HETEROGENEITY IN THE URBAN LANDSCAPE:
IMPACTS ON HYDROLOGIC PROCESSES AND NITROGEN POLLUTION

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ABSTRACT

MONICA LIPSCOMB SMITH: Heterogeneity in the Urban Landscape: Impacts on Hydrological Processes and Nitrogen Pollution
(Under the direction of Lawrence E. Band)

The objective of this dissertation was to define the most critical features of the heterogeneous urban landscape that characterize nitrate source/sink dynamics and hydrology driving stream nutrient pollution. This volume of research evaluated the usefulness of the commonly used National Land Cover Database (NLCD) for deriving urban hydrologic parameters, defined metrics linking suburban landscape structure and nitrogen fluxes, and determined variance of hydrologic properties of residential lawns according to social and physical factors. Field research and remote sensing analysis took place within watersheds of the Baltimore Ecosystem Study (BES) Long-Term Ecological Research (LTER) site.

Results suggested that the NLCD is insufficient for urban hydrologic studies due to biases and variability of these datasets. However, nitrate concentrations of suburban streams were better characterized by watershed infrastructure than land cover composition or location. Septic-managed watersheds' stream nitrate correlated with fine-scale and spatially explicit metrics, including population/septic density, septic location and presence of wetlands. However, the spatiality of sewer nitrate-N sources was not assessed because infrastructure displaced the source downstream from sampling points.

Hydrologic properties of residential soils were found to vary spatially at the parcel and watershed scales. Reduced saturated infiltration rates in residential lawns caused only marginal differences in overland flow when compared to regional rain records. However, the reduction in lawn soil structural properties implies watershed-scale changes in hydrologic connectivity between nitrogen sources and streams. Controlling for geographic differences in soil properties, saturated infiltration rates correlated with housing age; percent organic matter correlated with property value and fertilizer application rate. However, these relationships were non-monotonic, and the ability to use social and physical data to explain the range of soil properties among residential lawns was limited.

This dissertation defines a range of soil parameters of residential lawn properties for spatially explicit modeling. Of the factors assessed in this dissertation, waste management infrastructure was defined as the most critical feature explaining nitrate source/sink dynamics of the heterogeneous urban landscape. This finding suggests that previous regional-scale studies linking nutrient enrichment to urban land cover variables may be substituting land cover as a surrogate measure for waste management infrastructure.

To Victor

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LIST OF ABBREVIATIONS

BES	Baltimore Ecosystem Study
BWI	Baltimore Washington International Airport
D-8	8 direction
DEM	Digital Elevation Model
EPA	U.S. Environmental Protection Agency
HERCULES	High Ecological Resolution Classification of Urban Landscapes and Environmental Systems
IDW	Inverse Distance Weighted
LID	Low Impact Development
LiDAR	Light Detection and Radar
LTER	Long-Term Ecological Research
NLCD	National Land Cover Database
N	Nitrogen
Nm	nanometer
NSF	National Science Foundation
PTF	Pedotransfer Function
TMDL	Total Maximum Daily Load
SCS	Soil Conservation Service
SLAMM	Source Loading and Management Model
SRA	Septic Reserve Area
SWM	Storm Water Management
TR-55	Technical Release 55
UNC	University of North Carolina

USGS	U.S. Geological Survey

LIST OF SYMBOLS

α	soil air resistance (cm^{-1})
D_1	average D-8 flow distance from each SRA to the downstream sampling site
D_2	average D-8 flow distance from each SRA to the stream
D_3	Euclidean distance from SRA to the stream:
D_f	flow path distance at SRA centroid
D_{si}	flow path distance where flow path intercepts stream
D_{ss}	flow path distance at the stream sampling site
Ks	Saturated hydraulic conductivity
n	Van Genuchten retention curve descriptor

CHAPTER 1: HETEROGENEITY IN THE URBAN LANDSCAPE: IMPACTS ON HYDROLOGIC PROCESSES AND NITROGEN POLLUTION

1.1 Introduction

The objective of this dissertation is to identify key metrics of hydrology and nitrate source/sink dynamics in the urban landscape that affect nutrient transport to streams. Attempts to limit total maximum daily loads (TMDLs) of nutrients in urban areas are currently under way in an effort to reduce nitrogen and phosphorus delivery to receiving freshwater and coastal water bodies. However, such efforts are limited by our lack of knowledge about spatial heterogeneity of hydrologic soil properties and nitrogen source/sink dynamics in the urban landscape. While fine-scale heterogeneity characterizes the urban environment, it is important from a land management perspective to identify dominant features related to nutrient transport from readily attainable datasets. This study aims to inform localized nutrient reduction strategies by addressing the 3 following questions:

1) How sufficient is the moderate-scale National Land Cover Database (NLCD) for deriving urban land cover parameters for hydrologic modeling?
2) What is the utility of high-resolution image products in developing metrics to be used to characterize key aspects of suburban landscape structure as they relate to stream nitrate fluxes?

3) How can variance of hydrologic properties of residential lawns be attributed to social and physical factors?

While land cover is typically used as a basis for water quality modeling, other aspects of residential land use are most relevant in controlling stream chemistry and hydrologic processes. This research elucidates dominant residential land use features affecting soil hydrology and stream nitrate, and relates them to coarse-scale datasets for use in localized land use decisions.

1.2 Background

This study examines aspects of nutrient transport from residential suburban catchments according to the conceptual framework shown in Figure 1.1. The urban landscape is characterized by tremendous spatial heterogeneity attributable to individual (parcel level) choice and practices, and land-use planning strategies, including: zoning regulations dictating residential density and pattern; and associated storm and sanitary infrastructure. Thus, this study aims to identify aspects of residential pattern as they relate to parcel variation in hydrology, headwater catchment differences in nitrate source/sink dynamics, and the integration of these properties for improved understanding of nutrient transport and retention within suburban catchments.

1.2.1. Nutrient pollution from urban areas

Nitrogen pollution resulting from land development has degraded the health of U.S. coastal rivers and bays (NRC 2000, Howarth et al. 2002). Humans have approximately doubled the input rate of terrestrial nitrogen cycle causing significant changes in composition and function of estuarine and coastal ecosystems (Vitousek et al. 1997). Local decision makers require methods to abate nutrient runoff in their jurisdictions to achieve national water quality goals. However, linking aspects of the heterogeneous urban landscape with nitrogen fluxes is challenging in light of the coarse-scale land use/land cover data available to land managers. An enhanced understanding of the interactions between residential hydrology and nitrogen source/sink dynamics is needed in order to develop such methods.

1.2.2 Source/ sink dynamics in suburbs

Nitrogen source/sink dynamics are dramatically modified in urban areas. Previous work in the Baltimore Ecosystem Study (BES) has shown that the bulk of metropolitan stream nitrogen loads are derived from suburban and exurban residential land use (Shields et al. 2008), much of which is presumed to be from sewage overflow and septic sources. Annual input of nitrogen from fertilizer application constitutes a major component of nitrogen budgets in suburban areas (Groffman et al. 2004), but application rates are highly variable according to socioeconomic factors (Law et al. 2004). While loss of nitrogen from urban and suburban systems is up to eight times higher than forested watersheds, nitrogen retention in suburban watersheds is surprisingly high—as much as 75% of inputs (Groffman et al. 2003). Nitrate leaching from urban grassland is higher than forested land, but differences were not as high as would be expected (Groffman et al. 2009). Alteration of urban soil moisture regimes impacts riparian zone nitrification and denitrification patterns (Groffman et al. 2002). Inorganic N retention and nitrate attenuation are much reduced in headwater streams of residential catchments (Paul and Meyer 2001, Kaushal et al. 2006, and Claessens et al. 2009a, b, and c). Discernment of key land features that contribute to these altered source/sink dynamics, such as differences in nutrient sources and hydrologic connectivity warrant further exploration to estimate suburban nitrogen budgets.

1.2.3 Altered hydrology in the heterogeneous urban environment

Many scientific studies have described the ecological and hydrological impacts of the composition of impervious land cover (Carter et al. 1961, Andersen 1970, Walsh et al. 2005a). However, very little has been discerned regarding impacts of location and pattern of development (Brabec et al. 2002). The urban landscape is characterized by tremendous spatial heterogeneity occurring at shorter length scales than most natural systems (Band and Tague 2005, Band et al. 2005). Disconnection of impervious surfaces from the stormwater conveyance system is a method to retain surburban runoff (Walsh et al. 2005b). Thus, alteration of urban residential patterns and associated stormwater infrastructure holds promise for reducing the impacts of urbanization on stream discharge and nutrient transport.

Percent impervious surface is frequently cited as an indicator for stream degradation. However, it is important to recognize that percent imperviousness is not an independent predictor; it is coincident with the reduction of another type of land cover, i.e., reduction of canopy cover (King et al. 2005) and the type of sanitary infrastructure. In highly urbanized areas (over 15% impervious), the amount of lawn area is typically inversely proportional to impervious area (Milesi et al. 2005). Saturated infiltration rates of lawns are reduced compared to forest soils (Kelling and Peterson 1975) and runoff from pervious areas is known to contribute to a large portion of runoff (Burges et al. 1998). Given the great extent of lawn areas, examination of the role of lawns in driving urban runoff is warranted.

Soil properties such as soil texture, organization, and aggregation are important controls of water infiltration rates and subsequent soil moisture. Inclusion of complex anthropogenic factors should be incorporated into modern concepts of soil formation (Effland and Pouyat 1997). "Anthropic" soil horizons are not frequently parallel to the soil surface and have properties that are affected by construction equipment and debris (Florentin et al. 1998 and Schleuss et al. 1998). Typical assumptions regarding infiltration and subsurface flow in urban areas neglect the heterogeneity of hydrologic soil properties. Natural flow paths are altered due to less-regular organization of watershed-scale soil moisture (Tenenbaum et al. 2006). Thus, techniques for determining the spatial variation of soils in the urban landscape are needed to advance our understanding of hydrologic processes in these areas.

1.2.4 Hydrologic modeling of urban nutrient transport

Currently, we lack sufficient knowledge about the spatial heterogeneity of residential hydrology and nitrogen source/sink dynamics to adequately model the impacts of low impact development (LID) on nutrient transport to streams. A critical assumption of lumped empirical models, e.g., TR-55, is that pattern can be ignored for purposes of runoff production. These models assume uniform hydrology that is much unlike the heterogeneous urban landscape and neglect spatial variation in evapotranspiration, interception, infiltration, vertical drainage and subsurface flow (Tague and Pohl-Costello 2008). While they may be appropriately applied to flood prediction, they are not sufficient to model the transport of nonpoint source pollutants (Garen and Moore 2005, Donigan and Huber 1991).

Storm water conveyance systems and changes in watershed-scale soil moisture connectivity mediate the effect of urbanization in complex ways, and use of spatially explicit process-based models allows the linkage of urban design to urban nutrient transport (Tague and Pohl-Costello 2008). Use of spatially-explicit models has been used to demonstrate differences in runoff production created by urban features (Easton et al. 2007). Thus, adoption of spatially-explicit process-based models is needed to mitigate impacts of development on water quality and flooding, and assess the potential of LID strategies. Despite the growing availability of spatially explicit data, lumped empirical models of urban landscapes remain the most common approach to hydrologic studies (NRC 2008, Moglen and Beighly 2002, Beven 1992).

This dissertation seeks to identify critical features of residential watersheds as they relate to nutrient transport so that informed land management decisions can be made using relevant scientific information (Montgomery, Grant, and Sullivan 1995). Chapter 2 examines the representation of urban landscape heterogeneity within the most commonly used land cover dataset, the NLCD. Chapter 3 and 4 address the role of parcel and watershed scale heterogeneity in driving nitrogen pollution and hydrological processes. Identifying key features of urbanized watersheds affecting nutrient transport to streams is needed to develop parameter sets for spatially-explicit process-based models.

1.3 Methods

1.3.1 Evaluation of moderate-resolution NLCD 2001 datasets for hydrologic purposes

In Chapter 2, we compared the NLCD 2001 land cover, impervious, and canopy data products to land cover data derived from 0.6 m resolution 3-band digital imagery and ancillary data. We conducted this comparison at the 1 km^2, 9 km^2, and gauged watershed scales within the BES. At these scales, we determined the usefulness and limitations of the NLCD in heterogeneous urban to exurban environments for the determination of land cover information for hydrologic applications. Percent canopy and impervious areas were compared directly. Land cover composition and variability of developed land classes were determined for the BES watersheds. In addition, grass-related classes were examined to reveal which NLCD land classes contain lawn cover and the variability of lawn cover per land class.

1.3.2 Effects of fine-scale residential pattern on suburban stream nitrogen

In Chapter 3, we evaluated the effects of residential fine-scale land cover and management features on stream nitrate concentration and source/sink dynamics through analysis of discrete water chemistry samples and stream discharge measurements taken in the BES. This study examined differences in nitrate-nitrogen concentrations of streams in residential catchments characterized by a range of fine-scale land cover and management features. Metrics included population density, waste management strategies, distance from storm water outfalls, distance from septic reserve areas, land cover, distance-weighted land cover, and the effect of wetlands. The objective was to determine metrics that are most applicable to link landscape structure and nitrogen fluxes.

1.3.3 Physical & social impacts on hydrologic properties of suburban soils

Chapter 4 examined saturated infiltration rates and water retention property differences between residential and forested soils, and the variance of these soil properties within and among suburban lawns. The objective of this study was to characterize the variance of hydrologic soil properties of residential lawns according to social and physical factors that are available through cadastral or land cover datasets. Saturated infiltration rates were measured using the Cornell Sprinkle Infiltrometer (Ogden et al. 1997), and soil cores were collected from each residence to measure bulk density, water retention characteristics, soil texture, and percent organic matter. These soil properties were compared to social and physical factors, including housing age, property value, parcel area, percent coarse vegetation per parcel, land use legacy, lawn area, lawn fertilization rate, and distance to stream.

1.4 Significance of dissertation research

The heterogeneous urban landscape is characterized by substantially altered nitrate source/sink dynamics and hydrology driving nutrient delivery to streams. This research contributes to the current state of knowledge of spatially-explicit nitrate sources and soil hydrology in residential catchments. The dissertation is significant in determining data needs for process-based modeling of suburban nutrient pollution. The findings included in the following chapters are of utility to land managers for evaluating and targeting LID strategies in suburban areas to achieve TMDL goals.

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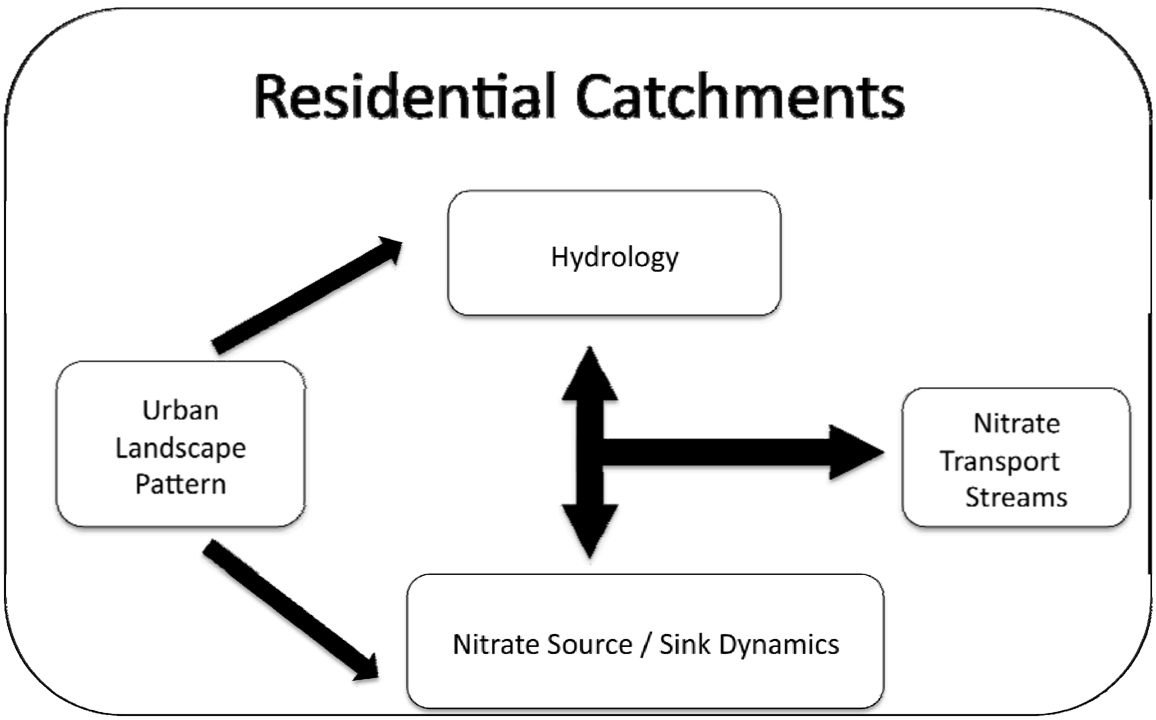

Figure 1.1 Conceptual model of relationship between urban landscape pattern and nitrate transport to streams.

CHAPTER 2. EVALUATION OF THE NLCD FOR HYDROLOGIC APPLICATIONS IN URBAN AND SUBURBAN BALTIMORE, MD

2.1 Preface

Stream nitrate fluxes have been well-explained by catchment land cover composition at a scale > 10 km^2; however, the explanatory power of this relationship drops off for areas 1 - 10 km^2 suggesting that spatially explicit watershed characteristics may be more important for small areas of interest (Strayer et al. 2002). While analysis of the stream chemistry impacts of spatially explicit watershed characteristics yields important urban design implications, this analysis is often limited by a lack of readily available fine-scale land cover data. The following chapter discusses the use of the NLCD for deriving land cover parameters for hydrologic modeling.

The NLCD is a nationally available and broadly used dataset to derive land cover metrics. The NLCD 2001 includes a canopy and impervious layer that may allow for more spatially explicit land cover. We compared the canopy, impervious and land cover layers with a high-resolution object-based land cover dataset available for land area within the Baltimore Ecosystem Study (Zhou and Troy 2008). The research in this chapter was carried out to determine the usefulness and limitations of the NLCD for determination of residential spatial patterns for urban hydrologic study. The following research was written in collaboration with L. Band, University of North Carolina, Chapel Hill; W. Zhou and M. Cadenasso, University of California, Davis; and J. M. Grove, U.S. Forest Service. The research in this chapter was published in the *Journal of the American Water Resources Association,* April 2010.

2.2 Abstract

We compared the National Land Cover Database (NLCD) 2001 land cover, impervious, and canopy data products to land cover data derived from 0.6 m resolution 3-band digital imagery and ancillary data. We conducted this comparison at the 1 km^2, 9 km^2, and gauged watershed scales within the Baltimore Ecosystem Study (BES) to determine the usefulness and limitations of the NLCD in heterogeneous urban to exurban environments for the determination of land cover information for hydrological applications. While the NLCD canopy and impervious data are significantly correlated with the high-resolution land cover dataset, both layers exhibit bias at < 10 and > 70 % cover. The ratio of total impervious area and connected impervious area differs along the range of percent imperviousness—at low percent imperviousness, the NLCD is a better predictor of pavement alone, while at higher percent imperviousness, buildings and pavement together more resemble NLCD impervious estimates. The land-cover composition and range for each NLCD urban land category (developed open space, low intensity, medium intensity and high intensity developed) is more variable in areas of low intensity development. Fine-vegetation land cover / lawn area is incorporated in a large number of land use categories with no ability to extract this land cover from the NLCD. These findings reveal that the NLCD may yield important biases in urban, suburban and exurban hydrologic analyses where land cover is characterized by fine-scale spatial heterogeneity.

2.3 Introduction

Land cover greatly influences runoff production, groundwater levels, channel incision and stream baseflow in urbanized catchments (National Research Council 2008, Walsh et al. 2005, Naiman and Turner 2000, Wigmosta and Burges 1997). Impervious surface area is known to increase overland flow, stream flow peaks (Leopold 1968) and create the urban heat island effect (Kalnay and Cai 2003). Percent impervious area is often used as a predictor of hydrologic changes that degrade waterways because it prevents natural soil processes that immobilize pollutants (Schueler 1994, Arnold and Gibbons 1996, Brabec et al. 2002), reduces infiltration and evapotransipiration rates (Brun and Band 2000), alters patterns of soil moisture (Tenenbaum et al. 2006), and increases sediment loads associated with construction that compromise stream processes (Wolman and Schick 1967).

Many urban policy applications from storm water modeling to land conservation may rely on land cover information. An accurate determination of land cover variables is critical for hydrologic analyses. Hydrologic models are tools that are typically used to link contributing area and polluting sources to their effects on receiving water bodies. However, there is insufficient linkage between regional-lumped and fine-scale distributed approaches; an improved modeling paradigm linking these approaches is needed (National Research Council 2008). Progress has been made in determining impacts of heterogeneous land-cover inputs on downstream water quality (Maestre and Pitt 2006); however, urban hydrologic models developed to examine such impacts, e.g., SLAMM, rely on high-resolution land-cover data due the heterogeneity of urban storm-water pollutant sources (Pitt and Voorhees 1989). In addition, a large variability in land use categories required by models and provided by land cover datasets further complicates extensive understanding of land cover effects on water quality (NRC 2008).

The National Land Cover Database (NLCD) is widely used for hydrologic study because this dataset is the most detailed land-cover information source made freely available on a national scale. While extensive quality control and independent evaluations have been conducted (Homer et al. 2004, Chen et al. 2006, and Smith et al. 2003), the focus has been the dataset's regional-scale accuracy. The dataset has not been evaluated specifically for urban environments. Urban environments are challenging to summarize with coarse-scale imagery because they are characterized by fine-scale land cover heterogeneity when compared to less developed landscapes (Band et al. 2005).

Most urban land within the NLCD is classified by type of development, rather than raw land cover, which prompted the development of canopy and impervious datasets for the 2001 NLCD (Homer et al. 2004). The NLCD classification incorporates lawn area into developed and agricultural land use classes, e.g., low density developed and pasture. While the NLCD 2001 provides impervious and canopy data sets, there is no simple way to determine the percent lawn area in urban regions from this dataset. Incorporation of the effects of urban pervious area in hydrologic models is not common despite indications that suggest pervious areas can account for a large portion of runoff sources in suburban watersheds (Burges et al. 1998). Soil compaction associated with residential lawns alters hydrologic properties of land cover in increasing bulk density and decreasing infiltration rates (Partsch et al. 1993, Hamilton and Waddington 1999, Gregory et al. 2006) and subsequently affects suburban watershed hydrology. In addition, lawn area comprising over

40 million acres of the U.S. (Milesi et al. 2005) is rarely incorporated as a separate land cover category in hydrologic analyses.

We investigate how well key land cover elements with the fine spatial scale of heterogeneity in urban environments can be discerned using NLCD products. It is likely that some urban landscapes may be better represented by the NLCD than others according to ranges of percent imperviousness or canopy cover. In addition, NLCD land uses are evaluated to elucidate land cover composition within each developed category.

This paper evaluates the relative accuracy of NLCD 2001 data in urban areas by comparing the 30m NLCD 2001 with land cover data derived from 0.6m resolution, 3-band color-infrared imagery (green: 510-600 nm; red: 600-700 nm, and near-infrared: 800-900 nm). We conducted this comparison at the 1 km^2, 9 km^2, and gauged watershed scales within the Baltimore metropolitan area (Figure 2.1). The extent to which the 30m pixel resolution NLCD can be applied in urban environments for the purposes of watershed management, estimates of evapotranspiration, baseflow and urban heat island effects is the focus of this research.

2.4 Datasets

The NLCD 2001 is based on medium-resolution imagery, elevation and ancillary GIS layers. The benchmark dataset was developed from high-resolution imagery, elevation and ancillary GIS layers. The high-resolution dataset is comprised of images obtained in 1999 whereas the NLCD 2001 is a composite of multiple images attained from summer 1999 to spring 2001. 1999 Landsat images were used for all seasons, except spring. Thus, the difference in the imagery used in these datasets is negligible. While some difference between these datasets may be expected due to land cover change between 1999 and 2001, an analysis of this change in the Baltimore metropolitan area indicates very little change from 1999 to 2004 (Zhou et al. 2008). The greatest change occurred to percent pavement—an increase 1.9 % in this 5 year time period. Decreases of 1.3 % fine vegetation and 1.2 % bare soil were also measured during this time period. Percent buildings and coarse vegetation increased 0.4 and 0.2 % respectively (Zhou et al. 2008). Thus, the maximum attributable error due to the difference in imagery is less than 1 %. The relative accuracies of both datasets are noted in Table 2.1. While percent accuracy is not much lower for the NLCD, note that the high-resolution data accuracies are reported for a scale 2500 times finer than the 30m NLCD pixel size. Further detail of the classification processes of the two datasets is reported below.

2.4.1 NLCD

The second generation NLCD 2001 was designed by the Multi-Resolution Land Characterization team to provide an updated and improved land-cover classification dataset of the U.S. The NLCD layers used in this analysis are derived from mapping zone 60, including most of Maryland. NLCD 2001 is based on multi-temporal Landsat 7 ETM+, Landsat 5 TM imagery and ancillary data, e.g., digital elevation model data for slope and aspect, population density, buffered roads, NLCD 1992, and NOAA City Lights dataset. The classification scheme is based on Level II thematic detail (Anderson et al. 1976). The Anderson classification scheme was defined at the conference on Land Use Information and Classification in 1971. The system was designed to make LANDSAT data usable by the majority of user groups and adopted a “resource-oriented,” rather than a “people-oriented” approach. Anderson level I categories include data attainable at scales smaller than 1:24,000, e.g., urban, agriculture, forest and wetlands. Anderson level II categories are subsets of level I categories, i.e., urban land is comprised of residential, commercial and mixed urban land uses, using data available at the 1:24,000 to 1:250,000 scale.

In addition to 29 land cover classes, percent imperviousness and percent canopy products are included in NLCD 2001 (Figure 2.2). The impervious layer was modeled by comparing several 1m digital orthophoto quadrangles and Landsat spectral data according to a regression tree algorithm (Yang et al. 2002). The canopy layer was classified according to methods outlined in Huang et al. (2001). An assessment of single 30m-pixel land cover accuracies is reported in Table 2.1.

2.4.2 High-resolution land cover data

The high-resolution land cover datasets for the Gwynns Falls and Baisman Run watershed were derived from digital high-resolution color-infrared aerial imagery collected in 1999 with pixel size of 0.6m (Zhou and Troy 2008) (Figure 2.2). This dataset, referred to in this text as the “high-resolution dataset,” incorporates ancillary data into its classification strategy and infers greater quality to the resulting data beyond its use of finer scale imagery. The imagery used was of 3-band color-infrared, green (510-600 nm), red (600-700 nm) and near-infrared (800-900 nm).

An object-based classification approach was implemented to classify imagery. Ancillary data, such as Light Detection And Ranging (LIDAR) data, parcel boundaries, and building footprint layers were used to aid in the classification. An object-based classification approach allows the definition of classification rules to be developed using multiple datasets, e.g., low-height green space is fine vegetation and high-height green space is coarse vegetation. Conventional image classification, such as that used in the definition of the NLCD, defines land classes using a pixel-based approach. Using DeFiniens Imaging eCognition software (Definiens 2007), this rule-based classification method was used to first group pixels into objects based on a fractal net evolution algorithm (Baatz and Schape 2000). This approach allows the use of not only spectral response, but also object characteristics such as shape, spatial relations (e.g., connectivity and connectedness) and reflectance statistics for the classification of these objects (Zhou and Troy 2008).

Five land cover classes were included in the land cover dataset according to the HERCULES land cover classification system: fine vegetation (grass & herbs), coarse vegetation (trees & shrubs), building, pavement, and bare soil (Cadenasso et al. 2007). The HERCULES approach to classification captures land cover heterogeneity in urban areas in a more consistent way defining land cover explicitly so that relative density of vegetation or development types can be redefined at the time of use. Further details about the classification methods and results of the high-resolution dataset are documented in Zhou and Troy (2008).

2.5 Methods

This analysis was conducted within the Baltimore Ecosystem Study (BES) Gwynns Falls and Baisman Run watersheds (Figure 2.1). These watersheds represent a gradient of suburban to urban land cover in addition to agricultural, exurban and forested parkland. Thus, the land cover being analyzed in the BES represents a range of urban density.

The benchmark high-resolution dataset has an overall accuracy of 92.3 % at the 0.6m scale (Zhou and Troy 2008). Given that most metropolitan areas do not have access to such an accurate and detailed land cover dataset, the purpose of the study is to use this high-resolution dataset as reference data to assess the usefulness of coarse resolution NLCD to urban applications given the fine-scale heterogeneity that characterizes urban watersheds. However, this evaluation will not elucidate NLCD misclassifications that coincide with errors in the high-resolution dataset. For example, given that the high-resolution dataset was developed with leaf-on imagery, canopy may obscure roads and sidewalks, which may infer minor underestimation of percent pavement. Systematic bias within this dataset was reduced in building classification by incorporating building footprint data, and in fine- and coarse-vegetation classes by use of LIDAR ancillary data.

A 1-km^2 and 9-km^2 square grid system was created, and the percent land cover composition was compiled per grid cell for each spatial scale to examine dataset accuracy and the effects of scale (Figure 2.3). Given the coarse resolution of the NLCD, it is likely to be more accurate at the 9-km^2 than 1-km^2 scale if errors are random and average out at the coarser scale. These grids allow the examination of NLCD applicability when single pixel differences (between the NLCD and fine-resolution dataset) are averaged over a larger area of interest.

The segment boundaries of each gauged BES watershed were used as a third scale of analysis (Figure 2.3). Watershed-scale analysis in this study compares watershed “segments”, that is, the contributing area of each watershed minus the contributing area of the nested gauged headwaters catchments (as shaded in Figure 2.3). The segment approach is used so that calculation of land cover does not occur in overlapping areas and creates independent data. The use of the watershed scale in this study illustrates the percent land cover differences at a scale relevant in tying land cover to BES stream gage data. The catchment segments range from 0.3 to 26 km^2 in area. Regression and residual analysis was conducted to determine biases of the NLCD canopy and impervious layers in characterizing the urban environment.

The different estimates of percent imperviousness derived from the NLCD and high-resolution dataset were entered into the Long-Term Hydrologic Impact Assessment (L-THIA) model to compare modeling results based on the two data products (Harbor and Grove 1997). L-THIA is a very simple hydrologic model based the TR-55 curve number runoff model. Each modeled scenario was based on a 1 km^2 catchment with the noted percent imperviousness and remaining percent as forested land cover on type B soils.

NLCD developed land use categories (Table 2.2) were extracted for the study area. These developed land categories make up the majority of urbanized areas in the NLCD land cover product. The extracted NLCD categories were combined with the high-resolution dataset's land cover classes (i.e., fine vegetation, pavement, etc…) to determine the composition of *land cover* that comprise each of the NLCD developed classes (i.e., open, high-intensity, etc…) within the Gwynns Falls watershed.

In addition, the fine-vegetation class was extracted from the high-resolution land cover dataset for the Gwynn's Falls watershed. This layer was used to determine which NLCD classes include fine vegetation or lawn area--which is a major urban land cover class of interest that is absent in current NLCD products.

2.6 Results

2.6.1 NLCD Canopy Layer

A regression analysis between NLCD canopy layer and the high-resolution coarse vegetation land class (trees and woody shrubs) was conducted, resulting in an r^2=0.94 at the 1-km^2 scale (Figure 2.4). The slope of the regression equation associated with this correlation is unity. The intercept, however, is 10.66, which indicates that the NLCD canopy product generally under-reports urban canopy cover by 11 % as determined by the high-resolution dataset. The heteroscedastic scatter of the residual analysis (Figure 2.4) reflects the bias of the NLCD classification with respect to the high-resolution dataset. The analysis suggests that the NLCD largely under-predicts canopy cover of less than 10 % of a 1 km^2 area of interest (Figure 2.4). When the correlation between the NLCD canopy layer and the high-resolution dataset's coarse vegetation class was assessed according to a 9-km^2 square grid size, the resulting linear equation was $y = 1.07x + 8.96$ with an $r^2 = 0.98$, n=21 (Figure 2.5). The residual analysis of the larger area of interest results in reduced error (+/- 5 %) and more homoscedastic scatter. The canopy layer evaluated on a watershed scale according to individual segments (i.e., excluding upstream segments) of gauged BES watersheds correlated well with the high-resolution dataset, $r^2 = 0.99$, with an intercept over 10 (Figure 2.6). The residual analysis of the watershed scale results in reduced error (+/- 3 %) and more homoscedastic scatter.

2.6.2 NLCD impervious layer

The NLCD impervious data layer is significantly correlated to the high-resolution land-cover data for pavement and imperviousness (buildings + pavement) (Figure 2.7). Inclusion of buildings improves correlation from an r^2 of 0.86 to an r^2 of 0.94 at the 1-km^2 scale and increases the slope towards unity (from 0.6 for pavement alone) with a larger y-intercept term (8 to 10, respectively). The residual error of the impervious layer is narrower (largely within +/- 5 % scatter of residuals) than the canopy layer's 10 to 40 % impervious land cover range as predicted by the high-resolution dataset. The canopy layer's residual error spread +/- 10 % in both directions at that same 10 to 40 % interval (Figure 2.4). However, the range of the residual error of the total imperviousness analysis widens +/- 15 % for areas greater than 40% imperviousness. The dramatic increase in the residual error at 40 % imperviousness is also seen in the residual plot between the high-resolution dataset's percent pavement and the NLCD imperviousness (Figure 2.7). If separate regressions are run for grid cells ranging from 0 to 10 % imperviousness, the regression coefficients increase, but the intercept values drop significantly: 1.6x+3.72, r^2=0.77 for imperviousness; 1.2x+2.4, r^2=0.80 for pavement alone. However, correlation coefficients are much lower for the 0 to 10 % than for the entire range of imperviousness.

Using the L-THIA model, the differences in runoff and nitrogen loads resulting from a consistent 10% difference in impervious surface was estimated based on the y-intercept term 10.17 of the impervious regression in Figure 2.7. The resulting figure (Figure 2.8) suggests a significant underestimation of changes in annual runoff and nitrogen loads based on the NLCD product, rather than a high-resolution data product, 40,000 m^3 and 80 kg, respectively.

Changing the scale of analysis to the 9-km^2 grid slightly improves correlation between these datasets from an r^2 of 0.86 to 0.88 (for pavement) and 0.94 to 0.95 (for total imperviousness) (Figure 2.9). Regression analysis of percent impervious datasets at the watershed scale found a correlation of $r^2 = 0.94$, but the slope coefficient of its regression equation steepens ($y = 1.15x + 7.38$); pavement alone is $y = 0.77x + 5.38$, $r^2 = 0.89$, $n=9$, and p-value = 0 (Figure 2.10).

2.6.3 NLCD Developed Classes

We conducted an analysis to determine which land-cover classes comprise the developed land-use classes of the NLCD of the Gwynns Falls watershed (Figure 2.11). NLCD developed classes (see Table 2.2) range substantially in land-cover composition. Both building and pavement classes increase proportionally from open to high-intensity developed NLCD classes (Figure 2.11). Both coarse and fine vegetation classes decreased from open to high intensity development.

The distribution of the land cover composition within the developed classes was examined in more detail (Figure 2.12). The interquartile range of the percent imperviousness, fine vegetation and coarse vegetation is narrow for the high intensity development class. However, the interquartile range in predicting land cover from these NLCD classes widens as development intensity declines. While the interquartile range spans less than 5 % for high intensity development, the interquartle range of the canopy cover in the open development land class spans over 15 %.

2.6.4 NLCD grass-related classes

The NLCD includes fine-vegetation land cover within four land-use classes: developed open space, pasture, grassland, and cultivated crops. No NLCD "grasslands" are classified in the Gwynns Falls watershed. The fine vegetation class was extracted from the high-resolution land cover dataset to determine which NLCD classes incorporate fine vegetation land cover into their land use categories (Figure 2.13). The majority of fine vegetation or grass is found in the developed open space and low-density residential NLCD classes. The remainder exists primarily in the pasture and crop categories. The range/distribution of the percent fine vegetation of these grass-related classes was examined (Figure 2.14). This figure displays the median, interquartile range, and confidence interval of percent fine vegetation coinciding with NLCD land cover categories within 1 km^2 grid cells. The interquartile range is over 20 % for open and low intensity development.

2.7 Discussion

2.7.1 Canopy

The correlation between the NLCD canopy layer and the high-resolution dataset is weakest for 1 km^2 areas with less than 10 % canopy cover. However, the y-intercept of all of these regression models is near 10, indicating that the NLCD consistently under reports canopy cover by nearly 10 % in urbanized areas. The regression intercept term and residuals indicate that NLCD sub-pixel canopy-cover algorithms poorly discern small or patchy tree cover. Because the assumption of heteroscedasticity is violated, the regression equation cannot be universally applied to NLCD data. Thus, adding 11 % to all percent forest calculations will not consistently account for the bias of the canopy dataset. The NLCD predictions of canopy cover are highly variable at canopy covers between 10 and 70 %. Canopy cover over 70 % is frequently over-predicted by the NLCD. While the regression equation indicates a slope of 1 and a high r^2 value, this effect occurs largely due to the balance of biases at the low and high percent canopy levels with a large degree of scatter at the mid-range percent canopy cover.

Increasing the area of interest from 1km^2 to 9 km^2, improved the fit indicating that that regional studies of canopy cover with the NLCD canopy layer have high correlation with a very fine-resolution dataset. As expected, land cover analysis of areas exceeding 9 km^2 is more accurate and more heteroscedastic. However, percentages are averaged over a larger area of interest and subsequently, the major ranges of bias < 10 % and > 70 % are not included. Thus, augmenting percentages by the intercept, 9 %, may adjust for the urban bias or simply obviate the bias by averaging out the extremes.

2.7.2 Imperviousness

The high correlation between the NLCD impervious layer and the high-resolution dataset is surprising given that many buildings are smaller than the 30m detection limit of the NLCD. The effect of combining 1m digital orthophoto quadrangles and Landsat spectral data, and dense row-house development with minimal intervening yard space may account for the accuracy of the product in urban environments. The differences in slopes of these regression lines, 0.59 (pavement alone) and 0.96 (total imperviousness), also indicates that determination of percent pavement / directly connected or effective imperviousness, is roughly 60 % the NLCD reported impervious layer value at the 1 km^2 scale of analysis. Directly connected or effective imperviousness refers to the fraction of impervious surfaces that convey directly to the stream through gutters and storm water infrastructure. However, biases along the range of imperviousness should be factored in if considering this estimation of effective imperviousness.

The error of the NLCD increases at 40 %, which is surprising given that one might expect medium-resolution data to better define areas of lower heterogeneity (Figure 2.7). Areas with large percent imperviousness, > 70 %, for example, are most frequently over-predicted by the NLCD relative to the high resolution dataset—vegetated areas surrounded by large percent impervious surface (e.g., road medians or parking lot rain gardens) are not discerned by the NLCD, and the entire area is attributed as impervious. Thus, fine-scale low-impact development practices are not apparent in the NLCD.

Areas < 10 % impervious are largely underestimated by the NLCD with low correlation. The difference between the NLCD makes a large difference for areas of less than 10 % imperviousness because this percentage marks a critical threshold with respect to the relationship between land cover and hydrologic response. When the high-resolution dataset suggests that an area is 10 % impervious, the NLCD typically reports that it is less than 10 %. When the NLCD reports that the percent imperviousness is 10 %, the high-resolution imagery suggests that the imperviousness is approaching 20 %. Because areas with < 10% imperviousness maintain stream function and are important areas to target for land conservation or other mitigation practices, the inaccuracy at this threshold is not marginal. The 10% underestimation of the NLCD is based on the y-intercept term does not factor in the biases at high and low percent imperviousness. However, the L-THIA model indicates that the overall impact of using the NLCD land cover estimates in commonly used hydrologic models may be quite substantial (Figure 2.8). Given that the modeled error is consistent for the range of imperviousness, the proportionality of this error is greater in areas of low percent imperviousness, i.e., low-density developed areas.

Improved accuracy of the 9 km^2 scale results from decreasing areas that fall within the ranges of bias <10 % and > 70 %. Regression analysis at the watershed scale found a correlation of $r^2 = 0.94$, but the steeper slope coefficient of its regression ($y = 1.15x + 7.38$) indicates a bias of imperviousness by the NLCD relative to the high-resolution dataset (Figure 2.10). Thus, use of the NLCD in urban areas for developing modeling parameters for areas exceeding 9 km^2 may be valid.

This analysis indicates that overall accuracy of the NLCD impervious layer is beyond that reported for mapping zone 60 of 91 % (Homer et al. 2004). The residual analyses indicate that at percent imperviousness less than 20, the NLCD residuals for pavement alone are less than pavement plus buildings. Thus for areas of low-density development (< 20 % impervious), the NLCD impervious layer is more representative of pavement alone—directly connected or effective impervious area—than total imperviousness. However, the residuals suggest that in areas of higher density development (> 70% impervious), the NLCD is better indicator of total imperviousness including buildings. In medium density areas (40 to 70 % impervious), the NLCD exhibits the least amount of similarity with the high-resolution data, indicating that studies of areas of medium density should supplement NLCD to gain more accurate estimates of total imperviousness.

Use of the NLCD canopy and impervious products for hydrologic purposes in urban areas may be possible when the land cover is 10 to 40 % at 9 km^2 because error increases dramatically at 40 %. Comparatively, the error for areas < 10 % impervious or canopy cover is greater. This difference is of particular importance with regards to the important threshold of stream degradation defined at 10 % imperviousness. Separate regression models for the < 10 % range of imperviousness has a weaker correlation than the full range. This result emphasizes the irregularity of the NLCD in defining fine-scale imperviousness.

2.7.3 Land cover

Land cover composition of developed land classes falls within the expected range of impervious cover as described in Homer et al. (2004) (Table 2.2). However, no detailed information for vegetation composition within NLCD land cover categories has been reported previously. The land cover breakdowns illustrated in Figure 2.11 indicate more consistent land cover composition within the NLCD highly developed land class than in the less developed land classes. The reduced consistency of land cover composition in less dense land classes may be due to the trend to develop either former forest or farm to low density neighborhoods attributing greater percent coarse or fine vegetation, respectively. Fortunately, the NLCD canopy layer provides a useful tool to help discern total tree cover. However, the interquartile range for fine vegetation or grass in the NLCD open development class spans over 20 %—emphasizing the high variability of land cover composition of the NLCD land cover categories. The ranges of land cover composition of NLCD developed and grass-related classes denote critical limitations in the use of the NLCD alone for urban hydrologic applications. This evaluation did not elucidate errors in the high-resolution dataset coinciding with those of the NLCD. However, the error of the high-resolution dataset averaged at the 1km^2 scale (~2.8 million pixels) is likely less than error for 30m data for the same area of interest (~1111 pixels).

2.8 Conclusions

This study aims to evaluate the usefulness of the NLCD to estimate hydrologically significant land cover parameters in an urban environment and finds three primary limitations to the use of NLCD for urban hydrologic applications. 1) The canopy and impervious layers exhibit bias at <10 % and >70 %. 2) The ratio of total impervious area and connected impervious area differs along the range of percent imperviousness. 3) The variability of vegetation of NLCD categories limits the usefulness of the NLCD for determining the composition of pervious urban land cover.

Urban hydrology depends on many factors--slope, sewer infrastructure, soil type and compaction, and other management practices, which cannot be derived from urban landcover datasets. The emphasis of this paper was derivation of land cover parameters for hydrologic use in urban settings. Land cover is a major factor controlling catchment response in urban systems and is an important parameter in most hydrologic models. Land-cover parameters are frequently derived from the NLCD for the purpose of hydrologic modeling. However, given the biases of the NLCD at low and high percent canopy or imperviousness, ground-truthing with high-resolution imagery or orthophotos is necessary to acquire accurate estimates of land cover parameters.

The NLCD canopy layer is biased by 10 to 11 % at the 1-km^2, 9-km^2, and watershed scales. However, the agreement is best for larger areas of interest due to the averaging of error. The systematic error of the NLCD percent canopy dataset in areas < 10 and > 70 % is important due to urban tree canopy goals that are associated with storm-water runoff controls (see Raciti et al. 2006). A critical aspect of these urban canopy policies and their implementation is the ability to measure land cover, including both canopy and impervious surface cover, at a high spatial resolution and accuracy to facilitate assessments, long-term monitoring, and watershed management. The NLCD would most likely report that small tree patches, comprising less than 10 % area, are closer to 0 % canopy cover. This omission could translate into a reduced estimate of hydrologic sinks, increased prediction of floods and pollutant transport, and misguide urban canopy policies. For areas of high canopy cover, the NLCD more often overestimates percent forest cover, which may inaccurately indicate that urban canopy goals are met. The overall accuracy of the canopy dataset is balanced by averaging the biases at each end of the land cover spectrum. Use of higher resolution imagery is suggested when possible given this bias and the range of residual error.

Similarly, the NLCD impervious layer does not detect the fine-scale impervious features that make up less than 10 % of the area of interest. In addition, the proportionality of the modeled error associated with the NLCD under-prediction of imperviousness is greatest in low-density developed areas. Channel degradation associated with urban catchments is commonly cited to occur when the threshold of imperviousness exceeds 10 % effective impervious area (Booth and Jackson 1997, Schueler 1994). Thus, the 0 to 20 % range of total imperviousness is a particularly important threshold for determining changes in the resulting hydrograph. While the lack of correlation could potentially be attributed to errors within high-resolution dataset, it is unlikely given the degree of ancillary data used in the classification of the high-resolution dataset. The shift in residuals at the 10 % point makes the use of the NLCD for hydrologic applications particularly difficult. Percent imperviousness at and beyond the 10 % critical threshold cannot be consistently corrected using the included regression equations because of the biases of the associated residuals.

A rough estimate of connected imperviousness is indicated to be an overall 60 % of the NLCD total imperviousness. However, this percentage differs for areas of low and high percent imperviousness, i.e., in areas of high development density, the NLCD more accurately reports total imperviousness and areas of low density development, the NLCD reflects connected imperviousness (pavement) alone. Inability to accurately estimate this variable is critical given that effective impervious area (the product of total imperviousness and connected imperviousness) is a strong predictor of stream ecological condition (Walsh et al. 2005 and Hatt et al. 2004). Estimating effective imperviousness from the NLCD is a moving target given the inclusion of buildings in high percent impervious areas and exclusion of such structures at low density.

The NLCD land categories limit users' ability to discern land cover composition in developed areas. While this paper attempts to provide information on the land cover composition comprising the developed land categories, the information is more variable for less densely developed areas frequently categorized as low density development, open development or row crops by the NLCD. Thus, the NLCD is less applicable in lawn-dominated suburbs—the most pervasive and rapidly growing development in the U.S. (Brown et al. 2005). In addition, suburban development yields the highest urban nutrient pollutant loads (Shields et al. 2008 and Law et al. 2004) and is a key target for nonpoint source pollution reduction.

The differences identified among the developed classes of NLCD 2001 suggest misclassification errors based on an Anderson level II classification system (Anderson et al. 1976) and the subjectivity of incorporating land use into the land cover datasets. The HERCULES approach offers potential improvement to capturing land cover heterogeneity in urban areas in a more consistent way (Cadenasso et al. 2007). Using this system, land cover is defined explicitly as building, pavement, coarse vegetation, fine vegetation, or bare land. Based on the HERCULES system, the relative density of vegetation or development types can be redefined at the time of use. The NLCD 2001 use of development density classes imposes land use information into the land cover database. While the added value may be useful to some users, the imposed definitions cannot be removed to determine the underlying land cover types more explicitly.

Hydrologic models rely on accurate land cover inputs, including impervious surface, lawn and canopy data to predict water quality and quantity impacts of policy changes and climate variability. Water quality impacts may include the changes in pollutant sources and deposition related to vegetation data and pollutant transport via impervious surface and the connectivity of subsurface flow. Water quantity impacts related to flash flooding and groundwater recharge are greatly influenced by percent imperviousness or soil compaction. Thus, assessment of land cover variables is an important part of land conservation policy and targeting of low impact development strategies. The findings of this study hold implications for other disciplines, e.g., the estimation of urban nutrient fluxes and micro-climate effects.

The bias of the impervious and canopy layers of the NLCD inhibits the development of comprehensive watershed models based on an inability to link regional and fine-scale data. The large variability in land use categories in this dataset further complicates its use for the determination of land-cover parameters for hydrologic modeling applications. The NLCD is a great resource for many regional scale applications and initial analyses; however, it is limited given the fine-scale heterogeneity of urban land cover, lack of discernment of lawn area, and the biases of both the canopy and impervious sub-pixel classification layers.

2.9 Acknowledgements

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Table 2.1 Reported accuracy of high-resolution (0.6m) and NLCD land classes (30m).

Land Class	Dataset	Accuracy (%)
Building	High-resolution	83.6[1] user, 94.4[1] producer
Coarse Vegetation	High-resolution	97.7[1] user, 94.4[1] producer
Fine Vegetation	High-resolution	94.9[1] user, 89.3[1] producer
Pavement	High-resolution	91.9[1] user, 88.3[1] producer
Bare soil	High-resolution	90[1] user, 100[1] producer
Overall	High-resolution	92.3[1] producer
Percent canopy	NLCD	93[2] producer
Percent imperviousness	NLCD	91[2] producer
Land class categories	NLCD	77[2] producer

[1]Zhou and Troy 2008; [2]Homer et al. 2004

Table 2.2 Table describing NLCD developed land categories

NLCD Developed Category Number	Name	Description (Homer et al. 2004)
21	Developed open space	some constructed materials, but mostly lawn grasses with less than 20 % imperviousness
22	Low intensity developed	areas with 20-49 % imperviousness
23	Medium intensity developed	areas with 50 to 79 % imperviousness
24	High intensity developed	areas with greater than 80 % imperviousness

Table 2.3 Percent land cover for each of the Baltimore Ecosystem Study gauged watersheds as reported by Zhou and Troy (2008) objected-oriented classification of high-resolution imagery.

Watershed	Building	Coarse Veg.	Fine Veg.	Pavement	Water	Bare Ground
Horse Head	5	40	37	14	1	3
Baisman Run	2	80	15	2	0	0
Glyndon	9	39	30	20	0	1
Villa Nova	9	38	32	21	0	1
Gwynnbrook	10	33	35	19	0	3
Red Run	4	47	30	13	0	6
Scotts Level	12	34	32	22	0	1
Carroll Park	16	31	23	29	0	1
Dead Run	12	23	29	34	0	1
Entire Gwynns Falls	12	34	30	24	0	2

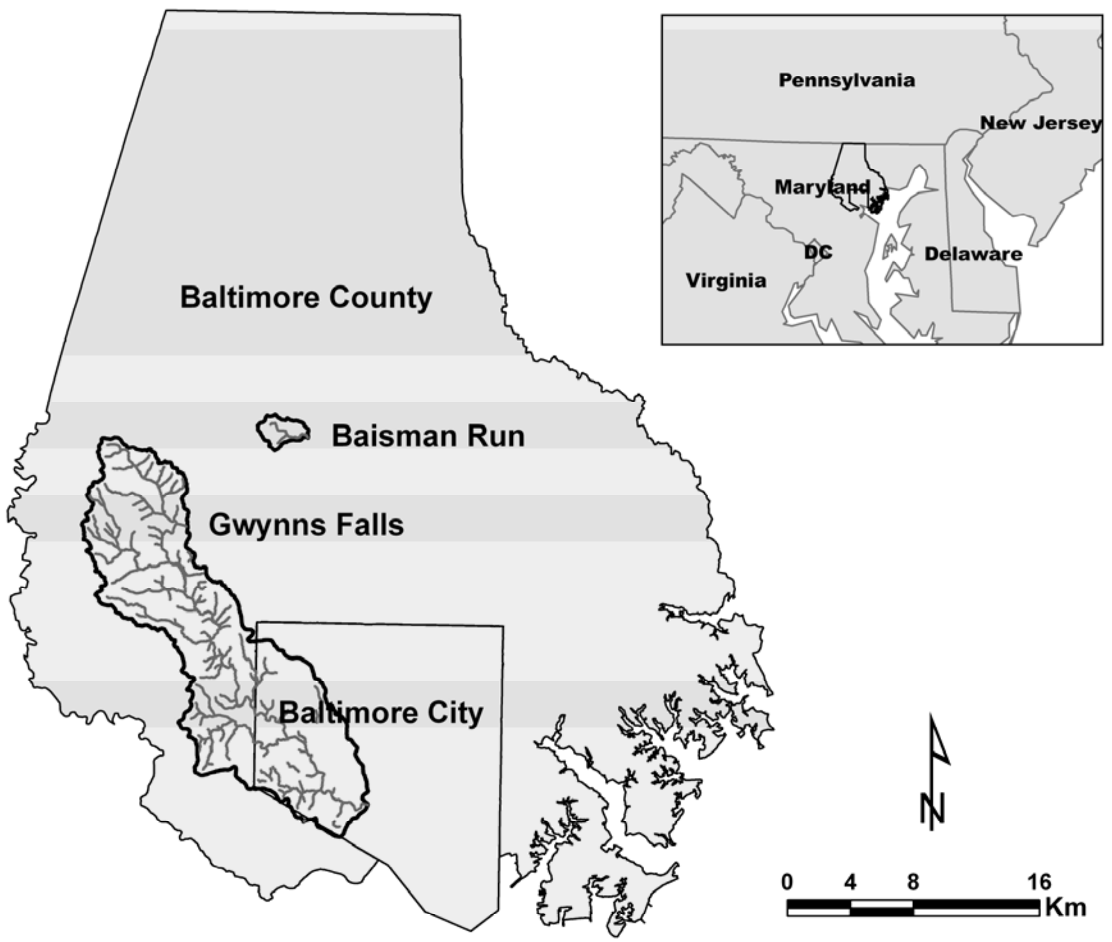

Figure 2.1 Map of Baltimore Ecosystem Study. Map includes outline of Baltimore City, part of Baltimore County, Gwynns Falls and Baisman Run main watershed delineations.

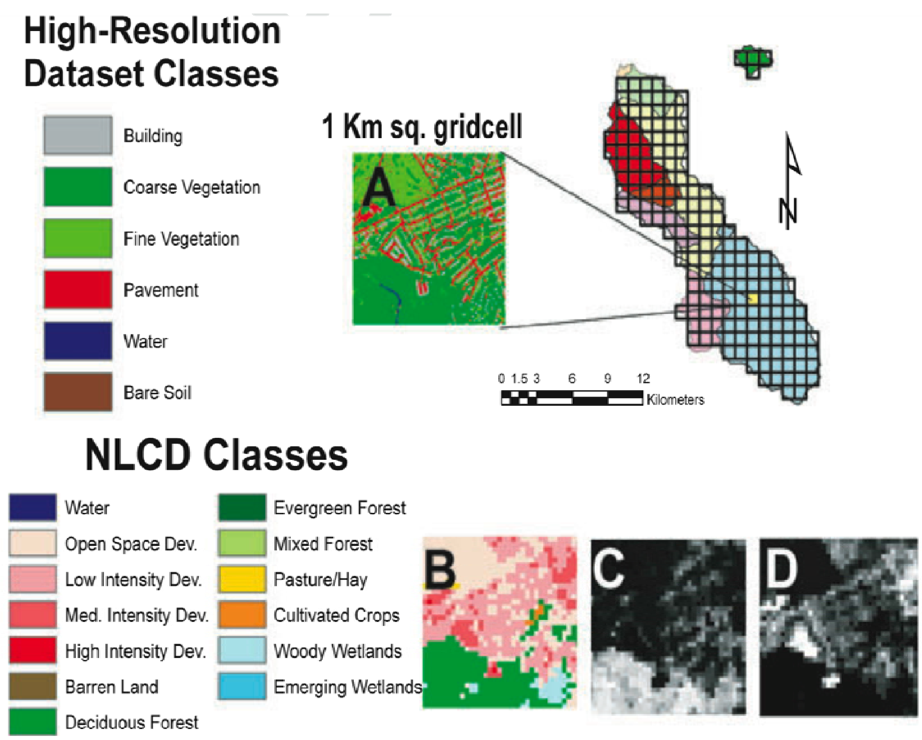

Figure 2.2 1-km^2 extraction of each of four datasets included in this analysis: a) Zhou and Troy's object-oriented classification of high resolution dataset (2008); b) Gwynns Falls watershed depicting 1-km^2 grid cell where image classification was extracted; c) NLCD land cover dataset; d) NLCD percent impervious dataset—white is 100%, black is 0%; 3) NLCD percent canopy dataset—white is 100%, black is 0%.

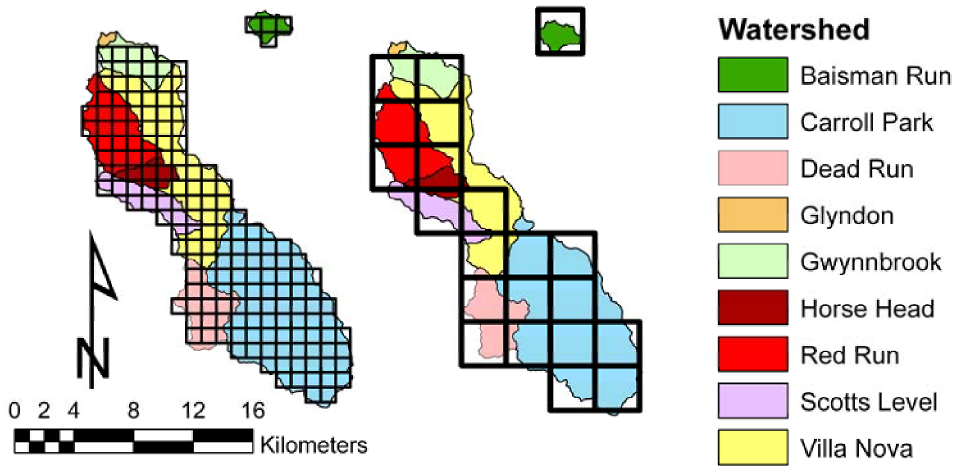

Figure 2.3 Illustration of the three spatial scales used in this analysis: Left) 1-km^2 grid; Right) 9-km^2 grid overlaying the gauged watersheds (third scale) of the Baltimore Ecosystem Study.

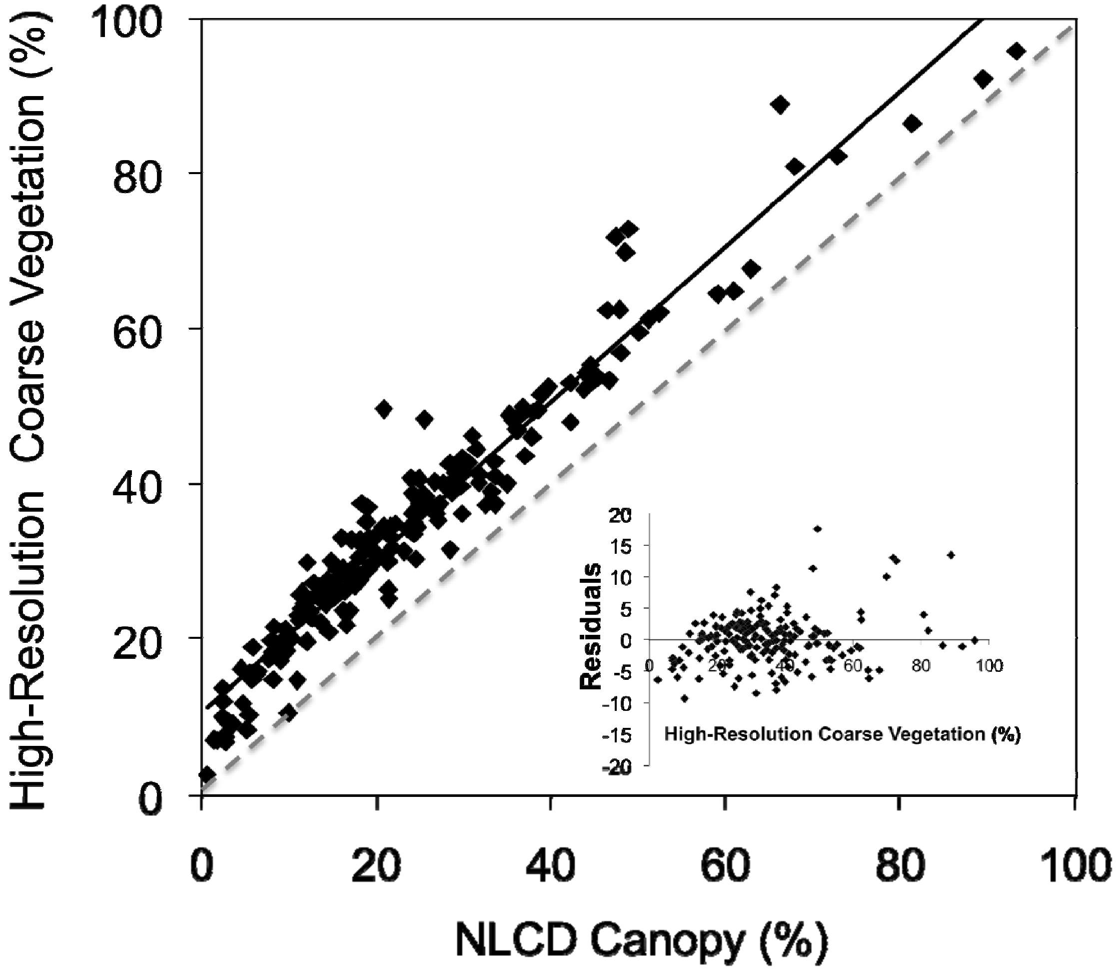

Figure 2.4 Correlation between the coarse vegetation class and the NLCD canopy data. r^2 = 0.94, *n*=174, *p*-value=0. The regression equation is: $y = x + 10.66$. The 1 to 1 line of the plot area is depicted as a dotted grey line. Regression residuals are included in inset.

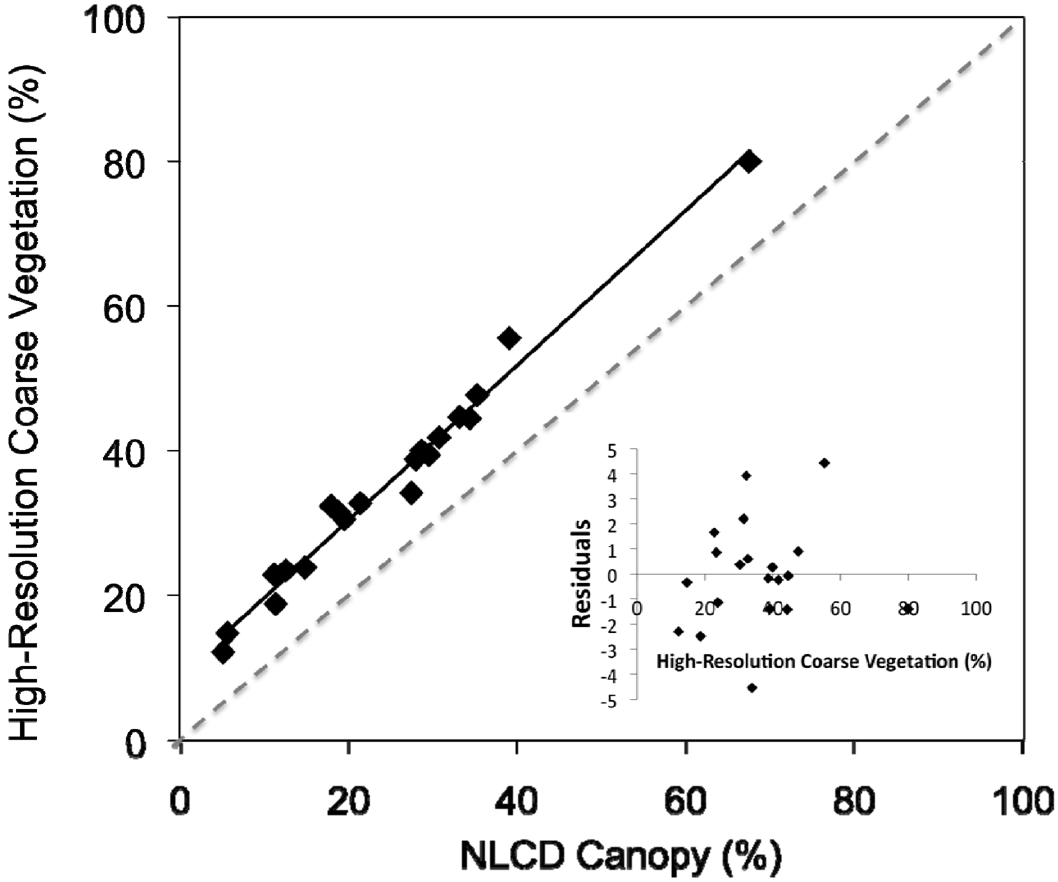

Figure 2.5 Correlation between the coarse vegetation class and the NLCD canopy data for 9 km^2 grid. r^2 = 0.98, n=21, p-value=0. The regression equation is: $y = 1.07x + 8.96$. The 1 to 1 line of the plot area is depicted as a dotted grey line. Regression residuals are included in inset.

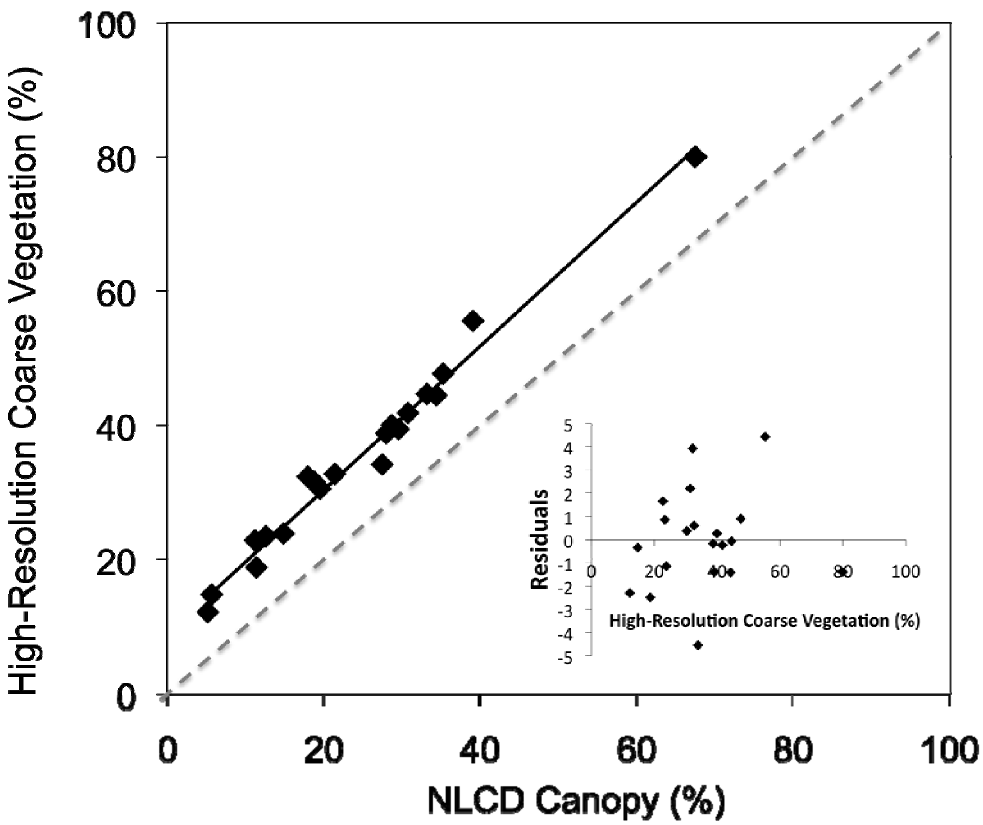

Figure 2.6 Correlation between the coarse vegetation class and the NLCD canopy data for BES subwatershed scale. The regression equation is: $y = x + 10.23$, $r^2 = 0.99$, n=9, p-value=0. The 1 to 1 line of the plot area is depicted as a dotted grey line. Regression residuals are included in inset.

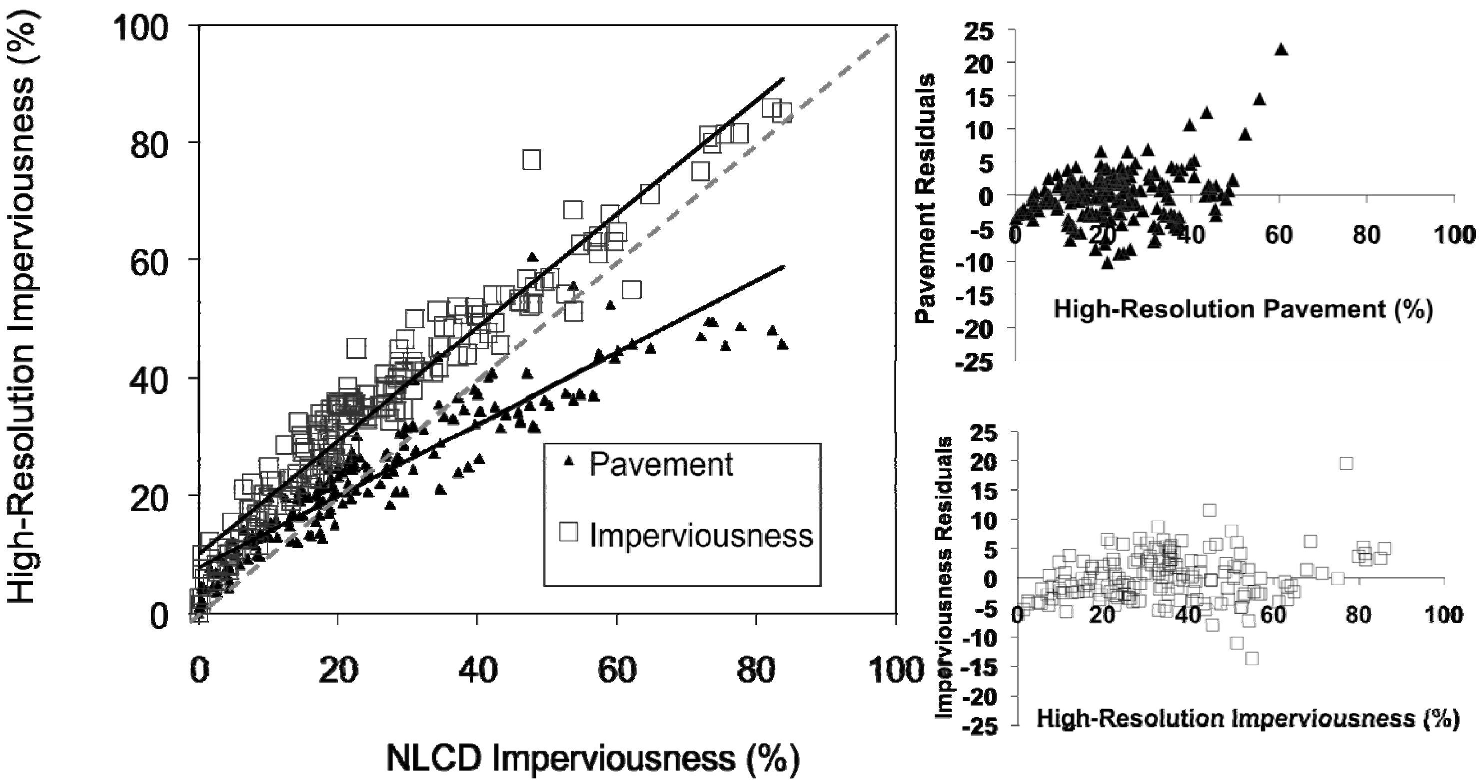

Figure 2.7 Correlation between NLCD percent imperviousness and high-resolution dataset at the 1km^2 scale. Two lines compare percent pavement class (black triangles) and total percent imperviousness (i.e., percent pavement + percent building, as white squares) for each 1 km^2 grid cell. Pavement: $y = 0.61x + 7.87$, $r^2 = 0.86$, n= 174, p- value=0. Impervious: $y = 0.96x + 10.17$, $r^2 = 0.94$. The 1 to 1 line of the plot area is depicted as a dotted grey line. Residuals of each regression are included to right.

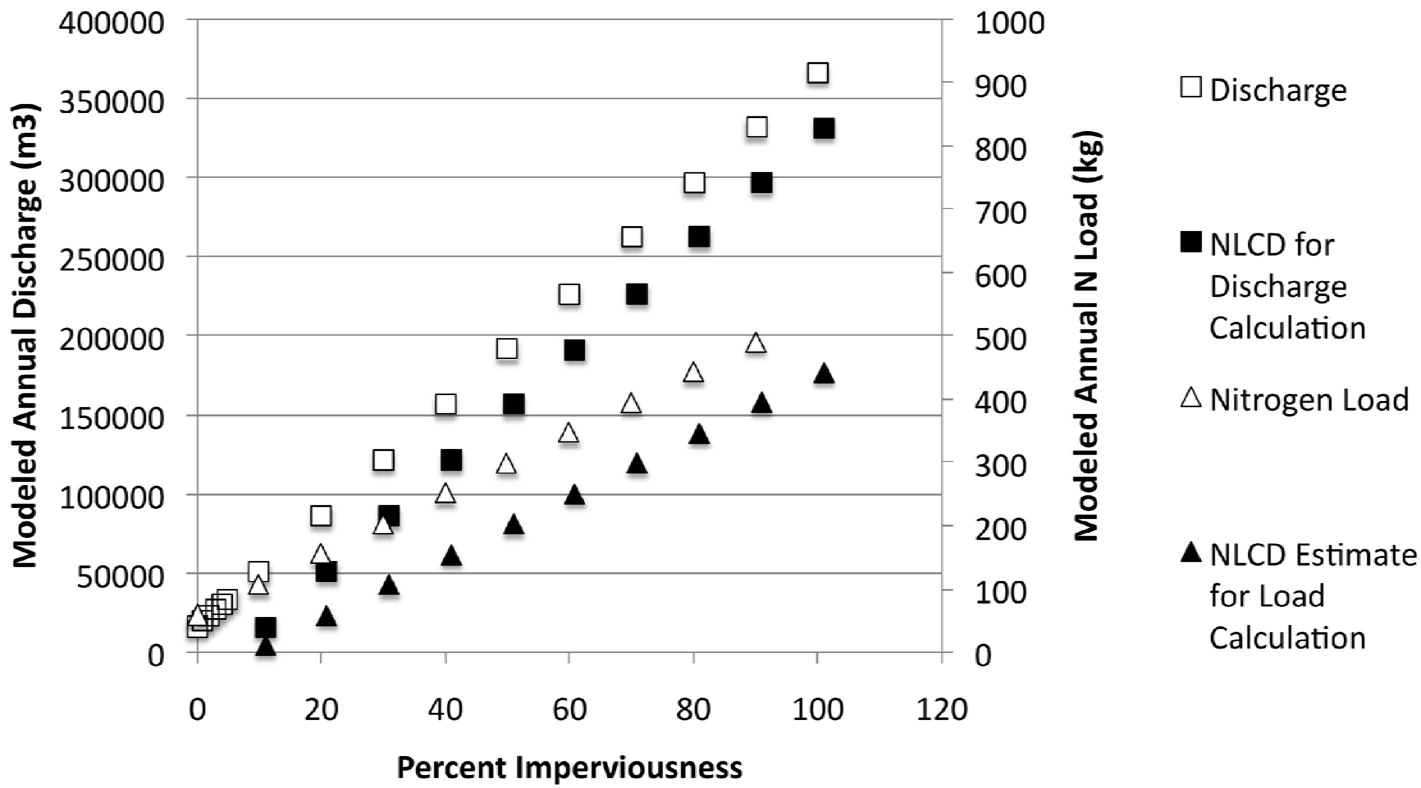

Figure 2.8 Estimates of annual discharge and nitrogen load differences calculated using L-THIA model based on 10% difference in impervious surface area.

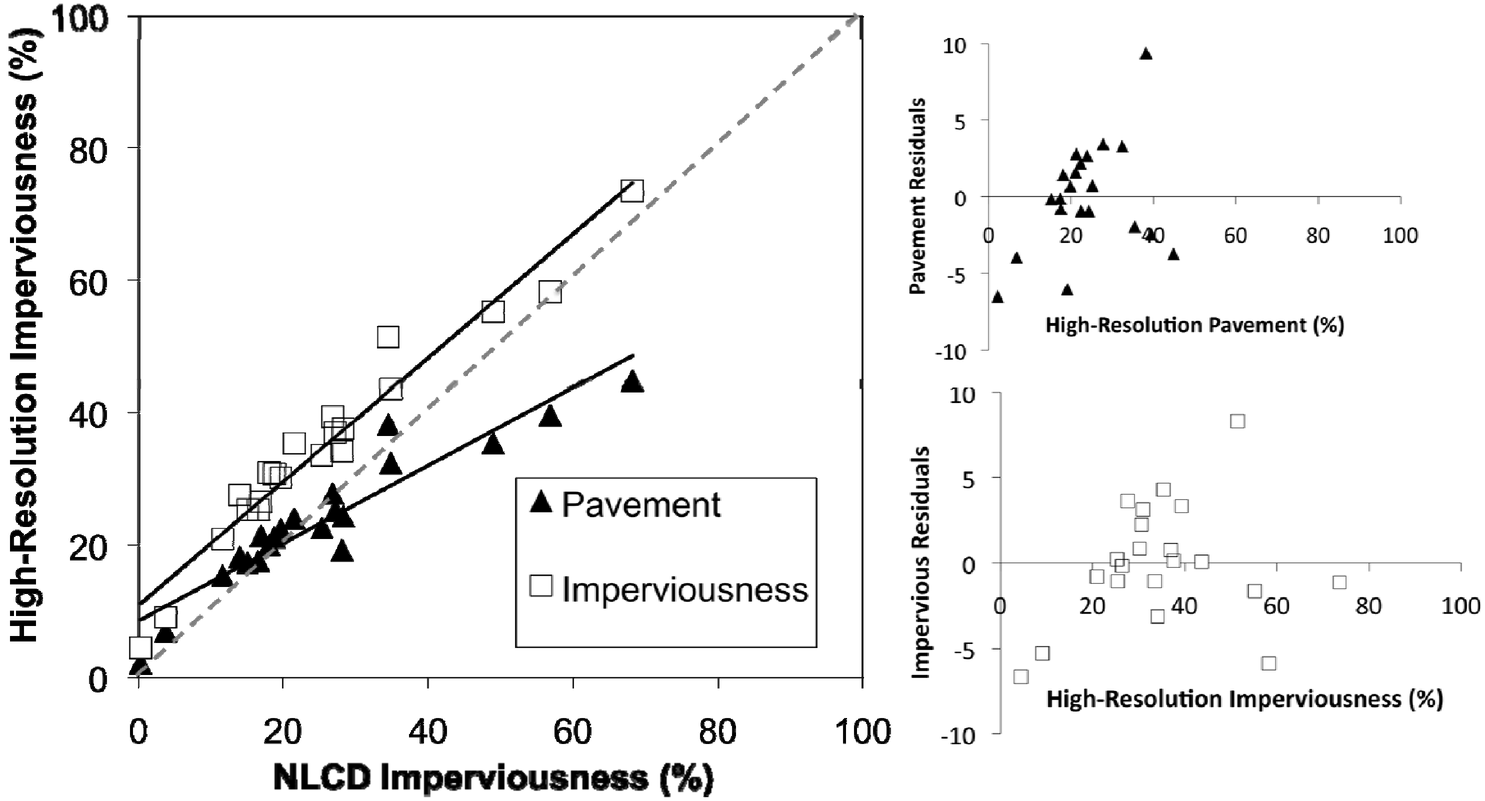

Figure 2.9 Correlation between NLCD percent imperviousness and high-resolution dataset at the 9 km^2 scale. Two lines compare percent pavement class (black triangles) and total percent imperviousness (i.e., percent pavement + percent building, as white squares) for each 9 km^2 grid cell. The relationship at the 9 km^2 scale for pavement: $y = 0.59x + 8.56$, $r^2 = 0.88$, p-value=0, and impervious is: $y = 0.94x + 10.91$, $r^2 = 0.95$, p-value=0. The 1 to 1 line of the plot area is depicted as a dotted grey line. Residuals of each regression are included to right.

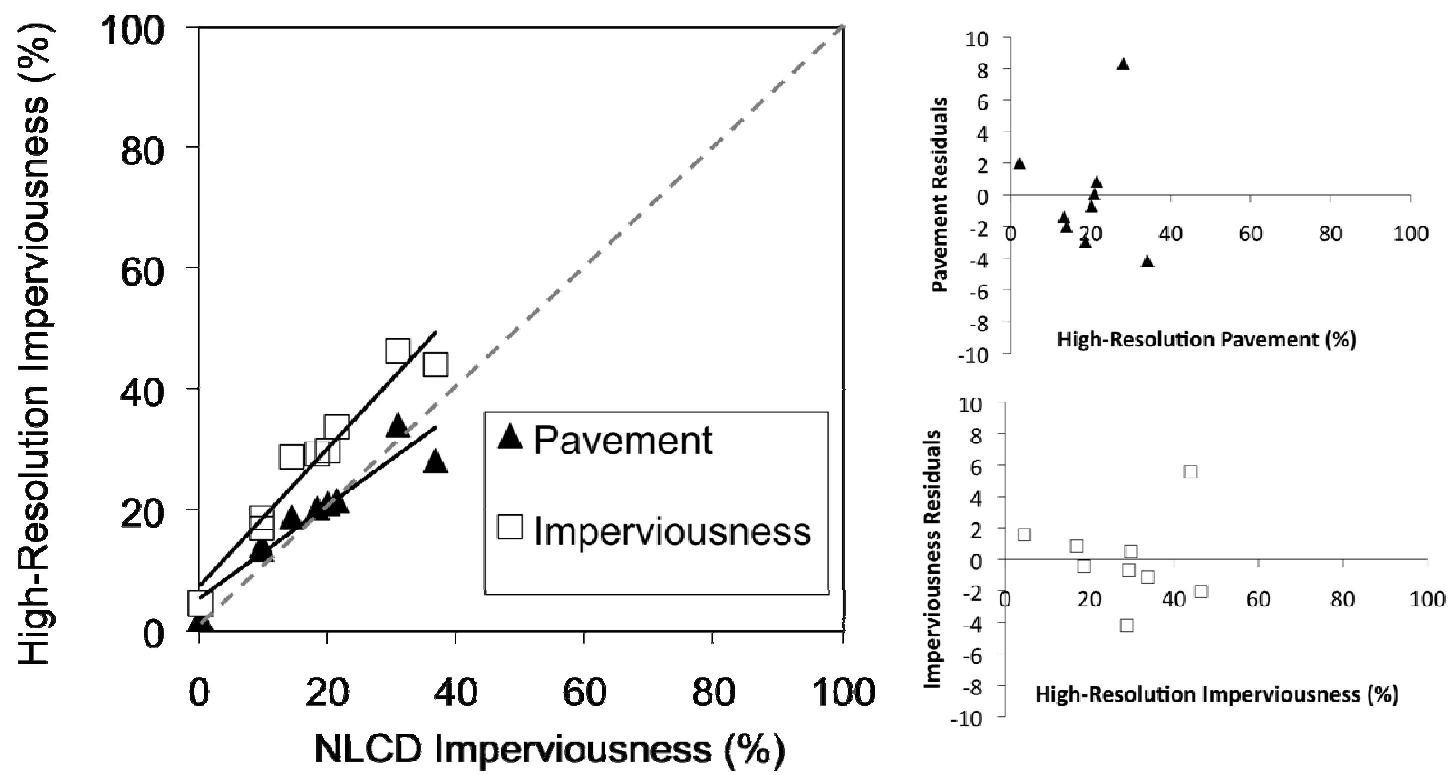

Figure 2.10 Relationship between NLCD percent imperviousness layer and percent pavement + building classes in Zhou and Troy (2008) high-resolution dataset at the watershed scale. The regression equations are: Total imperviousness: $y = 1.15x + 7.38$, $r^2 = 0.94$, n=9, and p- value=0; Pavement alone: $y = 0.77x + 5.38$, $r^2 = 0.89$, n=9, and p-value = 0. The 1 to 1 line of the plot area is depicted as a dotted grey line. Residuals of each regression are included to right.

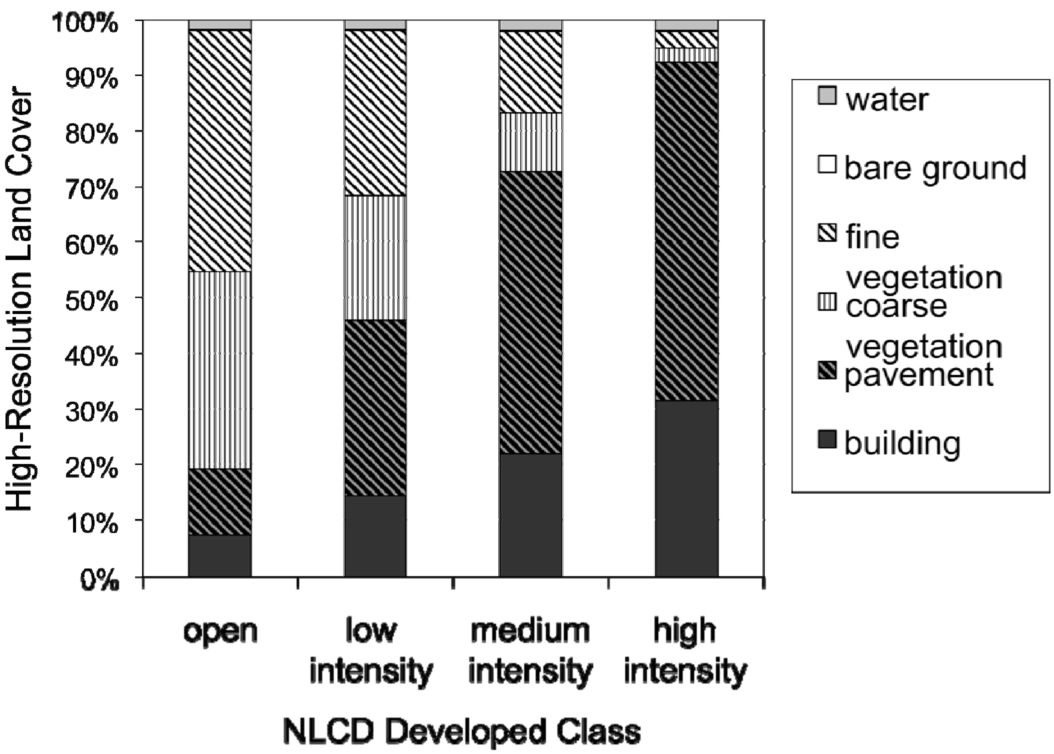

Figure 2.11 Land cover composition of NLCD developed classes: open, low intensity, medium intensity, and high intensity based on high-resolution dataset (Zhou and Troy 2008).

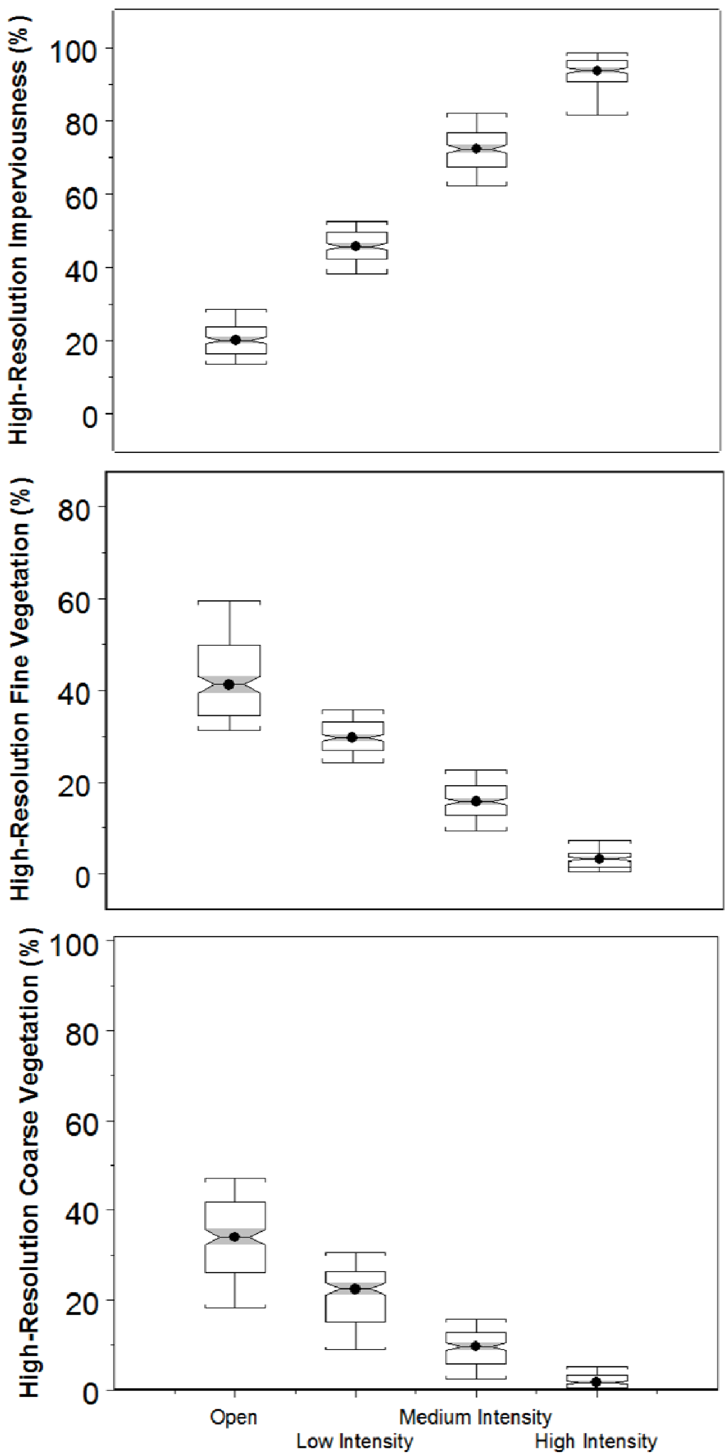

Figure 2.12 Comparison of NLCD developed land classes to high-resolution dataset (Zhou and Troy 2008) according to 1km^2 grid cells. Box plots of NLCD development classes: open, low-, medium- and high-intensity for impervious, fine vegetation and tree cover composition within each. The circle depicts the median, the shaded notch represents the 95% confidence interval, the box indicates the interquartile range, and the 10 and 90% quartile ranges are illustrated with the "whisker" bars.

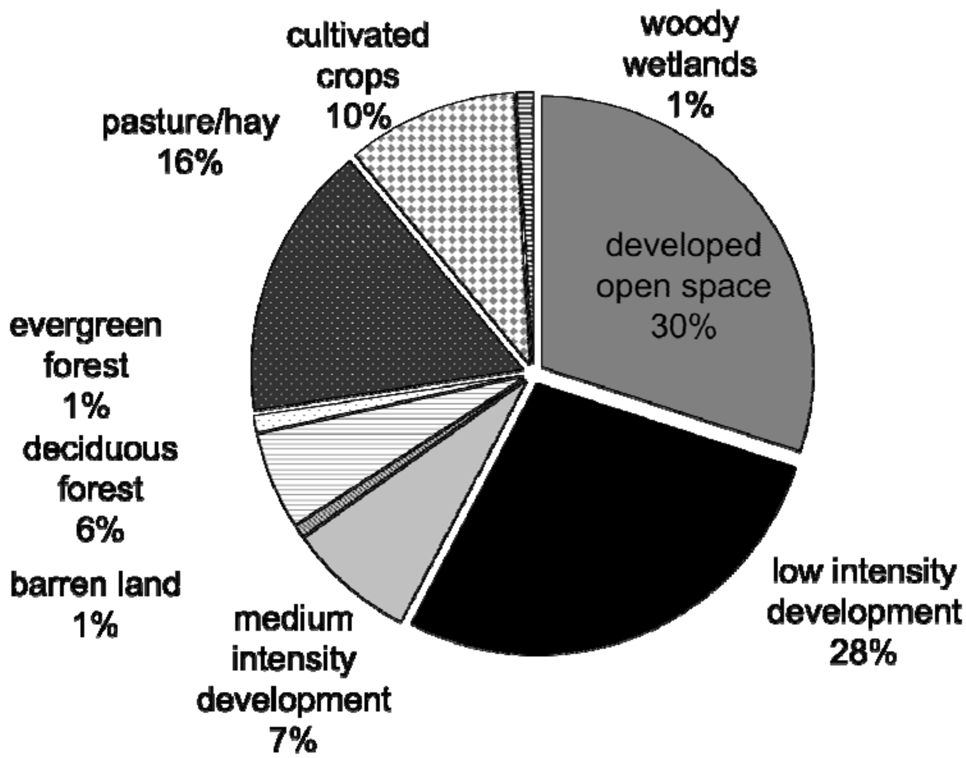

Figure 2.13 Apportionment of fine vegetation in NLCD mixed land cover categories. The fine vegetation land cover class of Gwynn's Falls was extracted from the high-resolution dataset (Zhou and Troy 2008) to determine which land use categories are primarily comprised of lawn.

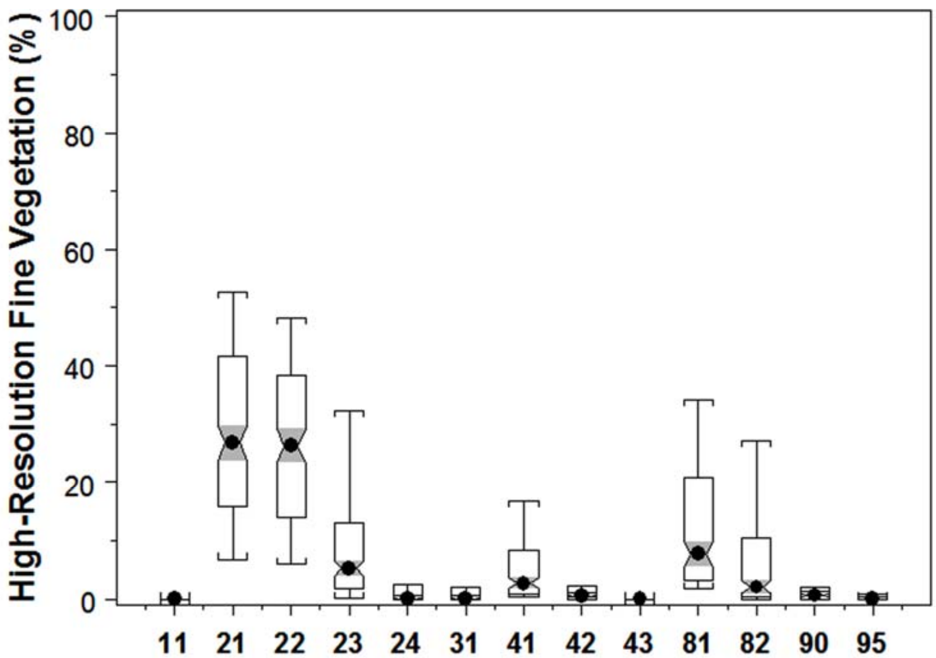

Figure 2.14 Distribution of NLCD grass-related categories displaying percent of 1 km^2 grid cells occupied by fine vegetation as defined by high resolution dataset (Zhou and Troy 2008). NLCD classes on the x-axis are defined as 11: open water; 21: developed, open; 22: developed, low density; 23: developed, medium density; 24: developed, high density; 31: barren; 41: deciduous forest; 42: evergreen forest; 43: mixed forest; 81: pasture/hay; 82: cultivated crops; 90: woody wetlands; 95: emergent herbaceous wetlands. The circle depicts the median, the shaded notch represents the 95% confidence interval, the box indicates the interquartile range, and the 10 and 90% quartile ranges are illustrated with the "whisker" bars.

CHAPTER 3. EFFECTS OF FINE-SCALE RESIDENTIAL PATTERN ON SUBURBAN STREAM NITROGEN

3.1 Preface

The previous chapter revealed that the moderate-resolution NLCD is limited in discerning spatially explicit land cover patterns in the heterogeneous urban landscape. Due to this limitation, the following study linking spatially explicit urban landscape features to nitrogen fluxes in small watershed areas makes use of the high resolution object-based land cover dataset (Zhou and Troy 2008) used as the benchmark dataset in Chapter 2. The following chapter derives not only land cover composition from this dataset, but also an inverse-distance weighted land cover metric with which to evaluate the impacts of land cover arrangement. In addition, digitized maps of septic reserve areas were derived from records at the Maryland Department of Natural Resources and Environmental Protection for further information regarding spatially explicit management features attributing to suburban nitrogen fluxes. Chapter 3 is the result of a collaborative effort with M. Cadenasso, L. E. Band and P. M. Groffman and will soon be submitted to the *Journal of Environmental Management.*

3.2 Abstract

This study examined complex interactions of heterogeneous land cover, position, and water management practices that characterize the urban landscape, building on previous, larger-scale efforts in the U.S. National Science Foundation funded urban long-term ecological research (LTER) project, the Baltimore Ecosystem Study (BES). The objective was to determine metrics that are most applicable to link landscape structure and nitrogen fluxes. We found wastewater infrastructure, population density and setback of septic reserve areas (SRAs) explain significant variation of residential area headwater stream nitrate concentrations. Of these, waste management strategy, septic or sewered, had the most-significant impact. Within septic-managed watersheds, fine-scale metrics, including population density, location of septic systems and the existence of a small wetland correlated with in-stream nitrate concentration. Fine-scale influences in catchments served by sanitary sewers were not obvious. Within residential land use, spatially explicit land cover proportions and location do not explain variation in stream nitrate; however, other aspects of water quality and stream health were not assessed. Results suggest that consideration of neighborhood infrastructure and design is key to understand links between urban landscape structure and nitrogen fluxes.

3.3 Introduction

Land development has degraded the health of U.S. coastal rivers and bays, and nitrogen pollution is responsible for the greatest amount of damage (NRC 2000, Howarth et al. 2002). Urban nonpoint sources are among the greatest contributors to stream nitrogen pollution (Vitousek et al. 1997, Carpenter et al. 1997, Puckett 1994). Research in the city of Baltimore, MD, USA has shown that the greatest metropolitan nitrogen loads originate from suburban and exurban residential areas (Shields et al. 2008, Kaushal et al. 2008, Groffman et al. 2004). This type of residential land use is the most rapidly expanding in the U.S. (Brown et al. 2005). Attempts to limit total maximum daily loads (TMDLs) of nitrogen in urban areas are currently under way in an effort to reduce nitrate delivery to estuaries. However, such efforts are limited by our lack of knowledge about urban nitrogen fluxes.

While nitrogen flux differences among land use types is an active area of study (e.g., Boyer et al. 2002, Poor and McDonnell, 2007), less research has focused on determining the dominant features controlling source/sink dynamics within residential land uses. Currently, nitrogen source/sink dynamics in suburban areas cannot be easily explained with simple relationships between percent land use and stream chemistry metrics (Burns et al. 2005, Groffman et al. 2004, Cadenasso et al. 2007). A modeling study evaluating the Mid-Atlantic regional impacts of land cover on stream ecosystem parameters, including nitrate, found that the relationship between nitrate and land cover drops off areas for areas less than 1 to 10 km^2 (Strayer et al. 2002). These results suggest that spatially explicit watershed characteristics may be more important for small areas of interest (Strayer et al. 2002).

The need for spatially explicit land cover data has been cited as critical to study the effects of fine-scale spatially heterogeneous land cover of suburban areas (Cadenasso et al. 2007, Ellis et al. 2006, Pickett et al. 2005, Grimm et al. 2000). Unfortunately, data used to inform studies of landscape-nutrient flux interactions are typically comprised of coarse regional-scale coverages that conflate land cover and human activities (Cadenasso et al. 2007). Use of the National Land Cover Dataset (NLCD) canopy and impervious surface products in urban areas is limited due to biases that affect predictive hydrologic modeling of nitrogen transport (Smith et al. 2010, Jones and Jarnigan 2009). Previous work has shown that more refined land cover analysis may better account for human influences on nitrogen loading (Cadenasso et al. 2007). Yet, it is critical from a watershed management perspective to define dominant features from readily attainable datasets for land management purposes. Thus, there currently exists a paradox with respect to land cover-nutrient flux linkages: while fine-scale human and natural features likely play a large role in controlling residential nitrogen fluxes, managers must often rely on studies defining coarse-scale source-sink dynamics to make localized land use decisions.

Further obfuscating our understanding of urban nitrogen fluxes is that biogeochemical hotspots—typically occurring at the interface of terrestrial and aquatic ecosystems (McClain et al. 2003)—are difficult to identify in urban settings due to alteration of natural flow patterns in the built environment, stormwater drainage and sewer infrastructure (Burges et al. 1998, Tenenbaum et al. 2006). Given the extent of heterogeneity of urban landscape features, fine-scale features, such as residential pattern (Cadenasso et al. 2008) and in-line wetlands (Burns et al. 2005), are likely responsible for many of these dynamics. This study examined changes in stream nitrogen concentrations of residential-catchments characterized by a range of fine-scale residential land cover and waste management to identify dominant features controlling suburban N fluxes.

The ecological functions of headwater streams are key to downstream water quality in forested areas (Alexander et al. 2007). However, headwater streams in residential catchments are much less retentive of inorganic N (Paul and Meyer 2001, Kaushal et al. 2006). Thus, characterization of residential nitrate sources, impacts of stormwater management (SWM), and wetland function is particularly critical in headwater catchments given the reduced nutrient uptake of these receiving streams.

Land cover composition, particularly effective imperviousness, is known to affect the delivery of water and pollutants (Walsh et al. 2005, Schueler 1995), but few studies have examined the effects of impervious location (Brabec et al. 2002). Urban land cover class percentages covary, i.e., increased impervious area necessitates the reduction of another land cover type. Spatial arrangement and autocorrelation of landcover has been found to be an important modulator of watershed land-cover effects on streams (King et al. 2005). This study aims to elucidate some of the complex interactions of heterogeneous land cover, position, and water management practices that characterize the urban landscape, building on previous, larger-scale efforts in the U.S. National Science Foundation funded urban long-term ecological research (LTER) project, the Baltimore Ecosystem Study (BES, http://beslter.org).

The objectives of this study were to: 1) evaluate the effects of fine-scale features on stream water quality predictors and source/sink dynamics through analysis of synoptic samples taken in the suburban Baltimore metropolitan area, and 2) determine metrics that are most applicable to link landscape structure and nitrogen fluxes in residential headwater catchments. Fine-scale features examined include waste management strategy, land cover composition and location, presence of wetlands or stormwater outfalls, age of housing development, and location of septic reserve areas (SRAs)—areas set aside on each parcel for septic systems. Further elucidation of critical fine-scale features that regulate urban nitrogen fluxes can allow for more effective targeting of practices aimed at increasing nitrogen sinks or reducing sources.

3.4 Methods and Site Selection

3.4.1 Study Sites

In the BES, we use a watershed approach to investigate ecosystem function. The BES long-term research program includes sites within the Gwynns Falls and Baisman Run catchments tracing an urban to rural gradient (Figure 3.1) of nested watersheds to estimate ecohydrologic function. The long-term gauged watersheds include sites along the main channel and smaller watersheds (5 to 1000 ha) ranging in land use from suburban, exurban, agricultural, old residential, forested, and urban core. These sites lie within the Piedmont Physiographic Province and are underlain by crystalline bedrock and saprolite (Doheny, 1999).

For this study, we identified headwater catchments nested within two long-term study watersheds. Springhill Farm and Jonathans Court are nested within Baisman Run, the most minimally developed BES long-term study catchment, and Black Friar is nested within Dead Run, the most heavily developed BES long-term study watershed (Figure 3.1). These sites capture a range of fine-scale features (Figure 3.2, Table 3.1, and Table 3.2). Both Baisman Run and Dead Run share common loamy soils and physiography, underlain by deep saprolite in the uplands and shallow to absent saprolite soils in slopelands (Costa and Cleaves 1984). The Springhill Farm and Jonathans Court watersheds are steeper than Black Friar due to both natural and human factors (e.g., grading for commercial parking lots). Medium-density residential land use, sewered waste management, and commercial development characterize the Black Friar watershed. Septic waste management and 1.2-ha minimum lots characterize Jonathans Court and Springhill Farm watersheds in an effort to minimize development in the contributing area of the Loch Raven Reservoir, a major drinking water source for the City of Baltimore.

The Springhill Farm watershed includes sampling sites upstream and downstream of a natural-gas line easement along two tributaries (characterized by differing upland housing character) and a site ~ 70 meters downstream of the confluence of these tributaries (Figure 3.2). One of these tributaries includes a small wetland along the gas-line easement. A large concrete barrier housing the gas pipeline underlies the gas-line easement, which may affect the hydrogeology. Jonathans Court sites (Figure 3.2b) include a stormwater outfall and a site downstream. Black Friar sites include a stormwater outfall, and two downstream sites, one in a forested park and one in a residential area downstream of the park.

3.4.2 Synoptic sampling approach

Monthly measurements were collected at the 10 study sites from August 2006 to October 2007. At each date, a water sample was taken for chemical analysis, and channel dimensions and stream velocity were measured. Depending on flow conditions, velocity was measured with either a pygmy flow meter determining discharge using the mid-section method (Hipolito and Loureiro 1988), or at low flow, volume was measured with a large pliable funnel. We validated the accuracy of the volumetric funnel and pygmy meter measures by comparing discharge methods at one of the long-term BES gauged watershed sites. Volumetric measures at the weir averaged 0.0002 m^3/s; the USGS gauge reported 0.00023 m^3/s; and the pliable funnel method averaged, 0.0002 m^3/s.

We calculated runoff ratios for subcatchments by deriving rating curves between the synoptic discharge samples and 5-minute data at the Baisman Run and Dead Run USGS gauges downstream. Due to the variability of the discharge measures at high flows when comparing the Springhill Farm outlet to the downstream gauge, two rating curves were derived to indicate a minimum and maximum predicted rating curve for this catchment. The equations from the rating curve analyses were applied to downstream daily gauge data from 2004 to 2008 to calculate total discharge. Total rainfall was calculated using data derived at the McDonogh School rain station.

Each sample was analyzed for conductivity using a LaMotte Model DA-1 meter, pH using an Oakton pHTestr30 meter, and turbidity using a HF Scientific DR15 turbidometer. Filtered and unfiltered water samples were packed in ice and sent to the Cary Institute of Ecosystem Studies in Millbrook, New York for chemical analysis. Nitrate, sulfate, and chloride were determined on filtered samples using an ion chromatograph (Tabatabai and Dick 1983). Total nitrogen was measured on unfiltered samples by persulfate digestion followed by analysis of nitrate on a flow injection analyzer (Ameel et al. 1993).

We determined watershed areas using a 10m digital elevation model (DEM) for Black Friar and a 5m DEM, derived from 0.6 m AirBorne LiDAR, for the Springhill Farm and Jonathans Court delineations due to the small size of each subwatershed. However, additional manipulation was required to properly account for drainage within Springhill Farm. Flow differences between Sites 1 and 2 were much larger than would be expected from the relatively small difference in contributing area between these watersheds (Figure 3.3). We conducted field reconnaissance comparing the original LiDAR data to observed elevations and discovered a canopy-covered path indiscernible from the digital data. We manipulated the DEM to "burn" in this road. However, flow differences remained larger than would be expected with new area corrections. Thus, calculation of area-corrected loads did not yield a metric that could be used to compare these watershed "slivers." Details relating to the "sliver" effect are included in Section 3.5, and the implications are discussed in Section 3.6.

We calculated percent land cover using a high-resolution dataset published by Zhou and Troy (2007). Land cover classes defined by this dataset include: building and pavement (which was combined for impervious surface), fine vegetation (referred to as lawn area), and coarse vegetation (which is referred to as forest area). Percent land cover for the contributing area to each measurement point was determined for these three land classes. We examined the effect of land cover percentage and location on stream chemistry. Inverse-distance weighted land cover was calculated based on flow distance. Flow distances were calculated using the ArcHydro flow length and trace flow path tool. The resulting layer produced flow distances from all points in the DEM to a final outlet point. The trace flow path tool allows the derivation of the path of least resistance according to the DEM-based eight-direction (D-8) flow grid. The resulting inverse-distance weighted (IDW) land cover metric was calculated using a method described in King et al. (2005).

Septic Reserve Areas (SRAs) in Springhill Farm were digitized based on maps obtained from the Maryland Department of Environmental Protection and Natural Resources. This analysis was carried out solely in the Springhill Farm watershed because the study sites within Jonathans Court did not provide fine-spatial differences in terms of septic location. That is, over 40 septic systems were located "upstream" of the stormwater outfall at Site 6 and only 2 additional septic systems contributed to Site 7. Distances from SRAs to sampling sites in the Springhall Farm tributaries were calculated using three distinct metrics (Figure 3.4). SRA distance metric 1, D_1, was the average D-8 flow distance from each SRA to the downstream sampling site:

$$D_1 = D_{ss} - D_f$$

D_f = Flow path distance at SRA centroid

D_{ss} =Flow path distance at the stream sampling site

SRA distance metric 2, D_2, is the average D-8 flow distance from each SRA to the stream:

$$D_2 = D_{si} - D_f$$

D_{si} = Flow path distance where flow path intercepts stream

SRA distance metric 3, D_3, is the Euclidean distance from SRA to the stream:

$$D_3 = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

x_1, y_1 = SRA centroid coordinates

x_2, y_2 = Nearest stream pixel coordinate

To determine the population density per watershed, we derived the number of parcels / households per watershed segment using the Maryland Property View dataset. These data were modified to remove inconsistencies between the parcel dataset and 0.6m resolution imagery. Population was determined from the 2000 Census. Given that the Census blocks could not be corrected for watershed size and shape, population was calculated per household; 3.01/household in Baisman Run and 2.24/household in Dead Run. Given the commercial development in the Black Friar subwatershed, daytime population is much higher than numbers reported in the Census. The population density calculation did not account for this difference.

3.4.3 Statistical methods

Samples were not independent due to the nested design of the study sites. To account for the nested site design, mixed-effect models were used, rather than linear regression models. These models allow the evaluation of samples from multiple dates without pseudo-replication of input variables (Zuur et al. 2009). A maximum-likelihood random intercept model was selected to control for site-specific effects (Zuur et al. 2009). In addition, a dummy variable for waste management strategy, septic vs. sewer, was included as an interaction term. Univariate mixed effects models were evaluated according to the impact of land cover composition, distance-weighted land cover composition, population density, SRA distance, and stream discharge on nitrate concentration. Welch-modified two-sample t-tests were used to compare samples because equal variance could not be assumed.

3.5 Results

There was a high degree of inter- and intra-site variability in nitrate concentrations (Figure 3.5). Variability between sites was greater than sample date effects at each site. This variability was driven by differences in residential infrastructure, density and pattern.

Calculations for area-corrected nitrate loads for Sites 2 and 7 appeared disproportionately high due to a large increase in discharge measures relative to a small gain in contributing area <5 ha (see Figure 3.3). The average area-corrected load was 295 g N/d/ha at Site 2 and 331 g N/d/ha at Site 7, while the average for all other Baisman watersheds was 26 g/d/ha (Sites 1, 3, 4, 5 and 6). The implications of the mismatch between area and discharge gain are included in the discussion section. However, given this apparent error, nitrate concentrations were used for the majority of analyses in this study.

3.5.1 Infrastructure and density

A Welch modified two-sample t-test found that mean nitrate concentrations for these watersheds differed significantly according to waste management infrastructure (p-value = 0) (Figure 3.6). Stream nitrate concentration increased with population in the septic-managed sites (Figure 3.7; *p*-value < 0.03). However, there was no relationship between population density and concentration in the sewer-managed sites.

3.5.2 Development patterns

Land cover composition variables: percent imperviousness, lawn and forest, did not correlate with nitrate concentrations in any sampled watershed (all *p*-values > 0.2). Use of inverse-distance weighted land cover metrics did not improve correlation. Inclusion of discharge in these models also did not statistically improve correlation between land cover variables and stream nitrate concentration.

Within the septic-managed study area, there were significant inverse correlations between nitrate concentration and distance from SRAs according to flow distance metrics. Distance metric 1 (*p*-value = 0.003), flow distance to sampling site, was a significant factor explaining nitrate variation at these sites (Figure 3.4b). Distance metric 2, flow distance to stream, was marked by a sharper, more scattered decline in nitrate concentration (Figure 3.4c) without significant correlation (*p*-value = 0.12). Distance metric 3, (Figure 3.4d) Euclidean distance, did not have a significant relationship with stream nitrate concentration (*p*-value =0.57).

We explored other fine-scale effects, including the influence of median age of housing stock, existence of storm water outfalls, and the presence of a small wetland area. Age of housing stock was weakly correlated with nitrate concentration among sampled sites ($p=0.07$). Sites at the mouth of storm drain pipes in both Black Friar and Jonathan Court watersheds exhibited the greatest range of nitrate concentration measures, > 4ppm, compared to other sites. Sites not associated with storm water outfalls had typical ranges of 2 ppm (See Figure 3.6). The largest decline in adjacent-site nitrate concentrations occurred between sites

3 and 4, which were upstream and downstream, respectively, of a wetland. The wetland-mediated reduction in nitrate concentration was significantly different than nitrate changes occurring along a similar tributary reach (t-test p-value = 0.0004). However, the area-corrected loads of the sites downstream of the wetland and non-wetland treatments (Sites 2 and 4) did not significantly differ.

The change in nitrate-N across the wetland is negative for all but one measure, collected during snowmelt (Figure 3.8). A similar reduction in nitrate-N concentration did not occur along the adjacent stream reach without the wetland treatment (Figure 3.8). Similarly chloride concentrations did not change substantially across the stream reach without the wetland treatment (Figure 3.8). The attenuation of nitrate-N concentration through the wetland tributary appears to be dependent on discharge (Figure 3.8). Chloride concentrations are inversely proportional to stream discharge (Figure 3.8). All high flows with decreases in downstream chloride concentrations in the wetland-treated tributary were characterized by concentrations > 100 mg/L upstream from the wetland and were collected from March to May, 2007 following the first road salting in late February. The wetland tributary gains 9 contributing parcels at the downstream site. The non-wetland tributary gains only 2 additional parcels draining to the downstream site.

3.6 Discussion

Despite greater residential density and inclusion of commercial development, Black Friar watershed nitrate concentrations were lower than those measured in Jonathans Court and Springhill Farm. The difference in stream chemistry between these two areas is likely due to sanitary infrastructure. In Jonathans Court and Springhill Farm, on-site wastewater disposal via septic systems leads to enrichment of groundwater and streams with nitrate, while in Black Friar, waste is removed from the watershed by sanitary sewer infrastructure. Thus, metrics linking landscape characteristics and nitrate fluxes in suburban watersheds cannot be created independent of waste management strategy. Traditionally used land-cover composition metrics were not significantly correlated with stream chemistry in these small headwater catchments. This finding contradicts the expectation that use of fine-scale spatially explicit land cover data will reveal land cover impacts on stream nitrate.

The effect of population density on nutrient enrichment displayed two distinct patterns according to waste management strategy. The correlation between nitrate concentration and population density in septic-managed watersheds, i.e., septic density, is consistent with previous studies (Gardner and Vogel 2005, Drake and Bauder 2005, Wernick et al. 1998, Cole et al. 2006, Gold et al. 1990, Moore et al. 2003). The effect of population density appears to be curtailed by sewer infrastructure (Figure 3.6). However, the lack of relationship between population density and nitrate concentration in the sanitary sewer managed catchment is possibly due to a lack of urban "quick flow" samples or the displacement of the land use signal. While a range of seasonal flow conditions were sampled, the largest discharges were measured during snowmelt (which only includes a few inches of snow in Baltimore) and several hours following a storm event. A previous study showed that the majority of nitrate export in Dead Run (downstream from Black Friar) occurs at high flows (Shields et al. 2008) because large percent impervious surface area and drainage infrastructure quickly convey runoff and nutrient pollution to the stream during storm events. In addition, sewer overflows have been reported in the Black Friar area (Maryland Reported Sewer Overflow Database) and such events can displace the land use /

water chemistry signal. When sewer systems perform optimally, the land use / water chemistry signal may be displaced to the outflow of sewage treatment plant.

Location effects of waste management practices on stream nitrate concentrations were prominent at the 10-meter scale within the septic-managed watersheds. Location of SRAs may play a role in determining the connectivity between septic plumes and stream discharge. The watershed connectivity concept proposes a threshold at which a watershed's soil saturates to maximize lateral subsurface flow, subsequently connecting the watershed source area (Tromp-van Meerveld and McDonnell 2006). Previous studies found a sharp decline in nitrate in Baisman Run during the drought of 2002 (Shields et al. 2008) because few nitrate sources were hydrologically connected to streams under these conditions. Increasing SRA distance to stream also hydrologically disconnects septic nitrate plumes from streams by essentially stretching the threshold of connectivity in septic-managed watersheds. Had only Euclidean distance been considered in this analysis, the results would indicate a lack of relationship between SRA distance to stream and nutrient concentrations. This result underscored the importance of considering hydrological metrics, rather than Euclidean distance measures.

Larger differences between length of overland flow and Euclidean distance occur where overland flow is sinuous. Length of overland flow is associated with the ratio of stream slope and ground slope; hillslopes with low stream slope to ground slope ratios have shorter lengths of overland flow (Horton 1932). Thus, the flow paths along headwater hillslopes are short compared to flow paths along the mainstem flow paths. Thus, differences in septic setback and stream buffer requirements may need to account for catchment geomorphology. In addition, increasing the length of overland flow through increased microtopography, e.g., retention ponds, also hold promise for extending the flow distance between septic reserve areas and streams.

Small wetland areas are biogeochemical hotspots in the urban environment, which reduce septic effluent contributions to stream nitrate. The downstream nitrate reduction through the small wetland is likely due to denitrification (Groffman and Crawford 2003). The increase in downstream chloride concentrations indicates additional sources, possibly including water softener drainage from the 9 additional septic systems. Despite the new sources of nitrate associated with 9 additional parcels, there is an attenuation of nitrate through the wetland. The greatest nitrate reduction occurs at low flows when the hydrologic system is groundwater dominated. At high flows, the chloride concentration is dominated by road salt sources. High flows reduce retention time within the wetland and nitrate reduction is less effective.

The increased nitrate concentration with increased stream flow at Site 4 aligns with previous findings that small wetlands in urban areas mitigate nitrate sources at moderate and baseflow (Groffman and Crawford 2003, Burns et al. 2005). The effectiveness of the wetland appeared to decrease at high flows, suggesting that the capacity of wetlands to function as denitrification nitrate sinks is limited by hydrologic constraints on residence time and biological processing. The lack of significant difference between these tributaries' nitrate loads is attributable to the shift in nitrate to flow relationship. Comparing area-corrected nitrate load changes between upstream and downstream sites was not possible due to the limitation of the "sliver" sized watershed areas.

A major challenge to this study was that traditional hydrologic and fluvial methods are limited at fine scales in headwater reaches of urban and suburban watersheds. Simple measurement of stream discharge was difficult. Calculations for area-corrected nitrate loads for the Sites 2 and 7 appeared disproportionately large. The very small size of these "slivers" was a shared characteristic of these sites distinguishing them from others (Figure 3.3). There appeared to be reduced correlation of surface and subsurface topography at this fine scale. Given the low discharge of these streams, a small measurement error is equivalent to a relatively large percent error. While estimated contributions are subject to measurement error, the discharge measures were quite consistent among sample days, and sampling technique was validated at a gauged site. The mismatch between derived contributing area and discharge gains is partly explained with the concept of representative elementary area—the decrease of variability of catchment streamflow with increased catchment size (Wood et al. 1988). Tenenbaum et al. (2006) demonstrated that delineation of urban flow paths requires finer-resolution DEMs compared to less developed catchments. However, our attempts to resolve the "sliver" problem with finer-resolution elevation data did not adequately resolve the mismatch.

A threshold of < $1km^2$ is thought to mark a sharp decline in consistent streamflow responses in fully forested catchments (Wood et al. 1994); this threshold exceeds catchment area of all sites assessed in this study. It is likely that at such a fine scale, the effects of surface microtopography and differences between bedrock and surface topography are not averaged out over the catchment. Previous study of hillslope-scale surface flow has indicated that spatial patterns are better indicated by bedrock topography than digital terrain analysis in catchments dominated by subsurface flow (Freer et al. 2002). Thus, the use of LiDAR data to define < 5 ha watersheds may not be an appropriate method for defining contributing area.

3.7 Conclusions

Within residential land use, spatially explicit land cover proportions and location did not appear to explain stream nitrate. The method of sewage waste management was the biggest factor underlying differences in residential stream nitrate dynamics in this study. Despite the greater size, commercial land use, and extent of effective imperviousness in the Black Friar watersheds, measured nitrate concentrations were lower within these watersheds than those in the Jonathans Court and Springhill Farm watersheds at measured flows. Nutrient flux metrics relevant at this scale, including population density and septic distance to stream, were only explanatory within the septic-managed watersheds.

In the areas of non-sewered, extensive and growing low-density residential land use, septic systems are likely responsible for the dominant nitrate source to streams. Population density and position of SRAs appeared to play key roles in the delivery of this nitrate source. The location impacts of SRAS were most evident when using hydrologically relevant distance metrics, (i.e., flow path rather than Euclidean distance), which may hold implications for septic setback requirements. The 1.2-ha minimum lot size zoning and lack of sewered infrastructure in the Springhill Farm and Jonathans Court watersheds exists to limit development density and to protect the headwaters of one of Baltimore's drinking water reservoirs. As new homes are constructed in this area, the septic loadings of these upper reaches may compromise the water quality of this reservoir, particularly because the nitrate attenuation capacity of the larger Baisman Run watershed stream channels appears to be low, with the exception of the lowest flows (Claessens et al. 2009a, b, c). This fact is particularly important given that the 2007 American Housing Survey estimates that 1.45 million additional septic systems were constructed in the U.S. since 1990 (U.S. Census Bureau 2008). The EPA reports that on-site treatment systems are growing primarily in suburban metropolitan areas (EPA 2000) where population density is more likely to be a concern.

Better management of septic systems may be an additional regulatory or design framework that warrants further attention—particularly in critical headwater areas. Potential solutions include land preservation (Cole et al. 2006), septic improvement measures such as the installation of geotextiles (Yaman et al. 2005), or addition of denitrifying components to the septic system (Robertson and Cherry 1995). The Maryland Department of Environment is attempting to resolve this problem through the provision of free septic upgrades funded through the Chesapeake Bay Restoration Fund. Septic systems are designed to aerate influent, oxidize ammonium to nitrate, and kill disease-causing anaerobic organisms. Thus, the nitrate concentrations of the receiving streams indicate that the septic systems are functioning properly, but are prominent sources.

The effect of population density on stream nitrate is attenuated by sewer infrastructure when functioning properly (i.e., not leaking, or overflowing and properly treated) because this infrastructure transports waste out of the watershed to be treated at centralized wastewater treatment plants. Even a well-functioning sewer pipe system can simply relocate the nutrient pollution problem depending on waste treatment procedures at the end of the pipe. End of pipe treatment is typically an easier management target for reducing nutrient loads than is nonpoint source pollution. For example, over-enrichment and nitrogen pollution in the upper Potomac and Patuxent Rivers were significantly reduced in the 1970s following wastewater treatment upgrades (Jaworski 1990 and Boesch et al. 2001).

The small wetland within the study region may have provided a nutrient sink during baseflow and moderate conditions. Wetlands in headwater tributaries are prioritized for restoration in Maryland for the purpose of water quality; however, compromised residential headwaters are not listed as targets for restoration (Maryland Department of Environment 2008). Our results demonstrate the effectiveness of upland headwater wetlands in residential catchments. Storm water and nutrient management strategies should consider protection, restoration and creation of residential wetlands, especially if their hydrology can be managed to maximize retention time and biological activity.

Our results show that fine-scale features of residential areas appear to influence nitrate concentrations of suburban streams with respect to infrastructure, population density and location of SRAs. While land cover affects the timing and speed of stormwater runoff (see Table 3.2), land cover within residential land uses is not the primary driver of nitrate pollution in receiving streams. Fine-scale spatially explicit land cover composition or location, including lawn cover, does not explain stream nitrate for small headwater catchments within residential land uses. Previous studies finding regional correlation between stream nitrate and land cover may suggest that land cover functions as a proxy measure for infrastructure at a regional scale. Further study of these fluxes is confounded by the lack of available fine-scale data and limitations of hydrologic methods for very small streams. Mitigation strategies focused on wastewater infrastructure improvements and wetland restoration are more likely to reduce nitrogen export from residential areas.

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Table 3. 1 Description of site characteristics

Site number	Site Description	Area (ha)	WM	Dist (m)	% for	% lawn	% imp	MYD	PD (#/ha)
1.	Springhill Farm north tributary, just **upstream** of gasline easement	12	*	0	58	31	11	1989	4.4
2.	Springhill Farm northern tributary, just **downstream** of gasline easement	2	*	48	65	32	4	1992	2.9
3.	Springhill Farm southern tributary, just **upstream** of gasline easement	.5	*	0	59	36	5	1990	5.4
4.	Springhill Farm southern tributary 3, just **downstream** of gasline easement	6	*	66	55	40	5	1978	4.6
5.	Outlet of the Springhill Farm watershed	48	*	155	85	10	5	1988	1.5
6.	Jonathans Court watershed, just downstream from daylighting storm pipe	29	*	0	45	42	13	1978	4.3
7.	Jonathans Court watershed, downstream from an old weir originally installed by Reds Wolman	5	*	223	72	19	9	1983	3.0
8.	Black Friar watershed, storm pipe where the tributary daylights in Gilston Park	41	+	0	25	25	50	1980	30.7
9.	Black Friar watershed, upstream from outlet in Gilston Park	49	+	342	40	30	30	1963	21.8
10.	Black Friar watershed outlet	15	+	745	26	36	37	1961	17.3

WM refers to waste management type: * is septic, + is sewered
Distance is distance downstream from most upstream sampling site
MYD is median year of development
PD is population density per segment

Table 3.2 Runoff ratios for downstream gauges and major subwatersheds

Watershed	Runoff Ratio
Dead Run	59 %
Baisman Run	35 %
Black Friar	50 %
Jonathans Court	38 %
Springhill Farm	31 to 53 %

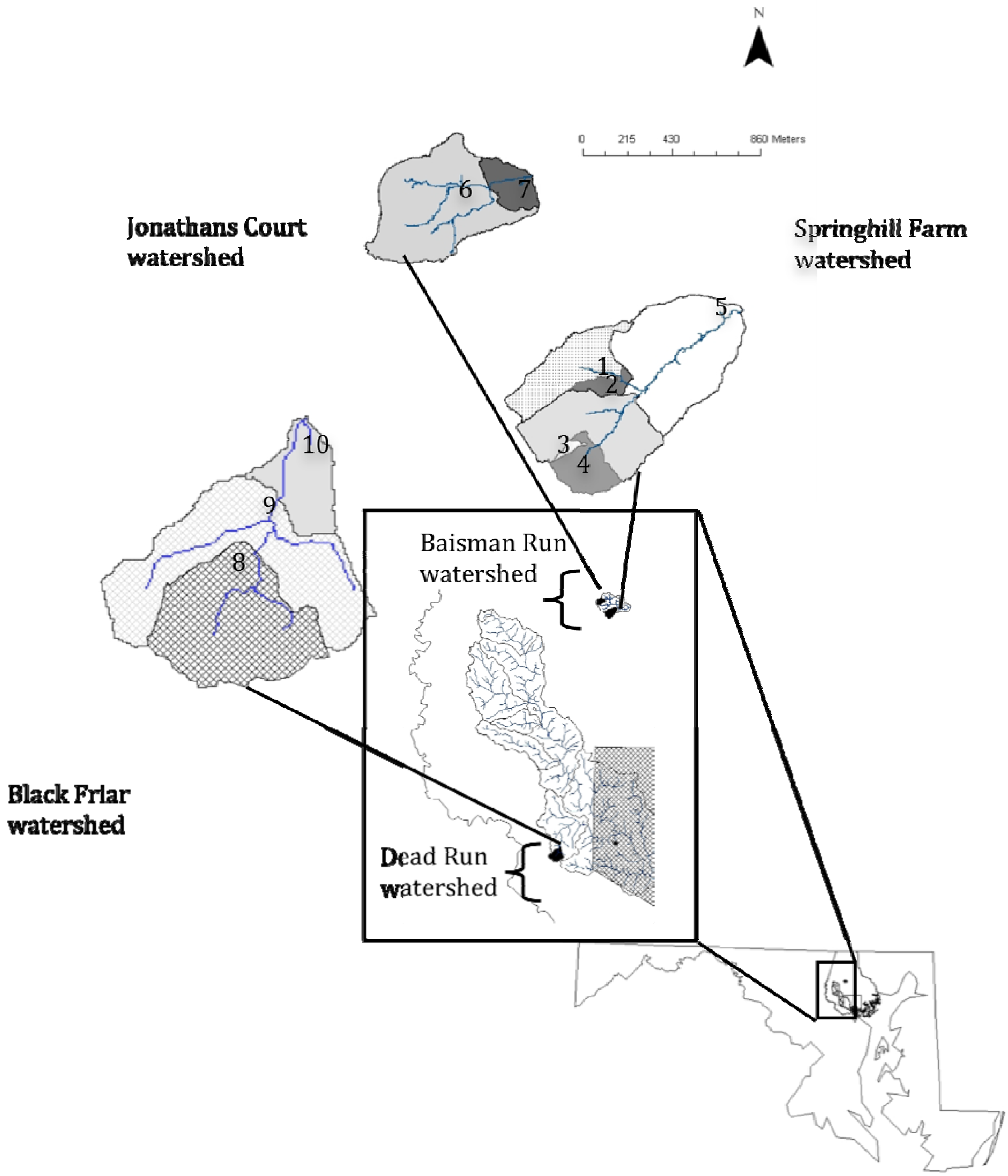
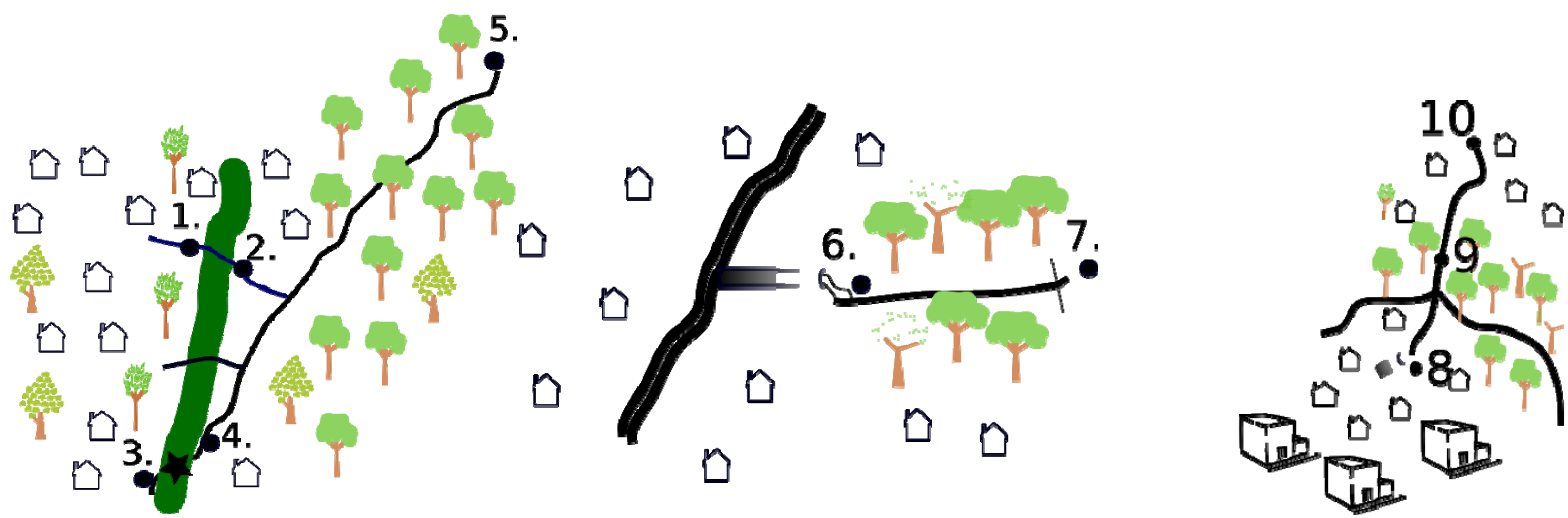


Figure 3.1 Map of synoptic sampling sites, 1-10, within the Baltimore Ecosystem Study urban LTER, Maryland. Springhill Farm and Jonathans Court are in the Baisman Run headwaters. Black Friar is in the Dead Run headwaters.



a). Springhill Farm b). Jonathans Court c). Black Friar

Figure 3.2 Cartoon of fine-scale land cover features at each synoptic sampling site by watershed; not to scale. Numbers coincide with those listed in Figure 3.1 and Table 3.1 and are referred to throughout the text. The thick green line is the grassed gasline easement. The star in Springhill Farm refers to a small constructed wetland that exists at that point along the gas line easement.

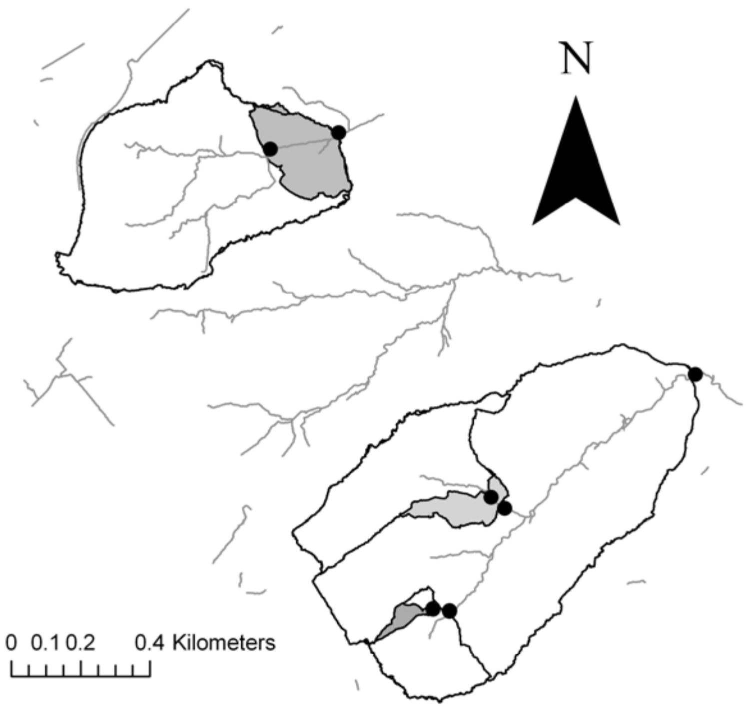


Figure 3.3 Fine scale delineations and creation of catchment segment "slivers." Catchment delineations in gray are those that are < 5 ha segment area.

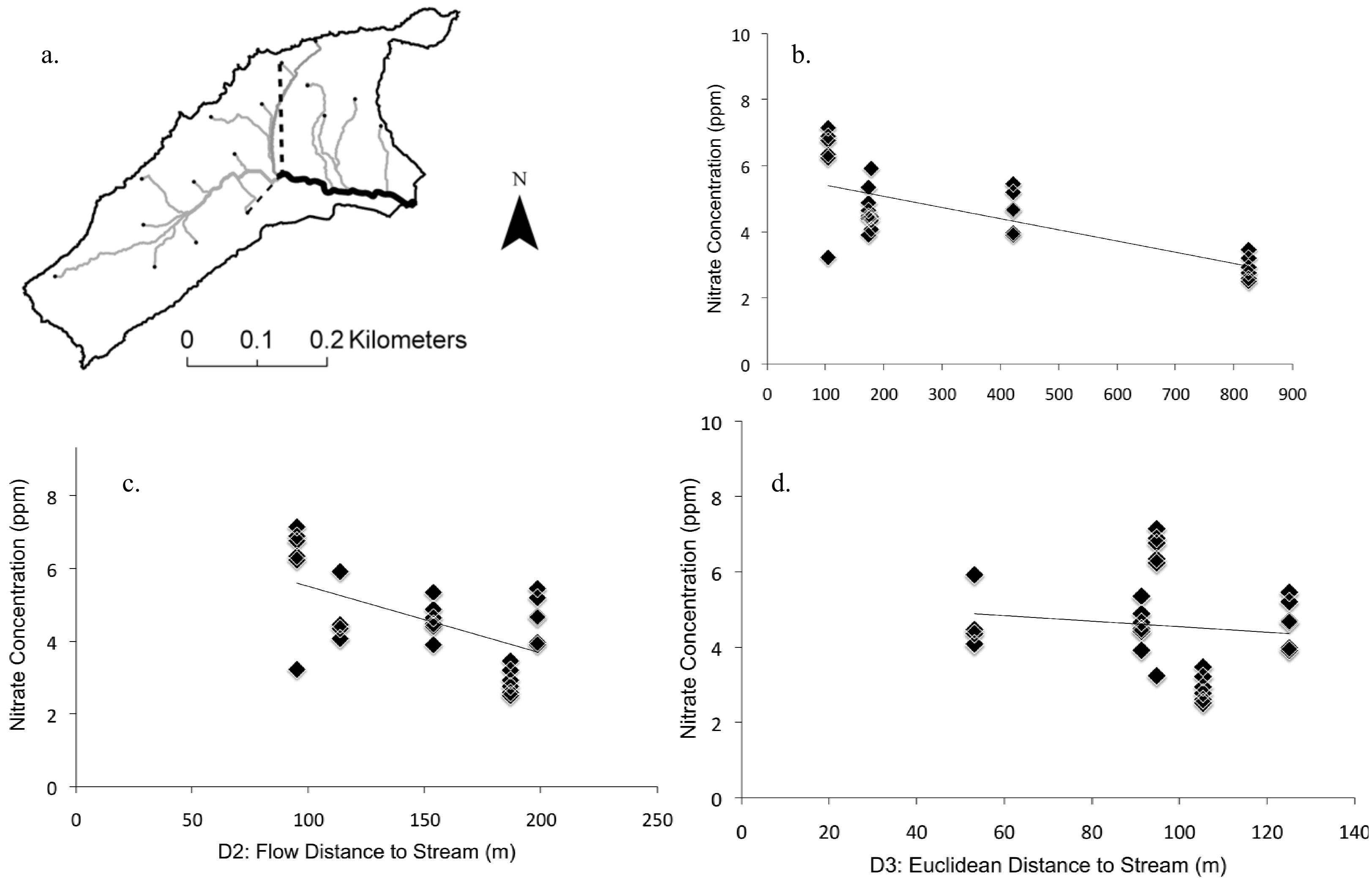


Figure 3.4 Septic Reserve Area (SRA) distance metrics. a) D1, D2 and D3. D1 includes flow distances (in grey) and stream distance to site (thick black line); D2 includes flow distance (grey line only). D3 includes Euclidean distance to stream depicted by black dotted line. 4b) c) and d) Plots of nitrate concentrations in Springhill Farm catchments according to distance metrics, D1, D2 and D3.

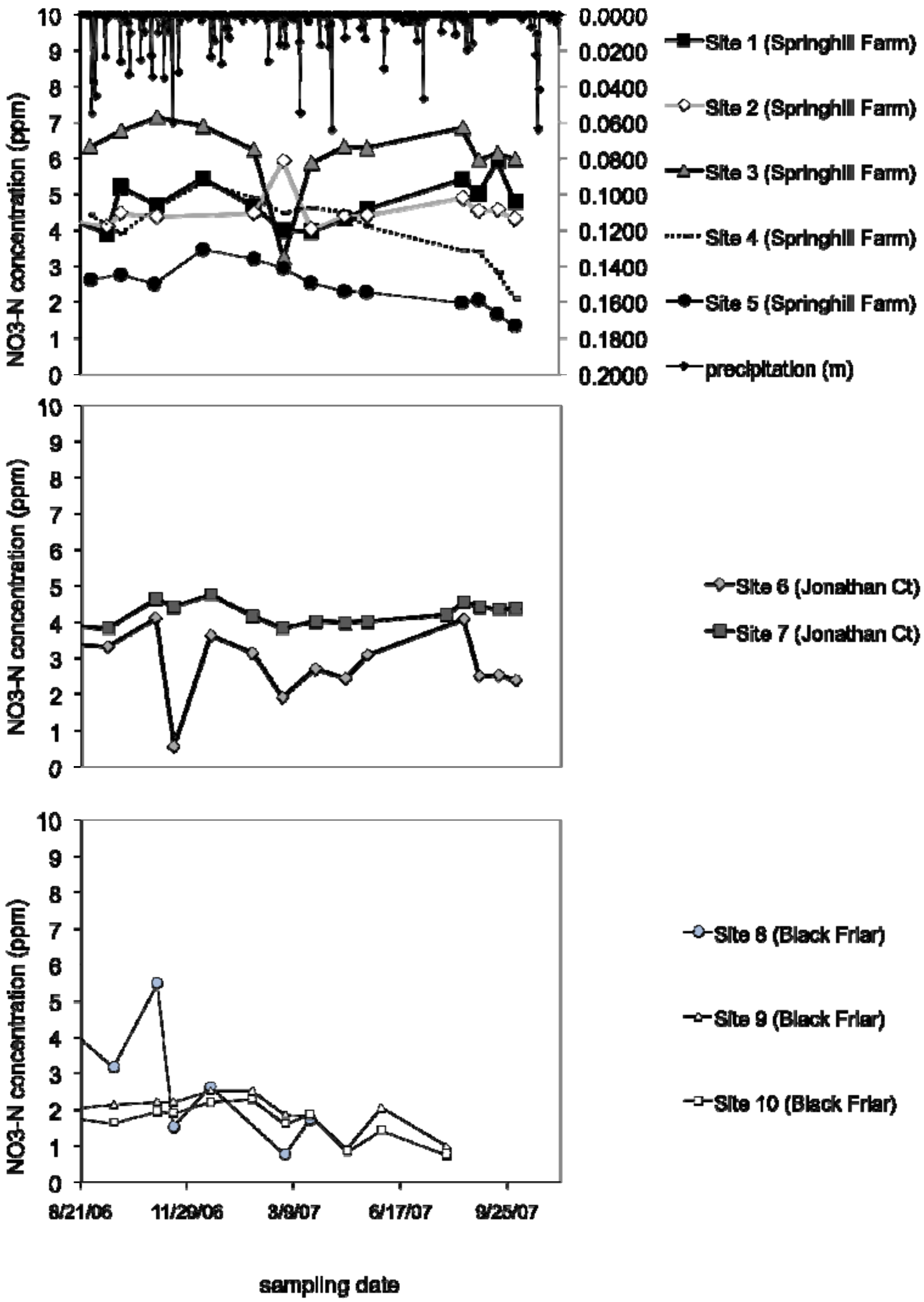


Figure 3.5 Time series of nitrate concentrations for all sites according to major watershed at all sampling dates, and BWI precipitation data.

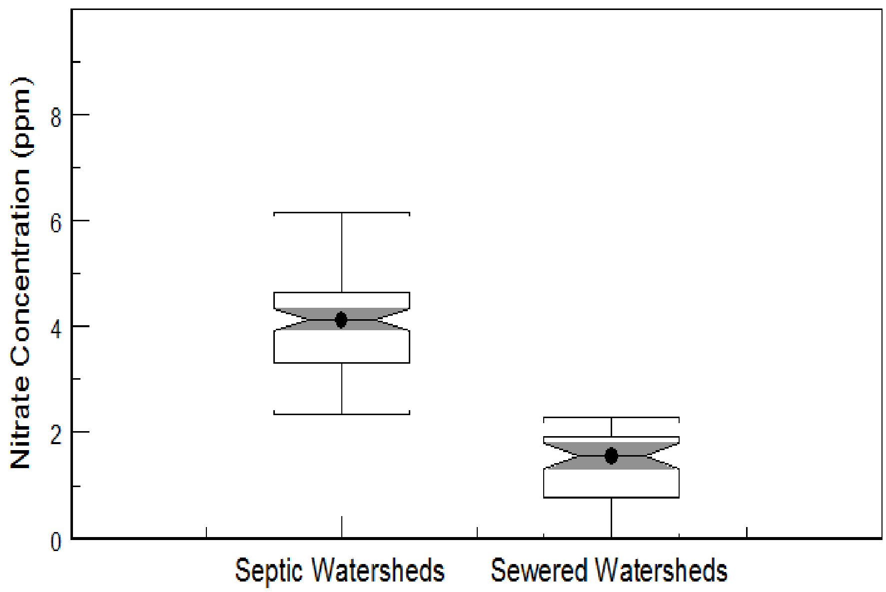


Figure 3.6 Boxplot comparing nitrate concentrations in septic managed watersheds, Springhill Farm and Jonathans Court, and sewered watersheds in Black Friar.

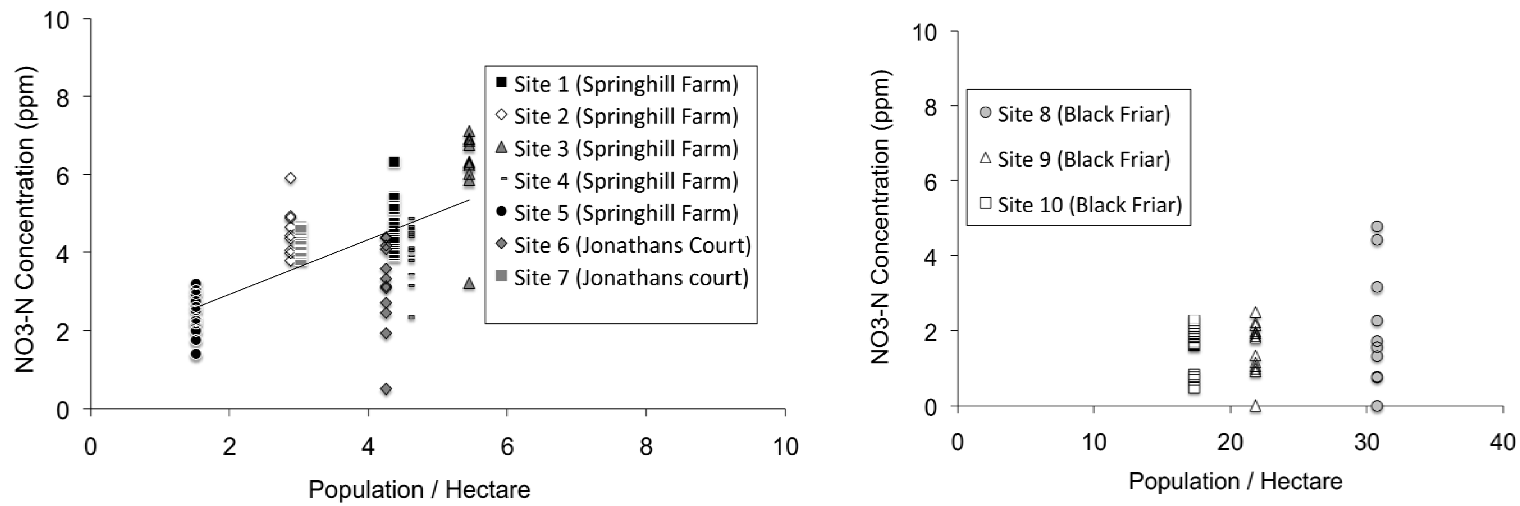


Figure 3.7 Nitrate concentrations plotted by estimated population density (people per hectare according to Census 2000) in each subcatchment. The catchments in the left figure are septic managed; sewer-managed catchments are on the right.

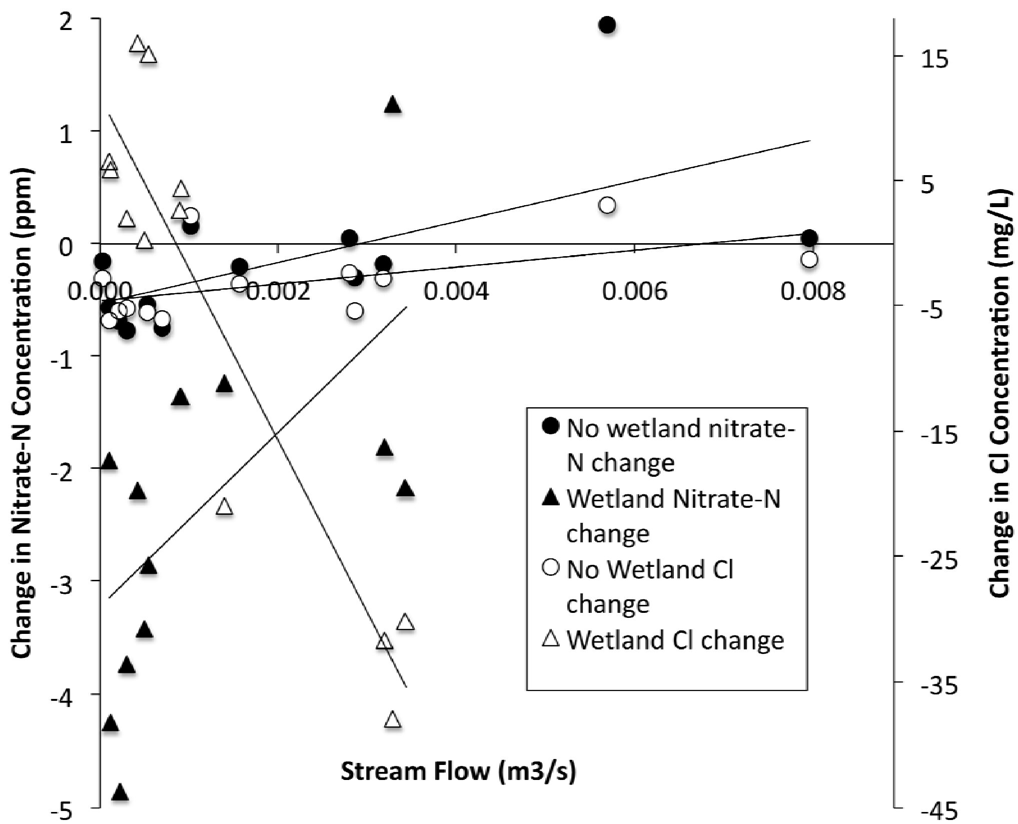


Figure 3.8 Comparison of the nitrate and chloride changes along two adjacent tributaries—with and without wetlands. The differences are calculated between Sites 3 and 4 for the wetland treatment and Sites 1 and 2 for the "control."

CHAPTER 4. A CHARACTERIZATION OF HYDROLOGIC PROPERTIES OF SUBURBAN SOILS

4.1 Preface

Findings in Chapter 2 detailed the limitations of the NLCD in deriving spatially explicit land cover parameters for small urban areas. However, in Chapter 3, we find that fine-scale land cover composition and pattern did not explain nitrogen fluxes in small suburban headwater catchments. The impact of sanitary and storm water management are greater than the impacts of land cover pattern. Within septic-managed watersheds, however, there exist spatially explicit patterns with respect to septic density and location. The connectivity of septic plumes and the stream was partly mediated by the location of septic reserve areas with respect to the stream. This chapter examined aspects of residential soil properties, such as saturated infiltration and hydraulic conductivity, which affect the transmission of septic plumes to streams during rain events.

The mismatch between terrain analysis and bedrock flow in small area catchments found in Chapter 3 limited the assessment of land cover impacts on catchment-scale flows and nutrient loads. The infiltration rates of residential lawns are significantly reduced (Gregory et al. 2006, Kelling and Peterson 1975); yet the alteration of urban soils is not generally considered in hydrologic modeling studies related to stream flow and nutrient transport. Thus, this chapter attempts to characterize the range of soil hydrologic properties of residential lawns for more accurate suburban hydrologic process modeling.

4.2 Abstract

This study examines saturated infiltration rates and water retention property differences between residential and forested soils, and the variance of these soil properties within and among suburban lawns. Structural soil properties were statistically different than measures collected in forested sites despite similar mineral properties. We find that median saturated infiltration rate in residential lawns is approximately half of rates measured in comparable forest soils; however, these rates are highly variable. The lowest saturated infiltration rates measured in lawn soils are sufficiently low to cause overland flow and subsequently greater storm water runoff during extreme rainfall events. Within-parcel differences in bulk density and soil depth indicate that runoff from residential lawns is more likely from the near-house and near-curb areas, and the middle of the front yard and backyards will be less likely to saturate. While the ability to use social and physical data to explain the range of soil properties among residential lawns is limited, physical factors assessed in this study, coarse vegetation, land use legacy, and catenary effects were less important in describing variation of soil properties of residential lawns than factors related to land management, such as age of house construction, property value, and fertilizer application rate. These results hold implications for incorporating the range of soil parameters of residential lawn properties into hydrologic models.

4.3 Background

Land development practices result in compacted soils that filter less water, increase surface runoff and decrease groundwater infiltration (EPA 2006). While the impact of impervious surface on stream health is well-documented (Walsh et al., 2005; Arnold and Gibbons, 1996; Schueler 1995), much less attention has been paid to the impacts of urban pervious surfaces. However, hydrologic studies have found that runoff from pervious areas accounted for 40-60% of the total flows (Burges et al. 1998), and the volume of runoff from compacted lawns approaches the amount of runoff from paved surfaces (Schueler 1995).

While saturated infiltration rates vary dramatically from site to site, the impact of development on these rates is well documented in the literature (Table 4.1). The infiltration rates of undeveloped sites range from 14.7 to 48.7 cm/hr and are much lower than developed sites ranging 0.1 to 24 cm/hr (Table 4.1). The results of these studies indicate that soils of developed landscapes are highly variable in terms of soil texture, land use legacy and current land use, vegetation, and construction practices. This study seeks to determine key impacts on soil infiltration rates of residential lawns so that storm runoff can be more accurately predicted in urbanizing areas.

Most hydrologic models rely on the empirical Soil Conservation Service (SCS) curve number method (Rawls et al. 2001). The SCS curve number incorporates soil texture, land cover and hydrologic condition of the land surface. For example, the SCS curve number for open space or lawn ranges from 39 to 84 according to hydrologic soil group and percent grass cover; and from 51 to 92 for residential land use according to hydrologic soil group, lot size and percent imperviousness (U.S. Soil Conservation Service 1985). Selection of hydrologic soil group is typically based on soil texture derived from National Soil Conservation Service maps. The range of SCS curve numbers for parcels in this study range from 68 to 85 for loamy hydrologic soil group "B," corresponding to approximately 3 inches difference in cumulative direct runoff according to this model. The curve numbers of this model do not incorporate socio-demographic features that relate to lawn management and health (Zhou et al. 2008, Zhou et al. 2009, Law et al. 2004) despite the impact of lawn establishment on residential hydrologic properties (Easton and Petrovic 2004). This study seeks quantify the residential lawn soil properties according to a range of relevant social and physical factors discussed below.

Social factors examined in this study include year of house construction, parcel area, land use legacy, and property value. The impact of housing age on saturated infiltration rates has been previously reported (Hamilton and Waddington 1999 and Partsch et al. 1993). During the period of initial lawn establishment, lawns are most likely to transform rain into runoff (Easton and Petrovic 2004). Site preparation for development involves extensive grading of soils resulting in substantial hydrologic changes in the soil substrate in urban areas, rendering pre-development soil maps inaccurate (USDA 2001). Bulk density of soil has been shown to be higher for new developments than older residences, owing to soil compaction during construction (Law et al. 2004). Parcel area is one of the factors considered in the SCS curve number. Substantial hydrologic changes associated with agricultural plowed soils may also remain as a result of land use legacy of the parcels under study. In addition, social demographic differences relate to land management decisions (Law et al. 2004).

Physical factors assessed include flow distance from stream, percent coarse vegetation, lawn area, and fertilizer application rate. In this region, saprolite is thickest on the uplands and thin or absent along valley slopes (Costa and Cleaves 1984). Thus, flow distance to stream is expected to reflect catenary differences in soil properties. The impacts of percent coarse vegetation are examined because tree roots are known increase infiltration rates (Bartens et al. 2008, Bramley et al. 2003). Lawn area is included given that it appears to be a primary factor affecting fertilizer application rate (Wu and Band 2009), and fertilizer application rate is associated with lawn establishment affecting saturated infiltration rates (Easton and Petrovic 2004).

This study seeks to extend the current understanding of the impacts of development on storm water runoff by determining the effects of neighborhood location and residential characteristics on infiltration and soil water retention in residential lawns. If data attainable from land cover and cadastral datasets can explain variance in residential soil properties, it can be used to improve runoff and discharge estimates in hydrologic models. Equipped with an improved understanding of soil hydrology related to urbanization, it may be possible to improve hydrologic modeling of urban areas and better target the implementation of infiltration practices to reduce environmental degradation associated with urban storm water runoff.

4.4 Methods

4.3.1 Study sites

Study sites are in the greater Baltimore metropolitan area within the network of the Baltimore Ecosystem Study (BES) long-term ecological research (LTER) site. The sites fall within the Maryland Piedmont physiographic province and are characterized primarily by clay-rich soils overlaying saprolite (Costa and Cleaves 1984). Residential lawns were selected from a pool of participants in other BES projects, including the residential carbon project and a residential lawn practices study. This study required digging and refilling holes in the front lawns of homeowners. Thus, Baltimore-area residents who previously declined to participate in less invasive studies were not contacted. The UNC Chapel Hill Internal Review Board approved the permission letter and consent forms (Appendix A). The study sites were located in Catonsville, Reisterstown and Cockeysville, Maryland (Figure 4.1).

House age, parcel area and tax assessment data were selected from Maryland Property View 2002 for each study site parcel. We used ArcHydro and a 5-meter digital elevation model (DEM) to determine flow accumulation and flow distance based on 2000-meter minimum catchment area. Percent coarse vegetation was calculated using a high-resolution land cover dataset classified based on 0.6 meter imagery and 1-meter LiDAR DEM (Zhou and Troy 2008). Land use legacy was derived from a combination of a historical forestry GIS dataset and USGS orthophotos. Fertilizer application rates were attained for some properties from previous surveys conducted during the residential carbon project and residential lawn practices studies from which these sites were derived. Parcel-scale variation in bulk density was estimated using a static cone penetrometer. Measurements were collected at several parcel locations, including near-house, near-curb, mid-front and back yard. Five penetrometer measurements were collected at each parcel location.

4.3.2 *In situ* infiltration measurement

Infiltration rates were measured in 14 residential lawns and compared to measurements taken in the forested "control plot" in Oregon Ridge Park. We used the Cornell sprinkle infiltrometers because sprinkle infiltrometers should be used where surface conditions influence infiltration (Rawls et al. 2001). The device is also portable permitting 3 simultaneous measures of multiple lawns with relative ease. The Cornell sprinkle infiltrometer simulates rainfall by slowly dripping several gallons of water through a ring of capillary tubes (Ogden et al. 1997) into a single-ring cylinder. A mariotte tube controls the rainfall rate. Runoff volume is measured through a tube releasing any ponding within the infiltrometer's metal ring. Rainfall rate and runoff volume are recorded; their difference is infiltration rate (Ogden et al. 1997).

Field-saturated infiltration indicates the steady-state infiltration capacity of the soil after saturation. Figure 4.2 illustrates the infiltration measures over time collected at the same site. Due to the variability of the infiltration measures, a best-fit function was established. The saturated infiltration rates used in this study are based on the value derived from the best-fit function after 40-minutes of high-intensity rainfall. Due to the single ring of the runoff collection area, the infiltration rate is adjusted for three-dimensional flow according to 15-cm insertion depth and soil type (Reynolds and Elrick 1990).

4.3.3 Soil properties

Three to six 5cm soil cores were collected at each site to calculate other soil properties. Bulk density and water retention parameters were measured and calculated at the Rutgers Center for Turfgrass Science. Bulk density of undisturbed samples was measured using the saran-resin coating method (Brasher et al. 1966). Porosity was estimated based on bulk density (Rawls et al. 2001, equation 5.1.1.).

To measure water retention, soil clods were placed in contact with a ceramic plate contained in a cell for the pressure potentials at 0, 0.3, -0.6, -1, -1.5, -3, -6, and -10 kPa by measuring the volume of released water. We physically disturbed samples by shaking air-dried, crushed soil samples with 10 glass spheres of 0.5 mm in diameter for 24 hours. Water retention at pressure potentials of -100, -300, and -1500 kPa were measured on disturbed samples packed into 5 cm x 2.5 cm cores using pressure plate extractors (Richards, 1949).

The van Genuchten (1980) water retention model parameters were estimated using ROSETTA software (Schaap et al. 2001) from information on soil texture (sand, silt, and clay fractions), bulk density, and measured water content at -33 and at -1500 kPa. The lognormal water retention model of Kosugi (1996) was fitted to all water retention data. The Kosugi (1996) water retention model assumes a lognormal distribution of pore radii according to the distribution of measured water retention with respect to the presumed saturated equilibrium point at -0.1 kPa. Organic matter loss on ignition (Schulte, 1995) was measured and particle size measurement was conducted with the hydrometer method (Gee and Bauder 1986) at the Penn State Agricultural Analytical Services Laboratory.

4.3.4 Saturated hydraulic conductivity estimates

We estimated saturated hydraulic conductivity, Ks, based on two pedotransfer functions (PTFs) derived from different sets of input variables: 1) Han et al. (2008); and 2) Nemes et al. (2005). The method outlined in Han et al. (2008) estimates the Ks based on van Genuchten parameters, α and n, (air resistance and water retention curve shape parameters) and the slope of the water retention characteristic curve at the inflection point, i.e., where the direction of this curve changes and indicates saturation. This PTF was selected because it is based soley on water retention characteristics, rather than textural information. The other PTF used to estimate Ks includes the effect of soil texture and organic matter (Nemes et al. 2005). This PTF was selected from a review of commonly used PTFs, based on the lowest random mean square error available based on available inputs (Wosten et al. 2001). The PTF was derived by curve fitting equations based on percent sand, percent clay, bulk density, and percent organic matter.

4.3.5 Statistical Analyses

A series of Welch-modified t-tests were used to compare soil attributes of lawns and forests. In order to incorporate all data without pseudo-replication of site characteristics, correlation analyses were based on random effects models, including fixed effects of social and physical factors on soil properties with random effects of parcel address. In addition, it was necessary to control for watershed using a dummy variable, i.e., whether the parcel was located in Baisman Run or Gwynns Falls. Models were selected according to highest-ranking Akaike weights with p-values < 0.05.

4.4 Results

4.4.1 Differences between forests and residential lawn soil properties

Hydrologic properties of residential lawn soils are significantly different than forest soils. We measured significantly higher saturated infiltration rates in the forest floor than lawns, both residential (*p*-value = 0) and institutional (*p*-value = 0.0127), using Welch modified t-tests. Welch modified t-tests revealed that forest or lawn is a significant factor explaining differences between saturated infiltration, bulk density and porosity (*p*-values = 0) and percent organic matter (*p*-value = 0.0128) (Table 4.2). Residential lawns had significantly lower porosities and percent organic matter, and higher infiltration rates and bulk densities than forests (Figure 4.3). Despite these differences, water retention characteristics were not significantly different between forest and residential lawn soils (Figure 4.4); t-tests comparing forest and lawn soils for air resistance, van Genuchten *n*, median pore size; and distribution of pore sizes, yielded *p*-values > 0.3 (Table 4.2).

The selection of PTF affected whether Ks differed in forests and lawns. The Nemes method (Nemes et al. 2005) indicates that Ks was significantly different between forests and lawns (*p*-value = .0231, Figure 4.5). However, this difference is not reflected in those values estimated using Han et al. 2008 (*p*-value = 0.3955). The Ks estimates are much lower than the *in situ* measurements for infiltration rate with respective median values of forest and lawn at 20 and 11 cm/hr (Figure 4.5).

The measures for saturated infiltration rates for residential lawns in this study ranged from 1 to 20 cm/hr while 20 cm/hr was the maximum measurable value. The median value was 10.6 cm/hr. According to rain gauge information collected at the BWI field station, 639 rainfall events between 1949 and 2009 exceeded the minimum measured saturated rate of 1.07 cm/hr. These events constitute 2 percent of recorded hourly rainfall events in Baltimore (Figure 4.6) resulting in overland flow from the most compromised of soils. Rainfall events on record would have caused overland flow from five of the sampled properties. No rainfall events exceeded the median lawn infiltration rate of 10.6 cm/hr or the infiltration rates of any of the forest soils.

4.4.2 Parcel-scale effects

Cone penetrometer measures were collected to estimate the intra-parcel variation in soil depth and bulk densities (Figure 4.7). Estimates of near-curb bulk density are significantly higher than mid-yard bulk density of the lawn (p-value < 0.03). Lawn soils of the middle of the front yard are significantly deeper than those near the house and in the backyard (p-value > 0.03) (Figure 4.7). However, mid-yard depths were not significantly different than measurements collected near-curb (p-value > 0.06) across all samples. Existence or lack of a constructed curb for “near curb” depth measurements did not explain the depth or bulk density variance within these samples.

Only one residence among these study sites had piped roof drainage, which was piped to lower portions of the yard to drain to the stream. Five properties’ curbs had holes for piping roof drainage or other home drainage directly to the gutter; however, all of these connections remained closed. Most gutters drained to the lawn mulch beds supporting foundation plantings of shrubs although one property did drain directly to a paved surface spilling to the lawn.

4.4.3 Physical and social impacts on soil properties

Despite similar soil texture, we find significant differences between infiltration rates in Baisman and Gwynns Falls sites (Figure 4.8). Saturated infiltration rate, soil pore size distribution, air resistance, percent organic matter, and bulk density differed significantly between these watersheds (Figure 4.8). Differences in social factors between these two watersheds were known to be great at the outset of the study, which is why these two regions were included in the sampling design (Figure 4.9). Analyses of soil properties described below control for geographic differences between Baisman and Gwynns Falls. The lawn properties displayed in Figure 4.3 remain different when Baisman Run lawn properties, alone, are compared to forest soils.

According to Akaike weight analysis, housing age was the best fixed factor explaining variation in saturated infiltration rate with a p-value < 0.02 (See Figure 4.10). The relationship between age and saturated infiltration rate differs between these watersheds. Coarse vegetation also had a significant p-value < 0.05, but the Akaike weight was 4 times lower than the housing age.

The rate of fertilization significantly correlated with percent organic matter in soils (Figure 4.11; p-value < 0.02). Homeowners who fertilize their lawns appear to do so at a rate that is inversely proportional to the percent organic matter in the soil. Rate of fertilizer application was not available for all sites; thus this factor could not be included in the Akaike weight analysis used for model selection. For the other factors assessed, the Akaike weights suggested that property value best explained variation in percent organic matter (Figure 4.12;

p-value = 0.5). However, the directionality of the relationship differs between Gwynns Falls and Baisman Run sites (Figure 4.12).

With the exceptions of the relationships mentioned above, there were no other relationships with the highest ranking Akaike weights and *p*-values < 0.05 between measured soil properties, including: water retention characteristics, saturated infiltration, bulk density and percent organic matter; and the social and physical factors assessed in this study: house age, parcel area, property value, lawn fertilizer rate, property distance to stream, percent coarse vegetation, land use legacy, and lawn area.

4.5 Discussion

4.5.1 Forest v. lawns

Saturated infiltration rates of residential lawns are half as fast as rates measured in forested soils. The measured range of lawn saturated infiltration rates is comparable to the developed sites measurements displayed in Table 4.1, ranging from 0.1 to 24 cm/hr. The median infiltration rate, 10.6 cm/hr, is similar to values reported in Hamilton and Waddington (1999) for established lawns.

This study indicates that overland flow occurs on some residential lawns, but not in forest soils. However, overland flow would have only occurred in the most compromised residential soils for 2 % of rain events on record for the past 50 years. The median saturated infiltration rate of ~10 cm/hr is surprisingly high and has never been exceeded by rainfall events on record in Baltimore. While rainfall intensities only rarely exceed the saturated infiltration rates of lawn soils, the decreased rates of Ks suggest increased rates of subsurface storm flow or runoff due to return flow or Dunne type saturation overland flow due to perched water tables. Thus, inclusion of the modified properties of residential soils is likely necessary to accurately model hydrological response in urbanized catchments.

Other structural properties also differed significantly between residential and forest soils, including bulk density, porosity, and percent organic matter. The lack of difference between soil retention parameters suggests similarity in mineral properties between forest and lawn soils in this study. The laboratory protocol requires root matter to be removed from the sample prior to analysis. Thus, macroporosity created root biomass in both the lawn and forest floor is not included in the measurement of water retention. This result suggests that macroporosity in lawns is more variable—a finding echoed in the significant differences in organic matter within forested and residential lawns soils. Reduced physical structure of urban soils is common and is most often due to poor vegetation establishment (Bullock and Gregory 1991).

The estimates of Ks derived from texture and percent organic matter (Nemes et al. 2005) and water retention characteristic curves (Han et al. 2008) are gravely underestimated compared to saturated infiltration rates measured *in situ*. While measurement error in the field is much greater than what would be expected in laboratory settings, the differences in these saturated conductivity estimates reflect the soil properties used in their derivation. The Nemes et al. (2005) estimate indicates a greater difference between forest and lawn soils because percent organic matter is an important factor in this pedotransfer function and a key difference between lawn and forest soils. Han et al. (2008) estimates of saturated conductivity do not significantly differ as they are based on samples lacking root matter. Both estimates neglect the effects of macroporosity and preferential flow, which appear to assert the greatest influence over saturated infiltration rates.

4.5.2 Parcel-scale effects

All, but one, infiltration measures and soil cores were taken from the middle of the front yard. The front mid-yard is the portion of the parcel where soils are deepest and least dense, and therefore most infiltrative. These results suggest that the saturated infiltration measures collected in this study provide a conservative measure for estimating lawn runoff potential. The cone penetrometer provides only a rough estimate of relative bulk density and is affected by soil moisture and operator error. Little, if any, research has been conducted on the parcel-scale dependence of soil properties. Thus, collection of soil cores for analysis of parcel-scale differences of residential soils may be warranted. The results of this study suggest that infiltration rates are likely higher in the mid-lawn than the near-curb portion of the lawn and that saturated overland flow and return flow are more likely from this part of the lawn, which quickly drains to the stormwater conveyance system to the stream.

4.5.3 Physical and social impacts on soil properties

Despite loamy soil textures within the watersheds containing study sites (Baisman Run and Gwynns Falls watersheds), soil properties, including saturated infiltration rate, soil pore size, distribution, air resistance, percent organic matter and bulk density differed significantly between these watersheds. Thus, evaluating the impacts of these very different social parameters on soil properties was difficult. Statistical control of watershed region with a dummy variable permitted analysis of fixed effects of the social and physical properties considered in this study. The regional differences in soils may be attributable to differing geologic parent material. While the clay mineralogy of the eastern Piedmont region is dominant and geomorphology among headwaters systems is consistent, the saprolite environment is highly complex and variable from site to site (Costa and Cleaves 1984).

Age of house construction correlated with saturated infiltration rate. Previous studies of controlled turf grass experiments have indicated a correlation between lawn establishment and infiltration rates (Easton and Petrovic 2004), and lawn establishment is inversely related to housing age. However, age of house construction incorporates the both effects of lawn establishment and construction practices. Many of the newer larger homes constructed in Baisman Run were constructed to preserve tree cover. Many of the moderate-age homes in Gwynns Falls were constructed as multiple units as a single development with minimal tree preservation and rest atop a mound of fill material that slopes down toward the curb. Thus, the differences in age-related effects in these catchments may reflect a difference in construction practices. However, the study sites were not sampled to control for this effect.

Other factors related to root density correlated with saturated infiltration rate, including canopy cover, percent organic matter and fertilizer application rate. While percent coarse vegetation was found to correlate with saturated infiltration rate, it was not the best model explaining differences in infiltration rates. However, infiltration measures were collected from areas that were not characterized by extensive tree or shrub roots. Fertilizer application rate correlated with percent organic matter. While one would expect percent organic matter to increase with increased fertilizer application, the opposite occurs on the lawns under study. Homeowners who fertilize their lawns appear to do so at a rate that is inversely proportional to the percent organic matter in the soil, due either to attempts to improve poorly established lawns or poor lawn quality resulting from over-management.

While previous study has shown that less nitrogen runoff occurs on heavily fertilized plots than unfertilized control plots given deeper rooting depth, increased transpiration, and a rich organic matrix associated with well-fertilized grass (Easton and Petrovic 2004). However, fertilizer application choices appear to be too variable and complex to correlate with social factors on a parcel scale.

Property value also correlates to percent organic matter. However, Baisman Run sites exhibit an inverse relationship between percent organic matter with property value and a directly proportional relationship in Gwynns Falls. Several studies have indicated that compost amendments act to improve physical properties of urban soils (Paglai et al. 1993, Revinshield and Bassuk 2001, Aggalides and Londra 2000, Tester 1990, and EPA 2008). Thus, some of the variability of lawn structure found in this study may be attributable to land management practices as they associate with social variables.

4.6 Conclusions

The hydrologic soil properties of residential lawn soils were examined with respect to: 1) within parcel differences; 2) differences among parcels; 3) differences between residential and forested land use. Saturated infiltration rates of residential lawn soils were reduced to half the rates associated in forest soils. Similarity between mineral properties and divergent structural properties between land uses suggest that this change in hydrologic soil properties is likely due to reduced macroporosity. While rainfall rates on record have exceeded the saturated infiltration rates of several lawns in this study, such events have been very rare—constituting 2 % of all rain events in the area. However, the impact of reduced saturated infiltration rate and saturated hydraulic conductivity on return flow, subsurface flow and saturated connectivity on a watershed scale warrant further investigation.

The range of residential lawn saturated infiltration rates is large. While social factors and lawn establishment appear to influence infiltration rates and percent organic matter, the impact of social factors on soil properties is non-monotonic and differs regionally among the sites assessed in this study. The ability to use social and physical data to explain the range of soil properties in residential lawns is limited.

The distribution of residential lawn soil properties varied geographically between watersheds. While saturated infiltration rates are well explained by housing age, the relationship differs between these two watershed areas. Property values and percent canopy correlate with percent organic matter, but again the directionality of these relationships differs according to watershed. Physical factors assessed in this study, coarse vegetation and catenary effects were less important in describing variation of soil properties of residential lawns than social factors, such as age of house construction, property value, and fertilizer application rate. These factors appear to point towards impacts of lawn establishment, which is likely to vary according to housing age, fertilization rate, and property value.

However, the range of soil properties measured in this study reflects differences in mid-yard soil, which are characterized by less dense and deeper soils than found in other parts of the parcel. Further work characterizing residential lawn soil properties according to spatial orientation within the parcel may be necessary to improve models of suburban hydrology particularly as saturated infiltration rates and return flow are likely to be higher at the part of the lawn directly connected to streams.

This study extends the current understanding of the impacts of development on stormwater runoff by determining that age of house construction, property value and land management practices affect infiltration and soil water retention in residential lawns. These results hold implications for determining saturated infiltration rates and hydrologic conductivity parameters in urban storm water models and including stochastic error terms to account for the range of these values among parcels. In addition, the results of this study indicate that fertilizer application rates in suburban lawns impact not only nutrient sources, but also the hydrologic properties of soils. The impact of these altered soil properties on watershed-scale hydrology and nutrient transport to surface water and ground water should be investigated.

4.7 Acknowledgements

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We thank the USDA Forest Service Northeastern Research Station for site management, and in kind services to the BES. In addition, we thank the University of Maryland, Baltimore County for their contribution to the office and laboratory space at the Research Technology Center on their campus. The City of Baltimore Department of Parks and Recreation and Department of Public Works, the Baltimore County Department of Parks, the Maryland Department of Natural Resource, and the McDonogh School all kindly provide access or management of land used by the Baltimore Ecosystem Study for ecological, hydrological, and meteorological field studies. Additional support and assistances have been provided by agencies, communities and individuals who are specifically acknowledged in the datasets and publications summarizing work they facilitated.

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Table 4.1 Compilation of previous studies of changes in infiltration rates according to a range of development conditions.

	Area	Undeveloped (cm/hr)	Developed (cm/hr)
1. Kays et al. 1980	Charlotte, North Carolina	31.56[f]	0.45[hcs]; 0.67[hc]; 0.70[scp]; 1.25[hf]; 4.78[sc]; 11.20[st]
2. EPA 2000	Birmingham, Alabama	44.2[s]; 14.7[cl]	4.8[s]; 2.0[cl]
3. Gregory et al. 2006	Gainesville, Florida	22.5[p]; 48.7[w]	2.3 to 6.5[cp]; 2.0 to 7.9[cw]; 5.9[bp]; 6.8[pp]
4. Hamilton and Waddington 1999	State College, Pennsylvania	N/A	0.4 to 3.0[yi]; 8.5 to 10.0[oe]
5. Easton and Petrovic 2004	Ithaca, New York	N/A	10[5] to 24[10]
6. Kelling and Peterson 1975	Madison, Wisconsin	N/A	0.1 to 7.3
7. USDA 2001	Ocean County, NJ	38.1[w]; 25.1[p];	18.4[sh]; 0.4[sl]; 0.1[cl]

1. Study includes measures for [f]forest and a range of different developed conditions accounting for the large range resulting infiltration rates, including: [st]slightly disturbed lawns with preserved trees, [sc]slightly disturbed previously cultivated; [scp]slightly disturbed previously cultivated with plow pan, [hf]highly disturbed with fill soils, [hc]highly disturbed with cut soils, [hcs]highly disturbed cut and compacted soils with sparse grass.
2. Median rates from a total of 150 infiltration measurements for two soil types ([s] sand and [cl] clay) on noncompacted and compacted soils; study includes measures at 15, 30, 60 and 120 minutes. 60-minute value is included in this table.
3. Study includes before and after infiltration measures for [p]pasture and [w]wooded sites that are subjected to compaction by [c]controlled compaction, [b]backhoe and [p]pickup truck compaction. Developed measures include 30 second and 10 minute treatment for soil compaction accounting for the higher and lower resulting infiltration rates.
4. Study examines impacts of lawn quality, which found a difference between [yi] younger highly impacted lawns versus [oe]older more established lawns and those constructed without excavation.
5. Study examines impacts of shoot density (5 to 10 cm^2) on turfgrass infiltration.
Time of compaction and method of compaction matter, but only slightly; type of resulting development and lawn type matter
6. Study evaluates impacts of differing fertilization regimes on lawn infiltration rates and nutrient runoff.
7. Study evaluates impacts of varying development: [w]wooded, [p]pasture, [sh]single house lawn, [sl]subdivision lawn and a [cl]commercial lawn near a county parking lot.

Table 4.2 Welch modified t-test p-values comparing forest and residential lawn soil properties

Soil Property	p-value comparing forest and lawn
Saturated infiltration rate	0
Bulk density	0
Percent organic matter	0.01
Porosity	0
Air resistance	0.3
Van Genuchten n	0.6
Median pore size	0.9
Distribution of pore size	0.9
Ks estimate (Han et al. 2008)	0.4
Ks estimate (Nemes et al. 2005)	0.02

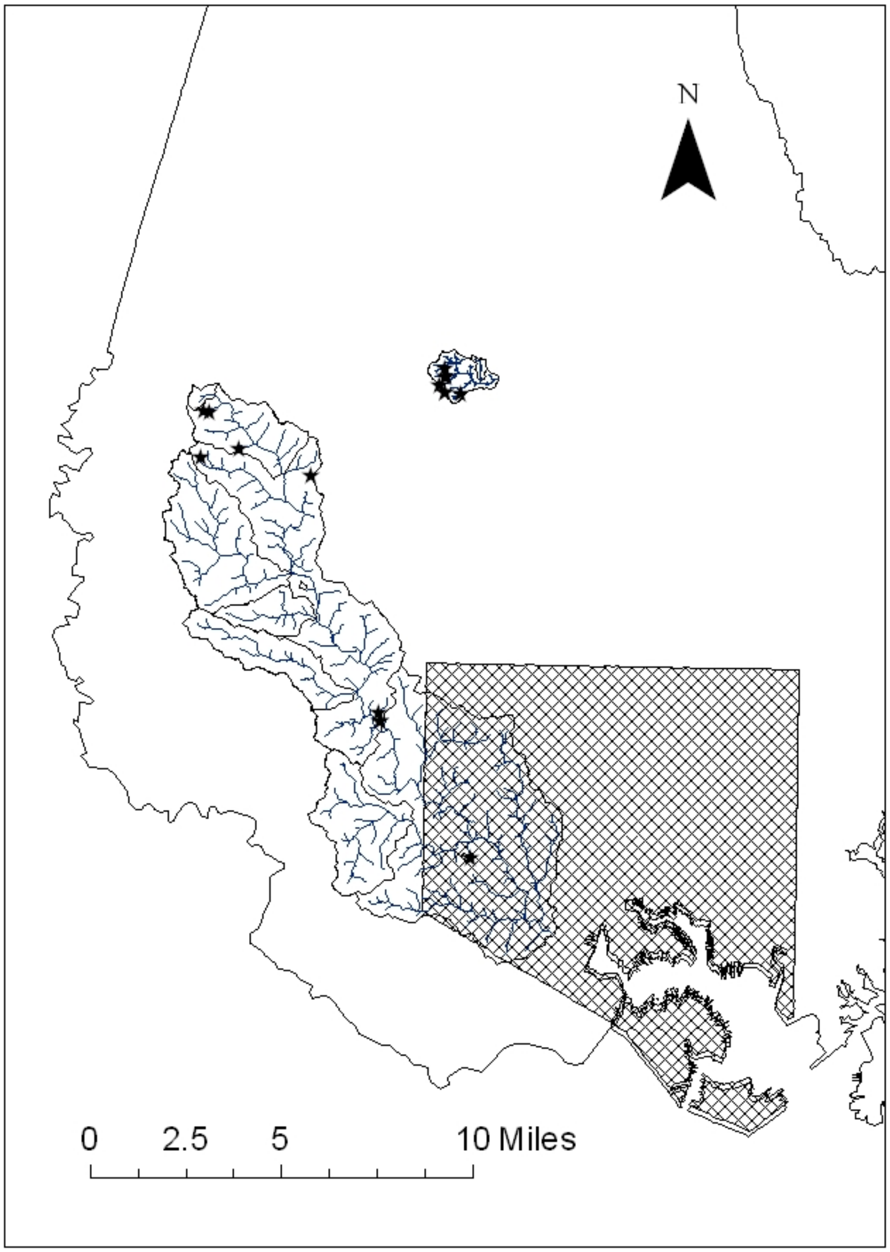

Figure 4.1 Infiltration measure site map.

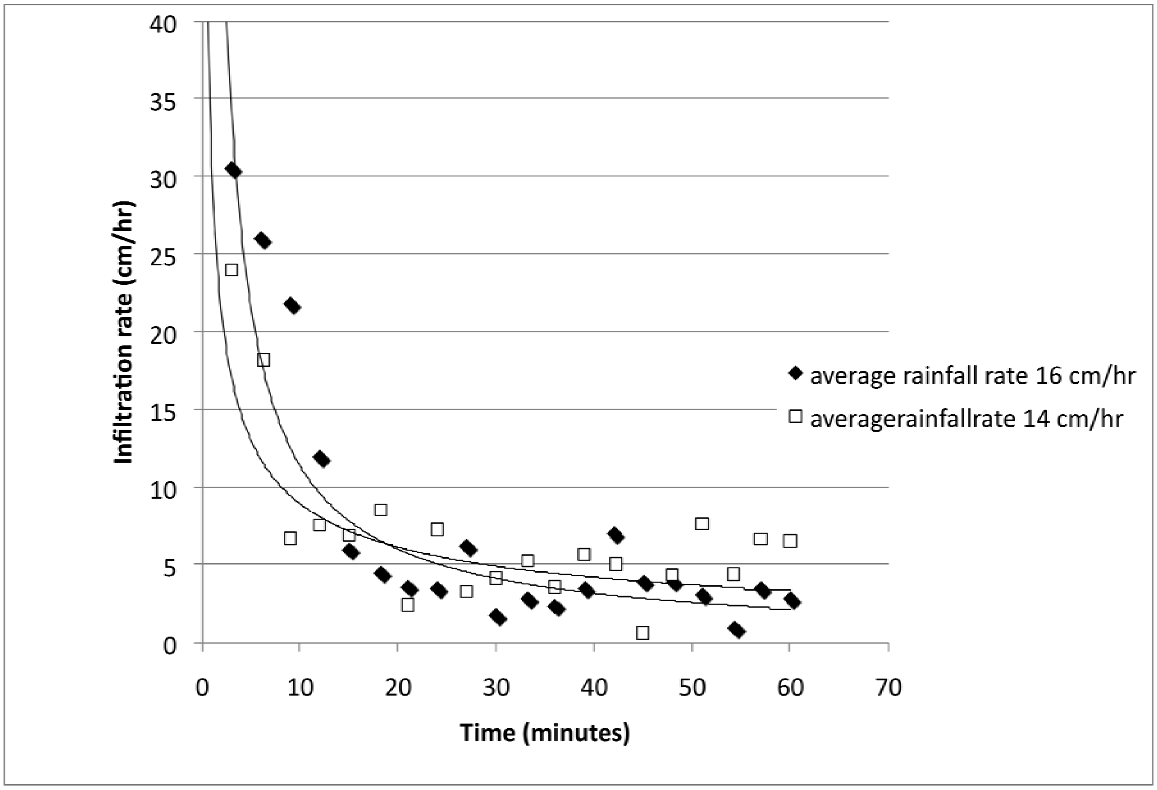

Figure 4.2 Saturated infiltration rate estimation: Best-fit functions were created and T(40) was used to estimate the saturated infiltration rate.

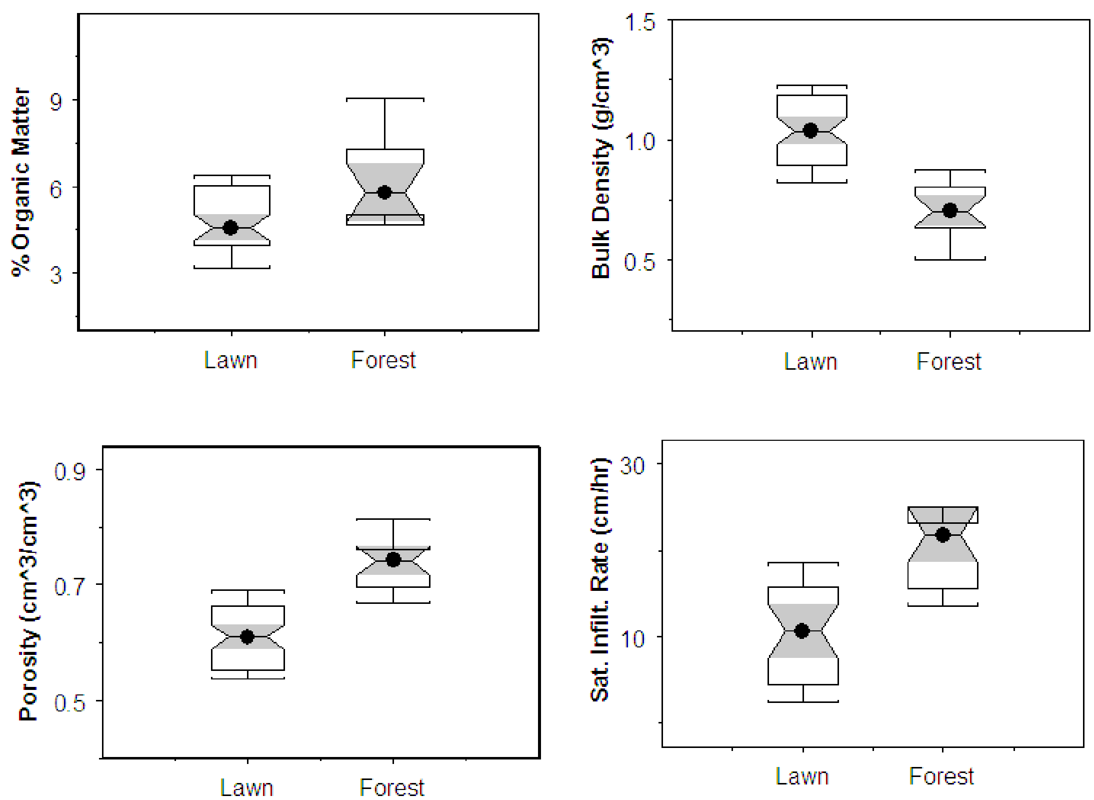

Figure 4.3 Structural soil properties differed significantly between sampled forest and lawn sites.

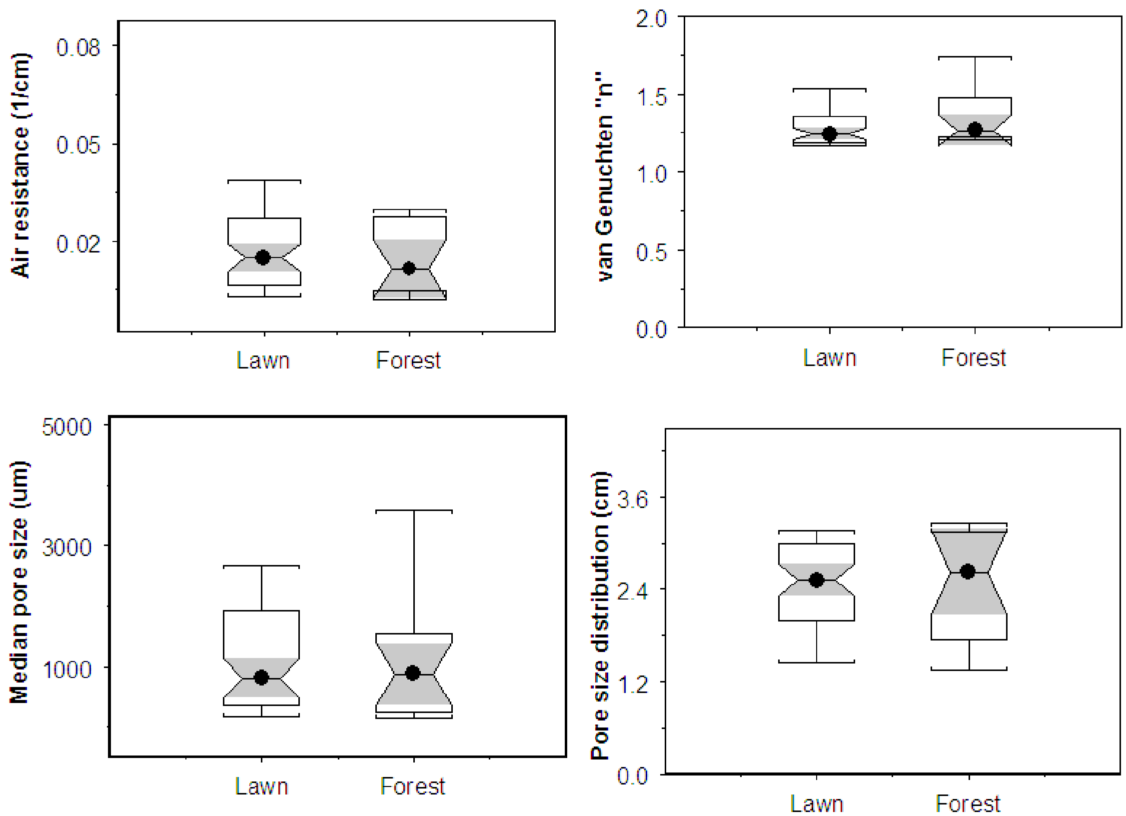

Figure 4.4 Mineral soil properties based on water retention characteristics did not differ between forest or lawn soils.

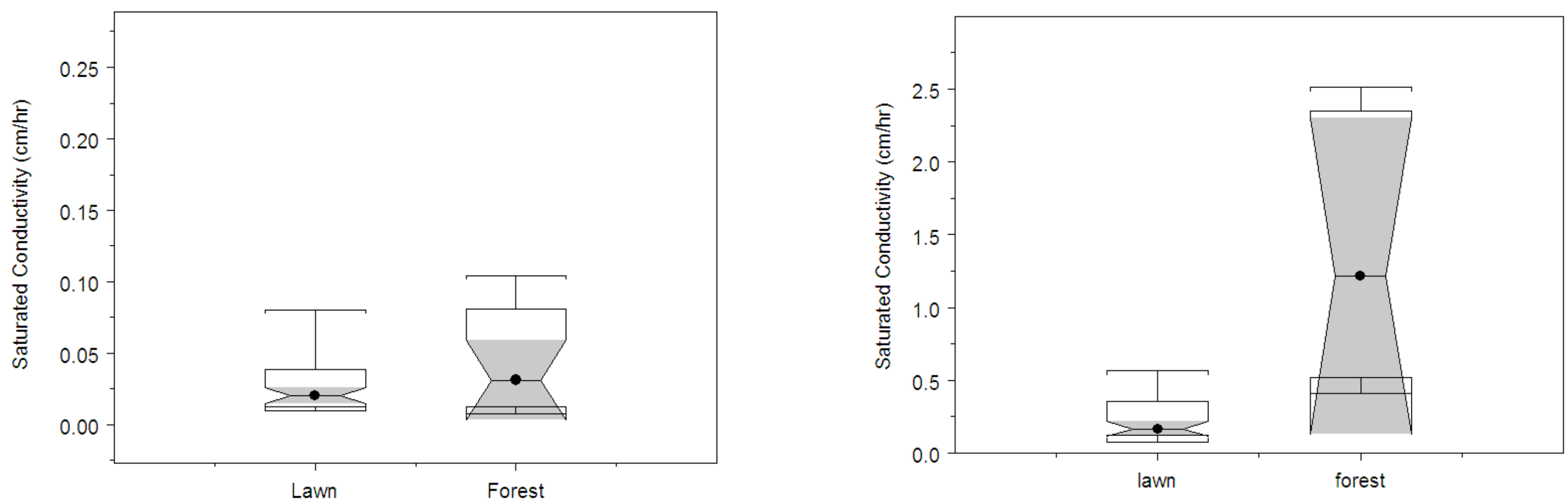

Figure 4.5 Comparison of saturated conductivity estimates Han et al. (2008) on left, Nemes et al. (2005) on right, in sampled lawn and forest soils(p-value = 0.02).

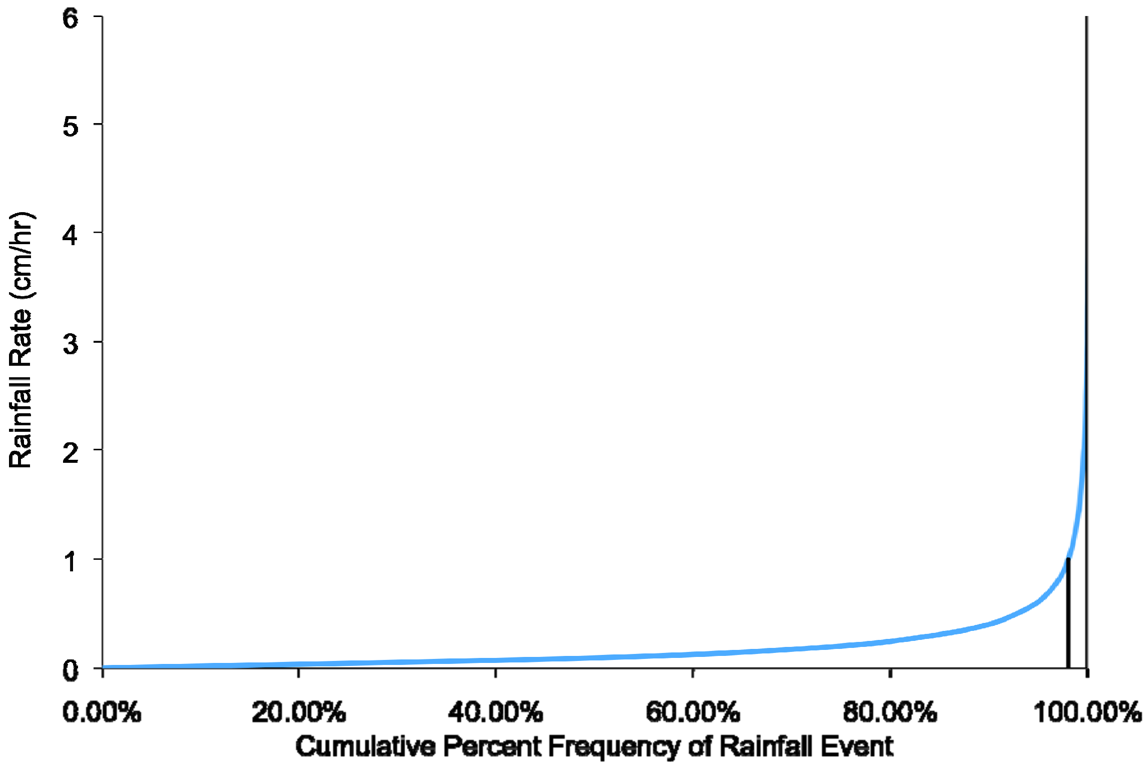

Figure 4.6 Cumulative percent frequency of 50 years of recorded rainfall events at BWI in blue line; black lines indicate range at which saturated overland flow would have occurred from most compromised soils in study.

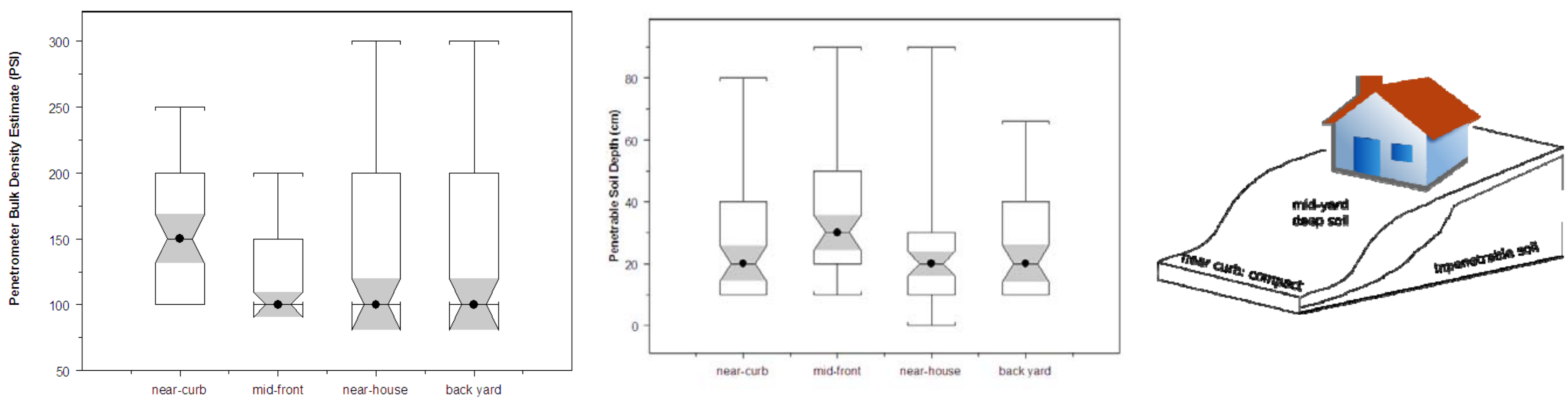

Figure 4.7 Parcel-scale variation in bulk density (on left); soil depth as estimated by cone penetrometer (in center); cartoon of parcel-scale soil profile depicted (on right).

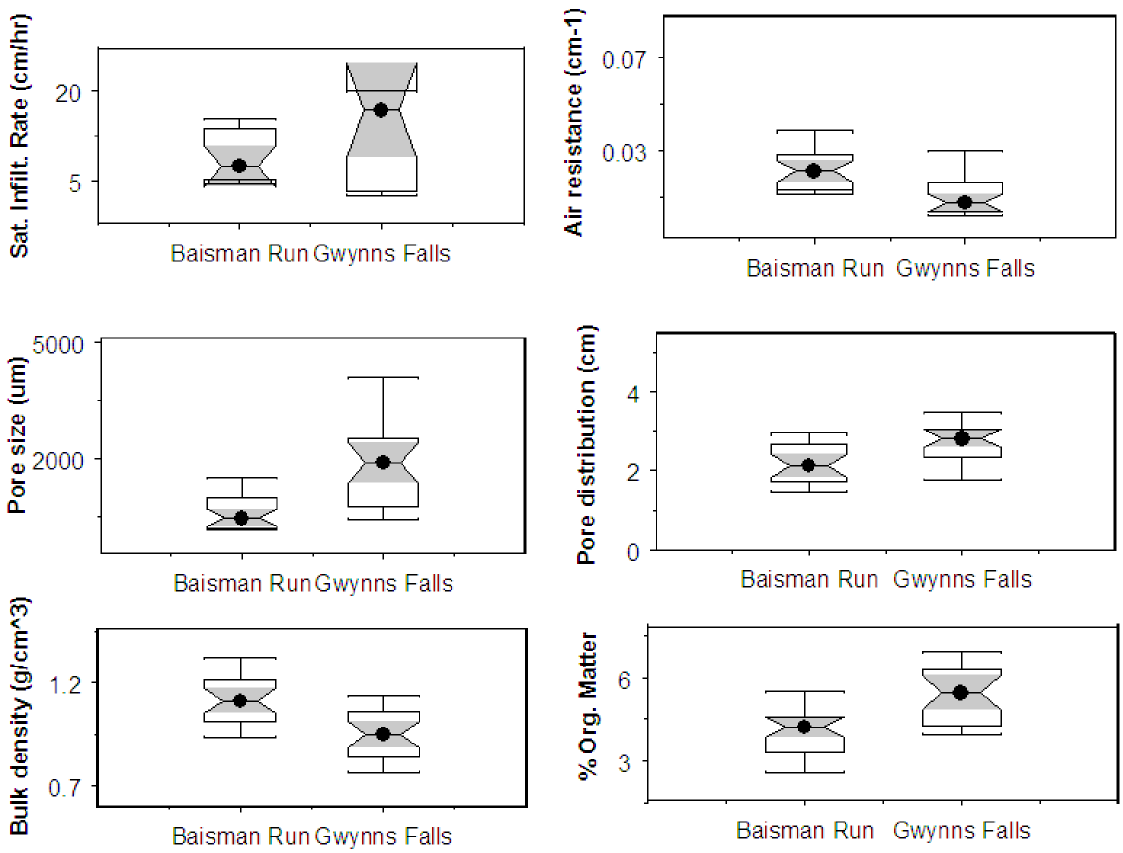

Figure 4.8 Significant differences between Baisman Run and Gwynns Falls soil properties.

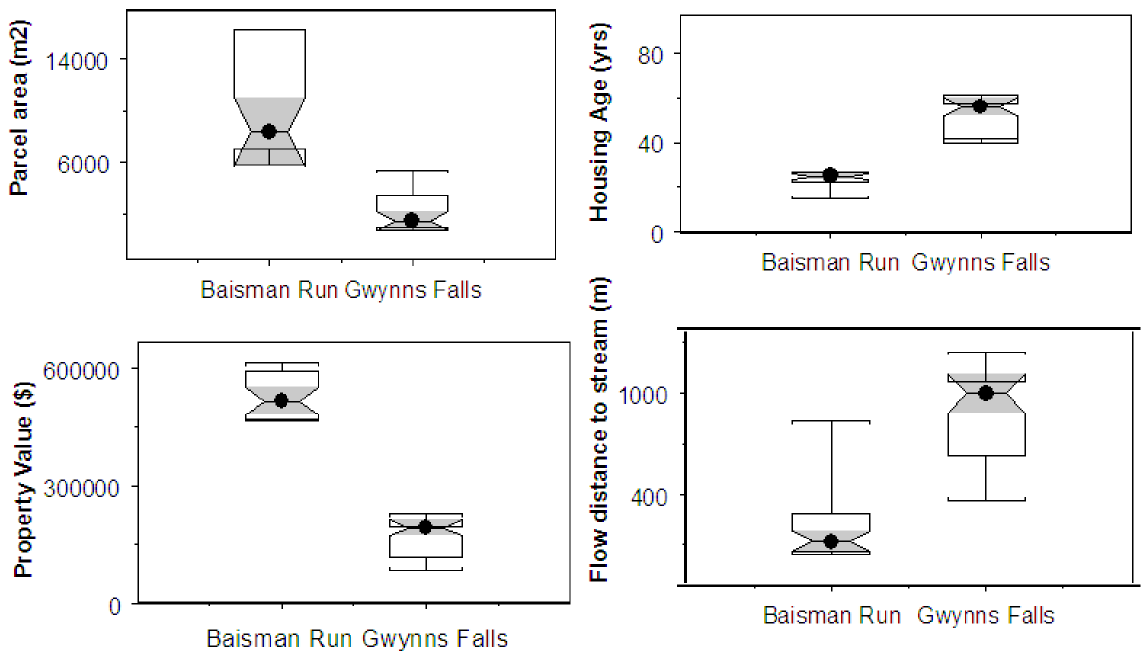

Figure 4.9 Differences between assessed social and physical factors in Baisman Run and Gwynns Falls.

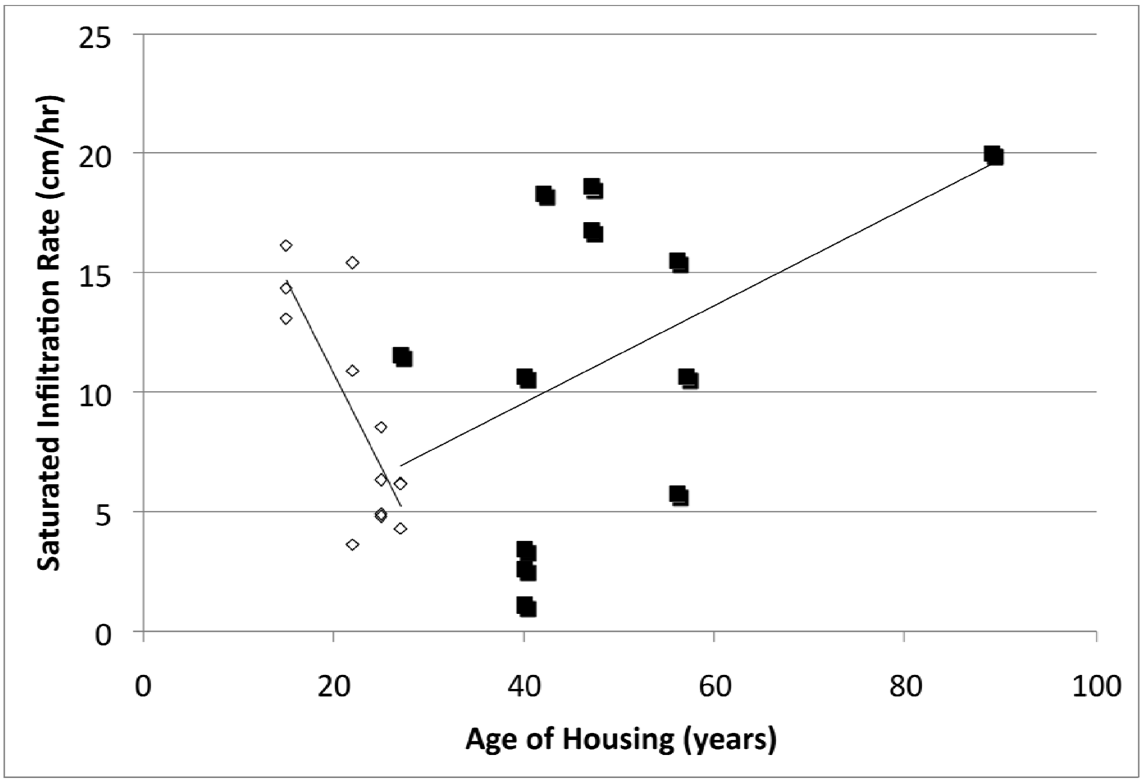

Figure 4.10 Impact of housing age on saturated infiltration rate in Baisman Run (white diamonds) vs. Gwynns Falls (black squares) watersheds.

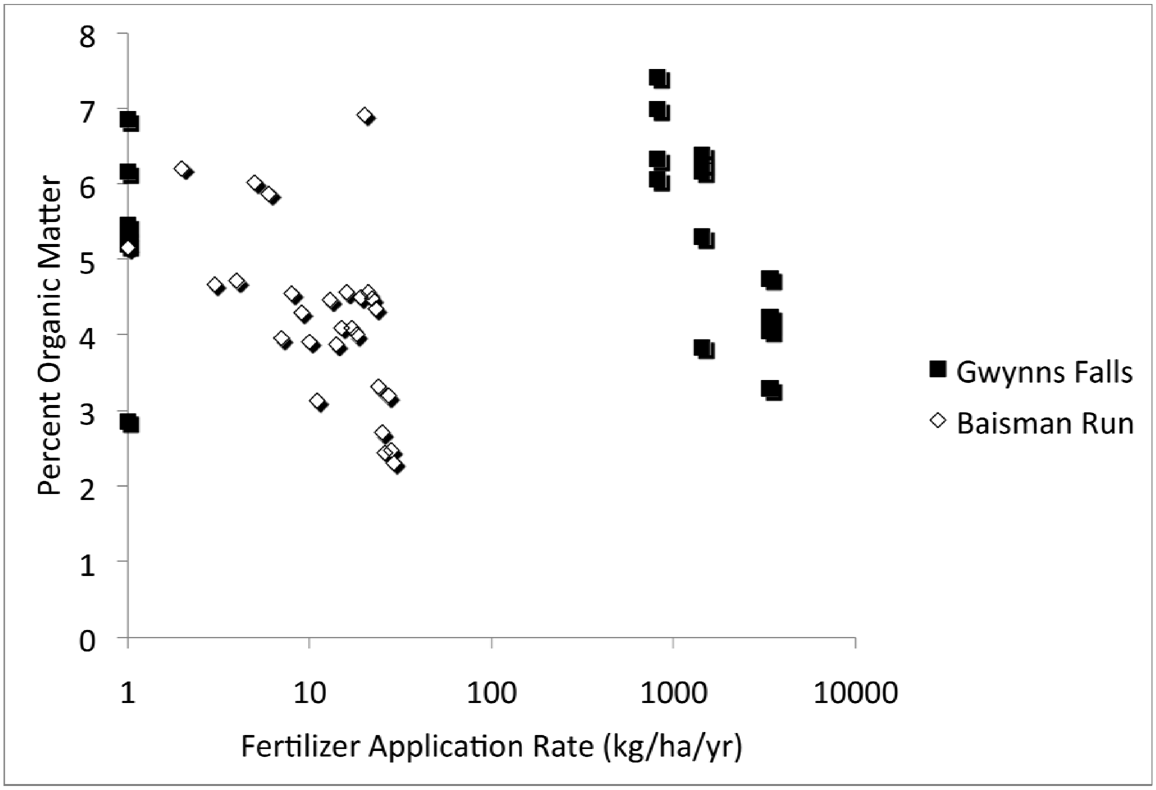

Figure 4.11 Correlation between fertilizer application rate (log scale) and percent organic matter in residential soils in Gwynns Falls and Baisman Run.

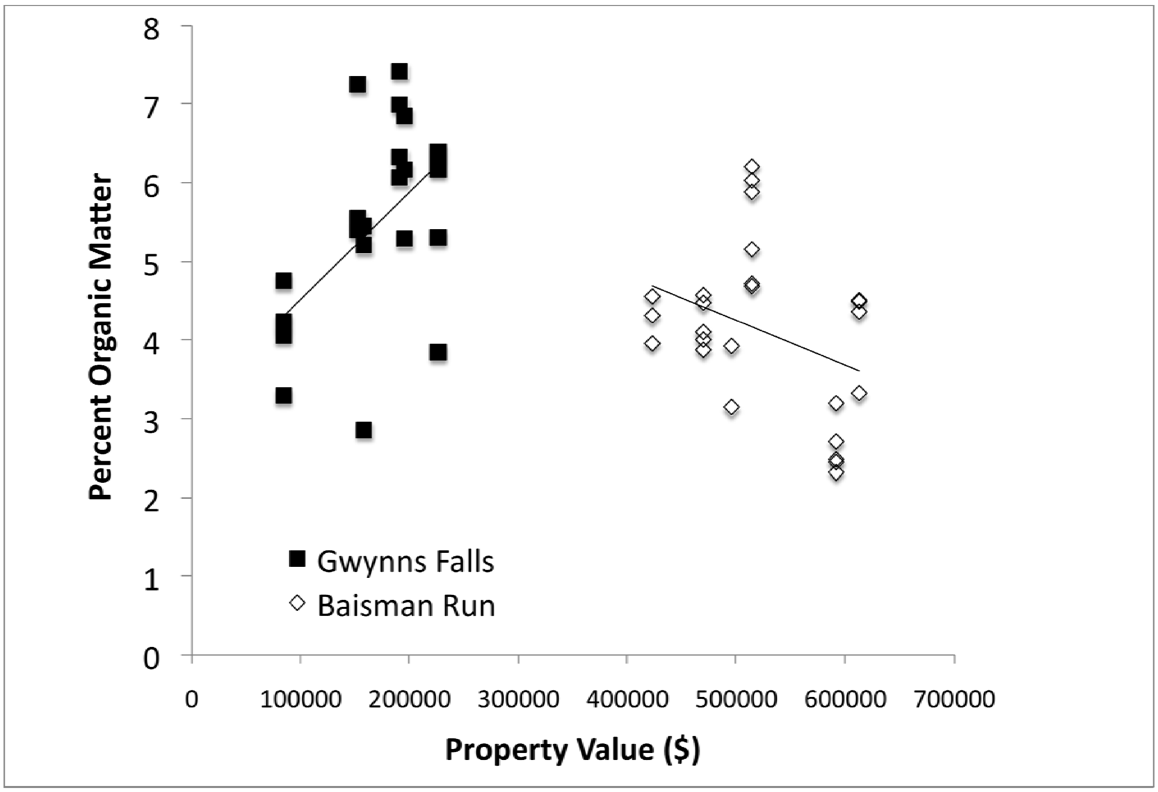

Figure 4.12 Correlation between percent organic matter and property value.

CHAPTER 5. CONCLUSION

This dissertation addressed three topics related to the data needs for land managers in addressing LID potential and limitations in suburban areas in controlling nitrogen export from urban and urbanizing catchments. These topics included: 1) an assessment of the NLCD for urban hydrologic purposes; 2) an evaluation of fine-scale residential features driving suburban nitrate source / sink dynamics; and 3) an examination of the variance of soil properties within and among suburban lawns.

Watershed management planners rely on modeling for estimating pollutant source loading and evaluating loading capacities to meet national water quality goals. The prevailing assumption has been that spatially explicit land cover may be more important for small areas of interest (Strayer et al. 2002) and that use of spatially distributed process-based models is frequently limited by a lack of fine-scale data that represents the heterogeneity of the urban environment.

This dissertation sought to identify critical features of the heterogeneous urban landscape that characterize nitrate source/sink dynamics and hydrology driving the delivery nutrients. This dissertation finds that 1) the frequently used NLCD does not consistently capture the heterogeneity of urban hydrologic purposes; 2) that residential infrastructure and wetlands better indicate suburban nitrate source / sink dynamics than spatially explicit land cover data; and 3) the altered hydrology of residential lawns likely affects watershed-scale hydrology, but the complexity of human-lawn interactions cannot be quantified on a parcel-scale and the parcel-scale variability in lawn hydrology warrants further investigation. This chapter outlines the conclusions from chapters 2, 3 and 4. Summary conclusions are included as they relate to issues of scale and suburban nitrate-N transport. Finally, overall significance, planning implications and future work are discussed.

5.1 Characterizing heterogeneous urban environments using the NLCD

The usefulness of the nationally available NLCD was evaluated for urban hydrologic applications. This study indicates that regardless of scale the NLCD estimates of percent canopy and impervious cover are 10 percent lower than estimates based on high-resolution data. This 10 % difference in percent impervious cover may result in differences in annual discharge and nitrogen load as much as 40,000 m^3 and 80 kg. In addition, within 1 km^2 areas, the NLCD appears to have important biases < 10 and > 70 % cover. Areas less than 10 % impervious surface approach an important threshold associated with stream degradation (Booth and Jackson 1991). The NLCD underestimates imperviousness in low-density areas and NLCD low-density land classes are composed of the most variable land cover composition. In addition, the proportionality of the modeled error associated with the NLCD under-prediction of imperviousness is greatest in low-density developed areas. Thus, the use of the NLCD for land cover parameters and residential areas in urban areas is most limited for the most rapidly growing land use type (Brown et al. 2005) associated with the highest metropolitan nitrate transport (Shields et al. 2008).

The ratio of total impervious area and effective impervious area (see Walsh et al. 2005) differs according to development density, which further limits the applicability of the

NLCD to hydrologic study. Fine-vegetation / lawn area comprises a large proportion of low-density residential areas and has reduced infiltration rates relevant to hydrologic modeling. However, lawn land cover is incorporated in a large number of land use categories with no ability to directly extract this land cover from the NLCD. Combined observations of aerial photography and site surveys yield the best results in determining land use, development characteristics, and the connectivity of features (NRC 2008). Thus, use of finer-resolution imagery or orthophotography is recommended when deriving land cover parameters for process-based modeling of urban areas.

5.2 Fine-scale Residential Patterns: Impact on Nitrogen Source/Sink Dynamics

Fine-scale aspects of residential pattern and management were assessed to determine key features driving nitrogen source / sink dynamics in suburban catchments. Our findings conclude that nitrate concentrations of suburban streams are better characterized by watershed infrastructure than land cover composition. Within septic-managed watersheds we find that population density, septic location and presence of wetlands explain source / sink dynamics. However, the impacts of residential pattern in catchments served by sanitary sewers were not obvious due to timing of nutrient transport and displacement of nitrogen by sewer infrastructure. Thus, the sewer infrastructure provides a localized benefit to stream water quality; whether the water quality improvement persists on a larger scale depends on downstream infrastructure and centralized wastewater treatment.

These results hold nutrient management implications for septic-managed watersheds. The results of Chapter 3 show that septic system density is directly proportional to septic system density, but this effect is not obvious in areas served by sanitary sewers. Thus, limitation of residential density in septic-managed catchments should be considered, and areas of high septic system density should be targets for nutrient management programs or installation of sewer infrastructure. Setback requirements based on length of overland flow, rather than Euclidean metrics, may be more effective in reducing nitrate-N pollution to suburban streams. Preservation, restoration, and creation of in-line wetlands hold potential for reducing nitrate in residential headwater streams. Results suggest that consideration of fine-scale heterogeneity, both composition and connectivity, expressed at the scale of neighborhood infrastructure and design is key to understand links between urban landscape structure and nitrogen fluxes.

5.3 Characterizing the soil properties of residential lawns

This study examined saturated infiltration rates and water retention differences between residential and forested soils, and the variance of these soil properties within and among suburban lawns. Structural soil properties of lawns were significantly different than measures collected in forested sites despite similar mineral properties, suggesting reduced macroporosity of lawn soils. Loss of soil structure and macroporosity in urban areas is commonly reported due to construction practices (Gregory et al. 2006, USDA 2001). The median saturated infiltration rate in residential lawns was approximately half of rates measured in comparable forest soils; however, these rates are highly variable. Within-parcel differences in bulk density and soil depth indicated that runoff from residential lawns is less likely from the mid-front yard and backyard, but near-house and near-curb areas are more likely to saturate. According to regional rain records, parcel-scale overland flow events are rare. However, reduced soil structure of residential lawns suggests reduced in-field water retention, which will affect watershed-scale hydrology. In addition, Dunne overland flow or return flow may be more likely on the lawn edge closest to the stormwater conveyance system.

We assessed the variance of lawn soil properties according to various physical factors, including percent coarse vegetation, land use legacy, and effects of topographic position. In addition, we considered the impacts of social factors, including age of house construction, property value, and fertilizer application rate. The range of saturated infiltration rates in residential lawns was large, and the utility of social and physical data to explain this range of soil properties in residential lawns was limited. While social factors related to lawn establishment appear to influence infiltration rates and percent organic matter, the impact of social factors on soil properties is non-monotonic and differs regionally among the sites assessed in this study. These results hold implications for incorporating the range of soil parameters of residential lawn properties into hydrologic models.

5.4 Summary conclusions

The heterogeneity of the urban landscape encompasses differences in land management decisions on the part of the homeowner and land use planner, such as fertilizer application rates, sanitary sewer and SWM infrastructure, or preservation of wetlands. The interconnectedness of these decisions as they relate to modified nutrient source / sink dynamics and hydrologic flow paths is defined by a large degree of complexity. Key spatially distributed parameters for process-based modeling of suburban nutrient pollution may not require high-resolution land cover data infrequently available to land managers because waste infrastructure indicates the primary nitrogen source in residential areas. However, altered lawn hydrology and spatially explicit land cover composition and position play a role in affecting the timing of nitrate delivery to streams (Shields et al. 2008), the flashiness of stream discharge, and transport of other non-point source pollutants.

5.4.1 Scale issues

While fine-scale analysis allows better isolation of variables, evaluation of small areas and use of fine-scale data infer an inclusion of extreme values that may be averaged out over larger areas of interest. For example, biases of the NLCD were most obvious in the analysis of 1 km^2 areas. Landscapes < 10 % and > 70 % canopy or impervious cover (biased ranges for 1 km^2 areas, see section 5.1) are not common in the Baltimore metropolitan region for areas exceeding 9 km^2 (Smith et al. 2010). Thus, use of the NLCD for areas exceeding 9km^2 is acceptable due to an averaging of the fine scale biases; however, adding an additional 10 % imperviousness or canopy cover is suggested. However, the fine-scale heterogeneity of urban environments is not well-captured by this moderate-scale land cover dataset, particularly due to the conflation of land cover types into developed categories.

Fine-scale land cover composition or location did not account for the range of nitrate-N source / sink dynamics in residential headwater catchments. Stormwater and sanitary management was the key factor in explaining nitrate stream concentrations. Sub-basin scale residential patterns related to sanitary management, such as septic location and density, were most important to characterizing nitrate-N sources. However, the fine-scale land cover and management impacts on nitrate-N transport were difficult to explore given the difficulty of conducting catchment scale analysis for such a small area of interest. For example, Chapter 3 found a mismatch between derived contributing area and discharge gains, which may be explained with the concept of representative elementary area—the decrease of variability of catchment streamflow with increased catchment size (Wood et al. 1988) and the influence of bedrock topography on spatial patterns of subsurface flow (Freer et al. 2002) that are not averaged out for studies of such small catchments.

Hydrologic properties of residential lawn soils varied within and among parcels and between watersheds. Within parcels, including areas less than 1000 m^2, spatial variation of soils appeared to exist with respect to distance from curb and home. Differences also existed between front and back yards. These results have management implications regarding the parcel-scale application of fertilizer, installation location of septic systems, targeting of infiltration best management practices, and exploration of parcel-scale soil-moisture influences on lawn nutrient cycling dynamics. While structural hydrologic properties of residential lawn soils were compromised compared to forest soils, regional differences explained the most variation among residential lawn soils. Short-length scales of near-surface hydrological processes due to urban heterogeneity (see Tenenbaum et al. 2004) can be explained partly due to intra-parcel and watershed-scale differences. Variation among residential lawns was non-monotonic and difficult to characterize due to complex social and environmental interactions and feedbacks relating to the hydrologic properties of residential lawns.

5.4.2 Suburban Nitrate-N Transport to Streams

Sources and sinks of nitrogen are altered due to management practices occurring at the parcel and watershed scale. Lawns are the source of much of the nitrate-N in residential catchments as they associate with fertilizer application, septic systems and pet waste (Law et al. 2004, Groffman et al. 2004). While lawn cover cannot be directly assessed using the NLCD, percent lawn can be estimated as approximately 25 % both open and low-density areas; however, the range of possible percentages is quite variable. According to our findings percent lawn cover or location does not relate directly to stream nitrate-N concentrations. These results align with previous studies that indicate that while lawn-associated sources of nitrate-N contribute to metropolitan nitrogen loads (Law et al. 2004), lawns are remarkably N-retentive (Groffman et al. 2004).

Previous isotopic analysis of stream nitrate in Baisman Run and Dead Run (Kaushal et al. 2009) confirms that the vast amount of suburban nitrate is derived from wastewater sources. While nitrate-control strategies frequently indicate lawn reduction (CWP 1999), lawns are not a primary source of suburban nitrogen pollution due to the overwhelming impact of wastewater. Nitrogen reduction should target wastewater point sources due to the nitrogen retentiveness of suburban lawns (Groffman et al. 2009). However, other types of suburban non-point source pollution are derived primarily from lawn management practices, such as pesticide and herbicide pollution (USGS 1999); thus, lawn management impacts on stream health remain an issue of concern.

While lawn reduction may also be a goal to reduce runoff (CWP 1999), this dissertation indicates that overland flow from most suburban lawn area is rare. The altered hydrology of residential lawn soils varied substantially and is difficult to quantify according to social and physical factors address in this dissertation. Factors associated with lawn establishment appeared to be most important, including year of house construction and fertilizer application rate. Fertilizer application rate, surprisingly, was inversely proportional to percent organic matter, which we attribute to the impact of over-management, the impact of poor lawn quality on human behavior, or the impact of good lawn quality on management behavior. The difference between structural properties of lawn and forest soils indicates that overland occurs more frequently and water retention is reduced in lawn soils compared to forest floors. While overland events from mid-yard lawns are rare, saturation of near-curb portions of the lawn are more likely. Thus, targeting lawn infiltration practices at the near curb may have the greatest impact in disconnecting flow and nutrient sources from receiving streams.

5.5 Significance

This dissertation examined fine-scale residential patterns relevant to nutrient transport to streams using datasets typically available to land managers. To this end, the study evaluated what aspects of fine-scale pattern relate to nitrate-N source / sink dynamics and residential lawn properties. This inquiry is novel in its multi-faceted approach to examining aspects of nutrient transport within suburban environments. While urban-rural gradient studies of changes in hydrology and nitrogen sources are common, less study exists examining aspects of nutrient transport related to differences among suburban neighborhoods of varying character.

While land cover composition explained nutrient transport differences *between* land uses (Poor and McDonnell 2005), this metric does not extend to comparing effects *among* suburban headwater catchments. Stormwater and sanitary management impacts are much greater than the relationship between land cover and the temporal variation of export of nitrate-N (Burns et al. 2001). While septic management generated greater nitrate-N sources in suburban catchments, potential exists for wetlands to restore water quality in catchments exporting the majority of nitrogen during low or moderate flows.

While studies of urban soils are becoming increasingly common, little work, if any, has examined hydrologic differences in residential soil properties within and among suburban parcels. Little work exists to relate anthropogenic lawn management factors to soil properties in human dominated landscapes. Such study is limited due to the difficulty of attaining permission from homeowners to dig holes and collect samples from their lawns. Most lawn studies are carried out on control plots to isolate impacts. However, nutrient source/sink dynamics and parcel and catchment scale hydrology do not occur in isolation and are subject to the interaction of multiple complex social and environmental processes.

The implications of this dissertation suggest that upgrading waste management infrastructure, preservation or conservation of wetlands, and modifying lawn management strategies hold potential for reducing nitrogen export from residential areas and quickflow in residential streams. The results of this study also provide information regarding altered hydrologic properties that can be used to examine catchment-scale impacts of low-impact development strategies using process-based models.

5.6 Planning tools

Priority funding areas (PFAs) exist within Maryland with the goal of targeting state funds towards areas that multiple stakeholders have identified for growth. However, PFAs have not been well integrated into land use decision-making, funding has not been exclusively directed towards these areas, and the existence of PFAs has not limited growth outside of their boundaries (Lewis et al. 2009). For example, the septic-managed Baisman Run area examined in this dissertation is outside of these priority areas, and much development has occurred in this area since 1997, the year that Maryland PFAs were initiated. Despite the lack of past success in directing growth, these boundaries still exist and could be better integrated into land use decision making to guide watershed-planning efforts.

This dissertation has cited that the largest source of suburban nitrate is wastewater management. While sewered systems appeared to mediate the impact of population growth on stream nitrogen loads, these systems within Baltimore are typically old and in need of repair. The Baltimore consent decree with the U.S. EPA has directed millions towards sewer improvements within Baltimore City and County. While the repairs are much needed and highly effective, the cost of infrastructure maintenance is very high. The cost of annual sewer and water costs for dispersed developments located far away from treatment plants costs 35 to 50% more than compact developments close to treatment plants (depending on lot size). Thus, the use of PFAs could provide a strategy for future cost savings with respect to infrastructure maintenance.

Little information currently exists for the targeting of low impact development strategies. By targeting lawn infiltration practices at the near-curb, there is a greater likelihood of hydrologically disconnecting lawns from streams. Thus, when reduction of impervious surface by street narrowing or change in street design is considered as a best management practice (EPA 2005), these efforts should include a buffering of the denser near-curb soils to maximize stormwater reduction efforts.

This dissertation holds implications for the current development of watershed implementation plans, which will be required by all jurisdictions regulated under Phases I and II of the National Pollutant Discharge Elimination System (NPDES). These jurisdictions within the Chesapeake Bay are required to establish total maximum daily loads and plans to reduce their watersheds' loading by 40 percent. The results of this dissertation hold implications regarding data sources, nitrate source sink dynamics and lawn infiltration rates, which can be integrated into current planning efforts.

5.7 Future work

Assessing residential pattern impacts on stream nitrate loads was limited by the selection of study sites with "sliver" catchments of < 5 ha. In addition, capture of fine-scale impacts in sewered watersheds may require a storm event sampling approach to capture "first flush" water chemistry samples. Thus, future study should approach the impacts of fine-scale features within septic-managed watersheds of larger size and storm-scale sampling in sewered catchments. Extension of this study to other regions is necessary to evaluate the applicability of these results to other regions beyond metropolitan Baltimore.

The impact of hydrologic soil property variation within and among lawns is worthy of further investigation. Reduced hydraulic conductivity and saturated infiltration rates of residential lawns are likely to alter the timing of catchment scale hydrologic connectivity of soil moisture and connectivity between nitrogen sources and receiving streams. Investigation of the impacts of reduced infiltration rates of lawn soils on catchment scale soil moisture and nitrate delivery can be carried out using spatially explicit process-based models.

The objective of this dissertation was to define the most critical features of the heterogeneous urban landscape for use by managers in addressing LID potential and limitations in suburban areas in reducing nitrogen loading to streams. Land cover and land use are good indicators of nutrient fluxes to streams at a regional scale. However, this relationship breaks down within smaller areas of interest within the heterogeneous urban landscape. This breakdown was previously attributed to the lack of spatially-explicit land cover data. However, the findings from this dissertation suggest that regional land cover may be a surrogate measure for waste management strategy. This dissertation finds that the impact of septic systems on stream nitrate is spatially-explicit; however, the spatiality of sewered catchments cannot be assessed directly because the source is displaced downstream. In addition, the hydrologic properties of residential soils are spatially explicit on the parcel scale due to differences in lawn management behavior. The impact of lawn management on in soil properties within and among residences may also affect nitrogen retention time in residential lawns due to their impact on percent organic matter and subsequently subsurface or return flow. Future study of fine-scale dynamics in other urban landscapes will broaden management implications of these findings within Baltimore and beyond.

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APPENDIX A: PERMISSION LETTER AND CONSENT FORM

Baltimore Ecosystem Study

UMBC, TRC Building, Room 134 • Baltimore, MD 21227 • 410-455-8019

Date

Dear resident:

My name is Monica Smith, and I am a graduate student at the University of North Carolina, Chapel Hill working in collaboration with Baltimore Ecosystem Study. The Baltimore Ecosystem Study (BES) conducts research on metropolitan Baltimore as an ecological system. The program integrates biological, physical, and social sciences. The program integrates biological, physical, and social sciences. As a part of the National Science Foundation's Long-Term Ecological Research Network, BES seeks to understand how Baltimore's ecosystems change over time. The ecological knowledge created by BES supports educational and community-based activities, and interactions with the Baltimore community. See http://bes.lter.org for more detail.

As part of my dissertation research, I am seeking to understand the relationship between residential lawns and storm water runoff. I would like your permission to measure how quickly water runs off from the surface of your lawn. I am asking for your permission to make these measurements from spring and summer 2007. If you agree, I would choose three spots in your lawn to insert a 1 ft. diameter metal ring 3 inches deep to hold a device called an infiltrometer. The infiltrometer contains 5 gallons of water that sprinkle from the bottom to simulate rain. I would remove and replace three 10 inch x 10 inch sections of grass at each of the three spots in the yard to collect the water that runs off. I will replace the 3 pieces of sod to cover these holes. I have tested this device several times in my own yard and find that it causes only minor visible lawn damage at the edges where the sod is replaced. This damage disappears in 2 weeks after grass growth. In addition, I would like your permission to use your outside water spigot to fill the infiltrometer, but I can bring large water containers to your yard if you prefer.

While collecting these measurements, as another component of the work I am asking your permission to use a device called a soil penetrometer at 18 sites to compare soil compaction in the back yard and front yard and to compare compaction near the house and street to middle of the yard. This device has a point of similar width to a ball-point pen. When I press down on the machine, it reports the soil's resistance to that push. This device does not leave any visible effects.

Also with your permission, I will extract six shallow 4-inch soil cores (2 from each of the 3 holes described for the infiltrometer) and replace this soil and grass. These soil samples will be used to measure soil texture, density, and "saturated hydraulic conductivity"--the rate at which water flows through your soil. If you wish, you can receive a report of your soil properties.

The set up and collection of these measurements will likely take several hours. No equipment would be left in your yard, and you should not be able to detect any permanent trace of these measurements having been taken. Based on my results, I may need to return to your property again for second measurements. However, I will contact you again prior to collecting these measurements.

Some residents of your neighborhood and others previously participated in a survey on lawn management practices conducted by a former UNC graduate student, Neely Law. I have enclosed a copy of the article that resulted from this research. It would be beneficial to supplement my study with the data from this survey because lawn management practices influence rain infiltration into the soil. However, the data are protected for your confidentiality, and I am required to obtain additional permission from you in order to see or use these data. Please indicate on the attached postcard whether you participated in the lawn management study AND are willing to allow me and other Baltimore Ecosystem Study researchers to access this data.

Please let me know whether you are willing to grant permission by filling out and signing the enclosed postcard. If you have any questions, please don't hesitate to email me at monica_smith@unc.edu or call my cell phone, (202) 494-4675. I would be more than happy to demonstrate these devices to you or provide more information or photos of how these devices operate. Please let me know what days and times are convenient to carry out my study. I will let you know when I arrive to do the study. If you have any questions, please do not hesitate to ask!

Sincerely,

Monica L. Smith

Doctoral Candidate, UNC Chapel Hill

Consent Form:

Name and Address: ______________________________

____

Phone/email (preferred contact):

____

____

___ Yes, I grant permission for the described experiments. These data may be shared with other Baltimore Ecosystem Study scientists. I would prefer that the work is conducted on the following days and times

________________________________,

___ I would like further information, please contact me at #: _______________

___ I would not like to participate in the described experiments.

Comments: