_4^{2-}, and HCO_3^- for low elevation watersheds, with concentrations of most constituents peaking during mid-autumn when flow is lowest and declining over winter months as precipitation and flow increase, with minimum values in January (Swank and Waide, 1998). Low concentrations continue until early summer, when they begin to rise again. Higher elevation streams show similar seasonal patterns, with a greater range of monthly change. Similarly, Likens and Bormann (1995) noted that chemical fluxes in Hubbard Brook Experimental Forest (HBEF) were strongly affected by seasonal streamflow variation, whereas annual streamflow variability imparted a longer-term stability. Swank and Waide (1998) found concentrations of NO_3^-, NH_4^+, and PO_4^{3-} in Coweeta to be very low in all streams, with little seasonal change.

Swank and Waide (1998) notes that in many cases, the impact of human activities on a forest ecosystem, as reflected by changes in stream chemistry, are quite subtle and difficult to describe in any cause-effect fashion.

Menzel et al. (1978) reported 10-year sediment and 4-year nitrogen and phosphorus discharges that were highly variable between different years and land uses in six small (<18ha) agricultural watersheds in Oklahoma. Menzel et al. (1978) concluded that long-term records are necessary to compare discharges from different land uses, especially since major discharges from different land uses may occur at different seasons of the year. Nevertheless, they noted that average annual concentrations appeared to be reasonably predictable, when considered with runoff volume, sediment discharge, soil characteristics, and fertilization history. Menzel et al. (1978) reported maximum annual nutrient fluxes of 13 kg/ha total N, 4 kg/ha nitrate-N, 11 kg/ha total P, and 2 kg/ha soluble P, while annual deposition in rainfall averaged 5 kg/ha nitrogen and 0.15 kg/ha phosphorus.

Owens et al. (1983) studied five small catchments (< 3.2 ha) in eastern Ohio over five years to evaluate surface runoff from rotational pastures. Nitrogen losses via surface runoff were seasonal, but not sufficient to greatly impair water quality. However, subsurface contributions of nitrate-nitrogen posed potential water pollution problems, especially during the winter grazing/feeding season (Owens et al., 1983). Greater precipitation was found to be the primary factor causing surface runoff during the growing season (May-October), while rotational management had a major impact on runoff increase during the dormant season (November-April). Good vegetative cover was found to be a major factor in limiting annual average surface runoff.

Johnston et al. (1988) used historic aerial photointerpretation, time-weighted water quality data from the STORET database, multivariate statistical analysis, and GIS techniques to relate 30 years of wetland abundance with stream water quality in the Minneapolis-St. Paul metropolitan area. Their analysis utilized GIS to derive numerical descriptors for each of 15 watersheds which were then empirically related to historic water quality. Results showed that the cumulative effect of wetlands on regional water quality depended on wetland location, providing an example of the utility of GIS in environmental water quality/land use analysis (Johnston, 1988).

Wernick et al. (1998) studied the linkages between residential development, agriculture, and streamwater NO_3-N dynamics in an urban-rural fringe watershed in British Columbia. A GIS-based approach was used to compare land use indicators including septic systems and animal unit densities. Nitrate-N concentrations reached 7.1 mg/L in the summer during low flow conditions when groundwater makes up a large part of the stream flow. Contamination of a major aquifer in the watershed was linked to both residential and agricultural activities in the two Salmon River tributaries studied.

Heidtke and Auer (1993) applied spatial data from a GIS to the Universal Soil Loss Equation (USLE) (Wischmeier, 1976) for prediction of land development impacts and associated runoff loading functions on water quality in Owasco Lake, New York. Spatial attributes such as specific land use, soil texture, and surface slope within specific hydrologic sub-basins were used to provide a more accurate depiction of critical landscape characteristics known to impact NPS runoff loadings (Heidtke and Auer, 1993). Kalkhoff (1993) used GIS to determine the relationship between stream quality and geology in an Iowa watershed. Dikshit and Loucks (1996) coupled a NPS simulation model to GIS-derived spatial data to assess land-use management policies in watershed in upstate New York. In a more complex application, Cressie and Majure (1997) fitted a geostatistical surface model of stream nitrate concentrations using 15 months of daily data collected at 17 densely-nested stream monitoring sites throughout an agricultural watershed in Texas. Their geostatistical surface model allowed prediction of stream contaminant concentrations across space and time using precipitation and GIS-derived physical landscape characteristics. Liang et al. (1999) utilized GIS to establish a NPS database for a small agricultural watershed.

2. Evaluation of Impervious Surface Estimates in a Rapidly Urbanizing Watershed*

Summary: Accurate measurement of impervious surface (IS) cover is an essential indicator of downstream water quality and a critical input variable for many water quality and quantity models. This study compares IS estimates from a recently developed satellite imagery/land cover approach with a more traditional aerial-photography/land use approach. Both approaches are evaluated against a high quality validation set consisting of planimetric data merged with manually-delineated areas of soil disturbance. The study area is the rapidly urbanizing 127 km^2 Cub Run watershed in northern Virginia, located on the fringe of the Washington, DC metropolitan region. Results show that photo-interpreted IS estimates of land class are higher than satellite-derived IS estimates by 100 percent or more, even in land uses conservatively assigned high IS values. Satellite-derived IS estimates by land class correlate well with planimetric reference data (r=0.95) and with published ranges for similar sites in the region. Basin-wide mean IS values, difference grids, and regression and density plots validate the use of satellite-derived/land cover-based IS estimates over photo-interpreted/land use-based estimates. Results of this site-specific study support the use of automated, satellite-derived IS estimates for planning and management within rapidly urbanizing watersheds where a GIS system is in place, but where time-sensitive, high quality planimetric data is unavailable.

KEYWORDS: impervious surface, urbanization, aerial photography, satellite imagery

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2.1. Introduction

Urban growth, frequently occurring in the form of urban or suburban “sprawl,” has been a consistent process in the Baltimore-Washington, DC metropolitan region over the last 50 years. Several authors (Crawford-Tilley et al., 1996; Masek et al., 2000; Jantz et al., in press) have documented methods and data collection criteria to define urban growth in this region, which currently makes up ten percent of the 168,000 km^2 Chesapeake Bay watershed and includes over forty percent of its total population. Masek et al. (2000) presented urban change detection methods that minimize confusion between urban green space and agriculture, reporting a notable increase in “built-up area” in the Washington, DC metropolitan region during the late-1980s. Jantz et al. (in press) predicted future sprawl in the Washington, DC-Baltimore area, at current growth and policy trends, of more than 7200 additional km^2 by 2030.

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

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

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

Study Area

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

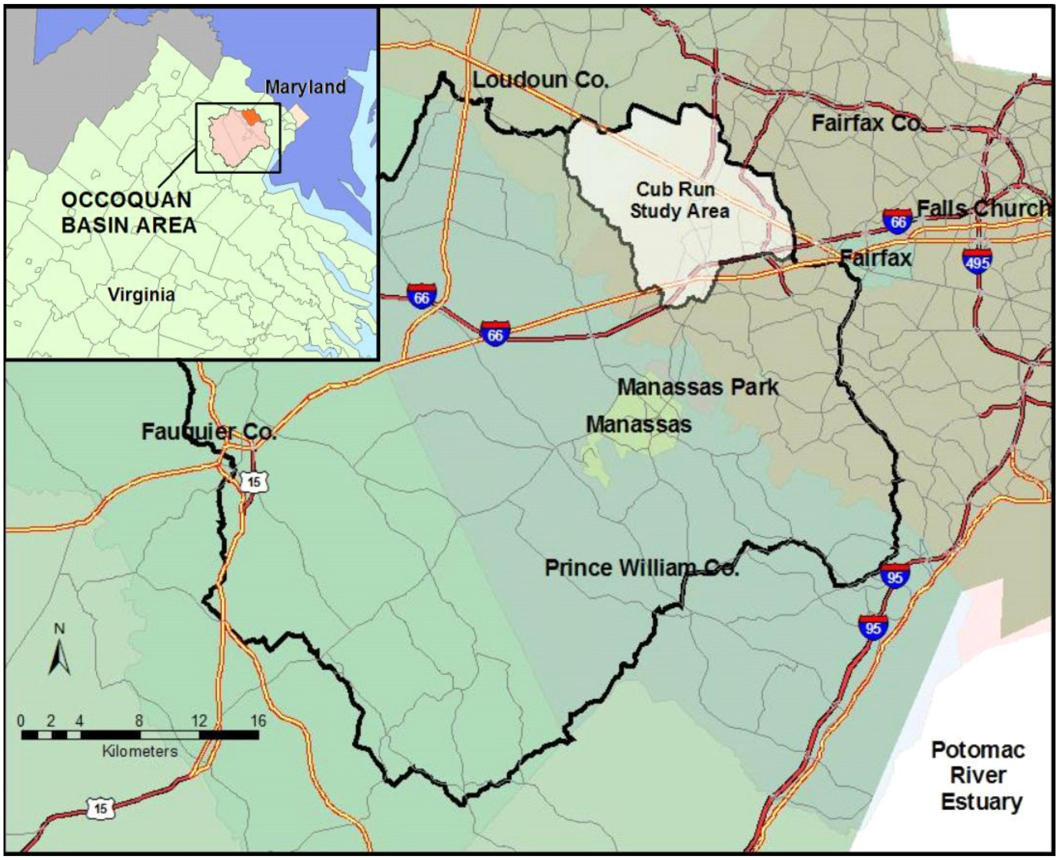


Figure 2-1. Occoquan basin map showing location of Cub Run study area.

Watershed is highly urbanizing, located approximately 20 km west of Washington, D.C.
Insert: Location map.

Data Sets

Predefined land use data for this study were supplied by the Northern Virginia Regional Commission (NVRC) as a hard copy base map, circa 1990 (Figure 2-2), and as polygon shapefiles, circa 1995 and 2000 (Figure 2-3a). Satellite impervious area estimates for the years 1990, 1996, and 2000 (Figure A-5), extracted from those developed by Smith et al. (forthcoming), were utilized as the land cover data set. Validation data include high quality planimetric data from local jurisdictions merged with manually-delineated areas of soil disturbance from same-era digital orthophotos.

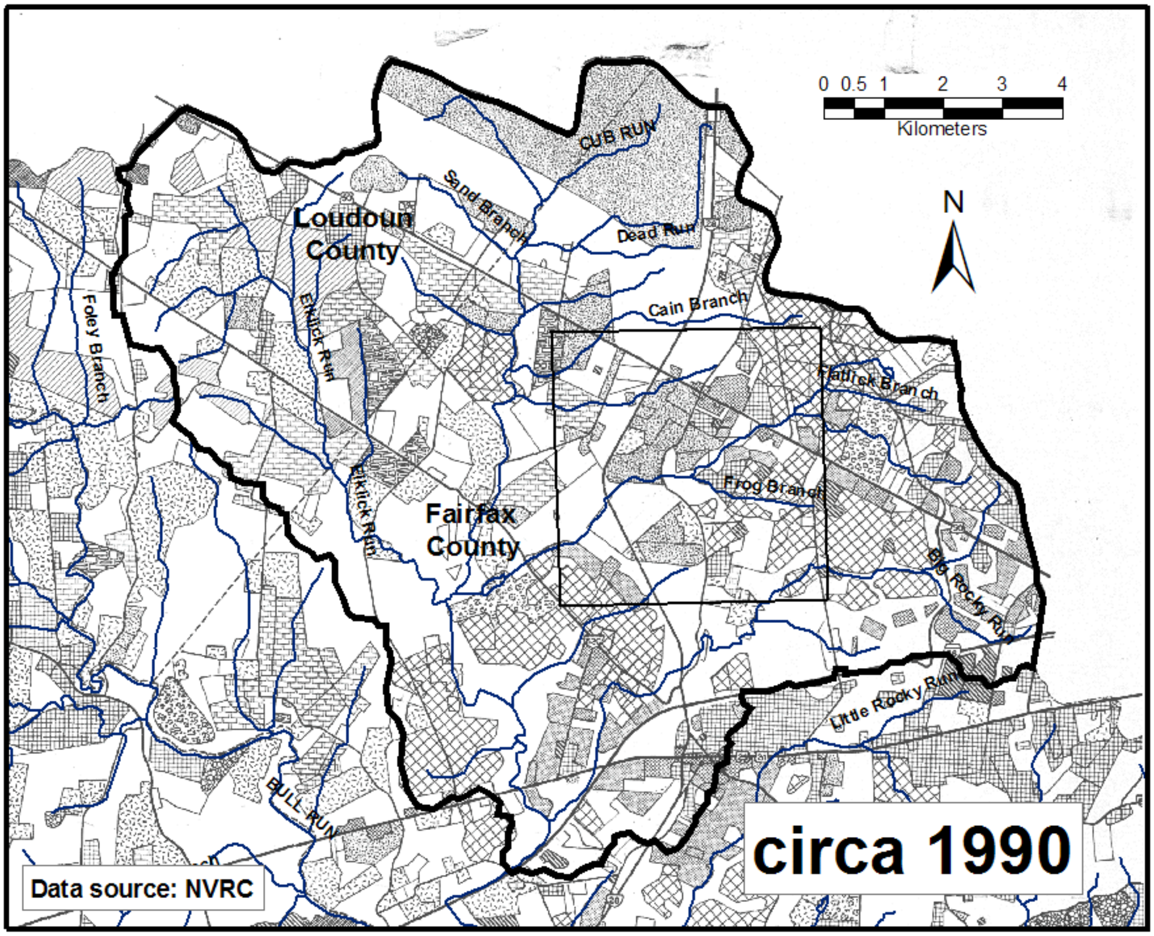
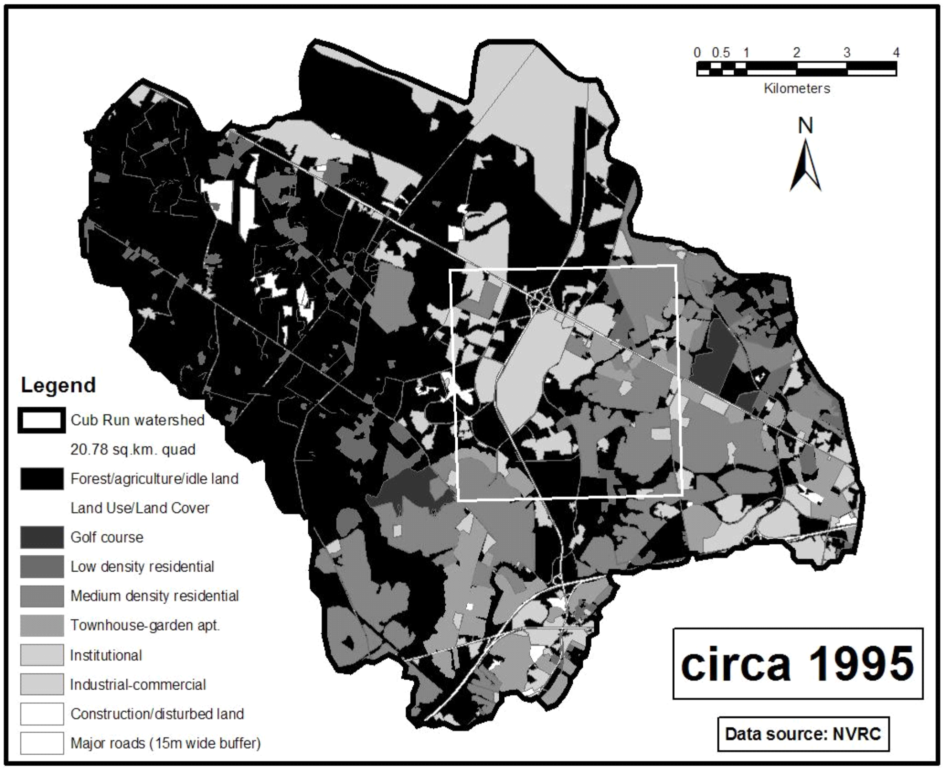
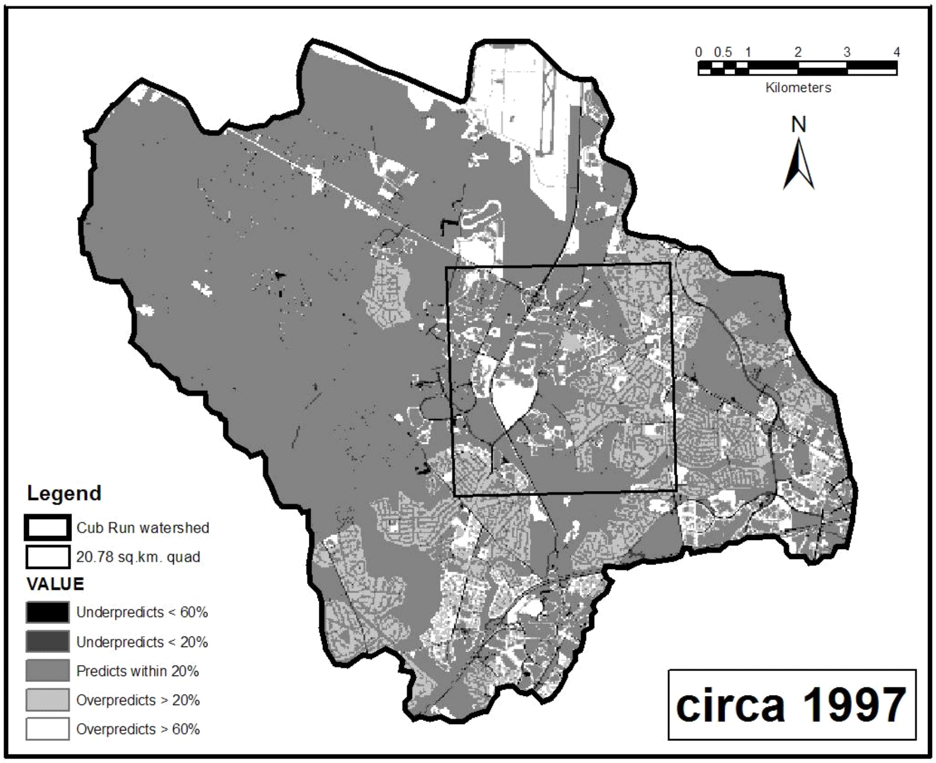


Figure 2-2. Georeferenced 14-class land use map of Cub Run watershed.
Showing 20.78 km^2 subset of Fairfax County.



a.



b.

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

NVRC Land Use

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

The 1990 land use data used in this study were derived from an historic NVRC base map dated December 1989, assembled from local land use maps, Master Plans, infrared (IR) photography (dated April 1974), field surveys, and information from the Virginia Department of Forestry and local Soil & Water Conservation Districts. The 1995 land use data supplied by NVRC consists of land use polygons delineated by NVRC staff from color IR aerial photography at a nominal scale of 1:40,000, taken during leaf-off conditions, with airborne photo centers and ground points identified by in-flight differential GPS. The resulting digital orthophotography had a map scale of 1:12,000 (1″=1,000′), at 25 micron scan resolution (1000 dpi), and a ground resolution of 1 m. The 1995 land use polygons for Cub Run basin had a minimum mapping unit of 500 m^2. The 2000 land use data were derived similarly, but from airborne true color photography at 0.6 m (2 foot) resolution, with a minimum mapping unit of 300 m^2.

Photo-interpreted Land Use and Impervious Area

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

Fauss (1992) utilized color photography in 9- by 9-inch format from the years 1979, 1984, and 1988 at scales from 1:20,000 to 1:80,000. Manually identified land uses were traced onto a clear overlay on a light table using a minimum mapping unit of 2.8 hectares (168 m X 168 m), then transferred to a map base of six individual USGS 7.5-minute topographic maps. Roads, houses, buildings, and other impervious surfaces were traced from color photographic enlargements onto drafting film overlays, then digitized and summed within a geographic information system (GIS) to produce average per-class IS estimates.

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

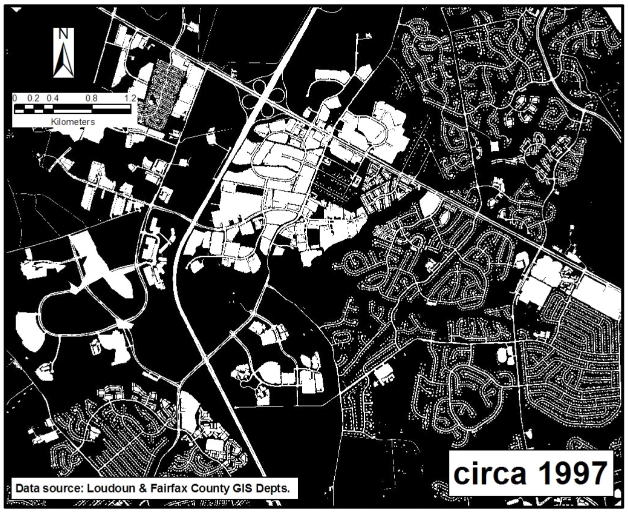
Satellite-derived Impervious Area

Subpixel impervious surface area estimates of the Baltimore-Washington metropolitan area were developed at 30 m resolution using Landsat satellite imagery (path 15 row 33), provided by the Mid-Atlantic Regional Earth Science Applications Center (RESAC). Details of the approach are provided by Smith et al. (forthcoming) and are briefly summarized here. Numerous Landsat scenes were orthorectified to within 0.5 pixel RMSE using the 30 m National Elevation Data DEM and at least 5 ground control points. Scenes were radiometrically corrected to limit topographic and seasonal differences due to solar illumination (Varlyguin et al. 2001). In order to provide reliable, high-resolution training data for automated IS extraction, vector data of impervious features for Montgomery County, Maryland (derived from 1:14,400 scale digital orthophotos from Spring 1993-2000) were rasterized to 3 m resolution. The resulting grid was aligned with the Landsat grid system for subsequent matching of Landsat spectral values. Zonal aggregation from 3 m to 30 m produced a continuous training grid of actual IS cover that corresponded to each Landsat pixel. Additional training data consisting of high resolution GIS data sets of agricultural field plots, non-impervious point data, and other data from the Mid-Atlantic region were collected and incorporated for improved IS extraction.

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

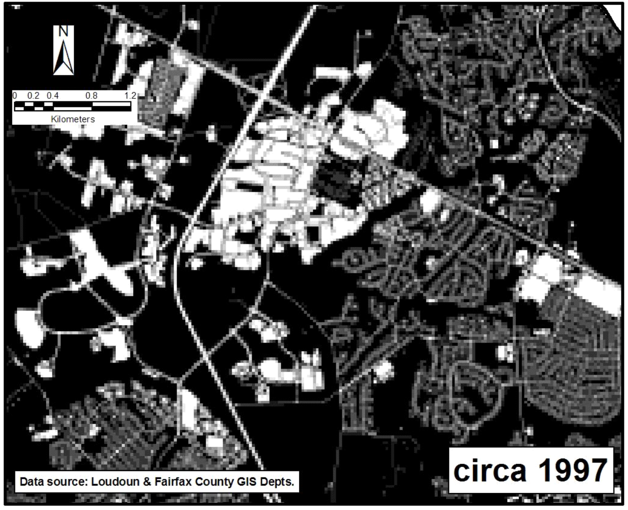
Accuracy of the resulting impervious cover data was assessed using matching IKONOS imagery (4 m resolution) and color-IR Digital Ortho Quarter Quads (DOQQ). The across adjacent-class overall accuracy of the Montgomery County impervious cover data set was 87.7 percent (Kappa=0.77), with some evidence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

Impervious surface maps for 1990 and 1996 were derived using binary impervious / pervious decision trees, effectively producing maps of urban extent. The subpixel 2000 IS values were then passed through to the 1990 and 1996 urban extent maps, assuming that pixel-level IS intensity remained constant through time. Resulting grids for all years had values ranging from zero through 100 percent IS (Figure 2-4c).



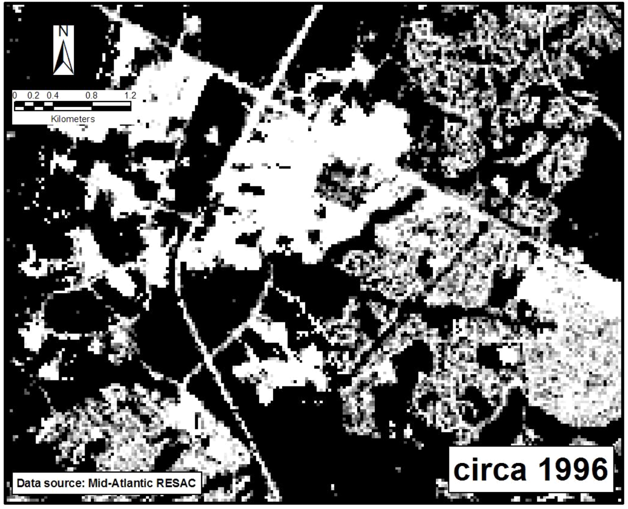
Data source: Loudoun & Fairfax County GIS Depts.

a. 3 m raster of planimetric reference data



Data source: Loudoun & Fairfax County GIS Depts.

b. 30 m aggregation of planimetric reference data



Data source: Mid-Atlantic RESAC

c. Landsat 30 m satellite-derived data

Figure 2-4. Reference vs. satellite-derived IS grids (20.78 km^2 subset of Fairfax Co.).

Cub Run Watershed Validation Data

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

2.2. Methods

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

Land Use Classification

In order to characterize the rapidly urbanizing Cub Run landscape, land use and land use changes were summarized for the years 1990-2000. To account for all impervious surface areas within the study area, two new land use categories were developed; 1) major roads (representing four-lane highways) and 2) disturbed land (representing urban expansion not otherwise identified by NVRC land use mapping). Land use in the Cub Run watershed was divided into seven generalized impervious surface classes, ranging from zero to 100 percent. This 7-class system was contrasted with a more detailed 9-class system by appropriate addition/substitution of the following three detailed land use categories; disturbed land, major roads, and airport and adjoining land (Table 2-1).

Table 2-1. Impervious surface classifications of Cub Run watershed. (from photo-interpretation).

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

Table adapted from Fauss (1992).

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

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

Map Data Preparation

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

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

Image Data Preparation

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

Air photo land use polygons were assigned average IS estimates corresponding to Fauss (1992) (Table 2-1). All 1990, 1995, and 2000 land use polygon classes were subsequently converted to 30 m raster format to create “aerial” IS grids with matching watershed extent. Two sets of grids were created for 1990, 1995, and 2000 to represent both the 7-class and the 9-class system, resulting in six raster grids for comparative analysis.

Comparisons and Statistical Analyses

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

Grid subtraction provided spatial differencing of IS estimates with validation data, affording a direct comparison between the two approaches being evaluated. In this process, planimetric reference data were subtracted from Landsat impervious cover grids and 7- and 9-class photo-interpreted IS area grids on a pixel-by-pixel basis. Mean differences provided a measure of how much the photo-interpreted IS estimates overpredict or underpredict IS cover within each land use class. Difference results were displayed spatially across the watershed for visual interpretation. Comparative density plots were used to visualize conformance between predicted IS distributions and planimetric reference data.

2.3. Results

Land use summaries from 1990 to 2000 reveal that the 127 km^2 Cub Run watershed continued changing from predominantly rural to predominantly urban (Table 2-2). Urban land use in the watershed increased approximately 30 percent over the 10-year study period at an average rate of 1.6 km^2 per year. Land use conversion in the Cub Run watershed was faster in the early 1990s than the late 1990s, similar to growth trends reported by Masek et al. (2000) for the Washington, DC metropolitan region. Mean impervious cover values for the entire Cub Run watershed revealed increasing imperviousness from 1990 to 2000 (13% to 17%), with good conformance of Landsat data to 1997 planimetric reference data (Table 2-3). Photo-interpreted IS estimates demonstrate increased conformance with 1997 reference data upon addition of more land use classes. Similar results were found for the 20.78 km^2 subset of Fairfax County (Table 2-3).

Table 2-2. Cub Run watershed land use summaries, 1990-2000.

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

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

[1] Includes 5.5 km^2 airport and 1.1 km^2 rock quarry.

[2] Majority of disturbed land consists of land clearing for new building construction or industrial expansion.

Table 2-3. Mean impervious cover estimates vs. 1997 planimetric reference data.

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

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

Photo-interpreted versus Satellite-interpreted IS Estimates

Comparison of photo-interpreted IS estimates with Landsat impervious cover estimates for all years and data sets in this study revealed differences between the two approaches. Photo-interpreted IS estimates for all urban land uses except golf courses were up to 100 percent higher than satellite-derived estimates for most years (Table 2-4), with differences more pronounced in land use classes conservatively assigned higher IS values. The townhouse-garden apartment land use category was identified as having the largest difference of all residential land use categories. Satellite-derived IS estimates from RESAC generally fell within directly-measured impervious cover ranges reported by Cappiella and Brown (2000) for selected jurisdictions in the Chesapeake Bay watershed.

Spatially distributed grid differencing between the two methods of IS estimation and planimetric reference data revealed widespread overestimation of IS cover by aerial-interpretation of land use in much of the urbanized portion of Cub Run basin (Figure 2-3b). Areas of highest overestimation were located in pervious areas classified as urban, such as the open and forested land surrounding Dulles International Airport (along the northern boundary of the watershed) and numerous other, widely dispersed urban land segments. Forest/agriculture/idle land and golf course land use categories, which presently make up approximately 50 percent of the land area of the Cub Run watershed, had the lowest differences (i.e., highest conformance) with planimetric reference data (Figure 2-3b) and correspond most closely to Landsat impervious cover estimates (Table 2-4).

Table 2-4. Photo-interpreted vs. satellite-interpreted impervious cover estimates. (by land class).

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

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

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

[3] Airports and rock quarries are included as industrial.

[4] Excludes airports and rock quarries.

IS Estimates versus Validation Data

Comparison of per class impervious cover estimates with 1997 planimetric reference data (Table 2-5) resulted in somewhat better correlation between Landsat IS estimates and the validation data (r=0.97), relative to the aerial-photo IS estimates (r=0.93) (Figure 2-5a).

The higher slope of the Landsat estimates (slope=0.80) compared to the 7- and 9-class aerial-interpreted estimates (slope=0.48 and m=0.57, respectively) provided additional evidence of IS overestimation by aerial-interpretation of land use compared to the Landsat and validation data sets. The higher slope for the 9-class system over the 7-class system demonstrated that IS estimates resulting from the 9-class aerial-interpreted system more closely corresponded, on a per-pixel basis, with planimetric reference data. Density plots representing IS cell-value distribution (Figure 2-5b) support linear regression results, illustrating the distributional similarity of 1996 Landsat IS estimates to the 1997 planimetric reference data.

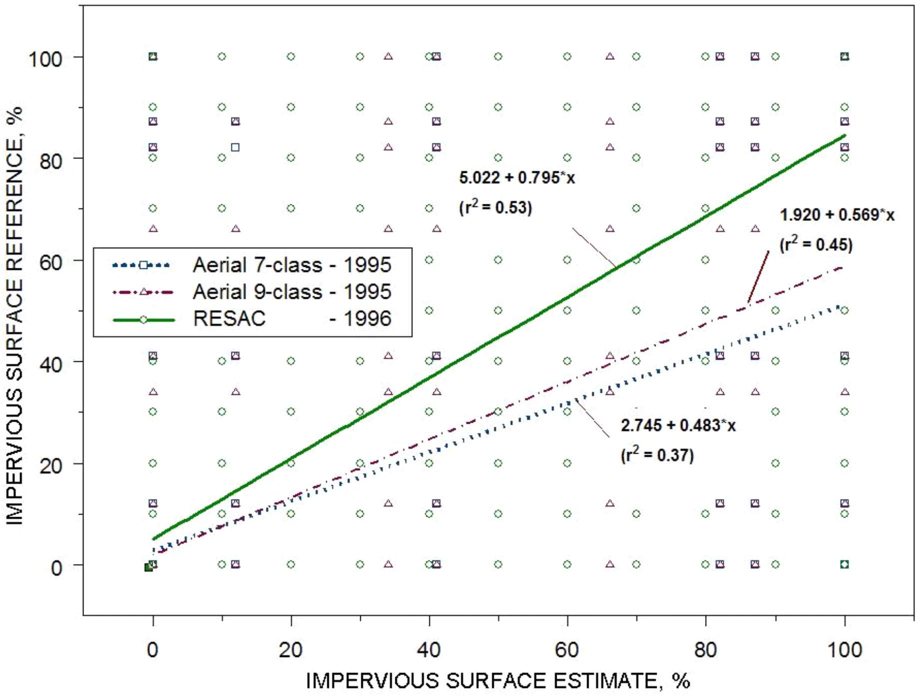
Table 2-5. Impervious cover estimates vs. 1997 planimetric reference data. (Cub Run watershed, by land class).

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

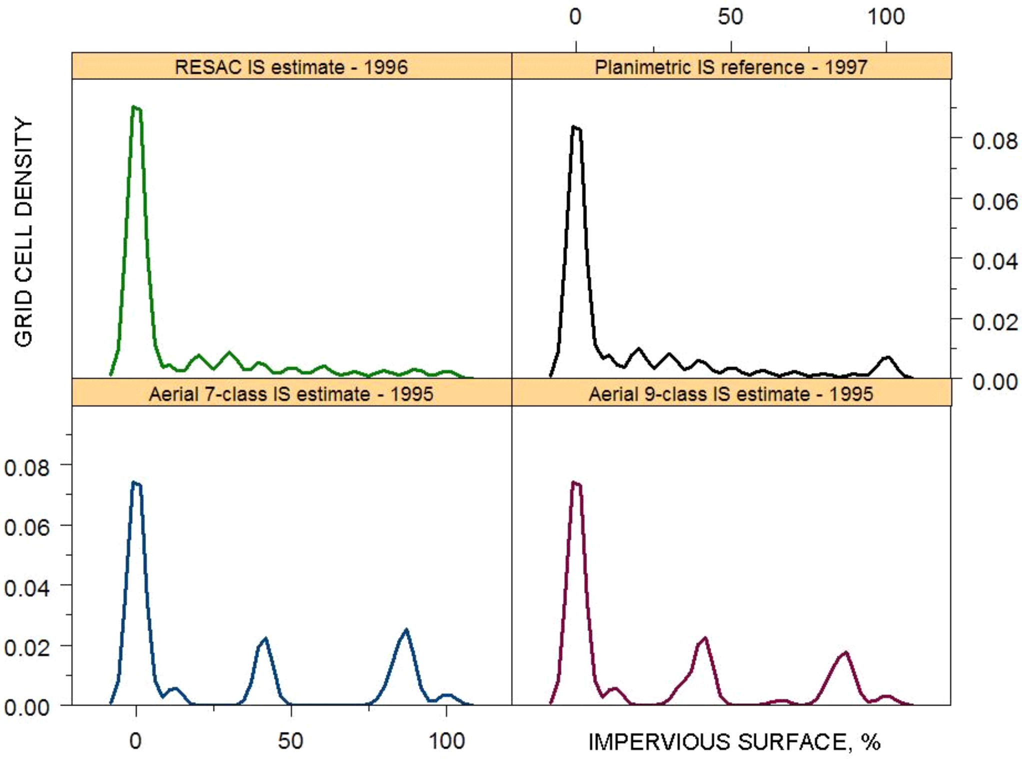
[1] From aerial photographic interpretation of Cub Run watershed by Fauss (1992)

[2] Mean of 1990, 1996, and 2000 Landsat 30 m impervious cover grids.

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



a.



b.

Figure 2-5. a) Per pixel regression analysis (entire basin, N=141,297 cells); b) Density plots showing derived IS estimates and planimetric reference data (entire basin, N=141,297 cells).

Fairfax County Subset

In order to increase the number of high quality data set comparisons, additional per pixel regression, density plot, and difference grid analyses were run on a 20.8 km^2 subset of Fairfax County having a more intricate suburban land cover mixture (mean IS=26%). Resulting linear regression slope values show that all IS subset estimates generally overpredicted compared with planimetric reference data, with aerial 7- and 9-class estimates overpredicting more than satellite-derived IS estimates. The satellite-derived IS estimates had a better fit (higher r^2) with planimetric reference data than photo-interpreted estimates (r^2=0.56 vs. r^2=0.35). Comparative density plots of the 23,083-cell subset (Figure 2-6) revealed the conformance of 1996 Landsat IS estimates with 1997 planimetric reference data. Mean IS estimates and reference values, by class, are presented for comparison with basin-wide means (Table 2-6).

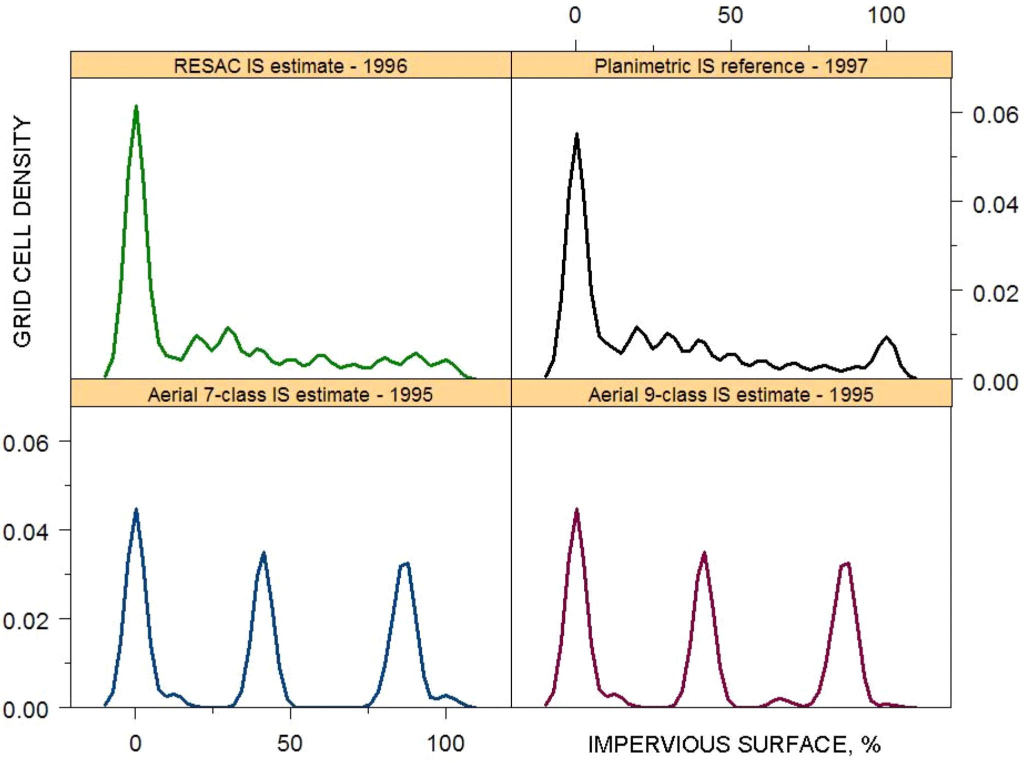


Figure 2-6. Density plots.
Showing derived IS estimates and planimetric IS reference data
(20.78 km^2 subset of Fairfax County, N=23,083 cells).

Table 2-6. Impervious cover estimates vs. 1997 planimetric reference data, subset. (20.78 km^2 subset of Fairfax County, by land class).

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

[1] From aerial photographic interpretation of Cub Run watershed by Fauss (1992)

[2] From Landsat 30 m impervious cover grid.

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

Difference grid analysis of the Fairfax County subset (Figure 2-7a) provides a more detailed visual analysis of IS over- and under-prediction in an urbanized section of the Cub Run watershed. Overprediction was more apparent and widespread in the aerial-interpreted IS estimates than in the Landsat estimates (Figure 2-7b). In spite of a general underprediction in the Landsat map at low IS values (Figure 2-6), the Landsat IS distribution provides a better match of the intricate suburban land cover represented by the reference data.

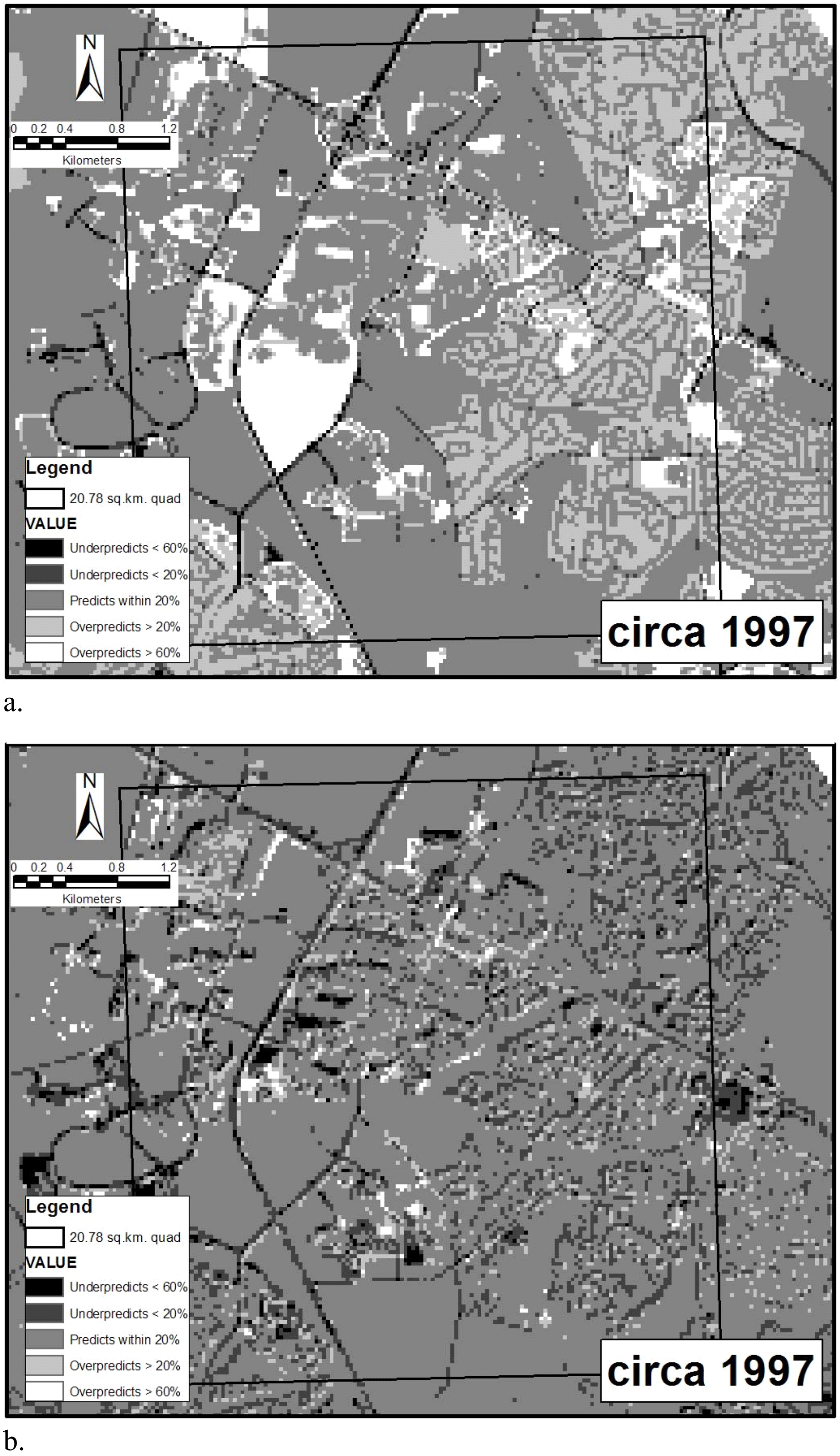


Figure 2-7. Difference grids:

a) Aerial 7-class 1995 – Planimetric reference 1997; b) Landsat 1996 – Planimetric reference 1997. Areas of overprediction are lighter.

2.4. Discussion

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

Results of this study, which further validate the use of Landsat IS estimates, show that the 100% IS assignment for areas delineated from aerial photography as disturbed/construction may be unrealistic. Based on validated Landsat estimates, IS values for disturbed/construction sites in the Cub Run watershed ranged from 50 to 70%, with major four-lane highways (including median strips) falling in a similar range. Recommended ranges of impervious cover resulting from this study, by land class, are summarized in Table 2-7.

Table 2-7. Expected range of impervious percent, by land use class. (Cub Run watershed).

Land use category	Impervious surface range
Disturbed/construction	50-70%
Major roads/highways w/median	50-70%
Institutional/commercial/industrial	35-55%
Townhouse-garden apts.	35-45%
Medium density residential	20-25%
Dulles Airport w/adjoining land	10-20%
Low density residential	5-10%
Ag/forest/golf/idle land	2-7%

Spatial analysis of grid differences identify areas where IS estimates over- or under-estimated compared to validation data, for example, the large area of overprediction by the photo-interpreted/land use approach in the forested buffer south of

Dulles International Airport (Figure 2-3b). In spite of noted uncertainties in the satellite-derived data, results suggest than an average imperviousness value closer to the Landsat impervious cover estimate of 16% (table 5) would be more realistic for the combined airport/adjoining property land use classification in this watershed. Grid differences in the vicinity of the airport raise the question of whether a single land use value for urban IS estimation has a strong physical meaning, given the accepted heterogeneity of all but the most impervious urbanized land covers (such as shopping mall parking lots, industrial warehousing, etc.).

The most prominent examples of urban heterogeneity in the Cub Run watershed were the residential areas in the more densely developed, eastern (Fairfax County) portion of the basin. In this study, aerial IS estimates for residential street patterns compare more favorably to validation data than the interspersed expanses of suburban lawn and forest, where widespread overprediction occurs (Figure 2-7a). These high IS estimates appear to be the result of noted bias and assumptions inappropriate for a watershed having such a complex mix of urban land cover. In spite of scattered underprediction, satellite-derived IS estimates (Figure 2-7b) demonstrate better overall conformance to validation data. Under-prediction of satellite-derived IS estimates may be attributed to the inability of Landsat 30 m observations to discern portions of small roads and other impervious surface features as discrete entities, particularly where there is obscuration by tree cover and associated shadows, even in leaf-off imagery.

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

Of all photo-interpreted IS estimates, agriculture/forest/idle land and golf course land use categories corresponded best with the validation data set (Table 2-5). As a result, inevitable reductions in rural land area in this watershed will further reduce the reliability of photo-interpreted IS estimates. At present, rural and idle lands make up approximately 50 percent of the Cub Run basin. As urban land conversion continues, with increasing segments of interspersed, heterogeneous land cover, the need for synoptic current satellite-derived estimates of impervious cover also increases. Stated in general terms, as a rural landscape increases in complexity with increased urbanization, so does the need for a land cover approach for IS estimation.

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

2.5. Conclusions

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

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

2.6. References

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